FATIGUE CRACK PROPAGATION IN TUBULAR STEEL OF OFFSHORE STRUCTURES

S. Shankare Gowda

Rakenteiden Mekaniikka, Vol. 18
No. 4 1985, s. 3...18

ABSTRACT

The paper describes the fatigue crack propagation behaviour in steel specimens with different crack orientations. The specimens were cut out from a large-size tubular joint instead of flat steel plate samples. From the test data, the variation in crack growth rate in different directions and crack orientations are compared. The relationship between crack growth rate, da/dN, and stress intensity factor range, ΔK, and the values of the material constants C and m have been evaluated. The effect of layers in the parent material, influence of welding and post- weld heat-treatment on the fatigue crack propagation are discussed in detail.

INTRODUCTION

The cyclic environmental loads induce critical stresses at tubular joint intersections of offshore steel structures which might lead to fatigue crack initiation, propagation and failure of the members. In tubular joints of laboratory specimens, the fatigue cracks are found to initiate at the weld toes of brace or chord members depending on the magnitude of the local stress range, thickness of the members, weld angle etc., and normally propagate along the weld toe.

In number of tubular joints of laboratory specimens, it was observed that the crack propagation in the thickness direction in the main chord was not unique. In many cases, although the crack started at the weld toe, it was not always perpendicular to the surface but propagated a few millimeters parallel to the surface as shown in Fig. 1, before reaching the through-thickness of the member.

The metallurgical examination of the tube material revealed the existence of many parallel layers (lamination) in the circumferential direction as can be seen in Fig. 2. The presence of laminations in steel material is not

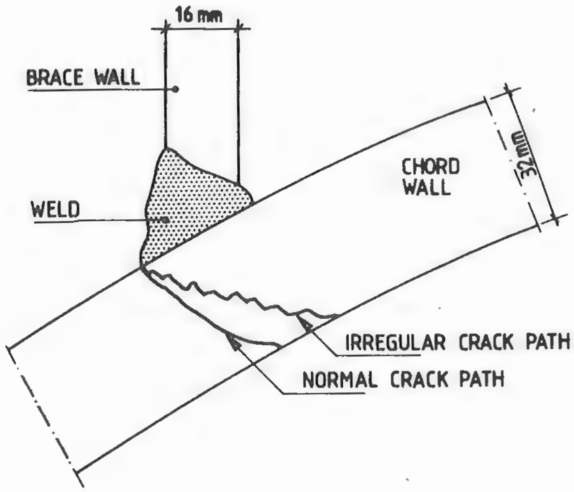


Figure 1. Crack propagations in tubular joints.

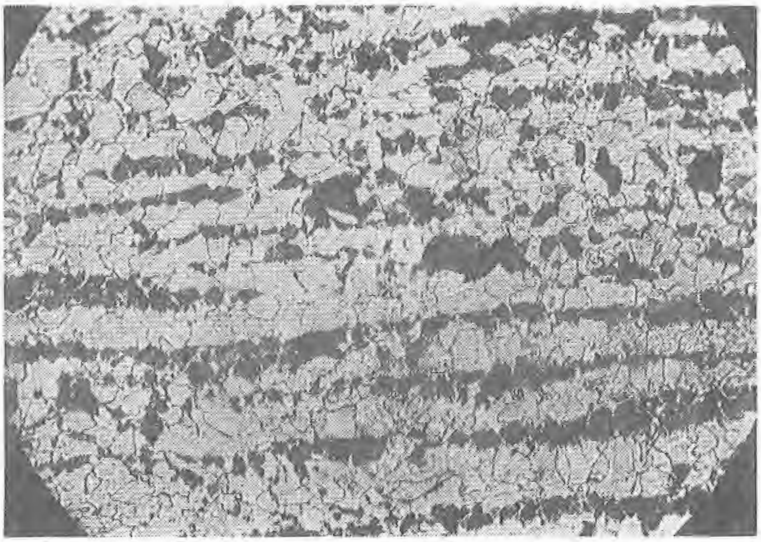
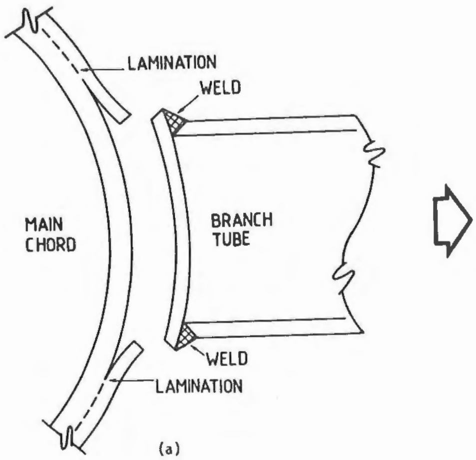


Figure 2. Microstructure (layer) distribution in tubular steel.

critical if the material is subjected to stresses parallel to the surface of the plate, but laminations can cause brittle failures and reduce load carrying capacity when steel is stressed in short-transverse (thickness) direction [6, 7]. Since tubular members are subjected to residual and tensile stresses, the presence of laminations in the chord members reduces the effective thickness of the plate and joint may fail by separation as shown in Figure 3(a). Due to lamination, the fatigue cracks may propagate along the weak paths of lamination in stepwise fashion or peel along separation as can be seen in Fig. 3(b).



(a)

(b)

Figure 3. Possible failures due to lamination.

Considerable amount of work on fatigue crack growth characteristics of steel specimens has been carried out by many investigators (1 - 4). In the majority of cases, the test specimens were taken mainly from flat steel plates. The findings of these investigators have indicated no significant effect of crack orientation on fatigue crack growth rates in air and in sea-water.

But in many other cases, the effect of microstructure orientation has indicated different crack growth rates. In these cases, the rate of crack growth was higher in the intergranular orientation compared to transgranular orientations (4, 5 - 8).

In the present study, the effect of lamination on the fatigue crack growth rate has been examined in four different crack orientations using five types of specimens.

SELECTION OF SPECIMENS AND CRACK ORIENTATIONS

In order to investigate whether the layers present in the chord tube material may be the cause for the irregular crack patterns in tubular joints, a large piece was cut out from the tube (Fig. 4), from which the specimens were prepared.

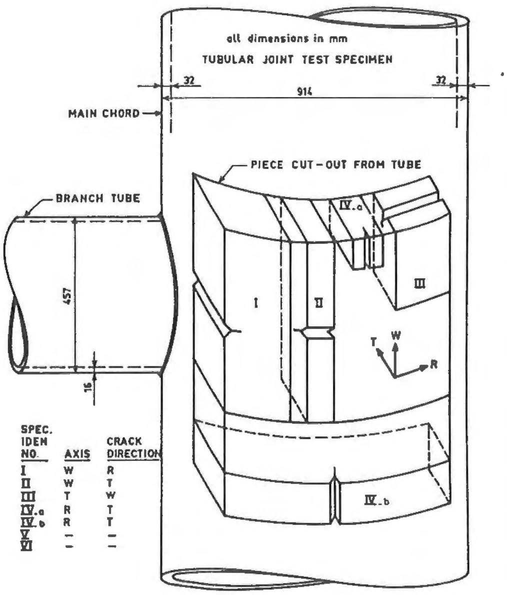


Figure 4. Sample piece with crack orientations of specimens.

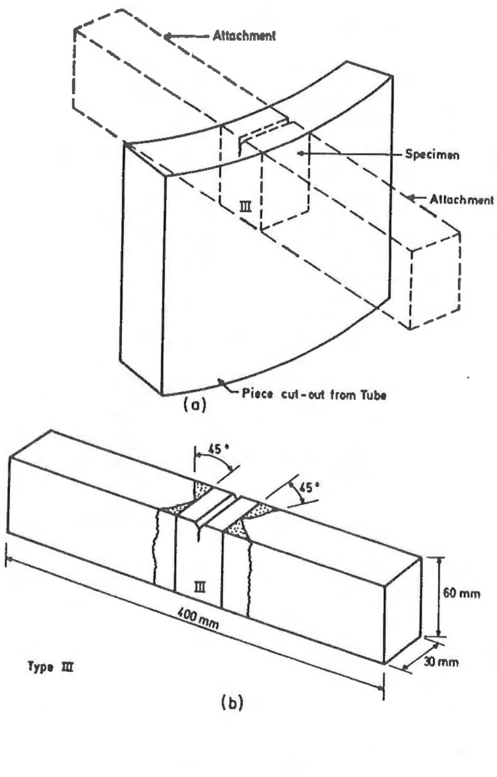


Figure 5. Large welded specimens.

In the present case, the crack propagations in four of the six possible directions of crack orientations have been studied using five different types of specimens as shown in Fig. 4. In order to obtain sufficient length for loading and supporting the specimen, for Types III and IV-a, extra attachments were welded as shown in Figs. 5 and 6.

A few specimens in all the types were post-weld heat-treated to study the difference in crack growth rates and to compare with those specimens tested without heat-treatment. The mechanical properties and chemical composition of

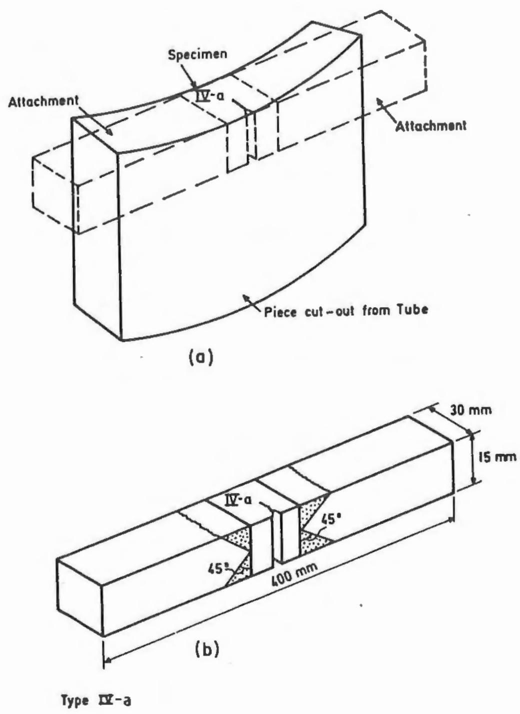


Figure 6. Small welded specimens.

steel are shown in Tables 1 and 2 respectively. The details of dimensions, crack orientations and the test conditions for all the specimens are given in Table 3.

The crack starter notches were introduced in all the specimens by machining. The notch shape and size were selected according to ASTM Specifications (9).

Table 1. Mechanical Properties of Steel

Yield stress N/mm^2	Ultimate Tensile Stress N/mm^2	Total Elongation (%)
426	605	48

Table 2. Chemical Composition (Wt. %) of steel

C	S_i	Mn	S	P	Al
0.180	0.250	1.33	0.006	0.024	0.029

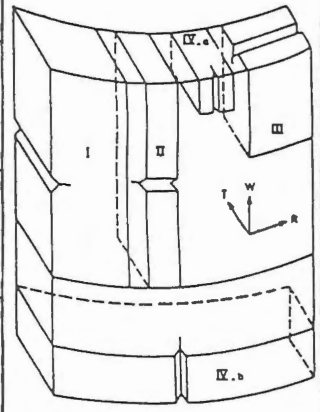
METHOD OF TESTING, CRACK GROWTH MONITORING AND PRESENTATION OF TEST DATA

All the specimens were tested in air at room temperature under four point bending with a stress ratio R = 0.1. The input signal selected was constant amplitude sinusoidal loading with frequency ranges of 3 - 10 Hz. To create an effective sharp crack front from the starter notch, fatigue pre-cracking was carried out with proper load shedding procedure. For all the specimens, the minor span was always kept equal to twice the specimen height, although the major span was varied with the overall length of the beam. The crack length on either side of the specimen was measured with microscopes, one on each side in addition to Crack Microgauge using A.C. potential drop method.

During testing, the number of cycles and the corresponding crack lengths were recorded frequently and the average crack length of two microscopes readings was used as the final value. The comparison between microscope and

Table 3: Details of test program.

Specimen		Crack Direction	Specimen Dimensions		Stress Range N/mm^2	Regular (parent) Specimens		Welded specimens		Remarks
Type	Axis		Width mm	Height mm		No HT	HT	As-welded	PWHT	
I	W	R	29	58	89 111	1 2	6	-	-	
II	W	T	15	30	118 148	10, 20 19	8 17	-	-	
III	T	W	30	60	89 111	-	-	3 5	4 7	
IV-a	R	T	15	30	118 148 180	-	-	-	9 11 18	
IV-b	R	T	15	32	118 148 180	13 15 12	14 16	-	-	



Note: Serial numbers 1 to 20 correspond to specimen numbers

Crack Microgauge readings yielded very good correlation. From the test data, the graphs of crack length versus number of cycles were generated for all the specimens, and the da/dN data were computed according to incremental polynomial method.

The stress intensity factor range, ΔK, was calculated using the following equation:

$$\Delta K = F(a/B)\ \Delta\sigma \sqrt{\pi a} \tag{1}$$

where the stress range Δσ is given by

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \tag{2}$$

a = average crack length, and

B = specimen height

The non-dimensional function F(a/B) is given by

$$F(a/B) = \left(\frac{0.923 + 0.199\left(1 - \sin\frac{\pi a}{2B}\right)^4}{\cos\frac{\pi a}{2B}}\right)\sqrt{\frac{2B}{\pi a}\tan\frac{\pi a}{2B}} \tag{3}$$

The computed crack growth rate data were plotted against the stress intensity factor range values on a log-log scale to obtain the characteristic crack growth rate curve for all the specimens.

RESULTS AND DISCUSSION

The main objective of the work was to determine the fatigue crack growth characteristics in the steel material of a tubular joint. In addition, the influence of factors such as, welding, stress relieving and natural parent metal behaviour on crack growth rates are investigated. The crack growth behaviour of specimens in each type, tested at the same stress range level are discussed in relation to their crack orientations and test conditions and compared with other types. The complete details of the test programme with all the particulars of specimens, crack orientations and test conditions are given in Table 3.

Although tests on twenty specimens were carried out, because of the space limitations, only the important test results in each type are presented in this paper. The complete test data of all specimens are given in reference (11).

Type I - Large Regular Specimens

The large specimens of Type I had crack orientations in the circumferential direction as can be seen in Fig. 4. Specimens 1 and 6 were tested at the same stress level but only specimen 6 was post weld heat-treated to observe the effect of stress relieving on regular specimens.

The a vs. N and da/dN vs. ΔK for specimens 1 and 6 are given in Figs. 7 and 8 respectively. As it can be seen from the graphs, a significant reduction in fatigue life and faster crack growth rate are found in the heat-treated specimen. This shows that the effect of stress relieving on normal specimens

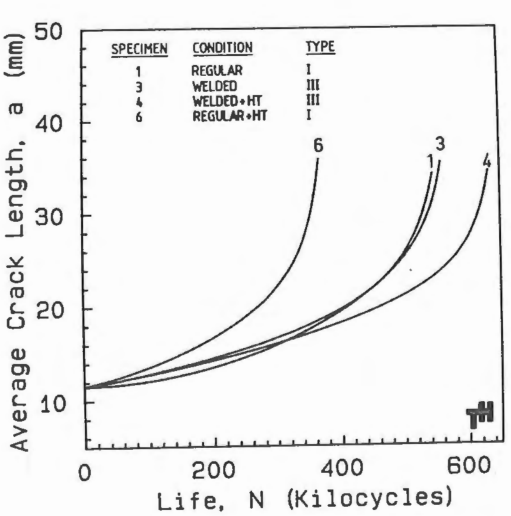


Figure 7. N data for specimens 1,3,4 and 6.

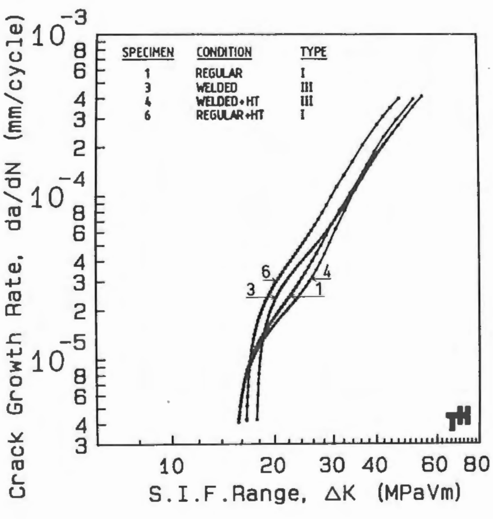


Figure 8. da/dN vs. ΔK plots for specimens 1,3,4 and 6.

reduces the resistance to crack growth rate. For the weld metals it has been found that the yield and ultimate strengths tend to decrease with post-weld heat-treatment in static tensile tests while elongation and reduction in area are not usually influenced (1, 10).

The crack growth rate relationships for specimens 1 and 6 are given by:

$$\frac{da}{dN} = 3.15 \cdot 10^{-10} \ (\Delta K)^{3.6} \qquad (4)$$

$$\frac{da}{dN} = 2.86 \cdot 10^{-10} \ (\Delta K)^{3.8} \qquad (5)$$

Type II - Small Regular Specimens

Two specimens of Type II, viz. 8 and 20 were tested at the same stress level, while only specimen 8 was heat-treated. In this case also, the heat-treated specimen had a shorter fatigue life and higher crack growth rate. The regular specimen (parent material-no welding), viz. 20, indicated much variation in the crack growth behaviour as can be seen in Figs. 9 and 10.

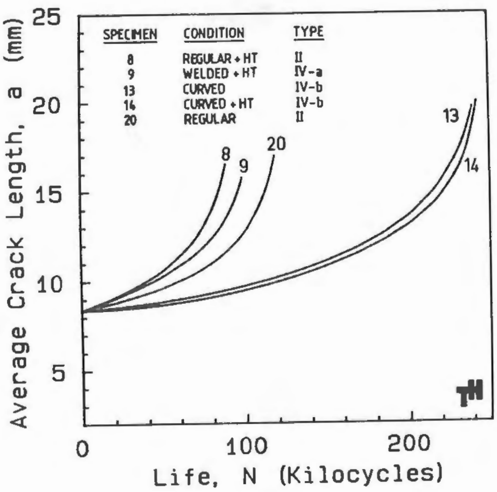


Figure 9. a vs. N data for specimens 8,9,13,14 and 20.

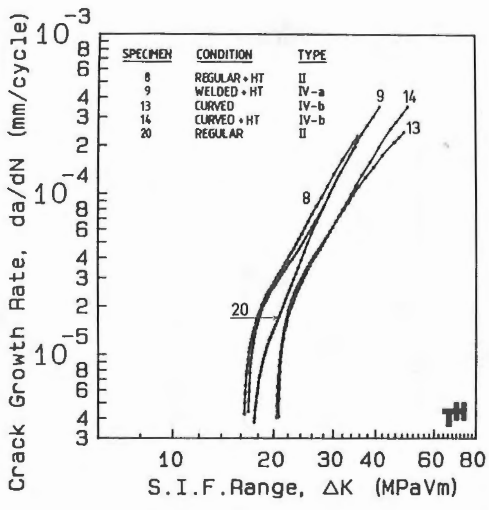


Figure 10. da/dN vs. ΔK plots for specimens 8,9,13,14 and 20.

The crack growth rate relation for specimens 8 and 20 are:

$$\frac{da}{dN} = 2.89 \cdot 10^{-11} (\Delta K)^{4.5} \qquad (6)$$

$$\frac{da}{dN}\ 9.97 \cdot 10^{-13} (\Delta K)^{5.5} \qquad (7)$$

Type III - Large Welded Specimens

The as-welded specimen 3 and heat treated specimen 4 of Type III were tested at the same stress level to study the effect of welding and stress relieving on crack growth rate. As can be seen in Fig. 7, the as-welded specimen 3 had very much reduction in fatigue life and higher crack growth rate (Fig. 8). This indicates that, in the case of welded specimens, stress relieving improves fatigue life and provides better resistance to crack growth rate compared to as-welded specimens.

Now the results of Type I (specimens 1 and 6) and Type III (specimens 3 and 4), which have crack orientations in transgranular and intergranular directions respectively will be compared. As can be seen in Fig. 8, the specimen 4 of Type III has lesser crack growth rate in the first half and higher crack growth rate in the second half of Region II of da/dN vs. ΔK curve compared to specimen 1 of Type I. The vice-versa is true for specimen 1 of Type I. This makes it difficult to asses the crack growth behaviour more accurately between Types I and III.

Let us now consider another set of specimens in Type I (specimen 2) and Type III (specimens 5 and 7), which were tested at the same stress range but at a higher level than the specimens 1, 3, 4 and 6.

From Figs. 11 and 12, it can be observed that the welded and stress relieved specimen 7 has a higher crack growth rate compared to specimen 2, indicating faster crack growth rate in transgranular direction. To confirm this fact more thoroughly, further tests are needed with more number of specimens. Because of heat treatment and due to the presence of welding stresses, the regular heat treated specimen 6 in Type I and as-welded specimens 3 and 5 in Type III respectively, are not taken into account in the above comparison.

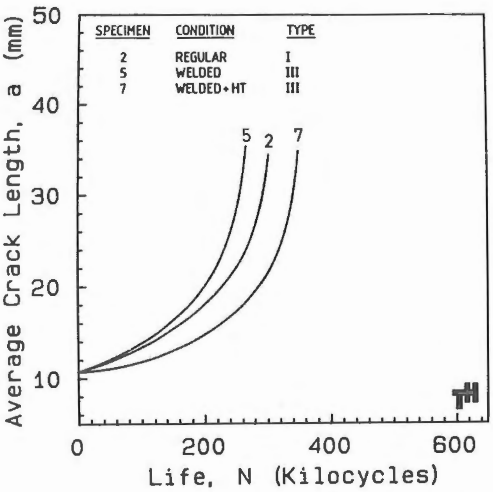


Figure 11. a vs. N data for specimens 2,5 and 7.

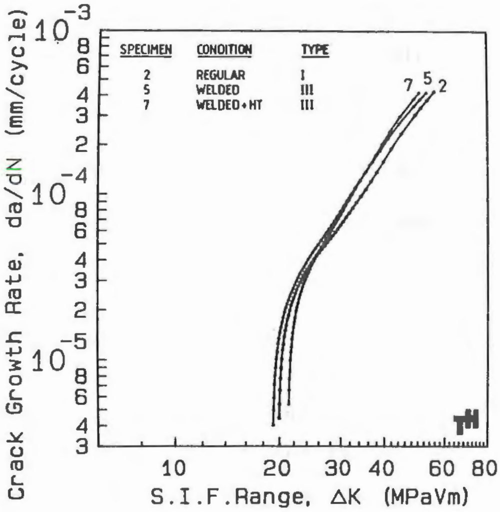


Figure 12. da/dN vs. ΔK plots for specimens 2,5 and 7.

The crack growth rate relationship for specimens 3 and 4 are given by:

$$\frac{da}{dN} = 7.07 \cdot 10^{-10} (\Delta K)^{3.4} \tag{8}$$

$$\frac{da}{dN} = 3.59 \cdot 10^{-10} (\Delta K)^{3.5} \tag{9}$$

Type IV·a - Small Welded Specimens

Three specimens, viz. 9, 11 and 18 were tested in Type IV-a and all of them were post weld heat treated (Table 3). The specimens had same crack orientation as those of Type IV-b. As can be seen in Figs. 9 and 10, there is variation in crack growth characteristics among Type II (specimen 8 and 20) and Type IV-a (specimen 9). The analysis indicates slower crack growth rate in specimen 20 of Type II compared to specimen 9 of Type IV-a.

The equation describing the crack growth rate relationship for specimen 9 is:

$$\frac{da}{dN} = 8.08 \cdot 10^{-11} (\Delta K)^{4.2} \qquad (10)$$

Type IV•b - Small Curved Specimens

The curved specimens were taken from the tube in the circumferential direction and tested with their actual curved profile and have crack orientations identical to Type IV-a. A total of five specimens were tested in this type and two of them were post- weld heat-treated.

The graphs of a vs. N and da/dN vs. ΔK are given in Figs. 9 and 10 respectively. Both specimens 13 (no heat-treatement) and 14 (heat-treated) exhibit identical crack growth behaviour. This indicates that, in the case of curved specimens with actual tube profile, the heat-treatment has no influence on crack growth data. This is opposite of the results observed for Type I and Type II specimens.

Now comparing the crack growth rate, da/dN vs. stress intensity factor range, ΔK curves (Fig. 10), of Type IV-b (specimens 13 and 14) and Type IV-a (specimen 9), significant difference exists between Types IV-b and IV-a. The welded and post-weld heat- treated specimen 9 of Type IV-a has higher crack growth rate than the curved specimens 13 and 14 of Type IV-b. Although the three specimens have same crack orientations, the curved specimens indicate better resistance to crack propagation. Similarly, specimen 8 (regular and heat-treated) and specimen 20 (regular and not heat-treated) in Type II which were tested at the same stress level as those specimens, viz. 13 and 14, reveal higher crack growth rate in comparison with the curved specimens in Type IV-b (Fig. 10). The crack growth rate relationships for specimens 13 and 14 are given by:

$$\frac{da}{dN} = 3.63 \cdot 10^{-11} (\Delta K)^{4.2} \qquad (11)$$

$$\frac{da}{dN} = 3.11 \cdot 10^{-11} (\Delta K)^{4.2} \qquad (12)$$

From the above comparison, it can be observed that there is considerable difference in crack growth behaviour between curved specimens (Type IV-b) and regular specimens (Type II). These two types have different crack orientations.

COMPARISON OF RESULTS

The fatigue crack growth data of the present investigation indicates significant effect of crack orientation on fatigue crack propagation in tubular steel specimens. The possible reasons seem to be factors such as the presence of residual stresses (in case of as-welded specimens) and lamination.

Similar observations on the effects of crack orientations on fatigue crack propagation have been confirmed by other investigators (5 - 8). However, the findings of other investigators (viz. 1 - 4) indicate no effect of crack orientations on fatigue crack growth data.

From the present investigation, the large variations in crack growth rates in different orientations observed on the tubular steel material indicate that the irregular crack propagations found in tubular joints probably might have been caused due to lamination. To confirm this fact, further investigation in this area in more detail seems to be inevitable. In this regard, further tests will be carried out at the Technical Research Centre of Finland, to study the fatigue crack propagation in tubular steel material as well as flat steel plates used in the construction of offsohre structures.

ACKNOWLEDGEMENT

The author would like to thank Dr. Tuomo Kärnä, AOEG, Group Leader, and Professor Pauli Jumppanen, Director of Laboratory of Structural Engineering for their interest and encouragement.

CONCLUSIONS

1. The effect of stress relieving of regular specimens (parent material) is found to reduce the resistance to crack growth, leading to a shorter fatigue life. However, no influence was found on curved specimens (Type IV-b).

2. In the case of welded specimens, the stress relieved specimens indicate improvement in fatigue life and a better resistance to crack growth compared to as-welded specimens.
3. The welded and stress relieved samples in Type IV-a, showed slower crack growth behaviour compared to regular specimens of Type II.
4. Considerable difference in crack growth behaviour was found between curved specimens (Type IV-b) and small regular specimens (Type II). These two types have different crack orientations. Type IV-b (curved) specimens indicate a better resistance to crack propagation compared to Types II and IV-a.
5. The fatigue crack growth data of tubular steel material indicate significant effect of crack orientation on fatigue crack growth rate.

REFERENCES

[1] De Back, J. and Vaessen, G.H.G.: "Fatigue and Corrosion Fatigue Behaviour of Offshore Steel Structures", Final Report of ECSC Convention 7210-KB/6/602, April 1981.

[2] Scholte, H.G. and Wildschut, H.: "Fatigue Crack Propagation Tests on Welded Specimens in Air and Seawater", Paper 5.2, International Conference - Steel in Marine Structures, October 1981.

[3] Johnson, R., Morgan, H.G. and Bretherton, I.: "Basic Fatigue Tests", Interim Technical Report UKOSRP 3/07, D.O.E, U.K, January 1980.

[4] Walker, E.F., Austen, I.M. and Rudd, W.J.: "Stress Corrosion and Corrosion Fatigue for the Offshore Oil Industry", ECSC Report No. 7210.KB. 8/802, March 1981.

[5] Lieurade, H.P.: "Application of Fracture Mechanics to the Fatigue of Welded Structures", Welding in the World, Vol. 21, No. 11/12, 1983.

[6] Braid, J.E.M. and Knott, J.F.: "Fatigue Crack Propagation in the Visinity of Weld Deposits in high Strength Structural Steel", I.I.W. Doc. No. XIII-1014-81.

[7] Diez, J.M.:" Influence du type d'acier et des Opérations de Soudage sur la Propagation des Fissures de Fatigue dans les aciers de Construction Métallique", Recherche CECA 6210-28, 1972.

[8] Maddox, S.J.: "Fatigue Crack Propagation Data Obtained from Parent Plate, Weld Metal and HAZ in Structural Steels", The Welding Institude Report E/48/72, September 1972.

[9] "Fracture Toughness Testing and its Applications", ASTM STP No. 381, June 1964.

[10] "Report of Committee 111.1 - Ferrous Materials", 8th International Ship Structures Congress, Gdansk, 1982.

[11] Gowda, S.S.: "An Experimental investigation on the Effect of Layers on Fatigue Crack Propagation in Steel used in Tubulars of Offshore Structures", Report Submitted to Stevin Laboratory, Delft University of Technology, Delft, The Netherlands, Nov. 1984.

S. Shankare Gowda, Ph.D., Technical Research Centre of Finland, Laboratory of Structural Engineering