Commission of European Communities
E.C.S.C. Sponsored Research Project

Directorate-General XII Science, Research and Development

CONFIDENTIAL

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ECSC Agreement Number:	**7210-MC/602 - (F5.05d/93)**
Commencement of Research:	**1 July 1993**
Scheduled Completion Date:	**30 June 1996**
Beneficiary:	**TNO Bouw**
Research Location:	**TU Delft Stevin Laborator**
Project Leader:	**C. Noordhoek**

Technical Report No.2
Period: January 1 - June 30 1994

TU Delft Delft University of Technology

TNO Building and Construction Research

BOMEL CONSULTING ENGINEERS

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SUMMARY

STATIC STRENGTH OF HIGH STRENGTH STEEL TUBULAR JOINTS

TNO-Bouw
ECSC Agreement No. 7210.MC/602 (93-F5.05d)
Technical report No. 2
Period: January 1 to June 30 1994

Effort has been concentrated on the procurement of the test specimens and the design of the test set-up. Finalisation of these was subject to delay owing to the reluctance of some contractors to provide firm price quotations for the work. This resulted in alteration of the test specimen dimensions, complete revision of the design aspects of specimen strength and test rig, and the procurement of new price quotations for work from other fabricators. However, these difficulties are now close to resolution.

Initial finite element analyses were augmented and the results assimilated and interpreted for trends. Indications are that increases in yield to ultimate strength ratio lead to strength enhancements. However, it is apparent that both influences of the yield strength and yield ratio need to be taken into account in determining joint capacity.

CONTENTS

STATIC STRENGTH OF HIGH STRENGTH STEEL TUBULAR JOINTS

1. INTRODUCTION

The use of high strength steels (HSS) in offshore structures has the potential to offer significant savings in weight and cost. They have been introduced for tubular members within jacket structures but to date nodes have been fabricated from regular 355 grade steels. One obstacle to the exploitation of HSS in these areas is the lack of data on the static strength performance of HSS tubular joints.

The programme of work in the project begins by identifying the trends in modern offshore grade steels to determine the practical range of yield to ultimate strength ratio compared with parameters in the historic databases on which design guidance has been based. Experimental work using 355, 450 and 700 grade steels will quantify the influences on joint capacity enabling rational factors to be recommended replacing the blanket figures in current guidance. Parent material properties will be measured and related, by means of finite element analysis, to the structural response of the tubular joints in the experiments. The need to differentiate between failure modes will also be identified to ensure design practices do not become unconservative by incorrect extrapolation.

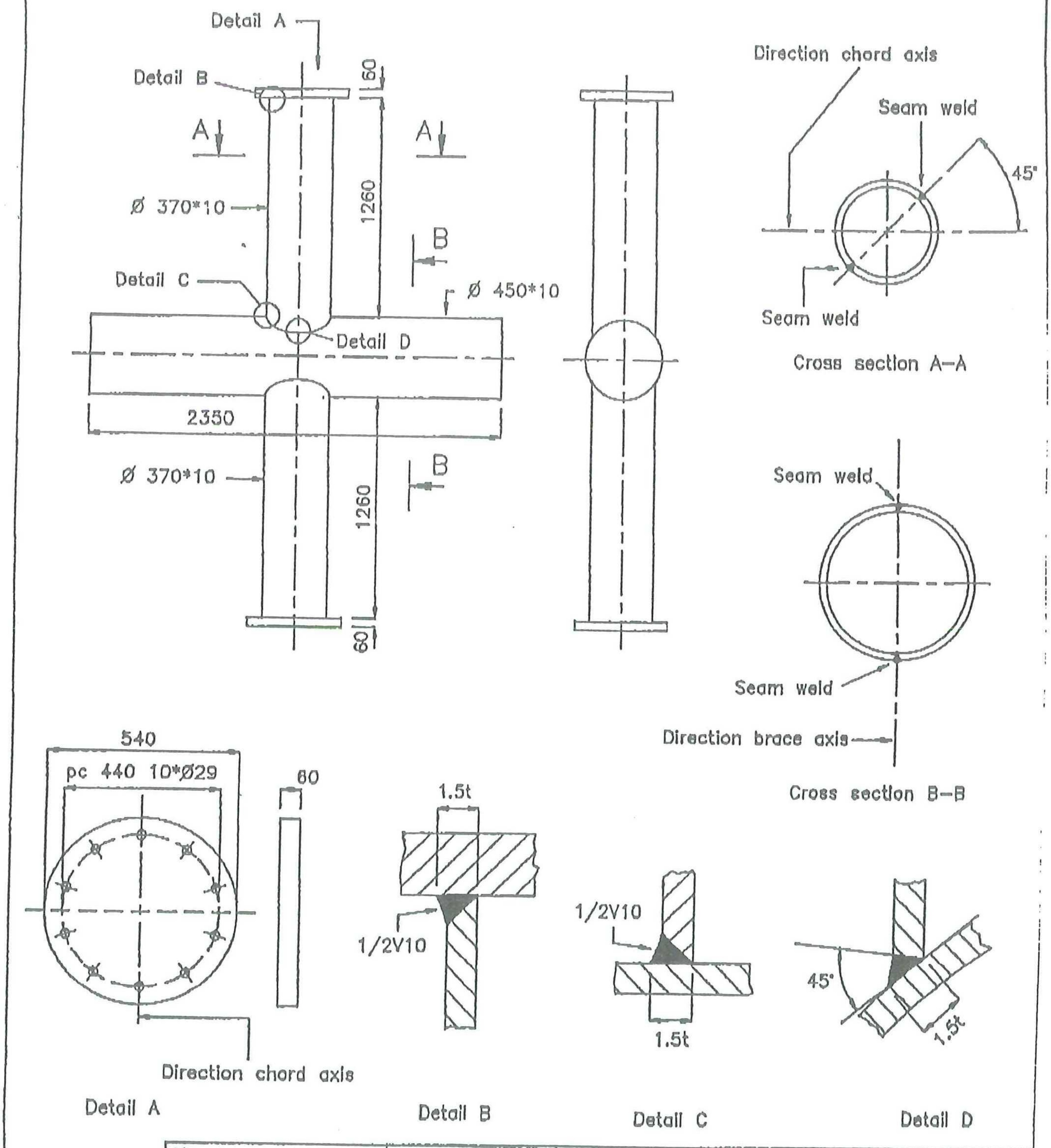
The outcome will be practical recommendations for the safe and economic exploitation of HSS for offshore structural nodes governed by static strength considerations.

2. TEST PROGRAMME

With the agreement of the Executive Committee F5 modifications have been made to the test programme. The objective now is to test double-tee (DT) joints in all cases: one in compression and one in tension for each of the three grades of steel, making a total of six specimens. This would make more clear the effects of material yield strength on joint response, and would separate out the influences of tension and compression in the brace stubs. These latter differing force actions would have been mixed in the joint types proposed earlier.

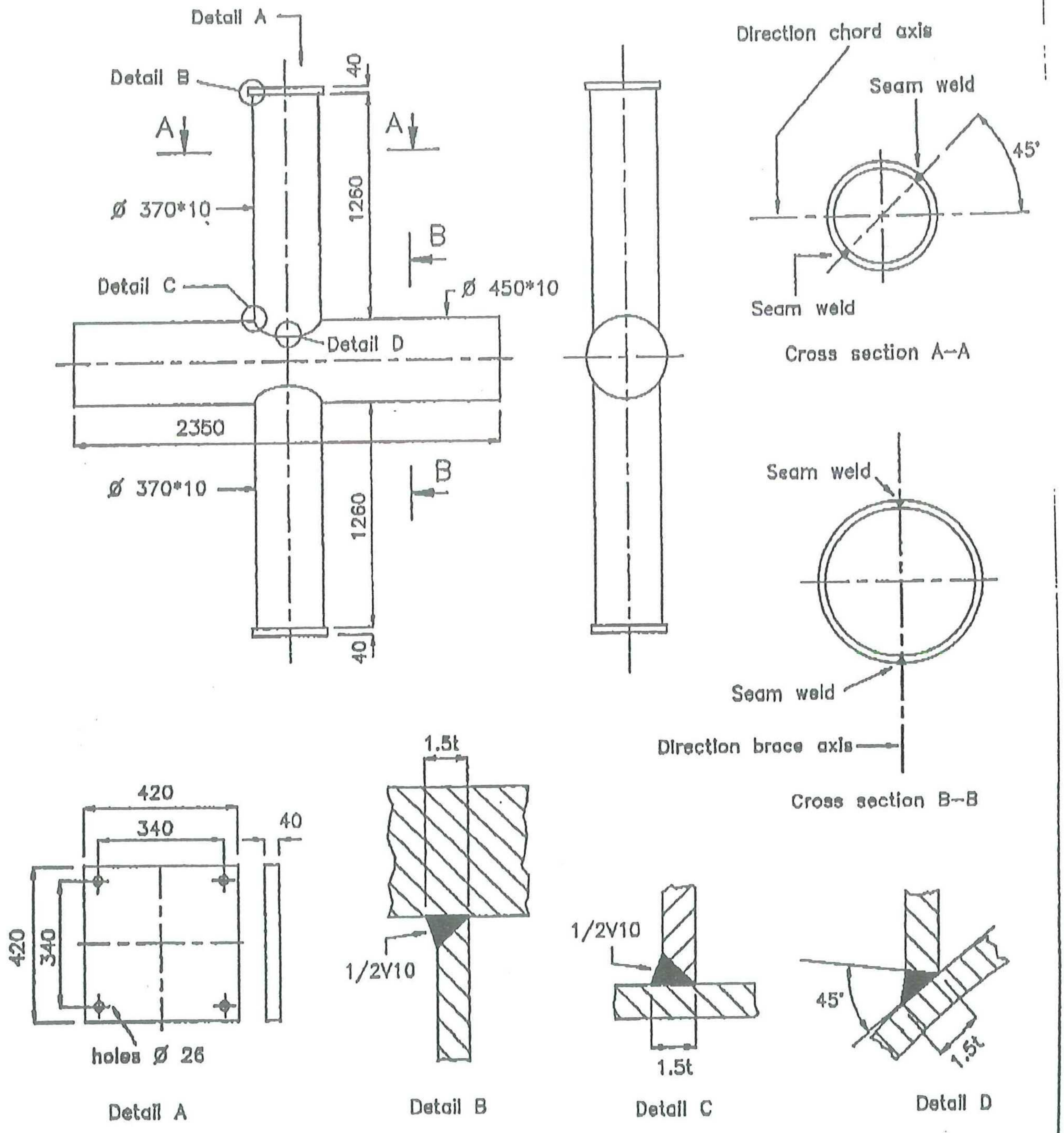
Finalisation of the joint dimensions, and a decision on the contractors to perform the rolling of the tubes to make up the specimens, have proved more difficult than anticipated and this has introduced delay into virtually all aspects of the project. This has stemmed from a combination of small diameters and wall thickness of the tubes involved, coupled with a lack of experience in the forming of the high grade material. Thus contractors have proved reticent in providing firm price quotations for the work. This contrasts very sharply with the situation which obtained in the early stages of the project when quotations for work were readily given without indication of the potential difficulties. In practice this meant that towards the end of the reporting period specimens had to be resized, design calculations reperformed, and joint end plates and test set-up redesigned. Moreover, the cycle of obtaining price quotations for specimen fabrication from contractors had to be begun again.

Notwithstanding this, the specimen dimensions have been finalised. A design report has been completed indicating the range of strengths that the joints are likely to exhibit, as an aid to gauging the test rig capacity requirements. The specimen end plates have been designed and fabrication drawings produced. These are shown in Figures 1, 2 and 3.



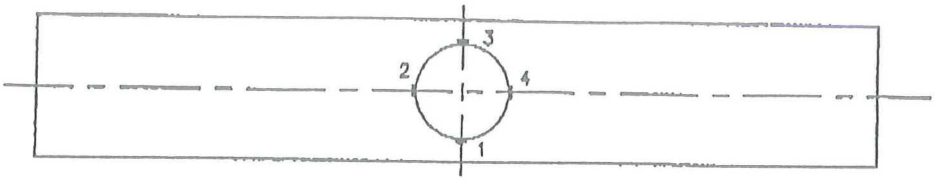
Number	3			STEVIN LABORATORIUM TUDELFT
Steel grade tubes	1*Fe355	1*Fe450	1*Fe700	
Steel grade endplate	min. Fe355	min. FeE355	min FeE355	
	Through thickness quality (Z quality)			
Tolerances	Max. angular divergence= 1/4°			
	Max. distance center lines= 1mm			

Figure 1 General arrangement of DT joint tension specimen

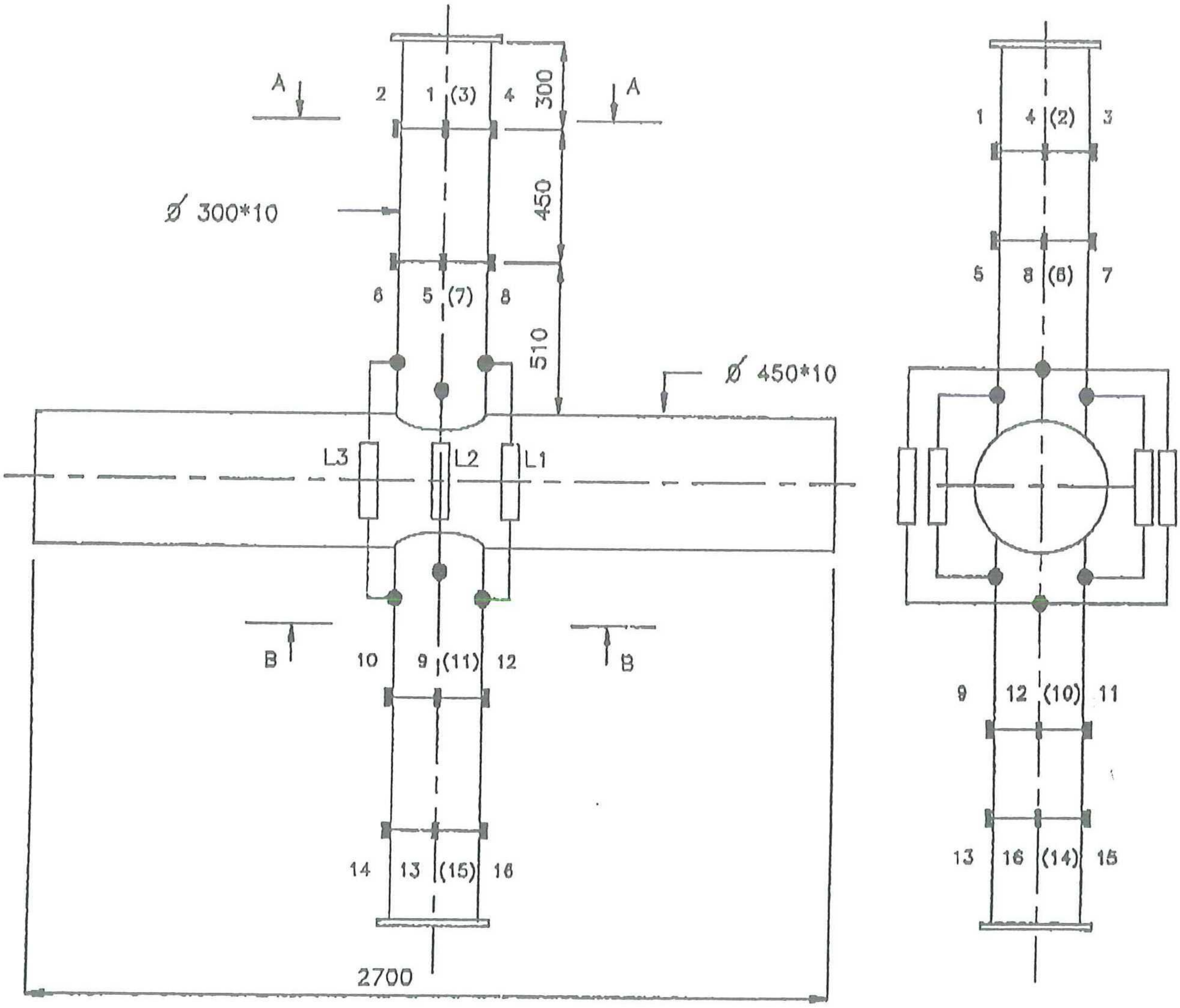


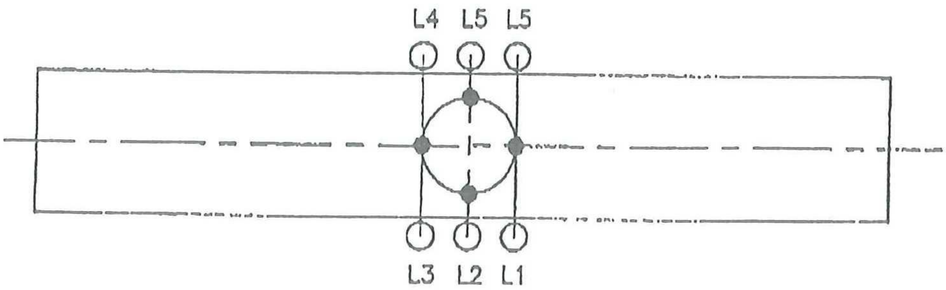
Number	3	STEVIN LABORATORIUM TUDELFT
Steel grade tubes	1*Fe355 1*Fe450 1*Fe700	
Steel grade endplates	Fe 355	
Tolerances	Max. angular divergence= 1/4°	
	Max. distance center lines= 1mm	

Figure 2 General arrangement of DT joint compression specimen



Cross section A–A





Cross section B–B

Figure 3 Strain gauge and transducer locations

3. FINITE ELEMENT WORK

In the absence of finalised dimensions of the test joint specimens further F.E. analyses were performed on a compression X-joint whose geometry was typical of that found in offshore construction. Analyses were undertaken employing different stress-strain characteristics as itemised in the table below.

Analysis	σ_y (N/mm^2)	UTS (N/mm^2)	σ_y/UTS	Comments
A	350	350	-	elastic-perfect plastic at baseline yield stress
B	350	525	0.66	typical offshore structural steel
C	491	525	0.90	higher strength steel ratio with yield plateau
D	491	491	-	elastic-perfect plastic at higher yield stress
E	491	525	0.90	higher strength steel ratio with gradual softening characteristic

It is recognised that for higher steel grades both UTS and σ_y would increase. The present analyses are performed at the stress levels indicated to enable the ready isolation of σ_y/UTS effects. By maintaining the ultimate strength of C to be the same as that for B, only the σ_y/UTS ratio changes, thus the effect of change in this can be identified by comparing the two analyses. Also by maintaining the same ultimate strength the structural design codes would ascribe the same design capacity to specimens from all steels. Thus the effect of the higher σ_y/UTS ratio on increasing actual joint capacity is clearly identified.

The results from the analyses, in terms of peak loads, are tabulated below. The value 1.0 represents the peak load achieved in Analysis B (the steel with σ_y/UTS = 0.66), the others being normalised relative to this.

Analysis	σ_y (N/mm^2)	UTS (N/mm^2)	Relative FE Capacity	Relative σ_y
A	350	350	0.945	1.0
B	350	525	1.000	1.0
C	491	525	1.276	1.4
D	491	491	1.260	1.4
E	350	525	1.066	1.0

The implication of the results is that an X joint with a σ_y/UTS ratio of 0.9 (typical of high strength steels) would have a 28% greater capacity than a joint with the same UTS level but σ_y/UTS ratio of 0.66. The structural codes would restrict the capacity of both joints to the lower value. Despite this obvious enhancement in capacity it should be noted that the capacity does not increase in direct proportion to the yield which is 40% higher in Case C. Case D confirms that the yield ratio is attributable to only about half the relative reduction in capacity and it is the increase in the absolute yield stress level which determines the remainder. Therefore both influences of the σ_y and the yield ratio need to be taken into account. Basing design capacities on the yield value would clearly be unconservative but a yield ratio restriction of 0.8 in the first instance would perhaps be more appropriate and still conservative with respect to the analysis results presented (1.276x350/525 = 0.851).

4. FUTURE WORK

During the next semester fabrication of the joint test specimens will proceed. This will enable specimens to be produced for crack tip opening displacement (CTOD) tests to be performed. Finishing touches will be put to the experimental set-up in preparation for the testing of the joint specimens.

Finite element analyses referred to earlier were directed towards gaining a general understanding of the effects of material yield to ultimate strength ratio on the capacity of compression joints. In the next semester this work will be extended to cover joints in tension. Work will commence on the analyses of DT joints having nominal dimensions, material properties and loading of the actual test specimens to enable their nominal responses to be established.

TECHNICAL ANNEX

Title: **DEVELOPMENT OF NEW STEELS FOR FUTURE OFFSHORE APPLICATIONS**

This annex gives a review of four projects in a multi-partner programme.

This report deals with: project No. P3239-4.

Title: **STATIC STRENGTH OF HIGH STRENGTH STEEL TUBULAR JOINTS**

ANNEX 1

Contract No: 7210-MC/807, 502, 935, 602,
7210-MC/110
P (or PP) No: P3239
93-F5.05a,b,c,d,e

TITLE: DEVELOPMENT OF NEW STEELS FOR FUTURE OFFSHORE APPLICATIONS

1. AIMS

A review of steel research requirements relevant to offshore production platforms identified several areas of study required to maintain and expand the use of steel. Two of these themes are addressed in this programme: Steel Development and Structural Behaviour, in the four projects which constitute this multi-partner programme.

The titles and aims of the individual projects are:

a) Development of Arctic Grade Structural Steels (P3239-1)

i) To develop structural steel chemistries which will provide sufficient parent plate and HAZ toughness at -50°C, the minimum design temperature for Arctic use.

ii) To extend the viable welding heat input programme for normal offshore structural use.

b) Development and Testing of High Strength Steels for Offshore Engineering (P3239-2)

To provide a comparative assessment of normalised, thermomechanically rolled, accelerated and direct quenched steels with a minimum yield strength of 450 N/mm^2.

c) Evaluation of High Strength Steel Beams for Offshore Applications (P3239-3)

To characterise the mechanical and technological properties of quenched and self-tempered sections with a minimum yield strength of 460 N/mm^2 and a thickness at the upper limit of EN 10225.

d) Static Strength of High Strength Steel Tubular Joints (P3239-4)

To determine the influence of high strength steel mechanical parameters on the capacity and ultimate response characteristics of tubular nodes to enable design guidelines for the safe and economic use of these steels to be written.

2. DESCRIPTION OR WORK

The partners and task allocation is as follows:

Coordinator - British Steel Technical, Swinden Laboratories.

P3239-1 -	CEMUL, Portugal and British Steel Technical, UK.
P3239-2 -	Thyssen Stahl AG, Germany.
P3239-3 -	ARBED, Luxembourg and SINTEF, Norway (sub-contract).
P3239-4 -	TNO - BOUW and Delft University of Technology, The Netherlands and BOMEL, UK. (Coordinated through Centrum Staal).

P3239-1

The first and major part of the programme will be concerned with HAZ microstructure and toughness characterisation. This will utilise experimental casts of various compositions and HAZ simulation techniques in order to process a large volume of HAZ data. HAZ toughness will be evaluated using thermal simulation techniques and a Gleeble 1500 simulator. The two microstructural regions known to be of most concern in terms of the local brittle zone (LBZ) phenomena, namely the grain coarsened HAZ (GCHAZ) and the intercritically reheated GCHAZ (ICGCHAZ), will be simulated at three heat inputs ranging from these currently utilised up to about 7.5 kJ/mm. HAZ toughness will be evaluated by defining Charpy impact and CTOD transition curves.

The second part of the programme will examine ways of meeting the arduous parent plate property requirements. The most promising compositions in terms of HAZ toughness will be subjected to plate processing trials to establish their capability to meet arctic steel tensile, Charpy and Pellini requirements. These trials are expected to examine controlled rolling, and controlled rolling plus accelerated cooling schedules, using a large scale laboratory rolling mill.

The third and final part of the programme will involve a demonstration of the developed steels. To this end, the best steel or steels identified in the programme will be welded by a high heat input submerged-arc welding procedure and the weld joint properties fully evaluated in terms of HAZ, Charpy CTOD and parent Charpy and Pellini properties.

P3239-2

Systematic testing of the strength and toughness properties, brittle fracture resistance and fatigue behaviour of parent metal and the heat-affected zone of typical welded joints will be performed in plates up to around 60 mm in thickness produced by normalising, thermomechanical rolling, accelerated cooling or direct quenching. Research on this physical metallurgy will be aimed at providing further information on the relations between the microstructure (transformation behaviour during heat treatment and welding) and mechanical properties of the different types of steel.

P3239-3

W 14 x 16 x 311 American wide flange sections with a yield strength of 460 MPa will be produced at the GREY heavy beam rolling mill of ARBED Differdange using the quenching and self-tempering process. The flange thickness of these sections being 57.4 mm and the metric weight 463 kg/m.

The characterisation of the base material will include CVN transition curves at different thickness locations and a CTOD transition curve using full thickness specimens.

In accordance with annex F of pr EN 10225, welding will be performed on highly restrained welding assemblies, using two welding processes and three heat inputs, i.e.:-

FCAW	0.8 kJ/mm
SAW	3.5 kJ/mm
SAW	5.0 kJ/mm

All welding will be performed without preheating.

The characterisation of the butt welded material will include the following:

- cross weld tensile tests
- CVN transition curves at cap, mid-thickness and root, each FL-2, FL, FL + 2, FL + 5
- Full thickness CTOD in GC HAZ and IC HAZ
- Hardness profiles
- Wide plate tests in GC HAZ and IC HAZ

Controlled thermal severity tests will be performed in order to assess the susceptibility of the material to HAZ hydrogen cracking.

P3239-4

The scope of work is divided into six activities as follows:-

1. Collate data from Manufacturers material certificates to identify relevant material properties for the steel grades 355, 450 and 700. This activity will be coordinated with other projects in the offshore sector in the 1993 ECSC research programme.

2. Undertake a series of tubular joint tests covering.

    - Axial compression DT joint tests to examine ductility and redistribution.
    - Balanced axially loaded K joint tests to examine mode of failure.

Each test will be undertaken for three geometrically identical specimens fabricated from steel of 355, 450 and 700 N/mm^2 steel grades. The first case will act as a benchmark to existing data. The second will quantify effects for those steels now most widely available for higher strength applications. The final tests will explore the potential use of higher strength materials in the future.

3. Supplement test programme with specific coupon tests, CTOD tests and measurements of elongation for both the test steels and for corresponding materials available from other European manufactures.

4. Cross reference 355 data with existing and revised offshore joint data to quantify the effects of changing material properties for higher strength steels. Compression, tension and combined tests will enable the effects of F_y, F_y/F_u, ductility and load redistribution to be separately assessed in terms of capacity and mode of failure.

5. Perform preliminary FE analysis of representative test joints using material characteristics for all three grades. Compare results to confirm and explain experimental trends and validate FE analysis for wider applications.

6. Combining information from the above, develop initial recommendations for revising design guidance to give rational treatment of F_y/F_u in tubular joint capacity equations and so enabling the economic use of high strength steels.

3. WAYS AND MEANS

Each partner in this collaborative programme has extensive experience in steel research together with all of the necessary experimental equipment and expertise. In this project it is important that the specific needs of steel users and designers within the offshore industry are addressed and the close association of several of the partners with this industry are essential to its success.

British Steel will be responsible for the overall management of the project which will be in the hands of a Project Manager. He will be responsible for preparing a detailed project plan indicating key dates and decision points. He will organise meetings twice a year at a location determined by the current stage of the project. Each partner will appoint a Technical Manager to coordinate activities in conjunction with the Project Manager.

The work will involve the interchange of results between the laboratories. This process of interchange will be facilitated by the close personal and professional relationships which already exist between the staff at the separate laboratories. Close contact will be maintained between the laboratories before and during the life of the project.

The financial control of the project will be carried out using the existing administrative and accounting systems in each laboratory. These are able to keep accurate records of all the manpower effort devoted to the project and of the expenditure in support of the project. These systems have proved to be completely satisfactory on audit by the Commission for the ECSC contracts that have been completed in the recent past.

Annual progress reports will be prepared by the Project Manager, and will cover:-

Work carried out;
Results;
Notification of accelerated progress/delays;
Notification of proposed changes to the programme.

Each Technical Manager will ensure that the Project Manager receives the reports he needs to prepare the annual report and immediate notification of any major diversions from the overall project plan.

4. KEYWORDS

1. Offshore Structures
2. High Strength Structural Steels
3. Tubular Joints
4. Weldability
5. HAZ Toughness
6. Fracture Toughness
7. Controlled Rolling
8. Accelerated Cooling
9. Static Strength
10. Sections
11. pr EN 10225
12. Design Guidance

5. The results of the project will be subject of a publication in the "Technical Steel Research" series.

The research described above will be placed in the area covered by the Executive Committee F5 - Plates and Heavy Beams.