Fatigue strength of welded connections
made of very high strength cast and rolled steels

R.J.M. Pijpers
Fatigue strength of welded connections
made of very high strength cast and rolled steels

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft;
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben;
voorzitter van het College voor Promoties
in het openbaar te verdedigen op dinsdag 18 oktober 2011 om 12.30 uur

door

Richard Johannes Mathias PIJPERS

Civiel ingenieur,
geboren te Limbricht
Dit proefschrift is goedgekeurd door de promotor:
Prof. ir. F.S.K. Bijlaard

Samenstelling promotiecommissie:
Rector Magnificus, voorzitter
Prof. ir. F.S.K. Bijlaard, Technische Universiteit Delft, promotor
Dr. M.H. Kolstein, Technische Universiteit Delft, copromotor
Prof. dr. I.M. Richardson, Technische Universiteit Delft
Prof. ir. C.A. Willemse, Technische Universiteit Delft
Prof. ir. H.H. Snijder, Technische Universiteit Eindhoven
Prof. A. Nussbaumer, Ecole polytechnique fédérale de Lausanne
Dr.-Ing. S. Herion, Karlsruher Institut für Technologie

This research was carried out under project number MC8.06265 in the framework of the Research Program of the Materials innovation institute (M2i) in the Netherlands (www.M2i.nl).


Printed by: Wöhrmann Print Service, Zutphen
Cover design: Marjolein Pijpers - Van Esch
Cover photo: Copyright © 2010 Sam Rentmeester

Keywords: Very High Strength Steel, Cast Steel, High Cycle Fatigue, Welded Connections

Copyright © 2011 Richard Pijpers. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission in writing from the proprietor.
Acknowledgements

Working on a PhD can be turbulent, especially when an experimental program is involved. When the opportunity of doing a PhD research was given to me, I did not doubt for a second. The Stevin Laboratory offers an outstanding possibility of testing structures on a macro scale. Being able to spend time in this lab was a great pleasure. I will never forget the sound of the dynamic loading of a full scale truss under fatigue loading, as if an old giant was breathing during his sleep.

First, I would like to thank my supervisors, Frans Bijlaard and Henk Kolstein, for their dedicated guidance. You gave me a lot of freedom in forming the research program. I know it was not easy in these financially hard times not to think of lab costs, but you always encouraged me to go on with the intended test program. This gave me the opportunity to do fatigue tests on a unique scale. I learned the direct scientific approach, as well as the indirect lessons involved in doing research, such as writing research proposals, discussions with the market and setting up test facilities.

Furthermore, I would like to acknowledge the valuable discussions and input of the committee members Dr. Herion, Prof. Nussbaumer, Prof. Richardson, Prof. Snijder and Prof. Willemse.

My special gratitude goes to my dear technicians in the lab, Arjen van Rhijn en John Hermsen. Without you, it would never have been possible to set up the large test frame for the truss structures and all the other test frames that were especially assembled for the research. You were a great support. You were my right hands in the lab. I especially enjoyed our shared passion for music. Most of our musical preferences totally match; we found each other in jazz. Unfortunately, I could not convince you with Bach.

Many thanks go to all my other colleagues in the lab and in the steel group. I think I will have been one of the few who have shared the room with four girls at Civil Engineering and Geosciences. Who says structural engineering is a man’s world? Edi, Carmen, Sofia and Neşen, thank you for the nice time! I would also like to mention the nice collaboration with master students Koen, Fatih, Balázs and all the student assistents of CT1112, ‘Technisch Tekenen’.

With the members of Cluster 8, Advanced Joining and Disassembly of the Materials innovation institute (M2i), I had fruitful discussions on welded connections. Thanks for your contribution. Also I would like to express my gratitude to M2i and the steel society ‘Bouwen met Staal’ for their support of the research. The attendance of representatives of a large group of engineering firms and contractors in the user group meetings was very inspiring.

Two German companies, Vallourec Mannesmann and Friedrich Wilhelms Hütte, gave the research a boost providing the essential materials for testing the truss structures. I would like to thank them for their contribution of circular hollow sections and cast joints and plates for the current research. Also thanks to Huisman Itrec and Mercon Steel Structures for the manufacturing of the specimens.

I would like to acknowledge the contribution of Onno Dijkstra of TNO in the fracture mechanics modelling, providing me with the FAFFRAM routine and a lot of insight in the theory of fatigue crack growth. I greatly enjoy working for TNO now and wish to thank my colleagues at Structural Reliability for their support in the last months.
My dear friends from ‘RIJSMINA’, ‘BANG’, Civil Engineering and music made it possible for me to escape the focused life of a PhD researcher. Special thanks to Christian Louter, for your willingness to be my paranymph, friendship and our companionship in the PhD work.

Finally, I would like to thank my parents, brother and parents in law, and my dear wife Marjolein. I could not have done the work without your everlasting support and love.

Richard Pijpers, September 2011
To my parents,
and my wife Marjolein
Summary

Fatigue strength of welded connections made of very high strength cast and rolled steels

Although Very High Strength Steels (VHSS) with nominal strengths up to 1100 MPa have been available on the market for many years, the use of these steels in the civil engineering industry is still uncommon. Lack of design rules and manufacturing experience, scarcity of special sections and conservatism limit the current structural application of VHSS. The introduction of EN 1993-1-12 (2007) permits the use of steels up to S700. Steels with higher yield strength are not yet covered in the code. The main goal of the research was the determination of the fatigue strength of welded connections made of VHSS, for an effective application of VHSS in civil engineering and offshore structures. The emphasis was put on quenched and tempered cast and rolled steels with yield strengths of 690 MPa up to 1100 MPa. The research comprised of a literature study, an experimental study and an analysis of the results.

Ideally, use of VHSS should lead to reduced wall thickness in comparison to mild steel solutions. The nominal stress in a VHSS structure is usually higher than in a structure made of lower grade steels, due to the reduced section dimensions, and self weight stresses are lower. In absolute and relative terms, this will lead to higher stress variation under dynamic loading. The fatigue strength of the welded connections is expected to be the limiting design criterion for VHSS structures. In fatigue loaded VHSS structures, high stress concentrations should therefore be avoided. Choosing high class details and high manufacturing quality for VHSS structures is thus required.

An effective application of VHSS is expected in truss-like structures, typically made of hollow sections. The modulus of elasticity of steel is independent of yield strength. Truss structures enable full exploitation of the high material strength of VHSS, because in such stiff structures the deflection is not the governing the design criterion. Improved design of VHSS truss structures should incorporate the application of very high strength cast joints, as an appropriate design of cast joints limits the stress concentrations in the joint. The fatigue strength of cast joints will therefore be relatively high compared to that of regular steel welded joints, as the stress concentration of the connection is limited and welds are shifted out of critical zones. The design and manufacturing process should be carried out in close cooperation with the cast steel foundry.

The total fatigue life of a structural component may be regarded as the summation of crack initiation life and crack propagation life. Notch stress theory shows that crack initiation life increases with yield strength in case of low notch stress concentration. The following parameters were found to be of governing influence on the crack initiation life of unnotched specimens: yield strength, mean stress and surface roughness. In welded specimens, additionally weld shape, plate thickness and loading mode were of influence. The fatigue notch factor of welded connections was determined by the theory of the microstructural notch support, originally conceived by Peterson (1974). An improved weld shape, characterized by increased weld toe radius or decreased weld toe angle, increases the fatigue strength with higher yield strengths. Next to geometric improvement, a compressive mean stress or a compressive residual stress state are beneficial for high strength steels.

Fracture mechanics theory shows that the crack propagation life depends on the crack growth rate as a function of the stress intensity range, which is typically characterized by
crack shape, thickness, width and weld shape. Material parameters in the relation of crack growth rate to stress intensity range, typically presented by the Paris law, are independent of yield strength. If the fatigue life is dominated by crack propagation life, there is no influence of yield strength on the fatigue strength.

Most design codes for the fatigue strength of welded connections, such as EN 1993-1-9 (2005), disregard the influence of yield strength on the fatigue strength. The reason for this neglect is that in welded connections residual stresses are expected to have the level of yield strength and that initial defects in the welds cause the fatigue life to be dominated by crack propagation life.

Materials and specimens for the experiments of the research were selected based on the literature survey. Three types of specimens were tested: specimens of base material, of welded plates and of trusses made of circular hollow sections (CHS) and cast joints. Plate test specimens were derived from base material of rolled steel and welded cast and rolled plates. Crack initiation and crack propagation life were studied as an effect of cyclic loading. Strain gauges were applied on the plate and truss specimens to identify crack initiation, after which crack growth was monitored visually until failure. During the fatigue tests, average and range values of forces, displacements and strain gauge measurements were digitally stored. An alarm system was used which immediately shut down the system in case of crack initiation, which made it possible to indicate the locations of crack initiation on the test specimens visually. In the experiments, crack initiation was defined as the number of cycles at which the strain gauge closest to the crack started to bend off the regular scheme.

The plate test series comprised of base material specimens, X-welded specimens and V-welded specimens. First, base material strips made of S690 and S1100 were tested under tension loading. Next, strip specimens derived from X-welded plates made of S355, S690 and S1100 were tested under tension loading. The majority of the plate tests was carried out on strip specimens derived from V-welded plates, tested under either bending or tension loading. The V-welded specimens were made in three alternative conditions: welded rolled steel to rolled steel parts, welded rolled steel to cast steel parts without use of a backing and of welded rolled steel to cast steel parts with use of a ceramic backing. The selected materials were steel grades S460, S690, S890 and S1100 with similar strength cast steels, G20Mn5, G10MnMoV6-3, G18NiMoCr3-6 and G22NiMoCr5-6 respectively. A V-weld was chosen to be able to make comparisons to the truss test specimens of welded CHS to cast joints, welded from one side only, because of limited CHS diameter.

Additionally, fracture mechanics tests were executed on welded specimens derived from the V-welded rolled steel to rolled steel parts with predefined crack in the base material and the heat affected zone. The fracture mechanics specimens were loaded in three point bending. By pre-defining the crack locations, crack growth could be monitored by potential drop measurements and a camera setup to derive the VHSS material parameters of crack growth based on fracture mechanics theory.

Two truss specimens made of CHS and cast joints were tested. The selected materials for the trusses were CHS made of S690 and S890 and cast joints made of G10MnMoV6-3 and G18NiMoCr3-6 respectively. The trusses contained 14 connections, which were V-girth-welded without backing in welding position vertical up. The welding procedures were similar to those used for the strip specimens that were V-welded without backing, made of S690 and S890. The test frame consisted of a hydraulic jack (Fstat = 10000 kN /
Fatigue strength of welded connections made of very high strength cast and rolled steels

Fatigue strength of welded connections made of very high strength cast and rolled steels, e.g., F_{dyn} = 6000 kN, pull bars and H-girders. Forces were transmitted through rotating supports in the plane of the truss, acting as hinges, to the girders. A static analysis was undertaken before the fatigue tests, which provided information on the strain distribution in the truss. The strain gauge measurements were compared with FEM-calculations, showing about 10% deviation at the governing locations. The test setup made it possible to load the truss specimens cyclically up to 6000 kN with frequency of 0.3 Hz.

The experimental results of plates and trusses were compared to prediction models for crack initiation and crack propagation. The notch stress theory was used for the prediction of the crack initiation life N_i and the linear elastic fracture mechanics theory for the crack propagation life N_p. It was assumed that crack initiation life lasted up to 0.15 mm, and crack propagation from that size onwards to a critical length of half the member thickness or the full member width. The fatigue life predictions of base material cracks and weld toe cracks were compared to the experimental results. The influence factors for thickness, loading mode and mean stress, defined from the literature survey, were used to adjust the parameters that were of indirect importance for the fatigue results. In this way, the test data were adjusted to obtain results for t = 25 mm, loading mode = tension and \( \sigma_{res} = \sigma_y \). This made it possible to address the influence of yield strength on the fatigue life and the influence of crack initiation location, cap or root. Next to weld toe cracks, base material cracks were evaluated. In the statistical analysis, the regression coefficient \( m \) was either taken as a variable, or was fixed to \( m = -3 \) or \( m = -5 \). The characteristic fatigue strength \( \Delta \sigma \) and the mean fatigue strength \( \Delta \sigma_{mean} \) at \( 2 \times 10^6 \) cycles were derived for all regression coefficients for adjusted and unadjusted stress ranges and were compared to the relevant results from literature.

The fatigue strength of base material specimens and X-welded specimens were found to increase with yield strength. The choice of regression coefficient \( b \), which is similar to the slope of the fatigue strength curve \( m \), was of large influence on the outcome of the statistical analysis, determining the mean and characteristic fatigue strength. Slope \( m = -3 \) led to conservative predictions. The fatigue life was found mainly to consist of crack initiation life. In comparison to the fatigue test results, the predictions tended to overestimate the crack initiation life of the base material specimens. The predictions for the crack propagation life were found to be conservative in comparison to the experimental results.

The fatigue strength of specimens made of V-welded rolled steel to rolled steel plates was found to be in the same scatter range as similar specimens made of V-welded rolled steel to cast steel plates. The S890 and S1100 specimens showed a large number of runouts, which were not included in the statistical evaluation with \( m = -3 \) and \( m = -5 \). The runouts gave an indication that with increased yield strength, the endurance limit of welded connections is higher, and that the slope of the fatigue strength curve is closer to \( m = -5 \) than to \( m = -3 \). The fatigue strength of the weld root was found to be lower than that of the cap side, mainly because of a higher weld toe angle in the root. Because of the small number of specimens with fatigue cracks in the weld root for the variants with ceramic backing or without backing, the influence of the backing could not be addressed. Next to weld toe cracks, base material cracks were found in the V-welded specimens made of S460, S890 and S1100, from initial defects.

The experiments on the truss specimens led to the following results. In V-girth-welded connections of cast steel joints and CHS, weld root cracks were found to occur more often
than weld cap cracks, because the quality in the root was lower than in the cap. Fatigue cracks were found in three weld roots of the S890 truss. In the S690 truss, one fatigue crack initiated from the weld root, for which the rising strain values at the weld toe were evidence and the fact that the crack was visible in the middle of the weld, not at the weld toe. Although it had been assumed no cracks would initiate in the cast joints, one crack initiated in a reinforcement position of cast joint made of S690 - G10MnMoV6-3. Any part of a cast joint, also the feeder, riser and cast reinforcement positions, should therefore be checked in the design as being potential crack initiation locations if there is no possibility of grinding after the casting. The fatigue strength of the S890 truss tended to be higher than the strength that was obtained in similar studies on girth welds between CHS and cast joints made of S355. For the weld toe cracks in the root, the truss test results were in line with the plate test results. The results of truss specimens met detail class 71 according to EN 1993-1-9 (2005), although the detail class for girth welds is only valid for wall thickness t < 12.5, whilst the average wall thickness of the specimens was 23 mm.
Samenvatting

Vermoeiingssterkte van gelaste verbindingen uit zeerhogesterkte gewalst en gietstaal

Hoewel Zeerhogesterktestalen (ZHSS) met nominale sterktes tot 1100 MPa al geruime tijd verkrijgbaar zijn op de markt, is de toepassing van deze stalen in de bouw nog ongebruikelijk. Een gebrek aan normen voor ontwerp en fabricage, schaarste van profielen en conservatisme zijn de belangrijkste achterliggende oorzaken voor de beperkte toepassing van ZHSS in constructies. De introductie van EN 1993-1-12 (2007) faciliteert het ontwerpen van constructies met stalen tot sterkte S700. Hogere sterktes zijn nog niet afgedekt in deze norm en constructieve veiligheid zal dus met alternatieve methoden moeten worden aangetoond. Het hoofddoel van dit promotieonderzoek is het vaststellen van de vermoeiingssterkte van gelaste verbindingen gemaakt van ZHSS, voor een effectieve toepassing van ZHSS in dynamisch belaste constructies. De nadruk is gelegd op geharde en ontlaten, gewalste stalen en gietstaalsoorten met vloeigrens 690 MPa tot 1100 MPa. Het proefschrift bestaat uit drie delen, de pijlers van het onderzoek: een deel literatuurevaluatie, een deel experimentele studie en een deel analyse, waarin de experimentele resultaten zijn vergeleken met modellering en literatuur.

Idealiter zou het gebruik van ZHSS moeten leiden tot slanke constructies met gereduceerde wanddiktes in vergelijking met regulier staal; de nominale spanning in een ZHSS constructie is door de gereduceerde doorsnede hoger en de spanningen ten gevolge van het eigen gewicht lager. Absoluut en relatief zal de spanningsvariatie dan ook groter zijn bij een wisselende belasting. Een realistisch uitgangspunt in het ontwerp van dynamisch belaste constructies is dat de vermoeiingssterkte van gelaste verbindingen maatgevend zal zijn. Voor een efficiënte toepassing van ZHSS zullen spanningsconcentraties bij de lassen vermeden moeten worden en zullen hoge kwaliteit lasdetails moeten worden gefabriceerd.

Van bakwerkachtige constructies, normaliter vervaardigd uit buisprofielen, bieden een efficiënte mogelijkheid voor het benutten van de sterkte van ZHSS. De elasticiteitsmodulus van ZHSS is gelijk aan die van reguliere stalen, dus onafhankelijk van de vloeig- of treksterkte. Bij een relatief stijve vakwerkconstructie zal doorbuiging bij toepassing van ZHSS dan ook niet maatgevend zijn. Om te voorkomen dat spanningsconcentraties in de gelaste verbindingen van vakwerkconstructies in een lage vermoeiingssterkte resulteren, kan de toepassing van gietstalen knooppunten een oplossing bieden. Ook gietstalen knopen kunnen worden vervaardigd met zeer hoge sterkte. Een optimaal ontwerp van de knoop verplaast de lassen naar minder kritieke locaties in de constructie en verlaagt de spanningspieken. Ontwerp en vervaardiging van gietstalen knooppunten zal weliswaar altijd in samenspraak moeten zijn met een vakken gieterij.

De vermoeiingssterkte van constructief element kan worden bepaald als de som van een scheurinitiatie- en een scheurgroeilevensduur. De scheurinitiatielevensduur is doorgaans gebaseerd op de kerfspanningstheorie. Vanuit deze theorie is bekend dat de initiatieleeduur stijgt met de sterkte van een materiaal, mits aanwezigheid van kerven, danwel locaties met spanningsconcentratie, minimaal is, zoals bij gepolijste proefstaven. De volgende parameters bepalen de initiatietermijn: vloeig-/treksterkte, gemiddelde spanning en oppervlaktereduisheid. In gelaste delen zijn daarnaast de lasgeometrie, dikte en
belastingmodus van invloed. De radius en hoek van de lasteen bepalen het belangrijkste deel de kerffactor van een lasgeometrie. Met behulp van de theorie van de “microstructural notch support”, (Peterson, 1974), kan de invloed van de kerf op de vermoeingssterkte worden bepaald, zodat ook de sterkte van een gelaste verbinding kan worden gerelateerd aan de vloei-/treksterkte. Hoe minder gekerfd de las is, m.a.w. hoe groter de kerfradius en hoe kleiner de hoek van de lasteen, hoe meer de vermoeingssterkte van de las zal toenemen met de vloei-/treksterkte. Naast de geometrische invloed speelt ook de restspanning als gevolg van temperatuursbehandeling een rol in de bepaling van de vermoeingssterkte. Bovendien wordt er doorgaans vanuit gegaan dat de initiatielengte bij een las beperkt kan zijn door de aanwezigheid van initiële defecten als een gevolg van het lasproces, die ervoor zorgen dat de vermoeingslengte uitsluitend bestaat uit scheurgroei.


In aanvulling op de vermoeingsexperimenten zijn scheurgroeitests gedaan aan proefstukken afgeleid van de V-assen met gewalst materiaal, onder buiging. Initiële defecten zijn aangebracht in het moedermateriaal en in de warmtebeïnvloede zone. Met behulp van camera en potentiaalmetingen is scheurgroei in een vroeg stadium gevolgd, voor het afleiden van de scheurgroeiparameters op basis van breukmechanica.

Twee vakwerkproefstukken zijn beproefd; de eerste vervaardigd uit S690 gewalst buismateriaal gelast aan G10MnMoV6-3 gietstaal en de tweede uit S890 gewalst buismateriaal, gelast aan G18NiMoCr3-6. De vakwerken bevatten 14 verbindingen uit enkelzijdige omtreksslagen, gelast zonder backing in laspositie PF. De lasprocedures voor het buismateriaal waren vergelijkbaar met de procedures van de gelaste platen. Het
Fatigue strength of welded connections made of very high strength cast and rolled steels

testframe bevatte een hydraulische vijzel ($F_{stat} = 10000\ \text{kN}$ / $F_{dyn} = 6000\ \text{kN}$), trekstangen en H-liggers. Krachten zijn door roterende opleggingen in het vlak van het vakwerk overgebracht naar de H-liggers. De vakwerken waren uitgebreid beïnstrumenteerd met rekstroken. Voorafgaand aan de vermoeingstesten is een statische analyse uitgevoerd, waarbij gemeten spanningen zijn vergeleken met de spanningen bepaald in FEM-software Abaqus. Hierbij is voor de maatgevende punten een afwijking tussen gemeten en berekende spanningen van gevonden van ongeveer 10%. Met het testframe is de vermoeingsproef uitgevoerd onder constante amplitudebelasting met krachtrange tot 6.000 kN in een frequentie van 0.3 Hz.

De experimentele resultaten van platen en vakwerken zijn vergeleken met levensduurvoorspellingen voor scheurinitiatielevensduur $N_i$ op basis van kerfspannings-theorie en scheurgroeilevensduur $N_p$ op basis van breukmechanicatheorie. Hiervoor is aangenomen dat itatielevensduur gold voor scheuren tot 0.15 mm en scheurgroeilevensduur vanaf die grootte tot kritieke scheurlengte, meestal de halve dikte of de volledige breedte van het constructieonderdeel. Voor het moedermateriaal zijn factoren gebruikt om kwalitatief de invloed te bekijken van gemiddelde spanning, restspanning, dikte, oppervlakteruwheid, belastingsmodus en scheurinitiatieelocatie. Voor gelaste verbindingen zijn daarnaast factoren bepaald voor de invloed van locale lasgeometrie op basis van lasradius en lashoek. De invloedsfactoren zijn gebruikt om de vermoeingsergebnissen aan te passen, m.a.w. te uniformeren voor referentiesituatie met $t = 25\ \text{mm}$, trekbelasting en restspanning gelijk aan vloeigrens. Op basis van de experimentele resultaten is de invloed bekeken van de vloeigrens en de scheurlocatie, laswortel of lasteen. Hiervoor is een statistische analyse uitgevoerd, waarbij de coëfficiënt voor lineaire regressie gekozen is als variabele of als $m = -3$ of $m = -5$. Voor alle coëfficiënten is de karakteristieke vermoeingsterkte en gemiddelde vermoeingsterkte bepaald bij $N_f = 2 \cdot 10^6$ wisselingen voor onaangepaste en aangepaste spanningsranges.

De vermoeingsterkte van moedermateriaalproefstukken en X-lassen stijgt met hogere vloeigrens. De keuze voor de regressiecoëfficiënt, gelijk aan de helling van de vermoeingsscurve, is van grote invloed op de resultaten. Helling $m = -3$ leidt tot conservatieve aannames voor de vermoeingsterkte. Voorvorspellingen voor gelaste verbindingen zijn nauwkeuriger, maar voor moedermateriaal wordt de levensduur overschat in vergelijking met de experimenten. De spreiding van de vermoeingsterkte van V-lassen uit ofwel gelaste aan gewalste plaat ofwel gelaste aan gegoten plaat is vergelijkbaar. Bij de S890 en S1100 proefstukken zijn een groot aantal doorlopers gevonden, proefstukken zonder scheurinitiatie. Deze zijn een indicatie dat de vermoeingsslimiet stijgt met hogere vloeigrens. Bovendien lijkt de helling van de vermoeingsscurve bij hogere vloeigrens te stijgen, wat betekent dat de helling $m = -3$ te laag is bij $m = -5$. Naast scheuren in de gelaste verbindingen zijn scheuren gevonden in gewalste en gegoten moedermateriaal in de series gemaakt van S460, S890 en S1100, vanwege initiële defecten. De vermoeingsterkte van de laswortel is lager dan die van de lasteen. Vanwege de belastingkeuze is het merendeel van de scheuren in de lasteen geïnitieerd. Het lage aantal proefresultaten van scheuren in de lastowals maakt het bepalen van de invloed van keramische backing onmogelijk.

De vakwerkexperimenten leiden tot de volgende resultaten. In de omtrekslassen van de vakwerken zijn alle scheuren vanuit de wortel geïnitieerd. Nadat rekstroomafbuigingen zijn waargenomen, werden scheuren aan de buitenkant zichtbaar in het midden van de las. De
Scheur lengte aan de binnenzijde, voor zover waarnembaar, was daarbij altijd groter dan aan de buitenkant. In het S890 vakwerk zijn drie scheuren gevonden in de gelaste verbindingen. In het S690 vakwerk is een scheur in de las gemaakt en een scheur in het moedermateriaal van een van de gietstukken, op de locatie van de lastinleiding. Mogelijke oorzaak hiervoor is de geometrische afwijking in het gietstuk vanwege een gietversterking. In het ontwerp van een gietknoop moet derhalve elk punt worden gecheckt als potentiële scheurinitiatielocatie, ook de posities van opkomers en gietversterkingen, indien voor deze locaties geen mogelijkheid is deze weg te slijpen na het gieten. De vermoeiingssterkte van het S890 vakwerk lijkt hoger te zijn dan waarden gevonden in vergelijkbare studies aan S355. De resultaten van de vakwerken, met buiswanddikte 23 mm, komen goed overeen met diverse resultaten aan scheuren uit de laswortel van de geteste platen. De resultaten van beide vakwerken liggen ruim boven detail categorie 71 op basis van EN 1993-1-9 (2005), hoewel deze code slechts van toepassing is op buizen met wanddikte t < 12.5 mm.
Table of contents

1. Introduction ................................................................................................................ 1
   1.1 Very High Strength Steel .................................................................................. 1
   1.2 Problem definition ......................................................................................... 2
   1.3 Research objectives ....................................................................................... 3
   1.4 Outline ......................................................................................................... 3

Part 1: Literature

2. Structural aspects of Very High Strength Steel ..................................................... 7
   2.1 Introduction .................................................................................................. 7
   2.2 Rolled steel .................................................................................................. 7
       2.2.1 Development ....................................................................................... 7
       2.2.2 Application ......................................................................................... 9
       2.2.3 Material aspects ............................................................................. 10
       2.2.4 Mechanical properties ................................................................ 13
       2.2.5 Manufacturing of welded structures ............................................... 16
   2.3 Cast steel ........................................................................................................ 17
       2.3.1 Development ....................................................................................... 18
       2.3.2 Application ......................................................................................... 18
       2.3.3 Material aspects ............................................................................. 19
       2.3.4 Mechanical properties ................................................................ 20
       2.3.5 Manufacturing of cast nodes ............................................................ 20
   2.4 Structural integrity ......................................................................................... 21
       2.4.1 Static strength ..................................................................................... 22
       2.4.2 Interaction plastic collapse/brittle fracture ...................................... 23
       2.4.3 Stability .............................................................................................. 23
       2.4.4 Fatigue ............................................................................................... 24
   2.5 Summary of findings .................................................................................... 24

3. Fatigue strength of welded joints ....................................................................... 27
   3.1 Introduction .................................................................................................. 27
   3.2 Fatigue strength approaches ........................................................................ 29
       3.2.1 Nominal stress approach ................................................................ 29
       3.2.2 Structural stress approach ................................................................. 34
       3.2.3 Notch stress/Notch strain approach ............................................... 35
       3.2.4 Fracture Mechanics approach ......................................................... 37
   3.3 Fatigue experiments on specimens made of VHSS ..................................... 38
       3.3.1 Base material plates ........................................................................ 38
       3.3.2 Transverse butt welds ..................................................................... 39
       3.3.3 Welded built-up sections ................................................................. 39
       3.3.4 Stiffeners, attachments and load carrying welded joints .......... 40
### Table of contents

3.3.5 Lattice girder node joints ................................................................. 41  
3.3.6 Post weld treated connections ......................................................... 41  
3.4 Fatigue experiments on specimens made of cast steel.......................... 42  
  3.4.1 Fatigue strength of cast steel base material ...................................... 42  
  3.4.2 Fatigue strength of welded connections made of cast and rolled steels  43  
3.5 Summary of findings ............................................................................ 45  

Part II: Experiments

4. Plate experiments ...................................................................................... 49  
  4.1 Introduction ............................................................................................ 49  
  4.2 Background on experimental program .................................................... 49  
    4.2.1 Fatigue test program ....................................................................... 49  
    4.2.2 Fatigue test rigs ............................................................................... 51  
    4.2.3 Crack monitoring ............................................................................ 54  
    4.2.4 Weld geometry ................................................................................ 57  
    4.2.5 Misalignment .................................................................................. 59  
  4.3 Base material plate specimens made of rolled steel ................................ 61  
    4.3.1 Preparation of specimens ................................................................. 61  
    4.3.2 Fatigue test results ......................................................................... 62  
  4.4 X-welded plate specimens made of rolled steel ...................................... 63  
    4.4.1 Preparation of specimens ................................................................. 63  
    4.4.2 Fatigue test results ......................................................................... 65  
  4.5 V-welded plate specimens made of rolled steel ...................................... 66  
    4.5.1 Preparation of specimens ................................................................. 66  
    4.5.2 Fatigue test results ......................................................................... 68  
  4.6 V-welded plate specimens made of cast and rolled steel ...................... 71  
    4.6.1 Preparation of specimens ................................................................. 71  
    4.6.2 Fatigue test results ......................................................................... 74  
  4.7 Crack growth specimens ....................................................................... 79  
    4.7.1 Introduction .................................................................................... 79  
    4.7.2 Preparation of specimens ................................................................. 80  
    4.7.3 Results ............................................................................................ 82  
  4.8 Summary of findings ............................................................................. 85  

5. Truss experiments ....................................................................................... 87  
  5.1 Introduction ............................................................................................ 87  
  5.2 Test program .......................................................................................... 87  
    5.2.1 Choice of specimens ....................................................................... 87  
    5.2.2 Fatigue test rig ............................................................................... 88  
  5.3 Manufacturing of specimens ................................................................... 91  
    5.3.1 Manufacturing of cast joints ............................................................. 91  
    5.3.2 Welding of trusses ........................................................................ 92  
  5.4 Static evaluation .................................................................................... 94
Fatigue strength of welded connections made of very high strength cast and rolled steels

Part III: Analysis

6. Fatigue life prediction

6.1 Introduction

6.2 Prediction of crack initiation life by the notch stress approach

6.2.1 Fatigue notch factor

6.2.2 Prediction of the initiation life of base material cracks

6.2.3 Prediction of the initiation life of weld toe cracks

6.3 Prediction of crack propagation life by the fracture mechanics approach

6.3.1 Paris law

6.3.2 Prediction of the propagation life of base material cracks

6.3.3 Prediction of the propagation life of weld toe cracks

6.4 Comparison of predictions and measurements

6.4.1 Base material cracks

6.4.2 Weld toe cracks

6.5 Summary of findings

7. Analysis of fatigue test results

7.1 Introduction

7.2 Analysis method

7.2.1 Selection and adjustment of test data

7.2.2 Statistical analysis

7.3 Fatigue test evaluation of plate specimens

7.3.1 Base material plate specimens made of rolled steel

7.3.2 X-welded plate specimens made of rolled steel

7.3.3 V-welded plate specimens made of cast and rolled steel

7.3.4 Base material parts of V-welded plate specimens made of cast and rolled steel

7.4 Fatigue test evaluation of truss specimens

7.5 Influence of yield strength

7.6 Summary of findings
8. Conclusions and Recommendations ................................................................. 205

8.1 Evaluation of research project ......................................................................... 205
8.2 Conclusions ........................................................................................................ 206
  8.2.1 Structural use of VHSS in fatigue loaded structures ..................................... 206
  8.2.2 Fatigue life prediction .................................................................................. 206
  8.2.3 Fatigue experiments on base material plate specimens made of rolled steel... 207
  8.2.4 Fatigue experiments on X-welded plate specimens made of rolled steel ....... 207
  8.2.5 Fatigue experiments on V-welded plate specimens made of cast and rolled steel .......................................................... 208
  8.2.6 Fatigue experiments on truss specimens ...................................................... 209
8.3 Recommendations for further research ............................................................. 209

List of symbols ......................................................................................................... xxi

References ................................................................................................................. 213

Appendix A, Fatigue results literature ................................................................. 223
Appendix B, Material specification ....................................................................... 231
Appendix C, Vickers test results ........................................................................... 235
Appendix D, Steps for the manufacturing of V-welded plate specimens .............. 241
Appendix E, Specimen drawings ......................................................................... 243
Appendix F, Fatigue test results ........................................................................... 247
Appendix G, Crack growth measurements ........................................................... 255
Appendix H, Numbering strain gauges on truss .................................................... 263
Appendix I, Formula notch stress concentration .................................................... 265
Appendix J, Crack growth calculations ................................................................. 267

Curriculum Vitae ..................................................................................................... 269
List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Crack length in plate thickness direction</td>
<td>[mm]</td>
</tr>
<tr>
<td>(a_N)</td>
<td>Intersection on log N axis</td>
<td>[-]</td>
</tr>
<tr>
<td>(a_T)</td>
<td>Critical crack size in thickness direction</td>
<td>[mm]</td>
</tr>
<tr>
<td>(a_i)</td>
<td>Initial defect size in thickness direction</td>
<td>[mm]</td>
</tr>
<tr>
<td>(b)</td>
<td>Regression coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>(b_1/b_0)</td>
<td>Ratio of width of brace and chord of RHS joint</td>
<td>[-]</td>
</tr>
<tr>
<td>(c)</td>
<td>Crack length in plate width direction</td>
<td>[mm]</td>
</tr>
<tr>
<td>(c_T)</td>
<td>Critical crack size in plate width direction</td>
<td>[mm]</td>
</tr>
<tr>
<td>(c_i)</td>
<td>Initial defect size in plate width direction</td>
<td>[mm]</td>
</tr>
<tr>
<td>(d_{a/dN})</td>
<td>Crack growth rate in plate depth direction</td>
<td>[mm/cycle]</td>
</tr>
<tr>
<td>(d_{c/dN})</td>
<td>Crack growth rate in plate width direction</td>
<td>[mm/cycle]</td>
</tr>
<tr>
<td>(e)</td>
<td>Eccentricity</td>
<td>[-]</td>
</tr>
<tr>
<td>(f)</td>
<td>Frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>(f_{ac, u/Np})</td>
<td>Initial crack size factor; base material; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{ac, w/Np})</td>
<td>Initial crack size factor; welded; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{cl, u/Np})</td>
<td>Crack location factor; base material; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{cl, w/Np})</td>
<td>Crack location factor; welded; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{L/w, Np})</td>
<td>Weld width factor; welded; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{max,Ni})</td>
<td>Loading mode factor; base material; crack initiation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{max,Np})</td>
<td>Loading mode factor; base material; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{max,Nf})</td>
<td>Loading mode factor; welded; total fatigue life</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{max,Nf,ax})</td>
<td>Factor for the tensile loaded welded specimens with misalignment</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{max,Ni})</td>
<td>Loading mode factor; welded; crack initiation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{max,Np})</td>
<td>Loading mode factor; welded; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_m)</td>
<td>Mean stress influence factor</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{mat})</td>
<td>Material factor</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{Ni})</td>
<td>Fraction Ni of total fatigue life (N_f)</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{Np})</td>
<td>Fraction (N_p) of total fatigue life (N_f)</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{nr, w/Ni})</td>
<td>Notch radius factor; welded; crack initiation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{rt, u/Ni})</td>
<td>Surface roughness factor; base material; crack initiation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{rt, w/Ni})</td>
<td>Thickness factor; base material; crack initiation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{th, u/Ni})</td>
<td>Thickness factor; base material; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{th, w/Ni})</td>
<td>Thickness factor for total fatigue life</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{th, w/Np})</td>
<td>Thickness factor; welded; crack initiation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{th, w/Np})</td>
<td>Thickness factor; welded; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{w, w/Np})</td>
<td>Width factor; welded; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{d, w, w/Ni})</td>
<td>Weld toe angle factor; base material; crack initiation</td>
<td>[-]</td>
</tr>
<tr>
<td>(f_{d, w, w/Np})</td>
<td>Weld toe angle factor; welded; crack propagation</td>
<td>[-]</td>
</tr>
<tr>
<td>(h)</td>
<td>Excess of weld metal</td>
<td>[mm]</td>
</tr>
<tr>
<td>(k)</td>
<td>Slope of the fatigue strength curve</td>
<td>[-]</td>
</tr>
<tr>
<td>(k_s)</td>
<td>Size effect for plate thicknesses</td>
<td>[-]</td>
</tr>
<tr>
<td>(k_{st})</td>
<td>Misalignment factor (t_1,t_2)</td>
<td>[-]</td>
</tr>
</tbody>
</table>
List of symbols

l  Half length of specimen  [mm]
l/i  Geometric slenderness  [-]
m  Slope of fatigue strength curve  [-]
n  Number of specimens  [-]
r  Notch radius  [mm]
s  Coefficient of variation  [-]
t  Thickness  [mm]
t₀, t₁, t₂  Wall thickness of CHS in truss  [mm]
xᵦ  Log Δσ  [-]
y  Curvature height in case of misalignment  [mm]
yᵢ  Log N  [-]

A  Elongation after fracture  [%]
Aᵥmax  Highest impact values  [J]
Aᵥmin  With low impact values  [J]
B  Weld width  [mm]
C  Carbon content  [wt%]
Cₐ  Crack growth rate coefficient in plate depth direction  [-]
Cₑ  Crack growth rate coefficient in plate width direction  [-]
D  Diameter  [mm]
E  Modulus of elasticity, taken E = 210000 MPa for all steels  [MPa]
D₀, D₁, D₂  Diameter of CHS in truss  [mm]
F stat  Static force  [N]
F dyn  Dynamic force  [N]
Kₐ  Fatigue notch factor  [-]
Kₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐₐ¢
Fatigue strength of welded connections made of very high strength cast and rolled steels

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_R)</td>
<td>Calculated number of cycles</td>
<td>[Cycles]</td>
</tr>
<tr>
<td>(N_t)</td>
<td>Number of cycles at which (a = t)</td>
<td>[Cycles]</td>
</tr>
<tr>
<td>(P)</td>
<td>Force</td>
<td>[N]</td>
</tr>
<tr>
<td>(R)</td>
<td>Stress ratio (= \sigma_{\min}/\sigma_{\max})</td>
<td>[-]</td>
</tr>
<tr>
<td>(R_{\text{y}})</td>
<td>Yield strength according to product standards</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(R_{\text{m}})</td>
<td>Tensile strength according to product standards</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(R_{\text{p0.2}})</td>
<td>Proof strength</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(R_s)</td>
<td>Surface roughness</td>
<td>[(\mu)m]</td>
</tr>
<tr>
<td>(S)</td>
<td>Span</td>
<td>[mm]</td>
</tr>
<tr>
<td>(S)</td>
<td>Displacement of piston</td>
<td>[mm]</td>
</tr>
<tr>
<td>(T_{100K})</td>
<td>Temperature at which fracture toughness is 100 MPa/(\sqrt{\text{m}})</td>
<td>[(^\circ)C]</td>
</tr>
<tr>
<td>(T_{27J})</td>
<td>Temperature with impact toughness &gt; 27 J</td>
<td>[(^\circ)C]</td>
</tr>
<tr>
<td>(W)</td>
<td>Width (weld length)</td>
<td>[mm]</td>
</tr>
<tr>
<td>(Y/T)</td>
<td>Yield strength to tensile strength ratio</td>
<td>[-]</td>
</tr>
</tbody>
</table>

\(\alpha^*\) | Critical distance                                | [mm] |
\(\beta_{\text{w}}\) | Correlation factor                               | [-] |
\(\beta\) | Ratio of diameter chord and brace of CHS joint   | [-] |
\(\varepsilon\) | Sum of unknown random errors                     | [-] |
\(\gamma\) | Ratio of diameter and twice the wall thickness of CHS | [-] |
\(\eta\) | Notch sensitivity factor                          | [-] |
\(\lambda_{\text{f}}\) | Correction factor for defect class               | [-] |
\(\lambda_{\text{i}}\) | Correction factor for inspection possibility      | [-] |
\(\lambda_{\text{R}}\) | Correction factor for mean stress                | [-] |
\(\lambda_{\text{W}}\) | Correction factor for wall thickness             | [-] |
\(\theta\) | Weld toe angle                                    | [\(^\circ\)] |
\(\theta_1, \theta_2\) | Truss angle                                       | [\(^\circ\)] |
\(\sigma_{\text{all}}\) | Fatigue endurance limit amplitude of polished specimen (\(K_t = 1\)) | [MPa] |
\(\sigma_{\text{aE;0}}\) | Fatigue endurance limit at alternating load      | [MPa] |
\(\sigma_{\text{eq}}\) | Equivalent von Mises stress                      | [MPa] |
\(\sigma_{\text{km}}\) | Stress including misalignment factor              | [MPa] |
\(\sigma_{\text{m}}\) | Mean stress                                       | [MPa] |
\(\sigma_{\text{aa}}\) | Endurable stress amplitude                        | [MPa] |
\(\sigma_{\text{aE}}\) | Fatigue endurance limit amplitude welded connection (\(K_t \neq 1\)) | [MPa] |
\(\sigma_{\text{nom}}\) | Nominal stress                                    | [MPa] |
\(\sigma_{\text{res}}\) | Residual stress                                   | [MPa] |
\(\sigma_{y}\) | Yield strength                                    | [MPa] |
\(\sigma_{u}\) | Tensile strength                                  | [MPa] |
\(\tau = t_1/t_0\) | Thickness ratio of CHS in truss                   | [-] |
\(\varphi\) | Elliptical integral                               | [-] |

\(\Delta \varepsilon\) | Strain range                                      | [-] |
\(\Delta \sigma\) | Stress range                                      | [MPa] |
\(\Delta \tau_b\) | Bending stress component                          | [MPa] |
\(\Delta \sigma_c\) | Characteristic fatigue strength (P95%, \(N = 2\cdot10^6\)) | [MPa] |
\(\Delta \sigma_{\text{cull, Nf}}\) | \(\Delta \sigma_c\) of adjusted data of base material | [MPa] |
### List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta \sigma_{\text{c,w:Nf}})</td>
<td>(\Delta \sigma) of adjusted data of welded connections</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{\text{FA}})</td>
<td>Applied tensile stress range, without inclusion misalignment</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{m})</td>
<td>Membrane stress component</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{\text{mean}})</td>
<td>Mean fatigue strength (P50%, N = 2 \cdot 10^6)</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{\text{mean,u:Nf}})</td>
<td>(\Delta \sigma)mean of adjusted data of base material cracks</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{\text{mean,w:Nf}})</td>
<td>(\Delta \sigma)mean of adjusted data of weld toe cracks</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{n})</td>
<td>Nominal stress range</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{n;}u;N_i)</td>
<td>Endurable stress range for Ni &gt; N0</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{n;}u;N_p)</td>
<td>(\Delta \sigma) of adjusted data for base material cracks in case N = Ni</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{n;}u;N_f)</td>
<td>(\Delta \sigma) of adjusted data for base material cracks in case N = Nf</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{n;}w;N_i)</td>
<td>(\Delta \sigma) of adjusted data for weld toe in case N = Ni</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{n;}w;N_p)</td>
<td>(\Delta \sigma) of adjusted data for weld toe in case N = Np</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{n;}w;N_f)</td>
<td>(\Delta \sigma) of adjusted data for weld toe cracks in case N = Nf</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta \sigma_{R})</td>
<td>Resulting (\Delta \sigma) in relation to the number of cycles</td>
<td>[MPa]</td>
</tr>
<tr>
<td>(\Delta F)</td>
<td>Dynamic force range</td>
<td>[N]</td>
</tr>
<tr>
<td>(\Delta K)</td>
<td>Stress intensity range</td>
<td>[MPa(\sqrt{\text{m}})]</td>
</tr>
<tr>
<td>(\Delta K_a)</td>
<td>Stress intensity range in plate depth direction</td>
<td>[MPa(\sqrt{\text{m}})]</td>
</tr>
<tr>
<td>(\Delta K_c)</td>
<td>Stress intensity range in plate width direction</td>
<td>[MPa(\sqrt{\text{m}})]</td>
</tr>
<tr>
<td>(\Delta T_{8/5})</td>
<td>Cooling time from 800 until 500 °C</td>
<td>[s]</td>
</tr>
</tbody>
</table>

### Abbreviations

- 3pb: Three point bending
- 4pb: Four point bending
- AX: Tensile loading mode
- BM: Base Material
- CA: Constant Amplitude
- CHSS: Conventional High Strength Steel
- CHS: Circular hollow section
- CTOD: Crack Tip Opening Displacement
- FZ: Fusion Zone
- HAZ: Heat Affected Zone
- HPS: High Performance Steel
- HV10: Vickers hardness, 10 kg
- N: Normalised rolled condition
- th: 0, weld toe angle
- TM: Thermomechanically rolled condition
- QT: Quenched and tempered condition
- VHSS: Very High Strength Steel
- wt%: Weight%
1. Introduction

1.1 Very High Strength Steel

Very high strength steel (VHSS) with nominal strength up to 1100 MPa (160 ksi) has been available on the market for many years. However, the use of VHSS in the civil engineering industry is still uncommon, due to lack of design and manufacturing knowledge and therefore limited inclusion in standards. Improved design and manufacturing recommendations could allow a greater use of high strength steels, with yield strengths above 690 MPa up to 1100 MPa. An effective structural use of VHSS should lead to reduction of section thicknesses in comparison to mild steel solutions. By decreasing the section thicknesses, the weights and volumes of structures could significantly be reduced, resulting in novel design possibilities as well as savings in costs of production, transportation and erection. Moreover, smaller sizes of structures would allow smaller weld volumes and reduced consumption of welding consumables. Finally, the ecological balance, both for production and application of the high strength steels may be improved by the reduction of the applied material volume, which diminishes the energy consumption and associated pollution.

Currently, plates can be produced up to yield strength of 1100 MPa. Hot rolled beam cross sections are only available up to 460 MPa yield strength. Circular hollow sections (CHS) are available in yield strength up to 890 MPa and rectangular hollow sections (RHS) up to yield strength of 700 MPa. Particularly in the civil engineering domain, design and manufacturing rules need to be developed to enable the application of VHSS in practice. In the crane industry, S690 is already regarded as the standard steel grade. Use of plates up to strengths of S890 is more and more daily practice. Use of S1100 is still very limited. Table 1.1 shows typical examples and potential application of various steel types.

Table 1.1. Typical examples and potential application of various steel types.

<table>
<thead>
<tr>
<th>Yield Strength [MPa]</th>
<th>Description</th>
<th>Other descriptions</th>
<th>Typical examples</th>
<th>Potential application</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 300</td>
<td>Regular structural steel</td>
<td>Mild steel</td>
<td>S235</td>
<td>Buildings</td>
</tr>
<tr>
<td>300-600</td>
<td>Conventional high strength steel (CHSS)</td>
<td>High performance steel/ High tensile steel</td>
<td>S355/S420/ S460/S550</td>
<td>Bridges/High rise buildings</td>
</tr>
<tr>
<td>700-1100</td>
<td>Very high strength steel (VHSS)</td>
<td>Ultra high strength steel/ Super high strength steel</td>
<td>S690/S890/ S960/S1100</td>
<td>Cranes/Bridges/ High rise buildings</td>
</tr>
</tbody>
</table>

The lack of demand for VHSS may be due to the reputation of VHSS. It is known as brittle; because in general, the higher the yield strength, the closer the ratio of the yield and tensile strength will be to unity. Due to impurities, older generations of VHSS were often depicted as brittle. With improved cooling processes and control of limited alloy elements, these main drawbacks are largely solved; therefore, acceptable material properties can nowadays be obtained for toughness, ductility and hardness of VHSS [Schröter, 2003].
1. Introduction

The emphasis of the current research is put on the high strength quenched and tempered steels with yield strengths of 690 MPa up to 1100 MPa. These steels obtain their properties through careful control of chemical composition together with appropriate heat treatment including a rapid water quench from 900ºC to room temperature followed by tempering, to form a fine grained martensitic microstructure.

Because of the delicate temperature treatment and the use of alloying elements, the weldability of the VHSS remains an important aspect for structural applications. With higher yield strength, the working window for a welder becomes smaller. Adequate heat input and preheat conditions are more critical for VHSS. Furthermore, welding consumables are often not matching the strengths of the base materials, as the yield strength of the available consumables is currently limited to 900 MPa [Heuser et al., 2007].

The development of producing steels with very high yield strength has not just been limited to rolled steels. In the past decade, more and more cast steel parts were used in bridges, offshore-structures and building structures [Herion, 2007]. Up till now, the common cast steel material used in bridge structures has been G20Mn5, with 355 MPa yield strength. Recent technology makes it possible to make cast steel up to yield strength of 1100 MPa, with good weldability.

1.2 Problem definition

The nominal stress in a VHSS structure is usually higher than in a structure made of lower grade steels and stresses due to self weight will be lower. In absolute and relative terms this will lead to higher stress variation due to the variable load. In general, increased presence of local notches or defects limits the relatively higher fatigue strength of VHSS compared to that of mild steels. Therefore, the benefits of using VHSS are questionable if the structural design entirely depends on the fatigue strength. Fatigue loading is an important design parameter for a large part of civil engineering structures, such as bridges and offshore structures. In fatigue loaded structures, use of joints with high stress concentrations should then be avoided, whilst choosing high class details and high manufacturing quality is required.

Copying the design of mild steels structures, governed by deflection criteria, to identical VHSS structures, would not lead to improved design. Use of VHSS is especially cost-effective in situations where the weight of the structure itself forms an important part of the total load on the structure; for example, in long-span bridges, high-rise buildings and cranes. An effective application of VHSS in civil engineering structures is expected in truss-like structures typically made of hollow sections. The modulus of elasticity of steel is independent of the yield strength. Truss structures could enable full exploitation of the high material strength of VHSS, because in such stiff structures the deflection is not the governing design criterion.

Improved design for truss structures made of VHSS would involve the application of cast joints. Use of steel cast joints limits the level of stress concentration in joints. The fatigue strength of cast joints will therefore be relatively high compared to that of regular steel welded joints as the stress concentration of the connection is limited and welds are shifted out of critical zones. The fatigue strength of the welded connection between the cast steel part and the hollow section will be the governing parameter for the fatigue strength of the joint. Next to crack initiation in the welded connections, attention needs to go to the crack development in the base material parts. The formulation and implementation of
quality requirements for the manufacturing of materials and welds will be important for the fatigue strength of the joint.

With a solid basis of experimental fatigue data, design and manufacturing recommendations can be formulated for an effective application of VHSS in fatigue loaded structures. To wrap up the problem definition, Figure 1.1 illustrates the line of reasoning for the focus of this research.

Use of VHSS

- Truss-like structures
- Fatigue strength properties
- Reduced stress concentration
- Cast steel joints
- Design and manufacturing recommendations

Figure 1.1. Research focus.

1.3 Research objectives

The main goal of the research is the determination of the fatigue strength of welded connections made of very high strength cast and rolled steels, for an effective application of VHSS in civil engineering structures.

In summary, the objectives of the research activities are to:

- review the development of VHSS joints with respect to application, design and manufacturing of cast and rolled steels with yield strength of 690 MPa up to 1100 MPa;
- determine the effects of fatigue loading on welded connections made of VHSS;
- determine the fatigue strength of hybrid joints with cast steel welded to rolled steel parts;
- evaluate fatigue influence parameters through a fracture mechanics investigation; analytical and numerical modelling of cracks;
- prepare recommendations for the design of welded VHSS connections.

1.4 Outline

The research consists of three parts: Part 1: Literature, Part 2: Experiments and Part 3: Analysis. Figure 1.2 gives a schematic representation of the thesis outline. Part 1: Literature consists of Chapters 2 and 3. Chapter 2 gives background on the development of rolled and cast steel with high yield strength and discusses structural aspects that lead to design and manufacturing issues. Chapter 3 focuses on the fatigue strength of VHSS. Part 2: Experiments consists of Chapters 4 and 5. Chapter 4 presents an extensive experimental program on the fatigue strength of plate specimens made of rolled and cast steels. Chapter 5 describes fatigue tests on trusses made of CHS welded to cast joints. Part 3: Analysis consists of Chapters 6 and 7. Chapter 6 presents predictions of crack initiation life based on notch stress approach and crack propagation life based on fracture mechanics. A statistical
analysis of the experimental results is given in Chapter 7. Finally, Chapter 8 presents the conclusions and recommendations.

Figure 1.2. Schematic representation of the thesis outline.
PART I: Literature

Part 1 of this thesis is an extensive literature review on structural aspects of Very High Strength Steel and the fatigue strength of welded joints. The part consists of two chapters.

Chapter 2 gives background on the development of rolled and cast steels with very high yield strength. Furthermore, applications, general material aspects and structural integrity issues are presented.

Chapter 3 focuses on the fatigue strength of VHSS, which is expected to be the governing design criterion for application of VHSS in dynamically loaded structures. The theory of several fatigue strength approaches has been evaluated. Also, the chapter presents the literature results of fatigue experiments on base material and welded connections made of VHSS and cast steel are presented.
2. Structural aspects of Very High Strength Steel

2.1 Introduction

The research objective of the current study is the determination of the fatigue strength of welded connections in very high strength steels (VHSS). It is expected that an effective use of VHSS in fatigue loaded structures requires high class fatigue details with minimal presence of stress concentrations. This may lead to the design of truss-like structures with joints containing cast steel nodes welded to rolled steel parts made of very high strength. First, background is needed on the type of steels that is the subject of the research; quenched and tempered steels with yield strengths typically in the range of 690-1100 MPa (=100-160 ksi).

The current chapter distinguishes between rolled and cast steels. Both types of steels are available in very high strength. Although the application of these steel strengths is rather limited, some examples can be given. As the material aspects of the microstructure lead to the relevant mechanical properties of the VHSS, some background will be given on material aspects in relation to the manufacturing processes. Whereas Chapter 3 focuses on fatigue strength, Chapter 2 highlights design aspects for structural integrity, such as the ratio of yield and tensile strength, deformation capacity and stability.

Section 2.2 presents development, application, material aspects and mechanical properties of VHSS; Section 2.3 focuses on cast steel. Structural integrity aspects for VHSS are discussed in Section 2.4.

2.2 Rolled steel

2.2.1 Development

The steel industry has developed steels with higher yield and tensile strengths than mild steels. The high strength of the steels is predominantly derived by heat treatment techniques in the manufacturing. Figure 2.1 shows the steel development of normalized steels (N-type), thermo-mechanically rolled steels (M-type) and quenched and tempered steels (Q-type). For the manufacturing of conventional high strength steels up to yield strength 460 MPa, steels are heated to 920 °C, followed by air cooling. This process is called normalising (σ_y = 355-460 MPa). S355N is a normalised steel with nominal yield strength of 355 MPa. An alternative procedure for obtaining high strength is thermo-mechanically rolling (σ_y = 355-700 MPa). The steels are rolled at relatively low temperatures and have excellent toughness and weldability properties [Schröter, 2003]. As the focus of the current research is on steels with yield strengths above 690 MPa, the thermo-mechanically rolled steels will have minor consideration in the current work. The highest yield strengths are obtained by the quench and temper process (σ_y = 460-1100 MPa).

Section 2.2.3 describes this manufacturing process in more detail. The quenching process creates a fine grained microstructure; the tempering procedure increases the toughness properties.
2. Structural aspects of Very High Strength Steel

Several steel manufacturers make VHSS plate material with nominal yield strength up to 1100 MPa with plate thickness up to 40 mm (See Tables 2.1 and 2.2); circular hollow sections (CHS) are available up to 890 MPa; rectangular hollow sections (RHS) up to 700 MPa. At present, availability of rolled H-sections is limited to 460 MPa yield strength [Weber, 2000].

Table 2.1. Available VHSS [Steel manufacturer product brochures].

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Name</th>
<th>$R_y$ [MPa]</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dillinger Hütte GTS</td>
<td>DILLMAX</td>
<td>690, 890, 960, 1100</td>
<td>Plate material</td>
</tr>
<tr>
<td>Thyssen Krupp</td>
<td>N-A-XTRA</td>
<td>700, 800</td>
<td></td>
</tr>
<tr>
<td>SSAB</td>
<td>XABO</td>
<td>890, 960, 1100</td>
<td></td>
</tr>
<tr>
<td>JFE</td>
<td>WELDOX</td>
<td>700, 800, 900, 960, 1100, 1300</td>
<td></td>
</tr>
<tr>
<td>Ilsenburger-Grobblech</td>
<td>MAXIL</td>
<td>690, 890, 960, 1100</td>
<td></td>
</tr>
<tr>
<td>Tenaris</td>
<td>TN 140</td>
<td>960</td>
<td>Circular Hollow Sections</td>
</tr>
<tr>
<td>Europipe</td>
<td>X100</td>
<td>690</td>
<td>(CHS)</td>
</tr>
<tr>
<td>Vallourec-Mannessmann</td>
<td>FGS78WV-FGS90WV</td>
<td>770, 790, 890</td>
<td></td>
</tr>
<tr>
<td>Ruukki</td>
<td>Optim HS 700 MH</td>
<td>700</td>
<td>Rectangular Hollow Sections</td>
</tr>
</tbody>
</table>

Table 2.2. Available plate thickness.

<table>
<thead>
<tr>
<th>Plate material</th>
<th>CHS</th>
<th>RHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>690</td>
<td>4 &lt; t &lt; 200</td>
<td>690</td>
</tr>
<tr>
<td>890</td>
<td>3 &lt; t &lt; 120</td>
<td>890</td>
</tr>
<tr>
<td>960</td>
<td>3 &lt; t &lt; 100</td>
<td></td>
</tr>
<tr>
<td>1100</td>
<td>4 &lt; t &lt; 40</td>
<td></td>
</tr>
</tbody>
</table>
2.2.2 Application

Although the VHSS have been available for a long time, they are not yet generally used by product manufactures in the field of civil engineering, offshore engineering or ship building engineering. There is missing knowledge how to design and manufacture structures with these materials. Therefore, design and manufacturing standards restrict the use of VHSS. The application of VHSS is further limited by lack of special profiles, and scarce availability of plates and hollow sections. High strength steels must be available in a range of types within a reasonable timescale for effective application. Delivery times tend to be long, which makes it less attractive to design structures with VHSS. In the past 10 years, consumption of VHSS has increased and delivery times have decreased. This trend is set to continue.

The number of applications where VHSS can be used to economic advantage over lower strength steels is growing. This is especially cost-effective in situations where the weight of the structure itself forms an important part of the total load on the structure; for example, in long-span bridges, high-rise buildings, cranes, and also in transportation. VHSS could further be advantageous when an optimization of dimension is a cost decisive parameter, for example the space of a column of a high rise building. Improved design and manufacturing guidelines should be developed for VHSS, which allow a larger use of these steels and thereby bring the following benefits for end users:

- By reducing the cross sections of the structural members, the weights would be significantly reduced, resulting in energy savings in transportation and erection and reduction of raw material input in the products (including foundations and elevations).
- The eco-balance both for the production and manufacturing of the needed steels would be improved (less energy input, less scarce alloy elements, less pollution etc.).
- The new steels would lead to slender and more aesthetic structures, which would enhance the competitive capacity.
- Smaller sizes of structural members would mean smaller weld volumes and reduced labour costs.

Several building industries already give examples of application of VHSS. Fukumoto and Nagai (2000) describe the development of new quenched and tempered steels for bridge application, which include welded built-up members in truss chords and stiffened plate panels of pylon legs of cable supported long span bridges. With improved properties of the steel composition, preheating for welding could be kept at low temperature. For the Akashi Kaykio - S690 welded box chord members were made with thickness 38 mm. Johansson (2003) discusses the use of hybrid girders with a S460 web and S690 flanges in composite twin girder bridges in Sweden. Hybrid means in this case the use of multiple steel grades within one structural element. For longer span bridges, the self weight becomes more dominating, which could make the use of VHSS even more effective. The paper also mentions the application of S1100 in a military bridge. In this case, restrictions of deflection were not governing the design, so the material could be used effectively in specially adapted, cold formed sections (t = 5 mm) of the bridge components. Ackermann (2005) reports of application of VHSS in the foot bridge over the Bayerstrasse in Munich. Hollow sections made of S690 were applied in two hinged truss arches.

An Italian application of S690 tubular sections is found in the Verrand viaduct, where a light-weight lattice launch girder was used for the assembly of the bridge [Günther et al.
2. Structural aspects of Very High Strength Steel

2005]. In other bridge structures in Sweden and France, hybrid structures with plate members of S460 and S690 in girders were used [Günther et al. 2005].

A building application is found in Berlin, where the roof structure of the Esplanade Residence near the Sony Centre contains a truss “bridge” with span 60 m, carrying the floors [Schröter, 2003]. The truss was made of S690 chords and S460 diagonals.

In the crane industry, S690 is a standard steel grade, while plates up to strengths of S1100 are more and more daily practice [Hamme et al. 2000]. Reduction of material directly influences the structural performance; lower self weight increases the lifting capacity. Cranes are frequently built as hybrid structures with multiple types of steel, for which the steels have been selected to serve the most efficient way [Romeijn and Luijendijk, 2009]. In case of heavy loads, high strength steels tend to be most efficient for limited allowable cross section sizes.

S890QL was applied in the penstock of the Cleuson-Dixence pressure shaft, built in 1992-1998. In 2000, a longitudinal weld in the steel lining failed. The penstock was torn open on a 9 m long and 60 cm wide section, which caused flooding of a large area. The origin of the crack was attributed to cold cracking as a result of bad workmanship and improper NDT; the hypothesis of the official expertise was the influence of stress corrosion cracking to explain the evolution of the crack [Chène, 2009].

Finally, the offshore industry has examples of VHSS applications. Billingham et al. (2003) report that steels with yield strength up to 800 MPa are found in jack-up structures such as the Harding Jack-up in the UK and the Siri Jack-up in Denmark. Also tension leg platforms, such as the Hutton platform in the UK, and semi submersible module offshore drilling units often contain VHSS, which reduce the weight of the top side of jacket structures. Therefore, crane barge installations can be placed with extra lifting capacity.

2.2.3 Material aspects

The production of VHSS is a delicate process, which involves the right combination of chemical ingredients and appropriate temperature treatment to obtain both strong and ductile steels. The key objective in the manufacturing of high strength steels is grain refinement. By increasing the carbon content, steels would obtain higher strengths, but lose ductility. Moreover, higher carbon content has a negative influence on the weldability of steels. VHSS obtain fine grained microstructures by the application of appropriate heat treatment, by which the steels are still weldable.
To understand the material properties it is needed to describe the microstructure in more detail. The iron-carbon diagram (See Figure 2.2) shows the different microstructures of the steel phases as a function of the temperature and carbon (C) content. Depending on the carbon content in the steel and the heating process, the following microstructures can be formed: austenite ($\gamma$), cementite (Fe$_3$C), pearlite ($\alpha +$Fe$_3$C), ferrite ($\alpha$) and martensite.

![Iron-Carbon Diagram](image)

**Figure 2.2.** Simplified representation of Iron-Carbon diagram based on Den Ouden & Korevaar (1996).

Den Ouden & Korevaar (1996) give an overview of the microstructural phases. Austenite is a soft and metallic material that can dissolve considerably more carbon in comparison with ferrite (maximum 2.03 weight% carbon at 1154 °C). Austenite has a face-centred structure (FCC, See Figure 2.3). Pearlite is formed by slowly cooling down austenite to a temperature below 727 °C. It has layered structure that consists of 88% ferrite and 12% cementite. Ferrite is a fairly soft metallic material that can dissolve only a small concentration of carbon (maximum 0.021 weight% carbon at 910 °C). Ferrite is the most stable form of iron at room temperature, with a body-centred cubic structure (BCC).

![Face centred cubic structure (FCC)](image)

**Figure 2.3.** Face centred cubic structure (FCC) and Body centred cubic structure (BCC), based on Den Ouden & Korevaar (1996).

Most quenched and tempered steels have a martensitic microstructure (maximum 0.22 weight% carbon). Martensite is obtained when the steel is cooled down at a very high
speed, since the carbon does not get enough time to precipitate. Thus the carbon remains in unsaturated solution in the ferrite. Due to this, the material gets a high hardness and minor deformation capacity. The microstructure has similarities with a ferrite crystal. The microstructure depends on the carbon ratio and additive alloy elements. Elements like manganese, nickel, chrome and silicon do not find a place between the iron molecules, but substitute them. Tempering allows the carbon to diffuse within and out of the martensite, and to form carbides. Also, during tempering, the dislocation density and internal stresses decrease. This causes the strength to decrease as well, but more importantly, the ductility to increase.

Figure 2.4 presents the quench and temper process, based on Schröter (2003). At first, the steels are heated up and rolled above the austenite recrystallisation temperature (Ac3). At this high temperature, the ferritic pearlitic microstructure totally changes to an austenitic microstructure. After air cooling, the as rolled condition is obtained, comparable to mild steels. If the steels are reheated followed by air cooling, normalised steels are obtained. In the quench and temper process, the steels are reheated to temperature Ac3, after which a water quenching process rapidly cools down the austenitic steel to obtain a ferrite, from which also martensite is formed. The accelerated cooling process is realized by the development of roller water quench installations. For increased toughness properties micro alloys are added such as Nickel (Ni), Chrome (Cr) and Molybdenum (Mo) [Pors et al., 2008], in such a way that weldability is guaranteed. In the final step, a tempering process heats the steel up to the temperature just below the formation of austenite (Ac1), after which air cooling is applied.

Figure 2.4. Temperature/time dependence in the manufacturing of rolled steel based on Schröter (2003).
2.2.4 Mechanical properties

The characteristic property of VHSS is the very high yield strength. Whereas the yield strength of VHSS is significantly larger than that of mild steels, the tensile strength is lacking behind. The yield strength values of VHSS are therefore close to the tensile strength. The tensile strength of the material is strongly affected by carbon content, solid solution strengthening and the volume fraction of the microstructural phases. Figure 2.5 presents a monotonic increasing (Yield strength)/(Tensile strength)-ratio, here indicated as $Y/T$-ratio ($=\sigma_y/\sigma_u$), which can be formulated as a function of proof strength $\sigma_y$, based on numerous test results [Fourneaux et al. 2001].

![Figure 2.5. Yield to tensile strength ratio vs. yield strength of S355, S460, S690 and S890 [Fourneaux et al. 2001].](image)

Design codes tend to restrict the use of VHSS by requiring upper limits for the $Y/T$-ratio. Therefore, Fourneaux et al. (2001) investigated the effect of the $Y/T$-ratio on other mechanical properties. The authors claim that the significance of the $Y/T$-ratio cannot be extrapolated in terms of crack initiation or propagation as these properties are directly related to toughness. For increasing yield strengths, both yield point elongation and strain hardening rate decrease; yield point elongation may relieve the crack tip opening constraint and induce remote yielding, which also depends on the thickness. The $Y/T$-ratio decreases where there are a large number of mobile dislocations. Provided sufficient crack initiation toughness is present, the maximum $Y/T$-ratio is recommended to be 0.9 for $t < 12$, 0.93 for $12 < t < 25$ mm and 0.95 for $25 < t < 50$ mm. According to En 1993-1-12 (2007), the limiting values of the ratio $R_{th}/R_m$ for steels greater than S460 up to S700 may be defined in the National Annex; the following values are recommended: $R_{th}/R_m > 1.05$.

EN 10025-6 (2004) defines strength classes for quenched and tempered plate steels 460Q up to 960Q; S1100Q is not included in this manufacturing code. Table 2.3 lists the minimal specified yield strength, tensile strength and elongation after fracture of the quenched and tempered steel plates of interest in this study, which is indicated qualitatively in Figure 2.6. It should be noticed that in practice these values may be prone to variation.

Table 2.3. Mechanical properties of VHSS [EN 10025-6, 2004].

<table>
<thead>
<tr>
<th>Nominal thickness</th>
<th>3 &lt; t &lt; 50</th>
<th>50 &lt; t &lt; 100</th>
<th>100 &lt; t &lt; 150</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{eh}$ minimal specified yield strength [MPa]</td>
<td>S690Q</td>
<td>690</td>
<td>650</td>
</tr>
<tr>
<td></td>
<td>S890Q</td>
<td>890</td>
<td>830</td>
</tr>
<tr>
<td></td>
<td>S960Q</td>
<td>960</td>
<td></td>
</tr>
</tbody>
</table>

| $R_m$, tensile strength [MPa] | S690Q | 690 | 650 | 630 |
| | S890Q | 890 | 830 | |
| | S960Q | 960 | | |

| $A$, elongation after fracture % | S690Q | 14 | |
| | S890Q | 11 | |
| | S960Q | 10 | |

Improved manufacturing processes lead to the production of steels with higher purity by control of inclusions, and finer grain sizes. This increased the toughness, generally indicated by the Charpy notch values. Structures should be able to withstand the presence of initial defects under static and dynamic loading. Also for lower temperature applications, a ductile behaviour is needed. Charpy tests are used to relate the impact toughness to temperature. The impact energy is usually measured on small specimens, 10 mm thick, sometimes only part of total thickness, for various temperatures. As a result of multiple
Charpy tests, which tend to be prone to large scatter, the Charpy toughness is plotted as a function of the temperature. A brittle region, the lower shelf region, shows low impact values ($A_{v_{\min}}$) at lower temperatures; with increasing temperature a region is found where gradually higher impact values can be found, which is called the brittle to ductile transition region; the temperature region with the highest impact values ($A_{v_{\max}}$) is called the upper shelf region.

Fourneau et al. (2001) report of results of Charpy tests on S690, S890, S960 steels. The transition temperature varied between -160 °C and 0 °C. $A_{v_{\max}}$ range was found to be 80-230 J. On average, the toughness values at the centre of the plates were lower than for the subsurface, which is found to be common practice for quenched and tempered high strength steels with mid thickness segregations. With increasing strength level, the Charpy-V transition curves tended to shift to higher temperatures. Van Wortel (2006) found that for VHSS the upper shelf energies are low, in comparison to mild steels. This was also mentioned by Defourny et al. (2001), claiming that VHSS have lower maximum Charpy values, but they also mention that the transition temperature of VHSS enters into very low temperatures. According to Billingham et al. (2003), next to steel grade, the transition temperature is influenced by geometry and strain rate. Higher thickness and higher strain rates increase the transition temperature.

Standards require minimal impact values for specific service temperatures. T27J is a defined temperature, at which the minimal impact toughness is 27 J. EN 10025-6 (2004) prescribes minimal impact energy of various types of quenched and tempered steels, indicated by Q (30 J at -20 °C), QL (30 J at -40 °C) and QL1 (30 J at -60 °C) (See Table 2.4).

Table 2.4. (EN 10025-6, 2004), minimal impact energy [J].

<table>
<thead>
<tr>
<th>Grade</th>
<th>T [°C]</th>
<th>0</th>
<th>-20</th>
<th>-40</th>
<th>-60</th>
</tr>
</thead>
<tbody>
<tr>
<td>S690Q</td>
<td>40J</td>
<td>30J</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S890Q</td>
<td>50J</td>
<td>40J</td>
<td>30J</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S960Q</td>
<td>60J</td>
<td>50J</td>
<td>40J</td>
<td>30J</td>
<td></td>
</tr>
<tr>
<td>S690QL</td>
<td>70J</td>
<td>60J</td>
<td>50J</td>
<td>40J</td>
<td>30J</td>
</tr>
<tr>
<td>S890QL</td>
<td>80J</td>
<td>70J</td>
<td>60J</td>
<td>50J</td>
<td>40J</td>
</tr>
<tr>
<td>S960QL</td>
<td>90J</td>
<td>80J</td>
<td>70J</td>
<td>60J</td>
<td>50J</td>
</tr>
<tr>
<td>S690QL1</td>
<td>100J</td>
<td>90J</td>
<td>80J</td>
<td>70J</td>
<td>60J</td>
</tr>
<tr>
<td>S890QL1</td>
<td>110J</td>
<td>100J</td>
<td>90J</td>
<td>80J</td>
<td>70J</td>
</tr>
<tr>
<td>S960QL1</td>
<td>120J</td>
<td>110J</td>
<td>100J</td>
<td>90J</td>
<td>80J</td>
</tr>
</tbody>
</table>

BS 7448-2 (1997) gives an elastic-plastic fracture mechanics procedure for the determination of the toughness, which is based on the determination of the crack tip opening displacement (CTOD). The CTOD is a measure of the fracture toughness of the material, which can also be determined for welded connections. The CTOD can be converted to the fracture toughness $K_{\text{mat}}$. Although also the impact toughness is related to fracture toughness, the exact correlation is uncertain.

According to Billingham et al. (2003), fracture toughness is related to both the yield strength and the CTOD. Improved toughness may be necessary in case of relatively high applied stress values, but the toughness is also related to the expected flaw size. As the use of VHSS should reduce the thickness of structural members, the local constraint could
change. Plane stress conditions are not necessarily derived in VHSS, because the toughness will often not increase as much as the yield strength, which limits the reduction of potential member thickness if toughness would be the governing design criterion.

Van Wortel (2006) concludes from an extensive CTOD test series at -20 °C that S690, S890 and S1100 (t = 10 mm) give acceptable toughness values for membrane stresses up to level of 2/3 of yield stress, determined according to BS7910 (2005) level 2A (See Section 2.4). This means, the critical defect sizes that not lead to brittle fracture, could be detectable in practice. The toughness of S960 (t = 60 mm) and S1100 (t = 40 mm) may be not sufficient at this or lower service temperatures.

The Wallin toughness master curve relates the material toughness to the application temperature [Sedlacek and Müller, 2005]. Normally, the Charpy value is an easily obtainable material parameter. With the modified Sanz relation, a correlation of Charpy values to $K_{\text{mat}}$ can be made. The temperature with impact toughness > 27 J ($T_{27J}$) is related to the temperature at which fracture toughness is $100\,\text{MPa}\sqrt{\text{m}}$ ($T_{100K}$). For S690 en S890, good correlation of the expected and measured temperature levels are found [Defourny et al., 2001]

### 2.2.5 Manufacturing of welded structures

Improved properties of the base material alone do not guarantee the quality of the welded connection. Because of the induced heat of the welding process, locally microstructures can change to increased grain sizes. The way VHSS structures can be manufactured strongly depends on the production process of the materials. For every thermal treatment, it should be realized, the materials have got their specific properties through thermal treatment in an earlier stage. Especially if warm deformation, cutting or welding are involved in the building process, the execution should be carried out according to the specifications of the steel manufacturers. Heat treatments, such as warm deformation and stress relieving, should be performed at temperatures below the temperature of the last thermal treatment in manufacturing of the steels. Schröter (2003) recommends the temperature of flame straightening below 600 °C during 10 minutes. The maximum stress relief temperature should be 520 °C (which is a margin of 30 °C below 550 °C) and should only be used for reduction of residual stress, not for increased toughness. Temperature maxima for hot forming should be between 550°C and 580°C. For the cutting of VHSS, all processes are possible, such as plasma cutting and water jet cutting. If the outer temperature is below 5 °C, preheating is necessary. The general recommendation is preheating at 50-100 °C for $t > 75$ mm.

It is of vital importance for the welding of VHSS, to act within the given working window for the specific combination of base material, welding material, preheat temperature, heat input and control of hydrogen content in the consumables [Schröter, 2003]. Development of steels goes side by side with the improvement of welding procedures. The Dutch welding institute NIL reports general recommendations for the welding of VHSS [Pors, 2006]. Quick cooling leads to increased hardness, and therefore the risk of cold cracking because of hydrogen locked in the microstructure. High heat input is preferred for economic welding in practice. However, a high heat input may reduce the material toughness, whilst low heat input may cause increased hardness [Schröter, 2003].
The recommended preheat temperature depends on the carbon equivalent (CET)\(^1\), the hydrogen content, heat input and material thickness. Heat input should be between 0.8 and 1.5 kJ/mm for VHSS. The maximum interpass temperature should be 225 °C. For preventing the diffusion of hydrogen, soaking is recommended, which is heating up for 2 hours to 250 °C. The hydrogen level of the filler material should be less than 5 mL/100g. The cooling time can be determined graphically from EN 1011-2 (2001).

Welding consumables derive their strength through micro-alloying [Heuser et al, 2007] and not by controlled heat treatment, such as the base material. The combination of the base and weld material strength and the welding procedure, i.e. thermal cycling during welding, lead to the properties of the heat affected zone and the fusion zone. The toughness of the welding material is usually improved by adding nickel. Welding consumables are available up to yield strength 900 MPa. This means that base materials above the yield strength of 900 MPa cannot be welded with matching weld material. For these VHSS, undermatching has given acceptable weld qualities [Van Wortel, 2006]. Especially for root welds, undermatching strength may lead to increased toughness, because the root is constantly reheated, which reduces the cooling time. Especially the cooling time from 800 until 500 °C is of importance, the ΔT\(_{8/5}\), which leads to restrictions of heat input and welding speed for optimal material properties.

Too fast cooling leads to high hardness, which may cause hydrogen induced cracking (cold cracking), induced by welding [Defourny et al., 2001]. In case of too long cooling times, softening may occur. The limiting factor for the fracture behaviour in the weld is the coarse grained heat affected zone (HAZ). In multilayer welds, the first pass is exposed to high residual stresses, because of the thermal cycling for the other weld runs, which is therefore prone to development of cold cracks. The use of undermatching weld material, with lower preheat temperature, could be a solution. Afterwards the root layer could be removed if accessible, to replace it with matching weld material. If the undermatched root is not removed, the coarse microstructure causes low toughness in the root zone. However, if this zone is relatively small, this problem is found to be negligible [Defourny et al., 2001].

### 2.3 Cast steel
The previous sections made clear that for making use of VHSS in civil engineering structures the most efficient way, VHSS should preferably be designed for stiff truss-like structures. Otherwise, displacement or stability might be the governing design criteria, whilst not utilising the full material strength of VHSS.

Application of cast steel joints in combination with rolled steel parts may be an appropriate possibility for a more effective strength utilisation of VHSS. The use of cast joints gives freedom to the designer in shaping the connection, which can reduce the stress concentration in the joint, particularly in joints of truss structures made of CHS. Cast steels are available in very high yield and tensile strength, by similar heat treatments as applied on quenched and tempered rolled steels, presented in Section 2.2. The current section deals with specific aspects in the development of cast steel, highlights recent applications and discusses material properties and structural design and manufacturing of cast joints.

\[\text{CET}=C+(\text{Mn}+\text{Mo})/10+(\text{Cr}+\text{Cu})/20+\text{Ni}/40, \text{ for } 300 < \text{R}_{\text{e0}} < 1000 \text{ MPa [EN 1011-2, 2001]}\]
2. Structural aspects of Very High Strength Steel

2.3.1 Development
The use of cast steels in civil engineering leads back to times long before rolling techniques were developed. In famous bridges, such as the Firth of Forth bridge in Edinburgh, cast joints were applied. Cast steel should not be mistaken by cast iron, which cannot be welded because of high carbon equivalent. Typically, cast iron has 2.5-3 wt% Carbon (C) content, whereas cast steel has 0.2-0.5 wt% C. This makes the cast steel better weldable and more ductile than the cast iron. The chemical composition of cast steel can be chosen in such a way that the cast steels derive good welding properties, high strength and toughness.

Recent technology makes it possible to make cast steel parts up to yield strength of 1000 MPa (See Table 2.6). A recent document on the properties and use of modern cast steels is published in the 'Stahlbau Kalender – Guss im Bauwesen' [Herion, 2007]. In a literature review by Van Goolen (2006), more background on fabrication processes, codes and applications of cast iron and cast steel can be found.

2.3.2 Application
Use of cast steel gives freedom to the designer in choice of geometry and steel quality. In the past decade, more and more cast steel parts have been used in bridges, offshore-structures and building structures. The cost-effective use of castings depends on the size, repetition, thickness and quality level [Glijnis and Crommentuyn, 2003].

Up till now, the common steel casting material used in bridge structures is G20Mn5, with 355 MPa yield strength. A lot of experience on the fatigue strength of cast joints for bridge applications was gained in the building of the Humbolthafen railway bridges [Herion, 2007], in which steel arches were made of cast steel joints and CHS (See Figure 2.7), supporting pre-stressed concrete decks.

In the traffic bridge over the Nesenbachtal near Stuttgart, S355 hollow sections with cast joints G20Mn5 were used in the steel structure of the steel-concrete bridge [Schlaich et al., 2000]. Veselic et al. (2003) and Puthli et al. (2010) give the example of the bridge across the river Würm near Krailling, which contains cast inserts welded to the truss chords made of CHS, with connecting rods to the braces. Angelmaier (2004) describes the use of cast steel nodes in the valley bridge Korntal-Münchingen. This bridge consists of a steel tube truss structure, monolithically connected to the concrete substructures.

The St. Kilian bridge [Denzer et al., 2006] is another steel truss-composite deck bridge, near Schleusingen, Germany. Multiplanar triangular steel truss with CHS welded to KK-cast joints were applied.

A Dutch application of cast joints is in the composite steel concrete railway bridge over the Nederrijn near Oosterbeek.
Schlaich and Schober (1999) discuss the use of cast joints in building structures, such as roof structures made of multiplanar trusses, in the Messe Hannover, and forked supports for roof structures in the Stuttgart Airport hall and VW-Skoda factory in Czechia.

The roof of the railway station “Lehrter Bahnhof” in Berlin contains cast elements and the main structure contains forked supports made of cast joints and CHS [Herion, 2007].

The UEG (1985) report of the use of cast joints in offshore structures, where joints are designed for a demanding environment, with high stresses and corrosive atmosphere.

Marston (1991) describes the use of cast nodes in an offshore oil platform. Application of cast joints in padeyes and lifting beams is found in tension leg platform Hutton, UK (See Section 2.2.2). Results of tests on X joints used in the Conoco Victor platform are found in Hurden et al. (1986).

A more recent application of cast joints in offshore structures is found in the Ekofisk platform [Broughton et al., 1997]. For the 2/4J jacket of the platform cast joints were applied, leg nodes (D = 2m), X-joints (D = 1m) and K-joints (D = 1.2 m), with 300 MPa yield strength, which reduced the cost and weight in comparison to the use of conventionally welded joints.

2.3.3 Material aspects

A large amount of cast steel alloys is available. In principal, the material aspects and properties of cast steels are similar to the aspects mentioned in sections 2.2.3. Code EN 10293 (2005), "Steel castings for engineering uses", gives typical properties of the range of cast steels for engineering uses. Cast steels are named after their chemical composition according to EN 10027-1 (2005).

Table 2.5 gives comparative data on structural cast steel grades. With secondary metallurgy, the properties of the steels can be adapted. This means, additional heat treatment, or the application of alloying. For instance, increased carbon content raises the strength; increased nickel content raises the toughness.
2. Structural aspects of Very High Strength Steel

<table>
<thead>
<tr>
<th>Material name</th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$R_{m}$ [MPa]</th>
<th>Impact energy $-40^\circ$C [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G20Mn5</td>
<td>355-460</td>
<td>500-600</td>
<td>27-40</td>
</tr>
<tr>
<td>G10Mn7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G10MnMoV6-3</td>
<td>500-600</td>
<td>600-800</td>
<td>27-45</td>
</tr>
<tr>
<td>G14NiCrMo10-6</td>
<td>700-900</td>
<td>800-1000</td>
<td>60-90</td>
</tr>
<tr>
<td>G18NiMoCr3-7</td>
<td></td>
<td></td>
<td>27-46</td>
</tr>
<tr>
<td>G17NiCrMo13-6</td>
<td>960-1100</td>
<td>1000-1200</td>
<td>27-40</td>
</tr>
<tr>
<td>G22NiMoCr5-6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Naming according to EN 10027-1 (2005)

**Example:** G20Mn5, 0.20% C; 1.25% Mn

EN 10293 (2005) should be used in conjunction with EN 1559-1 (2011) and EN 1559-2, (2000). ASTM E 446-98 (1998) gives classification details for cast steel parts. German code DIN 1690-2 (1985) classifies cast steel parts in quality levels, for which the presence of internal defects is based on ultrasonic testing [EN 12680-1, 2003] or Radiographic testing, by X-ray [EN 12861, 2003. Severity levels 1 to 5 of ASTM E 446-98 (1998) are considered to coincide with quality levels 1 to 5 of casting of code DIN 1690-2 (1985). In general, a medium quality of 3 is required for the inner material. For the surface, the required quality should be higher, level 1-2, and the highest quality is needed at the welding locations, level 1.

### 2.3.4 Mechanical properties

The mechanical properties of cast steels depend on the material composition and the execution quality. The quench and temper process for obtaining VHSS cast material is similar to that of rolled materials. As for the material aspects, the mechanical properties are similar to those of rolled steels. Given the material specification, the cast joints can be heat treated for grain size refinement. Parts of the cast joints or separate reference blocks are used for determination of the mechanical properties, such as Charpy impact toughness, yield and tensile strength and hardness. For the mechanical properties of cast steels made of high strength is referred to section 2.2.4. Appropriate execution quality should guarantee homogenous properties of the cast member.

### 2.3.5 Manufacturing of cast nodes

The manufacturing of cast nodes takes several steps to be undertaken in close cooperation of designer and foundry. Because of the large variety of cast materials, production choices and options for repetition, the design is an iterative process. In the Eurocode 3, no specific design rules for cast steel parts are given.

At first, the general shape of the cast joints needs to be designed. The material can be chosen according to the governing design criteria, such as toughness, ductility, and strength. With FEM-modelling, the shape of the cast joints can be determined and be given
adequate rounding and local thickness for a good stress flow in the node, whilst lowering the stress concentrations. The geometry of the FEM-model can be interchanged with the cast steel supplier. The second step is the modelling of the casting process, the casting of the liquid steel in the mould, followed by the solidifying process. The casting model gives the possibility to predict the local shrinkage during solidification and the effect of placing risers in the cast mould for saturation. Risers or feeders are meant to provide enough material to fill the eventual gap after shrinkage. Eventual adaptations in the shape of the cast joints for an optimized casting process are to be communicated with the design engineer, who can recalculate the static model.

If the shape of the cast joints and the casting process, including positions of feeders, is determined, a 1:1 copy of the joint is made out of polyester or timber. Usually, the model is made slightly larger than intended, because of the expected shrinkage after cooling. Based on the 1:1 copy, the mould is formed of sand and epoxy. For openings inside of the cast joint, cores are positioned in the mould.

The cast material is heated up and melted in the furnace. In dependence of wall thickness, temperature and loading case, the material components can be adapted. In general, rising Ni levels will lead to higher toughness making possible increased wall thickness. Rising C levels will lead to higher strength. A recent development in the steel casting process is VARP® (Vacuum-Argon Refining Process), which minimizes sulphur, nitrogen, hydrogen and oxygen levels, making possible the production of highly weldable castings [Müller, 2007].

After the production of the steel, the material is cast in the mould. The solidifying process should take place from the outside to the inside, progressively to the position of the feeders/risers. Characteristic locations that solidify late are called hot spots. Air holes should be prevented. For the avoidance of solidification cracks, an angle of 4° increase of wall thickness towards feeder is necessary or a constant wall thickness over a length smaller than 3 times the wall thickness [Haldmann-Sturm, 2005]. When the material is solidified, the cast joint can be draft out of the mould. The exhaust of material, such as the risers, is ground from the joint.

All cast joints are checked for discontinuities, blowholes and flaws by NDT for assessing the quality level, by ASTM E 446-98 (1998). If necessary, repairs are made, followed by NDT. Dye penetrant and magnetic particle testing indicate surface defects, ultrasonic inspection shows the in thickness location of internal defects, whereas X-ray may be used for local size checks. Global size checks are made with 3D scanning devices. With software, a comparison is made to the computer model. In case of unacceptable deviations, repairs are made by welding or surface treatment.

2.4 Structural integrity
For a safe use in structural applications, mechanical properties, such as static and dynamic strength, ductility and toughness of the base materials must be known. The weak point in a structure is formed by welded connections, inevitably present in large steel structures. Welded parts in the structure are delicate because of the change of local geometry, creation of a heat affected zone and a residual stress distribution. As it is inevitable to connect various parts in a structure, in particular the capacity of welded connections needs to be understood. This section presents the main aspects for structural integrity of VHSS structures; fatigue strength is discussed in Chapter 3 in more detail.
High strength steels were initially excluded from the European steel design codes, by limiting the scope to specified yield strengths up to 355 MPa only and by limiting the ratio of the tensile strength to the yield strength to be larger than 1.2. Extensive research initiated by Arbed lead to the development of Annex D to ENV 1993-1-1 (1992), ENV 1993-1-1-A1 (1994). This has been the door opener for the use of conventional high strength steels, in particular rolled sections, with yield strength of 420 MPa to 460 MPa, without needing particular technical approvals. For these conventional high strength steels, the welding factor was complemented and a reduction factor was implemented for the use of S420 and S460 in tubular connections. A broad survey of literature on high strength steels, a collaboration of several European universities and institutes, lead to the development of Eurocode 3: Design of steel structures, Part 1.12 : Additional rules for the extension of EN 1993 to steel grade S690, EN 1993-1-12 (2007), which allows the use of high strength steel up to S700.

2.4.1 Static strength

Kuhlmann et al. (2009) evaluated the deformation capacity of lap joints, cruciform joints and butt joints made of S355, S460 and S690. With increasing strength, reduced deformation was found. The yield strength of welded connections was determined by the $\Delta T_{85}$; lower $\Delta T_{85}$ was found to increase the yield strength. With increasing strength of filler metal, a raise of load bearing capacity was found, with reduction of deformation capacity. Undermatched welding of S690 hardly reduced the strength of the connection, whilst the deformation capacity increased. For connections with equal base metals and compatible filler metals 5% increase of load bearing capacity was found with S690Q compared to S460M. All failures occurred in the weld area. For the determination of the static strength of welded connections made of high strength steels, EN 1993-1-12 (2007) prescribes the use of correlation factor $\beta_w$, by defining the allowable stress to be smaller than $\sigma_u/(\gamma_M \beta_w)$. In case of welded connections, the tensile strength of the base material should be replaced by the tensile strength of the weld material. Kuhlmann et al. (2009) suggest updated values for $\beta_w$.

Dijkstra & Kolstein (2006) tested the deformation capacity of cross plate joints, X-joints with high SCF and X-joints with low SCF, made of S690 (overmatched and undermatched condition) and S1100 (undermatched condition). Overmatched welded joints made of S690 showed a sufficient static strength and deformation capacity. Undermatched welds could be compensated with reinforcement, which means, thickening of the weld cross section. Load deflection curves were based on FEM analyses and the failure criterion of Lemaitre (1985), which is a function of triaxiality. This could predict both the static strength and the deformation capacity adequately.

Girão Coelho et al. (2009) present an experimental study of web shear panels fabricated by welding S690 and S960 steel plates. The panels were tested to failure under four-point bending, which simulated the shear force from beam moment carried by beam-column joints. The modes of failure limited the panel resistance and ductility. High-strength steel web panels in shear could exhibit ductile behaviour and satisfied very high deformation demands, depending on the web slenderness, which ultimately was found to determine the failure mode.
2.4.2 Interaction plastic collapse/brittle fracture

Structural integrity is guaranteed if for specific service temperatures, geometry and loading levels, presence of defects will not lead to either brittle or ductile fracture of the component. Gross section yielding should take place before brittle failure; this leads to determination of critical defect size. Increased material toughness should lead to increased admissible defect size. Decreased temperature lowers the allowable defect size.

For the correlation of fracture toughness and plasticity, the Failure Assessment Diagram (FAD) has been developed, based on the R6-method [BS7910, 2005]. This procedure allows for assessing the effect of a load on brittle fracture failure in combination with plastic collapse. Brittle failure depends on fracture toughness and the present stress intensity factor, whereas plastic collapse depends on the loading level and the yielding of the remaining ligament. The FAD is based on interaction of brittle fracture ratio $K_R$ and plasticity ratio $L_R$. $K_R$ is the ratio of active stress intensity factor, $K_{appl}$, based on stress level, geometry and defect size, and $K_{mat}$, the fracture toughness. The fracture toughness can be determined either from CTOD measurements or from Charpy measurements, through the Wallin toughness master curve, (See Section 2.2.4). The plasticity ratio $L_r$ is defined as the ratio of the active force $F_a$ and the force needed to yield the remaining ligament of the cross section, $F_y$. If the assessment point is within the given boundary, the structure is safe. The residual stress level can be taken into account in the procedure.

Van Wortel (2006) concludes, fracture toughness requirements according to BS7910 (2005) lead to low critical defect sizes for VHSS. This means, the initial defect size should be relatively small to refrain from brittle or ductile fracture at a given geometry and loading. Welded specimens reach lower toughness values than base material. The toughness of material in the welding fusion line and weld metal can however be better than base metal in case of undermatching weld material.

EN 1993-1-10 (2005) gives design rules for the use of minimum plate thickness, based on the application temperature, yield strength and stress level. For a standard detail, an initial crack size is assumed to have been fatigue loaded for 500000 cycles. Given the fracture toughness of the base material, in dependence of temperature, the maximum allowed material thickness was calculated based on CEGB R6-routine Option 2. EN 1993-1-12 (2007) gives additional design rules for the use of EN 1993-1-10 (2005) for steels with yield strength up to 700 MPa.

2.4.3 Stability

Resistance to global buckling predominantly depends on the structural slenderness and the modulus of elasticity and yield strength of the material. The modulus of elasticity is independent of material strength. The imperfection factor $\alpha$ reflects the sensitivity to imperfections. In case of low geometric slenderness (e.g. $l/i = 40$), the relative resistance to instability increases with higher yield strength material. Also, the relative resistance in case of imperfection is higher for high strength steel. As the expected residual stresses form a smaller part of the yield strength, the effects of residual stresses on the resistance may be less detrimental [Clarin, 2007]. For local buckling, a similar reasoning is valid [Johansson, 2003]. In order to get an incentive for VHSS, the slenderness has to be kept low. Therefore, an efficient use of VHSS is foreseen in truss-like structures.
2.4.4 Fatigue

The nominal stress in a VHSS structure is usually higher than in a structure made of mild steels and stresses due to self weight will be lower. In absolute and relative terms, this will lead to higher stress variation due to the variable load. Therefore, the benefits of using VHSS are questionable if the structural design entirely depends on the fatigue strength. In general, regarding the fatigue strength of welded connections, design codes do not differentiate for yield strength.

The yield strength of the material is of influence on the fatigue strength if stress concentrations are kept at a low level. In case of plain machined specimens, the notch stress theory shows that the fatigue strength increases with yield strength, (See Section 3.2.3). Fracture mechanics theory shows, the crack propagation life is independent of yields strength, (See Section 3.2.4).

In fatigue loaded structures, use of joints with high stress concentrations should be avoided. Choosing high class details and high execution quality of the welded connections is thus required. Lower class details will not benefit from higher yield strength, (See Section 3.3).

Post weld treatment techniques are found to have a beneficial effect on the fatigue strength of welded connections, especially in case of high strength steel connections, (See Section 3.3.6). The reason is that these techniques improve the weld toe profile, whilst increasing notch radii and introducing residual compressive stresses up to the level of the yield strength. However, it is costly to apply post weld treatment techniques and the weld profile cannot always be reached for treatment, for instance the weld root of CHS connections with limited diameter.

An effective application of VHSS is foreseen by use of cast joints, (See Section 3.4). By choosing an optimal shape of the joint, the welds are shifted out of the highly stressed areas, and stress concentrations can be limited.

Chapter 3 focuses entirely on the fatigue strength of VHSS structural members made of rolled and cast steels, based on the nominal stress approach, the notch stress and strain approach and the fracture mechanics approach.

2.5 Summary of findings

Chapter 2 introduced the development, application, material and structural aspects of very high strength cast and rolled steels. Steels with very high yield strength (690-1100), have been available for more than 20 years. Appropriate heat treatment, such as the quench and temper process, results in steels with low grain sizes, with very high yield strength and acceptable ductility.

The yield strength to tensile strength ratio of the VHSS is close to unity. Because of restrictions in design and manufacturing standards, the use of these steels is still limited in civil engineering structures. Several research projects contributed to increased knowledge on deformation capacity of structural members, on the understanding of toughness properties in relation to low temperature application and welding, and on the stability properties of VHSS structures. This lead to the introduction of [EN 1993-1-12], which permits the use of steels up to S700. Steels with higher yield strength are not yet covered in the code.
An effective use of VHSS is expected in truss-like structures, typically made of CHS. Application of conventionally welded joints would lead to relatively high stress concentration factors. Cast steel joints, also available in very high strength, are more and more applied in civil engineering structures. The design and manufacturing process should be carried out in close cooperation with the cast steel foundry. Choice of alloying elements and appropriate heat treatment determine the desired material properties. With appropriate design, stress concentration factors can be limited.

Chapter 3 highlights the potentially governing design criterion for VHSS structures, the fatigue strength. In order to benefit from VHSS in dynamically loaded structures, the most important means is the reduction of stress concentrations. Therefore, the application of cast steel joints in combination with VHSS rolled steel is studied.
3. Fatigue strength of welded joints

3.1 Introduction
Use of VHSS should lead to reduction of thickness of structural members. As a result, absolute and relative stress levels are higher compared to those of structures made of regular steel. The weak points in the structures are mainly formed by the welded connections, inevitably present. Welded parts in the structure require special attention, because of the local geometry changes and residual tensile stresses are present in the transition to the weld toe and the heat affection zone.

Cyclic stresses, even far below the material yield strength, may give rise to the development of small cracks that eventually can cause failure of structural components. The total fatigue life of a structural component can be regarded as the sum of a crack initiation life and a crack propagation life. The crack initiation life is characterised by the movement of dislocations (~10⁻⁹ m) up to crack nucleation, characterised by the formation of micro-cracks (10⁻⁶ m ~ 10⁻⁴ m). The stable growth of these micro-cracks is referred to as the crack propagation life, which continues for macro-cracks (10⁻⁴ m ~ 10⁻² m) up to instable crack growth if a critical size of the cracks introduces failure of the remaining ligament. The main influence factors on the fatigue strength of structural members are summarised in Table 3.1.

Table 3.1. Fatigue influence factors.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Material</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notch size</td>
<td>Strength</td>
<td>Stress range (for N &gt; 50000 cycles)</td>
</tr>
<tr>
<td>Connection type</td>
<td>Residual stress</td>
<td>Strain range (for N &lt; 50000 cycles)</td>
</tr>
<tr>
<td>Execution quality</td>
<td>Crack growth rate</td>
<td>Loading mode (such as tension and bending)</td>
</tr>
<tr>
<td>Initial defect size</td>
<td>Welding process</td>
<td>Mean stress level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environment</td>
</tr>
</tbody>
</table>

Geometrical influence is dominated by the stress level, in particular the stress range, which is determined by the connection geometry. Notch size in combination with the shape of the structural detail, in other words, the connection geometry, may cause local stiffness differences, which influence the stress flow through the structural detail. Both stresses and strains concentrate in a smaller area. Global stress concentration is indicated by the stress concentration factor (SCF); local stress concentration is indicated by the notch stress concentration factor $K_t$.

With use of cast joints, the global stress concentration could be reduced. However, the cast joints still need to be welded to rolled parts in structural applications. And, the cast joints are prone to presence of manufacturing defects, which makes fatigue strength assessment of the base material necessary. The geometry of a weld influences the local stress concentrations at the junction of the weld zone and the base material; the execution quality of welded connections implicitly addresses the notch size. In welded elements, initial defects are assumed to have the size of 0.1-0.5 mm. Therefore, the fatigue life of welded connections is generally regarded to be dominated by crack propagation life. The number and severity of flaws is likely to increase with the size of the structural member.

The yield strength of the material could be of positive influence on the crack initiation life if stress concentrations are minimised. Gurney (1979) concluded that the fatigue
Fatigue strength of welded joints

strength of VHSS is more sensitive to the presence of notches and to the surface condition, than mild steels. The fatigue strength also depends on the effect of the loading mode, by influence of the stress gradient. The stress gradient is a function of the maximum stress and the derivative of the stress and the structural thickness at maximum stress. Membrane stresses as a result of axial loading have a lower stress gradient than bending stresses. A high stress gradient reduces the influence of the local notch concentration on the fatigue strength. Therefore, axially loaded specimens obtain lower fatigue strengths than specimens loaded in bending.

Next to the loading mode, the loading history and environmental conditions influence the fatigue strength. Most tests are based on constant amplitude loading, whereas in practice the load distribution may differ considerably in time.

Thermal cycling in the welding process causes expansion and shrinkage in the weld zone and the heat affected zone (HAZ) and change of microstructural material phases. It is a natural condition that residual stresses occur that are in balance within the body of the material [Maddox, 1991]. As a general rule, the stress levels at the weld toe are expected to have the level of the material yield strength. The mean stress level is regarded to be of minor influence on the fatigue strength of welded connections, as the stresses redistribute around the yield strength, irrespective of the stress level. Therefore, stress range is the dominant factor in case of cyclic loading. High strength steels have a higher mean stress sensitivity than mild steels; the more compressive the mean stress, the higher the fatigue strength of VHSS.

The number of cycles of the total fatigue life $N_f$ is the sum of the number of cycles to crack initiation $N_i$ and the number of cycles of crack propagation $N_p$. Figure 3.1 shows the fatigue life represented by the phases crack initiation (I), crack propagation (II) and fracture (III). Figure 3.2 shows the fracture surface of a fatigue loaded specimen, with visible initiation locations, stages of crack growth represented by semi-elliptical beach marks, and a fracture region of the remaining ligament.

![Figure 3.1. Typical example of fatigue life. I: Crack initiation phase, II Crack propagation phase, III Final failure.](image-url)
The next section, 3.2, gives background information on the fatigue strength approaches that may be used to qualify the fatigue strength of welded connections; the nominal stress approach, the notch stress approach, the notch strain approach and the fracture mechanics approach. Section 3.3 discusses the effect of notch sensitivity on the fatigue strength of welded connections made of VHSS. Furthermore, the section presents a literature summary on numerous fatigue experiments on welded details made of VHSS and the positive effect of using high detail class for these steels and post weld treatment. Section 3.4 focuses on the fatigue strength of cast joints and hybrid connections made of cast and rolled steels.

3.2 Fatigue strength approaches
Through choice of the appropriate detail category, the total fatigue life of a wide range of welded connections can be determined by the nominal stress approach. The structural stress approach and the notch stress approach provide improved incorporation of local influence factors, such as the weld shape. The crack initiation life can be determined accurately by the notch stress and notch strain approach. Fracture mechanics approach addresses the crack propagation life.

This section gives the basic principles of the fatigue strength approaches. Chapter 6 and Chapter 7 deal with the fatigue strength approaches in more detail, to illustrate the effect of geometrical and material parameters on the crack initiation and crack propagation life of base material and welded fatigue test specimens.

3.2.1 Nominal stress approach
The most commonly used method for the determination of fatigue strength of connections or structural members is the nominal stress approach. This approach is widely adopted in design standards of several steel industries, like the civil engineering, offshore and crane industries. In general, the number of cycles until failure is determined based on the nominal stress range, which is typically presented in a log-log graph, the fatigue strength curve (also called the Δσ-N, s-N, or Wöhler curve). The nominal stress is defined as the stress in the parent material or in a weld adjacent to a potential crack location, which is calculated in accordance with elastic theory excluding all stress concentration effects; thus without effects of weld geometry and hot spot stress. Secondary stresses as a result of distortion or misalignment of a fatigue loaded part, should be determined according to elastic theory.
3. Fatigue strength of welded joints

Secondary stresses should therefore be incorporated in the nominal stress, both in fatigue testing [Lieurade et al, 2005] as in the structural analysis. Preferably, the nominal stress approach is used for expected number of cycles in the high cycle domain (N > 50000 cycles) and stress ranges up to values of half the yield strength of the material. Fatigue strength design curves are given for all sorts of connections, by use of various detail categories, for which the local geometry is taken into account implicitly.

The basic design code for the determination of the fatigue strength of steel structures is EN 1993-1-9 (2005); the code uses the nominal stress approach including detail classifications independent of steel type. A choice of an appropriate design fatigue curve of EN 1993-1-9 (2005) is only valid if the geometry of the welded detail meets the requirements for execution of steel work according to EN 1090-2 (2008). EN 1090-2 (2008) includes hot-rolled, structural steel products up to grade S960; EN 1993-1-12 (2007) gives additional rules increasing the validity of EN 1993-1-9 (2005) up to steels of grade S700. EN 1993-1-9 (2005) is only valid for rolled steels, not cast steel joints. The fatigue strength of individual detail categories is based on numerous experiments; summarized and evaluated by Sedlacek et al. (2003). Figure 3.3 presents the fatigue strength curves as given in the EN 1993-1-9 (2005) for all detail categories. The direct stress range is plotted in the vertical axis against the number of cycles until failure on the horizontal axis. Every type of connection is classified in a detail category defined as the endurable stress range \( \Delta \sigma_{c} \) at \( N = 2 \cdot 10^{6} \) cycles. For constant amplitude nominal stress ranges \( \Delta \sigma_{R} \), the fatigue strength, in other words, the endurable number of cycles until failure \( N_{R} \), can be obtained by Eq. 3.1.

\[
\Delta \sigma_{R} \cdot N_{R} = \Delta \sigma_{c}^{m} \cdot 2 \cdot 10^{6} \tag{3.1}
\]

\( m \) Slope of fatigue strength curve; \( m = -3 \) for \( N \leq 5 \cdot 10^{6} \)

\( \Delta \sigma_{0} \) is the constant amplitude fatigue limit at \( N = 5 \cdot 10^{6} \) cycles. Constant amplitude stress ranges below the fatigue limit are not expected to contribute to fatigue damage. For variable amplitude loading with typical stress ranges below the constant amplitude fatigue limit and above the stress range of the cut off limit, the slope is changed to \( m = -5 \).

For rolled or extruded products like plates, flats, rolled sections and seamless hollow sections, rectangular or circular, category 160 is valid provided that sharp edges, surface and rolling flaws are removed by grinding and smooth transition has been achieved, (See Table 3.2). Machine gas cut or sheared material with subsequent dressing is classified in category 140 if all visible signs of edge discontinuities and all burns have been removed and cut areas have been machined or ground. Also any machinery scratches for example from grinding operations can only be located parallel to the stresses. Category 125 is valid for material with machine gas cut edges, having shallow and regular draglines or manual gas cut material, subsequently dressed to remove all edge discontinuities.
Table 3.2. Detail classification of welded plates according to EN 1993-1-9 (2005).

<table>
<thead>
<tr>
<th>Detail cat.</th>
<th>Constructional detail</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>1) Plates and flats with as rolled edges; 3) Seamless hollow sections, either rectangular or circular.</td>
<td></td>
</tr>
<tr>
<td>140</td>
<td>4) Machine gas cut or sheared material with subsequent dressing.</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>5) Material with machine gas cut edges having shallow and regular drag lines or manual gas cut material, subsequently dressed to remove all edge discontinuities.</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.3. Fatigue strength curve according to EN 1993-1-9 (2005).
The detail category of a transverse butt weld, X-welded from both sides, is 90 MPa in the as-welded condition (See Table 3.3). The following criteria account for this detail class: transverse splices in plates or flats; weld run-on and run-off pieces to be used and subsequently removed; plate edges to be ground flush in the direction of stress; welded from both sides in flat position; NDT applied. Also, the detail depends on the execution quality, with reference to EN 1090-2 (2008) for the visual quality of the weld. If the excess of weld metal is large, the detail category may drop to 80. If all welds are ground flush to the plate surface parallel to the direction of the stress, category 112 may be obtained. For the categories up to 112 the welds must be checked by NDT. The size effect for plate thicknesses $t > 25$ mm is defined as the factor $k_s$ (See Eq. 3.2).

$$k_s = \left( \frac{25}{t} \right)^{0.2} \quad (3.2)$$

For V-welds made from one side only, the fatigue design curve to be used varies between category 36 and 71. The lowest category (36) counts for transverse butt welds without backing strips, without NDT. If full penetration for welds without backing strips is checked by NDT category 71 is valid for plate thicknesses $t \leq 25$ mm. For transverse butt welds with backing strip the fatigue strength depends on the location of the backing strip fillet welds. Where backing strip fillet welds $< 10$ mm from the plate edge, or a good fit cannot be guaranteed, category 50 must be considered. Fillet welds attaching the backing strip terminating $\geq 10$ mm from the edges of the stressed plate and when the tack welds are situated inside the shape of the butt welds category 71 applies. For a transverse butt weld with different plate thicknesses without transition category 71 is valid if the centre line of the connecting plates is aligned. For plate thicknesses $t_i > 25$ mm and or generalization for eccentricity ($e$) of the connecting plates a misalignment factor $k_{s1}$ must be taken into account (See Table 3.3).

Without additional information, the given fatigue categories for hollow section joints in EN 1993-1-9 (2005) are limited to wall thickness $t < 12.5$ mm, (See Table 3.4). The transverse butt welds in end-to-end connections between circular or rectangular structural hollow sections require the following two restrictions. The weld convexity must be $\leq 10\%$ of the weld width with smooth transitions. The weld must be welded in a flat position, inspected and found free from defects outside the tolerances of EN 1090-2 (2008). For circular joints category 71 applies and for rectangular joints category 56 is valid. If the wall thickness $t > 8$ mm, the detail may be classified two categories higher to 90 or 71 respectively.
Table 3.3. Detail classification of butt welded plates according to EN 1993-1-9 (2005).

<table>
<thead>
<tr>
<th>Detail cat.</th>
<th>Constructional detail</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>1) Transverse splices in plates and flats.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4) Transverse splices in plates or flats tapered in width or in thickness, with a slope ( \leq \frac{1}{4} ).</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>5) Transverse splices in plates or flats.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7) Transverse splices in plates or flats tapered in width or in thickness with a slope ( \leq \frac{1}{5} ). Translation of welds to be machined notch free.</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>11) Transverse splices in plates, flats, rolled sections or plate girders.</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>13) Butt welds made from one side only.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Without backing strip. No NDT.</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>13) Butt welds made from one side only when full penetration checked by appropriate NDT.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Without backing strip.</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>14) Transverse splice. With backing strip:</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>15) Transverse butt weld tapered in width or thickness with a slope ( \leq \frac{1}{4} ).</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>16) Transverse butt weld on a permanent backing strip tapered in width or thickness with a slope ( \leq \frac{1}{4} ). Where backing strip fillet welds end &lt; 10 mm from the plate edge, or if a good fit cannot be guaranteed.</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>17) Transverse butt weld, different thicknesses without transition, centrelines aligned.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( k_s = \left( 1 + \frac{6e}{t_i t_1^{0.5} + t_2^{0.5}} \right)^{0.2} )</td>
<td></td>
</tr>
</tbody>
</table>

\( t_2 \geq t_1 \)
3. Fatigue strength of welded joints

Table 3.4. Detail classification of butt-welded end-to-end connections between circular structural hollow sections according to EN 1993-1-9 (2005).

<table>
<thead>
<tr>
<th>Detail cat.</th>
<th>Constructional detail</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3) Butt-welded end-to-end connections between circular structural hollow sections.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Another code which is based on the nominal stress approach is the crane code NPR-CEN/TS 13001-3-1 (2004) which is applicable to design of crane structures with yield strength up to 960 MPa. There is made distinction in yield stress level and execution quality level in the determination of the fatigue strength of welded joints. A background document on the crane code detail categories is not known to the author.

Hobbacher (2007) gives the IIW recommendations for the fatigue strength of welded connections. Detail categories are mentioned for the application of nominal stress approach. All steels up to yield strength 960 MPa are included in the recommendations; however, no distinction in yield strength is made.

DNV (2005) presents detail categories for assessment of fatigue strength of offshore structures. A detail class for the fatigue strength of base material with grade > 500 MPa is given. Moreover, the effect of post weld treatment is included, which is not covered in EN 1993-1-9 (2005). The effect of grinding, TIG-dressing and hammer peening can increase the fatigue life up to a factor 4 depending on the treatment method and the yield strength of the material, either $\sigma_y < 350$ MPa, or $\sigma_y > 350$ MPa.

3.2.2 Structural stress approach

The structural stress approach, also called hot-spot stress approach, takes account of influence of the geometrical stress distribution on fatigue strength of structural members, without consideration of local notch effects. In particular for the determination of the fatigue strength of welded CHS, the structural stress approach is used in the classification of detail categories. With use of the hot spot theory, the influence of characteristic parameters for hollow section joints, such as the thickness ratios of chords and braces, joint angle, gap length, loading type and location, are taken into account. The stress may be determined from FEM method or strain gauge measurements. Contributions of various load cases may be superpositioned. An extrapolation of the stress is made up to the location of the weld toe. The positions of the elements and strain gauges used for extrapolation are typically taken at 0.4t and 1.0t from the weld toe; by this, the stress concentration factor is determined (SCF). The effect of the weld shape on the local stress concentration is not covered in the hot-spot stress approach.

strength of details based on the structural stress approach. Especially for the design of lattice structures made of hollow section components, the CIDECT design guides [Zhao et al., 2000] are suitable, also with reference to the structural stress approach.

3.2.3 Notch stress/Notch strain approach
In contrary to the nominal stress approach, the notch stress approach does address local parameters for the determination of the fatigue [Radaj et al., 2006]. Fatigue cracks tend to grow from microstructural defects to a level of visibly detectable flaws, which could eventually lead to failure of a structural member. According to the notch stress theory, the local geometry, given by the surface condition and the local geometry of a structural member, determines the notch stress concentration, which is the governing parameter for the fatigue strength. Every sharp geometrical change could be defined as a notch; the sharper the notch, the higher the local stress concentration.

3.2.3.1 Notch stress approach
In the notch stress approach, the concept of the microstructural notch support can be adopted, conceived by Peterson (1974). This theory says the maximum notch stress according to elastic theory is not decisive for crack initiation and propagation, but an averaged lower stress value over a small length, determined by the fatigue notch factor. The fatigue notch factor depends on both the microstructural support length, which is a function of the yield or tensile strength and the notch radius. Lawrence et al. (1981) set up a procedure for determining the fatigue strength of welds by the notch stress approach. The first step is to identify the critical crack initiation location. The elastic stress component is based on the notch stress approach. With this, the fatigue notch factor can be determined. According to Heywood (1962) and Maddox (1991), the experimentally determined stress concentration factor, or notch factor, is called Kt. The experimentally determined influence of Kt on fatigue strength is called the fatigue notch factor Kf, which is calculated by Eq. 3.3:

\[
K_f = \frac{\sigma_{f}}{\sigma_{aE}}
\]

\[
\sigma_{aE} \text{ Fatigue endurance limit welded connection } (K_t \neq 1)
\]

\[
\sigma_{aE} \text{ Fatigue endurance limit polished specimen } (K_t = 1)
\]

The notch sensitivity factor \(\eta\), defined by Eq. 3.4, indicates the effectiveness of the notch stress concentration factor on the fatigue strength.

\[
\eta = \frac{(K_f - 1)}{(1 - K_t)}
\]

\(K_f\)  Fatigue notch factor
\(K_t\)  Notch stress concentration factor
3. Fatigue strength of welded joints

Heywood (1962) showed, for low values of $K_t$, $K_f$ approaches $K_t$, but will be lower. $K_f$ may depend on the structural size. For high values of notch stress concentration factor $K_t$, the fatigue notch factor $K_f$ is much lower than $K_t$. $K_f$ increases if the grain size of the material decreases and therefore depends on material grade. In case of low $K_t$, high strength steel has higher fatigue strength than mild steels; however, the ratio of the fatigue strength is lower than the ratio of yield strength and will be smaller in case of high surface roughness. In strongly notched bars the advantage of high performance material will be cancelled out by the higher notch sensitivity.

The notch stress values can be related to the endurable number of cycles until failure, similar to the fatigue limit defined in the nominal stress approach. The Haigh diagram can be used in combination with the notch stress approach, to incorporate the influence of mean stress and the residual stresses at the notch root on the endurance limit.

The notch radius $r$ is an important geometrical parameter in the determination of both the notch stress concentration factor and the fatigue notch factor. In general, the smaller the notch radius the less effective the notch stress concentration will be on the fatigue strength. Chapter 6 will focus on the application of the notch stress theory for the prediction of crack initiation life in more detail. Anthes et al. (1994) give calculation rules for the local stress concentration from the weld geometry, including weld toe radius and weld toe angle and loading mode, membrane or bending loading. Hübner (1996) proved these formulas also to be valid for very high strength steels S890 and S960.

3.2.3.2 Notch strain approach

For the incorporation of the effect of large plastic stresses, the notch stress approach is extended by the notch strain approach. Originally, the notch strain approach was developed for mild notches in the low cycle domain ($N < 50000$ cycles). Fatigue stresses remain predominantly elastic in the high cycle fatigue domain. In the low cycle fatigue domain, the contribution of the plastic strains needs to be taken into account. The notch strain approach considers the influence of non-uniform material parameters, residual stresses and surface hardening on the fatigue strength. The theory is based on the use of a so-called un-notched comparison specimen, to be taken from the crack initiation critical areas of structural members. Differentiation can be made in location of base material, fusion zone or heat-affected zone of welded parts.

In a structural application, notch stress and notch strain may be determined by elastic plastic FEM. Alternatively, through macrostructural support formula of Neuber (1946) these values can be determined analytically. In the notch strain approach, the cyclic stress-strain relations are determined first, which gives additional material parameters to the standard monotonic stress strain relations. The incorporated theory of Ramberg and Osgood (1943) relates the cyclic stress to the cyclic strain analytically. Next, the material parameters are used in the fatigue strength curve according to Manson-Coffin relation [Radaj et al. 2006], which relates the total strain and the number of cycles until crack length $0.1 < a < 1$ mm. Figure 3.4 presents the Manson-Coffin curve for the determination of the fatigue strength in the low cycle regime, with separation of the contribution of the elastic strains and the plastic strains.
3.2.4 Fracture Mechanics approach

With the fracture mechanics approach, fatigue crack growth can be addressed. In general, three phases in the crack growth are relevant, the crack initiation phase, the crack propagation phase and the final fracture phase. The fracture mechanics representation of the crack growth is given by the relation of the crack growth rate and the stress intensity range. The crack growth rate \( \frac{da}{dN} \) is generally defined as the derivative of the crack growth in thickness and the number of cycles. The key geometry parameter in crack growth is the stress intensity range, \( \Delta K \), which is a function of the applied stress range, crack size and local geometry.

In order to start fatigue crack growth, a threshold value for the stress intensity range needs to be exceeded, either by a high stress range or a large crack size. With increasing growth of the crack, a stable crack propagation phase is entered, (See Figure 3.5). The Paris law describes the stable crack growth region, which is a log-linear relation of the \( \frac{da}{dN} \) against \( \Delta K \) with material parameters \( C \) and \( M \) (See Eq. 3.5).

\[
\frac{da}{dN} = C \cdot \Delta K^M \tag{3.5}
\]

The final failure is preceded by an unstable crack growth phase. The toughness of the material determines the final crack size at fracture. More complex representations of the relation of the crack growth rate and the stress intensity range, with inclusion of mean stress level, threshold intensity range and the fracture toughness are presented by Dijkstra & Van Straalen (1997). The British standard BS 7910 (2005) and Hobbacher (2007) give calculation rules for the determination of the crack growth of initial flaws in welded connections.
3. Fatigue strength of welded joints

For structural steels, the crack growth rate does not vary significantly, and certainly not consistently, with material strength [Barsom and Rolfe, 1999]. This means, any beneficial effect of yield or tensile strength on fatigue must relate to the crack initiation process, which may form a significant proportion of the fatigue lives of base material parts.

3.3 Fatigue experiments on specimens made of VHSS

In the past, numerous studies on the fatigue strength of welded connections were conducted to address the influence of yield strength on the fatigue strength. Individual structural details, such as transverse butt welds, stiffeners and girth welds were loaded under cyclic stress until failure. Appendix A (Figures A1 up to A26) summarizes the studies, in which the effect of high yield strength on the fatigue strength was addressed. The literature is evaluated per detail category. In general, for low detail categories no improvement by higher strength material was found. However, in certain cases, the fatigue strength was found to increase with yield strength; for effectiveness of higher yield strength, the quality of the weld was shown to be of great influence.

3.3.1 Base material plates

Hübner (1996) studied the fatigue strength of base material cracks in S890 and S960 steels. Fatigue strength curves were derived for unnotched 10 mm specimens; axial constant amplitude loading was applied with $R = 0$. The fatigue strength of the unnotched specimens was found to increase with yield strength, (See Figure A1).

Sonsino et al. (1992) studied the influence of the cutting process on fine grained, high strength steels S355, S460 and S690. For a milled surface and ground edges, the fatigue strength was found to increase with yield strength, (See Figure A2). Preheating up to $T = 200 \, ^\circ C$ was not found to be of influence on the fatigue strength. Also the cutting speeds...
of 350 to 650 mm/min were not of influence; nor the yield strength of the specimens. Fatigue strength of as rolled surface was lower than that of flame cut edges. No advantage was found for higher yield strength, if grid blasting or hammering were applied on the edges. In case of (high) average tensile stresses the high yield strength steels were found to be in favour.

3.3.2 Transverse butt welds

A recent research project relating to the fatigue classification of high strength steel is the project ‘Efficient Lifting Equipment with Extra High Strength Steel’ [Lagerqvist et al. 2007]. The main research topic was the fatigue behaviour of welded high strength steel details up to yield strength of 1100 MPa. Puthli et al. (2006) and lieurade et al. (2008) showed fatigue results on base materials, welded and post weld treated joints made of S690, S960 and S1100. Tests were performed on symmetric and asymmetric plate specimens (t = 6-8 mm), with V-shaped butt weld details, with various backing conditions, (See Figure A3 and A4). The following conclusions were drawn on the use of high strength steel regarding fatigue. For symmetrical details, the yield strength was found to increase the fatigue strength. On the whole, the investigated steel grades were found to confirm the detail categories given in EN 1993-1-9 (2005). For some details, higher values were found for the calculated slope of the fatigue strength curves; $-5 < m < -4$ instead of $m = -3$. The fatigue resistance was influenced by the design of the weld detail and the execution quality of the weld. In this context, advantage of higher yield strength could also be achieved using post weld treatment.

Hübner (1996) studied butt welded connections made of S890 and S960 steel. Fatigue strength curves were obtained for t = 10 mm V- and HV-welded connections, with and without application of TIG dressing (See Figures A5, A6 and A7). In the fatigue tests, axial constant amplitude loading was applied with variable R-ratio. Only in case of TIG dressing with improved weld toe shape, fatigue strength was found to increase with yield strength. TIG dressing was especially effective in case of high mean stress values.

Demofonti et al. (2001) and Kaufmann et al. (2005) performed axial fatigue tests on X-welded plate specimens (t = 10 mm and 30 mm) made of S355M, S355N, S690 and S960 (See Figures A8 and A9). The results of the investigation showed that there is no clear advantage of higher yield strength on the fatigue strength. In the investigation, no significant strength differences under constant amplitude loading were found in favour of use of higher steel strengths, although advantages for the S960 steel could be noticed in case of variable amplitude loading. Machining of welds, in order to achieve low notch factors was found to give an advantage for high-strength steels. In case of applied variable amplitude loading, a large part of fatigue life was associated with crack propagation. The higher the amplitude, the higher are the residual compressive stresses at the crack front, caused by plastic deformation. The S960Q material was able to build up the highest compressive residual stresses. Therefore, this material’s butt welds endured 30 % higher local stresses than those made of lower grades.

3.3.3 Welded built-up sections

Anami & Miki (2001) reported rearrangements of fatigue test data from 1971-2000 on longitudinal welds in small size specimens and full-scale girder beams made of different types of steel, (See Figure A10). The tensile strength varied between 400 and 900 MPa. The
authors concluded that there is no clear dependence of the fatigue strength on the steel strength of welded built-up sections. Main reason for this was the observation in the past that the fatigue strength of longitudinal welded joints was greatly influenced by the size of embedded discontinuities, such as blowholes. Fatigue strength of welded joints in full scale girders showed lower fatigue strengths than small scale welded specimens.

3.3.4 Stiffeners, attachments and load carrying welded joints
Fatigue tests on cover plates on S960 QL beams were reported by Bucak (2000) and Herion & Müller (2000). Higher classification than the category according to EN 1993-1-9(2005) was found for cover plates, (See Figure A11). Also, the slope of the fatigue strength curve differed considerably; \( m = -7 \) instead of \( m = -3 \). An analysis of fatigue details typically used in crane structures was undertaken. A general increase of the fatigue strength by high strength steel could only be observed at details with low notch effects.

Fatigue tests by Herion and Müller (2000) on rectangular hollow sections with a tensile strength of 600 MPa and longitudinal attachments with a length 200 mm resulted in a \( \Delta \sigma = 87.9 \) MPa. Also test results for a longitudinal attachment with a radial transition of 40 mm resulted in a higher category compared to EN 1993-1-9 (2005). Fatigue resistance of studs welded of high strength steel grade S960QL resulted in category 80.

Investigations on special notch cases from mobile crane structures showed a positive fatigue behaviour for high strength steels [Bleck et al., 2004], [Hummel et al. 2006], [Hamme et al., 2000]. A real structure of a crane part and small scale specimens made of S960Q and S1100Q were tested on a test rig Stuttgart University under 3-point bending.

Bergers et al. (2006) and Puthli et al. (2006) report of an extensive research program on the fatigue strength of crane details, (See Figures A12, A13, A14 and A15). The following details were studied: longitudinal stiffeners, circular openings (with and without strengthenings), plates with welded cover plates and K-Joints made of L-sections (\( t = 10, t = 7 \) mm). The fatigue resistance of VHSS was found to be at least on the level of lower grade steels. High notch factors lead to a relative disadvantage for VHSS.

Puthli et al. (2006), Lagerqvist et al. (2007) and Lieurade et al. (2008) reported fatigue test results on longitudinal attachments of plates with \( t = 8 \) mm, (See Figure A16). The length of the attachment varied between 80 mm and 200 mm. This constructional detail was made of steel grades S690, S960 and S1100. For all steel grades, the fatigue behaviour of the as-welded specimens was compared to specimens with the weld toe improvement techniques burr grinding and TIG dressing. Also, cruciform welded joints were investigated in the as welded condition, with grinding and TIG- dressing, (See Figure A17).

Cruciform, non-load carrying fillet welded joints made of S1100 (\( t = 8 \)mm) were tested under constant amplitude loading by Sonander (2000). Three weld metals (Union X90, Union NiMoCr, Union K56) with varying inherent strength were used for HV- and K-weld shapes. Half the number of specimens was TIG-dressed at the critical weld toes. The stress ratio \( R = 0 \), except in a few cases where \( R > 0 \) was applied. The R-value (in the range tested) did not influence the fatigue performance. Properly performed TIG-dressing increased the fatigue life with factor 3 till 4. No influence of a varying degree of mismatch in strength between base material and filler metal was detected.

Demofonti et al. (2001) performed axial fatigue tests on transverse stiffeners (\( t = 10 \) mm and 30 mm) made of S355M, S355N, S690 and S960, under cyclic constant and variable amplitude loading, (See Figures A18 and A19).
Agerskov et al. (1999-1, 1999-2) studied fatigue damage accumulation in steel highway bridges under random loading. The fatigue life of welded joints was determined both experimentally and from a fracture mechanics analysis. Fatigue test series were executed on welded cruciform joints and CHS double T-joints made of conventional structural steel with yield stress $\sigma_y = 400–410$ MPa and high-strength steel with yield stress $\sigma_y = 810–840$ MPa. The results showed a significant difference between constant amplitude and variable amplitude fatigue test results. Both the fracture mechanics analysis and the fatigue test results indicated that Miner’s rule, which is normally used in the design against fatigue in steel bridges, may give non-conservative results. The validity of the results obtained from Miner’s rule depended on the distribution of the load history in tension and compression.

3.3.5 Lattice girder node joints
Stauf et al. (1998) investigated hollow section joints with material yield strengths of 235, 355 and 690 MPa. The results of fatigue investigations on hollow section connections (fillet weld, butt weld, longitudinal rib, transverse rib) and hollow section joints (X-joints and K-joints) are presented. An upward shift of fatigue strength curves was found in case of stiff joints ($b_1/b_0 = 1.0$ and 100% overlap).

3.3.6 Post weld treated connections
Local improvement of the weld shape by post weld treatment could be highly beneficial for very high strength steels, because of the high notch and mean stress sensitivity of VHSS and the possibility of building up high compressive residual stresses. By grinding or TIG dressing the notch stress concentration could be reduced and hammering or ultrasonic peening could result in compressive residual stresses.

Manteghi and Maddox (2004) presented the main findings of a joint-industry project concerned with the application of weld toe improvement techniques to fillet welds in medium and high-strength steels. The investigated techniques were hammer peening, burr grinding and mechanised TIG dressing; the steels were grades S355 and S700. Use of the investigated techniques tended to be very effective for the improvement of the fatigue strength of welded connections made of high strength steels.

According to Kuhlmann et al. (2006), use of ultrasonic peening could increase the characteristic fatigue strength at 2 million cycles of welded transverse stiffeners made of S460 with 40 up to 100% (See Figures A20, A21, A22, A23 and A24). Ultrasonic peening proved to be even more effective at stiffeners made of S690. Cracks initiated in parent material instead of in the welds; the slope fatigue strength curve differed. For the as-welded condition $m = -3.5$ was obtained; for TIG dressing/grinding $m = -3.9$; for peening $m = -5.2$. In large scale test girders, hardly any influence of tensile strength on fatigue strength was found (See Figures A25, A26 and A27). The fatigue strength of large scale test girders was 20% below the strength of small scale specimens.

Ummenhofer et al. (2007&2010) report of fatigue tests on transverse butt welded connections and longitudinal stiffener connections made of S355 and S690: untreated and treated with ultrasonic treatment techniques HiFIT/UIT (See Figure A28 and Figure A29). Various conditions were applied: $t = 16$ and 30 mm; $R = 0.1$ and 0.5; influence of stress relief and blasting. For all conditions, S690 was found to have higher fatigue strength than S355. A relative higher improvement by HiFIT/UIT was found for longitudinal attachments compared to the transverse butt welds.
3. Fatigue strength of welded joints

3.4 Fatigue experiments on specimens made of cast steel

If joints are designed in such a way that stress concentrations are lowered and welds are avoided in the highest loaded locations, fatigue strength may be optimized for VHSS. This is possible by the use of cast joints, which form hybrid connections when welded to rolled steel parts. Section 3.4.1 addresses the strength of the cast steel base material; Section 3.4.2 discusses the experimental results on the fatigue strength of the welded connections of cast and rolled steels.

3.4.1 Fatigue strength of cast steel base material

Bergmann et al. (1981) did research on influence of cast defects on the fatigue strength of cast steel type GS13MnNi6-4. Based on the test results a calculation concept was derived, also described in [UEG, 1985]. In this concept, a reference fatigue strength curve was defined with $\Delta \sigma_c = 100$ MPa for $m = -5$; defect group 4; $R = 0$ and $t = 25$ mm. Influence of other stress ratios, wall thicknesses, defect groups and inspection levels could be accounted for by influence factors. With respect to cast joints, internal defect sizes should be assessed to adjust the quality of the cast member to the defect groups 1 to 5 according to ASTM E 446 (2004). The calculation rules were based on fatigue experiments on Hoesch GS-ARK 10 cast steel base material, taken from K-joints.

Eq. 3.6 presents the procedure to derive the fatigue strength curve of cast members taking account of influence factors for the defect group of the cast joint.

$$\log N = 16.30 - 5 \cdot \log \Delta \sigma_c$$

(3.6)

with,

$$\Delta \sigma = \lambda_R \cdot \lambda_F \cdot \lambda_W \cdot \lambda_I \cdot \Delta \sigma$$

where,

$\Delta \sigma$ Stress range
$\Delta \sigma_c$ Characteristic stress range at $2 \cdot 10^6$ cycles of chosen detail category
$N$ Number of stress cycles
$\lambda_R$ Correction factor for mean stress; $\lambda_R = 0.85$ if $R > 0$, $\lambda_R = 1$ if $R < 0$
$\lambda_F$ Correction factor for defect class; $\lambda_F = 0.85^{i+4}$, with $i$ representing defect classes 1-5 [ASTM E 446, 2004]
$\lambda_W$ Correction factor for wall thickness; $\lambda_W = (25/t)^{0.15}$
$\lambda_I$ Correction factor for inspection possibility

Figure 3.6 shows the predicted fatigue strength of the cast steel base material for defect groups 1, 2 and 3, given $R > 0$, and $t = 25$ mm.
3.4.2 Fatigue strength of welded connections made of cast and rolled steels

Sonsino & Umbach (1993) tested large scale tubular joints with cast steel inserts. Both constant and variable amplitude fatigue tests were conducted on K-joints in the as-welded state. The cast inserts were made of medium strength GS8Mn7 cast steel (S355) and high strength GS12MnMo7.4 cast steel (S500). The fatigue life to crack initiation of the high strength cast steel inserts was found to be by a factor of two superior to the inserts from medium-strength inserts, despite a thickness reduction from 38 to 28 mm. Also, the crack propagation life of the high-strength cast steel was much higher than the life of the medium-strength cast steel.

For the building of the railway station “Lehrter Bahnhof” in Berlin, fatigue tests on welded cast steel plates of 25-40 mm, with and without backing, were reported by Mang et al. (1999 & 2003) at constant amplitude, $R = 0.1$. The steel type used was S355 and the cast steel type GS-20Mn5 (currently depicted as G20Mn5). The following results were found for the specimens with $t = 25$ mm. The $\Delta \sigma_{\text{mean}} (P50\%, N = 2 \cdot 10^6)$ was 112.7 MPa with permanent backing and $\Delta \sigma_{\text{mean}} = 146.1$ MPa without use of backing. For the slope of the fatigue strength curve values $-4.3 < m < -3.9$ were found. Statistical evaluation resulted in a $\Delta \sigma_c = 87.5$ for the specimens with permanent backing and $\Delta \sigma_c = 123.5$ for the specimens without backing. For the $t = 40$ mm specimens, the $\Delta \sigma_{\text{mean}} = 96.9$ MPa, $\Delta \sigma_c = 78.8$ MPa with permanent backing, and $\Delta \sigma_{\text{mean}} = 154$ MPa, $\Delta \sigma_c = 135.1$ without use of backing. The scatter in the results with backing was higher than the results without backing. Next to small scale specimens, CHS to cast steel end-to-end connections (260x20) were tested. Constant amplitude axial loading was applied on specimens made of S355J2H rolled steels welded to cast members made of GS-20Mn5, with integrally cast backings [Mang et al., 2003]. The mean fatigue results of the large scale specimens fitted in the lower bound of the small scale results; given $m = -3$, $\Delta \sigma_{\text{mean}} = 71$ could be derived.
3. Fatigue strength of welded joints

At the EPFL Lausanne, experimental and numerical work was carried out on the fatigue strength of cast steel joints [Haldimann-Sturm, 2005]. The allowable initial defect sizes of the cast steel joints were determined based on fatigue experiments on real scale bridge truss girders with K-joints with CHS (dimensions chord: 244x10; braces: 193.7x8, 193.7x16) made of S355 welded to cast members of G20Mn5, (See Figure 3.7).

![Figure 3.7. Fatigue truss specimen with CHS and cast joints [Haldimann-Sturm, 2005].](image)

It was concluded that the fatigue resistance of the welded joints needed to be substantially improved in order to benefit from the high fatigue resistance of the cast nodes. Although defects were not detectable by NDT, all cracks initiated from the weld root. It was found in this research that V-girth-welds without backing bars (See Figure 3.8, L1) could be classified into detail class 60, $\Delta\sigma_c = 60$ MPa, according to EN 1993-1-9 (2005). The use of backings bars (See Figure 3.8, L2) raised the detail class to 90 MPa. A global FEM-model was made with the castings applied in a truss bridge structure. With the help of an additional crack growth model, at several locations stress intensity factors were calculated for several initial defect sizes until crack depth through thickness. The maximum allowable defect size, $a_{crit}$, was based on two criteria. The first was an analysis based on the Failure Assessment Diagram (See Section 2.4). The second criterion was limitation of the defect size to 90% of the wall thickness.

The research project "Fatigue Of End-To-End CHS Connections" [Puthli et al., 2007] initiated by the University of Karlsruhe was a follow up research on the work performed in Lausanne. The research subject was the fatigue resistance of the transition of chord members to the cast members, of which the welds were manufactured in different variations of the inner diameter, the outer diameter, use of permanent backing plate and misalignment tolerances, (See Figure 3.8). In the research, both axial setup and four point bending test setups were used. The research project comprised of fatigue experiments on S355 and S460 specimens and corresponding cast steel grades G20Mn5 + QT and G10MnMoV6-3 +QT3 (CHS dimensions: 193.7x20, 298.5x30, 508x55). Results up till now showed no remarkable differences in the fatigue strength of S355 and S460 [Veselcic et al., 2006]. All failures started in the roots of the welds. In the resulting fatigue strength curve a slope $m = -8.1$ was found when evaluating all variants of butt welded CHS connections. With a slope $m = -5$, detail class 100 according to EN 1993-1-9 (2005) tended to be possible; with $m = -3$ a tendency was found to detail class 67, $\Delta\sigma_c = 67$ MPa (Veselcic et al. 2009). Moreover, it was concluded that with a good weld quality a weld backing may be omitted.
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 3.8. Sketches of tested variants of CHS-cast steel connections K1 - K6 after Veselcic et al. (2009) and L1 - L2 after Haldimann-Sturm (2005).

The conclusions of the work of Lausanne and Karlsruhe are summarized in Nussbaumer et al. (2010). New fatigue strength curves are proposed for details of CHS-cast joints for structural steels up to S460, with differentiation for bending and tension. These values are valid for wall thickness between 20 and 60 mm; if the welds are UT controlled, if the quality of the cast steel at the weld meets V1S1, quality 1 according to ASTM E 446 (2004), and NDT is applied on surface cracks.

For connections with equal thickness of CHS and cast steel that are made with use of ceramic or steel backing ring, class 112 is suggested for bending and class 71 for tension; given \( m = -0.5 \).

For connections with different thickness made with bevel and tack welded steel backing ring (\( t = 3 \) to 4 mm), with ceramic backing or with TIG root as backing, also class 112 is suggested for bending and class 71 for tension; given \( m = -0.5 \). The thickness variation should not exceed 40\%. In case the CHS are not beveled and made without backing ring or with a tack welded backing ring, class 100 is suggested for bending and 71 for tension; given \( m = -0.5 \).

The suggested detail categories are compared to the fatigue strengths that are obtained in the current study for CHS-Cast steel connections, (See Figure 5.21 and Figure 7.40).

3.5 Summary of findings

Use of VHSS should ideally lead to the smaller cross sections and light weight structures. Whereas absolute and relative stress levels increase, the fatigue strength of the welded connections is expected to be the limiting design criterion for VHSS structures.

The fatigue strength mainly depends on the stress range. As a result of geometrical changes, stresses may be raised locally, quantified by stress concentration factors. In case the stress concentration is high, yield strength is found to be independent of material yield strength, if the total fatigue life of welded connections tends to be determined by only the crack propagation life, not on crack initiation life. The nominal stress approach is the base for most of the fatigue design codes. These codes do not give a relation between steel grade and the fatigue strength of structural members. With the notch stress theory, the initiation life of fatigue crack can be assessed, with the fracture mechanics theory, the propagation life of fatigue cracks. The fatigue notch factor is the key parameter for the assessment of the
3. Fatigue strength of welded joints

influence of yield strength on the crack initiation life. According to the fracture mechanics theory, crack growth is independent of material strength. Experimental work on the fatigue strength of welded connections makes clear that low class welded details have similar fatigue strength independent of steel grade. For higher class details the fatigue strength may increase with yield strength, if high quality welds are made. Improvement techniques, such as grinding and peening are found to have a positive influence on the fatigue strength, especially in case of high yield strengths. Application of cast joints, leading to a reduction of stress concentration, is found to have a positive influence on the fatigue strength of mild steel joints.

For base material parts of structural members, fatigue strength correlations have been derived, but there is still lack of fatigue life prediction models for welded connections. Experimental data on the fatigue strength of welded parts of structural members made of rolled steel with yield strength above S690 MPa are scarce; fatigue test data on welded cast joints with very high yield strength are unknown to the authors.

Based on the literature evaluation of fatigue strength of welded joints, an experimental program was determined to investigate the fatigue strength of welded connections made of rolled steel and cast steels with very high yield strength. Part II of this dissertation presents the results of the experimental work. In Part III, analysis, the nominal stress approach, the notch stress approach and the fracture mechanics approach will be applied in more detail for evaluation of the experimental results.


**PART II: Experiments**

Part II: Experiments consists of Chapters 4 and 5 and presents an experimental program on the determination of the fatigue strength of base material and welded connections made of very high strength steels. The work comprised of plate experiments and truss experiments.

Chapter 4 presents fatigue tests to determine the fatigue strength of plate specimens made of rolled and cast steels. Base material specimens, X-welded and V-welded plates, made of steels with yield strength of 355 up to 1100 MPa and similar cast steel grades were tested.

Chapter 5 describes fatigue tests on trusses made of circular hollow sections welded to cast joints. The rolled and cast materials of the truss specimens had yield strengths of 690 and 890 MPa.
4. Plate experiments

4.1 Introduction
The literature study presented in the first part of the dissertation summarized the state of the art on the development, application and structural aspects of welded connections made of rolled and cast steels with very high yield strength. The fatigue strength was found to be one of the governing design criteria for an effective application of VHSS.

Because of the large variety in steel grades available and the great variety of welded connection types, relatively few fatigue strength data have been available for welded connections made of VHSS. The effect of yield strength on the fatigue strength has limitedly been part of design codes, because there is lack of experimental proof for the effect of steel grade on the fatigue strength. However, if notch stress concentration is minimized by choice of high class details and high execution quality, a beneficial effect of the use of VHSS on the fatigue strength could be expected, for instance in case of X-welded and V-welded plate connections. In the current study, experimental work was carried out to determine the fatigue strength of welded connections made of VHSS. The fatigue tests gave insight in the initiation and propagation of fatigue cracks in the base material, weld toe and weld root, under various loading conditions.

Chapter 4 focuses on the experiments on plate specimens: base material specimens and X-welded specimens made of rolled steels and V-welded specimens made of cast and rolled steels up to yield strength of 1100 MPa. Also, crack growth tests were executed on pre-notched specimens made of rolled steels, for determination of fracture mechanics parameters. Section 4.2 lists the experimental program of the plate specimens and describes the test procedure, test rigs and specimen geometry. Sections 4.3, 4.4, 4.5 and 4.6 give background on the preparation of the specimens and present the fatigue test results. Section 4.7 discusses the crack growth tests.

4.2 Background on experimental program

4.2.1 Fatigue test program
Table 4.1 summarizes the experimental program for the determination of the fatigue strength of base material and welded plates made of VHSS. All fatigue tests were carried out at constant amplitude cyclic loading, with \( R = 0.1 \). First, base material strips, made of S690 and S1100 were tested (FAM-series, S690; FBM-series, S1100), for which it was expected that the yield strength would be of positive influence on the fatigue strength. Next, X-welded specimens made of rolled steel in grades S355, S690 and S1100 were tested (SA-series, S355; FA-series, S690; FB-series, S1100). Finally, fatigue tests were executed on V-welded specimens, made of steel grades S460, S690, S890, S1100 and similar strength cast steels, G20Mn5, G10MnMoV6-3, G18NiMoCr3-6 and G22NiMoCr5-6. The V-welded specimens were produced in three alternative conditions: specimens made of rolled steel and rolled steel parts (V-series); specimens made of rolled steel and cast steel parts welded without backing (C-series); specimens of rolled steel and cast steel parts welded with use of a ceramic backing (CB-series). In the fatigue tests, it was not always known in advance where exactly fatigue cracks would grow. This made an accurate monitoring of fatigue cracks difficult for crack lengths < 10 mm. A special type of fatigue testing involved the testing of crack growth specimens (GB-series and GH-series), with a
4. Plate experiments

pre-notch of a defined initial crack size, which was loaded cyclically up to failure, with a clear monitoring of the early fatigue crack growth up to failure. The crack growth test results are presented in section 4.7.

Table 4.1. Summary of plate test program\textsuperscript{2}; Ax = tension loading; 4pb = four point bending

<table>
<thead>
<tr>
<th>Name</th>
<th>Rolled steel grade</th>
<th>Cast steel grade</th>
<th>Thickness xWidth [mm]</th>
<th>Number of specimens</th>
<th>Loading</th>
<th>Weld type</th>
<th>Backing</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAM</td>
<td>S690</td>
<td>-</td>
<td>12x33</td>
<td>7</td>
<td>Ax</td>
<td>Base material</td>
<td></td>
</tr>
<tr>
<td>FBM</td>
<td>S1100</td>
<td>-</td>
<td>10x33</td>
<td>7</td>
<td>Ax</td>
<td>Base material</td>
<td></td>
</tr>
<tr>
<td>SA</td>
<td>S355</td>
<td>-</td>
<td>12x120</td>
<td>9</td>
<td>Ax</td>
<td>X-weld</td>
<td></td>
</tr>
<tr>
<td>FA</td>
<td>S690</td>
<td>-</td>
<td>12x120</td>
<td>7</td>
<td>Ax</td>
<td>X-weld</td>
<td></td>
</tr>
<tr>
<td>FB</td>
<td>S1100</td>
<td>-</td>
<td>10x100</td>
<td>7</td>
<td>Ax</td>
<td>X-weld</td>
<td></td>
</tr>
<tr>
<td>V46</td>
<td>S460</td>
<td>-</td>
<td>25x150</td>
<td>7/2</td>
<td>4pb / Ax</td>
<td>V-weld</td>
<td></td>
</tr>
<tr>
<td>V69</td>
<td>S690</td>
<td>-</td>
<td>25x150</td>
<td>7/2</td>
<td>4pb / Ax</td>
<td>V-weld</td>
<td></td>
</tr>
<tr>
<td>V89</td>
<td>S890</td>
<td>-</td>
<td>25x150</td>
<td>7/2</td>
<td>4pb / Ax</td>
<td>V-weld</td>
<td></td>
</tr>
<tr>
<td>V11</td>
<td>S1100</td>
<td>-</td>
<td>20x150</td>
<td>7/2</td>
<td>4pb / Ax</td>
<td>V-weld</td>
<td></td>
</tr>
<tr>
<td>C46</td>
<td>S460</td>
<td>G20Mn5</td>
<td>25x150</td>
<td>9</td>
<td>4pb</td>
<td>V-weld</td>
<td></td>
</tr>
<tr>
<td>C69</td>
<td>S690</td>
<td>G10MnMoV6-3</td>
<td>25x150</td>
<td>9</td>
<td>4pb</td>
<td>V-weld</td>
<td></td>
</tr>
<tr>
<td>C89</td>
<td>S890</td>
<td>G18NiMoCr3-6</td>
<td>25x150</td>
<td>9</td>
<td>4pb</td>
<td>V-weld</td>
<td></td>
</tr>
<tr>
<td>C11</td>
<td>S1100</td>
<td>G22NiMoCr5-6</td>
<td>20x150</td>
<td>9</td>
<td>4pb</td>
<td>V-weld</td>
<td></td>
</tr>
<tr>
<td>CB46</td>
<td>S460</td>
<td>G20Mn5</td>
<td>25x150</td>
<td>5</td>
<td>4pb</td>
<td>V-weld</td>
<td>Ceramic</td>
</tr>
<tr>
<td>CB69</td>
<td>S690</td>
<td>G10MnMoV6-3</td>
<td>25x150</td>
<td>3 / 2</td>
<td>4pb / Ax</td>
<td>V-weld</td>
<td>Ceramic</td>
</tr>
<tr>
<td>CB89</td>
<td>S890</td>
<td>G18NiMoCr3-6</td>
<td>25x150</td>
<td>5</td>
<td>4pb</td>
<td>V-weld</td>
<td>Ceramic</td>
</tr>
<tr>
<td>CB11</td>
<td>S1100</td>
<td>G22NiMoCr5-6</td>
<td>20x150</td>
<td>5</td>
<td>4pb</td>
<td>V-weld</td>
<td>Ceramic</td>
</tr>
</tbody>
</table>

Appendix B lists the chemical compositions and the mechanical properties of the above mentioned steels; mechanical properties were derived from the material certificates. The details of the specimen geometries and applied welding procedures are described in the sections on the preparation of the specimens. The surfaces of the base material parts were in the as-rolled condition; the welded parts in the as-welded condition. No surface treatments or post weld treatments were applied. Vickers hardness measurements were performed on several positions on the base material, heat affected zone and fusion zone (See Appendix C). An impression of the different weld shapes of the fatigue test specimens is given in Figure 4.1. Appendix D lists the manufacturing steps for the V-welded specimens. Detailed drawings of the test specimens are presented in Appendix E.

\textsuperscript{2} Test series SA was carried out in the MSc thesis work of Van Doremaele (2008); test series C69x, CB69x, C89x and CB89x were carried out in the MSc thesis work of Kizilarslan (2009).
For constant amplitude fatigue testing, at least at 3 stress levels 3 specimens need to be tested for a suitable statistical evaluation [Hobbacher, 2007]; for a proper evaluation according to Brozzetti et al. (1989) in comparison with EN 1993-1-9 (2005), even 12 specimens per sample are required. Therefore, the results of the individual studies were evaluated separately and where appropriate, the fatigue results were combined in the statistical analysis. Statistical evaluation of the fatigue test results is not included in Chapter 4, but is presented in Chapter 7.

**Figure 4.1. Weld shape of fatigue test specimens of the current study.**

### 4.2.2 Fatigue test rigs

All fatigue tests were carried out in the Stevin Laboratory of the Delft University of Technology. Two four point bending frames were set up for bending tests (See Figure 4.2); in one rig two specimens were tested simultaneously; in the other a single specimen was tested. A tensile test rig was available up to 600 kN (See Figure 4.3). Although fatigue tests are time consuming, by making use of multiple setups, a large number of tests could be performed in relatively short time.

Specimens were loaded cyclically to initiate fatigue cracks, of which the growth was monitored until failure. All tensile loaded specimens (Ax-mode, See Table 4.1) were loaded force controlled, which means that the force range was fixed during the test, even in case of loss of stiffness of the specimens when cracks were growing. The bending specimens (4pb, See Table 4.1) were tested displacement controlled, which means fixed displacement ranges.
Figure 4.2. a. Single and b. double four point bending rigs (100-200 kN).
By the use of the four point bending setup, a continuous bending moment was put on the weld area, resulting in a compressive and a tension zone over the thickness. Fatigue cracks most likely initiate in the tensile loaded parts of the specimens, because of mean stress sensitivity. In advance, it is not always known if cracks will initiate in the weld cap or weld root. Therefore, two bending loading modes were applied. A number of specimens was loaded with average tensile stresses in the cap region (Cap-mode, See Figure 4.4), other specimens with average tensile stresses in the root region (Root-mode, See Figure 4.4) to investigate the effect of the initiation location, cap or root. In the tensile loaded specimens (Ax-mode, See Figure 4.4), all cracks were expected to initiate in the weld cap. The reason for this was the effect of misalignment of the specimens as a result of welding. The misalignment introduced secondary bending moments, which caused the average tensile stresses in the cap region to be higher than the average tensile stresses in the root.
4. Plate experiments

4.2.3 Crack monitoring

Each specimen contained strain gauges (FLA-6-11) at 8 mm from the weld toe to monitor the strain distribution on both sides of the welded connection and to see the influence of strain concentration near the weld and near the sides of the specimen. The effect of strain concentration from the weld shape was found to be negligible. Strain gauges were applied at positions relatively close to the expected locations of crack growth, at 8 mm from the weld toe. At each side of the weld, both on the cap and the root side of the specimens, two or three strain gauges were attached. For obtaining nominal stresses, the average values of the strain gauges were converted by the uni-axial Hooke’s law. During the fatigue tests, average and range values of the measured forces, displacements and strains were stored.

Crack initiation was visible when the strain gauge data started to bend off the regular scheme. Figure 4.5 shows the strain ranges plot against the number of cycles of a fatigue specimen. The scatter in the strain range data of the various strain gauges could be explained by the misalignment, the variance in distance of the strain gauge to the weld toe and the difference in local plate thickness. The example of figure 4.5 shows at about 90000 cycles, strains start to deviate, which is an indication of crack growth near the strain gauges. Increase or decrease of the strain ranges depends on the orientation of the strain gauge to the crack, which could lead to increased tension, compression or release of strain.

An alarm system was used which immediately shut down the system in case of 10% deviations (other percentages also were used), which made it possible to indicate the locations of crack initiation on the test specimens visually.

Four stages of crack growth were distinguished, N1-N4 (See Table 4.2). In the current study, Ni was used for the number of cycles at which strain values started to bend off the regular scheme. N\text{fvc} was the number of cycles at which the first visual crack was noticed. Nt indicated the number of cycles at which the crack length was equal to the thickness of the specimen. Nf represented fracture failure.

Specimens with no crack initiation were indicated as runouts; all runouts exceeded the N = 5⋅10⁶ cycles.
Table 4.2. Stages of crack growth.

<table>
<thead>
<tr>
<th>Stages of Crack Growth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1 = Ni:</td>
<td>The first point shows the moment when cracks initiate. At this moment strain</td>
</tr>
<tr>
<td>N2 = Nfic:</td>
<td>The second stage involves the visual inspection of crack development of the first visual crack. A liquid (petrol) is put on the crack, which indicates bubbles if the crack grows.</td>
</tr>
<tr>
<td>N2 = Nt:</td>
<td>The third stage is the moment a crack length equals the thickness of the specimen (easily visible in practice), a = t. (See Figure 4.6).</td>
</tr>
<tr>
<td>N4 = Nf:</td>
<td>The fourth stage is the moment the cracks have critical length to introduce failure of the remaining ligament.</td>
</tr>
</tbody>
</table>

If the monitoring of crack growth in thickness direction was not possible, a crack marking procedure was used to produce beach marks at the crack boundaries, visible after fracture. In this procedure, the upper stress level was kept identical while increasing the lower stress level to 90% of the upper stress level during a limited number of cycles, in the order of 1-5% of the expected number of cycles until failure, (See Figure 4.5). Because of the altered stress range, crack boundaries became visible in the cross section, which gave information on the crack size in width and depth direction at a certain number of cycles. Because of the limited stress range in the crack marking procedure, the contribution of the crack marking cycles were expected to be negligible and were therefore later on excluded from the analysis.

Figure 4.5. Strain gauge measurement results of specimen V697 with crack marking phase.

3 For this specimen: number of cycles of crack initiation up to variation of strain gauge data is Ni; number of cycles of crack propagation is summation of Np1 and Np2; total fatigue lifetime is Nf = Ni + Np1 + Np2
Figure 4.6 illustrates the crack size at a given number of cycles in a rectangular cross section of a plate. Cracks grow in depth direction \(a\) and in width direction \(c\); the crack shape is quarter elliptical if the crack initiates from the edges of the cross section; the crack shape is semi-elliptical if the crack initiates from a distance to the edge, also referred to in this work as the middle of the weld.

Figure 4.6. Quarter and semi elliptical crack in rectangular cross section; \(c\) or \(2c\) = crack length, \(a\) = crack depth, \(t\) = thickness, \(W\) = specimen width (or weld length).

Cracks are likely to grow in multiple locations within the specimens simultaneously. For a proper evaluation of the fatigue results, all data should be filtered with respect to specimen type, but also to comparable crack initiation positions. Figures 4.7 and 4.8 illustrate possible locations of the fatigue cracks, which are weld toe of the cap or the root or the base material at a distance from the weld. Cracks initiating in the weld toe of the cap grow through the HAZ into the base material. Cracks initiating in the weld toe of the root grow through the HAZ into the fusion zone.

Figure 4.7. Crack initiation positions.

In Chapter 4, the results of all series are presented graphically. The graphs distinguish the subseries, such as Cap-mode, Root-mode and Ax-mode. Also, separation is made for weld toe cracks and base material cracks. Appendix F lists the fatigue test results in a table; Appendix G presents the measured crack growth data.
4.2.4 Weld geometry

The fatigue strength of X-welded specimens and V-welded specimens is evaluated in the current study. Overall, the weld quality of X-welds, welded from both sides, is higher than the quality of V-welds. The V-shape causes the weld width at the cap to be larger than on an X-weld. Moreover, full penetration of the root side of a V-weld is more difficult than on the cap side. According to EN 1993-1-9 (2005) the fatigue classification of X-welds is higher than V-welds.

However, in practice, the structural geometry could make it impossible to weld from two sides. The reason could be that the welding location is unreachable. Girth welded connections of CHS with relatively small diameter cannot be welded from the inside. Chapter 5 describes fatigue tests on trusses made of CHS to cast joints, with V-girth-welds. The weld shape of the plate specimens presented in Chapter 4 was adjusted to the V-girth weld shape needed for the truss specimens. In principle, similar welding procedures were used for the welding of the plate specimens and the circular hollow section to cast joint connections. This made it possible to compare the fatigue test results of the plate specimens and the truss specimens.

Several weld shape variants of the plate connections D1-D6 (See Figure 4.9) were discussed in a working group with participating steel manufacturers. In order to face the tolerances of the structural members and to increase the efficiency in fabrication, application of a small thickness difference between casting and CHS could be necessary, as presented in variants D1 and D2. A detail with gradually increased thickness of the cast steel specimen, commonly used in practice, is variant D3. In order to reduce local stress concentrations as a result of eccentricity, it is preferable for VHSS to obtain equal thickness of the connecting members, presented in variants D4, D5 and D6. Variant D4, with U-bevel and application of a tig-dressed root layer is a detail from the offshore practice, which is relatively expensive, but could lead to a high quality weld. A V-weld with the use of a ceramic backing, D5, could also lead to a high quality of the weld root. The backing is not permanently attached to the root, which makes it more preferable than a steel backing ring. If no backing is used, D6, full penetration should be checked by NDT.
Table 4.3 summarises the advantages and disadvantages of the choice of weld shape variant.

Table 4.3. Choice of weld shape variant.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>- Easy fabrication</td>
<td>- Unequal thickness plate/casting</td>
</tr>
<tr>
<td></td>
<td>- High tolerance</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>- Easy fabrication</td>
<td>- Unequal thickness plate/casting</td>
</tr>
<tr>
<td></td>
<td>- High tolerance</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>- Practical detail</td>
<td>- Unequal thickness plate/casting</td>
</tr>
<tr>
<td></td>
<td>- High tolerance</td>
<td>- Expensive detail</td>
</tr>
<tr>
<td>D4</td>
<td>- Equal thickness plate/casting</td>
<td>- Expensive detail</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Low tolerance</td>
</tr>
<tr>
<td>D5</td>
<td>- High quality weld</td>
<td>- Loss of backing in CHS K-joint</td>
</tr>
<tr>
<td></td>
<td>- Equal thickness plate/casting</td>
<td>- Expensive detail</td>
</tr>
<tr>
<td>D6</td>
<td>- High quality weld</td>
<td>- Attention to full penetration of root</td>
</tr>
<tr>
<td></td>
<td>- Equal thickness plate/casting</td>
<td>- Low tolerance</td>
</tr>
</tbody>
</table>

Based on the discussion with the industry, two weld variants were chosen for testing, with either ceramic backing (See Figure 4.9, D5) or without backing (See Figure 4.9, D6), with equal nominal plate thickness of the connecting members.

The execution quality of steel structures was determined by EN 1090-2 (2008). EN 1090-2 (2008) refers to EN-ISO 5817 (2003) for the quality of welded connections. EN-ISO 5817 (2003) distinguishes between three weld qualities, B, C and D, the excess of weld metal h, (See Table 4.4) and the weld toe angle $\alpha$. All the welded connections tested in the current study satisfied quality level C.
Fatigue strength of welded connections made of very high strength cast and rolled steels

Table 4.4. Weld qualities in dependence of geometrical parameters [EN-ISO 5718, 2003].

<table>
<thead>
<tr>
<th>Quality</th>
<th>D</th>
<th>C</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld Cap</td>
<td>h &lt; 1+0.25b, max 10 mm</td>
<td>h &lt; 1+0.15b, max 7 mm</td>
<td>h &lt; 1+0.1b, max 5 mm</td>
</tr>
<tr>
<td>Weld Root</td>
<td>h &lt; 1+b, max 5 mm</td>
<td>h &lt; 1+0.6b, max 4 mm</td>
<td>h &lt; 1+0.2b, max 3mm</td>
</tr>
<tr>
<td>Weld toe angle</td>
<td>α &gt; 90</td>
<td>α &gt; 110</td>
<td>α &gt; 150</td>
</tr>
</tbody>
</table>

4.2.5 Misalignment

Before starting the fatigue tests, static measurements were performed. In order to check the strain distribution in the plate length direction, the specimens were statically loaded up to stress levels of 30% of the yield strength. Strain gauges were positioned next to the weld and at 100 mm and 200 mm from the weld. Stresses were obtained by the uni-axial Hooke’s law, multiplying the modulus of elasticity (assumed to be E = 210000 MPa) with the measured strains.

Figure 4.10 shows the longitudinal stress pattern for various applied forces at six strain gauge positions on the X-welded tensile loaded specimens. With increasing force, the difference in stress level in the middle of the specimen and the positions at 100 mm and 200 mm was larger. The strain gauges next to the weld were not influenced by the notch stress concentration, as the strain was determined at 8 mm from the weld toe. The difference in stress was due to the misalignment in the test specimen, as a result of welding. Due to shrinkage after welding, the test specimens were all bent along the axis of the weld. This caused secondary bending stresses during loading. At high stress levels the test rig straightened the test specimens.

Hobbacher (2007) gives calculation rules (See Eq. 4.1 and Eq. 4.2) for determination of stress magnification factor $K_m$, in case of angular misalignment in transverse butt welded plates. $K_m$ is a function of the geometry and the average nominal stress level. Figure 4.11 illustrates the geometrical parameters used in these formulas.
4. Plate experiments

Figure 4.10. Longitudinal stress pattern, based on strain gauges, for various force levels.

\[ K_m = 1 + \frac{3y}{t} \cdot \frac{\tanh\left(\frac{\beta}{2}\right)}{\left(\frac{\beta}{2}\right)} \]  
(4.1)

with,

\[ \beta = \frac{2l}{t} \cdot \sqrt{\frac{3 \cdot \sigma_{nom}}{E}} \]

where,

- \( 2l \): Total length of specimen, (See Figure 4.11)
- \( t \): Plate thickness, (See Figure 4.11)
- \( y \): Curvature height, (See Figure 4.11)
- \( E \): Modulus of elasticity
- \( \sigma_{nom} \): Nominal stress

\[ \sigma_{km} = K_m \cdot \sigma_{nom} \]  
(4.2)

- \( K_m \): Misalignment factor
- \( \sigma_{km} \): Stress including misalignment factor
- \( \sigma_{nom} \): Nominal stress

Figure 4.11. Misalignment parameters after Hobbacher (2007).
4.3 Base material plate specimens made of rolled steel
For the determination of the fatigue strength of base material made of rolled steel, specimens were derived from plates of grades S690 and S1100. The fatigue tests were executed using a 600 kN tensile test rig, at constant amplitude fatigue loading with R = 0.1.

4.3.1 Preparation of specimens
The tables in Appendix B give the specifications of the available plate material. The fatigue specimens were water cut from base material parts of plates that were earlier used for the manufacturing of the X-welded specimens of Section 4.3.2. After cutting, the specimens were milled, to obtain a radius of 3 mm at the edges, in order to prevent crack initiation from the side. At the middle of the specimens, a 10 % taper was applied, with radius 20 mm. Also there, the specimens were ground and instrumented with 2 strain gauges per side (See Figure 4.12).

Table 4.5 and Appendix D give details on the base material fatigue specimens.

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>FAM</th>
<th>FBM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel type</td>
<td>S690</td>
<td>S1100</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>Unground: $R_z = 47 \mu m$</td>
<td>Unground: $R_z = 30 \mu m$</td>
</tr>
<tr>
<td></td>
<td>Ground: $R_z = 24 \mu m$</td>
<td>Ground: $R_z = 10 \mu m$</td>
</tr>
<tr>
<td>Number of test specimens</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Machining</td>
<td>Water cut; edges milled and ground</td>
<td>Water cut; edges milled and ground</td>
</tr>
</tbody>
</table>
4. Plate experiments

4.3.2 Fatigue test results

As was expected, most cracks initiated from the taper location in the middle of the S690 specimens. (See Figure 4.12). In all S1100 specimens however, cracks initiated outside of the tapered cross section. The surface at the tapered cross section was ground for the application strain gauges. This caused a lower surface roughness at the taper position compared to the rest of the specimen. Table 4.5 lists the measured surface roughness. Outside the tapered cross section, the as rolled surface roughness condition applied for the surfaces. Apparently, the fatigue strength of the S1100 material was more sensitive to the surface condition, which caused the cracks to initiate outside the 10% tapered cross section. Section 6.2.2.3 presents the influence of surface roughness on the fatigue strength, which depends on the yield strength.

Figure 4.13 shows the cross section of a S1100 specimen, with two fatigue cracks and with beach marks indicating the crack sizes at various stages, as a result of the crack mark procedure.

Figure 4.13. Cross Section of S1100 Specimen FBM3 with beach marks from crack marking.

Figure 4.14 presents the fatigue results of the FAM series; Figure 4.15 the results of the FBM series. Appendix F lists the results in a table. Especially for the S1100 specimens, cracks grew rapidly after crack initiation was detected by the strain gauges. All the specimens met the requirements of detail category 125 according to EN 1993-1-9 (2005). In one of the S690 specimens, cracks initiated next to the clamping location of the specimen in the test rig at a relatively low stress level. The fatigue strength of the S1100 specimens tended to be higher than the results of the S690 specimens.

Figure 4.14. Fatigue results of FAM series. S690; t = 12 mm; base material specimen.
Fatigue strength of welded connections made of very high strength cast and rolled steels

4.4 X-welded plate specimens made of rolled steel

For determination of the fatigue strength of X-welded plates of rolled steel, specimens were derived from plates of grades S355, S690 and S1100. The fatigue tests were executed using a 600 kN tensile test rig, at constant amplitude fatigue loading with $R = 0.1$.

4.4.1 Preparation of specimens

The material specifications can be found in Appendix B. The S690 and S1100 were cut from welded plates. For the S355 specimens, individual strips were welded separately. On the strips, run on and run off plates were attached. Table 4.6 presents the specimen details and the welding procedure. Figure 4.16 shows the geometry of the X-weld specimens. The width of the test specimens was taken ten times the thickness of the plate material. The edges of the welded plates were slightly ground (without applying a radius) for reducing the chance of crack initiation from the edges. Specimen drawings can be found in Appendix E.
The measured yield and tensile strength of the available weld material for the S1100 specimens was lower than the plate material strength of S1100. The undermatched S1100 welds have therefore been made relatively thick, which also increased the local weld toe angle.

Table 4.6. Specimen details of series SA (S355), FA (S690) and FB (S1100).

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>SA</th>
<th>FA</th>
<th>FB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel type</td>
<td>S355</td>
<td>S690</td>
<td>S1100</td>
</tr>
<tr>
<td>Number of test specimens</td>
<td>9</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Number of strain gauges</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>12</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>750</td>
<td>750</td>
<td>1000</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>120</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Machining</td>
<td>Strips, edges ground</td>
<td>Plasma cut; edges ground</td>
<td>Plasma cut; edges ground</td>
</tr>
<tr>
<td>Weld metal</td>
<td>Filcord ER70S 6</td>
<td>Megafill 742M</td>
<td>Tenacito 75 (root) SH Ni 2 K 140 (fill+cap)</td>
</tr>
<tr>
<td>Welding process</td>
<td>MIG</td>
<td>FCAW</td>
<td>SMAW</td>
</tr>
<tr>
<td>Welding position</td>
<td>1G</td>
<td>1G</td>
<td>1G</td>
</tr>
<tr>
<td>Number of weld layers</td>
<td>5</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Preheat temp.</td>
<td>-</td>
<td>100°</td>
<td>100°</td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>2-3</td>
<td>2-3</td>
<td>2-3</td>
</tr>
<tr>
<td>Heat input [kJ/mm]</td>
<td>-</td>
<td>1 - 1.5 (root)</td>
<td>0.6 - 0.9 (root)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 - 1.9 (fill)</td>
<td>0.8 - 1.2 (fill)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8 - 1.4 (cap)</td>
<td>0.5 - 0.9 (cap)</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>-</td>
<td>Unground: Rₐ = 47 μm</td>
<td>Unground: Rₐ = 30 μm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ground: Rₛ = 24 μm</td>
<td>Ground: Rₛ = 10 μm</td>
</tr>
</tbody>
</table>

Measured average stress values at 8 mm from the weld toe were compared to calculated stresses including the effect of misalignment factor $K_m$ according to Eq. 4.2. The stress measurements of both the S690 and the S1100 welds were found to be in good correspondence with the calculated results, (See Figure 4.18).
Fatigue strength of welded connections made of very high strength cast and rolled steels

4.4.2 Fatigue test results

Figures 4.19-4.21 present the fatigue results. Appendix F lists the results in a table. All cracks initiated from the edges of the specimens, resulting in quarter elliptical cracks. All specimens met the requirements for detail category 80 according to EN 1993-1-9 (2005). The results of the S355 and the S690 specimens are rather similar. One of the S690 specimens showed a short crack initiation life, because of a badly ground edge. The crack initiation life of the S1100 specimens was found to be relatively higher than the crack initiation life of the S355 and S690 specimens; crack propagation of the S1100 specimens tended to be relatively shorter. Section 7.3 evaluates the results statistically.

Figure 4.19. Fatigue results of X-welded plate series SA (S355).
4. Plate experiments

4.5 V-welded plate specimens made of rolled steel
For determination of the fatigue strength of V-welded plates of rolled steel, specimens were derived from plates of grades S460, S690, S890 and S1100. The fatigue tests were executed using two bending test rigs (100-200 kN) and a tensile test rig (600 kN), at constant amplitude fatigue loading with $R = 0.1$.

4.5.1 Preparation of specimens
The rolled material plates were plasma cut and welded to the cast plates by the FCAW process. Specimens made of S460, S690 and S890 were welded in overmatched condition; S1100 specimens in undermatched condition. Individual strips were plasma cut from the welded plates, having a width of 160 mm and a length of 1000 mm. In the middle, the specimens were finally ground at the sides to a width of 150 mm. In Appendix B, the material properties can be found. Appendix C gives the results of Vickers hardness tests.

Figure 4.20. Fatigue results of X-welded plate series FA (S690).

Figure 4.21. Fatigue results of X-welded plate series FB (S1100).
Figure 4.22 shows the geometry of the V-series specimens and the positions of the strain gauges.

Figure 4.22. Geometry of V-series, rolled steel to rolled steel strips.

Macro graphs of the welded connections are given in Figure 4.23. The macrograph of the V69 series was derived from a specimen that was used for the crack growth tests, which explains the ground cap and root and the pre-notch in the HAZ. Table 4.7 presents the specimen details and procedure that was applied for the welding of rolled to rolled plates. The specimens of the V11-series were taken after crack initiation in the root.

Figure 4.23. Macrographs of welds of series V46, V69 (ground cap), V89 and V11.
Table 4.7. Geometry and welding data of fatigue specimens V-series.

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>V46x</th>
<th>V69x</th>
<th>V89x</th>
<th>V11x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolled steel grade</td>
<td>S460</td>
<td>S690</td>
<td>S890</td>
<td>S1100</td>
</tr>
<tr>
<td>Number of test specimens</td>
<td>5 (Cap-mode); 2 (Root-mode); 2 (Ax-mode)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of strain gauges</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>25</td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Length [mm]</td>
<td>1000</td>
<td></td>
<td>980</td>
<td></td>
</tr>
<tr>
<td>Width [mm]</td>
<td>150</td>
<td></td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Rz rolled [μm]</td>
<td>27-44</td>
<td>11-100</td>
<td>20-118</td>
<td>8-82</td>
</tr>
<tr>
<td>Preheat temp</td>
<td>-</td>
<td>100</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Welding position</td>
<td>1G</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weld metal cap</td>
<td>E81T1K2M</td>
<td>E111T1K</td>
<td>E120T1G</td>
<td>E120T1G</td>
</tr>
<tr>
<td>Weld process cap</td>
<td>FCAW</td>
<td>FCAW</td>
<td>FCAW</td>
<td>FCAW</td>
</tr>
<tr>
<td>Heat input cap</td>
<td>0.6-1.2</td>
<td>1.0-1.8</td>
<td>0.92-1.32</td>
<td>0.92-1.32</td>
</tr>
<tr>
<td>Weld metal root</td>
<td>E80CG</td>
<td>ER100SG</td>
<td>E120T1G</td>
<td>E120T1G</td>
</tr>
<tr>
<td>Weld process root</td>
<td>FCAW</td>
<td>GMAW</td>
<td>FCAW</td>
<td>FCAW</td>
</tr>
<tr>
<td>Number of weld layers</td>
<td>23</td>
<td>23</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>Heat input root [kJ/mm]</td>
<td>1.1-2.4</td>
<td>1.1-2.4</td>
<td>0.92-1.32</td>
<td>0.92-1.32</td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>4.5 ± 1.5</td>
<td>4.5 ± 1.5</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

4.5.2 Fatigue test results

Appendix F lists the results in a table. In all S460 and S690 specimens, cracks initiated in the weld toe. In case of Cap-mode bending loading, cracks became visible in the weld toe at the cap of the specimen; in case of Root-mode loading at the toe of the weld root. In the Ax-mode, the highest stresses were present in the weld toe of the cap, so in all cases cracks developed in the cap. Although the stress concentration at the base material parts of the specimens was lower than in the welded parts, base material cracks occurred in one of the S890 and two of the S1100 specimens. The fatigue strength of the tensile loaded specimens was lower than the bending loaded specimens. For all test series, the strength of the root tended to be lower than the weld toe. The S890 and S1100 test series contained several specimens that did not have any crack initiation, indicated as runouts.

Figure 4.24 presents the results of the V46-series, with reference to detail category 71 according to EN 1993-1-9 (2005). All cracks initiated from the weld toe. Small differences could be noticed for results of axial and bending loading. It should be noted that the results from axial loading also contain portion of bending because of misalignment.

Figure 4.25 presents the results of the V69-series. All cracks initiated at the weld toe. No cracks initiated in the base material. Specimens with weld cap cracks showed relatively short crack propagation life, whereas crack propagation life of root cracks was relatively long. In specimen V699 a root crack was found, although the specimen was loaded in Cap-mode, so crack initiation and crack propagation were in compressive stress range.
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 4.24. Fatigue results of V46-series.

Figure 4.25. Fatigue results of V69-series.

Figure 4.26 presents the results of the V89-series. The results of this series show several runout specimens, without crack initiation. The specimens loaded in Cap-mode had a relatively short crack propagation life and relatively long crack initiation life. Fatigue cracks in the Root-mode loaded specimens tended to have a relatively longer crack propagation life. In specimen V898, cracks initiated in the base material of the rolled steel.
4. Plate experiments

Figure 4.26. Fatigue results of V89-series for a. weld toe cracks and b. base material cracks.

Figure 4.27. Fatigue results of V11-series for a. weld toe cracks and b. base material cracks.

Figure 4.27 presents the results of the V11-series. Again, several specimens showed runout without crack initiation. Three specimens, V113, V118 and V119 had crack initiation and propagation in the base material of the rolled steel; therefore no fatigue results were found for cracks initiating at the weld toe of the root side of the specimens.
4.6 V-welded plate specimens made of cast and rolled steel

For determination of the fatigue strength of V-welded plates of rolled steel, specimens were derived from plates of grades S460, S690, S890 and S1100 and cast steels with similar yield strengths G20Mn5, G10MnMoV6-3, G18NiMoCr3-6 and G22NiMoCr5-6 respectively. Part of the test specimens were welded with ceramic backing (CB-series), the other part without a backing (C-series). The fatigue tests were executed using two bending test rigs (100-200 kN) and a tensile test rig (600 kN), at constant amplitude fatigue loading with \( R = 0.1 \).

4.6.1 Preparation of specimens

Appendix B gives background on the rolled steel and cast steel plate material. The cast steel plates were made in thickness 35 mm. After casting, the plates were quenched and tempered, and machined down to 25 mm thickness. The thickness of the cast plates eventually varied between 25 and 28 mm. The cast plates satisfied the NDT requirements of class I according to ASTM E 446-98 (1998) for weld areas and class II for other areas (See Figure 4.28). The plates were checked by ultrasonic inspection according to EN 12680-1 (2003) and penetrant inspection according to EN 1371-1 (1997).

![Figure 4.28. Quality level of cast part of plate specimens; Quality I near weld and Quality II in rest of member.](image)

For tracking the cast steel during the fabrication, the manufacturer cast letters on the plates (See Figure 4.29). In case of fatigue loading these letters cause stress concentrations and may influence the fatigue strength of the test specimen. These letters were ground before starting the fatigue testing.

![Figure 4.29. Cast letters on CB895 specimen, for traceability.](image)
Appendix D lists the manufacturing steps for the V-welded hybrid specimens. The rolled material plates were plasma cut and welded to the cast plates by the FCAW process, after which individual strips were plasma cut from the welded plates. After cutting, the strips were ground to a width of 150 mm. The original rolled plates had a thickness of 25 mm. The rolled material plates were plasma cut and welded to the cast plates with weld seam length of 500 up to 1000 mm. Figure 4.30 shows the geometry of the specimens of the C- and CB-series.

Figure 4.30. Weld shapes of test series.

Up to S890 was welded in overmatched condition, predominantly by the FCAW process. The V-shape of the weld comprised a bevel angle of 60° and a gap of 3 mm. All welds satisfied the weld quality C according to EN-ISO 5817 (2003), regarding the excess of weld metal in the weld toe and weld root and the weld toe angle.

The ceramic backings were removed after welding. Individual strips were plasma cut from the welded plates, having a width of 160 mm and a length of 1000 mm. In the middle, the specimens were finally ground at the sides to the width of 150 mm. Table 4.8 summarizes the welding parameters of the C-series and the CB-series. Figure 4.31 shows macro graphs of the welded connections.
Figure 4.31. Macro graphs of series C46, C69, C89, C11, CB46, CB69, CB89 and CB11.
### 4. Plate experiments

Table 4.8. Geometry and welding data of fatigue specimens C-series and CB-series.

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>C46x</th>
<th>C69x</th>
<th>C89x</th>
<th>C11x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolled steel grade</td>
<td>S460</td>
<td>S690</td>
<td>S890</td>
<td>S1100</td>
</tr>
<tr>
<td>Cast steel grade</td>
<td>G20Mn5</td>
<td>G10MnMoV6-3</td>
<td>G18NiMoCr3-6</td>
<td>G22NiMoCr5-6</td>
</tr>
<tr>
<td>Number of test specimens</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>24-27</td>
<td>24-27</td>
<td>24-27</td>
<td>20-21</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Rz cast [μm]</td>
<td>20-176</td>
<td>11-180</td>
<td>12-180</td>
<td>11-100</td>
</tr>
<tr>
<td>Rz rolled [μm]</td>
<td>27-44</td>
<td>11-100</td>
<td>20-118</td>
<td>8-82</td>
</tr>
<tr>
<td>Preheat temp</td>
<td>-</td>
<td>100</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Welding position</td>
<td>1G</td>
<td>1G</td>
<td>1G</td>
<td>1G</td>
</tr>
<tr>
<td>Number of weld layers</td>
<td>23</td>
<td>23</td>
<td>24</td>
<td>17</td>
</tr>
<tr>
<td>Weld metal cap</td>
<td>E81T1K2M</td>
<td>E111T1K3</td>
<td>E120T1G</td>
<td>E120T1G</td>
</tr>
<tr>
<td>Weld process cap</td>
<td>FCAW</td>
<td>FCAW</td>
<td>FCAW</td>
<td>FCAW</td>
</tr>
<tr>
<td>Heat input cap [kJ/mm]</td>
<td>0.6-1.2</td>
<td>1.0-1.8</td>
<td>0.92-1.32</td>
<td>0.92-1.32</td>
</tr>
<tr>
<td>Weld metal Root</td>
<td>E80CG</td>
<td>ER100SG</td>
<td>E120T1G</td>
<td>E120T1G</td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>4.5 ± 1.5</td>
<td>4.5 ± 1.5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Weld process root</td>
<td>FCAW</td>
<td>FCAW</td>
<td>FCAW</td>
<td>FCAW</td>
</tr>
<tr>
<td>Heat input root [kJ/mm]</td>
<td>1.1-2.4</td>
<td>1.1-2.4</td>
<td>0.98-1.36</td>
<td>0.98-1.36</td>
</tr>
<tr>
<td>Specimen code</td>
<td>CB46x</td>
<td>CB69x</td>
<td>CB89x</td>
<td>CB11x</td>
</tr>
<tr>
<td>Number of test specimens</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Backing</td>
<td>ceramic</td>
<td>ceramic</td>
<td>ceramic</td>
<td>ceramic</td>
</tr>
<tr>
<td>Weld metal Root</td>
<td>E81T1K2M</td>
<td>E111T1K3</td>
<td>E120T1G</td>
<td>E120T1G</td>
</tr>
<tr>
<td>Heat input root [kJ/mm]</td>
<td>1.3-1.9</td>
<td>1.1-2.4</td>
<td>1.07-1.48</td>
<td>1.07-1.48</td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>6</td>
<td>6</td>
<td>5-5</td>
<td>5-5</td>
</tr>
</tbody>
</table>

All other variables similar to above

#### 4.6.2 Fatigue test results

Appendix F lists the results in a table. In the C46x series, See Figure 4.32, all cracks initiated at the weld toe. In case of Cap-mode loading in the weld toe of the cap; in case of Root-mode loading in the weld toe of the root. Cracks initiated both in the rolled steel as in the cast steel part of the weld, predominantly in the edges of the specimens. In general, a large part of the fatigue life was covered by crack propagation. In the figure, the cast and rolled steel parts are separated for readability.
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 4.32. Fatigue results of C46-series for weld toe cracks at a. cast side, b. rolled side.

Figure 4.33 presents the results of the CB46-series. In Root-mode loaded specimens, cracks initiated at the base material at the distance from the weld, one in the rolled part and one in the cast part of the specimen; no results were found of cracks initiating in the weld toe at the root side of the specimens. The results of the base material cracks show relatively short crack propagation life compared to the specimens with weld toe cracks.

Figure 4.33. Fatigue results of CB46-series for a. weld toe cracks and b. base material cracks.
Figure 4.34 presents the results of the C69-series. All cracks initiated in the weld toe, in both the rolled and the cast parts of the specimens. In specimens C696 crack initiated at the root side, while loading in Cap-mode. The scatter of the results of the C69-series tended to be relatively large.

Figure 4.34. Fatigue results of C69-series for weld toe cracks of a. cast part and b. rolled part.

Figure 4.35 gives the results of the CB69-series. All cracks initiated in the weld toe. Two specimens were tested in the Ax-mode. Crack initiation phase was relatively long for these specimens.

Figure 4.35. Fatigue results of CB69-series.
Figure 4.36 shows the results of the C89-series. Several specimens had no crack initiation. Specimens in Root-mode showed cracks in the base material of the cast part. Therefore, no results of cracks in weld toe of root were obtained. One specimen loaded in Cap-mode had crack in the base material of the cast part with a short crack propagation life.

Figure 4.36 shows the results of the C89-series. Several specimens had no crack initiation. Specimens in Root-mode showed cracks in the base material of the cast part. Therefore, no results of cracks in weld toe of root were obtained. One specimen loaded in Cap-mode had crack in the base material of the cast part with a short crack propagation life.

In the Root-mode loading of the CB89-series, cracks initiated in the base material; in one specimen a crack initiated in the rolled steel part, in another specimen in the cast steel part. There were many inclusions found in the tension zone of the fracture surface of the cast steel parts, (See Figure 4.37). It should be noted that in practice plate shape will never be cast. The test specimens were relatively small compared to cast joints used in practice. The steel plates were cast in a horizontal position. Due to this method of casting, the plates cooled down relatively fast. While the lower part was already cooled down and solidified, the upper part was still cooling down and enclosed gas bubbles during the process.

However, not only in some the cast steel parts, but also in several rolled steel parts initial flaws caused crack growth.

Figure 4.36. Fatigue results of C89-series for a. weld toe cracks and b. base material cracks.

In the Root-mode loading of the CB89-series, cracks initiated in the base material; in one specimen a crack initiated in the rolled steel part, in another specimen in the cast steel part. There were many inclusions found in the tension zone of the fracture surface of the cast steel parts, (See Figure 4.37). It should be noted that in practice plate shape will never be cast. The test specimens were relatively small compared to cast joints used in practice. The steel plates were cast in a horizontal position. Due to this method of casting, the plates cooled down relatively fast. While the lower part was already cooled down and solidified, the upper part was still cooling down and enclosed gas bubbles during the process.

However, not only in some the cast steel parts, but also in several rolled steel parts initial flaws caused crack growth.

Figure 4.37. Fracture surface of specimen CB893.
4. Plate experiments

Figure 4.38 shows the results of the CB89-series. In the specimens with weld toe cracks, crack propagation life was relatively long.

Figure 4.38. Fatigue results of CB89-series for a. weld toe cracks and b. base material cracks.

Figure 4.39 presents the results of the C11-series. Nearly all cracks initiated in the base material, in the cast part of the specimens. C114 showed relatively long crack propagation life.

Figure 4.39. Fatigue results of C11-series for a. weld toe cracks and b. base material cracks.
Figure 4.40 presents the results of the CB11-series. Nearly all cracks initiated in the base material, both in rolled and cast parts at cap and root. Only one weld toe crack was found, in the cap of the cast steel.

![Fatigue results of CB11-series for a. weld toe cracks and b. base material cracks.](image-url)

4.7 Crack growth specimens

4.7.1 Introduction

Fracture mechanics tests were executed to give more insight in the crack growth behaviour of VHSS. Using servo-hydraulic test rigs with a capacity of 20 kN, notched specimens were loaded in cyclic 3-point-bending. Table 4.9 shows the specimen series. The specimens were derived from the V-welded rolled steel to rolled steel plates, described in section 4.5. For each grade, 3 specimens were tested with either a pre-notch in the base material (GB-series) or in the heat affected zone (GH-series).

<table>
<thead>
<tr>
<th>Name</th>
<th>Rolled steel grade</th>
<th>Thickness xWidth [mm]</th>
<th>Number of specimens</th>
<th>Loading</th>
<th>Weld type</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB46</td>
<td>S460</td>
<td>25.5 x 25.5</td>
<td>3</td>
<td>3pb</td>
<td>-</td>
</tr>
<tr>
<td>GB69</td>
<td>S690</td>
<td>24.8 x 24.8</td>
<td>3</td>
<td>3pb</td>
<td>-</td>
</tr>
<tr>
<td>GB89</td>
<td>S890</td>
<td>24.7 x 24.7</td>
<td>3</td>
<td>3pb</td>
<td>-</td>
</tr>
<tr>
<td>GB11</td>
<td>S1100</td>
<td>20.2 x 20.2</td>
<td>3</td>
<td>3pb</td>
<td>-</td>
</tr>
<tr>
<td>GH46</td>
<td>S460</td>
<td>24.1 x 24.1</td>
<td>3</td>
<td>3pb</td>
<td>V-weld</td>
</tr>
<tr>
<td>GH69</td>
<td>S690</td>
<td>23.8 x 23.8</td>
<td>3</td>
<td>3pb</td>
<td>V-weld</td>
</tr>
<tr>
<td>GH89</td>
<td>S890</td>
<td>23.6 x 23.6</td>
<td>3</td>
<td>3pb</td>
<td>V-weld</td>
</tr>
<tr>
<td>GH11</td>
<td>S1100</td>
<td>19 x 19</td>
<td>3</td>
<td>3pb</td>
<td>V-weld</td>
</tr>
</tbody>
</table>

Table 4.9. Specimen details of crack growth tests.
4. Plate experiments

4.7.2 Preparation of specimens
The specimens were ground flush at the cap and the root, and machined to obtain a notch with a predefined shape of 1/10th of material thickness. The initial notches were made in the HAZ and base material location. Figure 4.41 shows the geometry of the specimens, with initial notch size.

![Diagram of specimens with notches in HAZ and base material](image)

During the test, crack length was measured periodically, both visually and by making use of the potential drop measurement technique. As a result, the crack length was plotted against the number of load cycles N. The appropriate shape factors for the stress intensity $\Delta K$ of a thickness notch over the full width of a specimen loaded in 3 point bending were obtained from Anderson (2005) to calculate the $\Delta K$ for any crack length. The test parameters were the stress ratio $R = 0.1$, test frequency $f = 8-12$ Hz, span $S = 240$ mm and force range $P = 5000 \text{ to } 10000$ N. Stress ratio $R = 0.1$ ($P_{\text{min}}/P_{\text{max}}$) was chosen to match the ratio used in the fatigue tests of sections 4.3-4.6. The notch location was also chosen to match the mostly observed crack location in the fatigue specimens.

The tests started with relatively high force range, to initiate a sharp fatigue crack. After crack initiation, the force was dropped to obtain $\Delta K$ levels in the range of 500-600 N/mm$^{3/2}$. In case of fast crack growth the force range was lowered again. Tests continued up to about $\Delta K = 2400$ N/mm$^{3/2}$.

Figure 4.41. Notch locations and micro graphs of notch crack growth:

a. weld specimen notch in HAZ
b. base material specimen with notch in BM
c. detail of notch shape
d. macrograph of notch in HAZ specimen and attachment points for potential drop measurement.
e. Ikegami camera image of crack tip
f. Ikegami camera image of opened notch tip, with crack length measurement scale.

During the test, crack length was measured periodically, both visually and by making use of the potential drop measurement technique. As a result, the crack length was plotted against the number of load cycles N. The appropriate shape factors for the stress intensity $\Delta K$ of a thickness notch over the full width of a specimen loaded in 3 point bending were obtained from Anderson (2005) to calculate the $\Delta K$ for any crack length. The test parameters were the stress ratio $R = 0.1$, test frequency $f = 8-12$ Hz, span $S = 240$ mm and force range $P = 5000 \text{ to } 10000$ N. Stress ratio $R = 0.1$ ($P_{\text{min}}/P_{\text{max}}$) was chosen to match the ratio used in the fatigue tests of sections 4.3-4.6. The notch location was also chosen to match the mostly observed crack location in the fatigue specimens.

The tests started with relatively high force range, to initiate a sharp fatigue crack. After crack initiation, the force was dropped to obtain $\Delta K$ levels in the range of 500-600 N/mm$^{3/2}$. In case of fast crack growth the force range was lowered again. Tests continued up to about $\Delta K = 2400$ N/mm$^{3/2}$.
The specimens were isolated from the test rig, (See Figure 4.42). Each cycle, an electric current and potential were measured over a cracked and an uncracked cross section of the specimen. A crack in the cross section raised the resistance. With a reference measurement over the uncracked cross section, the raising resistance was plot as a function of the crack depth. This made it possible to follow crack growth accurately. Next to this measurement of crack size, camera system Questar was used for determination of the crack length visually. The potential measurements were used to indicate crack growth, not quantitatively. The crack growth was measured from the readings of the camera manually by using a measurement scale reference next to the crack, (See Fig. 7.41).

Figure 4.42. Specimen in 3 point bending rig, with potential drop instrumentation: 
a. isolation of test specimen and attachment of current b. side view of 3 point bending and cables for potential measurement in reference point and over the crack in the middle c. Ikegami camera and 3 point bending setup.
4.7.3 Results

The results of the crack growth measurements of the series GB46, GB69, GB89 and GB11 are presented in Figure 4.43 and Table 4.10. The $da/dN$ is plotted against the $\Delta K$ on a log-log scale. With statistical analysis, the mean material parameters $M$ and $C$ were derived, according to the Paris law. Material parameter $C$ is the intersection at the y-axis, parameter $M$ is the slope of the crack growth curve. The threshold value $K_{th}$ and fracture toughness $K_{max}$ were not determined in the current research, and were not included in the results of Figure 4.44. The crack growth curves only described the linear part of the Paris law and extrapolated for low and high values of stress intensity, which is a simplified representation of the crack growth behaviour.

![Figure 4.43. Results of specimens with initial notch in base material.](image)

Table 4.10. Results of base material specimens.

<table>
<thead>
<tr>
<th></th>
<th>GB46x</th>
<th>GB69x</th>
<th>GB89x</th>
<th>GB11x</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ [-]</td>
<td>3.24</td>
<td>3.38</td>
<td>2.99</td>
<td>2.42</td>
</tr>
<tr>
<td>$C$ [N/mm$^{3/2}$]</td>
<td>6.45E-14</td>
<td>1.74E-14</td>
<td>4.07E-13</td>
<td>8.13E-12</td>
</tr>
</tbody>
</table>

A qualitative analysis shows only small differences in the various steel grades S460 up to S1100, which confirmed the literature [Barsom and Rolfe, 1999]. The material parameters of the Paris law seemed to be independent of material grade.
The results of the crack growth measurements of the specimens with notch in the HAZ - series GH46, GH69, GH89 and GH11 - is presented in Figure 4.44 and Table 4.11. The results of the S460 and S1100 specimens were found to be similar to the base material notched specimens; the results of the S690 and S890 material differed compared to the base material notched specimens. In much of the specimens with notch in the HAZ, cracks did not grow perpendicular to the stress direction. This influenced the local stress intensity. Therefore, in not all cases, these results gave the adequate material parameters.

![Figure 4.44. Results of specimens with initial notch in the HAZ.](image)

Table 4.11, Results of welded specimens

<table>
<thead>
<tr>
<th></th>
<th>GH46x</th>
<th>GH69x</th>
<th>GH89x</th>
<th>GH11x</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>-</td>
<td>3.26</td>
<td>1.86</td>
<td>1.73</td>
</tr>
<tr>
<td>C</td>
<td>3.54E-14</td>
<td>5.82E-10</td>
<td>1.18E-09</td>
<td>2.44E-11</td>
</tr>
</tbody>
</table>

A comparison of the crack growth parameters to results found in the literature is given in Table 4.12 and Figure 4.45. According to Dijkstra & Van Straalen (1997), the average values are for the Paris law, constant $C = 1.832 \times 10^{-13}$ and exponent $M = 3$, are valid for structural steels. For VHSS, values were determined by Demofonti et al. (2001). On the horizontal axis of Figure 4.44, the stress intensity is given in N/mm$^{3/2}$, on the vertical axis the crack growth rate $da/dN$ [mm/cycle]. For $R = 0.1$, the tendency is that slope $M$ is decreased with higher yield strength, and $C$ increased in the linear part of the crack growth curve, based on the Paris law. This was also found in Demofonti et al. (2001). This indicates relatively faster crack growth for higher yield strengths. However, no large differences were found.
4. Plate experiments

The choice of $R = 0.1$ could be the reason that the GH-series gave somewhat unexpected results, because of potential crack closure effect during minimal levels of $P$ in the load cycles.

Figure 4.45. Crack growth test results: a. results of base material specimens current study b. results of HAZ specimens current study c. results of base material cracks [Demofonti, 2001] d. results of base material cracks [Dijkstra & Van Straalen 1997].

Table 4.12. Comparison of crack growth results.

<table>
<thead>
<tr>
<th>Grade</th>
<th>$C {\text{MPa}\cdot\text{m}^{-1}}$</th>
<th>$C {\text{N/mm}^{3/2}}$</th>
<th>M</th>
<th>Type</th>
<th>R</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355N</td>
<td>3.2E-09</td>
<td>8.6E-14</td>
<td>3.05</td>
<td>BM</td>
<td>0.1</td>
<td>Demofonti et al. (2001)</td>
</tr>
<tr>
<td>S355M</td>
<td>4.4E-09</td>
<td>1.7E-13</td>
<td>2.94</td>
<td>BM</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>S690Q</td>
<td>6.0E-08</td>
<td>3.3E-11</td>
<td>2.17</td>
<td>BM</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>S960Q</td>
<td>3.3E-07</td>
<td>7.1E-10</td>
<td>1.78</td>
<td>BM</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>S355N</td>
<td>9.1E-09</td>
<td>7.5E-13</td>
<td>2.72</td>
<td>FZ</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>S355M</td>
<td>3.8E-08</td>
<td>1.2E-11</td>
<td>2.33</td>
<td>FZ</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>S235-S690.5E-09</td>
<td>3.0E-13</td>
<td>3.00</td>
<td>BM</td>
<td>-</td>
<td>Dijkstra &amp; Van Straalen (1997)</td>
<td></td>
</tr>
</tbody>
</table>
4.8 Summary of findings

From literature it is known, the more geometrical irregularities or notches are present, the worse is the effect on the fatigue strength of particularly (very) high strength steel connections. Relatively few fatigue strength data are available for welded connections made of VHSS. Experimental work was carried out within the current study, to study the effect of yield strength on the fatigue strength of welded structural members made of steels with yield strength above 690 MPa.

First, base material strips, made of S690 and S1100 were tested, for which it was anticipated that there should be an advantage of higher yield strength. Most of the cracks in the S690 specimens initiated from the edges at the tapered cross section. At the S1100 specimens, cracks initiated at the surface, outside of the tapered cross section. Particularly in the S1100 specimens, Nf was found to be very close to the Ni at various stress levels, which indicates rapid crack growth after crack initiation.

Next, X-welded strips made of S355, S690 and S1100 were tested under tension loading (SA-series, S355; FA-series, S690; FB-series, S1100). Comparing the fatigue strength curves of the S690 and the S1100 test specimens, differences in crack initiation phase versus crack propagation phase were found. The crack initiation portion of the fatigue life of the S1100 specimens was much larger while the crack propagation portion was smaller than the S690 specimens. In principal, the results of the SA series (S355) were relatively close to the results of the FA series (S690). The results of the FB series (S1100) showed larger scatter.

The majority of the fatigue test program was carried out on test series of V-welded connections, made of steel grades S460, S690, S890, S1100 and similar strength cast steels, G20Mn5, G10MnMoV6-3, G18NiMoCr3-6 and G22NiMoCr5-6. The specimens were made of rolled steel to rolled steel members (V-series), of rolled steel welded to cast steel members welded without backing (C-series) and of rolled steel welded to cast steel members welded with ceramic backing (CB-series). A number of specimens was loaded with average tensile stresses in the cap region, other specimens with average tensile stresses in the root region to investigate the effect of the initiation location, cap or root. In all of the rolled V-welded specimens, cracks initiated in the welds. In case of Cap-mode bending loading, cracks became visible in the weld toe at the cap of the specimen; in case of Root-mode loading at the toe of the weld root. Also, base material cracks occurred in some of the rolled steel parts S460, S890 and S1100, and cast steel parts G20Mn5, G18NiMoCr3-6 and G22NiMoCr5-6. The number of cycles to failure of the axially loaded specimens was lower than the bending loaded specimens. The strength of the root tended to be lower than the weld toe, for all series. The series contained several specimens that did not have any crack initiation, indicated as runouts. In general, the slope m of the fatigue strength curve of the S890 and S1100 specimens tended to be higher than the slope of the S460 and S690 specimens results.

As it was difficult to measure crack growth in an early stage in the regular fatigue tests, fracture mechanics tests were executed to give more insight in the crack growth behaviour of VHSS. The crack growth parameters were based on the linear part of the crack growth curve, for which the Paris law is valid. The specimens were ground flush at the cap and the root, and machined to obtain a notch with a predefined shape of 1/10th of material thickness. The initial notches were made in the HAZ and base material location. During the test crack length was measured periodically, both visually and by making use of the
potential drop measurement technique. For $R = 0.1$, slope M tended to decrease with higher yield strength, and C increased. This indicated relatively faster crack growth for higher yield strengths. However, no large differences were found for the various grades.

Chapter 5 discusses the fatigue results of girth welded connections of CHS and cast joints. Chapter 6 gives predictions of the crack initiation life and crack propagation life of fatigue cracks. The test results of the current chapter will be compared to the predictions. In Chapter 7, the experimental results will be statistically analysed for determination of the influence of yield strength, and for comparison to EN 1993-1-9 (2005).
5. Truss experiments

5.1 Introduction
An effective application of VHSS in civil engineering structures is expected in stiff, truss-like structures, typically made of Circular Hollow Sections (CHS). Use of cast members in combination with CHS could be promising for the design of highly fatigue resistant joints. Cast steel and CHS, available up to yield strength of 1100 MPa, are more and more applied in fatigue loaded bridge and offshore structures. Choosing optimal shapes of the cast steel parts could result in joints with low stress concentration, as the welds are shifted out of the most severe stress locations. The welded connection between the cast steel part and the CHS is expected to be the governing location for the fatigue strength of the joint. Therefore, the determination of the fatigue strength of welded connections made of cast and rolled steels is the main objective of the current study.

Chapter 4 presented the results of fatigue experiments on plate specimens with V-welded connections of cast and rolled steels. In practice, cast joints will be connected to CHS by V-girth-welds. In order to study the fatigue strength of VHSS connections on a more realistic scale, two truss girders made of welded CHS and cast joints were tested within a separate test program of the current study. The used materials were as identical as possible to the materials of the plate test specimens. For the welds, a similar V-weld shape was chosen. The first truss girder was made of S690 CHS and cast joints made of G10MnMoV6-3 cast steel; the second truss girder was made of S890 CHS and G18NiMoCr3-6 cast joints. The test frame consisted of a 10000 kN hydraulic jack, pull bars and H-girders. In this way, it was possible to load the truss specimens dynamically.

Cast joints in the truss behave as stiff joints, which results in a combination of axial loading and bending moments in the truss chords and braces. A static analysis was carried out before the fatigue tests were started up. The static analysis provided information on the strain distribution in the truss, measured by strain gauges, to be compared with the FEM-calculations.

Section 5.2 presents the test program and the lay-out of the test rig. Section 5.3 gives background on the manufacturing of the specimens. Section 5.4 gives the results of the static analysis. Section 5.5 presents the fatigue results of the S690 and the S890 trusses. Section 5.6 compares the results to literature.

5.2 Test program

5.2.1 Choice of specimens
Based on the literature review presented in Section 3.4, an experimental program was set up for the testing of V-girth-welded connections of CHS and cast joints with very high yield strength. In summary, Haldimann-Sturm (2005) tested a full scale truss made of CHS welded to cast joints with yield strength of 355 MPa. Veselcic et al. (2009) tested CHS-cast steel end-to-end connections with various weld shapes, made of S355 and S460 and cast steels with similar strength. Table 5.1 presents the research variables of the current study [Pijpers et al., 2010] compared to the work of Veselcic et al. (2009) and Haldimann-Sturm (2005). It was decided to test V-girth welded K-joints and CHS made of yield strength S690 and S890.
Table 5.1. Comparison of research variables of work in Karlsruhe [Veselcic et al., 2009], Lausanne [Haldimann-Sturm, 2005] and the current study in Delft [Pijpers et al., 2010].

<table>
<thead>
<tr>
<th>Variable</th>
<th>Karlsruhe</th>
<th>Lausanne</th>
<th>Delft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATERIAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rolled steel CHS</td>
<td>S355, S460</td>
<td>S355</td>
<td>S690, S890</td>
</tr>
<tr>
<td>Cast steel</td>
<td>G20Mn5 + QT G10MnMoV6-3 + QT3</td>
<td>G20Mn5</td>
<td>G10MnMoV6-3</td>
</tr>
<tr>
<td><strong>GEOMETRY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size specimens</td>
<td>CHS end-end welded connections</td>
<td>Truss</td>
<td>Truss</td>
</tr>
<tr>
<td>D x t [mm]</td>
<td>193.7x20 298.5x30 508x55</td>
<td>244x10 244.5x17.5 273.1x22.2</td>
<td>219.1x22.2</td>
</tr>
<tr>
<td>θ [°]</td>
<td>0</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td><strong>WELDING</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backing</td>
<td>Various shapes of backing</td>
<td>With and without backing</td>
<td>Without backing</td>
</tr>
<tr>
<td>Joint type</td>
<td>Girth weld</td>
<td>Girth weld</td>
<td>Girth weld</td>
</tr>
<tr>
<td>Welding process</td>
<td>MMA welding</td>
<td>MAG-welding</td>
<td>MIG/MAG welding</td>
</tr>
<tr>
<td>Welding position</td>
<td>PC; PF</td>
<td>PF</td>
<td>PF</td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>2 - 6</td>
<td>3</td>
<td>3 - 5</td>
</tr>
<tr>
<td>Bevel angle</td>
<td>40°</td>
<td>50°</td>
<td>60°</td>
</tr>
<tr>
<td><strong>TESTING</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test setup</td>
<td>CHS-end-to-end, Ax, 4PB</td>
<td>Truss</td>
<td>Truss</td>
</tr>
<tr>
<td>R [-]</td>
<td>0.1-0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

To be able to make a comparison to Haldimann-Sturm (2005), the mould of the cast joints was chosen to be identical; however, the available CHS material for the current research was larger. Therefore, the mould was adapted to the size of the available CHS dimensions. In cooperation with the foundry, K-joints were produced.

5.2.2 Fatigue test rig

Joints of a truss structure endure both axial and bending loading, because of the stiff character of the welded connections; in particular when cast joints are used. Experiments on truss joints are usually carried out on isolated joints, which are tested under various load cases. The fatigue strength of the joint is based on the contribution of the individual load cases to the local hot spot stress. The following loading cases are generally applied on the joints: axial loading chords; balanced bending moments in the braces; unbalanced bending moments in the braces [Schumacher, 2003].

In a preliminary stage of the current research, it was decided to test isolated welded K-joint connections. However, because of the large diameter and thickness of the available

---

4 All the cast members were produced at foundry Friedrich Wilhelms Hütte, Germany.
Fatigue strength of welded connections made of very high strength cast and rolled steels

CHS, the required fatigue (dynamic) loading was estimated to be 6000 kN for obtaining representative stress ranges for fatigue crack initiation. Because of expected difficulties for the test setup of isolated joints, in particular the design of tensile connections needed for transmission of dynamic forces in the test rig, it was chosen to reconsider the design of the test setup and to work out a configuration for a full scale truss test.

By testing a complete truss instead of isolated joints, the behaviour of the cast joints was more representative of actual loading cases. The behaviour of the cast nodes as stiff joints was expected to result in a combination of tension loading and bending moments in the truss chords and braces. In total two trusses were designed. The first truss was made of S690 CHS and K-joints of similar strength by using G10MnMoV6-3 cast steel. The second truss was made of S890 CHS and K-joints of similar strength by using G18NiMoCr3-6 cast steel.

The test frame consisted of a hydraulic jack ($F_{stat} = 10000$ kN / $F_{dyn} = 6000$ kN), pull bars and H-girders (See Figure 5.1). Forces were transmitted to the girders through rotating blocks in the plane of the truss, to which a hinge and a rolled support were connected. The direct loading of the cylinder acted on blocks, milled in the contra shape of the CHS. First, araldite was used to fill out space between the blocks and the truss specimens for an even load distribution in the specimen. However, aluminium plates were found to behave more appropriate as the araldite was crushed out of the blocks after a high number of cycles. The hydraulic jack pressed to the truss and to a lower block, to which 4 pull bars were connected, transmitting the force to the upper side of the H-girders. In this way, the forces were kept within the test frame, so that no dynamic forces needed to be transmitted to the lab floor. A support frame on the lab floor guided the cylinder vertically, preventing horizontal movement. With the given setup, it was possible to load the specimens on various locations, for different load cases. By making use of loading location, as shown in Figure 5.2, it was possible to obtain stress ranges far below the fatigue limit in most of the connections, whilst at more heavily loaded connections, the stress ranges could initiate fatigue cracks. After reaching a critical crack size, the specimen could be rotated in the setup, to introduce a second load case, leading to a new stress distribution in the truss. The former relatively unloaded parts, would now endure the high stress ranges, whilst the stresses in the cracked parts would be low. During the fatigue test, ranges and averages of strains, displacements and forces were recorded by about 100 channels. Change of strain ranges indicated crack initiation, after which an alarm setting stopped the test. Crack growth could then be monitored visually. The current setup made it possible to load the truss specimens up to 6000 kN with frequency of 0.3 Hz (See Table 5.2). The specimens were loaded in constant amplitude, with R value 0.1, defined by the strain ratio.

Table 5.2. Fatigue test parameters.

<table>
<thead>
<tr>
<th></th>
<th>S690</th>
<th>S890</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading</td>
<td>Constant Amplitude</td>
<td>Constant Amplitude</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.3 Hz</td>
<td>0.3 Hz</td>
</tr>
<tr>
<td>R</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$F_{min}$</td>
<td>200 kN</td>
<td>300 kN</td>
</tr>
<tr>
<td>$F_{max}$</td>
<td>6000 kN</td>
<td>5000 kN</td>
</tr>
<tr>
<td>$\Delta F$</td>
<td>5800 kN</td>
<td>4700 kN</td>
</tr>
</tbody>
</table>
5. Truss experiments

Figure 5.1. Truss test setup.
5.3 Manufacturing of specimens

5.3.1 Manufacturing of cast joints
For the manufacturing of the truss girder, thick walled CHS were available in the grades S690 and S890. The truss specimens were designed based on the available length of the CHS and the possibilities of testing in the Stevin Laboratory. The diameters of the relatively thick walled CHS were not equal for the two steel grades. Except from the diameter of the CHS and correspondingly the cast joints, the global dimensions of the S690 and S890 trusses were similar. In close cooperation with the foundry, the final shape of the joints was determined and the material specification to match the yield strengths of S690 and S890. For each material only one CHS was available, which made it necessary to design trusses with equal thickness and equal diameters of chords and braces per material. Table 5.3 lists the design parameters of the trusses; Figure 5.2 shows the dimensions of the truss.

Table 5.3. K-joint specimens.

<table>
<thead>
<tr>
<th>Steel grade CHS</th>
<th>S690</th>
<th>S890</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_0 = t_1 = t_2 )</td>
<td>22.2</td>
<td>22.2  [mm]</td>
</tr>
<tr>
<td>( D_0 = D_1 = D_2 )</td>
<td>273.1</td>
<td>219.1 [mm]</td>
</tr>
<tr>
<td>( \theta_1 = \theta_2 )</td>
<td>60</td>
<td>60 (^\circ)</td>
</tr>
<tr>
<td>( \beta = (D_1 + D_2)/2-D_0 )</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \gamma = D_0/2t_0 )</td>
<td>6.2</td>
<td>4.9</td>
</tr>
<tr>
<td>( \tau = t_1/t_0 )</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 5.2. Specimen with cast joints (K1-K5), weld positions (1-14), CHS (B1-B5), strain gauge positions (a-d), Force and displacement of the piston (F,s).
5. Truss experiments

In total 5 joints per material were cast, grade G10MnMoV (S690) and G18NiMoCr3-6 (S890). The cast joints satisfied the NDT requirements of class 1 for weld areas and class 2 for other areas, by ultrasonic inspection according to EN 12680-1 (2003) and penetrant inspection according to EN 1371-1 (1997). Appendix B gives the mechanical properties of the materials according to the data sheets of the steel manufacturers. Figure 5.3 shows the dimensions of the cast joints.

![Figure 5.3. Dimensions of cast joints: a. G10MnMoV6-3 (S690); b. G18NiMoCr3-6 (S890).](image)

Figure 5.3. Dimensions of cast joints: a. G10MnMoV6-3 (S690); b. G18NiMoCr3-6 (S890).

Special attention was paid to the shape of the castings in relation to the casting process. The feeder head was positioned on the middle of the joint (See the red areas of Figure 5.4a). The transition areas were ground to make a smooth transition between the casting and the feeder part, (See the green areas of Figure 5.4a). Figure 5.4b shows a casting reinforcement, indicated by the red area inside of the casting to guarantee saturation.

![Figure 5.4. Riser and reinforcement positions of cast joints [Friedrich Wilhelms Hütte, 2007].](image)

Figure 5.4. Riser and reinforcement positions of cast joints [Friedrich Wilhelms Hütte, 2007].

5.3.2 Welding of trusses

The connections between the cast joints and the CHS were V-girth-welds. The weld angle was 60° and the maximum initial gap 3 mm. The 14 connections were welded in position vertical up (5Gu / PF). First, the trusses were fit up, after which the chords and the braces were welded. During welding, the trusses were rotated several times. Table 5.4 gives details on the welding procedure. All welds of the S690 and S890 specimens were checked for...
Fatigue strength of welded connections made of very high strength cast and rolled steels

flaws by ultrasonic and penetrant inspection. The S690 specimens did not require repair
welds. At some locations of the S890 specimen repair welds were made.

The trusses were welded in such condition that restrained movements were minimized.
Start and stop positions overlapped, and positioned between at 1-2 and 7-8 o’clock, (See
Figure 5.5). Per weld, 4 quarter rounds were made in position 5Gu (PF).

Table 5.4. Welding parameters.

<table>
<thead>
<tr>
<th>Steel grade CHS</th>
<th>S690</th>
<th>S890</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding process</td>
<td>GMAW/FCAW</td>
<td>FCAW</td>
</tr>
<tr>
<td>Number of layers</td>
<td>23</td>
<td>30</td>
</tr>
<tr>
<td>Consumable</td>
<td>ER100SG (root)</td>
<td>E111T1K3M (fill, cap)</td>
</tr>
<tr>
<td></td>
<td>E120T1G (all)</td>
<td></td>
</tr>
<tr>
<td>Preheat T (°C)</td>
<td>100</td>
<td>125</td>
</tr>
<tr>
<td>Max. Interpass Temp. (°C)</td>
<td>200</td>
<td>225</td>
</tr>
<tr>
<td>Heat input [kJ/mm]</td>
<td>1.1-2.4 (root)</td>
<td>0.9-1.3 (root)</td>
</tr>
<tr>
<td></td>
<td>1.0-1.8 (fill/cap)</td>
<td>0.7-1.6 (fil</td>
</tr>
<tr>
<td>Welding Position</td>
<td>5Gu/PF</td>
<td>5Gu/PF</td>
</tr>
<tr>
<td>Gap [mm]</td>
<td>4.5 ± 1.5</td>
<td>3</td>
</tr>
<tr>
<td>Number of layers</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Start-Stop</td>
<td>12-6 o’clock</td>
<td>2-8 o’clock</td>
</tr>
</tbody>
</table>

Figure 5.5. Cross section of CHS, indicating welding direction and start and stop locations.

Figure 5.6 shows the manufacturing of the S890 in the workshop. Because of the given
tolerances in diameter and wall thickness of the CHS and cast joints, local eccentricities
could be detected. High-Low was measured for every connection in the S690 and S890
trusses. The resulting maximum difference was limited to 2 mm.
5. Truss experiments

Figure 5.6. Manufacturing of S890 truss.

5.4 Static evaluation

5.4.1 Predicted stress values based on FEM-model
With finite element modelling, a linear elastic stress analysis of the truss structure was carried out, to predict the local stresses in the castings and the welded connections. Finite element software packages MSC.Marc Mentat (2005) and Abaqus (2008) were used to model the truss setup with the geometries of the cast joints. The geometry of the cast joint had been modelled by the foundry for a casting analysis. The exact geometry was imported in the FEM-software. For the wall thickness of the cast joints and CHS, average values were used. Neither local thickness differences nor Hi-Low were modelled.

With MSC.Marc Mentat (2005), the geometry of the castings was imported by STL files. The imported geometry was converted to triangular elements. After sweeping the triangular elements, the MOM-remesher was used to reformulate the imported triangular mesh of the STL file. In this way, a new mesh was formed, with a variable size, and a shell fully enclosing the casting geometry. By defining the triangular elements, the mesh was converted to 3d tetrahedral elements by the Patran Surface mesher, by which a solid hexahedral mesh was created. Next, the MOM-remesher was used to reformulate the imported triangular mesh of the STL file. The nodes at the edges were moved to couple HEX elements of a connecting CHS to the cast joint.

The meshing procedure in MSC.Marc Mentat (2005) was relatively complex with use of the STL geometry, and it was difficult to obtain full control over the node locations, to build a full model of a truss structure with multiple castings. Therefore, it was decided to use Abaqus (2008). In the Abaqus model, the geometry of the cast joints was imported by IGES geometries. The geometries of cast joints and CHS were assembled and the geometries were coupled at the physical locations of the welded connections. The full truss geometry could directly be converted to automatically generated C3D4, 4-node linear tetrahedral elements.
In the experimental setup, the load of the piston was transmitted through rectangular blocks, filled out with aluminium plates, for an equal distribution of local forces. Also in the FEM-model, separate blocks were included to model the transmission of forces from the supports and piston to the truss. For the interaction properties of truss and block supports, surface to surface contact was applied, based on tangential behaviour with friction formulation ‘rough’.

5.4.2 Comparison of predictions and static measurements
As the cast joints in the truss behaved as relatively stiff joints, stresses near the cast nodes were the result of a combination of axial and bending loading. In order to have an understanding of the strain distribution in the cast nodes and the strain levels next to the welded connections, a static analysis was undertaken, before starting the fatigue tests.

The static analysis provided information on the strain distribution in the truss, measured by strain gauges, to be compared with the FEM-calculations. Strain gauges were positioned at 10 mm from the weld toe. On average, 8 strain gauges were attached at each of the 14 welded connections. About 100 channels were recorded simultaneously. The specimen was loaded statically up to 5000 kN, displacement controlled, the S690 truss up to 6000 kN.

The measured strains were multiplied by the modulus of elasticity, to obtain the stress levels according to the uniaxial Hooke’s law. These stress levels could be directly compared to the Von Mises stress levels calculated in the FEM-model. Figure 5.7 and Figure 5.8 compare the Von Mises stresses of the FEM-model with the measured values at weld positions 1, 12 and 14; also the stresses at the middle of CHS B5 are compared for S890 and Weld 5 for S690. The figures give the strain gauge positions a, b, c and d round the perimeter P of the cross section. At the S690 truss, strain gauges were attached at only the a and c positions, the S890 truss contained strain gauges at a, b, c and d.

The average difference in measured and calculated stress was below 10%; in some locations differences up to 20% were found. Reasons for difference are the fact that the stresses in the FEM-model were based on nominal thickness of the CHS and cast joints, whereas effects of tolerances were not taken into account. Moreover, the force transmission through supports was modelled in idealized boundary conditions, which might explain 20% deviation of measured and calculated results at for instance weld position 14. Also the fact that local misalignment and thickness variation were not modelled and minor changes in the load transmission could explain differences of modelling and measurements.

The force ranges were determined in such a way that the maximum stress ranges in both the S690 and the S890 would be similar. The S690 joints were slightly stiffer than the S890 members. This resulted in larger bending moments in the joints. Overall, the CHS were loaded predominantly axially. Therefore, the stresses in the cap and the root were expected to be similar. Stress measurements and calculated stresses show that the bending portion of total stress level in the characteristic points in the S890 specimen was 10% up to 30%, and 10% up to 40% in the S690 specimen.
Figure 5.7. Comparison of numerical results and measurements of stresses in S690 truss, load case 1.
Next to the weld locations, the measured strains at the centre line of the cast joints were evaluated. The strain values of attached rosette strain gauges, measuring in three directions were converted to equivalent stresses. These values were compared to the Von Mises stresses of the FEM-model (See Figure 5.9). The Von Mises stresses were averaged out over the elements, for which the plots are given at the surface. The predicted stress values reasonably fit the strain gauge measurements. Differences in model and predictions could be explained by slightly deviating load transmission of the support block to the truss.

Figure 5.8. Comparison of numerical results and measurements of stresses in S890 truss. load case 1.
5. Truss experiments

5.5 Fatigue test results

5.5.1 S690 - G10MnMoV6-3 truss

The S690 - G10MnMoV6-3 truss was dynamically loaded with force range $\Delta F = 5.800$ kN. The cylinder pressed at cast joint K1 (See Figures 5.2 and 5.7); K3 was supported by a rotating hinge and K5 by a roll. Weld 5 connected cast joint K2 to CHS B3, and was loaded in tension.

After about 200000 cycles, the strain ranges of the gauges that were applied on K-joint 1 started to bend off the regular scheme, which indicated crack initiation in the vicinity of the strain gauges (See Figure 5.10). The strain gauges were rosettes placed in the centre line of K-joint 1. On the outside of the truss no cracks were visible.
A camera was mounted inside the specimen, by which cracks on the inside of the cast joint could be inspected. Inside, cracks were visible after 560000 cycles. Because of the size of the test specimen, it was difficult to trace the exact point of crack initiation by the strain gauge measurements. Only if the strain gauge was very close to the crack, initiation could be noticed at an early stage.

For an adequate transmission of the force to the truss specimen, a milled block was used. The block distributed the load over a large surface of the cast joints. However, in the middle of the joint, a casting reinforcement was present, which introduced a geometrical transition, causing stress concentration on the inner part of the joint, exactly, where the load was introduced on the truss. The resulting tensile stresses in the cast joint were about 190 MPa, calculated from the FEM-model (See Figure 5.11), as there were no strain gauges attached next to the casting reinforcement.
5. Truss experiments

Figure 5.11. Modelling of load transmission though block into truss with casting reinforcement.
Fatigue strength of welded connections made of very high strength cast and rolled steels

After about 400,000 cycles, strain ranges at tensile loaded weld 5 began to rise. At 550,000 cycles a crack was visible in the middle of the weld, near strain gauges 25B354 and 26K254. (See Figure 5.12 and Appendix H for the coding of the strain gauge numbers). The crack initiated from the weld root, for which the rising strain values at the weld toe were evidence and the fact that the crack was visible in the middle of the weld profile, not at the weld toe.

Figure 5.12. Strain range at weld 5, load case 1.

Figure 5.13, shows the location of the cracks in the FEM-model of the S690 truss. The measured stress range at the crack location weld 5 was 130 MPa (tensile); the calculated stress range at K-joint 1 was 190 MPa (tensile).

Figure 5.13. Locations of crack initiation in S690 truss, with scaled deformation; load case 1.
5. Truss experiments

5.5.2 S890 - G18NiMoCr3-6 truss

The S890 - G18NiMoCr3-6 truss was loaded with dynamic force range $\Delta F = 4.700 \text{kN}$. In the first fatigue load case, the cylinder pressed at cast joint K1 (See Figures 5.2 and 5.8); K3 was supported by a rotating hinge and K5 by a roll. Weld 12 connected cast joint K4 to CHS B7; the weld was under predominantly axial loading. Weld 14 connected cast joint K5 to CHS B5, and was loaded compressively. The resulting stresses in the weld contained bending components which increased the stresses locally.

After 150000 cycles, strain ranges next to the weld toe of weld 12, 47K4124 ($\Delta \varepsilon = 913$, tensile) and 48B7124 ($\Delta \varepsilon = 963$, tensile), started to increase (See Figure 5.14). The cracks were visually detected after 271000 cycles in the weld toe of the tensile loaded weld 12. The root of weld 12 was inspected by a camera. The visual assessment showed that the geometrical variation in the root was larger than in the cap; also weld spatters were found in the root. The quality of the weld root was worse than the quality of the weld at the cap. The lower geometrical quality might be the reason for crack initiation at the weld root. Figure 5.15 presents the camera shot at the root side of weld 12 at the crack initiation location.

![Figure 5.14. Strain ranges at weld 12.](image1)

![Figure 5.15. Image of root of weld 12 at the crack initiation location.](image2)
The next fatigue crack initiated at compressively loaded weld 14. After 220000 cycles, strain gauge 54B5143 ($\Delta \varepsilon = 1600$, compressive) indicated crack growth at weld 14 (See Figure 5.16). Also at 271000 cycles, cracks became visible at the outside of the weld.

Figure 5.16. Strain ranges at weld 14 (See Appendix H for coding of strain gauges).

Figure 5.17 shows the location of the cracks in the FEM-model of the S890 truss. The measured stress range at the crack located at weld 12 was 180 MPa (tensile); the stress range at the crack located at weld 14 was 336 MPa (compressive).
In order to initiate new fatigue cracks, the S890 specimen was rotated in the test rig with 180°, referred to as load case 2. In this way, the stress distribution was altered to lower the stresses at the welds that already had crack initiation in the first load case and to increase the stresses at the welds that were not heavily loaded before because of stress levels of load case 1 below the expected fatigue limit. It was assumed that there was no crack initiation in load case 1, which means that the counter of number of cycles was reset before starting load case 2. The crack growth of the already existing cracks was monitored visually, as they could still grow under low cyclic stresses. If the cracks would become too large, the stiffness of the connections would be too low to transmit the forces through the truss. In the new load case, strain gauges at weld 8 (See Figure 5.19) started to rise at about 160000 cycles (431000 cycles when added up to the number of cycles in load case 1). The crack became visible on the outside at 205000 cycles (See Figure 5.18). The test was extended up to 263000 cycles. However, the number of cycles until through thickness crack was taken as the failure criterion.
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 5.19, shows the location of the cracks in the FEM-model of the truss. The measured stress range at the crack located at weld 8 was 218 MPa (tensile).

Figure 5.19. Locations of crack initiation in S890 truss, with scaled deformation; load case 2.

5.6 Comparison of truss test results
The fatigue results of both the S690 and the S890 specimens are presented in the fatigue strength curve of Figure 5.20. The number of cycles until through thickness crack was plotted against the stress range for the various crack locations. Because of the complexity of the large scale, time consuming fatigue testing of the trusses, it was not possible to generate many fatigue data points.

Figure 5.20. Fatigue results of truss tests.
Figure 5.21 shows that the results of the S890 truss tend to indicate a higher strength than did the results obtained in Lausanne [Haldimann-Sturm et al, 2005] and Karlsruhe [Puthli et al., 2007] on girth welds between CHS and cast joints made of S355. The difference could possibly be explained by the effect of the higher yield strength. The results of truss specimens S690 and S890 seem to meet detail class 71 according to EN 1993-1-9 (2005), although the detail class for girth welds is only valid for wall thickness $t < 12.5$, whilst the average wall thickness of the specimens was 23 mm.

![Fatigue results of truss tests with weld root cracks compared to literature (stress ranges adjusted to $t = 25$ mm by Eq. 3.2).](image)

As can be seen in Figure 5.22, the predictions for initiation of base material cracks by UEG (1985) reasonably match the result of the crack in the cast joint of the S690 truss. Categories 125 and 160 according to EN 1993-1-9 (2005) are also given in the figure, although those categories are not valid for cast steels.
5.7 Summary of findings

As it was expected that VHSS would be applied most effectively in truss-like structures, two truss specimens were fatigue tested, which were made of CHS and cast joints. The selected materials for the trusses were CHS made of S690 and S890 and cast joints made of G10MnMoV6-3 and G18NiMoCr3-6 respectively. The trusses contained 14 connections, which were V-girth-welded without backing in welding position vertical up. The welding procedures were similar to those used for the strip specimens that were V-welded without backing, made of S690 and S890. A static analysis was undertaken before the fatigue tests, which provided information on the strain distribution in the truss. The strain gauge measurements were compared with FEM-calculations. The test setup made it possible to load the truss specimens cyclically up to 6000 kN with frequency of 0.3 Hz.

The experiments on the truss specimens lead to the following results. In V-girth-welded connections of cast steel joints and CHS, weld root cracks were found to occur more likely than weld cap cracks, because the quality in the root was lower than in the cap. In the S690 truss, one fatigue crack initiated from the weld root, for which the rising strain values at the weld toe are evidence and the fact that the crack was visible in the middle of the weld, not at the weld toe. Although it had been assumed no cracks would initiate in the cast joints, one crack initiated in a reinforcement position of cast joint made of S690 - G10MnMoV6-3. Three fatigue cracks were found in the S890 truss. All cracks initiated in the weld root. Any part of a cast joint, also the feeder, riser and cast reinforcement positions, should therefore be checked as being potential crack initiation locations if there is no possibility of grinding after the casting process.

The results of the S890 truss tend to indicate a higher strength than did the results obtained by Haldimann-Sturm et al. (2005) and Puthli et al. (2007) on girth welds between CHS and cast joints made of S355. The difference could possibly be explained by the effect
of the higher yield strength. The results of truss specimens S690 and S890 seem to meet
detail class 71 according to EN 1993-1-9 (2005), although the detail class for girth welds is
only valid for wall thickness \( t < 12.5 \), whilst the average wall thickness of the specimens
was 23 mm.

The predictions for initiation of base material cracks by UEG (1985) reasonably match
the result of the crack in the cast joint of the S690 truss.

The fatigue strength results of V-welded plate with root cracks specimens of Chapter 4
and fatigue life predictions will be compared with the results of the truss specimens with V-
girth-welded CHS to cast joints with root cracks in Chapter 7.
PART III: Analysis

Part III: Analysis evaluates the experimental outcome of part II in more detail. In order to predict the fatigue strength of base material parts and welded connections, nominal stress theory, notch stress theory and fracture mechanics theory can be applied.

In Chapter 6, the test results described in part II of this thesis have been evaluated for the validity of the notch stress theory, for crack initiation life, and fracture mechanics theory for crack propagation life. The effect of the main influence factors on the fatigue strength has been studied quantitatively.

By the summation of crack initiation life and crack propagation life the total fatigue life is obtained that can be compared to the nominal stress theory. Chapter 7 confronts the fatigue life predictions of Chapter 6 with the experimental data on plates and trusses.
6. Fatigue life prediction

6.1 Introduction

In the manufacturing of structural joints, it is inevitable to introduce geometrical transitions with some kind of notch, such as radii, holes or connections. Local notch stress concentration introduces local plastic redistribution of stresses on the surface of the structural members. As a consequence, the stress concentration factor $K_t$ will not have full effect on the fatigue strength. The fatigue notch factor $K_f$ represents the effectiveness of the notch stress concentration on the fatigue strength.

The main research question of the current study is in what way and to which extent the fatigue strength of structural members is influenced by the yield strength of VHSS. In addition, many other parameters that are of influence on the fatigue strength, such as stress level, presence of defects, local and global geometry, should be addressed for a proper evaluation of the influence of the yield strength.

Section 6.2 presents the notch stress theory, summarised by Haibach (2006) and Radaj et al. (2006) that was used in the current study for the prediction of the initiation life of base material cracks and weld toe cracks. Section 6.3 presents the fracture mechanics theory and the FAFRAM model [Dijkstra & Van Straalen, 1997] that was used for the study of propagation life of base material cracks and weld toe cracks. In Section 6.4, a comparison is made between the predictions of Chapter 6 and fatigue strength results of plate experiments given in Chapters 4 and truss experiments given in Chapter 5.

6.2 Prediction of crack initiation life by the notch stress approach

With the notch stress approach (See Section 3.2.3), the local stresses in the vicinity of notch can be determined. The local stress, or notch stress concentration factor $K_t$, is influenced by member thickness, stress gradient, surface roughness and additionally weld toe angle and weld toe radius for welded connections. The fatigue notch factor $K_f$ represents the effectiveness of the notch stress concentration on the fatigue strength, which is influenced by the yield strength. The effect of mean stress and loading mode are also taken into account in the notch stress analysis. First, the definition will be given of the fatigue notch factor. Next, based on the fatigue notch factor and notch stress concentration factor, a prediction will be given for the crack initiation life of base material cracks, after which the influence of parameters for weld toe cracks will be discussed.

6.2.1 Fatigue notch factor

The fatigue-effective notch stress is substantially lower than the notch stress according to the theory of elasticity in case of sharp notches. This can be explained by the microstructural notch support theory, originally conceived by Peterson (1974). This theory states that the maximum notch stress according to the theory of elasticity is not decisive for crack initiation and propagation. Instead, some lower local stress is governing, which is gained by averaging the notch stresses over a material-characteristic small length, area or volume at the notch root (Radaj et al. 2006).

Lawrence et al. (1981) introduced an empirical relation for the fatigue notch factor $K_f$, based on the stress concentration factor $K_t$, the ratio of the notch radius $r$ and the critical distance $\alpha^*$, which is a function the tensile strength $\sigma_{ut}$ (See Eq. 6.1).
6. Fatigue life prediction

\[ K_f = 1 + \frac{K_n - 1}{1 + \frac{a}{r}} \]  
(6.1)

with,

\[ a' = 0.025 \cdot \left( \frac{2068}{\sigma_u} \right)^{1.8} \]

An alternative determination of the fatigue notch factor is given in the “Rechnerische Festigkeitsnachweis für Maschinenbauteile” [FKM, 2003], summarised by Haibach (2006) and in the design rules for movable bridges NEN 6786 (2001). Here, the fatigue notch factor depends on the stress gradient, which is defined as the ratio of the derivative of the notch stress at the notch tip and the maximum notch stress. If the stress gradient is relatively large, the stress concentration will have less detrimental effect on the fatigue strength. This means that the fatigue notch factor will be smaller in case of bending loading compared to tensile loading.

6.2.2 Prediction of the initiation life of base material cracks

The main parameters of influence on the initiation life of base material cracks are yield and tensile strength, mean stress level, residual stress, surface roughness, member thickness and loading mode. The crack initiation life is typically represented by the endurance limit, the endurable stress amplitude under cyclic loading.

6.2.2.1 Fatigue strength curve

For unnotched parts, the fatigue strength endurance limit is a function of either the yield strength, the tensile strength or the hardness. Other material parameters, such as grain size and chemical composition are generally not taken into account in the fatigue strength determination.

The fatigue endurance limit \( \sigma_{f_{\alpha,0}} \) is valid for fatigue loading with mean stress \( \sigma_m = 0 \) \((R = -1)\), which represents alternating stresses with equal compression and tension amplitudes. Hück (1981) proposes the following relation of material yield strength \( \sigma_y \) and \( \sigma_{f_{\alpha,0}} \), given in Eq. 6.2.

\[ \sigma_{f_{\alpha,0}} = 0.436 \cdot \sigma_y + 77 \]  
(6.2)

Calculation rules presented by Haibach (2006) give an alternative relation, which introduces an additional factor \( f_{mat} \) for including the effect of manufacturing, casting or rolling, based on a variation in material pureness and size effects and relates the endurance limit to the tensile strength \( \sigma_u \) (See Eq. 6.3).

\[ \sigma_{f_{\alpha,0}} = f_{mat} \cdot \sigma_u \]  
(6.3)

\( f_{mat} = 0.45 \) for rolled steel and 0.34 for cast steel
Equations 6.2 and 6.3 base the endurance limit either on the yield strength or the tensile strength respectively. In order to compare the equations, the following relation of $\sigma_y$ and $\sigma_u$ was used, which is given by Fourneaux et al. (2001) (See Eq. 6.4).

$$\sigma_u = \sigma_y \cdot (1-0.72 \cdot e^{-0.0027 \sigma_y})^{-1}$$  \hfill (6.4)

The validity of Eq. 6.4 was checked on the material parameters of the steels tested in the current study, S460, S690, S890 and S1100 (See Appendix B). As can be seen in Figure 6.1, the predicted relation between $\sigma_y$ and $\sigma_u$ is very accurate. Figure 6.1 also compares Eq. 6.2 and Eq. 6.3 after substitution of Eq. 6.4, to describe the given endurance limit as a function of yield strength instead of tensile strength. Eq. 6.2 gives a more conservative prediction of the endurance limit.

For the full representation of the fatigue strength curve, in addition to the endurance limit, the slope $k$ of the fatigue strength curve in the medium cycle domain should be known. According to Haibach (2006), $k$ depends on the fatigue notch factor $K_n$, given by Eq. 6.5.

$$k = \frac{12}{K_n^2} + 3$$  \hfill (6.5)
6. Fatigue life prediction

The knee point of the fatigue strength curve N1 is defined as the number of cycles after at which k = infinite, determined by Eq. 6.6.

\[ N_1 = 10^{N_0} \]  \hspace{1cm} (6.6)

with,

\[ N_0 = 6.4 \cdot \frac{2.5}{k} \]

Given the endurance limit \( \sigma_{naE} \), slope k and knee point N1, the endurable stress amplitude \( \sigma_{na} \) can be formulated for the medium and high cycle domain, according to Eq. 6.7. In the nominal stress theory, slope k of the fatigue strength curve is normally referred to by m.

\[
\sigma_{na} = \begin{cases} 
10^{\frac{\log(N1)-A}{-k}} & \text{for } N_1 < N_1 \\
\sigma_{naE} & \text{for } N_1 > N_1
\end{cases} \]  \hspace{1cm} (6.7)

with,

\[ A = N_0 + k \cdot \log (\sigma_{naE}) \]

For a comparison of the predictions according to the notch stress theory and the predictions of the nominal stress theory (See Section 3.2.1), the endurance amplitude \( \sigma_{na} \) can be converted to the endurable nominal stress range \( \Delta \sigma_n \) according to Eq. 6.8 (For \( N_1 > N_1 \), \( \Delta \sigma_n \) can be replaced by \( \Delta \sigma_{naE} \)).

\[
\Delta \sigma_n = \frac{2 \cdot \sigma_{na}}{K_t} \]  \hspace{1cm} (6.8)

\( K_t \) Notch Stress concentration factor

In the current study, the influence of mean stress, surface roughness, thickness and loading mode on the endurable stress range were studied. The influence of these factors on the endurable stress range of base material cracks in case of crack initiation \( \Delta \sigma_{n;u;Ni} \) can generally be presented as given in Eq. 6.9.

\[
\Delta \sigma_{n;u;Ni} = \frac{\sigma_{m;u;Ni} \cdot \Delta \sigma_{n;u;Ni,0}}{f_{m;u;Ni} \cdot f_{sr;u;Ni}} \]  \hspace{1cm} (6.9)

\( f_{sr;u;Ni} \) Surface roughness factor, (See Section 6.2.2.3)
\( f_{m} \) Mean stress factor, (See Section 6.2.2.2)
\( f_{m;u;Ni} \) Influence factor

For the various influence factors, the following indices5 were used for \( f_{sr;u;Ni} \):

\[ f_{m;u;Ni} = f_{m} \]

\[ f_{sr;u;Ni} = f_{sr;u;Ni} \]

\[ f_{m;u;Ni} = f_{m;u;Ni} \]

\[ f_{sr;u;Ni} = f_{sr;u;Ni} \]

5 In order to separate the influence of factors for base material cracks and weld toe cracks, the indices u (base material, unwelded) and w (welded) are used in the current study. The index Ni is used to separate influence factors for crack initiation as presented in the current section and influence factors for the crack propagation phase with index Np, as presented in Section 6.2.3.
Fatigue strength of welded connections made of very high strength cast and rolled steels

\( f_{\text{Ni}} \)  
Thickness factor, (See Section 6.2.2.4)

\( f_{\text{Ni,\Delta}} \)  
Loading mode factor, (See Section 6.2.2.5)

### 6.2.2.2 Mean stress factor

In addition to tensile strength or yield strength, the fatigue endurance limit depends on the mean stress. In general, tensile mean stresses reduce the fatigue life, whereas compressive mean stresses increase the fatigue life, because of crack closure effects. As a result of thermal cycling or local pressure, residual stresses could build up.

In general, the higher the yield strength, the higher the absolute value of mean stresses that can be endured. However, materials with higher yield stress are more sensitive to higher mean stress levels. On the contrary, if the mean stress is compressive, increased yield strength is of positive influence on the endurance limit. Eq. 6.10 presents the mean stress factor\(^6\) \( f_m \) as a function of the mean stress and residual stress based on Haibach (2006).

\[
f_m = \begin{cases} 
\frac{1}{1-M_f} & \text{when } \frac{\sigma_m + \sigma_{\text{res}}}{\sigma_{\text{ef,0}}} < -1 \\
\frac{1}{1+M_f} \cdot \frac{\sigma_m + \sigma_{\text{res}}}{\sigma_{\text{ef,0}}} & \text{when } -1 < \frac{\sigma_m + \sigma_{\text{res}}}{\sigma_{\text{ef,0}}} < 1 \\
\frac{1+M_f}{3} & \text{when } 1 < \frac{\sigma_m + \sigma_{\text{res}}}{\sigma_{\text{ef,0}}} < 3 \\
\frac{1}{(1+M_f)^2} & \text{when } 3 < \frac{\sigma_m + \sigma_{\text{res}}}{\sigma_{\text{ef,0}}} 
\end{cases}
\]  

(6.10)

with,

\( M_f = 0.00035 \cdot \sigma_y - 0.1 \)

where,

\( M_f \)  
Mean stress subfactor

\( \sigma_y \)  
Tensile strength

\( \sigma_m \)  
Mean stress

\( \sigma_{\text{res}} \)  
Residual stress

\( \sigma_{\text{ef,0}} \)  
Fatigue endurance strength at alternating load

\(^6\) In Eq. 6.10, \( f_m = 1 \) for \( \sigma_m = 0 \) and \( \sigma_{\text{res}} = 0 \); in the following sections and in Chapter 7, a different formulation is used: \( f_m = 1 \) for \( \sigma_m = 0.5 \cdot \sigma_y \) and \( \sigma_{\text{res}} = 0 \). Thus, \( f_m \) is calculated as follows:

\[
f_m = \begin{cases} 
\frac{f_{\text{Ni,\Delta,0.5}}}{} & \text{if } \frac{f_{\text{Ni,\Delta,0.5}}}{f_{\text{Ni,\Delta,0.5}}} = 0 \\
\frac{f_{\text{Ni,\Delta,0.5}}}{} & \text{if } \frac{f_{\text{Ni,\Delta,0.5}}}{f_{\text{Ni,\Delta,0.5}}} = 0 
\end{cases}
\]
Figure 6.2 illustrates the mean stress effect for $\sigma_y = 500$, with $\sigma_m = -200$, $\sigma_m = 200$ and $\sigma_m = \sigma_y$. Increased mean stress $\sigma_m$ reduces the fatigue endurance limit $\sigma_{ae}$.

Figure 6.2. Endurable stress cycles for three mean stress levels.

Figure 6.3 illustrates the mean stress effect for two yield strengths, $\sigma_y = 500$ MPa and $\sigma_y = 1000$ MPa, with $\sigma_{res} = -\sigma_y$, $\sigma_{res} = 0$ and $\sigma_{res} = \sigma_y$. The mean stress sensitivity of high strength steels is visible from the graphs. If the absolute maximum stress level exceeds the yield strength during the stress cycle, stresses are assumed to redistribute plastically. This explains that the mean stress influence is equal (horizontal line), after exceeding mean stress of yield strength (either positive or negative).

Figure 6.3. Mean stress factor $f_m$ for a. $\sigma_y = 500$ MPa and b. $\sigma_y = 1000$ MPa, with $\sigma_{res} = 0$ and $\sigma_{res} \pm \sigma_y$. 
6.2.2.3 Surface roughness factor

The surface roughness condition has a dominant influence on the endurance limit particularly of unnotched parts. The surface roughness factor $f_{sr;u;Ni}$ is given by Hück et al. (1981) as a function of surface roughness $R_z$ and the tensile strength $\sigma_u$ (See Eq. 6.11).

$$f_{sr;u;Ni} = 1 - 0.22 \cdot (\log R_z)^{0.64} \cdot \log \sigma_u + 0.45 \cdot (\log R_z)^{0.51} \quad (6.11)$$

Figure 6.4 presents the surface roughness factor for typical roughness values and material strength.

![Figure 6.4. Surface roughness factor $f_{sr;u;Ni}$ with typical surface roughness values.](image)

According to formulations of Gudehus & Zenner (1999), it was assumed that for the notch stress of base material cracks, given $K_t = 1$, the $K_f$ used in Eq. 6.5 could be replaced with $1/f_{sr;u;Ni}$. For the base materials tested in the current study, it was assumed that near the base material cracks $K_t = 1$ and $r = 1$.

As a result of surface treatment, residual stresses may be present at the surface. Figure 6.5 presents the surface roughness influence on the endurable stress range $\Delta\sigma_{E;u;Ni}$, for $\sigma_{res} = 0$ and $\sigma_{res} = \sigma_y$, for the case $K_t = 1$ and $r = 1$. 

<table>
<thead>
<tr>
<th>Condition</th>
<th>$R_z$ [(\mu m)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished</td>
<td>1-2</td>
</tr>
<tr>
<td>Ground</td>
<td>2-5</td>
</tr>
<tr>
<td>Smoothed</td>
<td>5-10</td>
</tr>
<tr>
<td>Roughed down</td>
<td>10-40</td>
</tr>
<tr>
<td>As rolled</td>
<td>40-160</td>
</tr>
<tr>
<td>Cast</td>
<td>160-300</td>
</tr>
</tbody>
</table>
6. Fatigue life prediction

6.2.2.4 Thickness factor

The fatigue notch factor for an unnotched plate is nearly independent of thickness. In case of \( K_t = 1 \), it is assumed that the thickness factor \( f_{t;u;Ni} = 1 \). For increased notch concentration, the thickness will be of influence the fatigue notch factor (See Section 6.2.3).

6.2.2.5 Loading mode factor

As for the thickness, the fatigue notch factor for an unnotched plate is nearly independent of the loading mode, tension or bending. In case of \( K_d = 1 \), it is assumed \( f_{d;u;Ni} = 1 \). For increased notch concentration, the thickness will be of influence the fatigue notch factor (See Section 6.2.3).

Figure 6.6 gives an example of the fatigue prediction of base materials based on Eq. 6.9. The influence of surface roughness on the crack initiation life is given for steel grades S235, S460, S690, S890 and S1100, given \( \sigma_{res} = 0 \), \( K_t = 1 \), \( r = 1 \) and loading mode = tension. For low surface roughness, there is a clear advantage of higher yield strength. For high surface roughness, the advantage of high yield strength is relatively smaller.

---

Figure 6.5. Surface roughness influence on \( \Delta\sigma_{u;Ni} \), given \( K_t = 1 \) and \( r = 1 \), for a. \( \sigma_{res} = 0 \) and b. \( \sigma_{res} = \sigma_y \).
Fatigue strength of welded connections made of very high strength cast and rolled steels

In Sections 6.4.1, 7.3.1 and 7.3.4, the predictions of the initiation life of base material cracks will be compared to the fatigue test data of section 4.3, tests on base material specimens made of rolled plates, and the test results of section 4.5 and 4.6, in case of crack initiation in base material parts of the welded specimens.

Figure 6.6. Influence of surface roughness on crack initiation life for various steel grades, given $\sigma_{res} = 0$, $K_t = 1$, $r = 1$ and loading mode = tension, given a. $R_z = 20 \mu m$ and b. $R_z = 160 \mu m$.

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>$\Delta\sigma_{min}$ [MPa]</th>
<th>Ni [Cycles]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S890</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S690</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S235</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In tension $\sigma_{res} = 0$

$a.$ 

$b.$ 

$K_t = 1$

$R_z = 20 \mu m$

$R_z = 160 \mu m$
6.2.3 Prediction of the initiation life of weld toe cracks

The approach for the calculation of various influence factors on the endurable stress range of weld toe cracks is similar to the approach for base material cracks as given in section 6.2.2. In addition, the effect of the weld shape is addressed by the notch radius factor $f_{nR;w;Ni}$ and the weld toe angle factor $f_{\theta;w;Ni}$. The influence of these factors on the endurable stress range of weld toe cracks in case of crack initiation $\Delta \sigma_{i;w;Ni}$ can generally be presented as given in Eq. 6.12.

$$\Delta \sigma_{i;w;Ni} = f_{c;w;Ni} \cdot \Delta \sigma_{i;w;Ni,0}$$  \hspace{1cm} (6.12)

For the various influence factors, the following indices were used for $f_{c;w;Ni}$:

- $f_m$: Mean stress factor, (See Section 6.2.3.1)
- $f_{nR;w;Ni}$: Notch radius factor, (See Section 6.2.3.2)
- $f_{\theta;w;Ni}$: Weld toe angle factor, (See Section 6.2.3.3)
- $f_{t;w;Ni}$: Thickness factor, (See Section 6.2.3.4)
- $f_{lm;w;Ni}$: Loading mode factor, (See Section 6.2.3.5)

6.2.3.1 Mean stress factor

As a result of thermal cycling during welding, the mechanical properties of the microstructure in the base material, heat affected zone and the fusion zone are changed. This influence is neglected in the calculation of the endurance limit of welded connections in the current study. The residual stresses of welded connections can reach values up to yield strength [Maddox, 1991]. The effect of mean stress and residual stress $f_m$ is calculated according to Eq. 6.10.

6.2.3.2 Notch radius factor

Anthes et al. (1994) present calculation rules for the notch stress concentration factor $K_n$ as a function of plate thickness, weld toe angle, notch radius and loading mode (See Figure 6.7 and Appendix I). Figure 6.8 presents the notch stress concentration factor for weld shape parameters $r$ and $\theta$, for $t = 25$ mm, in case of bending loading or tension loading according to these calculation rules.

$$\Delta \sigma_{i;w;Ni} = f_{c;w;Ni} \cdot \Delta \sigma_{i;w;Ni,0}$$

For the various influence factors, the following indices were used for $f_{c;w;Ni}$:

- $f_m$: Mean stress factor, (See Section 6.2.3.1)
- $f_{nR;w;Ni}$: Notch radius factor, (See Section 6.2.3.2)
- $f_{\theta;w;Ni}$: Weld toe angle factor, (See Section 6.2.3.3)
- $f_{t;w;Ni}$: Thickness factor, (See Section 6.2.3.4)
- $f_{lm;w;Ni}$: Loading mode factor, (See Section 6.2.3.5)

Figure 6.7. Definition of weld shape parameters notch radius $r$, weld toe angle $\theta$ and thickness $t$.
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 6.8. Notch stress concentration factor $K_t$ for weld toe radius $r$ and weld toe angle $\theta$, for thickness $t = 25$ mm, for a. bending loading and b. tension loading.

Figure 6.9 shows the stress concentration factor, and the fatigue notch factor, for two yield strengths, 500 and 1000 MPa; $\theta = 25^\circ$ and 60$^\circ$; $t = 25$ mm, tension loading. Clearly visible from the graphs is the notch radius resulting in $K_{f_{\text{max}}}$ that leads to the maximum value of the fatigue notch factor. For high values of the notch radius, the fatigue notch factor equals the notch stress concentration factor. In this study however, the average notch radius in welded connections is assumed to be $r = 1$ mm.

Figure 6.9, Notch stress concentration factor $K_t$ and fatigue notch factor $K_f$ as a function of weld toe radius $r$ for a. $\theta = 25^\circ$ and b. $\theta = 65^\circ$.
The notch radius factor is defined by the ratio of the endurable stress range $\Delta \sigma_{n,w,N_i}$ for the case $r \neq 1$ and $r = 1$ (See Eq. 6.13).

$$f_{n,w,N_i} = \frac{\Delta \sigma_{n,w,N_i} \neq 1}{\Delta \sigma_{n,w,N_i} r = 1}$$

(6.13)

Figure 6.10 presents the notch radius factor $f_{n,w,N_i}$ for $\theta = 25^\circ$ and $45^\circ$; $t = 25$ mm, tension loading, whereas Figure 6.11 shows measurements of notch radius and weld toe angle of V-welded specimens of Section 4.5, which confirm assumption of $r = 1$ mm in most cases.

![Figure 6.10. Notch radius factor $f_{n,w,N_i}$ for $t = 25$ mm, tension loading, a. $\theta = 25^\circ$ and b. $\theta = 45^\circ$.](image)

![Figure 6.11. Measurements of notch radius and weld toe angle of V-welded specimens.](image)
6.2.3.3 Weld toe angle factor

The weld toe angle factor \( f_{\theta,w;Ni} \) is defined by the ratio of the endurable stress range \( \Delta \sigma_{\text{end,w;Ni}} \) case \( \theta \neq 25 \) and \( \theta = 25 \), (See Eq. 6.14).

\[
f_{\theta,w;Ni} = \frac{\Delta \sigma_{\text{end,w;Ni}, \theta \neq 25}}{\Delta \sigma_{\text{end,w;Ni}, \theta = 25}}
\]  

(6.14)

The weld toe angle factor is presented in Figure 6.12, calculated for S460 and S1100, \( \sigma_{\text{res}} = 0 \) and the cases \( t = 25, 40 \) and 60 mm. Neither yield strength, nor loading mode is found to be of influence on the weld toe angle factor. However, the weld toe angle factor changes with varying thickness.

Figure 6.13 summarises the effectiveness of steel grade on the fatigue endurance limit of butt welded connections under tension stress. In the figure, the mean stress is chosen to be 50% of the yield stress. Variables in the figure are weld toe angle \( \theta = 25^\circ, 35^\circ \) or \( 65^\circ \), and residual stress levels \( \sigma_{\text{res}} = 0 \) or \( \sigma_{\text{res}} = \sigma_y \) under tension loading. The higher the weld toe angle, the less effective the higher yield strength will be with regard to the fatigue endurance limit, especially in case of high mean stress values.
6. Fatigue life prediction

6.2.3.4 Thickness factor

The thickness factor \( f_{t;w;Ni} \) is defined by the ratio of the endurable stress range \( \Delta\sigma_{t;w;Ni} \) for the cases \( t \neq 25 \) and \( t = 25 \), worked out for the representative cases \( \theta = 25^\circ \) and \( \theta = 65^\circ \) (See Eq. 6.15).

\[
f_{t;w;Ni} = \frac{\Delta\sigma_{t;w;Ni} \neq 25}{\Delta\sigma_{t;w;Ni} = 25} = \begin{cases} 
\left( \frac{25}{t} \right)^{0.4} & \text{for } \theta = 25^\circ \\
\left( \frac{25}{t} \right)^{0.7} & \text{for } \theta = 65^\circ 
\end{cases} \quad (6.15)
\]

Neither yield strength, nor loading mode were found be of influence on the thickness factor. The thickness factor is presented in Figure 6.14, calculated for S460 and S1100, \( \sigma_{res} = 0 \) and the cases \( \theta = 25^\circ, 45^\circ \) and \( 65^\circ \). In comparison to the thickness effect formula according to EN 1993-1-9 (2005), the influence of thickness is more pronounced.
Fatigue strength of welded connections made of very high strength cast and rolled steels

6.2.3.5 Loading mode factor

The fatigue notch factor of a welded plate depends on the loading mode, such as tension or bending. Presence of a notch increases the fatigue notch factor, which in its turn increases the influence of the loading mode. The loading mode factor $f_{lm;w;Ni}$ is defined by the ratio of the endurable stress range $\Delta\sigma_{n;w;Ni;lm}$ for the case loading mode $=\text{bending}$ and the case loading mode $=\text{tension}$ (See Eq. 6.16).

$$f_{lm;w;Ni} = \frac{\Delta\sigma_{n;w;Ni;lm=bending}}{\Delta\sigma_{n;w;Ni;lm=tension}} \quad (6.16)$$

Figure 6.15 compares the effect of loading mode of varying thickness and varying weld toe angle. The influence of yield strength on the effect of loading mode is relatively small. For $10 < t < 50 \text{ mm}$ and $15 < \theta < 65^\circ$, the loading mode factor varies from 1.17 to about 1.27.
Figure 6.15. Loading mode factor $f_{m,w,Ni}$ for various other influence factors.
Figure 6.16 summarizes the endurable stresses of welded structural members. The influence of weld toe angle on the crack initiation life is given for steel grades S235, S460, S690, S890 and S1100, given $\sigma_{\text{res}} = 0$ and loading mode = tension.

In Sections 6.4.2 and 7.3.2 and 7.3.3, these predictions will be compared to the experimental values obtained in Chapter 4.
6.3 Prediction of crack propagation life by the fracture mechanics approach

6.3.1 Paris law
Fatigue cracks initiate and grow from initial flaws such as inclusions or defects. With the fracture mechanics approach (See Section 3.2.4), a simulation of the crack growth can be made in order to predict the number of cycles \( N_p \) from an initial to a critical crack size. The key parameter for determination of crack growth is the stress intensity range, \( \Delta K \), which is a function of the applied stress range, crack size and local geometrical parameters. According to the Paris law, the crack growth rate can be described as a function of the stress intensity range and the material parameters Eq. 6.17 presents the Paris law, for the crack growth rate in plate depth direction \( \frac{da}{dN} \):

\[
\frac{da}{dN} = C_a \cdot \Delta K \cdot M_a
\] (6.17)

with,
- \( a \) Crack length in plate thickness direction
- \( N \) Number of cycles until crack growth
- \( \Delta K_a \) Stress intensity range in plate depth direction
- \( C_a \) Crack growth rate coefficient in plate depth direction
- \( M_a \) Crack growth rate exponent in plate depth direction

Eq. 6.18 presents the Paris law, for the crack growth rate in plate width direction \( \frac{dc}{dN} \):

\[
\frac{dc}{dN} = C_c \cdot \Delta K \cdot M_c
\] (6.18)

with,
- \( c \) Crack length in plate width direction
- \( N \) Number of cycles until crack growth
- \( \Delta K_c \) Stress intensity range in plate width direction
- \( C_c \) Crack growth rate coefficient in plate width direction
- \( M_c \) Crack growth rate exponent in plate width direction

Material parameters \( C \) and \( M \) define the relation of crack growth rate and stress intensity range. For various steel grades, S460, S690, S890 and S1100, the material parameters were experimentally determined within the current study (See Section 4.7.3). In the course of the current study it is assumed that the material response to crack growth is isotropic, which leads to uniform material parameters for crack growth in plate depth and in plate width direction, \( C_a = C_c \) and \( M_a = M_c \).

For 3-dimensional geometries, such as plates, crack growth has to be considered in the depth and width direction simultaneously [Dijkstra & Van Straalen, 1997], BS7910 (2005) gives calculation rules for the stress intensity range, based on correction factors for the local geometry and correction factors for the weld shape. Figure 6.17 presents the governing geometrical parameters, plate thickness \( t \) and plate width \( W \), weld toe angle \( \theta \) and weld
Fatigue strength of welded connections made of very high strength cast and rolled steels

width \( L \), and crack size parameters depth \( a \) and length \( c \), for quarter elliptical crack (referred to as edge crack) and \( 2c \) for semi-elliptical crack (referred to as middle crack).

![Diagram of weld connection and cracks](image)

Figure 6.17. Geometrical parameters of V-welded connection and cracks.

The correction factors are functions of the non-dimensional geometrical parameters such as relative crack depth \((a/t)\), crack aspect ratio \((a/c)\), relative weld width \((L/t)\) and relative crack length \((c/W)\). The stress intensity factors for crack growth in plate depth direction \( \Delta K_a \) and in plate width direction \( \Delta K_c \) are formulated as function of crack shape factors, weld shape factors, stress range and crack size, (See Eq. 6.19 and Eq. 6.20).

\[
\Delta K_a = (M_{km} \cdot M_{ma} \cdot \Delta \sigma_m + M_{kb} \cdot M_{ba} \cdot \Delta \sigma_b) \cdot \frac{\sqrt{\pi \cdot a}}{\phi}
\]  
(6.19)

\[
\Delta K_c = (M_{km} \cdot M_{mc} \cdot \Delta \sigma_m + M_{kb} \cdot M_{bc} \cdot \Delta \sigma_b) \cdot \frac{\sqrt{\pi \cdot c}}{\phi}
\]  
(6.20)

- \( M_{km} \) Weld shape factor for membrane stress component
- \( M_{mb} \) Weld shape factor for bending stress component
- \( M_{ma} \) Plate depth crack shape factor for membrane stress component
- \( M_{mb} \) Plate depth crack shape factor for bending stress component
- \( \Delta \sigma_m \) Membrane stress component
- \( \Delta \sigma_b \) Bending stress component
- \( a \) Crack length in plate thickness direction
- \( \phi \) Elliptical integral

Crack shape factors \( M_{ma} \), \( M_{mb} \), \( M_{mc} \) and \( M_{bc} \) depend on crack length and crack depth [Anderson, 2005]. Weld shape factors \( M_{km} \) and \( M_{kb} \) depend on weld shape and the ratio of crack width and depth versus plate thickness according to formula of Maddox et al. (1986).

MathCAD-routine FAFRAM [Dijkstra & Van Straalen, 1997] was used for a numerical integration of crack growth rates in depth and width direction, as a function of the stress intensity factor, based on Eq. 6.17 and Eq. 6.18. The model calculates the crack
growth in depth and width direction, and yields the number of cycles \( N_p \) for crack growth
from an initial crack size, with crack depth \( a_i \) and crack length \( c_i \), until \( a_f = 0.5t \) or
\( c_f = 0.5W \).

The following assumptions were made in the FAFRAM model. In the model, only one
initial crack was assumed to initiate and grow, crack coalescence was not incorporated in
the model even though in practice multiple cracks may initiate simultaneously. The Paris
law is a simplification of the crack growth. Effects of a threshold value, residual stress and
fracture toughness were not incorporated in the model. The weld shape was assumed to be
constant over the width of the specimens, whereas in practice, weld shapes are prone to
variation. The stress intensity factors of the weld shape influence are based on a 2D-model,
only for crack growth in depth. BS7910 (2005) says that the weld shape factors are directly
applicable to the case of straight-fronted weld toe cracks, but also for semi-elliptical cracks.
The influence of the weld shape on crack growth in depth direction is dependent on the
relative distance \( a/t \). For the crack growth in plate width direction a constant initial crack
size \( c_i \) was assumed, leading to a weld shape factor depending on a constant ratio of \( c_i/t \).
moreover, the weld shape factors were assumed to be applicable to quarter elliptical cracks.
Finally, it was assumed that the weld toe radius was sharp at an initial crack. The following
section describes the results of the fracture mechanics modelling.

6.3.2 Prediction of the propagation life of base material cracks
Figure 6.18 presents the predicted crack propagation life \( N_p \) as a function of the applied
stress range, for the reference situation of a semi-elliptical surface crack of a base material
plate, given \( t = 25 \text{ mm}, a_i = c_i = 0.15 \text{ mm}, W = 6t \) and tension loading, \( K_t = 1 \). The material
parameters for S460, S690, S890 and S1100 were based on experimental results presented
in Section 4.7 and for S235-S355 values were taken according to Dijkstra & Van Straalen
(1997).

\[ \Delta \sigma_{n,b} \text{ [MPa]} \]

![Graph showing predicted crack propagation life as a function of the applied stress range.](image)

Figure 6.18. Predicted crack propagation life as a function of the applied stress range.
Table 6.1 presents the investigated variables for the prediction of the propagation life of base material cracks.

Table 6.1. Variables for the prediction of the propagation life of base material cracks.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial crack depth  (a_i) [mm]</td>
<td>0.0375 - 4</td>
</tr>
<tr>
<td>Initial crack width  (c_i) [mm]</td>
<td>0.0375 - 4</td>
</tr>
<tr>
<td>Thickness  (t) [mm]</td>
<td>10 - 50</td>
</tr>
<tr>
<td>Width (weld length) (t/W) [mm]</td>
<td>0.0625 – 0.5</td>
</tr>
<tr>
<td>Loading mode</td>
<td>Tension or bending</td>
</tr>
<tr>
<td>Crack location</td>
<td>Edge crack or middle crack</td>
</tr>
<tr>
<td>Failure criterion</td>
<td>(a_f = 0.5 \cdot t) or (c_f = 0.5 \cdot W)</td>
</tr>
<tr>
<td>Crack growth exponent  (M)</td>
<td>3</td>
</tr>
<tr>
<td>Crack growth coefficient  (C)</td>
<td>(\sim -N/mm^2) 1.823 (\cdot 10^{-13})</td>
</tr>
</tbody>
</table>

With the FAFRAM model, the following influence factors on the propagation life of base material cracks were studied: initial crack size, plate width, plate thickness, loading mode and crack initiation location. For the determination of the influence factors, it was assumed \(M = 3\) and \(C = 1.823 \cdot 10^{-13}\). The influence factors on the endurable stress ranges of base material cracks in case of crack propagation \(\Delta \sigma_{n;u;Np}\) can generally be presented as given in Eq. 6.21.

\[
\Delta \sigma_{n;u;Np} = f_{\text{ini;u;Np}} \cdot \Delta \sigma_{n;u;Np;0}
\]

\(\Delta \sigma_{n;u;Np;0}\) Reference endurable stress range for base material cracks, \(K_t = 1\),
\(a_i = c_i = 0.15 \text{ mm}, t = 25 \text{ mm}, \text{ loading mode} = \text{ tension},\)
\(\text{crack location} = \text{ semi-elliptical crack}, W = 6t\)

\(f_{\text{ini;u;Np}}\) Influence factor

For the various influence factors, the following indices were used for \(f_{\text{ini;u;Np}}\):

- \(f_{\text{ini;u;Np}}\) Initial crack size factor, (See Section 6.3.2.1)
- \(f_{\text{ini;u;Np}}\) Width factor, (See Section 6.3.2.2)
- \(f_{\text{ini;u;Np}}\) Thickness factor, (See Section 6.3.2.3)
- \(f_{\text{ini;u;Np}}\) Loading mode factor, (See Section 6.3.2.4)
- \(f_{\text{ini;u;Np}}\) Crack location factor, (See Section 6.3.2.5)

Appendix J lists the calculated crack growth curves for \(a_i = c_i = 0.15 \text{ mm}, t = 10 \text{ or } 25 \text{ mm}, \text{ loading mode} = \text{ tension or bending}, \text{ crack location} = \text{ semi-elliptical crack}, W = 6t\). At the failure criterion, the aspect ratio \(a/c\) was compared for various configurations. The reference configuration lead to \(a/c = 0.73\) (tension) and 0.25 (bending) for middle cracks and 0.82 (tension) and 0.2 (bending) for edge cracks. This means relatively faster crack growth in plate width direction for bending and relatively faster crack growth in thickness direction for tension, in comparison to bending. This pattern could reasonably be confirmed by the crack growth measurements, (See Appendix G). Although, it should be mentioned that multiple cracks could initiate in the specimens, whereas only one crack was modelled.
The following sections give a qualitative study on the influence factors $f_{a_{i}Np}$, $f_{W[:,:Np]}$, $f_{a_{i}Np}$, $f_{m_{i}Np}$, and $f_{a_{i}c_{i}Np}$.

### 6.3.2.1 Initial crack size factor

The initial crack size factor $f_{a_{i}c_{i}Np}$ depends on the ratio of the number of cycles of crack propagation $Np$ for the cases $a_i \neq 0.15$ and $a_i = 0.15$, given $M = 3$, (See Eq. 6.22).

$$f_{a_{i}c_{i}Np} = \frac{\Delta \sigma_{a_{i}c_{i}Np}}{\Delta \sigma_{a_{i}=0.15c_{i}Np}} = \left( \frac{N_{a_{i}=0.15c_{i}Np}}{N_{a_{i}=0.15c_{i}Np}} \right)^{\frac{1}{M}}$$

(6.22)

Figure 6.19 shows the effect of defect size alteration for $t = 25$ mm, $W = 150$ mm and failure criterion crack depth $a$ equals plate thickness or crack length $2c$ equals plate width $W$.

![Figure 6.19. Initial crack size factor $f_{a_{i}c_{i}Np}$](image-url)
6.3.2.2 Width factor
The plate width size factor $f_{W,u;Np}$ depends on the ratio of the number of cycles of crack propagation $N_p$ for the cases $t/W \neq 1/6$ and $t/W = 1/6$, given $M = 3$, (See Eq. 6.23).

$$f_{W,u;Np} = \frac{\Delta \sigma_{n;u;Np}}{\Delta \sigma_{n;u;Np0}} = \left( \frac{N_{t/W=1/6;u;Np}}{N_{t/W=1/6;u;Np0}} \right)^{\frac{1}{M}}$$ (6.23)

Figure 6.20 shows the effect of plate width size ratios. In fatigue testing conditions, the width of specimens is finite, structural width in most cases may be regarded as infinite. Depending on the width $W$ (See Figure 6.17), the failure mode may either be $2c = W$ or $a = 0.5t$.

Figure 6.20. Width factor $f_{W,u;Np}$.
6.3.2.3 Thickness factor
The plate thickness factor $f_{tu,Np}$ depends on the ratio of the number of cycles of crack propagation $N_p$ for the cases $t \neq 25$ and $t = 25$, given $M = 3$, (See Eq. 6.24).

$$f_{tu,Np} = \frac{\Delta \sigma_{tu,Np}}{\Delta \sigma_{tu,Np,0}} = \left( \frac{N_{t=25,tu,Np}}{N_{t=25,tu,Np,0}} \right)^{\frac{1}{M}}$$

(6.24)

Figure 6.21 shows the effect of plate thickness size alteration for $t = 25$ mm. For unnotched plates, the stress concentration on the surface is practically independent of the thickness.

---

6.3.2.4 Loading mode factor
The loading mode factor $f_{lm,Np}$ depends on the ratio of the number of cycles of crack propagation $N_p$ for the cases loading mode = bending and loading mode = tension, given $M = 3$, (See Eq. 6.25).

$$f_{lm,Np} = \frac{\Delta \sigma_{lm,Np}}{\Delta \sigma_{lm,Np,0}} = \left( \frac{N_{lm-bending,Np}}{N_{lm-tension,Np}} \right)^{\frac{1}{M}}$$

(6.25)

Figure 6.22 shows the effect of bending loading or tension loading for variation of thickness $t$, initial crack size $a_i$, and plate width ratio $t/W$. The loading factor may vary between 1.05 until 1.15 for $10 < t < 50$ mm; between 1.05 and 1.4 for $0.15 < a_i < 4$ mm; and between 1.05 and 1.09 for $0.1 < t/W < 0.5$. 
Cracks were found to initiate from the edge and/or the middle of the plate. The crack location factor $f_{cl;u;Np}$ depends on the ratio of the number of cycles of crack propagation $N_p$ for cases crack location = edge crack and crack location = middle crack, given $M = 3$, (See Figure 6.17 and Eq. 6.26).

$$f_{cla;Np} = \Delta \sigma_{cla;Np} = \frac{N_{cl=\text{edge crack};Np}}{N_{cl=\text{middle crack};Np}}$$

(6.26)

Anderson (2005) presents stress intensity factors for cracks in plates, with separate formulations for quarter elliptical cracks initiating at the edge of the plate (edge cracks) and semi-elliptical cracks, initiating at a position far from the edge (middle cracks), (See Figure 6.17). Figure 6.23 presents the factor $f_{cl;u;Np}$ for variation in thickness $t$, initial crack size $a_i$, plate width ratio $t/W$ and loading mode tension or bending. For all variations, quarter elliptical cracks seam to have shorter crack propagation life than semi-elliptical cracks. Depending on the plate width, the failure criterion might change from through thickness crack size to crack length over the full width of the plate. For large initial cracks, the effect of loading mode on crack location factor increases. For large $t/W$ ratios the effect of loading mode on crack location factor decreases.
6. Fatigue life prediction

6.3.3 Prediction of the propagation life of weld toe cracks

Figure 6.24 presents the predicted propagation life of weld toe cracks as a function of the applied stress range, for the reference situation with semi-elliptical weld toe crack, given \( t = 25 \) mm, \( a_i = c_i = 0.15 \) mm, \( W = 6t \), \( L = 40 \), \( \theta = 25^\circ \) and tension loading. The material parameters for S460, S690, S890 and S1100 were based on experimental results presented in Section 4.7 and for S235-S355 values were taken according to Dijkstra & Van Straalen (1997).

Figure 6.24. Predicted crack propagation life as a function of the applied stress range.

Table 6.2 presents the variables for the prediction of crack propagation life of welded structural members.
Table 6.2. Variables for the prediction of crack propagation life of welded structural members.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial crack depth</td>
<td>$a_i$ [mm]</td>
</tr>
<tr>
<td>Initial crack width</td>
<td>$c_i$ [mm]</td>
</tr>
<tr>
<td>Weld width</td>
<td>$L/t$ [-]</td>
</tr>
<tr>
<td>Weld toe angle</td>
<td>$\theta$ ['']</td>
</tr>
<tr>
<td>Thickness</td>
<td>$t$ [mm]</td>
</tr>
<tr>
<td>Plate width</td>
<td>$W$ [mm]</td>
</tr>
<tr>
<td>Loading mode</td>
<td>Tension or bending</td>
</tr>
<tr>
<td>Crack location</td>
<td>Edge crack or middle crack</td>
</tr>
<tr>
<td>Failure criterion</td>
<td>$a_i = 0.5 \cdot t$ or $2c_i = 0.5 \cdot W$</td>
</tr>
<tr>
<td>Crack growth exponent</td>
<td>$M$ [-]</td>
</tr>
<tr>
<td>Crack growth coefficient</td>
<td>$C$ [N/mm$^{\frac{3}{2}}$]</td>
</tr>
</tbody>
</table>

The following influence factors on the crack propagation life of welded plates were studied with the FAFRAM model: initial crack size, weld width, weld toe angle, plate width, plate thickness, loading mode and crack initiation location. The influence of these factors on the endurable stress ranges of weld toe cracks in case of crack propagation $\Delta \sigma_{n;w;Np}$ can generally be presented as given in Eq. 6.27.

$$\Delta \sigma_{n;w;Np} = f_{k;w;Np} \cdot \Delta \sigma_{n;w;Np;0}$$

$\Delta \sigma_{n;w;Np;0}$: Stress range for crack propagation life of welded structural member,

- $a_i = c_i = 0.15$ mm, $t = 25$ mm, loading mode = tension,
- crack location = semi-elliptical crack, $W = 6 \cdot t$, $L/t = 1.6$, $\theta = 25^\circ$

For the various influence factors, the following indices were used for $f_{k;w;Np}$:

- $f_{k;w;Np}$: Initial crack size factor, (See Section 6.3.3.1)
- $f_{L/t;w;Np}$: Weld width factor, (See Section 6.3.3.2)
- $f_{\theta;w;Np}$: Weld toe angle factor, (See Section 6.3.3.3)
- $f_{W;w;Np}$: Width factor, (See Section 6.3.3.4)
- $f_{t;w;Np}$: Thickness factor, (See Section 6.3.3.5)
- $f_{m;w;Np}$: Loading mode factor, (See Section 6.3.3.6)
- $f_{x;w;Np}$: Crack location factor, (See Section 6.3.3.7)

Appendix J lists the calculated crack growth curves for $a_i = c_i = 0.15$ mm, $t = 10$ or 25 mm, loading mode = bending or tension, crack location = semi-elliptical crack, $W = 6 \cdot t$, $L/t = 1.6$, $\theta = 25^\circ$. At the failure criterion, the aspect ratio $a/c$ was compared for various configurations. The reference configuration lead to $a/c = 0.3$ (tension) and 0.2 (bending) for middle cracks and 0.18 (tension) and 0.15 (bending) for edge cracks. This means relatively faster crack growth in plate width direction for bending and relatively faster crack growth in thickness direction for tension, compared to bending. This pattern could reasonably be confirmed by the crack growth measurements, (See Appendix G). Although, it should be mentioned that multiple cracks could initiate in the specimens, whereas only one crack was modelled.
6. Fatigue life prediction

The following sections give a qualitative study on the influence factors $f_{\text{ai}\text{w}Np}$, $f_{L/t\text{w}Np}$, $f_{\theta\text{w}Np}$, $f_{t\text{w}Np}$, $f_{W\text{w}Np}$, $f_{\text{incl}\text{w}Np}$ and $f_{\text{cl}\text{w}Np}$.

6.3.3.1 Initial crack size factor

The initial crack size factor $f_{\text{ai}\text{w}Np}$ depends on the ratio of the number of cycles of crack propagation $Np$ for the cases $a_i \neq 0.15$ and $a_i = 0.15$, given $M = 3$, (See Eq. 6.28).

$$f_{\text{ai}\text{w}Np} = \frac{\Delta \sigma_{n\text{w}Np}}{\Delta \sigma_{a_i=0.15\text{w}Np0}} = \left( \frac{N_{a_i=0.15\text{w}Np}}{N_{a_i=0.15\text{w}Np0}} \right)^{\frac{1}{M}}$$  (6.28)

Figure 6.25 shows the effect of defect size alteration for $t = 25$, $W = 150$, $L/t = 1/6$ for $\theta = 25$ and $\theta = 65$. As microcracks are expected to be present in the weld toe, BS7910 (2005) recommends, setting the initial crack size to 0.15 mm in calculations. The numbers of cycles to failure was calculated for varying initial crack sizes $a_i = c_i$. A small difference between membrane and bending loading was found.

6.3.3.2 Weld width factor

The weld width size factor $f_{L/t\text{w}Np}$ depends on the ratio of the number of cycles of crack propagation $Np$ for the cases $L/t \neq 1$ and $L/t = 1$, given $M = 3$, (See Eq. 6.29).

$$f_{L/t\text{w}Np} = \frac{\Delta \sigma_{L/t\text{w}Np}}{\Delta \sigma_{L/t=1\text{w}Np0}} = \left( \frac{N_{L/t=1\text{w}Np}}{N_{L/t=1\text{w}Np0}} \right)^{\frac{1}{M}}$$  (6.29)

Figure 6.26 shows the effect of plate width size ratios.
Weld width $L$ depends on the thickness ($V$-shape). The bevel angle of the $V$-shaped weld was $60^\circ$; the initial gap, before tack welding, was about 3 mm, resulting in an average weld width $L = 40$ mm at the cap side of a specimen thickness of 25 mm. On the root side of the weld, the width of the weld is much smaller in case of a single side welded specimen, about $1/5$th of the width at the cap side. The weld width $W$ was found to have an effect on the fatigue strength of tensile loaded specimens. There was a difference found in tension loading or bending loading, caused by a change of failure criterion either through thickness crack or crack over plate width. For bending, the $L/t$ ratio > 1 did not effect the crack growth in width direction, which was still the limiting failure criterion in this case.

### 6.3.3.3 Weld toe angle factor

The weld toe angle factor $f_{\theta,w,N_p}$ depends on the ratio of the number of cycles of crack propagation $N_p$ for the cases $\theta \neq 25^\circ$ and $\theta = 25^\circ$, given $M = 3$, (See Eq. 6.30).

$$f_{\theta,w,N_p} = \frac{\Delta \sigma_{w,N,p}}{\Delta \sigma_{w,N,p0}} = \left( \frac{N_{\theta=25,w,N_p}}{N_{\theta=25,w,N_p0}} \right)^{\frac{1}{M}} \quad (6.30)$$

Figure 6.27 shows the effect of plate width size ratios. A large weld toe angle negatively influences the fatigue strength (See Figure 6.29).
6. Fatigue life prediction

6.3.3.4 Width factor

The plate width size factor $f_{W;w;Np}$ depends on the ratio of the number of cycles of crack propagation $N_p$ for the cases $t/W \neq 1/6$ and $t/W = 1/6$, given $M = 3$, (See Eq. 6.31).

$$f_{W;w;Np} = \frac{\Delta \sigma_{W;w;Np}}{\Delta \sigma_{w;Np;0}} = \left( \frac{N_{W=W_{1/6};w;Np}}{N_{W=1/6;w;Np}} \right)^{1/M}$$ (6.31)

Reference plate width ratio $t/W$ was taken $1/6$. Figure 6.28 shows the effect of plate width size ratios.

Figure 6.27. Weld toe angle factor $f_{\theta;w;Np}$ for a. $t = 25$ mm and b. $t = 60$ mm.

Figure 6.28. Plate width factor $f_{W;w;Np}$. 

---

For $t = 25$ mm and $t = 60$ mm:

- **Tension**
- **Bending**

$t/W = 1/6$:
- $L/t = 1.6$
- $a_i = c_i = 0.15$ mm
- $N_f, 2c = W$
- semi-elliptical crack

$t = 25$ mm

$t = 60$ mm
6.3.3.5 Thickness factor

The plate thickness factor $f_{t;w;Np}$ depends on the ratio of the number of cycles of crack propagation $Np$ for the cases $t \neq 25$ and $t = 25$, given $M = 3$, (See Eq. 6.32).

$$f_{t;w;Np} = \frac{\Delta\sigma_{t;w;Np}}{\Delta\sigma_{t;w;Np0}} = \left( \frac{N_{t=25;w;Np}}{N_{t=25;w;Np0}} \right)^{\frac{1}{M}}$$

(6.32)

Figure 6.29 shows the effect of plate thickness size alteration for $t = 25$ mm.

Increased thickness negatively influences the fatigue strength, as a larger thickness relatively increases the chance of defects and crack initiation locations. The influence of stress concentration increases with decreasing stress gradient.

Larger thickness lowers the fatigue strength. In Eurocode 3, a reduction factor is included for reduced fatigue strength of structural members with $t > 25$ mm. With $\theta = 35^\circ$, the calculated factor $f_{t;w;Np} = (25/t)^{0.2}$ perfectly resembles the Eurocode 3 formula (See Figure 6.30). The loading mode is of negligible influence on the thickness factor. The measured weld toe angle $\theta$ in the welded specimens varied from $20^\circ$ to $40^\circ$ in the weld toe of the cap; in the weld toe of the root, higher values were found, even up to $80^\circ$. 
6. Fatigue life prediction

6.3.3.6 Loading mode factor

The loading mode factor $f_{lm;w;Np}$ depends on the ratio of the number of cycles of crack propagation $N_p$ for cases loading mode = bending and loading mode = tension, given $M = 3$, (See Eq. 6.33).

$$f_{lm;w;Np} = \frac{\Delta \sigma_{lm;w;Np}}{\Delta \sigma_{lm;w;Np,0}} = \left( \frac{N_{lm;w;Np}^{bending}}{N_{lm;w;Np}^{tension}} \right)^{\frac{1}{M}} \quad (6.33)$$

Figure 6.30 shows the effect of bending loading or tension loading for variation in thickness $t$, initial crack size $a_i$, plate width ratio $t/W$, weld toe angle $\theta$ and weld width ratio $L/t$. The loading mode factor varied between 1.1 and 1.6. For most cases the loading mode factor was found to be around 1.4.

![Figure 6.30](image_url)

Figure 6.30. Loading mode factor $f_{lm;w;Np}$ for variation in a. thickness, b. initial crack size, c. plate width ratio, d. weld toe angle and e. weld width ratio.
6.3.3.7 Crack location factor

The crack location factor \( f_{\text{cl,w,Np}} \) depends on the ratio of the number of cycles of crack propagation \( N_p \) for cases crack location = edge crack and crack location = middle crack, given \( M = 3 \). (See Eq. 6.34).

\[
f_{\text{cl,w,Np}} = \frac{\Delta \sigma_{\text{cl,w,Np}}}{\Delta \sigma_{\text{cl,m,Np}}} = \left( \frac{N_{p-\text{edge,w,Np}}}{N_{p-\text{middle,w,Np}}} \right)^{\frac{1}{3}}
\]  

(6.34)

Figure 6.31 shows the effect of edge crack or middle crack for variation in thickness \( t \), initial crack size \( a_i \), plate width ratio \( t/W \), weld toe angle \( \theta \) and weld width ratio \( L/t \) and loading mode. The crack location factor was about 0.95 for all variations, except from larger initial crack sizes.

Figure 6.31. Crack location factor \( f_{\text{cl,w,Np}} \) for variation in a. thickness, b. initial crack size, c. plate width ratio, d. weld toe angle and e. weld width ratio.
Figure 6.32 gives an impression of the crack growth of edge cracks and middle cracks, visible in the fracture surfaces of failed fatigue specimens.

Figure 6.32. Fracture surfaces of fatigue failed fatigue specimens, a. edge crack, b. middle crack.

6.4 Comparison of predictions and measurements

The predictions for crack initiation and crack propagation of base material cracks and weld toe cracks given in Chapter 6 were compared with the experimental results of Chapter 4. In the experiments, specimens were used with various thicknesses. Moreover, loading modes tension and bending were applied. Finally, the residual stress level as a result of welding, which was not measured in the experiments, was assumed to be of influence on the results.

In order to study the specific influence of the yield strength on the fatigue strength, adjustment factors were applied to the measured nominal stress ranges to obtain reference stress ranges \( \Delta \sigma_{n;u;Ni} \), \( \Delta \sigma_{n;w;Ni} \), \( \Delta \sigma_{n;u;Np} \) and \( \Delta \sigma_{n;w;Np} \) for thickness \( t = 25 \), loading mode = tension, residual stress \( \sigma_{res} = \sigma_y \) and \( \sigma_m = 0.5 \sigma_y \) with \( K_t = 1 \) for the base material cracks and additionally \( r = 1 \) and \( \theta = 25 \) for the weld toe cracks (\( K_t \neq 1 \)). The factors were applied on the measured nominal stress range \( \Delta \sigma_n \) by use of Eq. 6.35; for the crack initiation life of base material cracks; by use of Eq. 6.36 for the crack initiation life of weld toe cracks; by use of Eq. 6.37; for the crack propagation life of base material cracks; by use of Eq. 6.38 for the crack propagation life of weld toe cracks.

\[
\Delta \sigma_{n;u;Ni} = f_m \cdot f_{u;Ni} \cdot f_{\text{init;Ni}} \cdot \Delta \sigma_n \quad (6.35)
\]

\( f_m \): Mean stress factor, (See Section 6.2.2.2)

\( f_{u;Ni} \): Thickness factor for initiation life of base material cracks, (See Section 6.2.2.4)

\( f_{\text{init;Ni}} \): Loading mode factor for initiation life of base material cracks,
(See Section 6.2.2.5)

\[
\Delta \sigma_{n;w;Ni} = f_m \cdot f_{w;Ni} \cdot f_{\text{init;Ni}} \cdot \Delta \sigma_n \quad (6.36)
\]

\( f_m \): Mean stress factor, (See Section 6.2.2.2)

\( f_{w;Ni} \): Thickness factor for initiation life of weld toe cracks, (See Section 6.2.3.4)

\( f_{\text{init;Ni}} \): Loading mode factor for initiation life of weld toe cracks, (See Section 6.2.3.5)
Fatigue strength of welded connections made of very high strength cast and rolled steels

\[
\Delta\sigma_{\text{m}} = f_m \cdot f_{W,NP} \cdot f_{\text{lm},Np} \cdot \Delta\sigma_u
\]  
(6.37)

- \( f_m \): Mean stress factor, (See Section 6.2.2.2)
- \( f_{W,NP} \): Thickness factor for propagation life of base material cracks, (See Section 6.3.2.3)
- \( f_{\text{lm},Np} \): Loading mode factor for propagation life of base material cracks, (See Section 6.3.2.4)

\[
\Delta\sigma_{\text{m}} = f_m \cdot f_{W,NP} \cdot f_{\text{lm},Np} \cdot \Delta\sigma_u
\]  
(6.38)

- \( f_m \): Mean stress factor, (See Section 6.2.2.2)
- \( f_{W,NP} \): Thickness factor for propagation life of weld toe cracks, (See Section 6.3.3.5)
- \( f_{\text{lm},Np} \): Loading mode factor for propagation life of weld toe cracks, (See Section 6.3.3.6)

Section 4.2.5 showed that the tensile loaded specimens endured a combination of tension and bending loading as a result of misalignment. Therefore, the factors for the welded tensile loaded specimens with secondary bending moments was defined as \( f_{\text{lm},K,Nx,ax} \) according to Eq. 6.39.

\[
f_{\text{lm},K,Nx,ax} = \frac{K_m}{1 + \left( \frac{(K_m - 1)}{f_{\text{lm},K,Ns}} \right)}
\]  
(6.39)

- \( K_m \): Misalignment factor (See Section 4.2.5) [Hobbacher, 2004]
- \( f_{\text{lm},K,Ns} \): Loading mode factor for initiation or propagation of base material or weld toe cracks

The relevant factors for the various specimens are listed in Appendix F. In the experiments, crack initiation life \( N_i \) was determined by the number of cycles at which strain gauge ranges close to the crack started bending off the regular scheme. If the strain gauges were close to the initiating crack, this was a reasonable assumption. For measured deviations at a larger distance from the crack, crack propagation phase had already started in most cases.

The number of cycles of crack propagation \( N_p \) were calculated from the total fatigue life \( N_f \) with subtraction of the number of cycles of crack initiation \( N_i \). Appendix F lists the experimental results, with \( N_i, N_p \) and \( N_f \); also, the measured and adjusted stress ranges are given. In the fracture mechanics model, initial crack sizes were taken \( a_i = c_i = 0.15 \) mm, which was assumed to be the transition from crack initiation life to crack propagation life.

Section 6.4.1 compares the predictions and adjusted results of base material cracks. Section 6.4.2 compares the predictions and adjusted results of weld toe cracks.
6. Fatigue life prediction

6.4.1 Base material cracks

6.4.1.1 Base material in rolled steel parts of plate specimens

Figures 6.33 (S690) and 6.34 (S1100) show the predicted and measured initiation and propagation life of base material cracks in strips made of rolled steel (See Section 4.3). The experimental results of crack initiation were compared to predictions for the cases $R_z = 20$, 40 and 160 $\mu$m, given $K_t = 1$, $r = 1$. The predictions of $Ni$ were rather accurate for S690, but overestimated the strength of S1100. The predictions of $Np$ were conservative for both S690 and S1100.

![Figure 6.33. Comparison of a. $Ni$ and b. $Np$ of base material specimens made of S690.](image)

![Figure 6.34. Comparison of a. $Ni$ and b. $Np$ of base material specimens made of S1100.](image)

In some of the welded specimens described in Section 4.5 and Section 4.6, base material cracks initiated in the rolled steel at a distance from the welds. It was difficult to trace the...
number of cycles of crack initiation; the strain gauges that were used for monitoring crack initiation were located at a relatively large distance from the crack initiation locations and therefore, cracks were discovered relatively late. Moreover, in some cases, inspection of the fracture surfaces indicated porosities near the surface from which the cracks were initiated. This reduced the crack initiation life to a large extent. Predictions of the crack propagation life were conservative. However, the predictions overestimated the crack initiation life for steel grades S460, S890 and S1100, as can be seen in Figures 6.35 to 6.57. No cracks initiated in the base material of the S690 specimens.

Figure 6.35. Comparison of a. Ni and b. Np in rolled steel parts made of S460.

Figure 6.36. Comparison of a. Ni and b. Np in rolled steel parts made of S890.
6. Fatigue life prediction

6.4.1.2 Base material in cast steel parts of plate specimens

Base material cracks initiated in the cast steel parts of the specimens described in Section 4.6. Porosities were found in the fracture surface, which probably caused early crack propagation. The predictions of crack initiation and crack propagation were reasonable for G20Mn5, (See Figure 6.38).

Figure 6.37. Comparison of a. Ni and b. Np in rolled steel parts made of S1100.

Figure 6.38. Comparison of a. Ni and b. Np in cast steel parts made of G20Mn5.
The predictions of crack initiation life were non-conservative for these base material cracks of G18NiMoCr3.6 and G22NiMoCr5.6, even at assumption of $R_z = 160 \mu$m (See Figures 6.39 and 6.40).

The crack propagation life of G22NiMoCr5.6 was rather accurate except from one crack initiation in the cap side.


Figure 6.40. Comparison of a. Ni and b. Np in cast steel parts made of G22NiMoCr5.6.
6.4.2 Weld toe cracks

6.4.2.1 X-welded plate specimens

The fatigue life predictions and fatigue test results of the X-welded specimens described in Section 4.4 are given in Figures 6.41 (S355), 6.42 (S690) and 6.43 (S1100). All predictions for crack initiation and crack propagation life of S355 were found to be conservative, even for an assumption of average weld toe angle \( \theta = 25^\circ \), See Figure 6.41. For the S690 specimens, the predictions for crack initiation and crack propagation were conservative for the assumption \( \theta = 45^\circ \), See Figure 6.42.

Figure 6.41. Comparison of a. Ni and b. Np in X-welded specimens made of S355.

Figure 6.42. Comparison of a. Ni and b. Np in X-welded specimens made of S690.
Also for the S1100 specimens, the predictions for both crack initiation and crack propagation were quite accurate, (See Figure 6.43).

6.4.2.2 V-welded plate specimens

Figures 6.44 to 6.47 present the crack initiation and crack propagation life predictions and fatigue strength results of the V-welded specimens made of S460, S690, S890 and S1100 as presented in Section 4.5 and Section 4.6. For both weld root cracks and weld toe cracks, the predictions were conservative.

Figure 6.44. Comparison of Ni and Np in V-welded specimens made of S460 and G20Mn5.
6. Fatigue life prediction

- Figure 6.45, Comparison of a. Ni and b. Np in V-welded specimens made of S690 and G10MnMoV6-3.

- Figure 6.46, Comparison of a. Ni and b. Np in V-welded specimens made of S890 and G18NiMoCr3.6.
6.5 Summary of findings

This chapter presented predictions for crack initiation life $\text{Ni}$ and crack propagation life $\text{Np}$ of base material cracks and weld toe cracks. For these predictions, the notch stress theory was used for the crack initiation life and the linear elastic fracture mechanics theory for the crack propagation life.

Crack initiation life was found to increase with yield strength in case of low notch stress concentration. However, structural members cannot be made without notches, due to the presence of holes, initial flaws or welds. Fatigue strength effective notch factor is the key factor for the determination of the influence of yield strength on the fatigue strength, based on the theory of microstructural support, originally conceived by Peterson (1974).

For unnotched plates, the following variables were found to be governing the crack initiation life: yield strength, mean stress and surface roughness. The plate thickness and loading mode, such as tension or bending, will be of influence in notched plates, for instance in case of welded connections. The weld shape is typically characterised by the weld toe angle and the weld toe radius. A small weld toe radius and a large weld toe angle increase the notch stress concentration. High notch concentration factors are shown to be less effective on mild steels, than on high strength steels. Particularly, an increased weld toe radius improves the fatigue strength for higher yield strengths. Also, a compressive mean stress, or residual stress state might be beneficial for high strength steels, as the mean stress sensitivity increases with yield strength.

Crack propagation life depends on the crack growth rate as a function of the stress intensity range. In general, higher yield strength is not found to improve the crack growth behaviour. Therefore, if large initial defects can be expected, the fatigue life will only be characterised by crack propagation life, not by crack initiation life. This will dramatically reduce the benefits of high strength steels, as the main gain is expected for the crack

![Diagram a.](image)

![Diagram b.](image)
initiation life of areas with low notch concentration. The initial defect size, thickness, width and weld and crack shape were found to be of influence on the crack propagation life.

The fatigue life predictions were compared to measurements of crack initiation and crack propagation of fatigue tests described in Chapter 4. Next to yield strength, the parameters thickness, loading mode and residual stress were variables of the experiments. In order to study the influence of the yield strength on the fatigue strength, adjustment factors were used to obtain results for the reference situation with thickness $t = 25$ mm, loading mode = tension and residual stress $\sigma_{\text{res}} = \sigma_y$.

In comparison to the fatigue test results, the initiation life and propagation life of weld toe cracks was predicted accurately. Predictions overestimated the initiation life base material cracks. It is expected that at these locations relatively large initial flaws were present in the base material, so that the total fatigue life only consisted of crack propagation life.
7. Analysis of fatigue test results

7.1 Introduction
Chapter 7 presents a statistical analysis of the fatigue test results presented in Part II of this thesis. Chapter 4 gave background on the fatigue tests of base material specimens made of rolled steel (S690, S1100), X-welded specimens made of rolled steel (S355, S690 and S1100) and V-welded specimens made of rolled and cast steels (S460, S690, S890 and S1100, with corresponding cast steels). Chapter 5 presented fatigue tests on truss specimens made of circular hollow sections welded to cast joints (S690, S890 and corresponding cast steels). In Chapter 6, prediction models were given for initiation and propagation of base material cracks and weld toe cracks; several influence factors were determined.

The main objective of the analysis was to study the influence of yield strength on the fatigue strength. Therefore, the fatigue data were adjusted for other test variables that were of influence on the fatigue strength: thickness, loading mode and residual stress. In addition, data combinations were made in order to have a representative number of specimens for the statistical evaluation.

The mean lines of the regression analysis were compared to the predictions of fatigue life made in Chapter 6. The lower bound of the scatter was compared to design lines according to EN 1993-1-9 (2005). Also, the fatigue strength results of the plate specimens of Chapter 4 were compared to the results of the truss specimens of Chapter 5.

First, section 7.2 presents the analysis method. Section 7.3 analyses the results of the plate specimens. Section 7.4 compares the results of the plate specimens to the results of the truss specimens. Section 7.5 focuses on the influence of yield strength.

7.2 Analysis method
As the test specimens had variable thickness of 10 - 25 mm, were loaded in bending and tension, and had influence of residual stress as a result of welding, adjustment factors were applied to compare for the reference situation with thickness \( t = 25 \text{ mm} \), loading mode = tension and residual stress \( \sigma_{\text{res}} = \sigma_y \). In the fatigue tests, cracks were found to initiate in various locations in the test specimens, such as the weld toe of either the cap or the root of the specimens. In a small part of the specimens, base material cracks initiated at a distance from the weld. Therefore, data combinations were made where appropriate. In this way a better comparison could be made of the reference situation with details presented in EN 1993-1-9 (2005).

7.2.1 Selection and adjustment of test data
In Chapter 6, influence factors were presented for geometrical and loading parameters of influence on crack initiation and crack propagation life. Because the adjustment parameters were slightly different for crack initiation phase \( N_i \) or crack propagation phase \( N_p \), the fractions \( f_{N_i} \) and \( f_{N_p} \) of both parts of the total fatigue life \( N_f \) were determined first, See Eq. 7.1 and 7.2.
7. Analysis of fatigue test results

\[ f_{Ni} = \frac{N_i}{N_f} \]  

(7.1)

with,

\[ N_f = N_i + N_p \]

\[ f_{Np} = \left( \frac{1 - N_i}{N_f} \right) \]  

(7.2)

Adjustment factors were applied to the measured nominal stress levels \( \Delta \sigma_n \) to obtain reference stress ranges \( \Delta \sigma_{nu,Nf} \), \( \Delta \sigma_{nw,Nf} \) for thickness \( t = 25 \), loading mode = tension, residual stress \( \sigma_{res} = \sigma_y \) and \( \sigma_m = 0.5 \sigma_y \) with \( K_e = 1 \) for the base material cracks and \( r = 1 \) and \( \theta = 25 \) for the weld toe cracks (\( K_t \neq 1 \)). For the adjustment of the fatigue results of base material cracks, the influence factors were applied on the measured nominal stress ranges \( \Delta \sigma_n \) by use of Eq. 7.3; for the fatigue life of weld cracks by use of Eq. 7.4.

\[ \Delta \sigma_{nu,Nf} = f_m \cdot f_{tu,Nf} \cdot f_{lmu,Nf} \cdot \Delta \sigma_n \]  

(7.3)

\[ \Delta \sigma_{nw,Nf} = f_m \cdot f_{tw,Nf} \cdot f_{lmw,Nf} \cdot \Delta \sigma_n \]  

(7.4)

\( f_m \) Mean stress factor, (See Section 6.2.2.2)

\( f_{tu,Nf} \) Thickness factor for fatigue life of base material cracks

\( f_{lmu,Nf} \) Loading mode factor for fatigue life of base material cracks

\[ f_m \] Mean stress factor, (See Section 6.2.2.2)

\( f_{tw,Nf} \) Thickness factor for fatigue life of weld toe cracks

\( f_{lmw,Nf} \) Loading mode factor for fatigue life of weld toe cracks

The first adjustment concerned the residual stress state. The residual stress as a result of welding was not measured in the experiments. It was conservatively assumed that all test specimens had residual stress \( \sigma_{res} = 0 \). The data were adjusted by the influence factor for residual stress, according to Eq. 6.10, which was assumed to be valid for both the crack initiation and the crack propagation life. The results of base material cracks and weld toe cracks were adjusted to the case residual stress \( \sigma_{res} = \sigma_y \), given \( \sigma_m = 0.5 \sigma_y \). The resulting factors can be found in Appendix F.

The second adjustment addressed the influence of thickness. The tested specimens had thicknesses of 10, 12, 20 and 25 mm. All the measured stress ranges were adjusted to obtain results for reference thickness \( t = 25 \) mm. The thickness factor for total fatigue life \( f_{tu,Nf} \) was assumed to be 1; \( f_{tw,Nf} \) was defined by Eq. 7.5.

\[ f_{tw,Nf} = f_{tw,Ni} \cdot f_{N_i} + f_{tw,Np} \cdot f_{Np} \]  

(7.5)

\( f_{tw,Ni} \) Thickness factor for crack initiation life, (See Section 6.2.3.4)

\( f_{tw,Np} \) Thickness factor for crack propagation life, (See Section 6.3.3.5)

\( f_{N_i} \) Crack initiation life ratio

\( f_{Np} \) Crack propagation life ratio
The third adjustment factor concerned the loading mode. In the experiments, tension and bending loading were applied. To adjust all the results to tension loading, loading mode factor for total fatigue life $f_{lm;u;Nf}$ of base material cracks was formulated, according to Eq. 7.6.

$$f_{lm;u;Nf} = f_{lm;u;Ni} \cdot f_{Ni} + f_{lm;u;Np} \cdot f_{Np}$$

$\bar{f}_{lm;u;Ni}$ Loading mode factor for crack initiation life, 1.0 (See Section 6.2.3.5)  
$\bar{f}_{lm;u;Np}$ Loading mode factor for crack propagation life, 1.09 (See Section 6.3.3.6)  
$\bar{f}_{Ni}$ Crack initiation life ratio  
$\bar{f}_{Np}$ Crack propagation life ratio

To adjust all the results of the weld toe cracks, loading mode factor for total fatigue life $f_{lm;w;Nf}$ was applied, according to Eq. 7.7.

$$f_{lm;w;Nf} = f_{lm;w;Ni} \cdot f_{Ni} + f_{lm;w;Np} \cdot f_{Np}$$

$\bar{f}_{lm;w;Ni}$ Loading mode factor for crack initiation life, 1.2 (See Section 6.2.3.5)  
$\bar{f}_{lm;w;Np}$ Loading mode factor for crack propagation life, 1.37 (See Section 6.3.3.6)  
$\bar{f}_{Ni}$ Crack initiation life ratio  
$\bar{f}_{Np}$ Crack propagation life ratio

Section 4.2.5 showed that the tensile loaded specimens endured a combination of tension and bending loading as a result of misalignment. Therefore, the factor for the tensile loaded specimens with secondary bending moments was defined as $f_{lm;w;Nf;ax}$ according to Eq. 7.8, similar to Eq. 6.39.

$$f_{lm;w;Nf;ax} = \frac{K_m}{1 + \left(\frac{K_m - 1}{f_{lm;w;Nf}}\right)}$$

$K_m$ Misalignment factor (See Section 4.2.5) [Hobbacher, 2004]  
$\bar{f}_{lm;w;Nf}$ Loading mode factor for total fatigue life

### 7.2.2 Statistical analysis

The fatigue data were evaluated according to Brozzetti et al. (1989), summarized by Kuhlmann and Euler (2010) as this evaluation method was adopted by Eurocode. The characteristic stress range values at 2 million cycles $\Delta \sigma_c$ was calculated for a 95% survival probability on a two-sided confidence level of 75% of the mean, parallel to the mean.

The fatigue strength curve is represented by a log-log linear relationship between the stress range $\Delta \sigma$ and the number of cycles up to failure $N_f$. This is the mean regression line, survival probability of 50%, given by Eq. 7.9.

---

*For base material cracks, the $f_{lm;w;Nf}$ is substituted by the $f_{lm;u;Nf}$*
7. Analysis of fatigue test results

\[ y_i = a_N + b \cdot x_i + \varepsilon \quad (7.9) \]

\[ y_i \quad \text{Log } N_f \]
\[ x_i \quad \text{Log } \Delta \sigma \]
\[ a_N \quad \text{Intersection on log } N \text{ axis} \]
\[ b \quad \text{Regression coefficient} \]
\[ \varepsilon \quad \text{Sum of unknown random errors} \]

Parameters \( a_N \) and \( b \) should be estimated by the least squares method. If not a fixed value is assumed, the regression coefficient \( b \) is calculated by Eq. 7.10. Eq. 7.11 determines the intersection on the log \( N \) axis \( a \).

\[ b = \frac{n \cdot \sum (x_i \cdot y_i) - \sum x_i \cdot \sum y_i}{n \cdot \sum x_i^2 - (\sum x_i)^2} \quad (7.10) \]

\[ a_N = \frac{1}{n} \left( \sum y_i - b \cdot \sum x_i \right) \quad (7.11) \]

\( n \) Number of specimens

The mean stress range with survival probability of 50% for \( N = 2 \cdot 10^6 \) cycles is determined by Eq. 7.12

\[ \Delta \sigma_{\text{mean}} = 10^{s \cdot \log (y_{50\%})} \quad (7.12) \]

with,

\[ x_{50\%} = \frac{\log (y_{50\%}) - a_N}{b} \]

where,

\[ y_{50\%} = \log (2 \cdot 10^6) \]

For the calculation of the coefficient of variation, two degrees of freedom are valid for the case the regression coefficient was calculated; one degree of freedom for a fixed regression coefficient, (See Eq. 7.13).

\[ s^2 = \begin{cases} 
\frac{\sum [y_i - (a_N + b \cdot x_i)]^2}{n - 2} & \text{when } b \text{ = calculated} \\
\frac{\sum [y_i - (a_N + b \cdot x_i)]^2}{n - 1} & \text{when } b \text{ = fixed}
\end{cases} \quad (7.13) \]

\( s \) Coefficient of variation
Next, the characteristic stress range at $N = 2 \cdot 10^6$ cycles is calculated for a 75% confidence level of 95% probability of survival by the student-t-distribution factor $t_{0.95,n-x}$ (See Eq. 7.14).

$$\Delta \sigma_e = 10^{+0.5}$$

with,

$$x_{95\%} = \frac{y_{95\%} - a_{95\%}}{b}$$

where,

$$y_{95\%} = y_{50\%} - t_{0.95,n-x} \cdot s$$

$$a_{95\%} = y_{95\%} - b \cdot x_{50\%}$$

For a proper evaluation according to Brozzetti et al. (1989), the following conditions should be met. Results with $N_f > 5 \cdot 10^6$ cycles should not be included; the regression coefficient $b$, which is similar to the slope of the fatigue strength curve $m$, should be fixed to $b = -3$; the sample size should be $n > 12$; runouts should not be included in the regression analysis.

Although the statistical analyses were carried out for all the test series of the current study, not all test series contained more than 12 results per sample. For a relatively low number of specimens, conservative characteristic values of the fatigue strength were taken. In the following sections, the sample size used in the regression analysis is indicated in the results tables.

In addition to the evaluation according to Brozzetti et al. (1989) two modified analyses were carried out. The slope of the fatigue strength curve, which is similar to the regression coefficient, was assumed to be closer to $b = -5$ for VHSS. The first modification was an evaluation with $b = -5$. The second modification was the assumption of a free slope $m$, by use of the calculated regression coefficient, with inclusion of runouts and results with $N_f > 5 \cdot 10^6$ cycles.

### 7.3 Fatigue test evaluation of plate specimens

The fatigue test program consisted of various types of test specimens: base material strips (See Section 4.3), X-welded plates (See Section 4.4), V-welded rolled plates (See Section 4.5) and V-welded hybrid cast steel to rolled steel plates (See Section 4.6).

First, the unadjusted data is presented visually in fatigue strength curves, after which the characteristic fatigue strength and the mean fatigue strength results are plotted against the actual yield strength.

Next, the adjusted fatigue strength curves of all data series are presented in three different ways. The first graph shows the data with the results of the regression analysis, including mean, upper and lower bound of data scatter. The second graph compares the mean results of the statistical evaluation to the predictions described in Chapter 6. The total predicted fatigue life $N_f$ was calculated as the sum of crack initiation life $N_i$ and crack propagation life $N_p$, with the assumption of an endurance limit, the stress level below which there was no crack initiation. The third graph shows the lower bound of the scatter, compared to the design lines of EN 1993-1-9 (2005).
7. Analysis of fatigue test results

7.3.1 Base material plate specimens made of rolled steel

Table 7.1 presents the statistical analysis results on the unadjusted and adjusted data of base material specimens made of rolled steel (See Section 4.3).

Table 7.1. Statistical analysis results on adjusted data of base material specimens made of rolled steel.

<table>
<thead>
<tr>
<th>Grade</th>
<th>S690</th>
<th>S1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_y$ [MPa]</td>
<td>800</td>
<td>1197</td>
</tr>
</tbody>
</table>

**Unadjusted**

<table>
<thead>
<tr>
<th></th>
<th>$b = m$</th>
<th>$a_n$</th>
<th>$\Delta \sigma_{\text{max}}$</th>
<th>$\Delta \sigma_{c}$</th>
<th>$s$</th>
<th>$t_{\text{fpeak}}$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-5.77</td>
<td>-3.00</td>
<td>-5.00</td>
<td>-6.78</td>
<td>-3.00</td>
<td>-5.00</td>
<td>2.13</td>
</tr>
<tr>
<td>$a_n$</td>
<td>20.85</td>
<td>13.18</td>
<td>18.55</td>
<td>23.45</td>
<td>13.31</td>
<td>18.63</td>
<td>20.85</td>
</tr>
<tr>
<td>$\Delta \sigma_{\text{max}}$</td>
<td>332</td>
<td>196</td>
<td>282</td>
<td>339</td>
<td>216</td>
<td>293</td>
<td>332</td>
</tr>
<tr>
<td>$\Delta \sigma_{c}$</td>
<td>188</td>
<td>112</td>
<td>196</td>
<td>278</td>
<td>179</td>
<td>275</td>
<td>188</td>
</tr>
<tr>
<td>$s$</td>
<td>0.67</td>
<td>0.31</td>
<td>0.33</td>
<td>0.27</td>
<td>0.12</td>
<td>0.06</td>
<td>0.67</td>
</tr>
<tr>
<td>$t_{\text{fpeak}}$</td>
<td>2.13</td>
<td>2.35</td>
<td>2.35</td>
<td>2.13</td>
<td>2.13</td>
<td>2.13</td>
<td>2.13</td>
</tr>
<tr>
<td>$n$</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

**Adjusted**

<table>
<thead>
<tr>
<th></th>
<th>$b = m$</th>
<th>$a_n$</th>
<th>$\Delta \sigma_{\text{max}}$</th>
<th>$\Delta \sigma_{c}$</th>
<th>$s$</th>
<th>$t_{\text{fpeak}}$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-5.77</td>
<td>-3.00</td>
<td>-5.00</td>
<td>-6.78</td>
<td>-3.00</td>
<td>-5.00</td>
<td>2.13</td>
</tr>
<tr>
<td>$a_n$</td>
<td>20.55</td>
<td>13.02</td>
<td>18.29</td>
<td>22.94</td>
<td>13.08</td>
<td>18.26</td>
<td>20.55</td>
</tr>
<tr>
<td>$\Delta \sigma_{\text{max}}$</td>
<td>295</td>
<td>174</td>
<td>250</td>
<td>285</td>
<td>182</td>
<td>246</td>
<td>295</td>
</tr>
<tr>
<td>$\Delta \sigma_{c}$</td>
<td>166</td>
<td>99</td>
<td>174</td>
<td>234</td>
<td>150</td>
<td>232</td>
<td>166</td>
</tr>
<tr>
<td>$s$</td>
<td>0.67</td>
<td>0.31</td>
<td>0.33</td>
<td>0.27</td>
<td>0.12</td>
<td>0.06</td>
<td>0.67</td>
</tr>
<tr>
<td>$t_{\text{fpeak}}$</td>
<td>2.13</td>
<td>2.35</td>
<td>2.35</td>
<td>2.13</td>
<td>2.13</td>
<td>2.13</td>
<td>2.13</td>
</tr>
<tr>
<td>$n$</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Before the attachment of the strain gauges, the surface at the tapered cross section of the specimens (See Section 4.3) was ground. The rest of the specimens was not ground, which caused non-uniform surface roughness. Measured values indicated $R_z = 10 – 50 \mu m$. The crack initiation location was different for the S690 and S1100 specimens. In the S690 specimens all cracks initiated in the tapered, ground section of the specimens, whereas crack initiated in the non tapered, non ground parts of the S1100 specimens.

Figure 7.1a and Figure 7.1b show the unadjusted and the adjusted fatigue results of base material specimens made of S690 the results of regression analysis, including the mean, upper and lower bounds of the data scatter. Figure 7.2 compares the mean results of the statistical evaluation to the predictions for $R_z = 20$ and $160 \mu m$, given $K_t = 1$ and $r = 1$. The mean line reasonably fits the predicted fatigue life for $R_z = 20 \mu m$, mainly because of an accurate estimation of the slope $m = -5$ or $m = -5.77$. Figure 7.3 shows the lower bound of the scatter, compared to detail categories 125 and 160 of EN 1993-1-9 (2005). Given fixed slope $m = -3$, the prediction overestimates the strength for high load cycle domain (N > $10^6$) and underestimates the strength for the medium cycle domain (N < $10^6$). With $m = -5.77$, $\Delta \sigma_{\text{mean}}$ = 295 MPa, $\Delta \sigma_{\text{c}}$ = 166 MPa; with $m = -3$, $\Delta \sigma_{\text{mean}}$ = 174 MPa, $\Delta \sigma_{\text{c}}$ = 99 MPa; with $m = -5$, $\Delta \sigma_{\text{mean}}$ = 250 MPa, $\Delta \sigma_{\text{c}}$ = 174 MPa.
Figure 7.1a. Unadjusted fatigue results of FAM series on base material specimens (S690), with mean, upper bound and lower bounds of the scatter.

Figure 7.1b. Adjusted fatigue results of FAM series on base material specimens (S690), with mean, upper bound and lower bounds of the scatter.
7. Analysis of fatigue test results

Figure 7.2. Adjusted fatigue results of FAM series on base material specimens (S690), with mean lines compared to predictions for $R_q = 20$ and $R_q = 160$.

Figure 7.3. Adjusted fatigue results of FAM series on base material specimens (S690), with lower bound of the scatter compared to detail categories 125 and 160 of EN 1993-1-9 (2005).
Figure 7.4a and Figure 7.4b show the unadjusted and the adjusted fatigue results of base material specimens made of S1100, the results of regression analysis, including the mean, upper and lower bounds of the data scatter. Given fixed slope \( m = -5 \), the scatter in the results is very small, mainly because of the excluded value of the runout. Analyses with calculated slope lead to \( m = -6.78 \), which is much larger than \( m = -3 \) and larger than the slope of the S690 results. The calculated slope very well matches the predicted slope. Figure 7.5 compares the mean results of the statistical evaluation to the predictions for \( R_x = 20 \) and 160. Figure 7.6 shows the lower bound of the scatter, compared to detail categories 125 and 160 of EN 1993-1-9 (2005). Given fixed slope \( m = -3 \), the \( \Delta \sigma_{\text{c}};w;N_f \) is close to the value according to detail category 160. With \( m = -6.78 \), \( \Delta \sigma_{\text{mean}};w;N_f = 285 \) MPa, \( \Delta \sigma_{\text{c}};w;N_f = 234 \) MPa; with \( m = -3 \), \( \Delta \sigma_{\text{mean}};w;N_f = 182 \) MPa, \( \Delta \sigma_{\text{c}};w;N_f = 150 \) MPa; with \( m = -5 \), \( \Delta \sigma_{\text{mean}};w;N_f = 246 \) MPa, \( \Delta \sigma_{\text{c}};w;N_f = 232 \) MPa.

Figure 7.4a. Unadjusted fatigue results of series on base material specimens (S1100), with mean, upper bound and lower bounds of the scatter.
7. Analysis of fatigue test results

Figure 7.4b. Adjusted fatigue results of series on base material specimens (S1100), with mean, upper bound and lower bounds of the scatter.

Figure 7.5. Adjusted fatigue results of FBM series base material specimens (S1100), with mean lines compared to predictions for $R_z = 20$ and $R_z = 160$, given $K_t = 1$ and $r = 1$. 
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 7.6. Adjusted fatigue results of FBM series on base material specimens (S1100), with lower bound of the scatter compared to detail categories 125 and 160 of EN 1993-1-9 (2005).

7.3.2 X-welded plate specimens made of rolled steel
Table 7.2 presents the statistical analysis results on adjusted data of X-welded rolled plates (See Section 4.4). The X-welded specimens were loaded in tension. Because of the misalignment in the specimens as a result of welding, the highest strains were endured in the cap side of the welds. All cracks initiated in the weld, no cracks were found in the base material.

Table 7.2. Statistical analysis results on adjusted data of X-welded specimens made of rolled steel.

<table>
<thead>
<tr>
<th>Grade</th>
<th>S355</th>
<th>S690</th>
<th>S1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>σy [MPa]</td>
<td>395</td>
<td>800</td>
<td>1197</td>
</tr>
</tbody>
</table>

Unadjusted

<table>
<thead>
<tr>
<th>Grade</th>
<th>S355</th>
<th>S690</th>
<th>S1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>b = m</td>
<td>-4.07</td>
<td>-3.00</td>
<td>-5.00</td>
</tr>
<tr>
<td>a0</td>
<td>15.45</td>
<td>12.89</td>
<td>17.58</td>
</tr>
<tr>
<td>Δσmax</td>
<td>176</td>
<td>157</td>
<td>180</td>
</tr>
<tr>
<td>Δσy</td>
<td>125</td>
<td>106</td>
<td>137</td>
</tr>
<tr>
<td>s</td>
<td>0.32</td>
<td>0.27</td>
<td>0.31</td>
</tr>
<tr>
<td>t_{0.01}</td>
<td>1.89</td>
<td>1.89</td>
<td>1.89</td>
</tr>
<tr>
<td>a</td>
<td>9</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>
7. Analysis of fatigue test results

<table>
<thead>
<tr>
<th>Grade</th>
<th>S355</th>
<th>S690</th>
<th>S1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_y$ [MPa]</td>
<td>395</td>
<td>800</td>
<td>1197</td>
</tr>
<tr>
<td>Adjusted</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b = m$</td>
<td>-4.39</td>
<td>-3.00</td>
<td>-5.00</td>
</tr>
<tr>
<td>$a_0$</td>
<td>15.51</td>
<td>12.44</td>
<td>16.83</td>
</tr>
<tr>
<td>$\Delta\sigma_{\text{mean};w;/Nf}$</td>
<td>126</td>
<td>111</td>
<td>127</td>
</tr>
<tr>
<td>$\Delta\sigma_{\text{c};w;/Nf}$</td>
<td>95</td>
<td>77</td>
<td>100</td>
</tr>
<tr>
<td>$s$</td>
<td>0.29</td>
<td>0.25</td>
<td>0.28</td>
</tr>
<tr>
<td>$t_{\text{loS}}$</td>
<td>1.89</td>
<td>1.89</td>
<td>1.89</td>
</tr>
<tr>
<td>n</td>
<td>9</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 7.7a and Figure 7.7b show the unadjusted and the adjusted fatigue results of the X-welded plate specimens made of S355, the results of regression analysis, including the mean, upper and lower bounds of the data scatter. The scatter in the results is equal for the various regression coefficients. Figure 7.8 compares the mean results of the statistical evaluation to the predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$. For $m = -4.39$, the prediction of the fatigue strength with $\theta = 25^\circ$ exactly matches the mean line.

Figure 7.7a. Unadjusted fatigue results of SA series on X-welded specimens made of S355, with mean, upper bound and lower bounds of the scatter.
Figure 7.7b. Adjusted fatigue results of SA series on X-welded specimens made of S355, with mean, upper bound and lower bounds of the scatter.

Figure 7.8. Adjusted fatigue results of series on X-welded specimens made of S355, with mean lines compared to predictions $\theta = 25^\circ$ and $\theta = 45^\circ$. 
Figure 7.9 shows the lower bound of the scatter, compared to detail categories 80 and 90 of EN 1993-1-9 (2005). Given $m = -3$, category 80 reasonably fits the lower bound. With $m = -4.39$, $\Delta \sigma_{\text{mean};w;Nf} = 126 \text{ MPa}$, $\Delta \sigma_{\text{cw};Nf} = 95 \text{ MPa}$; with $m = -3$, $\Delta \sigma_{\text{mean};w;Nf} = 111 \text{ MPa}$, $\Delta \sigma_{\text{cw};Nf} = 77 \text{ MPa}$; with $m = -5$, $\Delta \sigma_{\text{mean};w;Nf} = 127 \text{ MPa}$, $\Delta \sigma_{\text{cw};Nf} = 100 \text{ MPa}$.

Figure 7.9. Adjusted fatigue results of series on X-welded specimens made of S355, with lower bound of the scatter compared to detail categories 80 and 90 of EN 1993-1-9 (2005).

Figure 7.10a and Figure 7.10b show the unadjusted and the adjusted fatigue results of the X-welded specimens made of S690, the results of regression analysis, including the mean, upper and lower bounds of the data scatter.

Figure 7.11 compares the mean results of the statistical evaluation to the predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$. For $m = -5$, the prediction of the fatigue strength with $\theta = 25^\circ$ is close to the mean line. However, the calculated slope $m = -3.52$ is much smaller than -5.

Figure 7.12 shows the lower bound of the scatter, compared to detail categories 80 and 90 of EN 1993-1-9 (2005). The results of the S690 specimens are close to the results of S355 specimens. With $m = -3.52$, $\Delta \sigma_{\text{mean};w;Nf} = 109 \text{ MPa}$, $\Delta \sigma_{\text{cw};Nf} = 83 \text{ MPa}$; with $m = -3$, $\Delta \sigma_{\text{mean};w;Nf} = 100 \text{ MPa}$, $\Delta \sigma_{\text{cw};Nf} = 77 \text{ MPa}$; with $m = -5$, $\Delta \sigma_{\text{mean};w;Nf} = 120 \text{ MPa}$, $\Delta \sigma_{\text{cw};Nf} = 87 \text{ MPa}$.
Figure 7.10a. Unadjusted fatigue results of FA series on X-welded specimens made of S690, with mean, upper bound and lower bound of the scatter.

Figure 7.10b. Adjusted fatigue results of FA series on X-welded specimens made of S690, with mean, upper bound and lower bound of the scatter.
7. Analysis of fatigue test results

Figure 7.11. Adjusted fatigue results of FA series on X-welded specimens made of S690, with mean lines compared to predictions $\theta = 25^\circ$ and $\theta = 45^\circ$.

Figure 7.12. Adjusted fatigue results FA series on X-welded specimens made of S690, with lower bound of the scatter compared to detail categories 80 and 90 of EN 1993-1-9 (2005)
Figure 7.13a and Figure 7.13b show the unadjusted and the adjusted fatigue results of X-welded specimens made of S1100, the results of regression analysis, including the mean, upper and lower bounds of the data scatter. The calculated scatter was very large for evaluation with fixed slope $m = -3$, and small for $m = -5$ and free slope $m = -5.51$.

Figure 7.14 compares the mean results of the statistical evaluation to the predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$. The prediction for $\theta = 25^\circ$ perfectly resembles the mean line for $m = -5$ and $m = -5.51$.

Figure 7.15 shows the lower bound of the scatter, compared to detail categories 80 and 90 of EN 1993-1-9 (2005). With $m = -5.51$, $\Delta\sigma_{\text{mean},w,Nf} = 134$ MPa, $\Delta\sigma_{\text{cw},Nf} = 108$ MPa; with $m = -3$, $\Delta\sigma_{\text{mean},w,Nf} = 95$ MPa, $\Delta\sigma_{\text{cw},Nf} = 60$ MPa; with $m = -5$, $\Delta\sigma_{\text{mean},w,Nf} = 126$ MPa, $\Delta\sigma_{\text{cw},Nf} = 106$ MPa.
7. Analysis of fatigue test results

Figure 7.13b. Adjusted fatigue results of FB series on X-welded specimens made of S1100, with mean, upper bound and lower bound of the scatter.

Figure 7.14. Adjusted fatigue results of FB series on X-welded specimens made of S1100, with mean lines compared to predictions $\theta = 25^\circ$ and $\theta = 45^\circ$. 

---

172
7.3.3 V-welded plate specimens made of cast and rolled steel

Most of the fatigue tests of the current study focused on V-welded specimens with connections of rolled steel to rolled steel parts (See Section 4.5) and hybrid specimens with rolled steel to cast steel parts (section 4.6). The fatigue strength of specimens made of V-welded rolled steel to rolled steel plates is found to be in the same scatter range as similar specimens made of V-welded rolled steel to cast steel plates. Therefore, the current section combines the results of all V-welded specimens.

For addressing the influence of yield strength, the data were filtered by yield strength, S460, S690, S890 or S1100 and corresponding cast steels G20Mn5, G10MnMoV6-3, G18NiMoCr3-6 and G22NiMoCr5-6 respectively.

Next, a distinction was made in crack initiation location. By this, the results of weld toe cracks in either cap or root were compared. Also, base material cracks, either cast or rolled steel, were evaluated. Furthermore, the influence of the difference of edge cracks (quarter elliptical shape) or middle cracks (semi-elliptical shape) on the fatigue strength was studied.
7.3.3.1 Weld toe cracks
Table 7.3 presents the statistical analysis results on unadjusted and adjusted data of weld toe cracks in V-welded specimens and mean yield strength based on Appendix B.

<table>
<thead>
<tr>
<th>Grade</th>
<th>S460 - G20Mn5</th>
<th>S690 - G10MnMoV6.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_p$ [MPa]</td>
<td>502</td>
<td>745</td>
</tr>
<tr>
<td><strong>Unadjusted</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b = m$</td>
<td>-3.47</td>
<td>-4.70</td>
</tr>
<tr>
<td>$a_n$</td>
<td>14.09</td>
<td>17.01</td>
</tr>
<tr>
<td>$\Delta\sigma_{\text{max}}$</td>
<td>177</td>
<td>190</td>
</tr>
<tr>
<td>$\Delta\sigma$</td>
<td>133</td>
<td>138</td>
</tr>
<tr>
<td>$s$</td>
<td>0.25</td>
<td>0.38</td>
</tr>
<tr>
<td>$n$</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Adjusted</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b = m$</td>
<td>-3.38</td>
<td>-4.94</td>
</tr>
<tr>
<td>$a_n$</td>
<td>13.42</td>
<td>16.82</td>
</tr>
<tr>
<td>$\Delta\sigma_{\text{max}}$</td>
<td>128</td>
<td>135</td>
</tr>
<tr>
<td>$\Delta\sigma$</td>
<td>93</td>
<td>101</td>
</tr>
<tr>
<td>$s$</td>
<td>0.27</td>
<td>0.37</td>
</tr>
<tr>
<td>$n$</td>
<td>20</td>
<td>23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade</th>
<th>S890 - G18NiMoCr3.6</th>
<th>S1100 - G22NiMoCr5.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_p$ [MPa]</td>
<td>987</td>
<td>1158</td>
</tr>
<tr>
<td><strong>Unadjusted</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b = m$</td>
<td>-4.84</td>
<td>-5.36</td>
</tr>
<tr>
<td>$a_n$</td>
<td>17.89</td>
<td>16.09</td>
</tr>
<tr>
<td>$\Delta\sigma_{\text{max}}$</td>
<td>248</td>
<td>244</td>
</tr>
<tr>
<td>$\Delta\sigma$</td>
<td>176</td>
<td>172</td>
</tr>
<tr>
<td>$s$</td>
<td>0.41</td>
<td>0.45</td>
</tr>
<tr>
<td>$n$</td>
<td>17</td>
<td>11</td>
</tr>
<tr>
<td><strong>Adjusted</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b = m$</td>
<td>-5.45</td>
<td>-4.67</td>
</tr>
<tr>
<td>$a_n$</td>
<td>18.51</td>
<td>16.49</td>
</tr>
<tr>
<td>$\Delta\sigma_{\text{max}}$</td>
<td>175</td>
<td>152</td>
</tr>
<tr>
<td>$\Delta\sigma$</td>
<td>123</td>
<td>94</td>
</tr>
<tr>
<td>$s$</td>
<td>0.48</td>
<td>0.54</td>
</tr>
<tr>
<td>$n$</td>
<td>17</td>
<td>11</td>
</tr>
</tbody>
</table>
Figure 7.16a and Figure 7.16b show the unadjusted and the adjusted fatigue results of the V-welded specimens made of S460, with the results of regression analysis, including the mean, upper and lower bounds of the data scatter. Figure 7.17 compares the mean results of the statistical evaluation to the predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$. Figure 7.18 shows the lower bound of the scatter, compared to detail category 71 of EN 1993-1-9 (2005).

The slope according to the regression analysis $m = -3.38$ is close to $m = -3$ according to EN 1993-1-9 (2005). The scatter in the fatigue results is relatively low compared to the specimens made of other yield strengths. The results of the Root-mode specimens are in the lower region of the scatter (See Figure 7.16), both for weld toe cracks in the rolled parts as for weld toe cracks in the cast parts. There were no run-out specimens. With $m = -3.38$, $\Delta \sigma_{\text{mean};w};N_f = 128 \text{ MPa}$, $\Delta \sigma_{\text{cw};w};N_f = 93 \text{ MPa}$; with $m = -3$, $\Delta \sigma_{\text{mean};w};N_f = 122 \text{ MPa}$, $\Delta \sigma_{\text{cw};w};N_f = 86 \text{ MPa}$; with $m = -5$, $\Delta \sigma_{\text{mean};w};N_f = 144 \text{ MPa}$, $\Delta \sigma_{\text{cw};w};N_f = 114 \text{ MPa}$.

![Fatigue strength of welded connections made of very high strength cast and rolled steels](https://example.com/fatigue_strength_chart.png)

Figure 7.16a. Unadjusted fatigue results of series on V-welded specimens made of S460 and G20Mn5, with mean, upper bound and lower bound of the scatter.
7. Analysis of fatigue test results

Figure 7.16b. Adjusted fatigue results of series on V-welded specimens made of S460 and G20Mn5, with mean, upper bound and lower bound of the scatter.

Figure 7.17. Adjusted fatigue results of series on V-welded specimens made of S460 and G20Mn5, with mean lines compared to predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$. 
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 7.18. Adjusted fatigue results of series on V-welded specimens made of S460 and G20Mn5, with lower bound of the scatter compared to detail category 71 of EN 1993-1-9 (2005)

Figure 7.19a and Figure 7.19b show the unadjusted and the adjusted fatigue results of the V-welded rolled plates (S690), the results of regression analysis, including the mean, upper and lower bounds of the data scatter. Figure 7.20 compares the mean results of the statistical evaluation to the predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$. Figure 7.21 shows the lower bound of the scatter, compared to detail category 71 of EN 1993-1-9 (2005).

The results of the C69-series, Cap-mode, are in the upper band of the scatter. Results of tension and bending loaded specimens agree. The root-crack results are in the lower bound of the scatter. Overall, no run-outs were found. The results of the tensile loaded specimens fall in the lower bound of the scatter. With $m = -4.94$, $\Delta\sigma_{\text{mean};w;Nf} = 135$ MPa, $\Delta\sigma_{c;w;Nf} = 101$ MPa; with $m = -3$, $\Delta\sigma_{\text{mean};w;Nf} = 115$ MPa, $\Delta\sigma_{c;w;Nf} = 69$ MPa; with $m = -5$, $\Delta\sigma_{\text{mean};w;Nf} = 136$ MPa, $\Delta\sigma_{c;w;Nf} = 102$ MPa.
7. Analysis of fatigue test results

Figure 7.19a. Unadjusted fatigue results of series on V-welded specimens made of S690 and G10MnMoV6-3, with mean, upper bound and lower bounds of the scatter.

Figure 7.19b. Adjusted fatigue results of series on V-welded specimens made of S690 and G10MnMoV6-3, with mean, upper bound and lower bounds of the scatter.
Figure 7.20. Adjusted fatigue results of series on V-welded specimens made of S690 and G10MnMoV6-3, with mean lines compared to predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$.

Figure 7.21. Adjusted fatigue results of series on V-welded specimens made of S690 and G10MnMoV6-3, with lower bound of the scatter compared to detail category 71 of EN 1993-1-9 (2005)
7. Analysis of fatigue test results

Figure 7.22a and Figure 7.22b show the unadjusted and the adjusted fatigue results of the V-welded rolled plates (S890), the results of regression analysis, including the mean, upper and lower bounds of the data scatter. Figure 7.23 compares the mean results of the statistical evaluation to the predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$. Figure 7.24 shows the lower bound of the scatter, compared to detail category 71 of EN 1993-1-9 (2005). With $m = -5.45$, $\Delta\sigma_{\text{mean};w;Nf} = 175$ MPa, $\Delta\sigma_{\text{c};w;Nf} = 123$ MPa; with $m = -3$, $\Delta\sigma_{\text{mean};w;Nf} = 126$ MPa, $\Delta\sigma_{\text{c};w;Nf} = 80$ MPa; with $m = -5$, $\Delta\sigma_{\text{mean};w;Nf} = 152$ MPa, $\Delta\sigma_{\text{c}} = 108$ MPa. In comparison to the other series, relatively many specimens were runout for S890. Only one weld root crack result was obtained.

![Graph showing fatigue results](image)

Figure 7.22a. Unadjusted fatigue results of series on V-welded specimens made of S890 and G18NiMoCr3-6, with mean, upper bound and lower bounds of the scatter.
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 7.22b. Adjusted fatigue results of series on V-welded specimens made of S890 and G18NiMoCr3-6, with mean, upper bound and lower bounds of the scatter.

Figure 7.23. Adjusted fatigue results of series on V-welded specimens made of S890 and G18NiMoCr3-6, with mean lines compared to predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$.
7. Analysis of fatigue test results

Figure 7.24. Adjusted fatigue results of series on V-welded specimens made of S890 and G18NiMoCr3-6, with lower bound of the scatter compared to detail category 71 of EN 1993-1-9 (2005).

Figure 7.25a and Figure 7.25b show the unadjusted and the adjusted fatigue results of the V-welded rolled plates (S1100), the results of regression analysis, including the mean, upper and lower bounds of the data scatter. Figure 7.26 compares the mean results of the statistical evaluation to the predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$. Figure 7.27 shows the lower bound of the scatter, compared to detail category 71 of EN 1993-1-9 (2005). With $m = -4.67$, $\Delta \sigma_{\text{mean},w,Nf} = 152$ MPa, $\Delta \sigma_{\text{cw},Nf} = 94$ MPa; with $m = -3$, $\Delta \sigma_{\text{mean},w,Nf} = 115$ MPa, $\Delta \sigma_{\text{cw},Nf} = 86$ MPa; with $m = -5$, $\Delta \sigma_{\text{mean},w,Nf} = 137$ MPa, $\Delta \sigma_{\text{cw},Nf} = 109$ MPa. Unfortunately, many base material cracks were found, in both cast and rolled parts. This limited the amount of data of weld toe cracks. No weld root cracks were obtained.
Figure 7.25a. Unadjusted fatigue results of series on V-welded specimens made of S1100 and G22NiMoCr5-6, with mean, upper bound and lower bound of the scatter.

Figure 7.25b. Adjusted fatigue results of series on V-welded specimens made of S1100 and G22NiMoCr5-6, with mean, upper bound and lower bound of the scatter.
Figure 7.26. Adjusted fatigue results of series on V-welded specimens made of S1100 and G22NiMoCr5-6, with mean lines compared to predictions for $\theta = 25^\circ$ and $\theta = 45^\circ$.

Figure 7.27. Adjusted fatigue results of series on V-welded specimens made of S1100 and G22NiMoCr5-6, with lower bound of the scatter compared to detail category 71 of EN 1993-1-9 (2005).
7.3.3.2 Influence of crack initiation location

In order to study the difference in fatigue strength of weld toe cracks in either the cap or the root of the specimens, the results of all test series were reanalyzed in two samples, with root cracks and with cap cracks. Figure 7.28 shows the results of cracks in the cap; Figure 7.29 shows the results of cracks in the root. Table 7.4 shows the results of the statistical evaluation.

Table 7.4. Adjusted fatigue results of V-welded plates; filtered by cap or root crack.

<table>
<thead>
<tr>
<th>Crack location</th>
<th>Cap</th>
<th>Root</th>
</tr>
</thead>
<tbody>
<tr>
<td>b = m</td>
<td>-2.93 -3.00 -5.00</td>
<td>-2.90 -3.00 -5.00</td>
</tr>
<tr>
<td>aN</td>
<td>12.41 12.57 17.11</td>
<td>12.05 12.27 16.73</td>
</tr>
<tr>
<td>Δσ_{mean,\tau,Nf}</td>
<td>121 123 145</td>
<td>96 98 122</td>
</tr>
<tr>
<td>Δσ_{c,Nf}</td>
<td>80 82 111</td>
<td>59 63 90</td>
</tr>
<tr>
<td>s</td>
<td>0.31 0.31 0.35</td>
<td>0.33 0.31 0.36</td>
</tr>
<tr>
<td>t_{0.03Nf}</td>
<td>1.68 1.68 1.68</td>
<td>1.89 1.86 1.86</td>
</tr>
<tr>
<td>n</td>
<td>43 43 43</td>
<td>9 9 9</td>
</tr>
</tbody>
</table>

Figure 7.28. Adjusted fatigue results of V-welded plates; weld toe cracks in cap.
The fatigue strength of the cap was found to be much higher than the strength of the root. It should be noted that most cracks initiated in the cap, and therefore, the number of specimens reduced the coefficient of variation. The difference in fatigue strength can be explained by the quality of the weld toe, which is relatively higher in the cap region. According to Eurocode 1993-1-9 (2005) detail category 36 is valid for weld root cracks. However, detail category 36 merely represents an assumption of a low quality weld root, with partial penetration, unchecked by NDT.

7.3.3.3 Influence of ceramic backing
Because of the very limited number of specimens with cracks in the root with either ceramic backing or no backing, this influence could not be addressed.

7.3.3.4 Influence of middle crack or edge crack
In order to study the difference in fatigue strength of weld toe cracks in either the middle of the plate (semi-elliptical cracks) or the edge (quarter-elliptical cracks), the results of all test series were reanalyzed in two samples, with edge cracks or middle cracks. Table 7.5 presents the results of statistical analysis for cracks which initiated predominantly in the middle or in the edge on the cap side of the welds.
Table 7.5. Adjusted fatigue results of V-welded plates; filtered by middle or edge cracks.

<table>
<thead>
<tr>
<th>Crack location</th>
<th>Middle</th>
<th>Edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>b = m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aN</td>
<td>14.61</td>
<td>12.64</td>
</tr>
<tr>
<td>(\Delta \sigma_{\text{mean},w,Nf} )</td>
<td>143</td>
<td>130</td>
</tr>
<tr>
<td>187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta \sigma_{\text{c},w,Nf} )</td>
<td>98</td>
<td>82</td>
</tr>
<tr>
<td>187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t_{\text{Nf}}</td>
<td>1.81</td>
<td>1.80</td>
</tr>
<tr>
<td>187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 7.30 shows the adjusted results of cracks in the edge of the plate and Figure 7.31 shows the results of middle cracks. The edge of the plate endures the effect of cutting and grinding, which might cause a difference in fatigue strength. Moreover, the stress intensity factors are different for semi-elliptical cracks or quarter elliptical cracks. As was found in Sections 6.3.2 and 6.3.3, crack propagation life was expected to be longer for semi-elliptical cracks. From the experiments also a small difference in fatigue strength could be derived, in favour of the semi-elliptical cracks.

Figure 7.30. Adjusted fatigue results of V-welded plates; cracks in weld toe at edge.
7.3.4 Base material parts of V-welded plate specimens made of cast and rolled steel

Next to weld toe cracks, base material cracks were found in some of the V-welded specimens of S460, S890 and S1100. The results of the base material cracks were analyzed separately from the results of weld toe cracks. A distinction was made between base material cracks in the rolled steel and cast steel. The cast steel parts were expected to be more prone to crack initiation, than the rolled steel parts. Because of the casting process, initial porosities and inclusions could be present in the cast material. It was difficult to obtain homogeneous cast quality for plate shapes.

Unexpectedly, base material cracks were also found in the rolled steels. Table 7.6 presents the fatigue results of statistical analysis for base material cracks in the cast steel or rolled steel parts.

Table 7.6. Unadjusted and adjusted fatigue results of V-welded plates; base material crack in cast or rolled part.

<table>
<thead>
<tr>
<th>Part of specimen</th>
<th>Cast</th>
<th>Rolled</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b = m$</td>
<td>-2.21</td>
<td>-3.00</td>
</tr>
<tr>
<td>$a_N$</td>
<td>11.20</td>
<td>13.10</td>
</tr>
<tr>
<td>$\Delta\sigma_{mean}/Nf$</td>
<td>166</td>
<td>184</td>
</tr>
<tr>
<td>$\Delta\sigma_{cum}/Nf$</td>
<td>105</td>
<td>132</td>
</tr>
<tr>
<td>$s$</td>
<td>0.25</td>
<td>0.34</td>
</tr>
<tr>
<td>$Y_{stem,L}$</td>
<td>1.78</td>
<td>1.77</td>
</tr>
<tr>
<td>$n$</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>
Fatigue strength of welded connections made of very high strength cast and rolled steels

<table>
<thead>
<tr>
<th>Part of specimen</th>
<th>Cast</th>
<th>Rolled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b = m</td>
<td>-1.87</td>
<td>-3.00</td>
</tr>
<tr>
<td>aN</td>
<td>10.27</td>
<td>12.90</td>
</tr>
<tr>
<td>Δσmean;u;Nf</td>
<td>133</td>
<td>159</td>
</tr>
<tr>
<td>Δσc;u;Nf</td>
<td>74</td>
<td>109</td>
</tr>
<tr>
<td>s</td>
<td>0.27</td>
<td>0.38</td>
</tr>
<tr>
<td>t_{0.95;P_{80}}</td>
<td>1.78</td>
<td>1.77</td>
</tr>
<tr>
<td>n</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

Figures 7.32a and 7.32b show the unadjusted and the adjusted fatigue test data of cracks in cast parts, the results of regression analysis, including the mean, upper and lower bounds of the data scatter. Given slope m = -5, the mean results of both cast and rolled steel parts are similar. Given free slope m, the results are different. Moreover, the cast steel results had a larger scatter, leading to lower design values of Δσc;u;Nf and a somewhat unrealistic value of slope m = -1.87.

Figure 7.33 compares the mean results of the statistical evaluation Δσmean;u;Nf to the predictions for yield strength of 460 MPa with Rz = 160 μm. Chapter 6 already indicated that the predictions were overestimating the fatigue strength of the base material cracks of the V-welded specimens. Also in the comparison of the total fatigue life as a sum of crack initiation life and crack propagation life, the fatigue results were lower than predicted, especially for the G18NiMoCr3.6 and G22NiMoCr5.6 parts. Predictions were conservative for G20Mn5. No base material cracks were discovered in the G10MnMoV6-3 parts.

Figure 7.34 shows the lower bound of the scatter, compared to the design lines of the UEG (1985). For the assumption of cast quality Q1, the calculation rules of UEG (1985) reasonably predicted the fatigue strength of the base material cracks in the cast steel.
7. Analysis of fatigue test results

Figure 7.32a. Unadjusted fatigue results of base material cracks in cast steel parts of V-welded plates, with mean, upper bound and lower bound of the scatter.

\[ \Delta \sigma_{\text{rms}} \text{[MPa]} \]

\[ C_{11}\text{-Cap-cast-BM} \]
\[ C_{11}\text{-Root-cast-BM} \]
\[ C_{89}\text{-Cap-cast-BM} \]
\[ C_{89}\text{-Root-cast-BM} \]
\[ m = -2.2 \]
\[ R = 0.1 \]
\[ S_{460}-G20Mn5 \]
\[ S_{890}-G18NiMoCr3.6 \]
\[ S_{1100}-G22NiMoCr5.6 \]

Figure 7.32b. Adjusted fatigue results of base material cracks in cast steel parts of V-welded plates, with mean, upper bound and lower bound of the scatter.

\[ C_{11}\text{-Cap-cast-BM} \]
\[ C_{11}\text{-Root-cast-BM} \]
\[ C_{89}\text{-Cap-cast-BM} \]
\[ C_{89}\text{-Root-cast-BM} \]
\[ m = -1.87 \]
\[ R = 0.1 \]
\[ S_{460}-G20Mn5 \]
\[ S_{890}-G18NiMoCr3.6 \]
\[ S_{1100}-G22NiMoCr5.6 \]
\[ t = 25 \text{ mm} \]
\[ m = -5 \]
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 7.33. Adjusted fatigue results of base material cracks in cast steel parts of V-welded plates, with mean lines compared to predictions for $\sigma_y = 460$ MPa, $R_z = 160 \mu$m.

Figure 7.34. Adjusted fatigue results of base material cracks in cast steel parts of V-welded plates, with lower bound of the scatter compared to detail category calculations of UEG (1985).
Unexpectedly, base material cracks were found in the rolled steel parts of S460, S890 and S1100. Figure 7.35 shows the fatigue test results of base material cracks in the rolled steel parts, the results of regression analysis, including the mean, upper and lower bounds of the data scatter.

Figure 7.36 compares the mean results of the statistical evaluation to the predictions for S460 with $R_s = 40 \mu m$. Chapter 6 already indicated that the predictions were overestimating the fatigue strength of base material cracks in the V-welded specimens. Except for the S1100 specimens, the predictions seemed to give a reasonable match to the data.

Figure 7.37 shows the lower bound of the scatter, compared to the design lines of the Eurocode 1993-1-9 (2005), detail category 160 (EC160) and detail category 125 (EC125). EC160 is found to be non-conservative, but EC 125 seems to be appropriate for the base material cracks in the rolled steel parts.

![Figure 7.35a. Unadjusted fatigue results of base material cracks in rolled steel parts of V-welded plates, with mean, upper bound and lower bound of the scatter.](image-url)
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 7.35b. Adjusted fatigue results of base material cracks in rolled steel parts of V-welded plates, with mean, upper bound and lower bound of the scatter.

Figure 7.36. Adjusted fatigue results of base material cracks in rolled steel parts of V-welded plates, with mean lines compared to predictions for $\sigma_y = 460$ MPa, $R_z = 160 \mu m$. 
7. Analysis of fatigue test results

Figure 7.37. Adjusted fatigue results of base material cracks in rolled steel parts of V-welded plates, with lower bound of the scatter compared to detail categories 125 and 160 according to EN 1993-1-9 (2005).

7.4 Fatigue test evaluation of truss specimens

Although the number of specimens was limited, the results of the truss specimens (See Section 5.5) were compared to the predictions of Chapter 6, to the results of the tests on V-welded plates (See Section 7.3.3) and EN 1993-1-9 (2005).

Figure 7.38 presents the fatigue strength of the girth welds of cast joints to rolled CHS with yield strength 690 MPa and 890 MPa. The fatigue results are compared to the predictions described in Chapter 6 for estimated weld angles of 25° and 45°. As the diameters of the CHS were too small for inspection on the inside, the angle size could not be measured at the root. It was assumed that there were residual stresses up to yield strength in the trusses, because of restrained displacement during welding. Therefore, the $f_m$ was assumed to be 1, and the predictions were based on $\sigma_{res} = \sigma_y$. The fatigue result in the compressively loaded joint was adjusted by $f_m = 0.67$ according to Eq. 6.10, for the assumption of mean stress $\sigma_m = -150$ MPa. The truss test results with root cracks show that the fatigue life predictions of Chapter 6 very accurate in comparison to the truss test results. Furthermore, the results are in line with the plate test results for root cracks, as can be seen in Figure 7.39.
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 7.38. Adjusted fatigue strength results of truss specimens.

Figure 7.39. Adjusted fatigue life predictions compared with fatigue test results of truss specimens.

Figure 7.40 presents the results of truss specimens compared to EN 1993-1-9 (2005) and the suggested detail class of welded connections of girth weld between CHS and cast members according to Nussbaumer et al. (2010). It should be noted that according to EN1993-1-9 class 71 is only valid for $t < 12.5$ mm. The results of the trusses, with average wall thickness of 23 mm, easily meet detail class 71. The S890 truss results also meet class 100 and are close to 112 according to Nussbaumer et al. (2010), but the trusses contain stresses as a result of tension and bending. The S690 truss just meets class 100. However, the number of test results of the trusses is very limited for a proper comparison.
7. Analysis of fatigue test results

Figure 7.40. Unadjusted fatigue life predictions compared with Eurocode and Nussbaumer et al. (2010).

As can be seen in Figure 7.41, the predictions for initiation of base material cracks by UEG (1985) reasonably match the result of the crack in the cast joint of the S690-G10MnMoV6-3 truss. Also the predictions of the base material cracks in plate specimens fit the result as do the results of base material cracks according to Section 7.3.4.

Figure 7.41. Comparison of adjusted fatigue result of base material crack in G10MnMoV6-3 truss to prediction of UEG (1985) and to results of base material cracks in the plate specimens (Section 7.3.4).
7.5 Influence of yield strength

In the previous sections, the unadjusted fatigue results $\Delta\sigma_{c}$, $\Delta\sigma_{\text{mean}}$ and the adjusted fatigue results $\Delta\sigma_{c\text{N}0}$, $\Delta\sigma_{\text{mean}N0}$ and $\Delta\sigma_{c\text{N}w}$, $\Delta\sigma_{\text{mean}Nw}$ were calculated for the various test series. In this section, the influence of the yield strength will be addressed. Figure 7.42a and Figure 7.42b show results of the base material specimens made of S690 and S1100. For the base material specimens, the fatigue strength seems to increase with yield strength, with calculated slope or slope $m = -5$. Given the results of the base material specimens, evaluation with fixed slope $m = -3$ leads to conservative predictions; for S690, even fatigue designs strength values below the Eurocode recommendations are found.

Figure 7.42a. Unadjusted fatigue strength results of base material specimens for a. $m = x$, b. $m = -3$ and c. $m = -5$; d. plots the absolute value of the calculated slope versus $\sigma_y$. 

Base material plates
EC125 = Detail class 125
EC160 = Detail class 160
R = 0.1 according to EN 1993-1-9 (2005)
S690; $t = 12$ mm
S1100; $t = 10$ mm
7. Analysis of fatigue test results

Figure 7.42b. Adjusted fatigue strength results of base material specimens for a. \( m = x \), b. \( m = -3 \) and c. \( m = -5 \); d. plots the absolute value of the calculated slope versus \( \sigma_y \).

The applied adjustment factor \( f_m \), with \( \sigma_{\text{res}} = \sigma_y \) and \( \sigma_m = 0.5 \cdot \sigma_y \), is more detrimental for S1100, than for S690, because of the assumed higher mean stress sensitivity of S1100. This explains why the fatigue strength of the adjusted results of S1100 is relatively closer to those of S690 in comparison to the unadjusted results.

Figure 7.43a and Figure 7.43b show the unadjusted and the adjusted fatigue results of the X-welded connections made of S355, S690 and S1100. The highest fatigue strength is found for the S1100 specimens if calculated with variable slope \( m \), or \( m = -5 \).
Fatigue strength of welded connections made of very high strength cast and rolled steels

With \( m = -3 \), the calculated fatigue strength is dramatically reduced for S1100. It should be noted that with \( m = -3 \), all results fall below the design values of EN 1993-1-9 (2005). The fatigue strength of the S690 specimens tends to be lower than both S355 and S1100 specimens. In case of unadjusted results, the higher strength of S1100 could be explained by both the effect of yield strength and a positive thickness effect. For the adjusted results, again the factor \( f_y \) is more detrimental for S1100, than for S690.
7. Analysis of fatigue test results

**Figure 7.43b.** Adjusted fatigue strength results of X-welded specimens for a. \(m = x\), b. \(m = -3\) and c. \(m = -5\); d. plots the absolute value of the calculated slope versus \(\sigma_y\).

**Figure 7.44a and Figure 7.44b** show the unadjusted and the adjusted fatigue results of the V-welded plates made of S460, S690, S890 and S1100, which were made of roller to roller plates and cast to rolled plate with cast steels of matching strengths. In the results, all cracks are included independent of initiation location, cap or root. After statistical evaluation with calculated regression coefficient, the fatigue strength increases with yield strength up to S890. The results of the S1100 do not completely fit in this trend. The S890 specimens showed a large number of runouts, which were not included in the statistical evaluation with \(m = -3\) and \(m = -5\).
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure 7.44a. Unadjusted fatigue strength results of V-welded specimens for a. \( m = x \), b. \( m = -3 \) and c. \( m = -5 \); d. plots the absolute value of the calculated slope versus \( \sigma_y \).

The number of runouts gives an indication that the endurance limit of welded connections is higher for S890. For \( m = -5 \), all results meet category 100 according to EN 1993-1-9 (2005).

V-welded plates
- CA
- \( R = 0.1 \)
- S460 - G20Mn5; \( t = 25 \)
- S690 - G10MnMoV6.3; \( t = 25 \)
- S890 - G18NiMoCr3.6; \( t = 25 \)
- S1100 - G22NiMoCr5.6; \( t = 20 \)

EC36 = Detail class 36
EC71 = Detail class 71

according to EN 1993-1-9 (2005)
7. Analysis of fatigue test results

Figure 7.44b. Adjusted fatigue strength results of V-welded specimens for a. \( m = x \), b. \( m = -3 \) and c. \( m = -5 \); d. plots the absolute value of the calculated slope versus \( \sigma_y \).

As there were a lot of specimens tested in bending, loading mode factor \( f_{inw:Nf} \) explains the overall lower fatigue strength of the adjusted compared to the unadjusted data. The effect of the applied adjustment factors \( f_m \) and \( f_{inw:Nf} \) is most detrimental for the S1100 specimens, as they have the highest mean stress sensitivity and smaller specimen thickness.
7.6 Summary of findings
This chapter presents an analysis of fatigue test results of base material specimens and welded specimens made of various steel grades, S355, S460, S690, S890, and S1100 and cast steels G20Mn5, G10MnMoV6-3, G18NiMoCr3-6, and G22NiMoCr5-6. The test data were adjusted to obtain results for reference case with thickness $t = 25$ mm, loading mode $= \sigma_{res}$, with $\sigma_{m} = 0.5 \sigma_{y}$, for representative comparison to detail categories according to Eurocode 1993-1-9 (2005).

In the statistical analysis, the slope of the fatigue strength curve $m$ was based on the linear regression coefficient $b$, or was fixed to $m = -3$ or $m = -5$. The characteristic fatigue strength at $2 \times 10^6$ cycles, $\Delta \sigma_c$, and the mean fatigue strength, $\Delta \sigma_{mean}$, were derived for the three slope values, for adjusted and unadjusted results. Next to the fatigue prediction of the medium cycle regime, the constant amplitude fatigue limit and the characteristic fatigue strength depend on the chosen slope $m$. For VHSS, the slope tends to be closer to $m = -3$ if the fatigue life is dominated by crack propagation life, whereas values up to $m = -5$ are found if the fatigue life is predominantly based on crack initiation.

In general, the fatigue strength of base material specimens, X-welded specimens, and V-welded specimens was found to increase with yield strength; this effect was mainly visible in the unadjusted results. The adjusted results meet the relevant detail categories of EN 1993-1-9 (2005) with slope $m = -3$. Increased fatigue strength was found if a more representative value $m = -5$ was assumed in the evaluation.

The fatigue life of the root and the cap side of the V-welded specimens was studied. The fatigue life of weld cap cracks tended to be higher than the fatigue life of weld root cracks. The main reason for this was the weld toe profile difference of the cap and the root side. The average weld toe angle was higher on the root side than on the cap side. Because of the limited number of specimens and weld toe cracks initiation, the effect of welding with ceramic backing could not properly be addressed within the current research.

Not only weld toe cracks but also base material cracks were found in the rolled and cast steels of specimens made of S460, S890, and S1100. The reason for this was the presence of initial defects, which caused the fatigue life to mainly consist of crack propagation. Predictions for the fatigue life were non-conservative for these base material cracks.

The plate test results were compared to the results of fatigue tests on trusses made of S690 and S890 presented in Chapter 5. The trusses were made of CHS, which were V-girth-welded to cast joints, with similar yield strength. Three fatigue cracks were found in the S890 truss, which all had initiated in the weld root, on the inside of the connection. One weld root crack was found in the S690 truss, another crack in one of the cast joints. Comparison of the test results of the truss specimens with root cracks were close to the results of the V-welded plate specimens with root cracks of similar strengths, S690 and S890. The fatigue life predictions of Chapter 6 are accurate in comparison to the truss test results. Furthermore, the results are in line with the plate test results for root cracks. The results of truss specimens meet detail class 71 according to EN 1993-1-9 (2005), although the detail class for girth welds is only valid for wall thickness $t < 12.5$, whilst the average wall thickness of the specimens was 23 mm. The predictions for initiation of base material cracks by UEG (1985) reasonably match the result of the crack in the base material of the
cast joint of the S690 truss. Also the results of the base material cracks in plate specimens fit to the truss result.
8. Conclusions and Recommendations

8.1 Evaluation of research project

The main goal of this research was the determination of the fatigue strength of welded connections made of very high strength steels (VHSS), for an effective application of VHSS in civil engineering and offshore structures. The emphasis was put on quenched and tempered cast and rolled steels with yield strengths of 690 MPa up to 1100 MPa. The research consisted of a literature study, an experimental study and an analysis of the results.

Materials and specimens for the experiments were selected based on a literature survey. Two types of specimens were tested: plate specimens and truss specimens. The plate test series comprised of base material specimens, X-welded specimens and V-welded specimens. The truss specimens were made of circular hollow sections (CHS) welded to cast joints. Crack initiation and crack propagation life were studied as an effect of cyclic loading. Strain gauges were applied on the plate and truss specimens to identify crack initiation, after which crack growth was monitored visually until failure.

First, base material strips made of S690 and S1100 were tested under tension loading, for which it was anticipated that there would be an advantage of higher yield strength. Next, strip specimens derived from X-welded plates made of S355, S690 and S1100 were tested under tension loading. The majority of the plate tests was carried out on strip specimens derived from V-welded plates. The V-welded specimens were made in three alternative conditions: welded rolled steel to rolled steel parts, welded rolled steel to cast steel parts without use of a backing and of welded rolled steel to cast steel parts with use of a ceramic backing. The selected materials were steel grades S460, S690, S890 and S1100 with similar strength cast steels, G20Mn5, G10MnMoV6-3, G18NiMoCr3-6 and G22NiMoCr5-6 respectively.

Additionally, fracture mechanics tests were executed on welded specimens derived from the V-welded rolled steel to rolled steel parts with predefined crack in the base material and the heat affected zone. The fracture mechanics specimens were loaded in three point bending. By defining initial crack locations, crack growth could be monitored to derive the VHSS material parameters of based on fracture mechanics theory.

As it was expected that VHSS would be applied most effectively in truss-like structures, two truss specimens were tested, which were made of CHS and cast joints. The selected materials for the trusses were CHS made of S690 and S890 and cast joints made of G10MnMoV6-3 and G18NiMoCr3-6 respectively. The trusses contained 14 connections, which were V-girth-welded without backing in welding position vertical up. The welding procedures were similar to those used for the strip specimens that were V-welded without backing, made of S690 and S890.

The notch stress theory was used for the prediction of the crack initiation life Ni and the linear elastic fracture mechanics theory for the crack propagation life Np. The fatigue life predictions were compared to the experimental results of weld toe cracks and base material cracks. The test results were adjusted for several influence factors, such as thickness effect, loading mode and residual stress state, for a representative comparison to detail categories according to EN 1993-1-9 (2005). In the statistical analysis, the regression coefficient was either taken as a variable, or was fixed to m = -3 or m = -5. For both adjusted and unadjusted results, the characteristic and the mean fatigue strength at $2 \times 10^6$ cycles are...
8. Conclusions and Recommendations

Cycles were derived for all regression coefficients and compared to the relevant results from literature.

Section 8.2 presents the conclusions of this dissertation; Section 8.3 outlines the recommendations for further research.

8.2 Conclusions

The fatigue life of structural members is characterized by the crack initiation life and crack propagation life. The main conclusion of this dissertation is that higher yield strength increases crack initiation life of base material and welded connections in case of low notch stress concentration and small initial imperfections.

The following sections present conclusions for the structural use of VHSS in fatigue loaded structures, fatigue life prediction and the conclusions for the individual test series.

8.2.1 Structural use of VHSS in fatigue loaded structures

With regard to the structural use of VHSS in fatigue loaded structures, the following can be concluded:

- Lack of design rules and manufacturing experience, scarcity of special sections as well as conservatism limit the current structural application of VHSS (literature, confirmed by current study);
- Effective application of VHSS should lead to reduced wall thickness in comparison to mild steel solutions. Inevitably, higher absolute and relative stress ranges will be obtained. Therefore, the fatigue strength of welded connections is expected to be the governing design criterion (literature);
- The modulus of elasticity of steel is independent of yield strength. Truss structures enable full exploitation of the high material strength of VHSS, because in such stiff structures the deflection is not the governing design criterion for VHSS applications (literature);
- In fatigue loaded VHSS structures, high stress concentrations should be avoided as these limit the effectiveness of VHSS. Choosing high class details and high manufacturing quality for VHSS structures is thus required (literature, confirmed by current study);
- Improved design of VHSS truss structures requires the application of very high strength cast joints, as an appropriate design of cast joints limits the stress concentrations (current study).

8.2.2 Fatigue life prediction

For the fatigue life prediction the following conclusions hold:

- Yield strength, mean stress and surface roughness govern the crack initiation life of unnotched structural members. Additionally, thickness, loading mode and weld shape determine the fatigue strength of notched structural members (literature, confirmed by current study);
- The fatigue notch factor of welded connections can be determined by the theory of the microstructural notch support, originally conceived by Peterson (1974), which links the fatigue notch factor to the tensile strength. An improved weld shape, characterized by increased weld toe radius or decreased weld toe angle, increases the fatigue strength with higher yield strengths (literature, confirmed by current study);
Fatigue strength of welded connections made of very high strength cast and rolled steels

- Next to geometric improvement, a compressive mean stress, or compressive residual stress state could be beneficial for high strength steels, because the mean stress sensitivity increases with yield strength (literature);
- The crack propagation life depends on the crack growth rate as a function of the stress intensity range, which is typically characterized by the crack shape, thickness, width and weld shape, not by the yield strength (literature, confirmed by current study).

8.2.3 Fatigue experiments on base material plate specimens made of rolled steel

The fatigue experiments on base material specimens made of rolled steel, carried out in the current study lead to these conclusions:
- The fatigue strength of base material specimens is found to increase with yield strength. The choice of regression coefficient b, which is similar to the slope of the fatigue strength curve m, is of large influence on the outcome of the statistical analysis8, determining the mean and characteristic fatigue strength, (See Table 8.1). Slope m = -3 leads to conservative predictions (current study);

<table>
<thead>
<tr>
<th>Detail</th>
<th>$\Delta\sigma_c$; $\Delta\sigma_{c\text{;u}}$</th>
<th>m</th>
<th>Rolled grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>188/112/196</td>
<td>-5.8 / -3 / -5</td>
<td>S690</td>
<td>Unadjusted t = 25 mm Bending + Tension</td>
<td></td>
</tr>
<tr>
<td>278/179/275</td>
<td>-6.8 / -3 / -5</td>
<td>S1100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>166/99/174</td>
<td>-5.8 / -3 / -5</td>
<td>S690</td>
<td>Adjusted t = 25 mm $\sigma_{\text{res}} = \sigma_c$; Tension</td>
<td></td>
</tr>
<tr>
<td>234/150/232</td>
<td>-6.8 / -3 / -5</td>
<td>S1100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The fatigue life of base material specimens is found to mainly consist of crack initiation life. In comparison to the fatigue test results, the predictions tend to overestimate the crack initiation life of the base material specimens. The predictions for the crack propagation life are found to be conservative in comparison to the experimental results (current study).

8.2.4 Fatigue experiments on X-welded plate specimens made of rolled steel

The fatigue experiments on X-welded specimens carried out in the current study show:
- Equal to the results of the base material specimens, the fatigue strength of X-welded specimens is found to increase with yield strength. Again, the choice of the slope of the fatigue strength curve m is of large influence on the outcome of the statistical analysis8, the mean and characteristic fatigue strength. Slope m = -3 leads to conservative predictions (current study);
- The fatigue strength of specimens made of S1100 is found to be higher than similar specimens made of S355 and S690, if the slope of the fatigue strength curve m is taken to be variable or fixed to m = -5. With m = -3, the calculated characteristic fatigue strength of the S1100 specimens is reduced, (See Table 8.2). Remarkably, the fatigue strength of the S690 specimens tends to be lower than both the results of the S355 and S1100 specimens. (current study).

8The number of results of base material specimens and X-welded specimens was smaller than 12.
Table 8.2. Summary of fatigue strength results of X-welded specimens.

<table>
<thead>
<tr>
<th>Detail</th>
<th>$\Delta \sigma_c; \Delta \sigma_{c,w}; N_f$</th>
<th>Rolled grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>125/106/137</td>
<td>-4.1/-3/-5</td>
<td>S355</td>
<td>Unadjusted</td>
</tr>
<tr>
<td>121/114/127</td>
<td>-3.5/-3/-5</td>
<td>S690</td>
<td>t = 25 mm, Bending + Tension</td>
</tr>
<tr>
<td>194/97/180</td>
<td>-6.1/-3/-5</td>
<td>S1100</td>
<td></td>
</tr>
<tr>
<td>95/77/100</td>
<td>-4.4/-3/-5</td>
<td>S355</td>
<td>Adjusted t = 25 mm</td>
</tr>
<tr>
<td>83/77/87</td>
<td>-3.5/-3/-5</td>
<td>S690</td>
<td></td>
</tr>
<tr>
<td>108/60/106</td>
<td>-5.5/-3/-5</td>
<td>S1100</td>
<td></td>
</tr>
</tbody>
</table>

8.2.5 Fatigue experiments on V-welded plate specimens made of cast and rolled steel

From the fatigue experiments on V-welded specimens carried out in the current study the following can be concluded:

- The fatigue strength of specimens made of V-welded rolled steel to rolled steel plates is found to be in the same scatter range as similar specimens made of V-welded rolled steel to cast steel plates (current study);
- The fatigue strength of V-welded specimens tends to increase with yield strength, (See Table 8.3) if evaluated with free slope. The highest fatigue strengths are found for the S890 specimens (current study);

Table 8.3. Summary of fatigue strength results of V-welded cast/rolled and rolled/rolled specimens.

<table>
<thead>
<tr>
<th>Detail</th>
<th>$\Delta \sigma_c; \Delta \sigma_{c,w}; N_f$</th>
<th>Rolled grade</th>
<th>Cast grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>133/121/158</td>
<td>-3.5/-3/-5</td>
<td>S460</td>
<td>G20Mn5</td>
<td>Unadjusted t = 25 mm, Bending + Tension</td>
</tr>
<tr>
<td>138/97/144</td>
<td>-4.7/-3/-5</td>
<td>S690</td>
<td>G10 MnMoV6-3</td>
<td></td>
</tr>
<tr>
<td>176/128/171</td>
<td>-4.8/-3/-5</td>
<td>S890</td>
<td>G18NiMoCr3-6</td>
<td></td>
</tr>
<tr>
<td>172/139/177</td>
<td>-5.4/-3/-5</td>
<td>S1100</td>
<td>G22 NiMoCr5-6</td>
<td></td>
</tr>
<tr>
<td>93/86/114</td>
<td>-3.4/-3/-5</td>
<td>S460</td>
<td>G20Mn5</td>
<td>Adjusted t = 25 mm, $\sigma_{res} = \sigma_y$</td>
</tr>
<tr>
<td>101/69/102</td>
<td>-4.9/-3/-5</td>
<td>S690</td>
<td>G10 MnMoV6-3</td>
<td></td>
</tr>
<tr>
<td>123/80/108</td>
<td>-4.8/-3/-5</td>
<td>S890</td>
<td>G18NiMoCr3-6</td>
<td></td>
</tr>
<tr>
<td>94/86/109</td>
<td>-4.7/-3/-5</td>
<td>S1100</td>
<td>G22 NiMoCr5-6</td>
<td></td>
</tr>
</tbody>
</table>

- The S890 and S1100 specimens show a large number of runouts, which are not included in the statistical evaluation with m = -3 and m = -5. The runouts indicate that the endurance limit of welded connections is higher, and furthermore that the slope of the fatigue strength curve is higher, which means closer to m = -5 than to m = -3 for increased yield strength (current study);
- Not only weld toe cracks, but also base material cracks were found in cast and rolled parts. The reason for this is the presence of initial defects in the base material, which caused the fatigue life to be dominated by crack propagation. The predictions of the fatigue life of these base material cracks are therefore non-conservative if they are based on summation of crack initiation and crack propagation life, whilst no NDT is performed on the base material parts. The fatigue strength of the base material parts fall above detail category 125, but below detail category 160 according to EN 1993-1-9 (2005) (current study);
- When performing tension loading in the fatigue tests, the tensile stress ranges in the cap were higher than in the root, because of angular misalignment of the specimens as a result of welding. Some specimens were therefore additionally loaded by four point bending, in such a way, that the highest tensile stress range was either in the root or in the cap of the specimens. The fatigue strength of the weld root was found to be lower than that of the cap side, mainly because of a higher weld toe angle in the root. Because of the small number of
Fatigue strength of welded connections made of very high strength cast and rolled steels

- Fatigue experiments on truss specimens
  - In V-girth-welded connections of cast steel joints and CHS, weld root cracks are more likely to occur than weld cap cracks, because the expected quality in the root is lower than in the cap (literature, confirmed by current study);
  - The fatigue strength results of V-welded plate specimens with root cracks and the results of truss specimens with V-girth-welded CHS to cast joints with root cracks were similar. The fatigue life predictions agreed with the results of the truss specimens (current study);
  - Although it was assumed that no cracks would initiate in the cast joints, one crack initiated in a reinforcement position of cast joint made of S690 - G10MnMoV6-3. Any part of a cast joint, also the feeder, riser and cast reinforcement positions, should therefore be taken in account in the design as being potential crack initiation locations if there is no possibility of grinding after the casting (current study);
  - The results of the S890 - G18NiMoCr3-6 truss specimen and to a smaller extent of the S690 - G10MnMoV6-3 truss specimen tend to show a higher fatigue strength than the results obtained by Haldimann Sturm et al (2005) on truss specimens made of similar V-girth-welded CHS to cast joint connections made of S355 - G20MN5 and results by Puthli et al. (2007) on V-girth welded CHS cast joint end-to-end connections made of S355 - G20Mn5. This is assumed to be related to the higher yield strength of the materials used in the current work (current study);
  - The results of the truss specimens meet detail class 71 according to EN 1993-1-9 (2005), although the detail class for girth welds is only valid for wall thickness t < 12.5, whilst the average wall thickness of the specimens was 23 mm. The S890 truss results also meet class 100 and are close to 112 according to Nussbaumer et al. (2010); the S690 truss just meets class 100. However, the number of test results of the trusses is very limited for a proper comparison (current study);
  - The predictions for initiation of base material cracks by UEG (1985) reasonably match the result of the crack in the cast joint of the S690 truss (current study).

8.3 Recommendations for further research
The following recommendations for further research can be formulated:
- For steels with yield strength larger than 690 MPa, design rules should be developed. Otherwise, the use of these steels will be limited in practice.
- For extension of design rules for VHSS, all fatigue test data on VHSS welded connections should be summarised and analysed, with detailed assessment of welding procedure, weld
8. Conclusions and Recommendations

quality, weld shape, welding position, sequence of welding, residual stress state, thickness and loading mode for appropriate adjustment of the data.
- In particular, the amount of data of girth welded connections made of VHSS should increase;
- The root part of the girth welded connections of cast steel joints to rolled parts, plates or CHS, is found to be the weakest part with regard to the fatigue strength. Improvement of the weld root is therefore expected to be the key to increase the fatigue strength of a cast joint, especially if made of VHSS. First, improved welding procedures are required, which should lead to an improved weld root shape, whilst guaranteeing full penetration welds, preferably with low residual stresses. This means assessment of the weld root quality, with emphasis on locations that cannot be monitored visually. In CHS connections, better weld root quality could be realised with application of a ceramic backing, if care is taken to obtain low weld toe angles. Hybrid laser-arc welding applications or choice of special weld consumables could improve the residual stress state in the root. Furthermore, application of a positive misalignment could increase the strength of the root. If for the root of the CHS and the cast member an identical inner diameter is taken, and the outer diameter is varied, the resulting secondary bending moment may increase the stresses in the cap and lower those in the root;
- Economic weld procedures should be developed for an effective use of VHSS in practice. Reduction of necessary preheat temperature and improvement of welding consumables would make the manufacturing more efficient. It is expected that use of automatic welding could improve the weld shape geometry compared to manual welding, which is favourable for VHSS. Also, the effect of repair welds should be assessed;
- Post weld treatment techniques have been found to have a positive influence on the fatigue strength, especially for VHSS if weld profiles are improved and high compressive residual stresses are obtained. It is expected that such techniques can only improve the weld cap, which is accessible from the outside. Fatigue data on TIG-dressing, grinding and peening should be combined for design recommendations;
- The design and manufacturing process of cast joints should be carried out in close cooperation with the cast steel foundry. This incorporates the choice of adequate shape, alloying elements, and temperature treatment;
- As the local geometry is of large influence on the fatigue strength, especially for VHSS, it is of importance to assess the quality by visual inspection and appropriate NDT. Better adjustment of execution quality to fatigue guidelines is necessary as well;
- Further study on the effect of variable amplitude is needed. In reality, dynamically loaded structures experience loading spectra with variable amplitudes. In some cases, the design assumption of constant amplitude may either be conservative or non-conservative. Crack retardation effect as a result of overloading may not be as beneficial for high strength steels as for mild steels.
- Further study of the determination of residual stress states is needed. VHSS are shown to have a higher mean stress sensitivity compared to mild steels. This means that the height of residual stresses, for instance as a result of welding, will be of relatively large influence on the fatigue strength of VHSS. In practice, it is assumed that residual stresses will reach the yield strength. The more compressive the residual stress ranges, the more beneficial their effect is on the fatigue strength;
- For a proper comparison of the economical efficiency of VHSS, cost calculations should be carried out for truss structures. Design comparisons should be made between conventionally welded joints made of mild steels and VHSS, and an improved design by use of cast joints made of mild steels and VHSS. Iteratively, the design should be optimised for repetition and total weld length for bridge and offshore applications;
- Next to the fatigue strength, the influence of stability on the VHSS truss design and its deformation capacity should be addressed;
- The influence of a corrosive environment as well as low temperature on the fatigue strength and toughness of welded VHSS connections should be studied;
- Next to welded connections, attention must go to the assessment of the fatigue strength of VHSS base material. With respect to surface roughness, the effect of blasting on the fatigue strength of VHSS base materials should be considered. The blasting process could improve the surface roughness and introduce compressive residual stresses on the surface.
References


<table>
<thead>
<tr>
<th>Reference</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
</tbody>
</table>
References


“Development of high-strength steels with optimised Y/T-ratio for high-loaded applications”, Final report EUR 19987, Luxembourg.


“To cast or not to cast”, Proceedings of the 10th International Symposium on Tubular Structures, Tubular Structures X, Madrid, pp. 129-134.


“Use and application of high performance steels for steel structures”, IABSE Structural engineering documents 8, Zürich.

Gurney, T.R. (1979)


Heywood, R.E. (1962)

Hobbacher, A. (2007)
“Recommendations for fatigue design of welded joints and

216


Lieurade, H.P., Huther, I. &
References


Fatigue strength of welded connections made of very high strength cast and rolled steels

“Fatigue experiments on hybrid welded connections made of Very High Strength Steels”, Fatigue & Fracture 2009, Philadelphia

“Fatigue strength of hybrid VHSS-cast steel welded plates”, Nordic Steel Construction Conference, Malmö, pp. 478-485

“Fatigue strength of truss girders made of Very High Strength Steel”, In: Young ed., Proceedings of the 13th international symposium on tubular structures, Hong Kong, pp. 499-505


Pors, W. et al. (2008)
“Constructiestaalsoorten met hoge sterkte” (In Dutch), “Structural steels with high strength”, VM Publicatie 125.


“Wirtschaftliches Bauen von Straßen- und Eisenbahnbrücken aus Stahlhohlprofilen”, [In German], Economic use of structural hollow sections for highway and railway bridges”, FOSTA Projekt 591, Verlag und Vertriebsgesellschaft, Düsseldorf


Ramberg, W. & Osgood, W.R. (1943)
“Description of stress-strain curves by three parameters”, Techn Rep 902, NACA


Sedlacek, G. & Müller, C.  “The use of very high strength steels in metallic construction”,
<table>
<thead>
<tr>
<th>Year</th>
<th>Reference</th>
</tr>
</thead>
</table>


Appendix A, Fatigue results literature

Section 3.3 of this dissertation summarizes a number of literature references on the experimentally determined fatigue strength of welded connections. The current appendix plots the fatigue results against the nominal yield strength of the tested materials. The following fatigue strength variables are given:

- $\sigma_{a,95}$ Characteristic value of endurable stress amplitude
- $\sigma_{a,50}$ Mean value of endurable stress amplitude
- $\Delta \sigma_{95}$ Characteristic stress range at $N_f = 2 \times 10^6$ cycles
- $\Delta \sigma_{50}$ Mean stress range at $N_f = 2 \times 10^6$ cycles

If the slope of the fatigue strength is known from the research, the absolute value of $m$ is also plotted against the nominal yield strength.

![Figure A1](image)

![Figure A2](image)

![Figure A3](image)
Appendix A, Fatigue results literature

Figure A4

Figure A5

Figure A6

Figure A7
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure A8

Figure A9

Figure A10

Figure A11
Appendix A, Fatigue results literature

Figure A12

Figure A13

Figure A14

Figure A15
Fatigue strength of welded connections made of very high strength cast and rolled steels

Figure A16

Figure A17

Figure A18

Figure A19
Appendix A, Fatigue results literature

Figure A20

Figure A21

Figure A22

Figure A23
Fatigue strength of welded connections made of very high strength cast and rolled steels

**Figure A24**

[Kuhlmann et al. 2006]
[Kuhlmann et al. 2005]
transverse stiffener
mid scale
CA, bend
\( t = 25 \) (\( B = 160 \))
\( R = 0.1 \)

**Figure A25**

[Kuhlmann et al. 2006]
[Kuhlmann et al. 2005]
transverse stiffener
mid scale
CA
\( t = 12 \) (\( B = 160 \))
\( R = 0.1 \)

**Figure A26**

[Kuhlmann et al. 2006]
[Kuhlmann et al. 2005]
transverse stiffener
HEA 300-stiffener
bending
\( R = -1 \)

**Figure A27**

[Kuhlmann et al. 2006]
[Kuhlmann et al. 2005]
transverse stiffener
HEA 300-stiffener
bending
\( R = 0.5 \)
Appendix A, Fatigue results literature

Figure A28

Figure A29
Appendix B, Material specification

Base material specimens and X-welded specimens

Table B1 presents the origin of the materials S355, S690 and S1100, which were used for the X-welded specimens of series SA, FB and FB. The S690 and S1100 materials were also used in the test series of base material specimens. Table B2 gives the chemical composition and table B3 the mechanical properties.

Table B1. Origin material

<table>
<thead>
<tr>
<th>Steel supplier</th>
<th>Grade</th>
<th>Steel supplier</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355J2+AR</td>
<td>Arcelor Mittal</td>
<td>S355J2+AR</td>
<td></td>
</tr>
<tr>
<td>Naxtra M 70</td>
<td>Thyssen Krupp</td>
<td>S690Q</td>
<td></td>
</tr>
<tr>
<td>Weldox S1100 E</td>
<td>SSAB</td>
<td>S1100Q</td>
<td></td>
</tr>
</tbody>
</table>

Table B2. Chemical composition.

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>V</th>
<th>Nb</th>
<th>Al</th>
<th>Ti</th>
<th>Cu</th>
<th>N</th>
<th>B</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355J2+AR</td>
<td>0.17</td>
<td>0.21</td>
<td>1.37</td>
<td>0.011</td>
<td>0.013</td>
<td>0.06</td>
<td>0.005</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S690Q</td>
<td>0.16</td>
<td>0.19</td>
<td>0.87</td>
<td>0.012</td>
<td>0.002</td>
<td>0.33</td>
<td>0.22</td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1100Q</td>
<td>0.16</td>
<td>0.23</td>
<td>0.86</td>
<td>0.007</td>
<td>0.002</td>
<td>0.6</td>
<td>0.586</td>
<td>1.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade</th>
<th>V</th>
<th>Nb</th>
<th>Al</th>
<th>Ti</th>
<th>Cu</th>
<th>N</th>
<th>B</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355J2+AR</td>
<td>0</td>
<td>0.033</td>
<td>0.05</td>
<td>0</td>
<td>0.11</td>
<td>0.005</td>
<td>0.0009</td>
<td>0.007</td>
</tr>
<tr>
<td>S690Q</td>
<td>0.026</td>
<td>0.085</td>
<td></td>
<td>0.0038</td>
<td>0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1100Q</td>
<td>0.029</td>
<td>0.02</td>
<td>0.066</td>
<td>0.004</td>
<td>0.04</td>
<td>0.005</td>
<td>0.002</td>
<td></td>
</tr>
</tbody>
</table>

Table B3. Mechanical properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>n</th>
<th>R_p;0.2 [MPa]</th>
<th>R_m [MPa]</th>
<th>R_p;0.2 /R_m</th>
<th>A</th>
<th>Z</th>
<th>Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S355</td>
<td>1</td>
<td>375</td>
<td>509</td>
<td>0.74</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S690</td>
<td>3</td>
<td>733</td>
<td>787</td>
<td>0.93</td>
<td>17</td>
<td>0.43</td>
<td>Plasma cut</td>
</tr>
<tr>
<td>S1100</td>
<td>3</td>
<td>1086</td>
<td>1135</td>
<td>0.96</td>
<td>11</td>
<td>0.57</td>
<td>Plasma cut</td>
</tr>
<tr>
<td>S1100</td>
<td>3</td>
<td>1117</td>
<td>1187</td>
<td>0.94</td>
<td>-</td>
<td>0.55</td>
<td>Water cut</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade</th>
<th>n</th>
<th>R_p;0.2 [MPa]</th>
<th>R_m [MPa]</th>
<th>R_p;0.2 /R_m</th>
<th>A</th>
<th>Z</th>
<th>Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data sheet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S355</td>
<td>-</td>
<td>395</td>
<td>544</td>
<td>0.73</td>
<td>26</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S690</td>
<td>-</td>
<td>800</td>
<td>830</td>
<td>0.96</td>
<td>16</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S1100</td>
<td>-</td>
<td>1197</td>
<td>1432</td>
<td>0.84</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### V-welded specimens

Table B4 presents the origin of the materials S460, S690, S890 and S1100, and cast steels G20Mn5, G10MnMoV6-3, G18NiMoCr3-6 and G22NiMoCr5-6, which were used for the V-welded specimens. Table B5 gives the chemical composition and table B6 the mechanical properties.

#### Table B4. Origin Plate material.

<table>
<thead>
<tr>
<th>Grade</th>
<th>t [mm]</th>
<th>Length [mm]</th>
<th>Width [mm]</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>S460</td>
<td>25</td>
<td>2000</td>
<td>2000</td>
<td>Dillinger Hütte</td>
</tr>
<tr>
<td>S690</td>
<td>25</td>
<td>3000</td>
<td>2600</td>
<td>Dillinger Hütte</td>
</tr>
<tr>
<td>S890</td>
<td>25</td>
<td>3000</td>
<td>2000</td>
<td>Dillinger Hütte</td>
</tr>
<tr>
<td>S1100</td>
<td>20</td>
<td>3000</td>
<td>2000</td>
<td>Dillinger Hütte</td>
</tr>
<tr>
<td>G20Mn5</td>
<td>25</td>
<td>1000</td>
<td>500</td>
<td>Friedrich Wilhelms Hütte</td>
</tr>
<tr>
<td>G10MnMoV6-3</td>
<td>25</td>
<td>1000</td>
<td>500</td>
<td>Friedrich Wilhelms Hütte</td>
</tr>
<tr>
<td>G18NiMoCr3-6</td>
<td>25</td>
<td>1000</td>
<td>500</td>
<td>Friedrich Wilhelms Hütte</td>
</tr>
<tr>
<td>G22NiMoCr5-6</td>
<td>20</td>
<td>1000</td>
<td>500</td>
<td>Friedrich Wilhelms Hütte</td>
</tr>
</tbody>
</table>

#### Table B5. Chemical composition.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>S460</td>
<td>0.075</td>
<td>0.20</td>
<td>1.57</td>
<td>0.011</td>
<td>0.0010</td>
<td>0.032</td>
<td>0.004</td>
<td>0.317</td>
</tr>
<tr>
<td>S690</td>
<td>0.160</td>
<td>0.282</td>
<td>1.280</td>
<td>0.011</td>
<td>0.0007</td>
<td>0.025</td>
<td>0.390</td>
<td>0.0320</td>
</tr>
<tr>
<td>S890</td>
<td>0.168</td>
<td>0.281</td>
<td>0.98</td>
<td>0.012</td>
<td>0.0008</td>
<td>0.494</td>
<td>0.511</td>
<td>0.98</td>
</tr>
<tr>
<td>S1100</td>
<td>0.158</td>
<td>0.271</td>
<td>0.87</td>
<td>0.012</td>
<td>0.0004</td>
<td>0.47</td>
<td>0.46</td>
<td>1.95</td>
</tr>
<tr>
<td>G20Mn5</td>
<td>0.21</td>
<td>0.56</td>
<td>1.45</td>
<td>0.013</td>
<td>0.002</td>
<td>0.15</td>
<td>0.13</td>
<td>0.20</td>
</tr>
<tr>
<td>G10MnMoV6-3</td>
<td>0.11</td>
<td>0.45</td>
<td>1.70</td>
<td>0.011</td>
<td>0.003</td>
<td>0.11</td>
<td>0.39</td>
<td>0.46</td>
</tr>
<tr>
<td>G18NiMoCr3-6</td>
<td>0.22</td>
<td>0.40</td>
<td>1.16</td>
<td>0.012</td>
<td>0.003</td>
<td>0.89</td>
<td>0.61</td>
<td>0.80</td>
</tr>
<tr>
<td>G22NiMoCr5-6</td>
<td>0.23</td>
<td>0.47</td>
<td>0.96</td>
<td>0.011</td>
<td>0.002</td>
<td>0.80</td>
<td>0.57</td>
<td>0.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>V</th>
<th>N</th>
<th>Cu</th>
<th>B</th>
<th>Ti</th>
<th>Al-T</th>
<th>Nb</th>
<th>Al</th>
<th>Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>S460</td>
<td>0.0037</td>
<td>0.160</td>
<td>0.0001</td>
<td>0.002</td>
<td>0.038</td>
<td>0.019</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S690</td>
<td>0.0420</td>
<td>0.024</td>
<td>0.0019</td>
<td>0.003</td>
<td>0.08</td>
<td>0.024</td>
<td>0.0002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S890</td>
<td>0.041</td>
<td>0.024</td>
<td>0.0022</td>
<td></td>
<td>0.011</td>
<td>0.074</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1100</td>
<td>0.02</td>
<td>0.0042</td>
<td>0.0016</td>
<td></td>
<td>0.013</td>
<td>0.061</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G20Mn5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G10MnMoV6-3</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G18NiMoCr3-6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G22NiMoCr5-6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table B6. Mechanical properties.

<table>
<thead>
<tr>
<th></th>
<th>$R_{p0.2}$</th>
<th>$R_m$</th>
<th>$A$</th>
<th>$Z$</th>
<th>RT</th>
<th>-40°C</th>
<th>HB</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>G20Mn5</td>
<td>510</td>
<td>622</td>
<td>25.6</td>
<td>64</td>
<td>172-181</td>
<td>98</td>
<td>185</td>
<td>940/water + 680/water</td>
</tr>
<tr>
<td></td>
<td>485</td>
<td>599</td>
<td>27</td>
<td>64</td>
<td>172-181</td>
<td>100</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td></td>
<td>512</td>
<td>611</td>
<td>26.6</td>
<td>67.5</td>
<td>172-181</td>
<td>100</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>G10MnMoV6-3</td>
<td>743</td>
<td>799</td>
<td>18.6</td>
<td>64</td>
<td>98-135</td>
<td>37</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td></td>
<td>718</td>
<td>785</td>
<td>21.2</td>
<td>70.8</td>
<td>98-135</td>
<td>45</td>
<td>243</td>
<td></td>
</tr>
<tr>
<td></td>
<td>775</td>
<td>841</td>
<td>18</td>
<td>67.5</td>
<td>98-135</td>
<td>40</td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>G18NiMoCr3-6</td>
<td>976</td>
<td>1042</td>
<td>15.8</td>
<td>57.7</td>
<td>67-80</td>
<td>43</td>
<td>321</td>
<td>940/water + 620/water</td>
</tr>
<tr>
<td></td>
<td>972</td>
<td>1052</td>
<td>13.8</td>
<td>46.7</td>
<td>67-80</td>
<td>46</td>
<td>331</td>
<td>920/water + 580/water</td>
</tr>
<tr>
<td></td>
<td>1001</td>
<td>1070</td>
<td>12</td>
<td>36</td>
<td>67-80</td>
<td>36</td>
<td>333</td>
<td>920/water + 580/water</td>
</tr>
<tr>
<td>G22NiMoCr5-6</td>
<td>1126</td>
<td>1185</td>
<td>12.6</td>
<td>40.7</td>
<td>86-75</td>
<td>33</td>
<td>366</td>
<td>920/water + 580/water</td>
</tr>
<tr>
<td></td>
<td>1113</td>
<td>1163</td>
<td>12.8</td>
<td>42.4</td>
<td>86-75</td>
<td>39</td>
<td>363</td>
<td>930/water + 560/water + 585/water</td>
</tr>
<tr>
<td></td>
<td>1118</td>
<td>1171</td>
<td>12.6</td>
<td>42.2</td>
<td>86-75</td>
<td>32</td>
<td>363</td>
<td>930/water + 560/water + 585/water</td>
</tr>
<tr>
<td>S460</td>
<td>469</td>
<td>590</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td>222</td>
<td></td>
</tr>
<tr>
<td>S690</td>
<td>792</td>
<td>843</td>
<td>17.9</td>
<td></td>
<td></td>
<td></td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>S890</td>
<td>1000</td>
<td>1065</td>
<td>16.1</td>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>S1100</td>
<td>985</td>
<td>1051</td>
<td>14.3</td>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>

Truss specimens

Table B7 presents the origin of the rolled steels S690 and S890, and cast steels G10MnMoV6-3 and G18NiMoCr3-6 that were used for the truss specimens. Table B8 gives the chemical composition and table B9 the mechanical properties.

Table B7. Origin material.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Dxt [mm]</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>S690</td>
<td>273.1 x 22.20</td>
<td>Vallourec Mannesmann</td>
</tr>
<tr>
<td>S890</td>
<td>219.1 x 22.20</td>
<td>Vallourec Mannesmann</td>
</tr>
<tr>
<td>G10 MnMoV6-3</td>
<td></td>
<td>Friedrich Wilhelms Hütte</td>
</tr>
<tr>
<td>G18NiMoCr3-6</td>
<td></td>
<td>Friedrich Wilhelms Hütte</td>
</tr>
</tbody>
</table>
### Table B8. Chemical composition

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>S690G2QL1</td>
<td>0.16</td>
<td>0.28</td>
<td>1.56</td>
<td>0.011</td>
<td>0.0010</td>
<td>0.68</td>
<td>0.26</td>
<td>0.11</td>
</tr>
<tr>
<td>G10MnMoV6-3</td>
<td>0.12</td>
<td>0.46</td>
<td>1.59</td>
<td>0.012</td>
<td>0.001</td>
<td>0.16</td>
<td>0.31</td>
<td>0.44</td>
</tr>
<tr>
<td>S890G1QL</td>
<td>0.18</td>
<td>0.39</td>
<td>1.41</td>
<td>0.014</td>
<td>0.0020</td>
<td>0.63</td>
<td>0.35</td>
<td>0.16</td>
</tr>
<tr>
<td>G18NiMoCr3-6 (1)</td>
<td>0.19</td>
<td>0.46</td>
<td>1.39</td>
<td>0.014</td>
<td>0.005</td>
<td>0.9</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>G18NiMoCr3-6 (2)</td>
<td>0.22</td>
<td>0.54</td>
<td>0.87</td>
<td>0.011</td>
<td>0.001</td>
<td>0.81</td>
<td>0.44</td>
<td>0.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>V</th>
<th>N</th>
<th>Cu</th>
<th>B</th>
<th>Ti</th>
<th>Nb</th>
<th>Al</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>S690G2QL1</td>
<td>0.06</td>
<td>0.0081</td>
<td>0.02</td>
<td>0.004</td>
<td>0.03</td>
<td>0.021</td>
<td>0.12</td>
</tr>
<tr>
<td>G10MnMoV6-3</td>
<td>0.07</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S890G1QL</td>
<td>0.05</td>
<td>0.0066</td>
<td>0.18</td>
<td>0.005</td>
<td>0.001</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>G18NiMoCr3-6 (1)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G18NiMoCr3-6 (2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table B9. Mechanical properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>R_p;0.2 [MPa]</th>
<th>R_m [MPa]</th>
<th>El. %</th>
<th>Red. %</th>
<th>RT  [J]</th>
<th>-40°C [J]</th>
<th>HB</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>S690G2QL1</td>
<td>791</td>
<td>851</td>
<td>18.5</td>
<td>149</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G10MnMoV6-3</td>
<td>716</td>
<td>801</td>
<td>19.2</td>
<td>69.7</td>
<td>170</td>
<td>81</td>
<td>252</td>
<td>940/ water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>620/ water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>635/ water</td>
</tr>
<tr>
<td>S890G1QL</td>
<td>879</td>
<td>949</td>
<td>20.0</td>
<td>62.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G18NiMoCr3-6 (1)</td>
<td>964</td>
<td>1017</td>
<td>16.6</td>
<td>56.4</td>
<td>83-87</td>
<td>34</td>
<td>326</td>
<td>920</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>580</td>
</tr>
<tr>
<td>G18NiMoCr3-6 (2)</td>
<td>935</td>
<td>989</td>
<td>13.4</td>
<td>59</td>
<td>45</td>
<td>45</td>
<td>311-315</td>
<td>920</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>580</td>
</tr>
</tbody>
</table>
Appendix C, Vickers test results

Appendix C presents the Vickers test results of the welded specimens. Chapter 4 presents the welding procedures and weld cross sections of the series. A rough estimation of the relation of the Vickers hardness and the tensile strength is the following:

\[ \sigma_u = 3.02 \cdot HV10 \] [Van Wortel, 2006]. This is also presented in the graphs, with \( \sigma_u \) based on the tensile strengths obtained from the 3.1 certificates of the steel manufacturers, which can be found in Appendix B. Vickers measurements were carried out under the surface of weld cap and weld root and in the middle of the specimens. In the graphs, the position of the Vickers points, which is a distance from the middle of the weld, is plotted against the HV10.
Appendix C, Vickers test results

SA-series

FA-series

FB-series

- Cap side high
- Root
- Cap side low

S355

ER70S6

Megafill 742 M

S690

Tenacito 75

SH NI2 K140

SA-series

FA-series

FB-series
Fatigue strength of welded connections made of very high strength cast and rolled steels

![Graphs showing HV10 hardness values for different steels and distances from the middle of the welds.](image-url)

- **S460**
- **E81T1K2M**
- **E80CG**

---

237
Fatigue strength of welded connections made of very high strength cast and rolled steels

![Diagram showing HV10 values for different zones (BM, HAZ, FZ) and distance from middle for V89-series, C89-series, and CB89-series.](image-url)
Appendix D, Steps for the manufacturing of V-welded plate specimens

Appendix D presents the steps for the manufacturing of V-welded plate specimens, described in Section 4.5 and Section 4.6. Rolled plates were plasma cut and welded. Additionally, rolled plates were welded to cast plates with similar yield strength. After welding, strips were plasma cut and machined to obtain the specimens, (See Appendix E).
Appendix D, Steps for the manufacturing of V-welded plate specimens

1. Cutting base plate

2. Welding

3. Cutting welded plates

Legend:
- White: Base Plate
- Light gray: Cast Plate
- Medium gray: Bump Material
- Dark gray: Cutlines
- Dashed line: Cutlines
Appendix E, Specimen drawings

Appendix E presents the drawings of the base material specimens described in Chapter 4. Figure E1 shows the base material specimens; Figure E2 the X-welded specimens; Figure E3 the V-welded specimens. Also strain gauge positions are indicated in the drawings.

Figure E1. Base material specimens, series FAM and FBM.
Figure E2. X-welded specimens series SA, FA and FB.
Figure E3. V-welded specimens series C, CB and V
Appendix F, Fatigue test results

The fatigue strength results presented in Sections 4.3 - 4.6 take into account the various stages in the fatigue life, Ni, Nt and Nf. Table F1 lists all fatigue results of the base material specimens, X-welded specimens, V-welded specimens and truss specimens. Also listed in the tables is detailed information on the crack initiation location for the governing cracks. The description in the legend can be read as follows (See Figure F1):

[Diagram of fatigue results]

Figure F1, Name description fatigue results
## Appendix F: Fatigue test results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Loading mode</th>
<th>Crack Location</th>
<th>( S_{max} )</th>
<th>( S_{min} )</th>
<th>( S_{max} )</th>
<th>( S_{min} )</th>
<th>( S_{max} )</th>
<th>( S_{min} )</th>
<th>( S_{max} )</th>
<th>( S_{min} )</th>
<th>( S_{max} )</th>
<th>( S_{min} )</th>
<th>( S_{max} )</th>
<th>( S_{min} )</th>
<th>( S_{max} )</th>
<th>( S_{min} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAM1</td>
<td>Ax</td>
<td>clamb, not included</td>
<td>222</td>
<td>268</td>
<td>197</td>
<td>197</td>
<td>358590</td>
<td>358590</td>
<td>373000</td>
<td>373000</td>
<td>358590</td>
<td>358590</td>
<td>373000</td>
<td>373000</td>
<td>358590</td>
<td>358590</td>
</tr>
<tr>
<td>FAM2</td>
<td>Ax</td>
<td>n/a out</td>
<td>271</td>
<td>242</td>
<td>241</td>
<td>243</td>
<td>440000</td>
<td>440000</td>
<td>440000</td>
<td>440000</td>
<td>440000</td>
<td>440000</td>
<td>440000</td>
<td>440000</td>
<td>440000</td>
<td>440000</td>
</tr>
<tr>
<td>FAM3</td>
<td>Ax</td>
<td>middle</td>
<td>508</td>
<td>459</td>
<td>447</td>
<td>450</td>
<td>100000</td>
<td>100000</td>
<td>151458</td>
<td>151458</td>
<td>151458</td>
<td>151458</td>
<td>151458</td>
<td>151458</td>
<td>151458</td>
<td>151458</td>
</tr>
<tr>
<td>FAM4</td>
<td>Ax</td>
<td>middle</td>
<td>431</td>
<td>372</td>
<td>382</td>
<td>386</td>
<td>540000</td>
<td>540000</td>
<td>563436</td>
<td>563436</td>
<td>563436</td>
<td>563436</td>
<td>563436</td>
<td>563436</td>
<td>563436</td>
<td>563436</td>
</tr>
<tr>
<td>FAM5</td>
<td>Ax</td>
<td>middle</td>
<td>530</td>
<td>453</td>
<td>452</td>
<td>456</td>
<td>550000</td>
<td>550000</td>
<td>840000</td>
<td>840000</td>
<td>840000</td>
<td>840000</td>
<td>840000</td>
<td>840000</td>
<td>840000</td>
<td>840000</td>
</tr>
<tr>
<td>FAM6</td>
<td>Ax</td>
<td>middle</td>
<td>479</td>
<td>426</td>
<td>425</td>
<td>429</td>
<td>270000</td>
<td>270000</td>
<td>326000</td>
<td>326000</td>
<td>326000</td>
<td>326000</td>
<td>326000</td>
<td>326000</td>
<td>326000</td>
<td>326000</td>
</tr>
<tr>
<td>FAM7</td>
<td>Ax</td>
<td>middle</td>
<td>447</td>
<td>399</td>
<td>397</td>
<td>400</td>
<td>450000</td>
<td>450000</td>
<td>76000</td>
<td>76000</td>
<td>76000</td>
<td>76000</td>
<td>76000</td>
<td>76000</td>
<td>76000</td>
<td>76000</td>
</tr>
<tr>
<td>FBM1</td>
<td>Ax</td>
<td>outside middle</td>
<td>587</td>
<td>587</td>
<td>493</td>
<td>493</td>
<td>200000</td>
<td>200000</td>
<td>74000</td>
<td>74000</td>
<td>74000</td>
<td>74000</td>
<td>74000</td>
<td>74000</td>
<td>74000</td>
<td>74000</td>
</tr>
<tr>
<td>FBM2</td>
<td>Ax</td>
<td>outside middle</td>
<td>459</td>
<td>459</td>
<td>386</td>
<td>386</td>
<td>154000</td>
<td>154000</td>
<td>200000</td>
<td>200000</td>
<td>200000</td>
<td>200000</td>
<td>200000</td>
<td>200000</td>
<td>200000</td>
<td>200000</td>
</tr>
<tr>
<td>FBM3</td>
<td>Ax</td>
<td>outside middle</td>
<td>408</td>
<td>408</td>
<td>343</td>
<td>343</td>
<td>300000</td>
<td>300000</td>
<td>420000</td>
<td>420000</td>
<td>420000</td>
<td>420000</td>
<td>420000</td>
<td>420000</td>
<td>420000</td>
<td>420000</td>
</tr>
<tr>
<td>FBM4</td>
<td>Ax</td>
<td>outside middle</td>
<td>430</td>
<td>430</td>
<td>345</td>
<td>345</td>
<td>357000</td>
<td>357000</td>
<td>360000</td>
<td>360000</td>
<td>360000</td>
<td>360000</td>
<td>360000</td>
<td>360000</td>
<td>360000</td>
<td>360000</td>
</tr>
<tr>
<td>FBM5</td>
<td>Ax</td>
<td>out n/a</td>
<td>378</td>
<td>378</td>
<td>318</td>
<td>318</td>
<td>2500000</td>
<td>2500000</td>
<td>2500000</td>
<td>2500000</td>
<td>2500000</td>
<td>2500000</td>
<td>2500000</td>
<td>2500000</td>
<td>2500000</td>
<td>2500000</td>
</tr>
<tr>
<td>FBM6</td>
<td>Ax</td>
<td>outside middle</td>
<td>461</td>
<td>461</td>
<td>388</td>
<td>388</td>
<td>155000</td>
<td>155000</td>
<td>170000</td>
<td>170000</td>
<td>170000</td>
<td>170000</td>
<td>170000</td>
<td>170000</td>
<td>170000</td>
<td>170000</td>
</tr>
<tr>
<td>Specimen</td>
<td>Loading mode</td>
<td>Crack location</td>
<td>Fatigue strength of welded connections made of very high strength cast and rolled steels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>------------------</td>
<td>----------------</td>
<td>-----------------------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA1</td>
<td>Ax WT_rolled_cap_edge</td>
<td>197 116 133 129 143</td>
<td>1194.73 475.99 138000 167032 0.72 1.69 1.09 0.87 1.12 1.29 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA2</td>
<td>Ax WT_rolled_cap_edge</td>
<td>290 241 206 249 227</td>
<td>118.00 467.49 12800 164749 0.72 1.21 1.04 1.03 1.05 1.29 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA3</td>
<td>Ax WT_rolled_cap_edge</td>
<td>266 165 182 176 196</td>
<td>194.09 989.30 22280 297903 0.66 1.61 1.08 1.07 1.11 1.28 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA4</td>
<td>Ax WT_rolled_cap_edge</td>
<td>234 203 164 162 185</td>
<td>110.00 1533.99 111500 123239 0.89 1.16 1.02 1.04 1.04 1.32 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA5</td>
<td>Ax WT_rolled_cap_edge</td>
<td>242 199 173 166 186</td>
<td>8344.04 4310.39 10852.0 1267843 0.66 1.21 1.04 1.03 1.05 1.28 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA6</td>
<td>Ax WT_rolled_cap_edge</td>
<td>179 188 134 128 149</td>
<td>449.00 230.37 475000 699327 0.64 0.95 0.99 0.99 0.99 1.28 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA7</td>
<td>Ax WT_rolled_cap_edge</td>
<td>202 151 145 137 154</td>
<td>478.74 492.26 65310 929000 0.52 1.34 1.06 1.04 1.07 1.23 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA8</td>
<td>Ax WT_rolled_cap_edge</td>
<td>188 139 135 127 143</td>
<td>355.00 377.34 479.44 732.81 0.48 1.35 1.06 1.05 1.08 1.25 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA9</td>
<td>Ax run out</td>
<td>167 121 112 112 126</td>
<td>6227.32 0 0.00 1.08 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA1</td>
<td>Ax run out</td>
<td>112 83 71 71 80</td>
<td>1672.00 0 1.00 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA2</td>
<td>Ax WT_rolled_cap_edge</td>
<td>298 237 198 190 235</td>
<td>203.00 1083.56 300.00 3113.56 0.65 1.25 1.04 1.03 1.06 1.28 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA3</td>
<td>Ax WT_rolled_cap_edge</td>
<td>289 239 192 186 211</td>
<td>241.09 946.08 300000 316006 0.72 1.21 1.04 1.03 1.05 1.29 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA4</td>
<td>Ax WT_rolled_cap_edge</td>
<td>141 137 97 91 107</td>
<td>130.00 592.19 180000 1892.98 0.49 1.03 1.01 1.00 1.01 1.28 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA5</td>
<td>Ax WT_rolled_cap_edge</td>
<td>213 144 143 133 140</td>
<td>220.00 368.18 50000 606.58 0.36 1.47 1.08 1.06 1.10 1.22 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA6</td>
<td>Ax WT_rolled_cap_edge</td>
<td>212 150 143 133 130</td>
<td>706.00 119000 0 0.37 1.41 1.07 1.05 1.09 1.23 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA7</td>
<td>Ax WT_rolled_cap_edge</td>
<td>389 306 256 248 240</td>
<td>60000 24000 0 0.71 1.27 1.04 1.04 1.06 1.28 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA8</td>
<td>Ax WT_rolled_cap_edge</td>
<td>496 314 269 259 250</td>
<td>50000 24348 0 0.67 1.28 1.05 1.04 1.06 1.28 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA9</td>
<td>Ax WT_rolled_cap_edge</td>
<td>135 114 92 87 99</td>
<td>130000 1219695 225000 2519695 0.52 1.18 1.03 1.03 1.04 1.25 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA10</td>
<td>Ax WT_rolled_cap_edge</td>
<td>172 136 117 110 124</td>
<td>421.00 479.84 0 0.47 1.26 1.05 1.04 1.06 1.24 1.34 1.16 0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FB1</td>
<td>Ax run out</td>
<td>214 146 118 118 137</td>
<td>827.371 0 1.00 1.46 1.06 1.06 1.09 1.44 1.20 0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FB2</td>
<td>Ax WT_rolled_cap_edge</td>
<td>529 353 324 291 337</td>
<td>5000 15295 20285 20298 0.25 1.50 1.09 1.06 1.10 1.26 1.44 1.20 0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FB3</td>
<td>Ax WT_rolled_cap_edge</td>
<td>362 191 171 165 190</td>
<td>300000 310000 410000 410000 0.73 1.58 1.08 1.07 1.11 1.38 1.44 1.20 0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FB4</td>
<td>Ax WT_rolled_cap_edge</td>
<td>277 172 161 151 174</td>
<td>151000 144000 250000 295000 0.51 1.61 1.09 1.07 1.11 1.32 1.44 1.20 0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FB5</td>
<td>Ax WT_rolled_cap_edge</td>
<td>236 147 131 129 149</td>
<td>1900000 280000 2140000 2180000 0.87 1.61 1.07 1.07 1.11 1.41 1.44 1.20 0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FB6</td>
<td>Ax WT_rolled_cap_edge</td>
<td>364 221 212 198 228</td>
<td>600000 62810 100000 122310 0.49 1.65 1.10 1.07 1.12 1.32 1.44 1.20 0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FB7</td>
<td>Ax WT_rolled_cap_edge</td>
<td>360 219 207 196 226</td>
<td>160000 121000 0 0.58 1.65 1.09 1.07 1.12 1.34 1.44 1.20 0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen</td>
<td>Loading mode</td>
<td>Crack location</td>
<td>$S_{\text{in}}$</td>
<td>$S_{\text{in}}/N_{\text{f}}$</td>
<td>$S_{\text{in}}/N_{\text{f}}$</td>
<td>$S_{\text{in}}/N_{\text{f}}$</td>
<td>$S_{\text{in}}/N_{\text{f}}$</td>
<td>$S_{\text{in}}/N_{\text{f}}$</td>
<td>$S_{\text{in}}/N_{\text{f}}$</td>
<td>$S_{\text{in}}/N_{\text{f}}$</td>
<td>$S_{\text{in}}/N_{\text{f}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>--------------------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C111 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>380</td>
<td>193</td>
<td>199</td>
<td>193</td>
<td>199</td>
<td>193</td>
<td>199</td>
<td>193</td>
<td>199</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>390</td>
<td>200</td>
<td>203</td>
<td>200</td>
<td>203</td>
<td>200</td>
<td>203</td>
<td>200</td>
<td>203</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>380</td>
<td>201</td>
<td>199</td>
<td>199</td>
<td>199</td>
<td>199</td>
<td>199</td>
<td>199</td>
<td>199</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C112 Cap</td>
<td>BM_cast_cap_edge</td>
<td></td>
<td>231</td>
<td>200</td>
<td>203</td>
<td>186</td>
<td>203</td>
<td>186</td>
<td>203</td>
<td>186</td>
<td>203</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>241</td>
<td>200</td>
<td>203</td>
<td>186</td>
<td>203</td>
<td>186</td>
<td>203</td>
<td>186</td>
<td>203</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C113 Cap</td>
<td>BM_cast_cap_edge</td>
<td></td>
<td>248</td>
<td>212</td>
<td>218</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C114 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>201</td>
<td>120</td>
<td>130</td>
<td>119</td>
<td>130</td>
<td>119</td>
<td>130</td>
<td>119</td>
<td>130</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C115 Root</td>
<td>BM_cast_root_middle</td>
<td></td>
<td>230</td>
<td>197</td>
<td>202</td>
<td>185</td>
<td>202</td>
<td>185</td>
<td>202</td>
<td>185</td>
<td>202</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C116 Root</td>
<td>BM_cast_root_edge</td>
<td></td>
<td>167</td>
<td>140</td>
<td>146</td>
<td>134</td>
<td>146</td>
<td>134</td>
<td>146</td>
<td>134</td>
<td>146</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C117 Cap</td>
<td>nun out</td>
<td></td>
<td>197</td>
<td>127</td>
<td>127</td>
<td>116</td>
<td>127</td>
<td>116</td>
<td>127</td>
<td>116</td>
<td>127</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C118 Ax</td>
<td>BM_cast_cap_middle</td>
<td></td>
<td>254</td>
<td>180</td>
<td>223</td>
<td>217</td>
<td>223</td>
<td>217</td>
<td>223</td>
<td>217</td>
<td>223</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>280</td>
<td>221</td>
<td>230</td>
<td>217</td>
<td>230</td>
<td>217</td>
<td>230</td>
<td>217</td>
<td>230</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C119 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>239</td>
<td>149</td>
<td>154</td>
<td>141</td>
<td>154</td>
<td>141</td>
<td>154</td>
<td>141</td>
<td>154</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C121 Cap</td>
<td>BM_cast_cap_edge</td>
<td></td>
<td>233</td>
<td>171</td>
<td>181</td>
<td>158</td>
<td>171</td>
<td>181</td>
<td>158</td>
<td>171</td>
<td>181</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C122 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>283</td>
<td>214</td>
<td>220</td>
<td>192</td>
<td>220</td>
<td>192</td>
<td>220</td>
<td>192</td>
<td>220</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C123 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>330</td>
<td>249</td>
<td>256</td>
<td>224</td>
<td>256</td>
<td>224</td>
<td>256</td>
<td>224</td>
<td>256</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C124 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>284</td>
<td>205</td>
<td>221</td>
<td>193</td>
<td>221</td>
<td>193</td>
<td>221</td>
<td>193</td>
<td>221</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C125 Root</td>
<td>WT_cast_root_middle</td>
<td></td>
<td>260</td>
<td>192</td>
<td>201</td>
<td>176</td>
<td>201</td>
<td>176</td>
<td>201</td>
<td>176</td>
<td>201</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C126 Root</td>
<td>WT_rooled_root_middle</td>
<td></td>
<td>200</td>
<td>138</td>
<td>155</td>
<td>136</td>
<td>155</td>
<td>136</td>
<td>155</td>
<td>136</td>
<td>155</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C127 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>247</td>
<td>179</td>
<td>192</td>
<td>168</td>
<td>192</td>
<td>168</td>
<td>192</td>
<td>168</td>
<td>192</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C128 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>279</td>
<td>192</td>
<td>216</td>
<td>189</td>
<td>216</td>
<td>189</td>
<td>216</td>
<td>189</td>
<td>216</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C129 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>292</td>
<td>202</td>
<td>226</td>
<td>193</td>
<td>226</td>
<td>193</td>
<td>226</td>
<td>193</td>
<td>226</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C130 Root</td>
<td>WT_rooled_root_middle</td>
<td></td>
<td>285</td>
<td>194</td>
<td>212</td>
<td>186</td>
<td>212</td>
<td>186</td>
<td>212</td>
<td>186</td>
<td>212</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C131 Root</td>
<td>WT_rooled_root_middle</td>
<td></td>
<td>263</td>
<td>179</td>
<td>196</td>
<td>172</td>
<td>196</td>
<td>172</td>
<td>196</td>
<td>172</td>
<td>196</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C132 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>292</td>
<td>200</td>
<td>218</td>
<td>191</td>
<td>218</td>
<td>191</td>
<td>218</td>
<td>191</td>
<td>218</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C133 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>191</td>
<td>127</td>
<td>144</td>
<td>126</td>
<td>144</td>
<td>126</td>
<td>144</td>
<td>126</td>
<td>144</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C134 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>236</td>
<td>180</td>
<td>191</td>
<td>167</td>
<td>191</td>
<td>167</td>
<td>191</td>
<td>167</td>
<td>191</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C135 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>199</td>
<td>133</td>
<td>149</td>
<td>130</td>
<td>149</td>
<td>130</td>
<td>149</td>
<td>130</td>
<td>149</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C136 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>191</td>
<td>133</td>
<td>143</td>
<td>125</td>
<td>143</td>
<td>125</td>
<td>143</td>
<td>125</td>
<td>143</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C137 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>236</td>
<td>186</td>
<td>176</td>
<td>154</td>
<td>176</td>
<td>154</td>
<td>176</td>
<td>154</td>
<td>176</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C138 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>322</td>
<td>219</td>
<td>232</td>
<td>203</td>
<td>232</td>
<td>203</td>
<td>232</td>
<td>203</td>
<td>232</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C139 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>309</td>
<td>200</td>
<td>223</td>
<td>195</td>
<td>223</td>
<td>195</td>
<td>223</td>
<td>195</td>
<td>223</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C140 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>206</td>
<td>149</td>
<td>149</td>
<td>130</td>
<td>149</td>
<td>130</td>
<td>149</td>
<td>130</td>
<td>149</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C141 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>212</td>
<td>153</td>
<td>153</td>
<td>134</td>
<td>153</td>
<td>134</td>
<td>153</td>
<td>134</td>
<td>153</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C142 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>329</td>
<td>283</td>
<td>293</td>
<td>268</td>
<td>293</td>
<td>268</td>
<td>293</td>
<td>268</td>
<td>293</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C143 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>192</td>
<td>138</td>
<td>138</td>
<td>121</td>
<td>138</td>
<td>121</td>
<td>138</td>
<td>121</td>
<td>138</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C144 Cap</td>
<td>WT_cast_cap_edge</td>
<td></td>
<td>233</td>
<td>178</td>
<td>183</td>
<td>160</td>
<td>183</td>
<td>160</td>
<td>183</td>
<td>160</td>
<td>183</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C145 Root</td>
<td>BM_cast_root_middle</td>
<td></td>
<td>316</td>
<td>272</td>
<td>281</td>
<td>258</td>
<td>281</td>
<td>258</td>
<td>281</td>
<td>258</td>
<td>281</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C146 Root</td>
<td>BM_cast_root_middle</td>
<td></td>
<td>310</td>
<td>269</td>
<td>275</td>
<td>253</td>
<td>275</td>
<td>253</td>
<td>275</td>
<td>253</td>
<td>275</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen</td>
<td>Loading mode</td>
<td>Crack location</td>
<td>( \frac{K_{\text{lm}}}{f_{\text{m}}} )</td>
<td>( \frac{N_{\text{f}}}{N_{\text{i}}} )</td>
<td>( \frac{N_{\text{p}}}{N_{\text{f}}} )</td>
<td>( \frac{N_{\text{t}}}{N_{\text{i}}} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB111 Cap</td>
<td>BM_cast_cap_middle</td>
<td></td>
<td>203783</td>
<td>292613</td>
<td>403783</td>
<td>0.56</td>
<td>1.04 1.00 1.09 1.00 1.00 1.00 0.88</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB112 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>244000</td>
<td>520000</td>
<td>680000</td>
<td>0.59</td>
<td>1.27 1.20 1.37 1.07 1.09 1.05 0.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB113 Cap</td>
<td>BM_cast_cap_edge</td>
<td></td>
<td>300000</td>
<td>1100000</td>
<td>1300000</td>
<td>0.77</td>
<td>1.02 1.00 1.09 1.00 1.00 1.00 0.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB114 Root</td>
<td>BM_rolled_root_edge</td>
<td></td>
<td>36418</td>
<td>451198</td>
<td>600118</td>
<td>0.46</td>
<td>1.05 1.00 1.09 1.00 1.00 1.00 0.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB115 Root</td>
<td>BM_rolled_cap_edge</td>
<td></td>
<td>625333</td>
<td>1233955</td>
<td>1475331</td>
<td>0.58</td>
<td>1.04 1.00 1.09 1.00 1.00 1.00 0.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB461 Root</td>
<td>BM_rolled_root_middle</td>
<td></td>
<td>945655</td>
<td>1131281</td>
<td>1131281</td>
<td>0.83</td>
<td>1.02 1.00 1.09 1.00 1.00 1.00 0.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB462 Root</td>
<td>BM_cast_root_edge</td>
<td></td>
<td>581728</td>
<td>1803003</td>
<td>2043728</td>
<td>0.72</td>
<td>1.03 1.00 1.09 1.00 1.00 1.00 0.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB463 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>468004</td>
<td>410521</td>
<td>495064</td>
<td>0.05</td>
<td>1.36 1.20 1.37 1.00 1.00 1.00 0.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB464 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>339</td>
<td>186</td>
<td>163</td>
<td>0.60</td>
<td>1.31 1.20 1.37 1.00 1.00 1.00 0.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB465 Cap</td>
<td>BM_cast_cap_edge/cap_middle</td>
<td></td>
<td>166472</td>
<td>226448</td>
<td>2311472</td>
<td>0.93</td>
<td>1.01 1.00 1.09 1.00 1.00 1.00 0.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB469 Cap</td>
<td>WT_rolled_cap_middle</td>
<td></td>
<td>198866</td>
<td>373673</td>
<td>484846</td>
<td>0.61</td>
<td>1.27 1.20 1.37 1.00 1.00 1.00 0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB469 Root</td>
<td>WT_cast_root_middle</td>
<td></td>
<td>1280045</td>
<td>682004</td>
<td>1326045</td>
<td>0.09</td>
<td>1.35 1.20 1.37 1.00 1.00 1.00 0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB695 Cap</td>
<td>WT_cast_cap_middle</td>
<td></td>
<td>175051</td>
<td>185051</td>
<td>0.05</td>
<td>1.36 1.20 1.37 1.00 1.00 1.00 0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB696 Ax</td>
<td>WT_rolled_cap_middle</td>
<td></td>
<td>14401</td>
<td>180000</td>
<td>246441</td>
<td>0.41</td>
<td>1.08 1.06 1.10 1.00 1.00 1.00 0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB697 Root</td>
<td>WT_rolled_cap_middle</td>
<td></td>
<td>49900</td>
<td>75200</td>
<td>832000</td>
<td>0.40</td>
<td>1.53 1.09 1.06 1.10 1.00 1.00 0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB891 Cap</td>
<td>BM_cast_cap_middle</td>
<td></td>
<td>1240000</td>
<td>500000</td>
<td>1290000</td>
<td>0.04</td>
<td>1.09 1.00 1.09 1.00 1.00 1.00 0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB892 Root</td>
<td>BM_cast_root_middle</td>
<td></td>
<td>221114</td>
<td>308240</td>
<td>508114</td>
<td>0.56</td>
<td>1.04 1.00 1.09 1.00 1.00 1.00 0.86</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB893 Root</td>
<td>BM_cast_root_edge</td>
<td></td>
<td>235431</td>
<td>167647</td>
<td>431341</td>
<td>0.43</td>
<td>1.05 1.00 1.09 1.00 1.00 1.00 0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB894 Cap</td>
<td>WT_cast_cap_edge/cap_middle</td>
<td></td>
<td>329553</td>
<td>302366</td>
<td>365333</td>
<td>0.10</td>
<td>1.35 1.20 1.37 1.00 1.00 1.00 0.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB895 Cap</td>
<td>WT_rolled_cap_edge/cap_middle</td>
<td></td>
<td>240782</td>
<td>159960</td>
<td>266782</td>
<td>0.10</td>
<td>1.35 1.20 1.37 1.00 1.00 1.00 0.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CB896 Cap</td>
<td>WT_rolled_cap_middle</td>
<td></td>
<td>227609</td>
<td>227753</td>
<td>257469</td>
<td>0.12</td>
<td>1.35 1.20 1.37 1.00 1.00 1.00 0.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen</td>
<td>Loading mode</td>
<td>Crack location</td>
<td>$N_f$</td>
<td>$N_i$</td>
<td>$N_p$</td>
<td>$K_{min}$</td>
<td>$f_l$</td>
<td>$f_t$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------------</td>
<td>----------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>----------</td>
<td>------</td>
<td>------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V111</td>
<td>Cap</td>
<td>WT_rolled_cap_middle</td>
<td>323</td>
<td>203</td>
<td>208</td>
<td>190</td>
<td>550000</td>
<td>749468</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V112</td>
<td>Ax</td>
<td>run-out</td>
<td>226</td>
<td>167</td>
<td>167</td>
<td>169</td>
<td>1000000</td>
<td>1000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V113</td>
<td>Cap</td>
<td>IM_rolled_2s</td>
<td>267</td>
<td>184</td>
<td>221</td>
<td>222</td>
<td>400000</td>
<td>500000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V114</td>
<td>Cap</td>
<td>WT_rolled_cap_middle</td>
<td>312</td>
<td>194</td>
<td>201</td>
<td>184</td>
<td>35152</td>
<td>590000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V115</td>
<td>Cap</td>
<td>WT_rolled_cap_middle</td>
<td>393</td>
<td>241</td>
<td>233</td>
<td>222</td>
<td>64687</td>
<td>86000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V116</td>
<td>Cap</td>
<td>run-out</td>
<td>257</td>
<td>166</td>
<td>166</td>
<td>152</td>
<td>1000000</td>
<td>1000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V117</td>
<td>Cap</td>
<td>WT_rolled_cap_middle</td>
<td>320</td>
<td>196</td>
<td>206</td>
<td>189</td>
<td>217000</td>
<td>316385</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V118</td>
<td>Root</td>
<td>IM_rolled_root_edge</td>
<td>320</td>
<td>260</td>
<td>266</td>
<td>244</td>
<td>60000</td>
<td>223061</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V119</td>
<td>Root</td>
<td>IM_rolled_root_edge</td>
<td>286</td>
<td>229</td>
<td>238</td>
<td>218</td>
<td>330000</td>
<td>250000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V461</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>318</td>
<td>227</td>
<td>247</td>
<td>216</td>
<td>90000</td>
<td>146525</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V462</td>
<td>Ax</td>
<td>WT_rolled_cap_edge</td>
<td>215</td>
<td>152</td>
<td>188</td>
<td>191</td>
<td>504000</td>
<td>288799</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V463</td>
<td>Root</td>
<td>WT_rolled_root_edge</td>
<td>169</td>
<td>126</td>
<td>131</td>
<td>115</td>
<td>121500</td>
<td>471201</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V464</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>271</td>
<td>193</td>
<td>211</td>
<td>184</td>
<td>180000</td>
<td>353265</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V465</td>
<td>Cap</td>
<td>WT_rolled_root_middle</td>
<td>164</td>
<td>115</td>
<td>127</td>
<td>111</td>
<td>1659000</td>
<td>3130630</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V466</td>
<td>Cap</td>
<td>WT_rolled_root_edge</td>
<td>289</td>
<td>216</td>
<td>224</td>
<td>196</td>
<td>175000</td>
<td>261926</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V467</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>312</td>
<td>229</td>
<td>242</td>
<td>212</td>
<td>325000</td>
<td>378700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V468</td>
<td>Ax</td>
<td>WT_rolled_cap_edge</td>
<td>186</td>
<td>135</td>
<td>164</td>
<td>165</td>
<td>2220000</td>
<td>877122</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V469</td>
<td>Root</td>
<td>WT_rolled_root_middle</td>
<td>244</td>
<td>180</td>
<td>189</td>
<td>166</td>
<td>330000</td>
<td>189700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V491</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>269</td>
<td>183</td>
<td>200</td>
<td>176</td>
<td>103000</td>
<td>121433</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V492</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>258</td>
<td>154</td>
<td>129</td>
<td>111</td>
<td>1110000</td>
<td>1403800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V493</td>
<td>Cap</td>
<td>WT_rolled_root_middle</td>
<td>276</td>
<td>188</td>
<td>206</td>
<td>180</td>
<td>302000</td>
<td>306043</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V494</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>344</td>
<td>235</td>
<td>256</td>
<td>223</td>
<td>53000</td>
<td>101000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V495</td>
<td>Ax</td>
<td>WT_rolled_cap_edge</td>
<td>202</td>
<td>154</td>
<td>172</td>
<td>173</td>
<td>620000</td>
<td>136000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V496</td>
<td>Ax</td>
<td>WT_rolled_cap_edge</td>
<td>220</td>
<td>155</td>
<td>183</td>
<td>187</td>
<td>2016000</td>
<td>239850</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V497</td>
<td>Root</td>
<td>WT_rolled_root_middle</td>
<td>207</td>
<td>138</td>
<td>154</td>
<td>133</td>
<td>69000</td>
<td>405246</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V498</td>
<td>Root</td>
<td>WT_rolled_root_middle</td>
<td>279</td>
<td>185</td>
<td>208</td>
<td>182</td>
<td>115000</td>
<td>69857</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V499</td>
<td>Cap</td>
<td>WT_rolled_root_middle</td>
<td>347</td>
<td>241</td>
<td>258</td>
<td>226</td>
<td>50000</td>
<td>50000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V491</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>247</td>
<td>178</td>
<td>178</td>
<td>156</td>
<td>7200000</td>
<td>720000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V493</td>
<td>Cap</td>
<td>WT_rolled_root_middle</td>
<td>264</td>
<td>182</td>
<td>190</td>
<td>166</td>
<td>870000</td>
<td>132415</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V494</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>354</td>
<td>238</td>
<td>255</td>
<td>223</td>
<td>209000</td>
<td>203900</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V495</td>
<td>Ax</td>
<td>WT_rolled_cap_edge</td>
<td>184</td>
<td>157</td>
<td>155</td>
<td>153</td>
<td>390000</td>
<td>390000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V496</td>
<td>Ax</td>
<td>WT_rolled_cap_edge</td>
<td>196</td>
<td>159</td>
<td>164</td>
<td>161</td>
<td>4000000</td>
<td>400000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V497</td>
<td>Cap</td>
<td>WT_rolled_cap_edge</td>
<td>311</td>
<td>215</td>
<td>224</td>
<td>196</td>
<td>920000</td>
<td>353339</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V498</td>
<td>Root</td>
<td>IM_rolled_root_edge</td>
<td>296</td>
<td>246</td>
<td>253</td>
<td>225</td>
<td>184000</td>
<td>407000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V499</td>
<td>Root</td>
<td>WT_rolled_root_middle</td>
<td>348</td>
<td>228</td>
<td>251</td>
<td>220</td>
<td>160000</td>
<td>303600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The table values are in some cases rounded for readability.
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Loading mode</th>
<th>Crack location</th>
<th>$f_a$</th>
<th>$f_m$</th>
<th>$f_c$</th>
<th>$f_s$</th>
<th>$f_t$</th>
<th>$f_p$</th>
<th>$N_f$</th>
<th>$N_i$</th>
<th>$N_p$</th>
<th>$N_t$</th>
<th>$N_{f(i)}$</th>
<th>$K_{fm}$</th>
<th>$K_{ft}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>K691_1</td>
<td>BM_cast joint 1</td>
<td>190</td>
<td>190</td>
<td>560000</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td>860000</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K691_1</td>
<td>root_middle_5</td>
<td>130</td>
<td>126</td>
<td>560000</td>
<td>1.03</td>
<td>1.00</td>
<td></td>
<td></td>
<td>860000</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K891_1</td>
<td>root_middle_12</td>
<td>180</td>
<td>176</td>
<td>271000</td>
<td>1.03</td>
<td>1.00</td>
<td></td>
<td></td>
<td>860000</td>
<td>1.03</td>
<td>0.67</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K891_1</td>
<td>root_middle_14</td>
<td>336</td>
<td>220</td>
<td>271000</td>
<td>1.03</td>
<td>1.00</td>
<td></td>
<td></td>
<td>860000</td>
<td>1.03</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K891_2</td>
<td>root_middle_8</td>
<td>218</td>
<td>212</td>
<td>205000</td>
<td>1.03</td>
<td>1.00</td>
<td></td>
<td></td>
<td>860000</td>
<td>1.03</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix G, Crack growth measurements

Appendix G presents the measured crack growth of the fatigue specimens of Sections 4.3 - 4.6. The graphs plot the crack length in depth direction \( a \) or crack length in plate width direction (\( 2c \) for middle cracks and \( c \) for edge cracks) versus the number of cycles.

[Graph of crack growth measurements]

---

255
Appendix G, Crack growth measurements

![Graph of crack growth measurements for different specimens, showing cycles vs. crack length in millimeters for various specimens labeled as FA2_a, FA4_a, FA5_a, FA2_2c, FA4_2c, FA5_2c, FB3_a, FB4_a, FB6_a, FB7_a, FB3_2c, FB4_2c, FB6_2c, FB7_2c, and FB5_a, FB5_2c.]
Fatigue strength of welded connections made of very high strength cast and rolled steels
Appendix G, Crack growth measurements

![Graph 1](image1)

![Graph 2](image2)

![Graph 3](image3)
Fatigue strength of welded connections made of very high strength cast and rolled steels

![Graphs showing fatigue strength data for different steels.](image-url)
Fatigue strength of welded connections made of very high strength cast and rolled steels

[Graphs showing fatigue strength data for various samples, with markers indicating different conditions or materials.]
Appendix H, Numbering strain gauges on truss

Appendix H explains the numbering of strain gauges on the truss specimens, described in Chapter 5.

For the numbering of the strain gauges, the following coding was used:

\[
\text{(strain gauge number: 1-100); (CHS: B number CHS: 1 - 7); (cast joint: K number cast joint: 1 - 5); (weld number: 1-14); (location in weld: 1 - 4)}
\]

An example is given below.

A: 25B354: strain gauge 25 at CHS B3, weld 5; location 4
B: 53K5143: strain gauge 53 at cast joint K5, weld 14, location 3
Appendix I, Formula notch stress concentration

Appendix I presents the formula for notch stress concentration $K_t$ in case of bending or tension, based on Anthes et al. (1994), which were used in Chapter 6, for prediction of crack initiation life of welded connections.

<table>
<thead>
<tr>
<th>Factor</th>
<th>a0</th>
<th>a1</th>
<th>a2</th>
<th>a3</th>
<th>b1</th>
<th>b2</th>
<th>l1</th>
<th>l2</th>
<th>l3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>0.169</td>
<td>1.503</td>
<td>-1.968</td>
<td>0.713</td>
<td>-0.138</td>
<td>0.2131</td>
<td>0.2491</td>
<td>0.3556</td>
<td>6.1937</td>
</tr>
<tr>
<td>Bending</td>
<td>0.181</td>
<td>1.207</td>
<td>-1.737</td>
<td>0.689</td>
<td>-0.156</td>
<td>0.207</td>
<td>0.2919</td>
<td>0.3491</td>
<td>3.283</td>
</tr>
</tbody>
</table>

$$K_t(t, r, \theta) = \left[ 1 + b_1 \left( \frac{t}{r} \right)^{l_3} \right] \left[ 1 + a_0 + a_1 \cdot \sin \left( \frac{\theta}{180} \cdot \pi \right) + a_2 \cdot \sin \left( \frac{\theta}{180} \cdot \pi \right)^2 + a_3 \cdot \sin \left( \frac{\theta}{180} \cdot \pi \right)^3 \right] \left( \frac{t}{r} \right)^{l_1} \cdot \sin \left( \frac{\theta}{180} \cdot \pi \right)^{l_2}$$
Appendix J, Crack growth calculations

Appendix J presents the crack growth calculations based on FAFRAM, used in Chapter 6 for the prediction of crack propagation life of base material and welded connections.
Appendix J, Crack growth calculations

\[ a \text{ or } 2c \ [\text{mm}] \]

- **Weld crack**
  - \( W = 6 \text{t} \)
  - \( a_i = c_i = 0.15 \text{ mm} \)
  - \( L = 40 \text{ mm} \)
  - \( \Delta \sigma = 200 \text{ MPa} \)

- **Surface crack**
  - \( W = 6 \text{t} \)
  - \( a_i = c_i = 0.15 \text{ mm} \)
  - \( L = 40 \text{ mm} \)
  - \( \Delta \sigma = 200 \text{ MPa} \)

- **Surface crack**
  - \( t = 25 \text{ mm} \)
  - \( W = 6 \text{t} \)
  - \( a_i = c_i = 0.15 \text{ mm} \)
  - \( \Delta \sigma = 200 \text{ MPa} \)

- **Surface crack**
  - \( t = 25 \text{ mm} \)
  - \( W = 6 \text{t} \)
  - \( a_i = c_i = 0.15 \text{ mm} \)
  - \( \Delta \sigma = 200 \text{ MPa} \)

- **Surface crack**
  - \( t = 25 \text{ mm} \)
  - \( W = 6 \text{t} \)
  - \( a_i = c_i = 0.15 \text{ mm} \)
  - \( \Delta \sigma = 200 \text{ MPa} \)

- **Surface crack**
  - \( t = 25 \text{ mm} \)
  - \( W = 6 \text{t} \)
  - \( a_i = c_i = 0.15 \text{ mm} \)
  - \( \Delta \sigma = 200 \text{ MPa} \)

- **Surface crack**
  - \( t = 25 \text{ mm} \)
  - \( W = 6 \text{t} \)
  - \( a_i = c_i = 0.15 \text{ mm} \)
  - \( \Delta \sigma = 200 \text{ MPa} \)
Curriculum Vitae

Richard Pijpers was born October 18th 1979 in Limbricht, The Netherlands. He attended grammar school at the Bisschoppelijk College in Sittard, from which he graduated in 1998. Subsequently, he began his academic education at the faculty of Civil Engineering and Geosciences at the Delft University of Technology.

During his studies, he was a student worker at an architectural firm in Sittard. In 2000, he interrupted his studies for a full year as president of the Delft Student Choir and Orchestra ‘Krashna Musika’. In 2005, he graduated with honours at the chair of steel structures. The Masters’ thesis focused on the dynamic behaviour of modular expansion joints. The work for this thesis was carried out at the Dutch Ministry of Transport (Bouwdienst Rijkswaterstaat).

After graduation, he took a position as junior researcher at the steel structures group of Prof. ir. Frans Bijlaard. Main activities were a study on noise emission of expansion joints and the preparation of the PhD project. In addition to the research activities, educational tasks were carried out as coordinator of BSc course “Technical drawings” at Civil Engineering and Geosciences.

From 2007, the PhD work was supported by the Materials innovation institute (M2i), formerly known as the Netherlands Institute for Metals Research (NIMR). The PhD work focused on the fatigue strength of welded connections made of very high strength cast and rolled steels. A large part of the experimental work was carried out in the Stevin Laboratory of the Delft University of Technology. During his PhD, he was invited twice as a lecturer at ‘PAO cursus Hogesterktestaal’, as a speaker at the ‘Nationale Staalbouwdag 2010’ and as a guest member of EFCS Technical Committee 6, ‘Fatigue’.

Since March 2011, Richard has been employed at TNO as scientist innovator at the group of Structural Reliability and is involved in several fatigue related projects, amongst which reviewing tasks regarding calculations on the lifetime extension of several Dutch steel highway bridges.

In the out-of office time he is most likely occupied with playing trombone in several orchestras and ensembles throughout the Netherlands. In 2011, he married Marjolein van Esch.
Surname: Pijpers
Birth names: Richard Johannes Mathias
Address: C. Fockstraat 35
2613 DC Delft
The Netherlands
Date of birth: 18-10-1979
Email address: rjmpijpers@gmail.com

PhD-research
2007-2011 Civil Engineering and Geosciences, Delft University of Technology
Subject: ‘Fatigue strength of welded connections made of very high strength cast and rolled steels’, supported by the Dutch steel society ‘Bouwen met Staal’ and the Materials innovation institute M2i

Education
1998-2005 Civil Engineering and Geosciences, Delft University of Technology
MSc Specialisation: Structural Engineering (with honours)
Subject MSc thesis: Modular expansion joints
1992-1998 Grammar school, Bisschoppelijk College Sittard

Work experience
2011-present TNO Technical Sciences, Delft, Scientist Innovator
2005-2006 Civil Engineering and Geosciences, Delft University of Technology
Junior researcher, coordinator CT1112 ‘Technical Drawings’
2000-2001 President Delft Student Choir and Orchestra ‘Krashna Musika’
1997-2004 Povše&Partners architecten en ingenieurs, Sittard, student worker

Scientific Publications