BRITTLE FRACTURE DURING FATIGUE LOADING AT $-10^{\circ}C$ OF A FULL-SCALE TUBULAR X-JOINT. INFLUENCE OF AGEING.

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A full-scale cross connection between two tubes has been subjected to high-stress low-cycle fatigue loading at $-10^{\circ}C$. A brittle fracture developed after a small number of load cycles. The yield point of the material which originally was equal to 810 N/mm^2, had obtained a value of 885 N/mm^2 after 5 years of rest. Therefore special attention has been paid to the ageing characteristics.

INTRODUCTION

In offshore structures the use of steels with high yield point is often promoted by designers and steel makers. On the other hand the fabricators of welding materials are more reluctant. They realize too well that weld defects are not easily avoided and that they are more dangerous in high strength steel structures than in structures made of mild steel. Equally important is, that the strength and toughness of the base metal may be seriously impaired in weld regions. The welding itself - including pre- and post-heating - may be expensive, despite the reduction in work due to the smaller thicknesses. For cyclically loaded structures post-weld heat treatment is very desirable in order to reduce the high welding stresses and remove hydrogen.

In general the authors are not so afraid of welding stresses in sea-loaded structures made of lower strength steels. Incidental high loads will free the structure soon from them, at least at the points of highest stresses. But in high yield structures the ratio between load stresses and yield point is smaller than in lower

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yield structures, so that residual stresses do not relax as soon and as much as in the latter. This means the possibility of quicker initiation of cracks (even if the stress level is the same in both structures!) and quicker propagation of cracks, as a consequence of absence of crack closure under compressive loads.

The main reasons for using high strength steels for instance in jack-up legs are that the compressive strength of the chords and braces is increased and consequently the weight is reduced. But then a new problem appears, viz. how much the compressive stability is impaired by the presence of eventual cracks. But this is outside the scope of this paper. Here attention will be focussed on the fatigue behaviour at -10°C, and the involved risk of brittle fracture. Fatigue loading at low temperature has been chosen for this experiment, because it conforms best to actual situations. Fatigue cracks may travel through the structure, thus providing constantly new possible initiation points for brittle fracture. When the crack tip meets a spot where the quality of base metal, weld or H.A.Z. is low, a brittle fracture may develop (Nibbering and Lalleman (1), Nibbering and Scholte (2)).

TEST SPECIMEN

The specimen was a full scale tubular X-joint consisting of tubes of 368 × 20 mm. It was made of steel with a yield point of 850 N/mm^2 and a tensile strength of 925 N/mm^2. The chemical composition was 0.13 C; 0.34 Si; 1.1 Mn; 0.02 P; 0.015 S; 0.06 Al; 1.18 Ni; 0.24 Mo; 0.08 V; 0.51 Cr; 0.012 N. For Charpy properties, see Figures 12, 13 and 14.

The weld metal properties were:

TABLE 1

Name	Conarc 70 (root passes)			Conarc 85		
Code	ASME SFA-5.5 E10016G DIN8575 EkbNiMoCr			ASME SFA-5.5 E12012G DIN8575 EkbNiMoCr		
Chemical	C	M	Si	Mo	Ni	Cr
composition	0.07	1.4	0.3	0.4	0.9	0.2
Yielding	Non-welded			Stress relieved		
strength N/mm	620			600		
Elongation at fracture	21			21		
Impact (temp.)	-20	-40		-20	-40	
energy J	135	80		140	80	

The welding and N.D.T. were carried out with the utmost care according to usual modern practices.

Figure 1 shows the specimen in the test rig. The special topic in this case was that the two tubes were not mutually perpendicular but positioned at an angle of 60°. The member, which is mainly under compression in the actual structure was the continuous one.

TEST SET-UP (FIGURE 1)

The specimen had been built in in the 1000 tons tension-compression fatigue testing machine of the Delft Ship Structures Laboratory. A separate rig had been constructed in order to be able to keep the load on the continuous tube (transverse in the machine) in static compression at -400 tons, (Figure 2).

The interrupted tube was loaded cyclically by the machine. The specimen had been provided with a large number of strain gauges in order to be able to measure the strains at hot spots, where cracks may start. During the fatigue loading the output of some gauges was constantly recorded, in order to be able to trace the first moments of crack initiation and follow the crack propagation.

FATIGUE TEST

The fatigue test was divided into two parts.

Fatigue Load with Ratio $R = -1$

Actual fatigue load:
F_{max} = +300 ton on the interrupted tube.
F_{min} = -300 ton axial stress is 20% of yield point.
Frequency = 0.033 cycles/sec.
P = -400 ton on the continuous tube, axial stress is 26.7% of yield point.
Temperature = 15°C.
Fatigue cycles = 1100.

Crack initiation. After 1100 fatigue cycles, three cracks were found at three toes of welds where peak strains occurred. The depth of the cracks was very shallow (about 1 to 2 mm). These cracks could only be seen with a magnifying glass under a tension load above 275 ton. The places where cracks occurred are shown in Figure 3.

Fatigue Load with Ratio $R = -0.5$

Actual fatigue load:
F_{max} = +400 ton on the interrupted tube.
F_{min} = -200 ton.

Frequency = 0.037 cycles/sec.
P = -400 ton on the continuous tube.
Fatigue cycles = 1068 under temperature = -5^{o}C.
Fatigue cycles = 116 under temperature = -10^{o}C.

Crack propagation. From inspection of the cracks the propagation process could be reconstructed:

1) Crack with a length of 115 mm (crack I).
   This crack first propagated along the toe of the weld in the wall of the continuous tube. Then one tip of this crack left the toe of the weld in the neighbourhood of gauge 164 and propagated into the longitudinal direction of the continuous tube. It stopped at a point about 80 mm from the toe. Another one left also the toe of the weld and propagated as a brittle fracture in the longitudinal direction of the continuous tube.
2) Crack with a length of 30 mm (crack II).
   This crack did not propagate through the wall; in fact the propagation in depth was small.
3) Crack with a length of 18 mm (crack III).
   This crack did not propagate through the wall.
4) Crack IV.
   This crack had not been detected after the first fatigue stage. It propagated completely through the continuous tube in a brittle way.

DISCUSSION OF THE FATIGUE RESULTS

Figure 4 shows results of Dutch experiments by Dijkstra (3) and De Back et al. (4) with tubular joints of various diameters. The well known influence of scale appears clearly. In the figure the AWS-XX curve is also given together with one point of a new British fatigue guidance note for 32 mm thick tubular joints (mean less two standard deviations). The present result is in line with the curve for Ø 457 for steel with yield point 350 N/mm^2 and with the one estimated for Ø 368.

It would be of interest to know whether the transverse constant compressive load of -400 tons has perhaps had a negative influence on the fatigue behaviour. At this moment no answer can be given, but it should be realized that 400 tons conforms to a stress of only 27% σ_y, (in (4) no influence was found). However it may be, it is confirmed once again that the fatigue strength of joints made of high strength steels is not superior to that of joints made of lower strength steels. That this is also true for the high stress region is disappointing because when benefits from the use of high strength material are hoped for, it is in that region. That this hope is not fulfilled is due to the residual welding stresses.

The present test result refers to rather small cracks because a brittle fracture developed soon. In the case that the experiment would have been carried out at $+20^{o}$C instead of -10^{o}C the fatigue test could probably have been continued for another 2000 cycles leading to a more favourable point in the diagram.

After fracturing of the specimen inspection of the crack surface revealed that there were several points where cracks had started (Figures 5 and 6). This is of interest because it shows that the low fatigue result was not caused by a single, incidentally serious defect. For all cracks started - as usual in defect-free welds - at the fusion line of the welds. Therefore the fatigue result of the specimen may be considered as rather characteristic for this material in its longitudinal direction (crack path). Not any fatigue crack has initiated at the fusion line on the side of the welds in the interrupted tube. Apparently cracks did not develop as easily transverse to the tube axis as they did in line with it; the resistance to crack initiation seems to be better. But it should be acknowledged that the stresses at the fusion line of the interrupted tube were some 20% lower than those at the fusion line of the transverse continuous tube (Ren Zijin (6)).

Some information about the crack propagation at high nominal stresses was obtained from the fatigue results of the fabricated COD-specimens. For a K-value of 1440 $N/mm^{3/2}$, da/dN was about 3.5×10^{-4} for cracks developing in the longitudinal tube material and about 2.5×10^{-4} for transverse cracks. These values are about half as high as those for steel Fe 510.

BRITTLE FRACTURE OF THE SPECIMEN AT -10°C

On page 3 the test procedure has been described. The latter 1184 of a total of 2284 load cycles had been applied at low temperature. Of these 1068 occurred at -5°C, the latter 116 at -10°C. The fatigue load was +400 ton/-200 ton, corresponding to nominal stresses $0.27\ \sigma_y/0.13\ \sigma_y$.

The test ended with a spontaneous brittle fracture. Figures 5 and 6 show the crack paths on both sides of the specimen. Figure 7 shows how far the brittle fracture extended in the transverse tubes. This is astonishing bearing in mind that in the greater part of the transverse tubes hardly any stresses were present perpendicular to the crack path. The starting point(s) of brittle fracture can be seen in Figures 8 and 9. The fracture probably did not develop in one moment but in stages. This can be seen in Figure 8. It seems that at least four partial fractures developed prior to the final one. The strain gauge records confirm this more or less. Of six strain gauges a continuous record was made during the fatigue loading at low temperature. Unfortunately they were not situated close (enough) to the part of the structure shown in Figure 8. But the gauge near point A II-4 in Figure 8 was connected to a peak detector (double amplitude of strain) which became active once in 12-13 load cycles. The result is shown in Figure 10. (The number of cycles refers to those effectuated at -5°C and -10°C). At 1000 there is a clear change in slope which might be due to a sudden extension of the shallow rusty fatigue crack at the edge of the plate. A second change of slope (to three horizontal points) occurs at about 1130 cycles. Next a small shift of the record is visible (two points), which again can only be caused by rather abrupt crack extension. The starting point of the final fracture will have been either at the left or the right side in Figure 8. It is of interest that the partial brittle fractures occurred mainly in the welded region (weld and H.A.Z.) and not in the base metal of the transverse tube. This confirms what will be discussed in the next section, that the resistance of the unwelded base material against longitudinal cracking was worse than that of the weld and H.A.Z.!

There is a possibility that primary cracking has started at the other side of the specimen (Figure 9), because the surface was more corroded than the one discussed before. Figure 11 which gives the record of the strain gauge in the vicinity of A 1-6 in Figure 11, supports this view. The shear lips all over the length of the fracture surface were rather small (Figure 8 left and right). Only at the origin and at a few intermediate spots and of course at the arresting points the shear lips were thicker. This confirms that the propagation of the brittle fracture occurred very 'easily'. It suggests that the material of the transverse tube would probably also not have been able to arrest cracks at somewhat higher temperatures, say 0°C. This is confirmed in the next section.

AGEING OF THE MATERIAL

The material had been supplied in 1980. Then the Charpy energy at -40°C was 44 J (notch $\perp$ tube axis). Lloyd's requirement was 32 J, so a wide margin was present.

After the experiment described in this report new Charpy bars were fabricated and tested (Figure 12). Now only 32 J was obtained at -40°C. It is curious that also the yield point and the tensile strength had changed during the course of 5 years:

	1980	1985
σ_y	810	885
σ_u	860	910

In order to be sure, that the same material was used, the chemical composition was investigated. The result was identical to that of 1980.

Apparently this material is sensitive to ageing. This would mean that structures made of that material (and perhaps similar ones) are less safe nowadays than at the time of fabrication. This is important enough for justifying some additional testing.

Influence on Tensile Properties

First of all pieces of the steel were subjected to heating at 230°C for two hours. The result was an increase in yield point and tensile strength of 20-30 N/mm^2. Apparently there was still room for ageing after the '5 years' effect.

Next other pieces obtained a 'stress relief' treatment: 600°C for two hours, in order to see whether the properties of 1980 could be recovered. The influence was negligible.

The next step was strain ageing consisting of 2.8% cold deformation followed by two hours heating at 230°C. This had a large effect. The tensile strength became 130 N/mm^2 higher than the 1985 one, which conforms to an increase of 180 N/mm^2 as compared to the 1980 value. The elongation was nearly halved.

Table 2 summarizes the results of the various treatments on the tensile properties.

TABLE 2

Specimen No.	Treatment	σ_t	σ_y	Elongation dp 100	Reduction of area
TL - 2	none	910	885	19%	60%
TL - 3	aged 2h., 230°C	949	908	17%	63%
TL - 4	" "	938	905	17.5%	64%
TL - 5	aged 2h., 600°C	928	888	19.4%	58%
TL - 6	strain aged 2.8% + 2h., 250°C	1042		7.9 (+2.8%)	52%

Influence on Charpy Values

The Charpy results were a bit surprising. Two hours ageing at 230°C led to a reduction in toughness in the low temperature region (Figures 15 and 16). At -10°C the toughness was improved in terms of energy (Figure 15) and did not change in terms of fracture appearance. But on the whole it is evident that the toughness of the L-material has been reduced to that for the D-material.

The results for specimens heated at 600°C are bad. The treatment has certainly not restored the properties up to the 1980 level as was hoped for. This is not surprising as it is known that for this type of steel long lasting heating at 600°C may be as well detrimental as beneficial. Therefore, although a positive result would have been of significance, a negative one - as found - says nothing.

The last treatment, being strain ageing, proves to be at least as detrimental as two hours heating at 230°C. But now the reduction in toughness appears at -10°C, where heating alone had little effect.

DISCUSSION OF CHARPY AND COD VALUES IN CONNECTION TO INITIATION AND ARRESTING OF CRACKS

Charpy Tests

An alarming thing is that the Charpy value for bars with notches in the longitudinal direction was as low as 22 J at -40°C. At -10°C (the testing temperature of the full scale specimen) the energy was still only 28 J. In Figure 12 are included requirements for this type of material according to Euronorm 113-72 (Fe E 355-KT). The correspondence is good. Then it must be concluded that for offshore applications - especially for parts above sea level - these requirements are not satisfactory. Figure 13 gives information about the fracture surface of the Charpy bars. For the tube thickness concerned (20 mm) at least 50% shear surface will have to be required, when crack arrest capability of the material is desired. But even for the L-bars this will only be possible at about 0°C. From the D- and T-results, which are indicative for the full scale test result, it may be concluded that crack arresting will only be possible at temperatures above +20°C.

A point which needs consideration is whether the initiation of the brittle fracture was influenced or not by the quality of the weld and the heat-affected zone. In Figure 14 Charpy results for weld and H.A.Z. of a similar structure as tested, made by the same firm, are added to the values for the tube material of Figure 12. It may be concluded that the poor result of the full scale test was not due to inferior welding.

C.O.D. Testing

The C.O.D. tests showed a clear difference in toughness for cracking in the transverse and in the longitudinal direction of the tubes. For the transverse direction the CTOD at -16°C was equal to 0.7 mm and at -25°C and -40°C about 0.25 mm. For the longitudinal direction it was only 0.22 mm at -4°C and 0.28 mm at +3°C. This result conforms to what has been observed in the full scale test, where no brittle fractures had developed in transverse sections of the longitudinal tube at -10°C.
In none of the C.O.D. tests crack-arresting or pop-ins occurred.

CONCLUSIONS AND OBSERVATIONS

1. The high stress - low cycle fatigue strength of as welded tubular cross connections made of high strength steels is about equal to that for lower strength steels.

2. Shallow cracks developed into brittle fractures when fatigue loading was applied at moderately low temperatures.

3. These brittle fractures were not arrested when running in the longitudinal direction of the tubes.

4. Ageing of the material may aggravate the situation for actual structures when they become older.

5. The notch toughness of tube material with respect to longitudinal cracking is a lot worse than that to transverse cracking.

6. Fatigue loading at low temperature proved to be once again a very realistic and efficient procedure for testing large structural components.

7. It should be emphasized that the poor results of the experiment must be attributed entirely to the bad state of the tube material. The joint-design was good as was proven by the values of the stresses measured close to the initiation points of the cracks.

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(2) Nibbering, J.J.W. and Scholte, H.G., 'Realistic Testing of Welds by Fatigue Bending at Low Temperature', IIW-doc. X-1014-82, 1982; I.S.P., Vol. 31, No. 355, March 1984.

(3) Dijkstra, O.D., 'Fatigue Strength of Tubular T- and X-joints', OTC 3696, May 1980.

(4) De Back, J., 'Vermoeiingsgedrag van Offshore Stalen Buisknooppunten', Report for Annual Conference of SMOZ, 1984.

(5) Iida, K., 'Fatigue Strength of Welded Tubular K-joints of 800 N/mm^2 Class High Strength Steel', IIW-doc. XV-419-78, 1978.

(6) Ren Zijin, 'Full Scale Test and Finite Element Calculation for a Tubular X-joint', Graduate work Delft University of Technology, Ship Structures Laboratory, Delft, 1985.

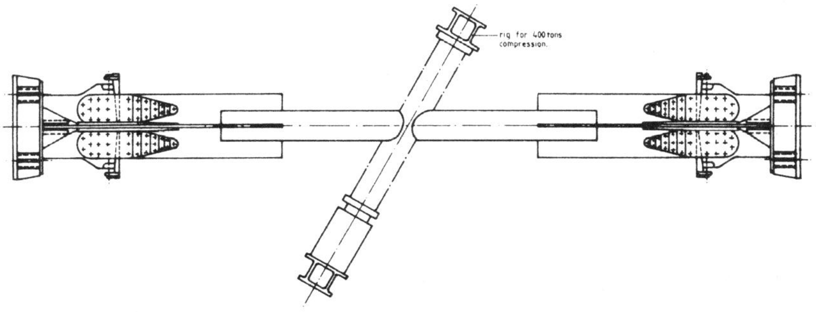


Figure 1. Top view of the test rig.

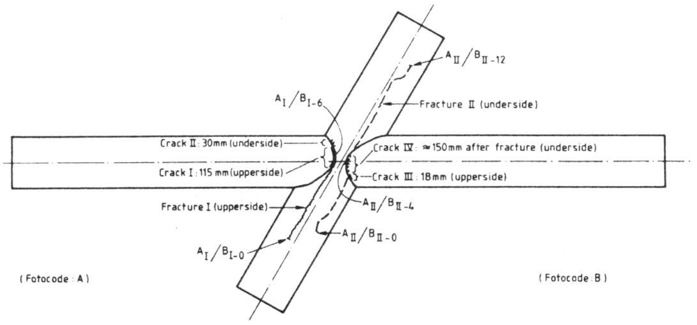


Figure 3. Situation of cracks (view from top side).

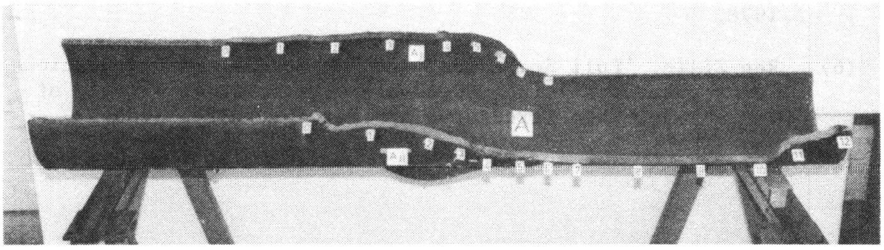
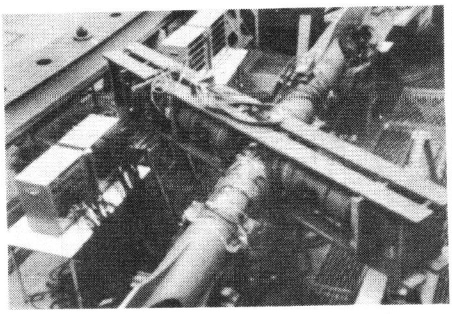


Figure 7. Brittle fractures in transverse tube.



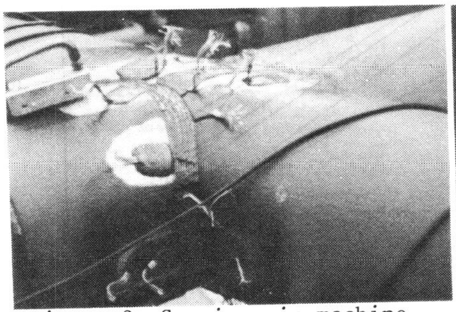
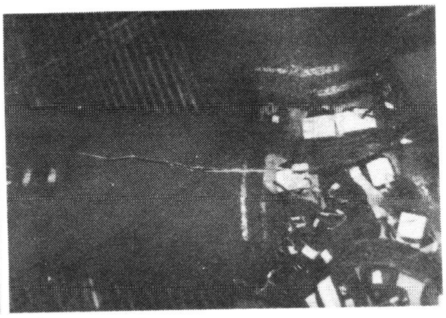


Figure 2. Specimen in machine.
Figure 2a. Detail.



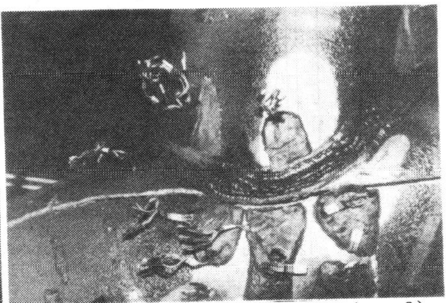


Figure 5. Crack I (key Fig. 3).
Figure 6. Crack IV (key Fig. 3).

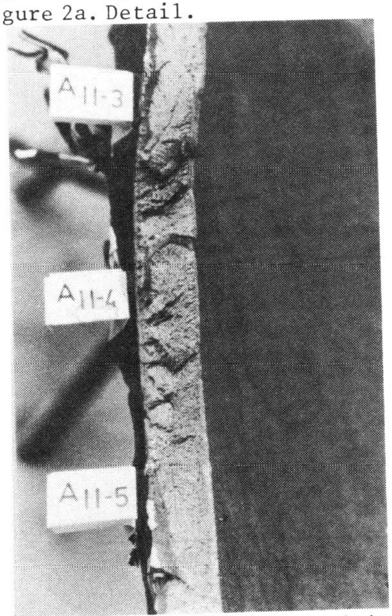


Figure 8. Brittle fracture initiations and arrests. At the right edge shallow fatigue cracks (IV).

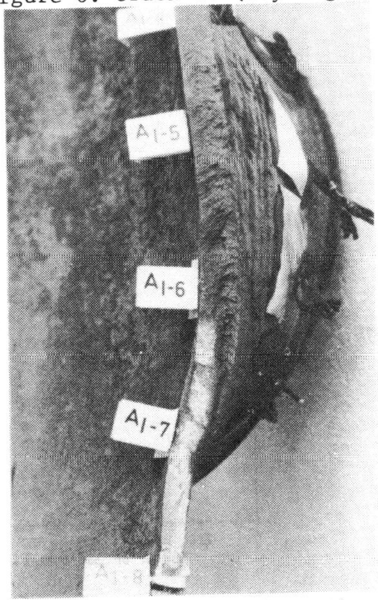


Figure 9. Crack I (key Fig. 3).

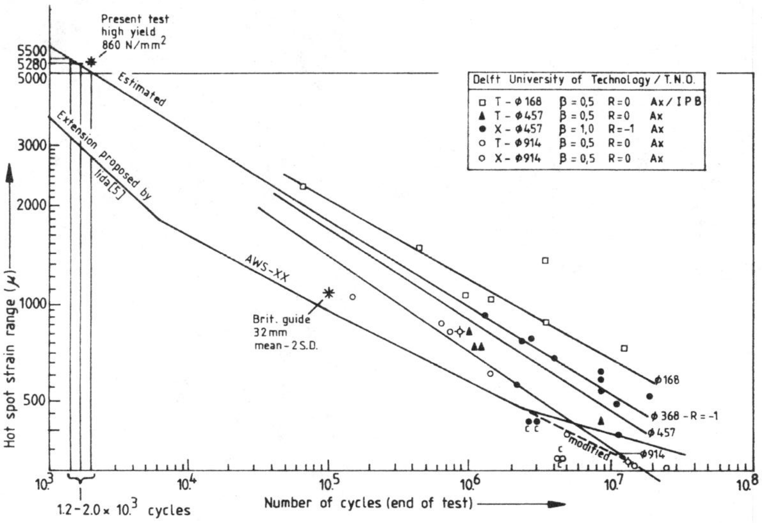


Figure 4. Dutch test results on T- and X-joints of circular hollow sections (3), (4).

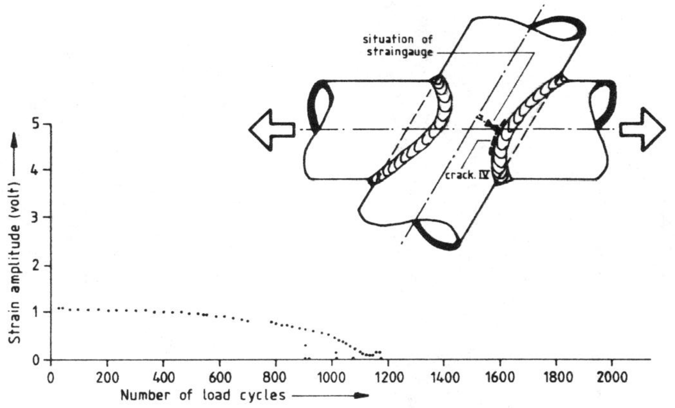


Figure 10. Strain amplitude close to A_{II-4} (Fig. 8).

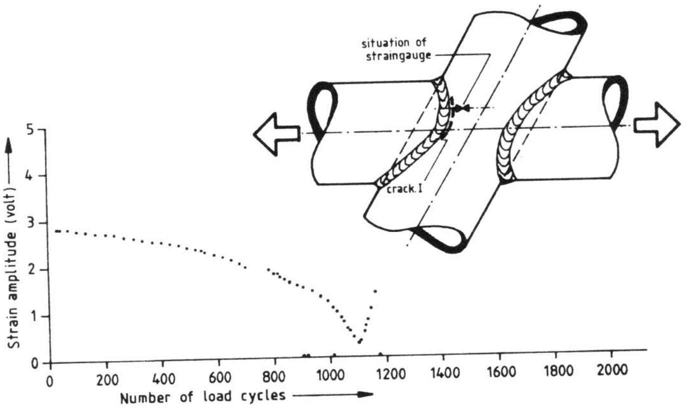


Figure 11. Strain amplitude near A_{I-6} (Fig. 9).

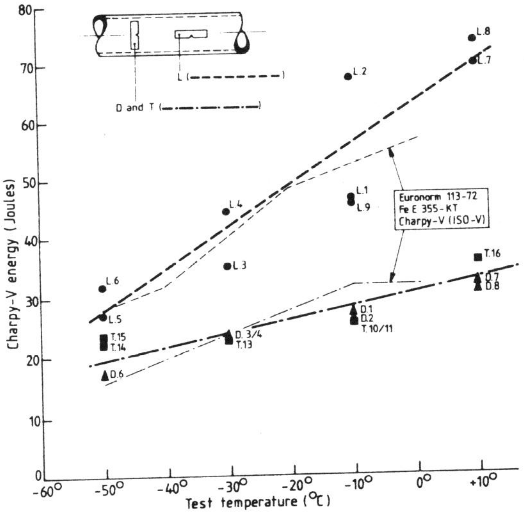


Figure 12. Charpy-energy for tube material as compared to Euronorm values.

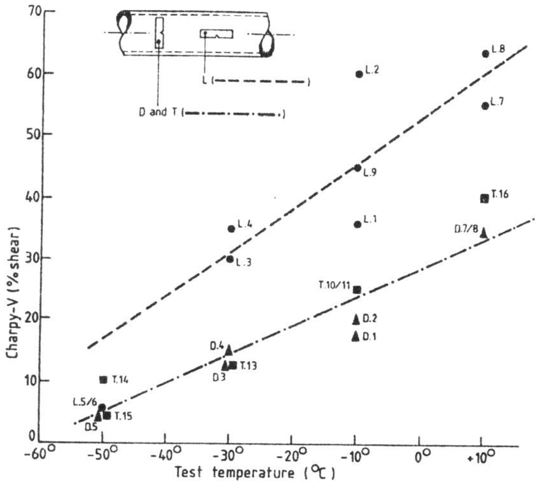


Figure 13. Charpy fracture appearance.

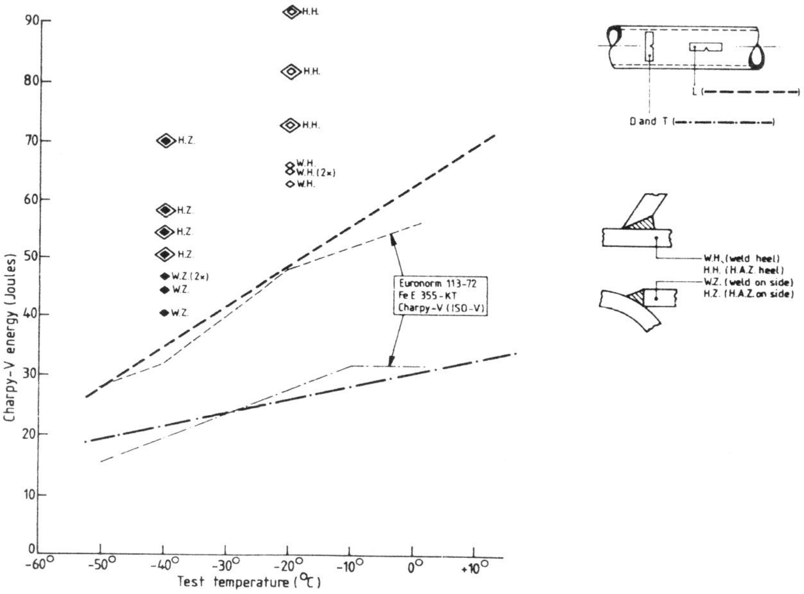


Figure 14. Charpy-energy of welds and H.A.Z.'s.

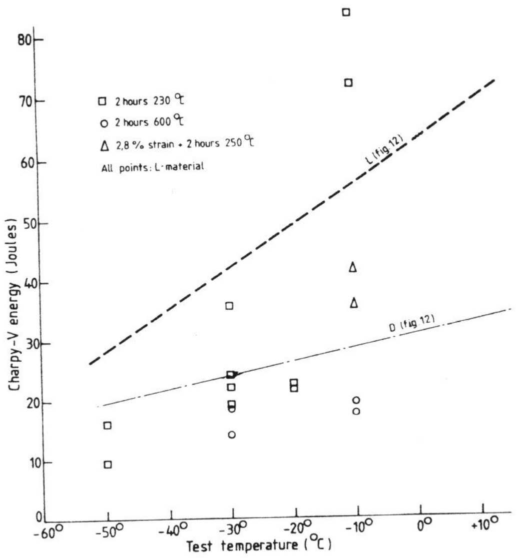


Figure 15. Influence of various ageing treatments in terms of Charpy-energy.

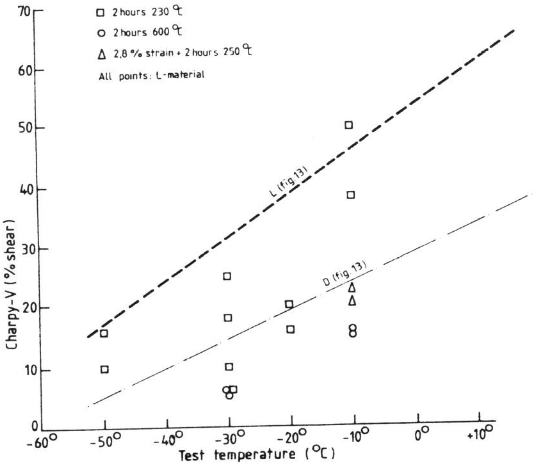


Figure 16. Influence of various ageing treatments in terms of fracture appearance.