CONFIDENTIAL

FATIGUE AND FRACTURE BEHAVIOUR OF WELDED JOINTS IN HIGH STRENGTH STEELS (Fe E 460)

Interim report no. 4

Period : 1 July 1991 - 31 December 1991

Project leader : C. Noordhoek
(Delft University of Technology)

ECSC Agreement number : 7210-KD/610 (F5/F1.5/89)

Beneficiary : Foundation for Materials Research in the Sea (SMOZ)
Rotterdamseweg 137
2628 AL Delft
The Netherlands

Period : 1 December 1989 - 30 November 1992

Participants : Delft University of Technology
Department of Civil Engineering
C. Noordhoek
Delft University of Technology
Ships Structures Laboratory
H.G. Scholte
Eindhoven University of Technology
Laboratory for Structural Fatigue
J.L. Overbeeke
TNO Institute of Production and Logistics Research
C. Koning
TNO Building and Construction Research
O.D. Dijkstra

DISTRIBUTION 7210.KD/610

a. Directorate General XII, Research Science, Developments (10 copies).

b. Executive Committee F5 - Plates and heavy beams:

Alting T.J.	Hoogovens Groep BV
Buzzichelli M.G.	CSM Spa
Debiez G.	Intitut de Soudure
Defourny M.J.	CRM
Dengler J.M.	Arbed Recherches
Demofonti G.	CSM Spa
Devillers L.	Irsid
Dufrane J.J.	Fabrique de fer de Charleroi
Duran J.	Cenim
Flossdorf F.J.	VDEh
Freier K.	Stahlwerke Peine-Salzgitter AG
Lanza M.	Instituto Italiano Saldatura
Maddox S.J.	Welding Institute
Manso F.	Ensidesa
Noordhoek C.	Delft University of Technology
Quintino L.	Instituto Soldatura e Qualidade
Seil M.P.	Arbed Recherches
Webster S.E.	British Steel

c. Representatives of the benificiares:

Anelli E.	CSM Spa
Bateson P.H.	British Steel
Barteri M.	CSM Spa
Bourges Ph.	Creusot Loire
Denys R.	Laboratorium Soete W.L.M.
Dhooge A.	Laboratorium Soete W.L.M.
Fuentes Peres M.	Ceit
Harrison P.L.	British Steel
Moura Branco C.	Cemul
Scheller P.R.	Krupp Stahl
Sonsino C.M.	LBF
Vittori O.	CSM Spa

CONTENTS

by O. D. Dijkstra

SUMMARY

During the second half year of 1991 the following activities have been carried out:

- manufacturing of the specimens
- erecting of test rigs
- material tests
- first nine fatigue tests on T-joints carried out
- finite element stress intensity factor analysis of 2D weld geometries
- pilot crack growth calculations

In the first half year of 1992 the following activities are planned:

- finalizing the manufacturing of the specimens
- further execution of experiments
- crack growth calculations

The preliminary conclusions from the nine fatigue tests on T-joints are that the results of the tests at ambient temperature are the same as for the earlier tests on normal strength steel (St 52) and the results of the tests at low temperature (-20°C) are better than the results of the tests at ambient temperature.

1 INTRODUCTION

The improved techniques in steel fabrication make available economic production of high strength steels with a good weldability. The use of this high strength steels leads to weight reduction and more economical solutions in the design.

The increase of the stress level in the structure, combined with a reduction of the due load gives higher stress variations in the structure due to the external loads. These higher stress variations (stress ranges) make fatigue more often the governing load case for the design. Therefore additional research in the field of fatigue of high strength steels is required.

The higher stress levels in a high strength steel structure make the structure more sensitive to unstable crack growth. Therefore brittle fracture needs also further investigation.

Brittle fracture mostly initiates from a fatigue crack at a peak load in the load spectrum. So it seems necessary to combine fatigue- and brittle fracture-testing of structural components under the expected most severe but realistic circumstances with high loads and low temperatures.

Fatigue cracks normally initiate at geometrical discontinuities such as welded details. Therefore the program is concentrated on welded connections. So the general objective of this research is to investigate the fatigue and fracture behavior of welded connections in high strength steel under a realistic fatigue loading and at low temperatures.

The geometry of the test specimens and a review of the test programme are given in figure 1 and table 1.

2 WORK IN PROGRESS

2.1 General

During this fourth period of the project the following activities have been carried out:

- manufacturing of the specimens
- erecting of test rigs
- first tests carried out
- finite element stress intensity factor analysis of 2D weld geometries
- pilot crack growth calculations

In 2.2, 2.3 and 2.4 detailed information about these subjects are given.

In the next period the following activities are planned:

- finalizing the manufacturing of the specimens
- further execution of experiments
- crack growth calculations

2.2 Manufacturing of test specimens and material tests

The test specimens were welded according to strict guidelines and welding procedures.

For the T-joints (T40 and T70) the following general conditions have to be met (see appendix A for more details):

- overall weld angle between 60° and 70°
- maximum local weld toe angle 85°
- no undercuts
- no arc strikes on the plate

- no grinding on final weld toe
- cap welds in 3G position

For the butt weld specimens (SB40, SB70, LP40 and LP70) the general conditions were chosen in such a way that the fatigue crack will grow into the HAZ (as already pointed out in interim report no 2). In appendix B more details of the weld preparation and the run sequence can be found.

The fracture toughness of the base material was determined by CTOD tests on the 70 mm thick plate material. Tests were carried out at -20°, -40°, -60° and -80° C. The results show a good CTOD level for all the test temperatures (see figure 2 and appendix C). The lowest CTOD value measured was 0.19 mm at -80° C.

2.3 Experiments

2.3.1 General

During this fourth period the fatigue tests have started and a total of 9 T-joints have been tested, viz:

2 specimens of the T40C+ type at IPL-TNO
3 specimens of the T70C+ type at TNO Building and Construction Research
4 specimens of the T70C- type at DUT-Civil Engineering

All tests have been carried out in four point bending. The inner span in the test rig was 7 * plate thickness and the outer span was 21 * plate thickness.

An overview of the results can be seen in table 2 and figure 3.

In figure 3 two reference curves based on previous work on normal strength steel are drawn. The 40 mm thick specimens tested at ambient temperature are below the reference curve, the 70 mm thick specimens tested at ambient temperature are on the reference curve and the 70 mm thick specimens tested at -20° C are above the reference curve.

Some more experimental details are given in section 2.3.2. In section 2.3.3 some information on the spectrum load (WASH) as to be used at the Technical University at Eindhoven will be given.

2.3.2 Experimental details

2.3.2.1 Dimensions

The most important dimensions of the specimens are defined in figure 4. The measured dimensions of the test specimens are given in table 3.

2.3.2.2 Strain gage measurements

All specimens were provided with strain gages.
The minimum number of strain gages on a specimen are 3. One gage for an overall control of the load and at each weld toe (left and right side of the stub) one gage for crack detection.
Some joints are provided with more gages to check the strain distribution and the working of the test rig in more detail.

Figure 5 showed an example of the more complex strain measurements on specimen T70C-/1. The strain gages for crack initiation are at a 10 mm distance from the weld toe, while the gages for load and test rig control are at a distance of the plate thickness from the weld toe.
A nearly perfect straight line under 45° was found for specimen T70C-/1 for the relation between the nominal strain (calculated from the applied load) and the measured strain at the top of the specimen (see figure 6).

During the fatigue test strain measurements were carried out at regular intervals. Figure 7 and 8 show the change in strain range of the gages near the weld toe for specimen T70C+/2 and T70C+/3. The strain range starts at a value above the nominal strain (as given in table 2) due the stress raising effect of the weld toe.
The vertical lines in these graphs gives the number of cycles at which a crack marking was carried out. The procedure of this crack marking and how the number of cycles is corrected for this is described in section 2.3.2.3. As can be seen in figure 7 and 8 the crack marking does not disturb the strain range curve. From this it can be concluded that the crack marking does not disturb the fatigue test.

2.3.2.3 Crack measurements

During the fatigue test the following crack measurements were carried out:

a Visual crack measurement at the surface of the specimen
b Alternating Current Potential Drop (ACPD) crack depth measurements
c Crack marking by changing the load range
d Crack opening displacement (COD) measurements

The first two methods (a and b) were used to find the first small cracks (crack initiation), to control the fatigue test and to decide whether a crack marking or COD measurement was needed.

The crack marking gives the most reliable and complete information of the crack shape during the fatigue test. During a crack marking procedure the load range is taken half the load range of the normal fatigue test. The maximum load is kept the same to avoid retardation effects. This lower load range gives smaller crack growth rates and thus a different appearance of the crack surface. Assuming a slope in a da/dN-ΔK curve of 3 the load cycles during a crack marking procedure are as effective as 1/8 (= $(1/2)^3$) of the number of load cycles with a normal load range. The test results are corrected in this way.

Figure 9 and 10 gives the crack markings of specimen T70C+/2 and T70C+/3. The number of cycles at with the crack markings were done can be found in figure 7 and 8.

The COD measurements were carried out to investigate whether crack closure occurs. Figure 11 shows no crack closure in specimen T70C+/2. COD measurements at specimen T70C+/1 and T70C+/3 showed no crack closure in these specimens.

2.3.3 Variable amplitude tests

Variable amplitude tests will be carried out at the Eindhoven University of Technology. Therefore the WASH.1 generator was built and tested in this period.
This generator consists of two parts:

a. data-generator
b. signal-generator

The data-generator reads the data (peaks and valleys) from the Wave Action Standard History, which are stored on an eprom disk and transfers these to the signal-generator.

The WASH.1 spectrum is developed by the LBF-Darmstadt, and IABG-Ottobrunn, and is described in LBF-report FB-181

It is a standardized load history for stiff and floating platforms, and it contains a fixed sequence of 5.10^5 cycles (10^6 extremes).
WASH.1 contains a variable load history composed of a defined series of six seastates, corresponding to long term observations on North Sea platforms during one year.

In this period the WASH.1 generator was tested for accuracy and compared with the WASH-tapes.

da/dn measurements were carried out at R = 0.1 on dummy specimens loaded with the WASH.1 sequence in order to get used to it.

2.4 Fracture mechanics

2.4.1 Finite element stress intensity factor analyses of 2D weld geometries

In the fracture mechanics part of the previous ECSC/SMOZ programme [1] finite element analysis were carried out for 2D and 3D geometries.

For the 2D T-joint geometries analyzed the thickness of the attached plate was the same as the thickness of the main plate. In the present programme the thickness of the attached plate is half the thickness of the main plate. There are indications that the thickness of the attachment (or the distance L between the weld toes) has an influence on the fatigue life of a T-joint. Therefore finite element stress intensity factor analyses of 2D weld geometries with various attachment/plate thickness ratios were carried out.

The analyses were carried out with the same technique as in [1] with the general purpose finite element program DIANA.

The geometry analyzed in [1] with t/T = 1 (= 4/4) is given in figure 12, while the present experimental geometry with t/T = 1/2 (= 2/4) is given in figure 13. To cover a wider range of t/T values four analyses were made with t/T ratios of 1/4 , 2/4 , 3/4 and 4/4. The other parameters are the same as in [1] for geometry C-0-1 (see also table 4 and figure 12 and 13).

The four geometries were analyzed for membrane and bending load cases (see figure 14 and 15) with a nominal stress at the surface of 1 N/mm^2. Each geometry was analyzed for the uncracked situation and for seven crack depth, ranging from 0.5 mm to 35 mm.

The finite element meshes used are given in figure 16. The stress distributions in the uncracked situation of geometry 1/4 and 4/4 near the weld toe are given in figure 17 to 20. The calculated stress in the integration point near the weld toe in the main plate are summarized in table 5. These figures can be regarded as stress concentration factors (SCF) (nominal stress = 1 N/mm^2). As can be seen for thicker attachments the SCF values increase and the SCF for bending load is higher than for membrane load.

The results in term of strain energy release rate (G), stress intensity factor (K), geometrical correction factor (f) and stress intensity concentration factor (M_K) are given in table 6 to 9. Table 10 summarizes the M_k factors for all the four geometries. The results are also plotted in figure 21 to 26. It can be seen that the M_k factors for bending are higher than those for membrane stresses and that the M_k factors increase with the thickness of the attachment.

2.4.2 Pilot crack growth calculations

Fracture mechanics fatigue crack growth analysis were carried out with the program FAFRAM. The M_k factors determined in the chapter are not available in FAFRAM at the moment. So, the IIW/OMAE M_k factors (based on PD 6493 and information in [1]) were used. An overview of the input parameters is given in table 11 and appendix D. A part of the results of the calculations are presented in appendix D. A graphical presentation of the relation between the crack depth and the number of cycles is given in figure 27. The experimental results are also plotted in figure 27. The 2D analysis are underpredicting the experimental lifetime as can be expected. The 3D analysis predict the results of the tests at ambient temperature rather good. The test at -20°C showed a longer life compared to other experiments and the FAFRAM analysis. The reason for this is not known at the moment.

The M_k factors of the previous section will be incorporated in FAFRAM and then more analysis will be made in the next period.

3 Preliminary conclusions

The preliminary conclusions based on the limited work done are:

a that the results of the fatigue tests at ambient temperature are the same as for the earlier tests on normal strength steel (St 52) and the results of the tests at low temperature (-20°C) are better than the results of the tests at ambient temperature.

b that a greater weld toe distance give higher M_k values and therefore a shorter fatigue life.

REFERENCES

1 Fatigue behaviour of welded joints in offshore steel structures. Part III: Fracture mechanics.
SMOZ, Delft, December 1988.
ECSC Convention 7210-KG/602(F7.5/84)
Dijkstra, O. D., Snijder, H. H., Overbeeke, J. L., Wildschut, H. and Scholte, H. G.

TABLES

Table 1 Review of test specimens
(Specimen code / number of specimens)

Plate thickness			40 mm		70 mm	
Testing temperature			+20°C	-20°C	+20°C	-20°C
Geometry	Special details 1)	Type of loading 2)				
SB40 / SB70 Small Butt welds	-	CA	SB40C+/2	SB40C-/4	SB70C+/2	SB70C-/4
	-	VA	SB40V+/2	SB40V-/4	SB70V+/2	SB70V-/4
	-	ΔK	-	SB40K-/4	-	SB70K-/8 3)
LP40 / LP70 Large Plate welds	-	CA	LP40C+/2	LP40C-/2	LP70C+/4	LP70C-/6
	Pre-cracked	CA	-	-	-	LP70PC-/4
T40 / T70 T-joints	-	CA	**T40C+/4**	T40C-/2	**T70C+/4**	**T70C-/6**
	Ground	CA	T40GC+/2	T40GC-/2	T70GC+/2	T70GC-/2

1) Pre-cracked = artificial initial semi-elliptical surface crack at weld toe
Ground = weld toe grinding

2) CA = constant amplitude loading
VA = variable amplitude loading
ΔK = constant ΔK loading with intermediate CTOD loads

3) Some tests at temperatures lower than -20° C

N.B. In this period some specimens of the bold figures are tested.!!

Table 2 Test results

Specimen	R	$\Delta\sigma_{nom}$ N/mm^2	$\Delta\epsilon_{nom}$ $*10^{-6}$	N_{f1} $*10^6$	N_{f2} $*10^6$	N_{f3} $*10^6$	N_{f4} $*10^6$
T40C+/1	0.1	200	952	0.055	0.205	0.213	0.235
T40C+/2	0.1	200	952	0.043	0.190	0.204	0.221
T70C+/1	0.1	200	952	0.031	0.108	0.108	0.203
T70C+/2	0.1	200	952	*)	0.110	0.110	0.187
T70C+/3	0.1	120	571	0.127	0.492	0.749	0.825
T70C-/1	0.1	200	952	0.060	0.147	0.186	0.299
T70C-/2	0.1	120	571	0.290	1.339	1.462	1.500
T70C-/3	0.1	200	942	0.056	0.226	0.226	0.270
T70C-/4	0.1	120	571	0.240	0.868	0.916	1.039

N_{f1}= crack initiation (10 mm surface crack)

N_{f2}= crack first corner

N_{f3}= crack second corner

N_{f4}= End of Test

*) first crack missed due to computer failure

Table 3 Dimensions of tested specimens

Specimen	plate thickness	plate width	stub thickness	weld toe distance		weld height			
						front		back	
				front	back	left	right	left	right
	T	B	t	L-f	L-b	H-fl	H-fr	H-bl	H-br
	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
T40C+/1	40.0	210.1	19.9	43.2	43.2	21.8	19.0	16.7	20.2
T40C+/2	40.0	209.9	19.93	43.3	43.8	17.2	20.8	15.7	18.9
T70C+/1	70.9	210.0	34.6	55.6	55.7	17.6	18.5	19.3	19.0
T70C+/2	70.6	209.9	34.5	53.4	54.5	18.8	23.21	19.1	18.1
T70C+/3	70.6	209.9	34.2	54.3	55.1	20.7	20.0	20.9	20.9
T70C-/1	70.7	210.0	34.6	53.8	53.0				
T70C-/2									
T70C-/3									
T70C-/4									

Table 4 Dimensions of FEM geometries

Geometry C-0-1-		1 / 4	2 / 4	3 / 4	4 / 4
Dimensions					
Plate thickness	T [mm]	70	70	70	70
Attachment thickness	t [mm]	17.5	35	52.5	70
Attachment height	h [mm]	30	30	30	30
Weld angle	θ [°]	70	70	70	70
Weld toe radius	ρ [mm]	0.	0.	0.	0.
Weld toe distance	L [mm]	39.3	56.8	74.3	91.8
Dimensionless parameters					
t / T	[-]	0.25	0.50	0.75	1.00
L / T	[-]	0.562	0.812	1.062	1.312
h / T	[-]	0.429	0.429	0.429	0.429
ρ / T	[-]	0.	0.	0.	0.

Table 5 Stress in integration point near weld toe.

Geometry C-0-1-	1 / 4	2 / 4	3 / 4	4 / 4
Membrane load	5.08	5.66	6.04	6.28
Bending load	5.63	6.55	7.21	7.63

Table 6 Geometry factors for C-0-1- 1/4
Load case: b = pure bending , m = membrane

$G = \frac{K^2}{E} * (1-\nu^2)$; $K = f\sigma\sqrt{\pi a}$; $\sigma = 1\ N/mm^2$; $f = f_{strip} * M_k$.

relative crack depth a/T [-]	load case b , m	G [10^{-3}N/mm]	K [$Nmm^{-3/2}$]	f [-]	f_{strip} [-]	M_k [-]
0.0071	b m	0.03305 0.02855	2.762 2.567	2.2038 2.0482	1.0995 1.1091	2.0043 1.8467
0.0250	b m	0.05120 0.04838	3.437 3.342	1.4658 1.4253	1.0777 1.1110	1.3602 1.2829
0.0625	b m	0.08440 0.09169	4.413 4.600	1.1903 1.2408	1.0560 1.1410	1.1272 1.0874
0.1375	b m	0.1488 0.2041	5.860 6.864	1.0657 1.2483	1.0362 1.2337	1.0284 1.0118
0.2750	b m	0.3175 0.6402	8.560 12.16	1.1007 1.5637	1.0960 1.5624	1.0043 1.0008
0.3875	b m	0.5607 1.514	11.38 18.69	1.2328 2.0246	1.2349 2.0333	0.9983 0.9957
0.5000	b m	1.047 3.704	15.54 29.24	1.4820 2.7885	1.4896 2.8057	0.9949 0.9939

Table 7 Geometry factors for C-0-1- 2/4
Load case: b = pure bending , m = membrane

$$G = \frac{K^2}{E} * (1-\nu^2); \quad K = f\sigma\sqrt{\pi a}; \quad \sigma = 1\ N/mm^2; \quad f = f_{strip} * M_k.$$

relative crack depth a/T [-]	load case b , m	G [10^{-3}N/mm]	K [$Nmm^{-3/2}$]	f [-]	f_{strip} [-]	M_k [-]
0.0071	b m	0.04249 0.03407	3.131 2.804	2.4982 2.2373	1.0995 1.1091	2.2721 2.0172
0.0250	b m	0.06268 0.05568	3.803 3.584	1.6219 1.5285	1.0777 1.1110	1.5050 1.3758
0.0625	b m	0.09608 0.09972	4.709 4.797	1.2702 1.2939	1.0560 1.1410	1.2028 1.1340
0.1375	b m	0.1590 0.2125	6.058 7.003	1.1017 1.2735	1.0362 1.2337	1.0632 1.0323
0.2750	b m	0.3234 0.6464	8.639 12.21	1.1109 1.5701	1.0960 1.5624	1.0136 1.0049
0.3875	b m	0.5657 1.524	11.43 18.76	1.2382 2.0322	1.2349 2.0333	1.0027 0.9995
0.5000	b m	1.056 3.740	15.61 29.38	1.4887 2.8018	1.4896 2.8057	0.9994 0.9986

Table 8 Geometry factors for C-0-1- 3/4
Load case: b = pure bending , m = membrane

$$G = \frac{K^2}{E} * (1-\nu^2); \quad K = f\sigma\sqrt{\pi a}; \quad \sigma = 1\ N/mm^2; \quad f = f_{strip} * M_k.$$

relative crack depth a/T [-]	load case b , m	G [10^{-3}N/mm]	K [$Nmm^{-3/2}$]	f [-]	f_{strip} [-]	M_k [-]
0.0071	b m	0.04954 0.03757	3.381 2.945	2.6976 2.3498	1.0995 1.1091	2.4535 2.1186
0.0250	b m	0.07102 0.06014	4.048 3.725	1.7264 1.5887	1.0777 1.1110	1.6019 1.4299
0.0625	b m	0.1044 0.1044	4.909 4.909	1.3241 1.3241	1.0560 1.1410	1.2539 1.1605
0.1375	b m	0.1665 0.2174	6.199 7.083	1.1273 1.2881	1.0362 1.2337	1.0879 1.0441
0.2750	b m	0.3279 0.6496	8.698 12.24	1.1185 1.5740	1.0960 1.5624	1.0205 1.0074
0.3875	b m	0.5694 1.531	11.46 18.80	1.2414 2.0366	1.2349 2.0333	1.0053 1.0016
0.5000	b m	1.060 3.751	15.64 29.42	1.4915 2.8057	1.4896 2.8057	1.0013 1.0000

Table 9 Geometry factors for C-0-1- 4/4
Load case: b = pure bending , m = membrane

$$G = \frac{K^2}{E} * (1-\nu^2); \quad K = f\sigma\sqrt{\pi a}; \quad \sigma = 1\ N/mm^2; \quad f = f_{strip} * M_k.$$

relative crack depth a/T [-]	load case b , m	G [10^{-3}N/mm]	K [$Nmm^{-3/2}$]	f [-]	f_{strip} [-]	M_k [-]
0.0071	b m	0.05377 0.03952	3.523 3.020	2.8109 2.4096	1.0995 1.1091	2.5565 2.1726
0.0250	b m	0.07596 0.06257	4.187 3.800	1.7857 1.6207	1.0777 1.1110	1.6570 1.4588
0.0625	b m	0.1093 0.1069	5.023 4.968	1.3549 1.3400	1.0560 1.1410	1.2830 1.1744
0.1375	b m	0.1709 0.2200	6.280 7.125	1.1420 1.2957	1.0362 1.2337	1.1021 1.0503
0.2750	b m	0.3304 0.6509	8.732 12.26	1.1229 1.5765	1.0960 1.5624	1.0245 1.0090
0.3875	b m	0.5710 1.533	11.48 18.81	1.2436 2.0376	1.2349 2.0333	1.0070 1.0021
0.5000	b m	1.060 3.753	15.64 29.43	1.4915 2.8066	1.4896 2.8057	1.0013 1.0003

Table 10 Summary of M_k factors geometry C-0-1 1/4, 2/4, 3/4 and 4/4

relative crack depth a/T [-]	load case b , m	t/T = 1/4 [-]	t/T = 2/4 [-]	t/T = 3/4 [-]	t/T = 4/4 [-]
0.0071	b m	2.0043 1.8467	2.2721 2.0172	2.4535 2.1186	2.5565 2.1726
0.0250	b m	1.3602 1.2829	1.5050 1.3758	1.6019 1.4299	1.6570 1.4588
0.0625	b m	1.1272 1.0874	1.2028 1.1340	1.2539 1.1605	1.2830 1.1744
0.1375	b m	1.0284 1.0118	1.0632 1.0323	1.0879 1.0441	1.1021 1.0503
0.2750	b m	1.0043 1.0008	1.0136 1.0049	1.0205 1.0074	1.0245 1.0090
0.3875	b m	0.9983 0.9957	1.0027 0.9995	1.0053 1.0016	1.0070 1.0021
0.5000	b m	0.9949 0.9939	0.9994 0.9986	1.0013 1.0000	1.0013 1.0003

Table 11 Input parameters crack growth calculations

Parameter	40 mm thick T-joints		70 mm thick T-joints	
	2-D	3-D	2-D	3-D
Thickness T (mm) Width B (mm)	40. -	40. 210.	70. -	70. 210.
A-law constant C (N, mm) exponent m	Paris .18320E-12 3.	Paris .18320E-12 3.	Paris .18320E-12 3.	Paris .18320E-12 3.
C-law constant C (N, mm) exponent m	- - -	Paris .18320E-12 3.	- - -	Paris .18320E-12 3.
Stress Intens. Fac Mk weld angle Θ (deg) toe radius ρ (mm) toe dist. L (mm)	Brown/S/O IIW-X/OMAE 60. .5 43.5	Newman/Raj IIW-X/OMAE 60. .5 43.5	Brown/S/O IIW-X/OMAE 60. .5 55.0	Newman/Raj IIW-X/OMAE 60. .5 55.0
Initiation	-	Single	-	Single
initial defects crack depth a_i (mm) crack width c_i (mm)	 .15 -	 .15 .75	 .15 -	 .15 .75
Process parameters α ($\Delta a = \alpha * a_i$) stopped when final depth a_n (mm)	 .05 $a_n > a_f$ 20.	 .05 $a_n > a_f$ 20	 .05 $a_n > a_f$ 35.	 .05 $a_n > a_f$ 35.
Stress range $\Delta\sigma_m$ (N/mm^2) $\Delta\sigma_b$ (N/mm^2)	 0. 200.	 0. 200.	 0. 200.	 0. 200.

FIGURES

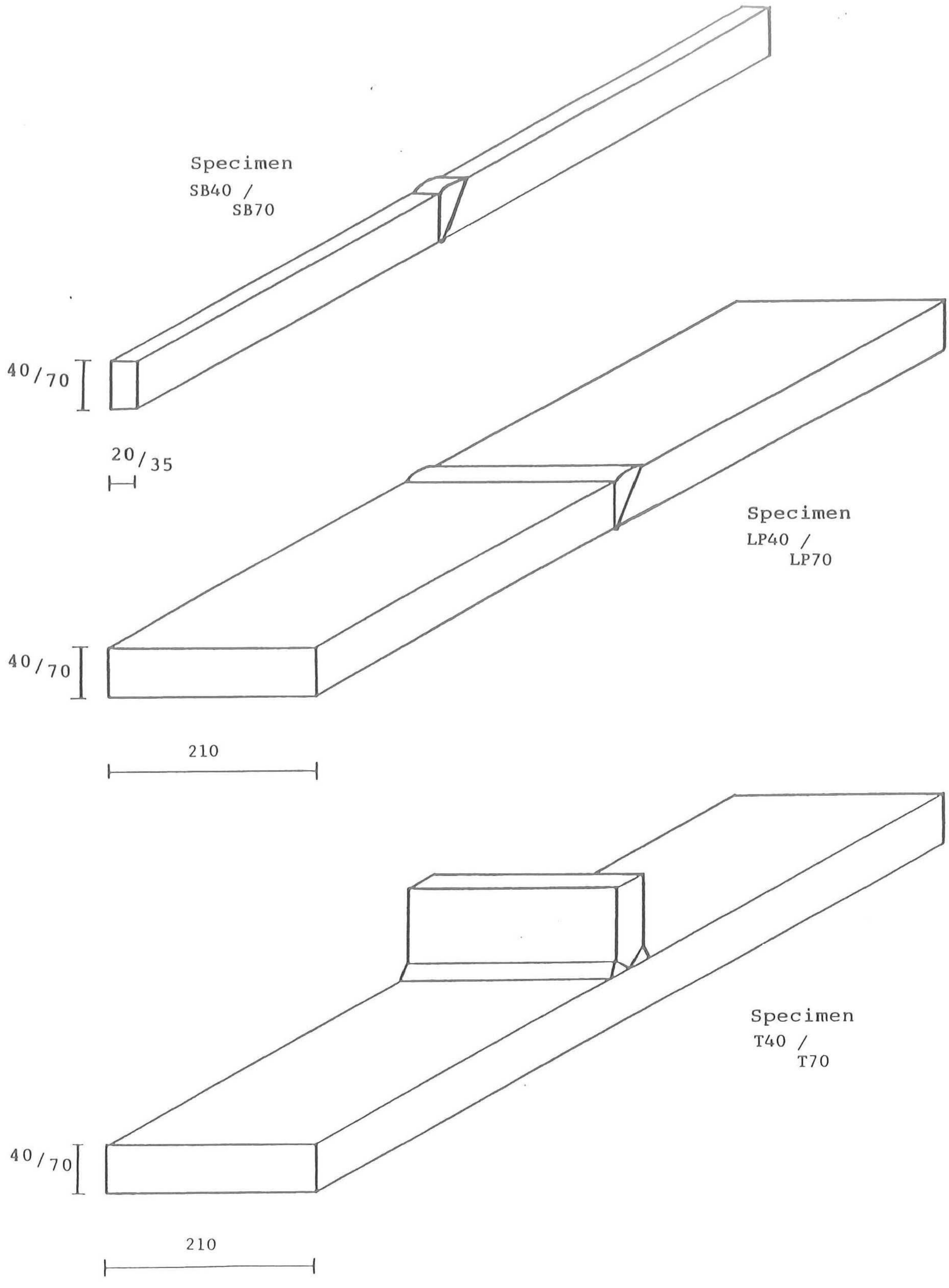


Figure 1 Geometry of test specimens.

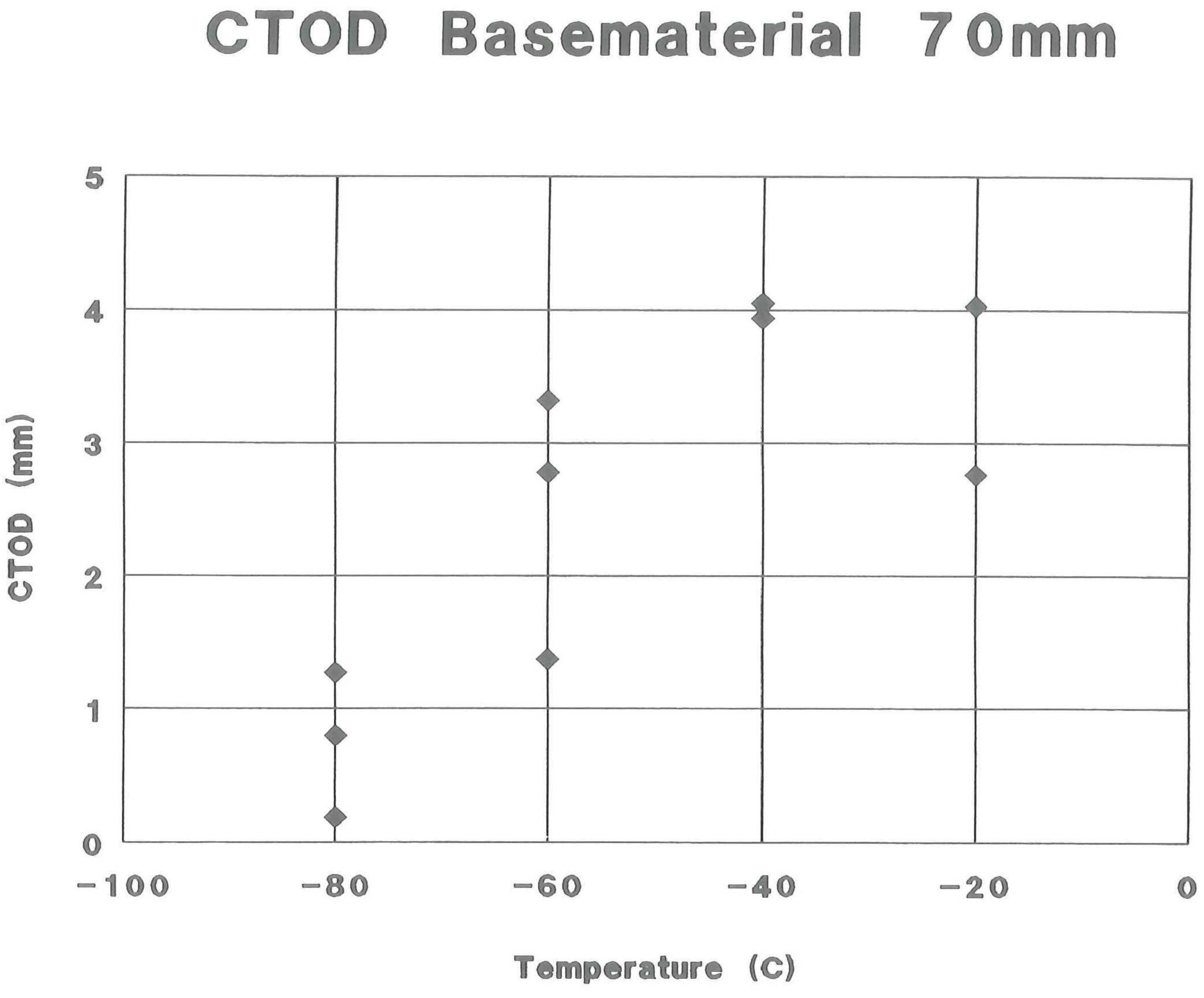


Figure 2 CTOD values for 70 mm plate material.

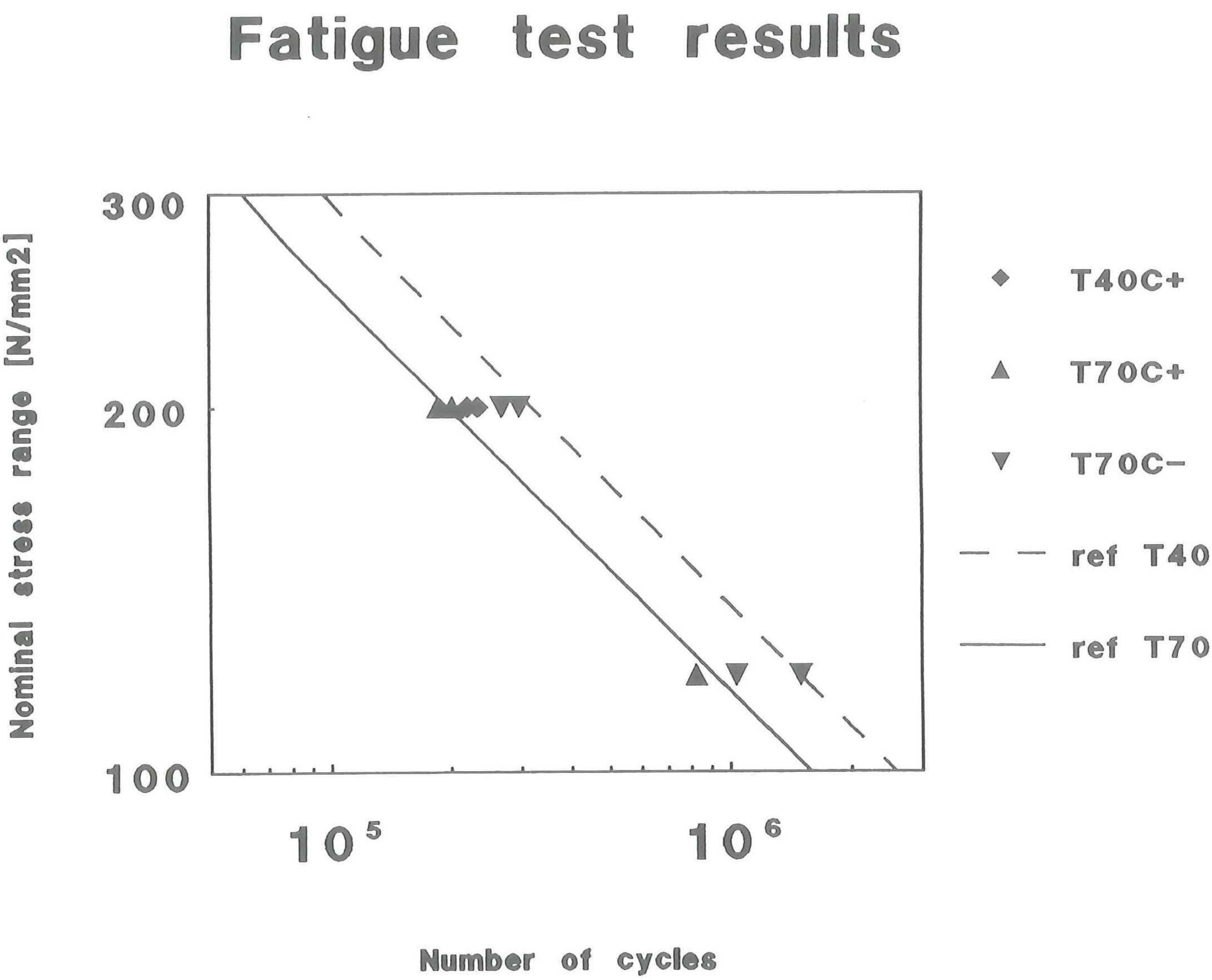


Figure 3 S-N curve for T-joints

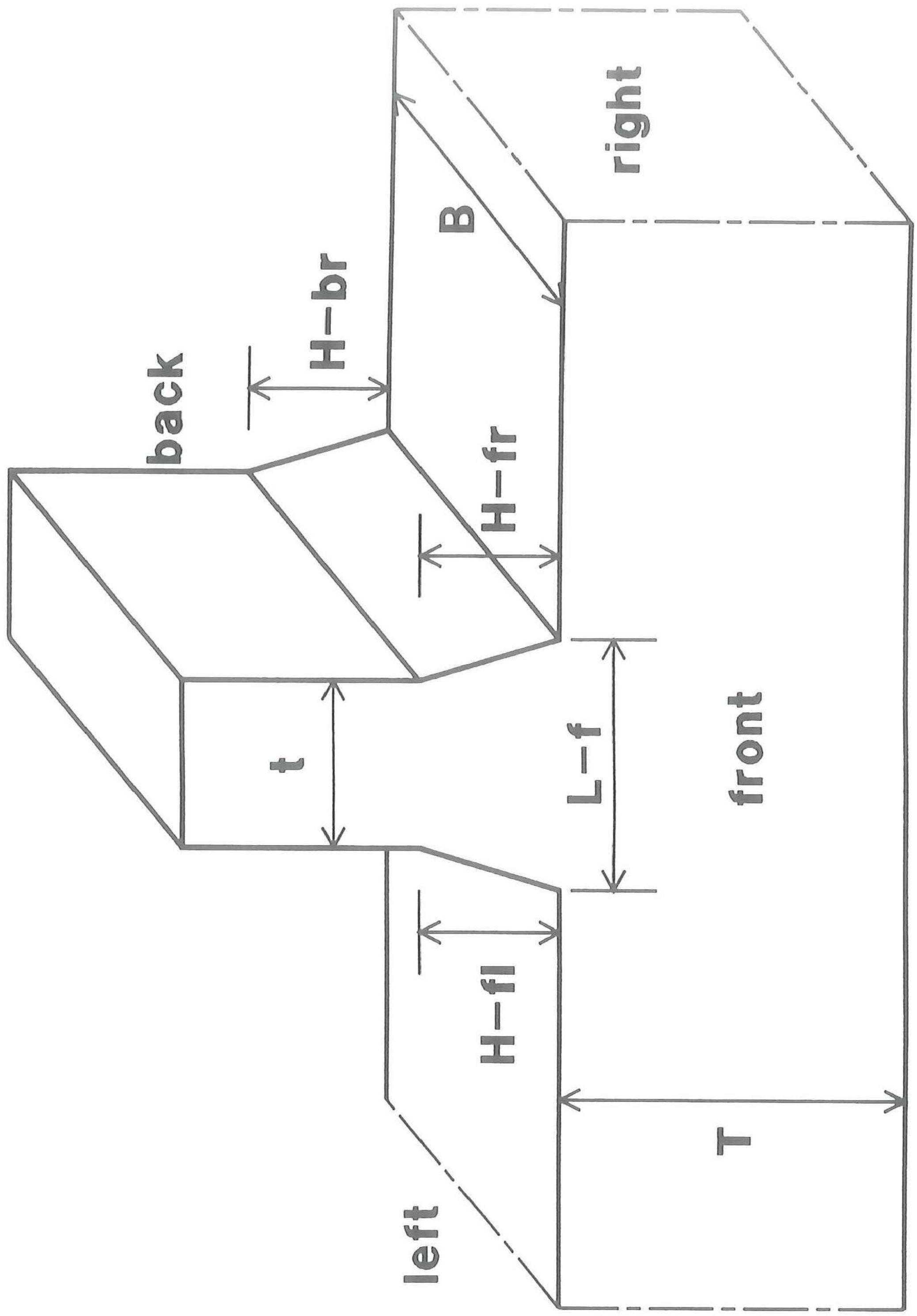


Figure 4 Dimensions of test specimens

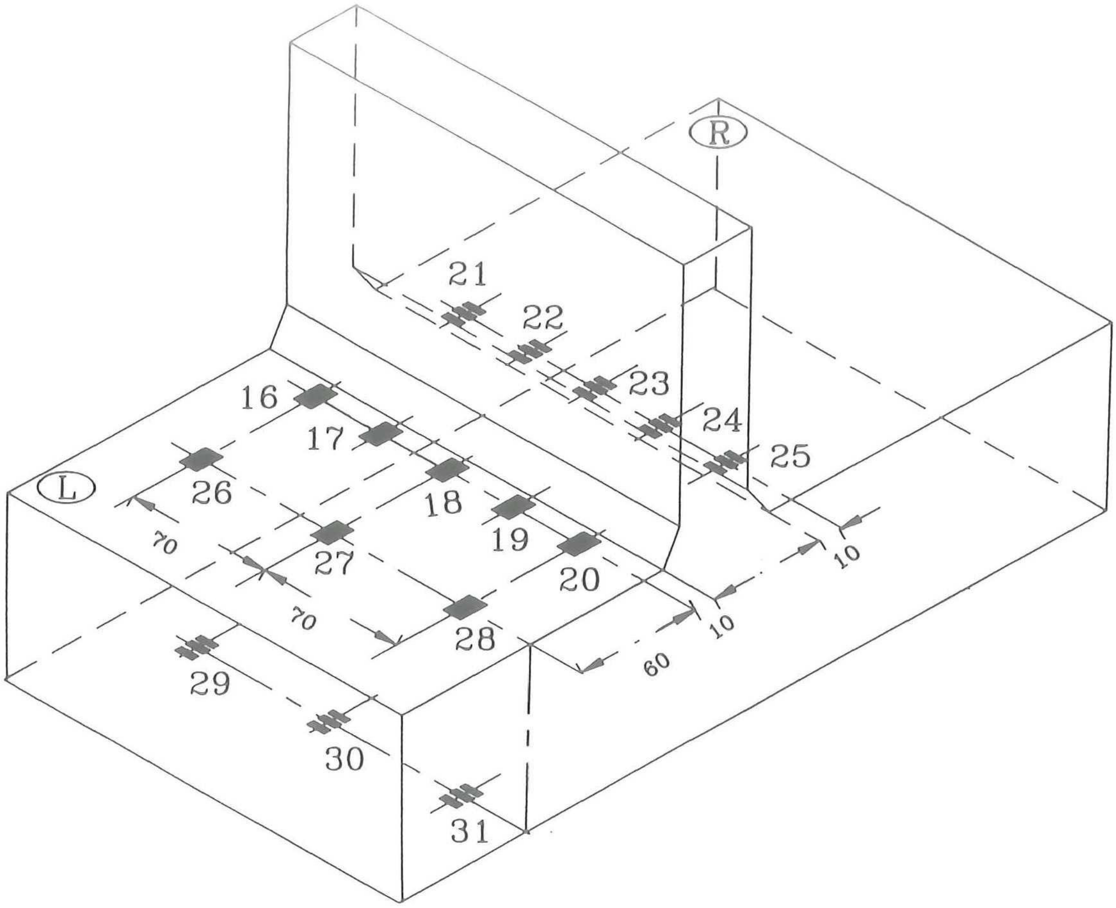


Figure 5 Location of strain gages on specimen T70C-/1

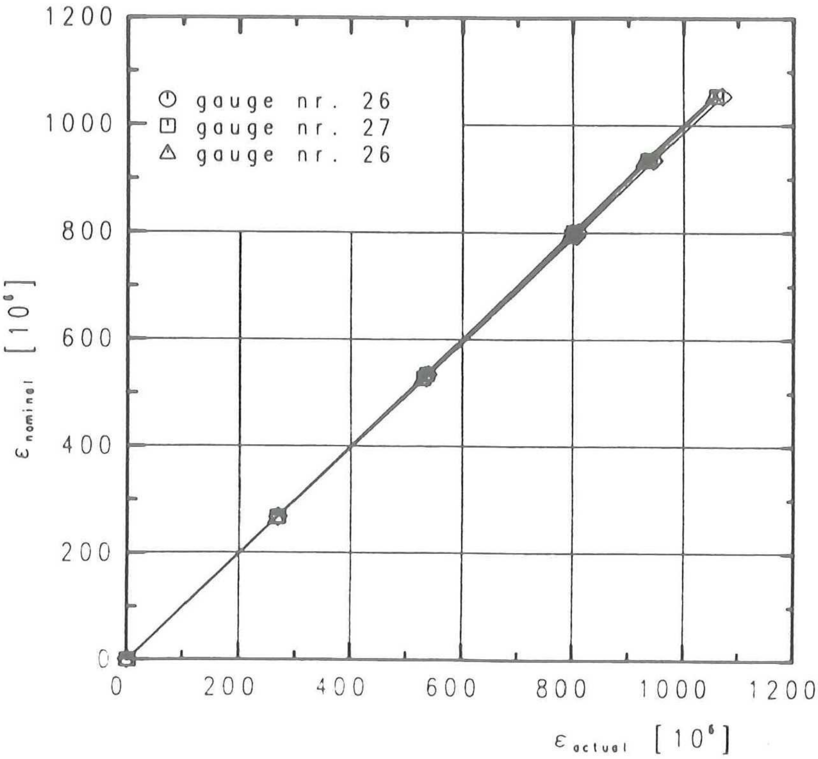


Figure 6 Relation nominal strain and measured strain for specimen T70C-/1

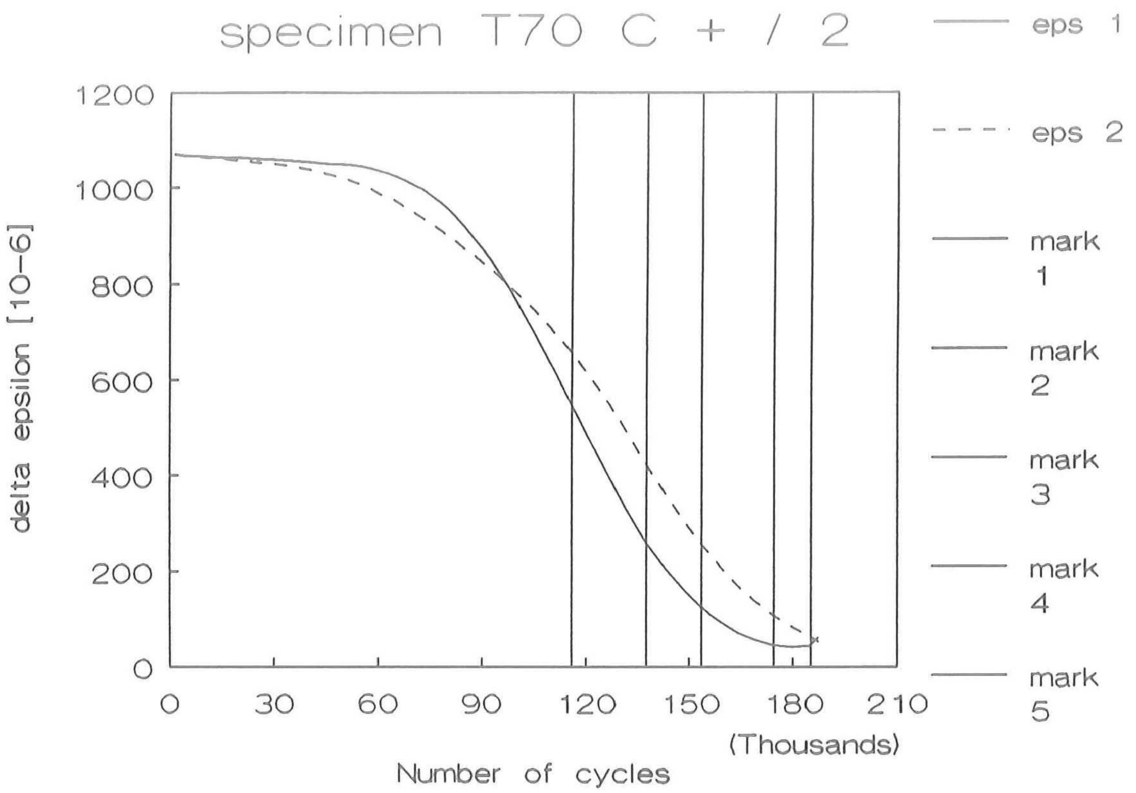


Figure 7 Relation strain range and number of cycles during the fatigue test for specimen T70C+/2

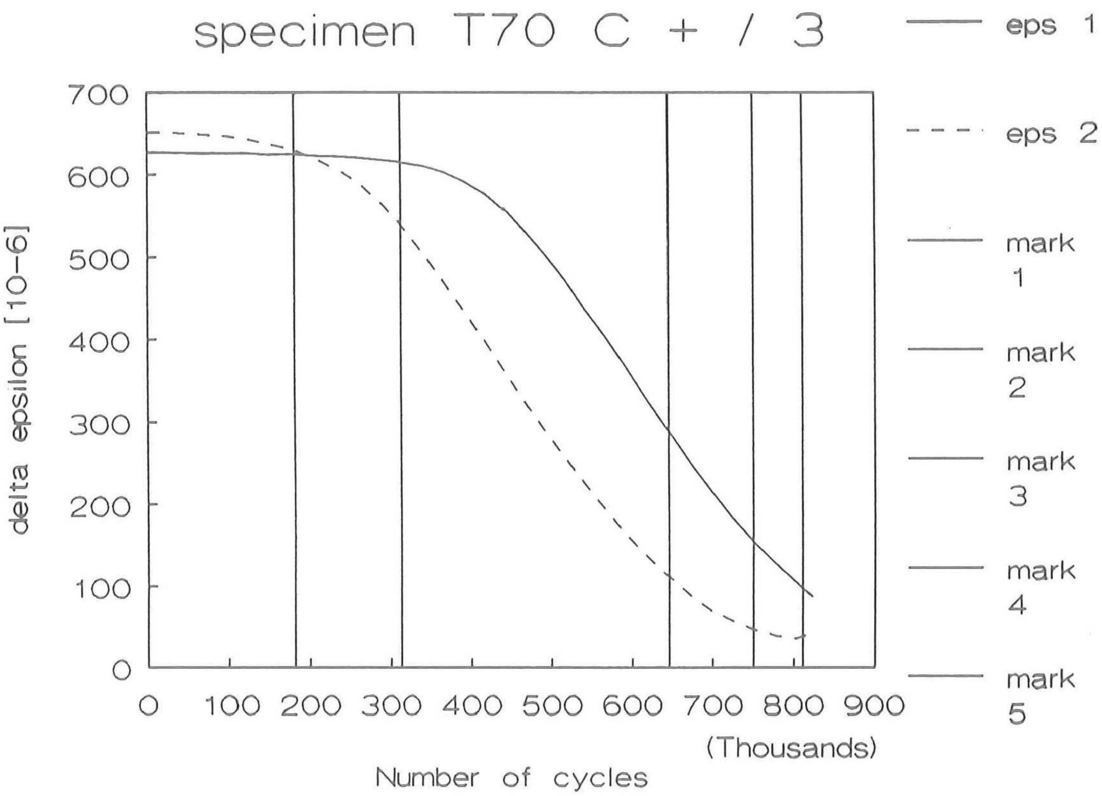


Figure 8 Relation strain range and number of cycles during the fatigue test for specimen T70C+/3

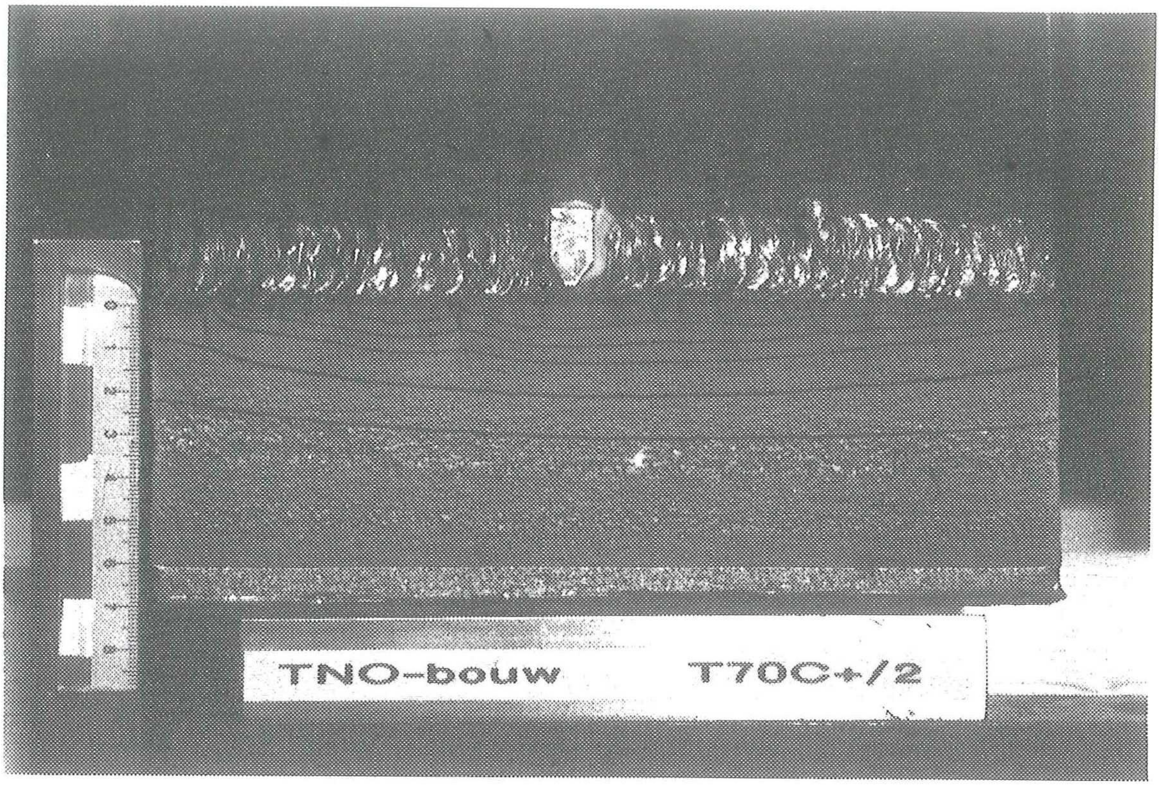


Figure 9 Fracture surface with crack marking on specimen T70C+/2

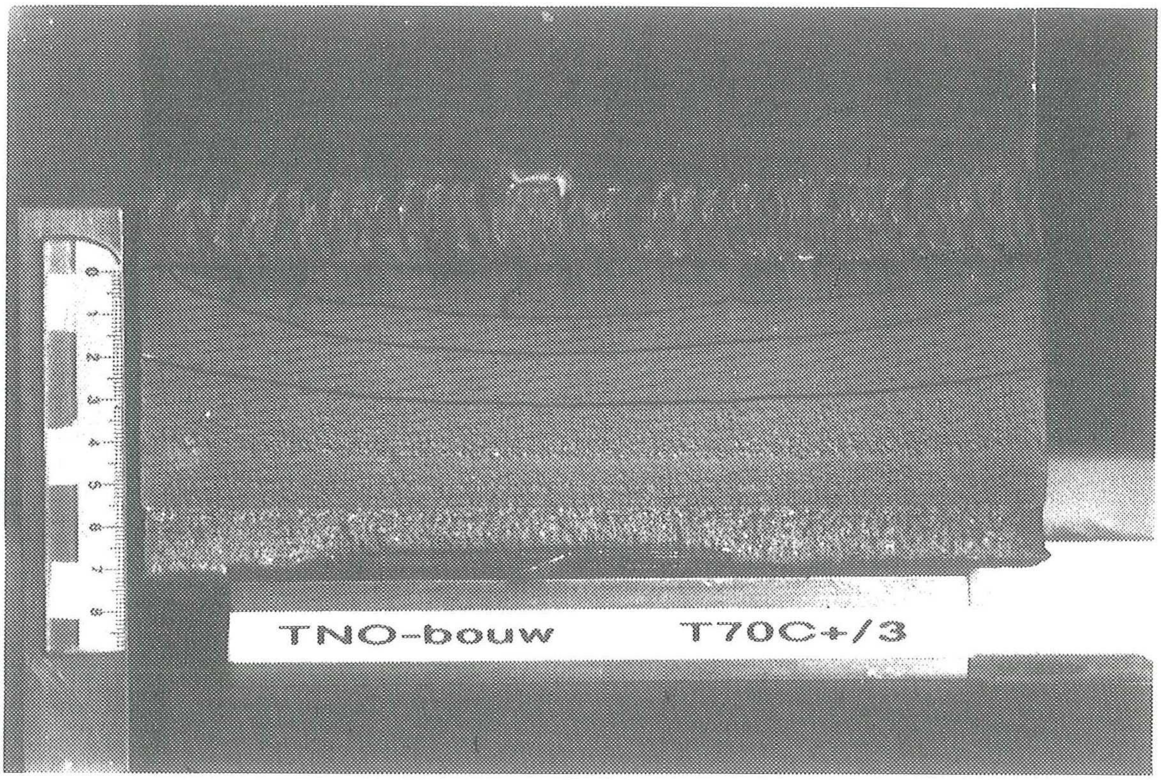


Figure 10 Fracture surface with crack marking on specimen T70C+/3

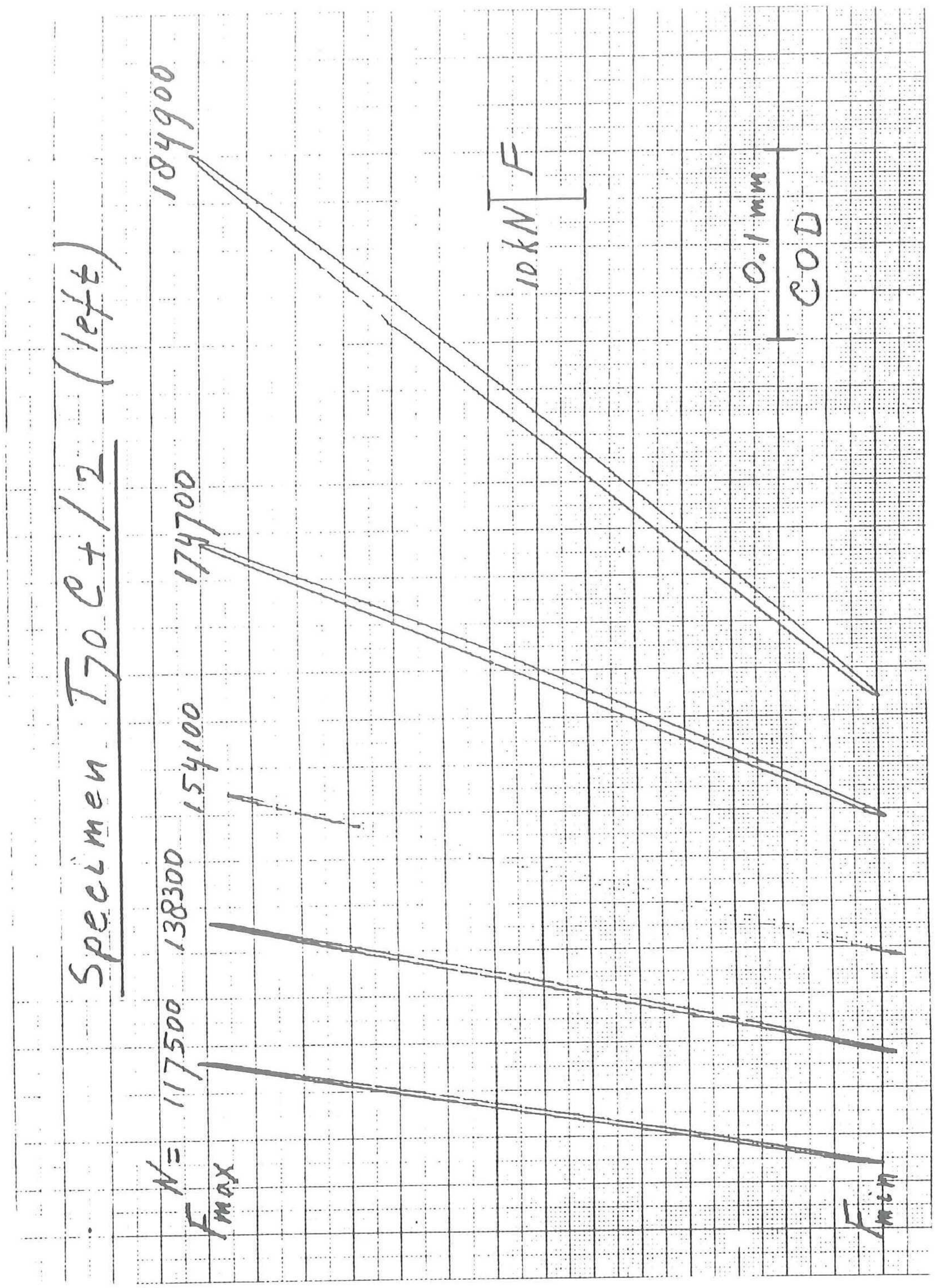


Figure 11 Crack opening displacement measurements on specimen T70C+/2

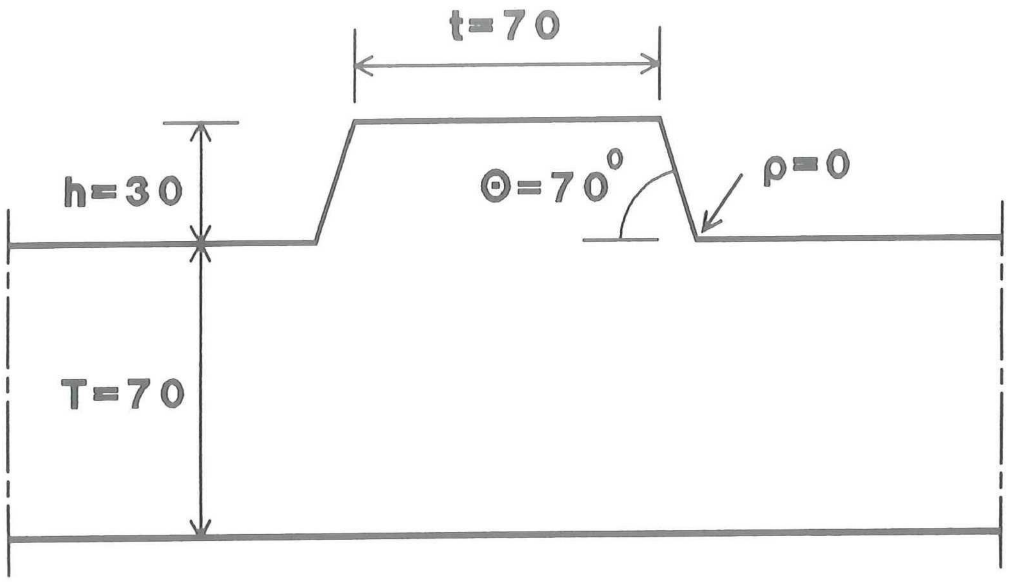


Figure 12 Geometry C-0-1- 4/4

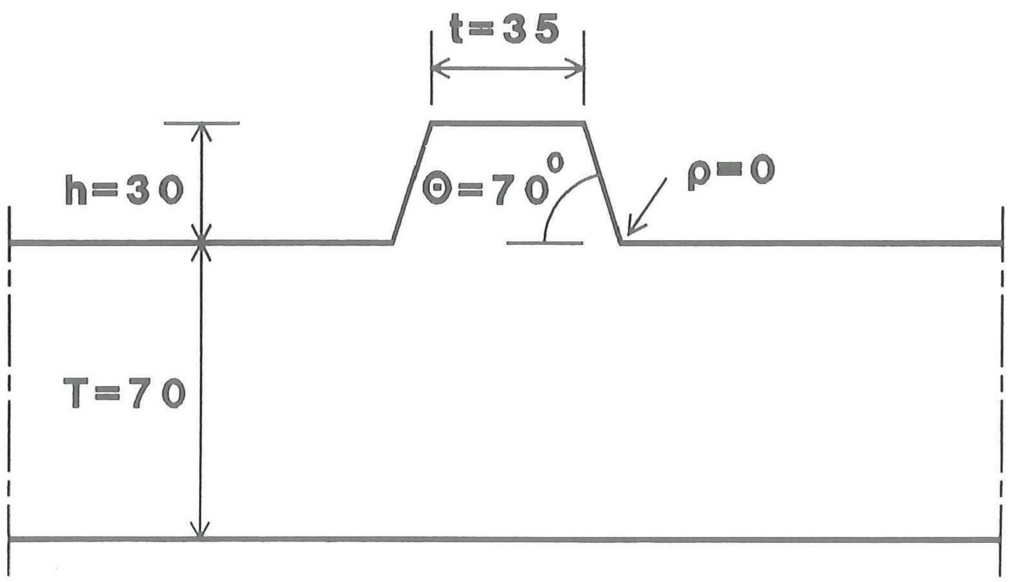


Figure 13 Geometry C-0-1- 2/4

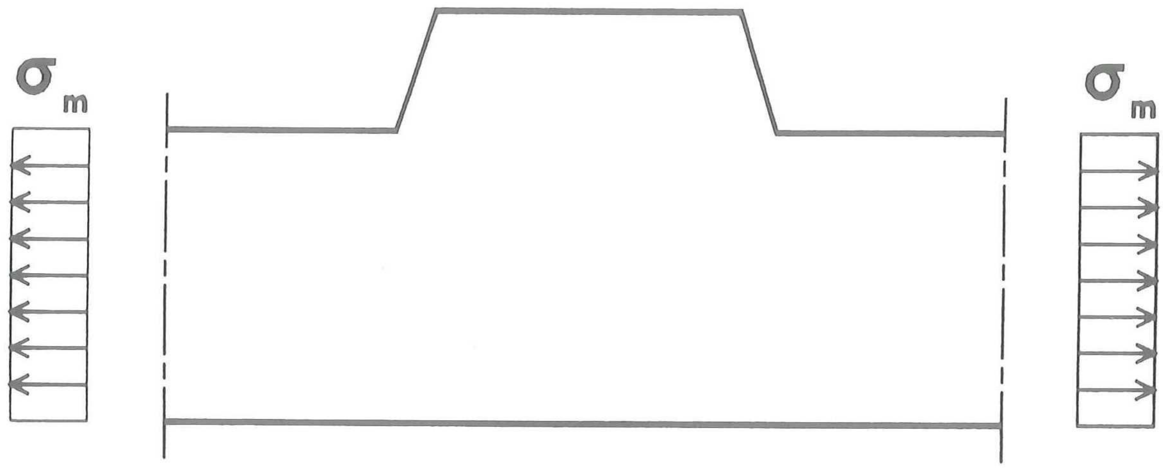


Figure 14 Membrane load case on FEM geometry

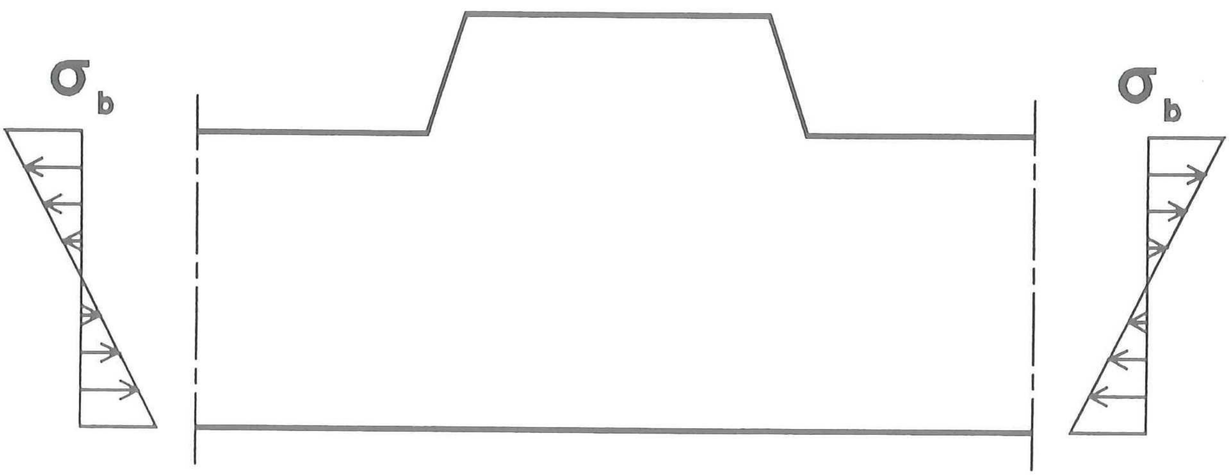


Figure 15 Bending load case on FEM geometry

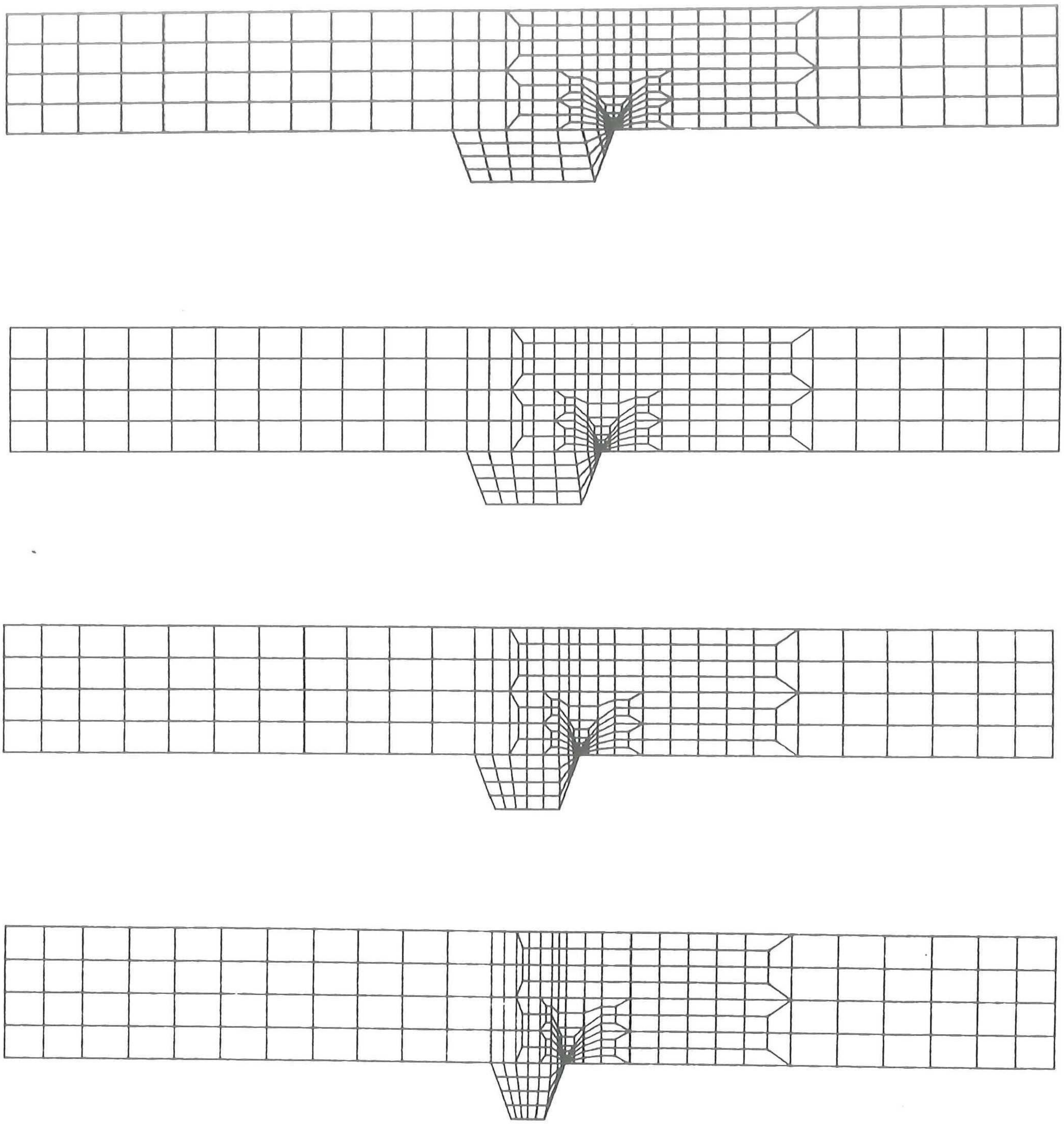


Figure 16 Finite element meshes

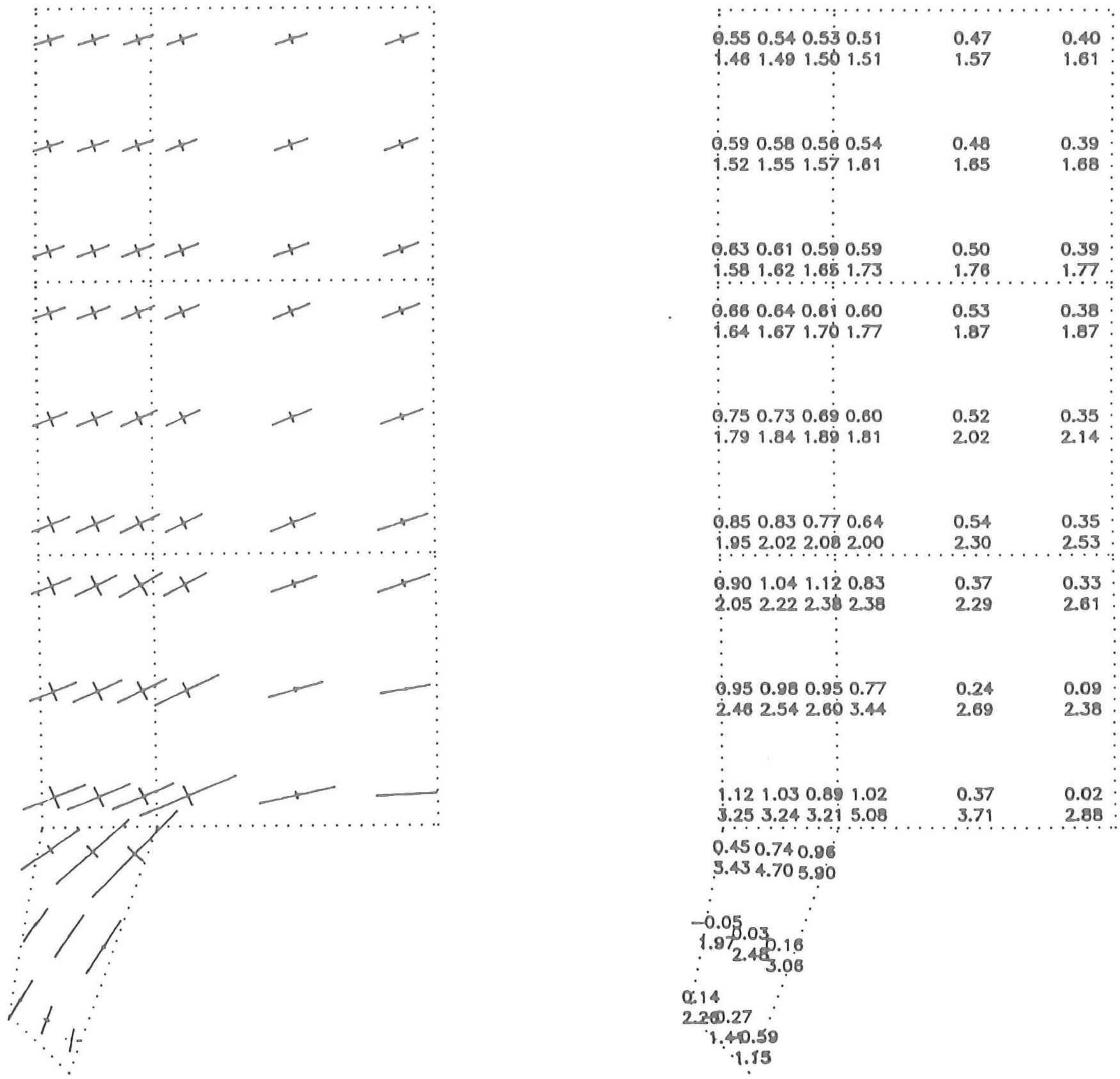


Figure 17 Stress distribution near weld toe for geometry C-0-1 1/4 (membrane loadcase)

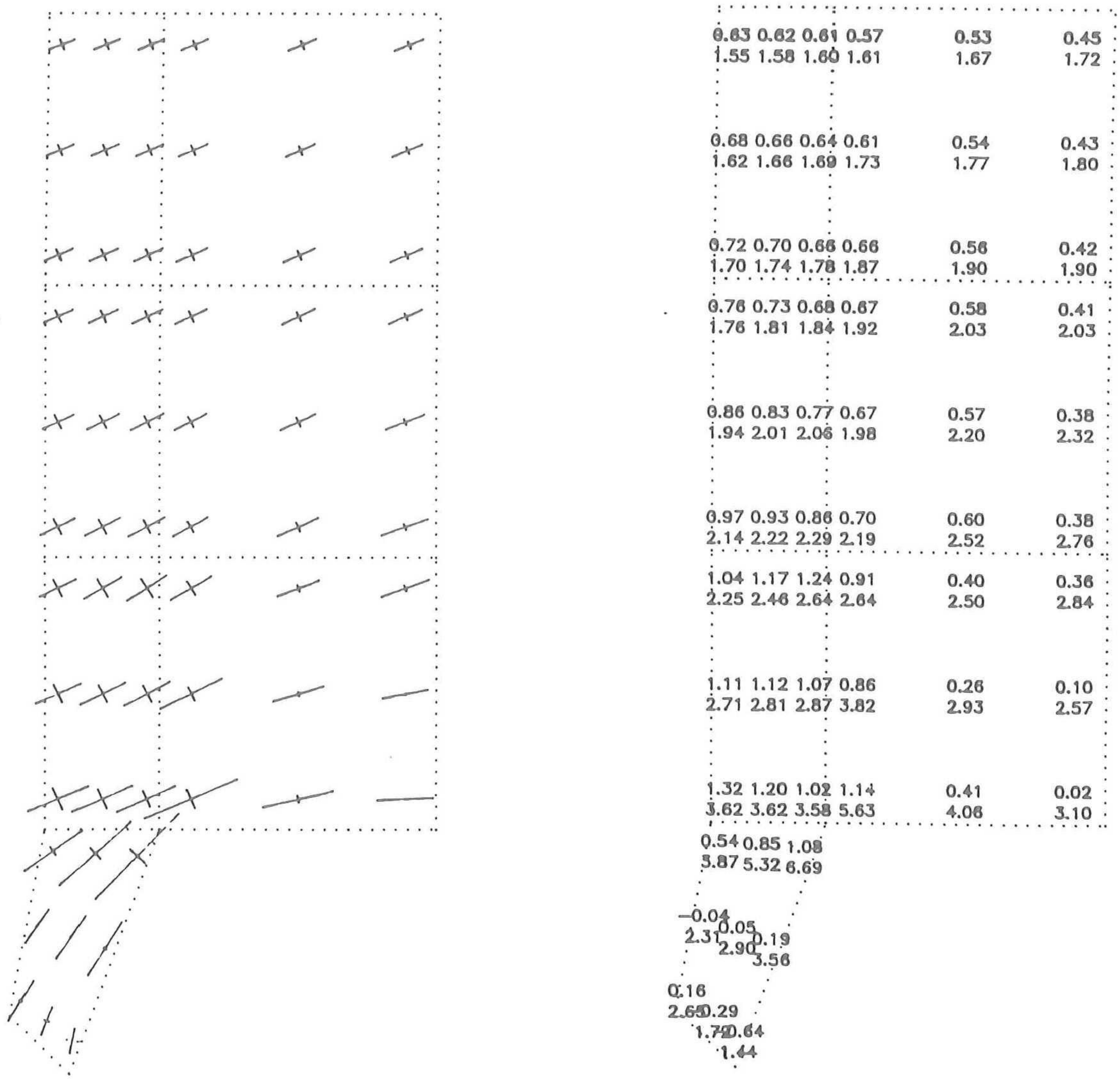


Figure 18 Stress distribution near weld toe for geometry C-0-1 1/4 (bending loadcase)

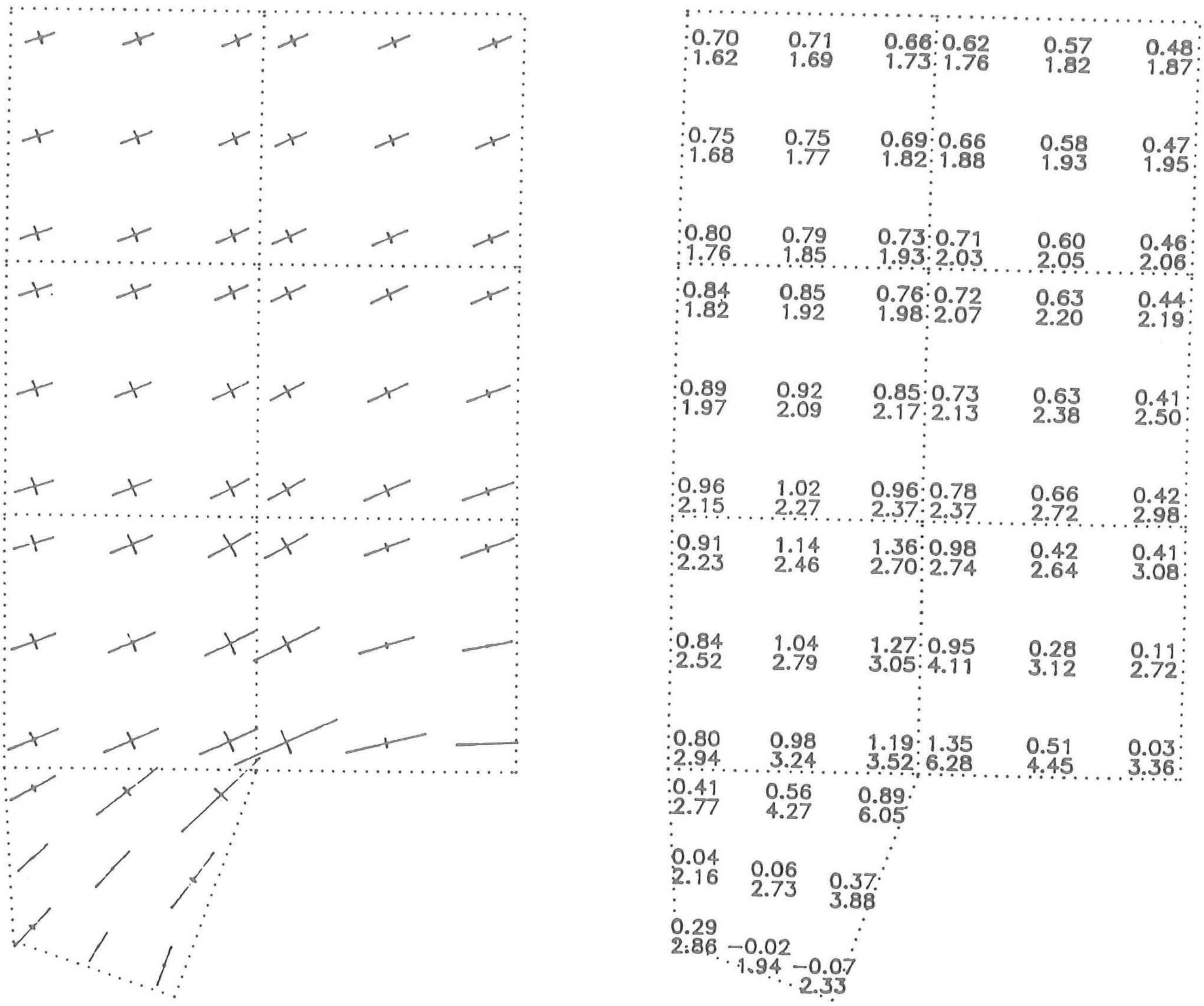


Figure 19 Stress distribution near weld toe for geometry C-0-1 4/4 (membrane loadcase)

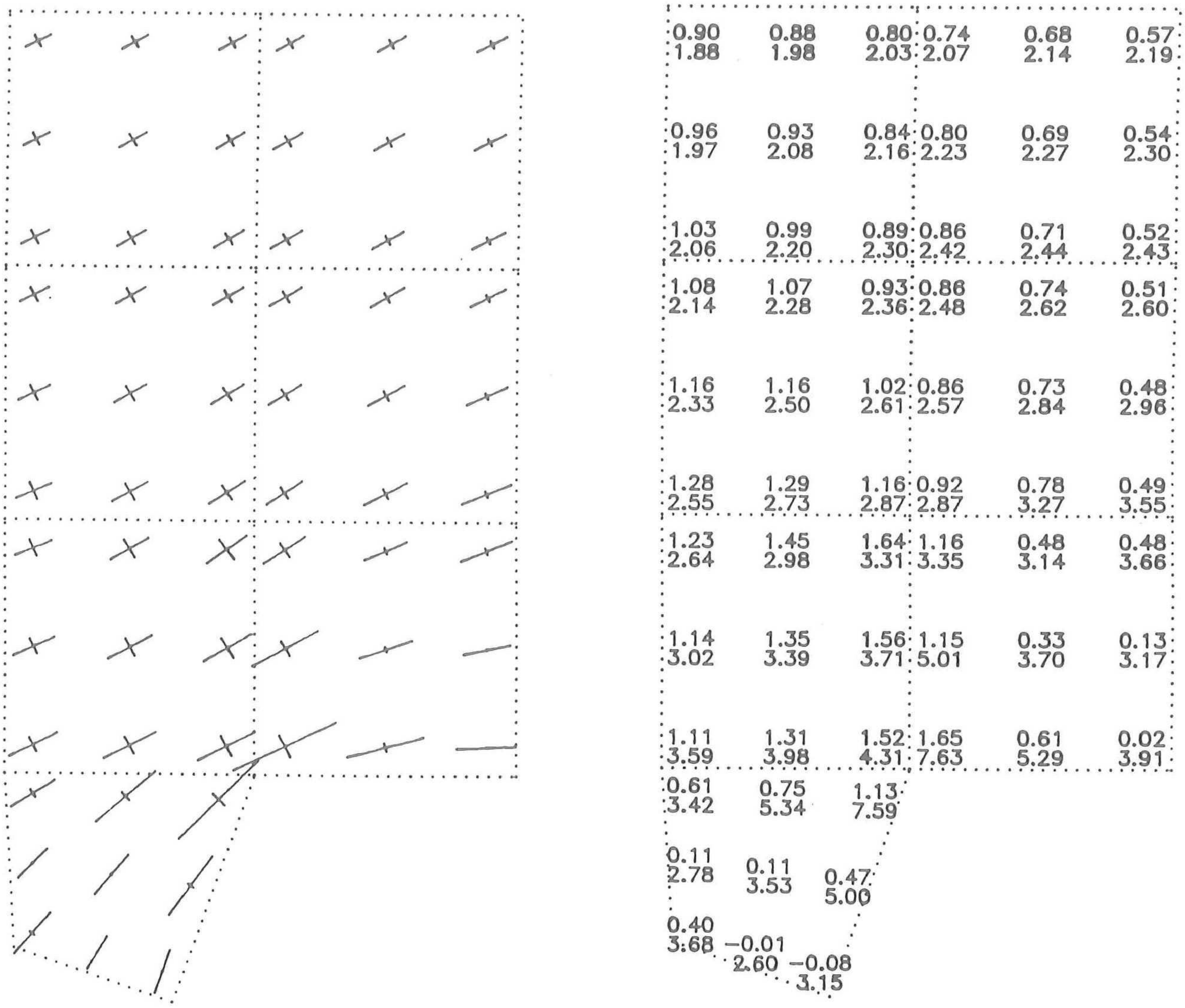


Figure 20 Stress distribution near weld toe for geometry C-0-1 4/4 (bending loadcase)

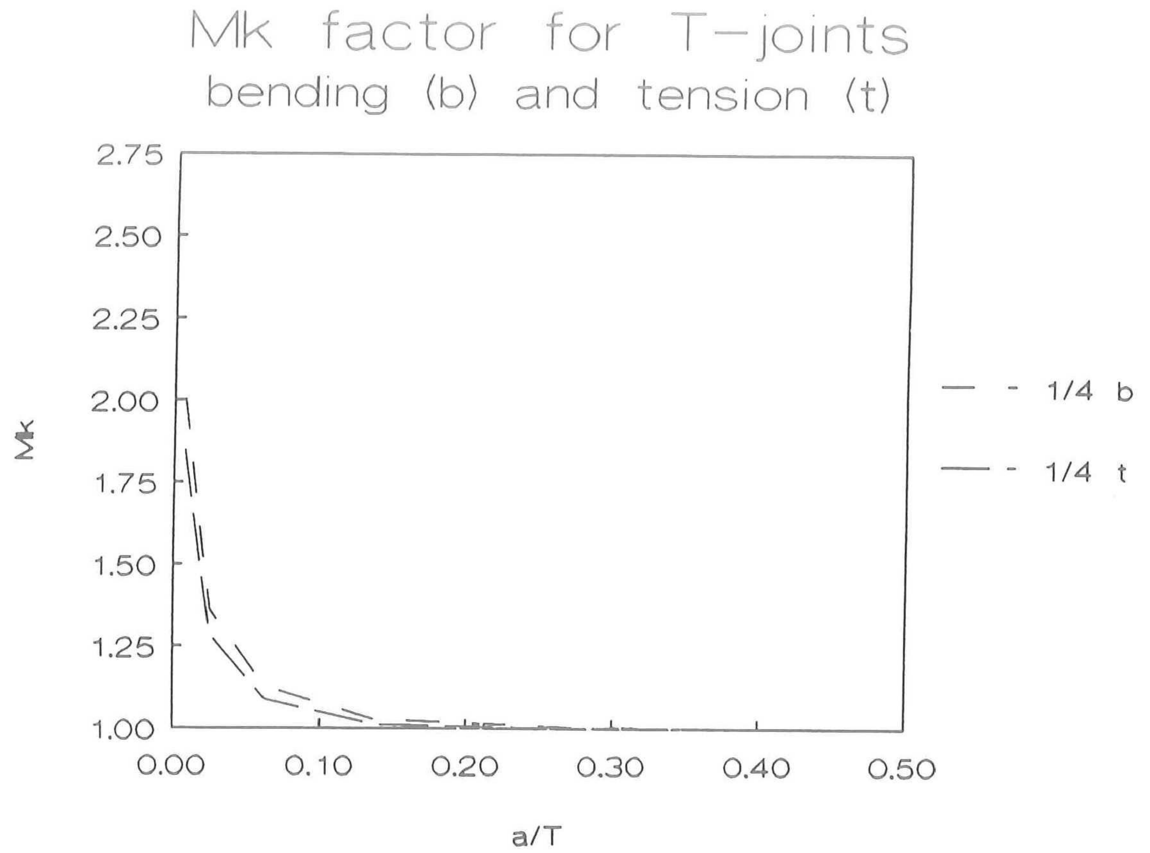


Figure 21 M_k factors for C-0-1- 1/4

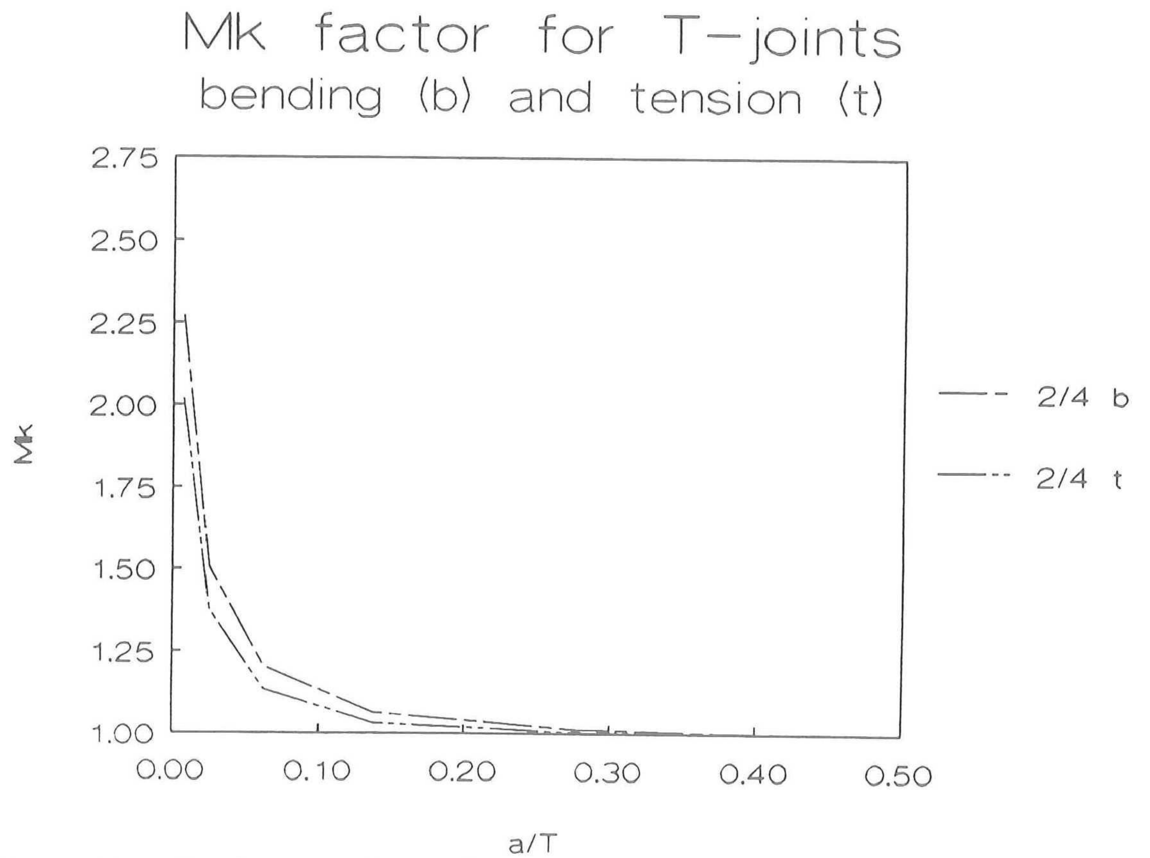


Figure 22 M_k factors for C-0-1- 2/4

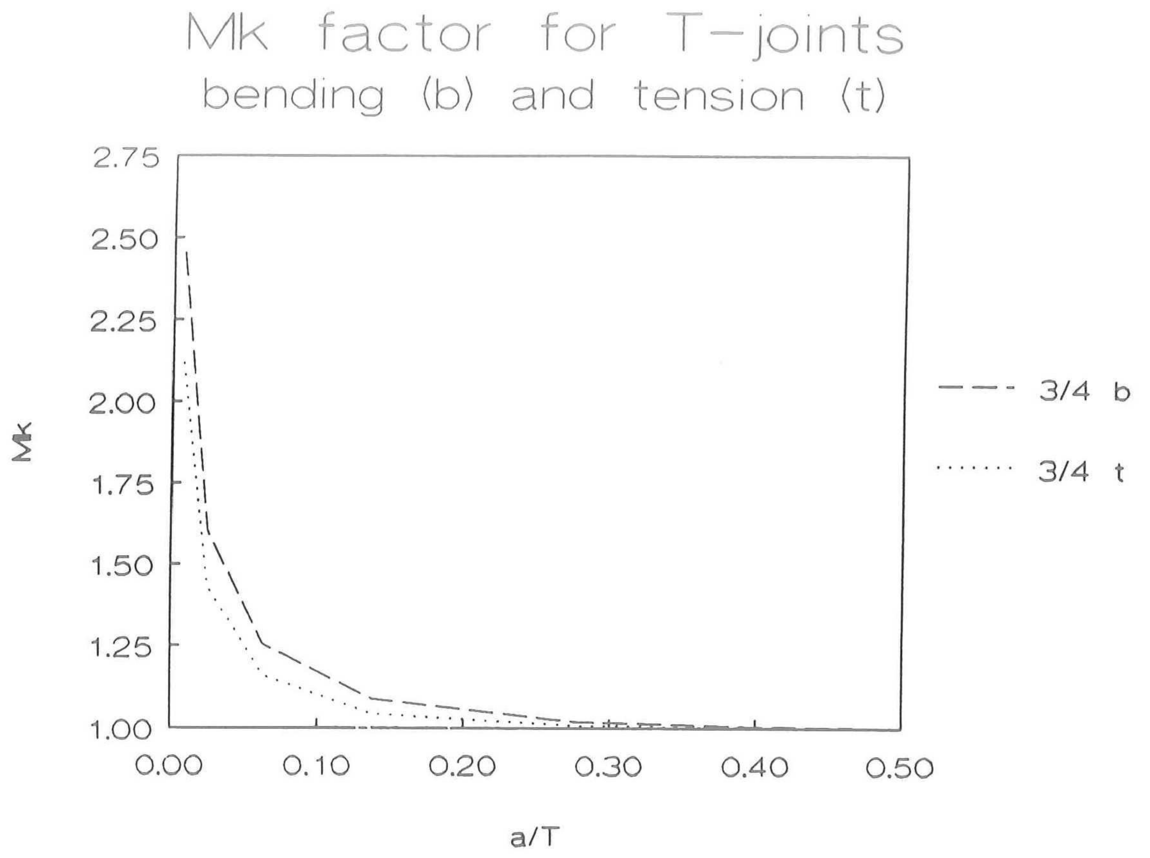


Figure 23 M_k factors for C-0-1- 3/4

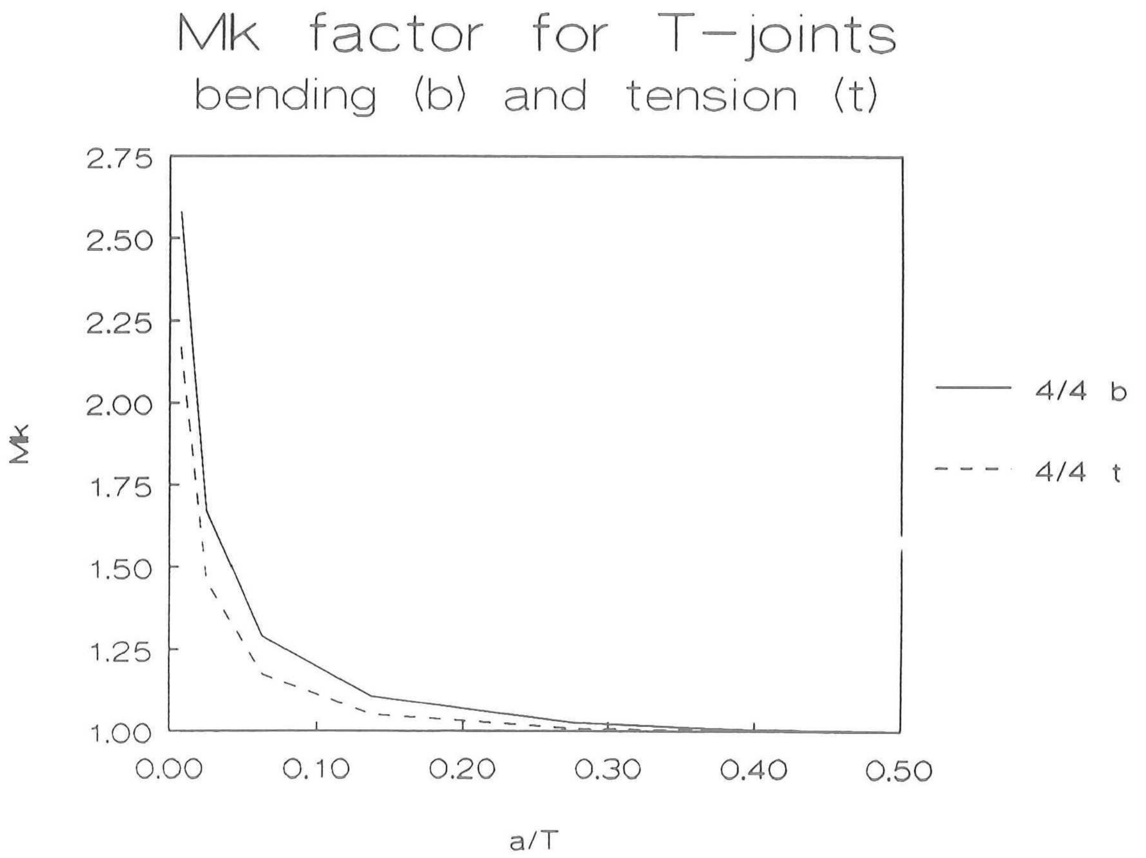


Figure 24 M_k factors for C-0-1- 4/4

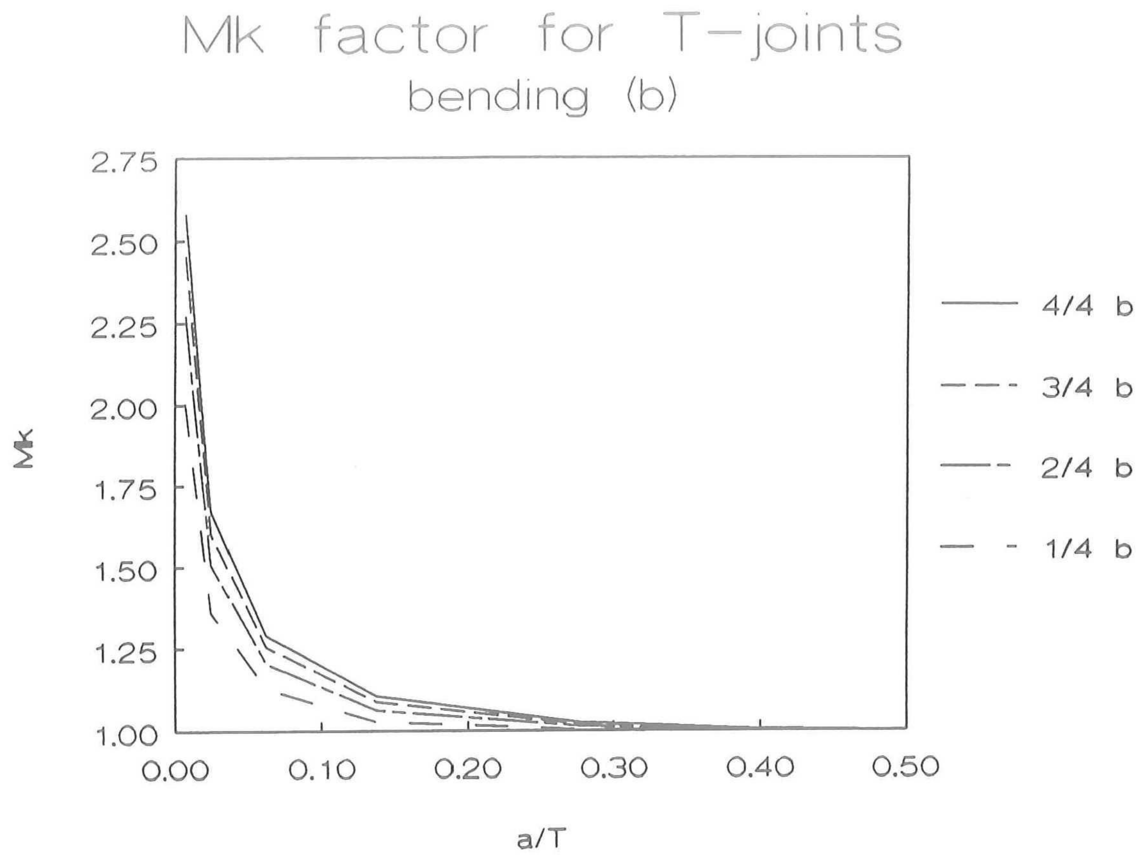


Figure 25 M_k factors for membrane stress

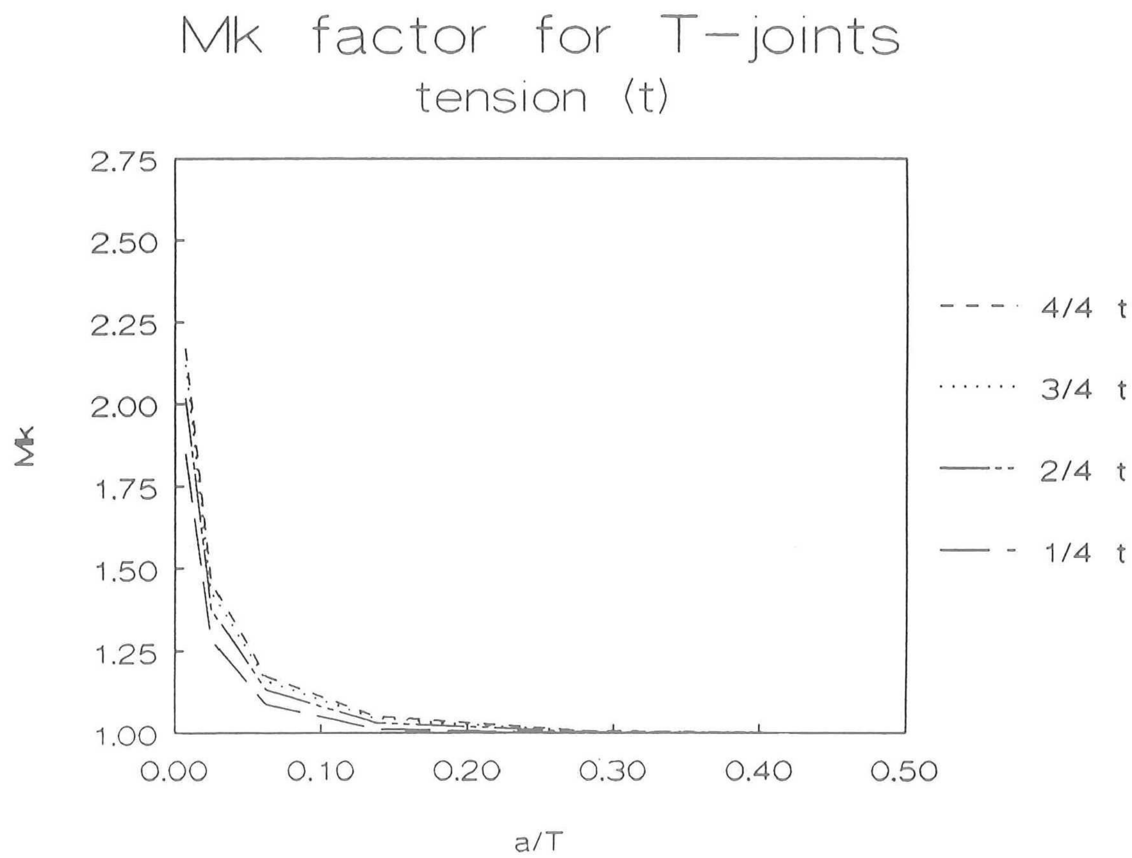


Figure 26 M_k factors for bending stress

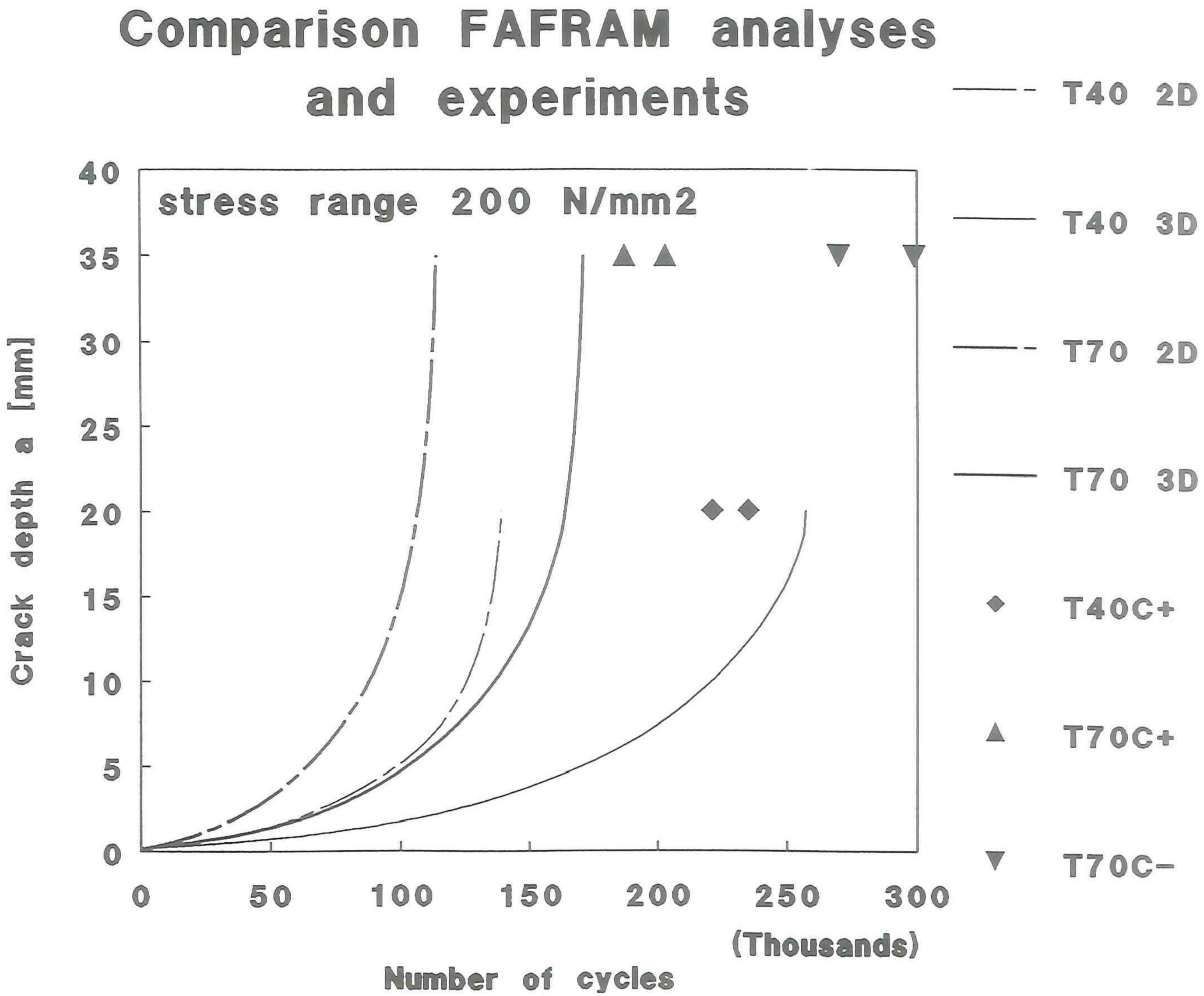


Figure 27 Comparison FAFRAM analysis and experiments

APPENDICES

A	Weld procedure of T-joints
B	Weld procedure of butt welds
C	CTOD results on 70 mm plate
D	FAFRAM analyses of T-joints

Appendix A Weld procedure of T-joints

AANWIJZINGEN VOOR HET LASSEN VAN DE T-PROEFSTUKKEN (40 en 70 mm).

De lassen zullen worden uitgevoerd met de parameters aangegeven in stuk 90-50.

De volgende punten dienen daarbij in acht te worden genomen.

a. de overall lashoek moet liggen tussen 60^0 en 70^0.

b. de max. locale lashoek mag 85^0 zijn.

c. er mogen geen inkartelingen aan de lasteen voorkomen.

d. er mogen geen arc-strikes op de plaat worden aangebracht.

e. er mag buiten de te beproeven las niet aan de plaat worden gelast.

f. er mag niet aan de uiteindelijke lasteen worden geslepen.

g. alle afzonderlijke proefstukken moeten, voordat ze worden uitgesneden, worden genummerd.

h. voordat de gelaste platen in afzonderlijke proefstukken worden verdeeld, moeten op de kopse kant proefstuknummers worden aangebracht.

i. de eerste laslagen mogen d.m.v. OP-lassen worden gelegd.

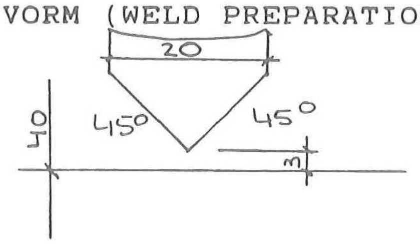
j. het aflassen moet in 3G-positie gebeuren (vertikaal opgaand).

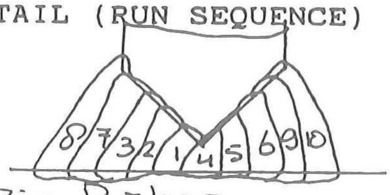
A - 5

CODE:- LMB(WPS): 5 WIJZ:0 REV DATUM(DATE):09/09/91
CERT NO: 0 LMK(PQR):253
PROJECT :Lasproeven Shoralsim ORDER: 30361
OPDR.GEVER(CLIENT):TNO/TU-Delft
INSPEKTIE:-
TEKENING(DRWG): 0 REV NO: 0
MATERIAAL:1:Fe E 510 D | DIKTE(THN):20 MM| MAX.Ceq:-
(MATERIAL)2:Shoralsim | DIKTE(THN):40 MM| MAX.Ceq:-
LASPROCES:1:SMAW POSITIE:1G POLARITEIT:+/-
(PROCES) 2:- POSITIE:- POLARITEIT:-
3:- POSITIE:- POLARITEIT:-
LAS MATL :1:Ni 55 SPEC.:A 5.5 CLAS.:E 8018 SCALE:D
(WELD-) 2:- SPEC.:- CLAS.:- SCALE:-
(CONS.) 3:- SPEC.:- CLAS.:- SCALE:-
GAS:- GAS SPEC.:- STR.SNH.(FLOW RATE- L
POEDER(FLUX):- POEDER(FLUX)SPEC.:- SCA

WARMTE :COMB. DIKTE(CTHN):100 MM|MAX.CEN WAARDE:-
VOORW.(PREH)TEMP:120C|METODE:Gas/electrical INTERP TEMP:180C
GLOEIEN (P.W.H.T.):- GLOEI PROCEDURE:-
VOORBWERKING: SLIJPEN!!!(PREPARATION BEFORE WELDING:GRINDING)

LASVORM (WELD PREPARATION) | LAS DETAIL (RUN SEQUENCE)





LAS GEGEVENS(WELD PARAMETERS)

LAAG PASS	DIAM SIZE MM	AMP A	VOLT V	SNH CM/MIM	UIT ROL CM	HI KJ/CM	STR AC/DC	LAS (WELD) METAL	POS
1	3.15	116	16	11	-	10.12	+/-	Ni 55	1G
2	4	160	25	17	-	14.12	+/-	Ni 55	1G
3	4	165	25	14	-	17.68	+/-	Ni 55	1G
4	3.15	137	30	16	-	15.41	+/-	Ni 55	1G
5	4	174	25	25	-	10.44	+/-	Ni 55	1G
6	4	170	25	25	-	10.20	+/-	Ni 55	1G

GUTSEN NA LAAG NO (GOUGING AFTER PASS) : 3
SLIJPEN NA LAAG NO (GRINDING AFTER PASS): 3

VEREISTE KWALIFICATIES (REQUIRED QUALIFICATIONS):
POSITIE(POSITION):1/3G METODE(METHOD):SMAW
TOEPASBAARHEID GRENZEN (RANGE OF APPROVAL):-
MATERIALEN (MATERIALS):- HOEKL.AFM.(FILLETSIZE):-
DIKTES (THICKNESS):- PIJP DIAM.(PIPE DIAM):-
DIAMETERS ELEKTRODEN(DIAM.WELDCONSUMABLES):-

HOLLANDIA	OPDRACHTGEVER(CLIENT)	INSPECTIE INST.
	TNO/TU-Delft	-
	NAAM:	NAAM: A de Jong
	DATUM: / 19	DATUM 12/ 9 1991
	ACC:JA / NEE	ACC:JA / ~~NEE~~
PARAAF :...	HANDTEK:..............................	HANDTEK: [signature]

Laslaag Pass	Diam Size mm	Amp A	Volt V	SNH. cm/min	HI KJ/cm	STR AC/DC	LAS (WELD) METAL	POS
7	3.15	117	27	5,5	34,5	AC	Niss	3G
8	3.15	126	28	5	42	AC	Niss	3G
9	3.15	126	28	5	42	AC	Niss	3G
10	3.15	126	28	5	42	AC	Niss	3G

Chargeno's v.d. draad
ø 3.15 16819-08111g
ø 4 17066-131220
ø 3.15 16434-131220
Laag 1 t/m 6 gelast door V.10 21/08/91
laag 7 ca 80cm R16 22/08/91
Restant O22 23/08/91

Plaats v.d. hechten
0 - 40mm
780 - 850mm
1420 - 1470mm
2140 - 2210mm
2600 - 2650mm
2800 - 2840mm
2880mm

Eén arc strike door het hechten in tweede hecht
83 cm van beginpunt
Deze arc strike zit in proef 5-4

De volgende proefstukken zijn voorzien van
nummers:

12-9-91

CODE:- LMB(WPS): 11 WIJZ:0 REV DATUM(DATE):01/10/91
CERT NO: 0 LMK(PQR):252
PROJECT :Lasproeven Shoralsim ORDER: 30361
OPDR.GEVER(CLIENT):TNO/TU-Delft
INSPEKTIE:-
TEKENING(DRWG): 0 REV NO: 0

MATERIAAL:1:Fe E 510 D	DIKTE(THN):35 MM	MAX.Ceq:-
(MATERIAL)2:Shoralsim	DIKTE(THN):70 MM	MAX.Ceq:-

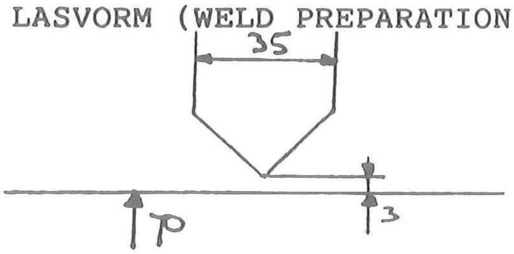
LASPROCES:	1:SMAW	POSITIE:1G	POLARITEIT:+/-
(PROCES)	2:SAW	POSITIE:1G	POLARITEIT:+
	3:SMAW	POSITIE:3G	POLARITEIT:+/-

LAS MATL	:1:Ni 55	SPEC.:A 5.5	CLAS.:E 8018	SCALE:D
(WELD-)	2:LNS 140A	SPEC.:A 5.2	CLAS.:F8A4	SCALE:D
(CONS.)	3:-	SPEC.:-	CLAS.:-	SCALE:-

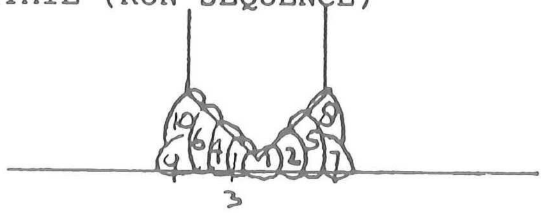
GAS:- GAS SPEC.:- STR.SNH.(FLOW RATE- L/MIN.
POEDER(FLUX):P230 POEDER(FLUX)SPEC.:EA1-A2 SCALE:D

WARMTE :COMB. DIKTE(CTHN):175 MM | MAX.CEN WAARDE:-
VOORW.(PREH)TEMP:120C | METODE:Gas/Electrical INTERP TEMP:180C
GLOEIEN (P.W.H.T.):- GLOEI PROCEDURE:-
VOORBWERKING: SLIJPEN!!!(PREPARATION BEFORE WELDING:GRINDING)

LASVORM (WELD PREPARATION)



LAS DETAIL (RUN SEQUENCE)



LAS GEGEVENS(WELD PARAMETERS)

LAAG PASS	DIAM SIZE MM	AMP A	VOLT V	SNH CM/ MIM	UIT ROL CM	HI KJ/CM	STR AC/ DC	LAS (WELD) METAL	POS
1	3.15	142	31	15		17.61	+/-	Ni 55	1G
2	4	190	28	13		24.55	+/-	Ni 55	1G
3	4	200	29	12		29.00	+/-	Ni 55	1G
4-6	4	660	32	30		42.24	+	135	1G
7-10	4	117	25	4		43.88	+/-	Ni 55	3G
		0	0	0		0.00			

GUTSEN NA LAAG NO (GOUGING AFTER PASS) : 2
SLIJPEN NA LAAG NO (GRINDING AFTER PASS): 2

VEREISTE KWALIFICATIES (REQUIRED QUALIFICATIONS):
POSITIE(POSITION):1/3G METODE(METHOD):S/SA
TOEPASBAARHEID GRENZEN (RANGE OF APPROVAL):
MATERIALEN (MATERIALS):- HOEKL.AFM.(FILLETSIZE):-
DIKTES (THICKNESS):- PIJP DIAM.(PIPE DIAM):-
DIAMETFRS ELEKTRODEN(DIAM.WELDCONSUMABLES):-

HOLLANDIA	OPDRACHTGEVER(CLIENT)	INSPECTIE INST.
	TNO/TU-Delft	-
	NAAM:	NAAM:
	DATUM: / 19	DATUM / 19
	ACC:JA / NEE	ACC:JA / NEE
PARAAF :...	HANDTEK:..........................	HANDTEK:...........

Appendix B Weld procedure of butt welds

AANWIJZINGEN VOOR HET LASSEN VAN DE PROEFLAS OP SHORALSIM VOOR DE BUTT WELDS.

1. Voor het lassen wordt een stuk materiaal gebruikt van ca. 775x300x70 mm. Na het doorbranden kan hierop een las van ca. 300 mm. worden aangebracht.

2. Tijdens het lassen zal ervoor gezorgd worden dat de inbrandingsdiepte van elke afzonderlijke lasrups 4 mm. bedraagt.

3. De lasrups die de lasteen met het moedermateriaal vormt, zal zo gelegd worden dat de lasteen 4 mm. verwijderd ligt van de oorspronkelijke zijkant van het moedermateriaal.
   De lasteen ligt zodoende boven de fusion line van alle eronder liggende lasrupsen.

   De hiervoor gekozen lasmethode is die volgens lasproefje 1.
   Hierbij is de afstand van de electrode tot het moedermateriaal 4 mm. en de oppervlakte van de voorlaatste lasrups tot het oppervlak van het moedermateriaal ook 4 mm.

4. Na het lassen zullen kerfslag proefstaafjes worden gemaakt en beproefd zoals ook voor de eerdere proeflas is gebeurd.
   Tevens moeten 2 macro's gemaakt worden.
   Hiervan dienen foto's gemaakt te worden om de structuur zichtbaar te maken en moeten hardheidsmetingen worden uitgevoerd.

5. Voor de gelaste platen in afzonderlijke proefstukken worden verdeeld, moeten op de kopse kanten proefstuknummers worden aangebracht.

CODE: LMB(WPS): 4 WIJZ:1 REV DATUM(DATE):15/11/91
CERT NO: 0 LMK(PQR):251
PROJECT :Lasproeven Shoralsim ORDER: 30361
OPDR.GEVER(CLIENT):TNO/TU-Delft
INSPEKTIE:
TEKENING(DRWG): 0 REV NO: 0

MATERIAAL:1:Shoralsim	DIKTE(THN):40 MM	MAX.Ceq:-
(MATERIAL)2:Shoralsim	DIKTE(THN):40 MM	MAX.Ceq:-

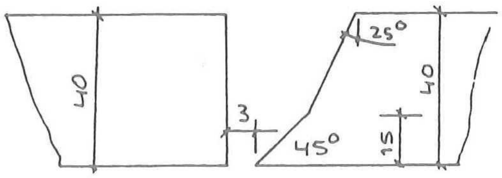
LASPROCES:1:SMAW	POSITIE:1G	POLARITEIT:+/-
(PROCES) 2:SAW	POSITIE:1G	POLARITEIT:+
3:-	POSITIE:-	POLARITEIT:-

LAS MATL :1:Ni 55	SPEC.:A 5.5	CLAS.:E 8018	SCALE:D
(WELD-) 2:LNS 140A	SPEC.:A 5.2	CLAS.:F8A4	SCALE:D
(CONS.) 3:-	SPEC.:-	CLAS.:-	SCALE:-

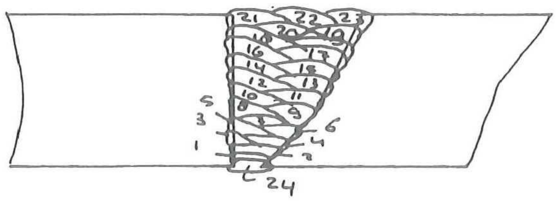
GAS:- GAS SPEC.:- STR.SNH.(FLOW RATE- L/MIN.
POEDER(FLUX):P230 POEDER(FLUX)SPEC.:EA1-A2 SCALE:D

WARMTE :COMB. DIKTE(CTHN):80 MM | MAX.CEN WAARDE:-
VOORW.(PREH)TEMP:120C | METODE:Gas/Electrical INTERP TEMP:180C
GLOEIEN (P.W.H.T.):- GLOEI PROCEDURE:-
VOORBWERKING: SLIJPEN!!!(PREPARATION BEFORE WELDING:GRINDING)

LASVORM (WELD PREPARATION)



LAS DETAIL (RUN SEQUENCE)



LAS GEGEVENS(WELD PARAMETERS)

LAAG PASS	DIAM SIZE MM	AMP A	VOLT V	SNH CM/ MIM	UIT ROL CM	HI KJ/CM	STR AC/ DC	LAS (WELD) METAL	POS
1	3.15	70	23	8		12.08	+/-	Ni 55	1G
2-8	4	175	25	18		14.58	+/-	Ni 55	1G
9	4	600	30	45		24.00	+	140A	1G
10	4	660	32	30		42.24	+	140A	1G
11	4	660	32	45		28.16	+	140A	1G
12	4	660	32	30		42.24	+	140A	1G

GUTSEN NA LAAG NO (GOUGING AFTER PASS) : 15
SLIJPEN NA LAAG NO (GRINDING AFTER PASS): 15

VEREISTE KWALIFICATIES (REQUIRED QUALIFICATIONS):
POSITIE(POSITION):1G METODE(METHOD):S/SA
TOEPASBAARHEID GRENZEN (RANGE OF APPROVAL):
MATERIALEN (MATERIALS):- HOEKL.AFM.(FILLETSIZE):-
DIKTES (THICKNESS):- PIJP DIAM.(PIPE DIAM):-
DIAMETERS ELEKTRODEN(DIAM.WELDCONSUMABLES):-

HOLLANDIA	OPDRACHTGEVER(CLIENT)	INSPECTIE INST.
	TNO/TU-Delft	
	NAAM:______________________	NAAM:______________
	DATUM:______/________19________	DATUM___/______19____
	ACC:JA / NEE	ACC:JA / NEE
PARAAF :...	HANDTEK:..........................	HANDTEK:...........

B-4

CODE: LMB(WPS): 9 WIJZ:1 REV DATUM(DATE):27/01/92
CERT NO: 0 LMK(PQR):250
PROJECT :Lasproeven Shoralsim ORDER: 30361
OPDR.GEVER(CLIENT):TNO/TU-Delft
INSPEKTIE:-
TEKENING(DRWG): 0 REV NO: 0
MATERIAAL:1:Shoralsim | DIKTE(THN):70 MM | MAX.Ceq:-
(MATERIAL)2:shoralsim | DIKTE(THN):70 MM | MAX.Ceq:-
LASPROCES:1:SMAW POSITIE:1G POLARITEIT:+/-
(PROCES) 2:SAW POSITIE:1G POLARITEIT:+
3:- POSITIE:- POLARITEIT:-
LAS MATL :1:Ni 55 SPEC.:A 5.5 CLAS.:E 8018 SCALE:D
(WELD-) 2:LNS 140 A SPEC.:A 5.2 CLAS.:F8A4 SCALE:D
(CONS.) 3:- SPEC.:- CLAS.:- SCALE:-
GAS:- GAS SPEC.:- STR.SNH.(FLOW RATE- L/MIN.
POEDER(FLUX):P 230 POEDER(FLUX)SPEC.:EA1-A2 SCALE:D

WARMTE :COMB. DIKTE(CTHN):140 MM|MAX.CEN WAARDE:-
VOORW.(PREH)TEMP:120C|METODE:Electrical INTERP TEMP:180C
GLOEIEN (P.W.H.T.):- GLOEI PROCEDURE:-
VOORBWERKING: SLIJPEN!!!(PREPARATION BEFORE WELDING:GRINDING)

===

LASVORM (WELD PREPARATION) | LAS DETAIL (RUN SEQUENCE)

See sheet ~~3~~ B-5 | See sheet ~~4~~ B-6

LAS GEGEVENS(WELD PARAMETERS)

LAAG PASS	DIAM SIZE MM	AMP A	VOLT V	SNH CM/MIM	UIT ROL CM	HI KJ/CM	STR AC/DC	LAS (WELD) METAL	POS
1	3.15	75	25	8		14.06	+/-	Ni 55	1G
2-14	4	175	25	18		14.58	+/-	Ni 55	1G
15	4	650	31	45		26.87	+	140A	1G
16	4	660	32	30		42.24	+	140A	1G
17	4	650	32	45		27.73	+	140A	1G
18	4	660	32	30		42.24	+	140A	1G

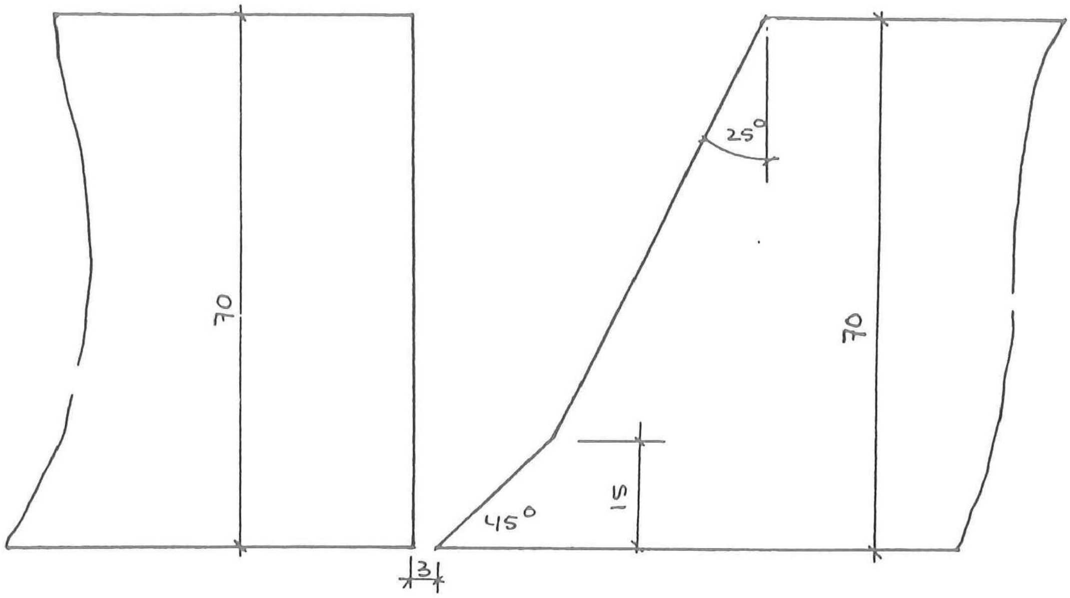
GUTSEN NA LAAG NO (GOUGING AFTER PASS) : 52
SLIJPEN NA LAAG NO (GRINDING AFTER PASS): 52

===

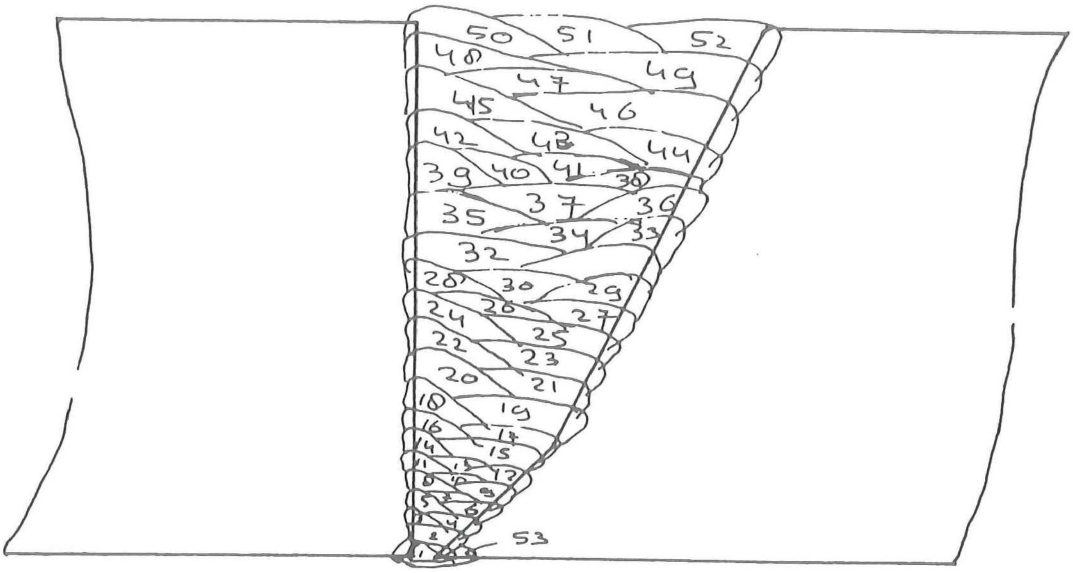
VEREISTE KWALIFICATIES (REQUIRED QUALIFICATIONS):
POSITIE(POSITION):1G METODE(METHOD):S/SA
TOEPASBAARHEID GRENZEN (RANGE OF APPROVAL):-
MATERIALEN (MATERIALS):- HOEKL.AFM.(FILLETSIZE):-
DIKTES (THICKNESS):- PIJP DIAM.(PIPE DIAM):-
DIAMETERS ELEKTRODEN(DIAM.WELDCONSUMABLES):-

HOLLANDIA	OPDRACHTGEVER(CLIENT)	INSPECTIE INST.
	TNO/TU-Delft	-
	NAAM:________	NAAM:________
	DATUM:____/____19____	DATUM__/____19____
	ACC:JA / NEE	ACC:JA / NEE
PARAAF :...	HANDTEK:..................	HANDTEK:...........

B-5



B-6


50
51
52
48
47
49
45
46
42
43
44
39
40
41
38
37
36
35
34
33
32
28
30
29
24
26
27
22
25
23
20
21
18
19
16
17
14
15
53

Appendix C CTOD results on 70 mm plate

C-2

Instituut voor Produktie en Logistiek TNO. 09-01-92

COD-data sheet Intended for:EGKS

Specimen No.		8-1	8-2
Fatigue pre-cracking			
- R_e (yield strength)	N/mm²	450	450
- K_f (final position of crack)	N/mm³/²	1063	1347
- R_f (fatigue force ratio)		0.1	0.1
- F_f	kN	80.0	100.0
- N_f	cycles.10⁻³	83.0	21.8
- a_0	mm	70.9	69.9
- a_4	mm	69.6	69.9
Bend test			
- S (loading span)	mm	560	560
- z (distance clip to surface)	mm	-1	-1
- T (test temperature)	°C	-20	-20
- B	mm	70.7	70.8
- W	mm	140.5	138.9
- a_1	mm	72.3	71.7
- a_2	mm	72.4	72.2
- a_3	mm	72.3	71.8
- $(\bar{a}_1 + a_2 + a_3) / 3$	mm	72.3	71.9
- a/W		0.51	0.52
- Y		11.14	11.24
Does fatigue crack satisfy:			
- minimum growth		Yes	Yes
- non planar growth		Yes	Yes
- multiple nucleation effects		Yes	Yes
Clip gauge displacement (plastic)			
- V_i	mm	-	-
- V_c	mm	-	-
- V_u	mm	-	-
- V_m	mm	> 9.40	>14.00
Appropriate critical applied force			
- F_i	kN	-	-
- F_c	kN	-	-
- F_u	kN	-	-
- F_m	kN	434.85	462.97
Critical COD-values (d)			
- δ_i (onset slow crack growth)	mm	-	-
- δ_c (unstable fracture/"pop-in")	mm	-	-
- δ_u (unstable fracture/"pop-in"(*))	mm	-	-
- δ_m (maximum force plateau)	mm	> 2.76	>4.03

According to BS5762: 1979

C-3

Instituut voor Produktie en Logistiek TNO. 09-01-92

COD-data sheet

Intended for:EGKS

Specimen No.		8-3	8-4
Fatigue pre-cracking			
- R_e (yield strength)	N/mm²	450	450
- K_f (final position of crack)	N/mm³/²	1242	1198
- R (fatigue force ratio)		0.1	0.1
- F_f	kN	90.0	90.0
- N	cycles.10⁻³	34.2	29.1
- a_0	mm	71.3	69.4
- a_4	mm	70.3	69.9
Bend test			
- S (loading span)	mm	560	560
- z (distance clip to surface)	mm	-1	-1
- T (test temperature)	°C	-40	-40
- B	mm	70.7	70.6
- W	mm	140.0	140.0
- a_1	mm	73.6	71.9
- a_2	mm	73.7	72.2
- a_3	mm	73.5	71.9
- $(a_1 + a_2 + a_3) / 3$	mm	73.6	72.0
- a/W		0.53	0.51
- Y		11.55	11.12
Does fatigue crack satisfy:			
- minimum growth		Yes	Yes
- non planar growth		Yes	Yes
- multiple nucleation effects		Yes	Yes
Clip gauge displacement (plastic)			
- V_i	mm	-	-
- V_c	mm	-	-
- V_u	mm	-	-
- V_m	mm	14.00	14.00
Appropriate critical applied force			
- F_i	kN	-	-
- F_c	kN	-	-
- F_u	kN	-	-
- F_m	kN	454.12	455.10
Critical COD-values (d)			
- δ_i (onset slow crack growth)	mm	-	-
- δ_c (unstable fracture/"pop-in")	mm	-	-
- δ_u (unstable fracture/"pop-in"(*))	mm	-	-
- δ_m (maximum force plateau)	mm	3.94	4.05

According to BS5762: 1979

C-4

Instituut voor Produktie en Logistiek TNO. 16-01-92

COD-data sheet Intended for:EGKS

Specimen No.		8-5	8-6	8-10
Fatigue pre-cracking				
- R_e (yield strength)	N/mm²	450	450	450
- K_f (final position of crack)	$N/mm^{3/2}$	1194	1213	1224
- R (fatigue force ratio)		0.1	0.1	0.1
- F_f	kN	90.0	90.0	90.0
- N	cycles.10^{-3}	29.3	31.8	28.7
- a_0	mm	69.1	69.7	69.0
- a_4	mm	69.8	69.9	69.4
Bend test				
- S (loading span)	mm	560	560	560
- z (distance clip to surface)	mm	-1	-1	-1
- T (test temperature)	°C	-60	-60	-60
- B	mm	70.7	70.5	70.6
- W	mm	140.0	140.1	140.0
- a_1	mm	71.8	72.4	72.8
- a_2	mm	72.1	72.9	73.3
- a_3	mm	71.9	72.3	72.7
- $(a_1 + a_2 + a_3) / 3$	mm	71.9	72.5	72.9
- a/W		0.51	0.52	0.52
- Y		11.10	11.24	11.36
Does fatigue crack satisfy:				
- minimum growth		Yes	Yes	Yes
- non planar growth		Yes	Yes	Yes
- multiple nucleation effects		Yes	Yes	Yes
Clip gauge displacement (plastic)				
- V_i	mm	-	-	-
- V_c	mm	-	-	-
- V_u	mm	4.48	9.60	11.60
- V_m	mm	-	-	-
Appropriate critical applied force				
- F_i	kN	-	-	-
- F_c	kN	-	-	-
- F_u	kN	387.60	414.90	437.18
- F_m	kN	-	-	-
Critical COD-values (d)				
- δ_i (onset slow crack growth)	mm	-	-	-
- δ_c (unstable fracture/"pop-in")	mm	-	-	-
- δ_u (unstable fracture/"pop-in"(*))	mm	1.37	2.78	3.32
- δ_m (maximum force plateau)	mm	-	-	-

According to BS5762: 1979

C-5

Instituut voor Produktie en Logistiek TNO. 15-01-92

COD-data sheet Intended for:EGKS

Specimen No.		8-7	8-8	8-9
Fatigue pre-cracking				
- R_e (yield strength)	N/mm²	450	450	450
- K_f (final position of crack)	N/mm³/²	1217	1214	1217
- R (fatigue force ratio)		0.1	0.1	0.1
- F_f	kN	90.0	90.0	90.0
- N_f	cycles.10⁻³	29.9	27.4	33.3
- a_0	mm	70.4	69.3	70.6
- a_4	mm	69.6	69.4	69.9
Bend test				
- S (loading span)	mm	560	560	560
- z (distance clip to surface)	mm	-1	-1	-1
- T (test temperature)	°C	-80	-80	-80
- B	mm	70.5	70.5	70.6
- W	mm	140.2	139.8	140.0
- a_1	mm	72.6	72.1	72.3
- a_2	mm	73.2	72.6	73.0
- a_3	mm	72.5	72.4	72.7
- $(a_1 + a_2 + a_3) / 3$	mm	72.8	72.4	72.7
- a/W		0.52	0.52	0.52
- Y		11.29	11.24	11.29
Does fatigue crack satisfy:				
- minimum growth		Yes	Yes	Yes
- non planar growth		Yes	Yes	Yes
- multiple nucleation effects		Yes	Yes	Yes
Clip gauge displacement (plastic)				
- V_i	mm	-	-	-
- V_c	mm	-	0.32	-
- V_u	mm	2.46	-	4.16
- V_m	mm	-	-	-
Appropriate critical applied force				
- F_i	kN	-	-	-
- F_c	kN	-	350.63	-
- F_u	kN	376.95	-	391.05
- F_m	kN	-	-	-
Critical COD-values (d)				
- δ_i (onset slow crack growth)	mm	-	-	-
- δ_c (unstable fracture/"pop-in")	mm	-	0.19	-
- δ_u (unstable fracture/"pop-in"(*))	mm	0.80	-	1.27
- δ_m (maximum force plateau)	mm	-	-	-

According to BS5762: 1979

Appendix D FAFRAM analyses of T-joints

FAFRAM 2D analysis of T40 specimens

```
Testname          : t40_2d
Geometry          : 2D-Surface
Edge crack
Thickness (mm):      40.000
A-law             : Paris
C       (N, mm):   .18320E-12
M                 :      3.000
SIF               : Brown/Scrawley/Orange
Mk                : IIW-X/OMAE
Theta      (deg):     60.000
Rho         (mm):       .500
L           (mm):     43.500
Process parameters
Alpha             :       .050
Ai          (mm):       .150
Ni                :         0.
Stopped when      : ai > af
Af          (mm):     20.000
Stress
SigM    (Nmm-2):       .000
SigB    (Nmm-2):    200.000
```

Ai mm	A/T	Mkm-a	Mm-a	Mkb-a	Mb-a	DK-a Nmm-1.5	Ai+1 mm	Ni+1
0.150	0.004	3.086	1.119	2.537	1.115	397.964	0.158	650
0.158	0.004	3.039	1.119	2.499	1.115	401.596	0.165	1313
0.165	0.004	2.992	1.119	2.462	1.114	405.282	0.174	1991
0.174	0.004	2.947	1.119	2.425	1.114	409.025	0.182	2684
0.182	0.005	2.903	1.119	2.390	1.114	412.824	0.191	3391
0.191	0.005	2.859	1.119	2.354	1.114	416.680	0.201	4113
0.201	0.005	2.816	1.119	2.320	1.113	420.594	0.211	4851
0.211	0.005	2.774	1.119	2.286	1.113	424.567	0.222	5603
0.222	0.006	2.732	1.119	2.253	1.113	428.599	0.233	6372
0.233	0.006	2.692	1.119	2.220	1.112	432.690	0.244	7156
0.244	0.006	2.652	1.119	2.188	1.112	436.841	0.257	7956
0.257	0.006	2.612	1.119	2.157	1.111	441.052	0.269	8772
0.269	0.007	2.574	1.119	2.126	1.111	445.322	0.283	9604
0.283	0.007	2.536	1.119	2.096	1.111	449.652	0.297	10453
0.297	0.007	2.498	1.119	2.066	1.110	454.040	0.312	11319
0.312	0.008	2.461	1.119	2.037	1.110	458.487	0.327	12202
0.327	0.008	2.425	1.119	2.008	1.109	462.991	0.344	13103
0.344	0.009	2.389	1.119	1.980	1.109	467.551	0.361	14021
0.361	0.009	2.354	1.119	1.952	1.108	472.166	0.379	14957
0.379	0.009	2.320	1.119	1.925	1.107	476.834	0.398	15911
0.398	0.010	2.285	1.119	1.898	1.107	481.554	0.418	16884
0.418	0.010	2.252	1.119	1.872	1.106	486.321	0.439	17875

etc.

FAFRAM 3D analysis of T40 specimens

Testname		: t40_3d
Geometry		: 3D-Surface
Finite width		
Thickness	(mm)	: 40.000
Width	(mm)	: 210.000
A-law		: Paris
C	(N, mm)	: .18320E-12
M		: 3.000
C-law		: Paris
C	(N, mm)	: .18320E-12
M		: 3.000
SIF		: Newman/Raju
Mk		: IIW-X/OMAE
Theta	(deg)	: 60.000
Rho	(mm)	: .500
L	(mm)	: 43.500
OMMA		: 1.000
OMMC		: 1.000
OMBA		: 1.000
OMBC		: 1.000
Initiation		: Single
Process parameters		
Alpha		: .050
Ai	(mm)	: .150
Ni		: 0.
Ci	(mm)	: .750
Stopped when		: ai > af
Af	(mm)	: 20.000
Stress		
SigM	(Nmm-2)	: .000
SigB	(Nmm-2)	: 200.000

Ai mm	Ci mm	DK-a Nmm-1.5	DK-c Nmm-1.5	Ai+1 mm	DC mm	Ci+1 mm	Ni+1
0.150	0.750	376.216	185.689	0.158	0.001	0.751	769
0.158	0.751	377.908	193.951	0.165	0.001	0.752	1565
0.165	0.752	379.516	202.499	0.174	0.001	0.753	2391
0.174	0.753	381.034	211.332	0.182	0.001	0.755	3248
0.182	0.755	382.458	220.447	0.191	0.002	0.756	4137
0.191	0.756	383.783	229.841	0.201	0.002	0.759	5061
0.201	0.759	385.006	239.507	0.211	0.002	0.761	6023
0.211	0.761	386.125	249.438	0.222	0.003	0.764	7023
0.222	0.764	387.141	259.625	0.233	0.003	0.767	8066
0.233	0.767	388.055	270.054	0.244	0.004	0.771	9153
0.244	0.771	388.871	280.714	0.257	0.005	0.776	10287
0.257	0.776	389.597	291.588	0.269	0.005	0.781	11471
0.269	0.781	390.241	302.660	0.283	0.006	0.787	12708

etc.

FAFRAM 2D analysis of T70 specimens

```
Testname          : t70_2d
Geometry          : 2D-Surface
Edge crack
Thickness (mm):        70.000
A-law             : Paris
C        (N, mm):  .18320E-12
M                 :     3.000
SIF               : Brown/Scrawley/Orange
Mk                : IIW-X/OMAE
Theta     (deg):       60.000
Rho        (mm):         .500
L          (mm):       55.000
Process parameters
Alpha             :      .050
Ai         (mm):         .150
Ni                :        0.
Stopped when      : ai > af
Af         (mm):       35.000
Stress
SigM   (Nmm-2):          .000
SigB   (Nmm-2):       200.000
```

Ai mm	A/T	Mkm-a	Mm-a	Mkb-a	Mb-a	DK-a Nmm-1.5	Ai+1 mm	Ni+1
0.150	0.002	3.650	1.120	3.143	1.117	493.863	0.158	340
0.158	0.002	3.590	1.120	3.091	1.117	497.699	0.165	689
0.165	0.002	3.530	1.120	3.040	1.117	501.571	0.174	1046
0.174	0.002	3.471	1.119	2.991	1.117	505.481	0.182	1413
0.182	0.003	3.414	1.119	2.942	1.116	509.430	0.191	1790
0.191	0.003	3.357	1.119	2.894	1.116	513.417	0.201	2176
0.201	0.003	3.301	1.119	2.847	1.116	517.443	0.211	2572
0.211	0.003	3.247	1.119	2.801	1.116	521.509	0.222	2978
0.222	0.003	3.193	1.119	2.755	1.116	525.616	0.233	3394
0.233	0.003	3.140	1.119	2.710	1.115	529.763	0.244	3821
0.244	0.003	3.088	1.119	2.667	1.115	533.952	0.257	4260
0.257	0.004	3.037	1.119	2.623	1.115	538.183	0.269	4709
0.269	0.004	2.987	1.119	2.581	1.115	542.456	0.283	5169
0.283	0.004	2.937	1.119	2.540	1.115	546.771	0.297	5642
0.297	0.004	2.889	1.119	2.499	1.114	551.130	0.312	6126
0.312	0.004	2.841	1.119	2.459	1.114	555.532	0.327	6622
0.327	0.005	2.794	1.119	2.419	1.114	559.978	0.344	7131
0.344	0.005	2.748	1.119	2.380	1.113	564.468	0.361	7653
0.361	0.005	2.703	1.119	2.342	1.113	569.002	0.379	8188
0.379	0.005	2.658	1.119	2.305	1.113	573.581	0.398	8736
0.398	0.006	2.615	1.119	2.268	1.112	578.203	0.418	9298
0.418	0.006	2.572	1.119	2.232	1.112	582.870	0.439	9874
0.439	0.006	2.530	1.119	2.197	1.112	587.581	0.461	10464

etc

FAFRAM 3D analysis of T70 specimens

```
Testname        : t70_3d
Geometry        : 3D-Surface
Finite width
Thickness (mm):       70.000
Width     (mm):      210.000
A-law           : Paris
C      (N, mm):  .18320E-12
M               :      3.000
C-law           : Paris
C      (N, mm):  .18320E-12
M               :      3.000
SIF             : Newman/Raju
Mk              : IIW-X/OMAE
Theta     (deg):      60.000
Rho        (mm):        .500
L          (mm):      55.000
OMMA            :      1.000
OMMC            :      1.000
OMBA            :      1.000
OMBC            :      1.000
Initiation      : Single
Process parameters
Alpha           :       .050
Ai         (mm):        .150
Ni              :         0.
Ci         (mm):        .750
Stopped when    : ai > af
Af         (mm):      35.000
Stress
SigM   (Nmm-2):         .000
SigB   (Nmm-2):      200.000
```

Ai mm	Ci mm	DK-a Nmm-1.5	DK-c Nmm-1.5	Ai+1 mm	DC mm	Ci+1 mm	Ni+1
0.150	0.750	466.897	230.118	0.158	0.001	0.751	402
0.158	0.751	468.369	240.366	0.165	0.001	0.752	821
0.165	0.752	469.713	250.967	0.174	0.001	0.753	1256
0.174	0.753	470.925	261.922	0.182	0.001	0.755	1710
0.182	0.755	471.999	273.227	0.191	0.002	0.756	2183
0.191	0.756	472.930	284.877	0.201	0.002	0.759	2677
0.201	0.759	473.718	296.864	0.211	0.002	0.761	3193
0.211	0.761	474.361	309.179	0.222	0.003	0.764	3733
0.222	0.764	474.860	321.808	0.233	0.003	0.767	4298
0.233	0.767	475.221	334.737	0.244	0.004	0.771	4889
0.244	0.771	475.451	347.947	0.257	0.005	0.776	5510
0.257	0.776	475.563	361.418	0.269	0.006	0.782	6161
0.269	0.782	475.573	375.129	0.283	0.007	0.789	6844

etc.