Random Loading Fatigue of the Welds in BS 4360 Steel

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ABSTRACT

The influence of residual stresses due to welding on crack growth rate of through and part-through cracks under random loading is examined.

KEYWORDS

Surface crack; Crack growth rate; Random loading; Residual stress; Heat affected zone.

INTRODUCTION

The fabrication of North Sea oil platforms cannot be accomplished without the use of welding. Due to the presence of defects and flaws and significant high residual stresses cracks may develop at welded joints at early stages in the life of these structures and may propagate through different zones of weld, HAZ and parent metal. Thus, it is crucial that these defects be detected and their influence on structural integrity assessed. Naturally the crack growth response of such cracks in the presence of the residual stress field of the weld and HAZ must be known beforehand to make possible any prediction of the fate of the structure.

Large amount of data are available with regard to the fatigue crack growth response of weld and HAZ of BS 4360-50D steel under constant amplitude (CA) loading. Hence, the purpose of this part of the investigation is to examine the fatigue resistance of HAZ and weldment under random loading in air.

Due to the presence of intrinsic defects and flaws, either in the weldments or in immediate adjacent sites, the initiation process of fatigue cracks will cover only a small portion of the fatigue lives of components or structures. Thus, the propagation-life estimation is more relevant for a structure in the design stage as a crack may initiate at locations where the stress concentration factor is high after only a few hundred cycles. The fatigue crack may then grow through three microstructurally different regions, namely, base metal, HAZ (heat-affected zone) and weldment. The crack growth response in each region can be different and this variation my be caused by both microstructural and mechanical properties as well as by the residual stresses developed because of the welding process. The significance of each of the above factors is dependent on the prevailing external loads and environmental conditions (Moghadam and Randon, 1984). It is well-established that at low and high growth rate regimes the microstructure plays a major role on the crack propagation response while in the mid range its influence is minimal (Ritchie and Suresh, 1982). The residual stresses can influence the growth rate at any stage depending on the magnitude of the stresses and applied ΔK.

Residual stress distribution and its influence on crack growth rate

The residual stresses due to welding are caused by two basic sources - shrinkage and solid state phase transformation, the former having a greater influence. The distribution of residual stresses in these welded plates (of 25mm or less of thickness) is known (Int.Conf.R.S. 1978). The longitudinal stress, σ_y, which acts in the direction of the weld-line, has its maximum value at the centre-line of the weld and decreases from tensile to compressive form as it moves away from the weld-line. Its variation in the y direction is such that at the edge of the plates its magnitude is zero. The maximum value of σ_y is of the same order as yield stress, σ_Y, of the weld metal. This, of course, is true only in the case of low-carbon steel weldments; for high-strength steels these stresses are considerably lower than yield stress.

The transverse residual stress, σ_x, which is normal to the weld-line varies symmetrically from high compressive stress at the edge of the plates to tensile stress at the centre-line of the weld. The maximum tensile stress of σ_x is no more than about 20% of σ_y (the longitudinal stress). The variation of σ_x in the x-direction is gradual. the distribution of σ_x and σ_y in the through-thickness direction is considered negligible and is generally taken as constant for thicknesses of 25mm or less (it will be shown later that this is only true when crack-growth rate is high). However, the thicker the plate thickness the larger is the variation of the stresses across the thickness (Wu and Carlsson, 1984). The magnitude of σ_x also increases with thickness to levels close to that of σ_y for extra thick plates.

It should be noted that the residual stresses that are here being discussed are those local ones which are induced in unrestrained structures. The effect of stress relieving is to reduce the magnitude of these stresses but not their distribution; such changes are very much dependent on the temperature and hold-time during the annealing process.

Specimens which are cut out of welded plates have produced a variety of fatigue crack growth-rate results, some of which indicate that compressive residual stresses exist ahead of the crack tip, while others appear to have tensile residual stresses. The major problem, however, is whether crack growth within structure releases some or part of these stresses, and whether residual stress-redistribution takes place. The main cause of crack growth is the relief of stress, hence the only remaining problem is that of stress-redistribution. the specimens which are cut from welded plates may have similar distributions to those discussed by Wu et al., 1984, but the position of the starter-notch of these specimens make all the difference to the crack growth behaviour of the test pieces. Thus, it is necessary to separate the fatigue results into two different categories based on position of notches, i.e.,

a) edge notch,
b) central notch.

The edge-notched specimens, such as CT and SEN specimens, generally have a compressive residual stress ahead of the crack tip whereas central-notched test-pieces, like CCT or surface crack bend (SCB) specimens have a tensile stress ahead of the notch tip. The orientation of the notch with respect to the weld is highly important. As mentioned previously, the longitudinal stress, σ_y, is much larger than σ_x and at first sight the presence of a notch or crack in the direction of x may appear to present the most severe case of crack growth across the weldment. Despite that, the crack-tip could be located in the compressive stress zone and the net effect of these stresses would become beneficial. Thus, the case of crack-growth along the weld-line affected by the transverse residual stress is of more interest, as Wu et al., 1984 stated, that K-factors for such an orientation of crack is larger than for the case where the crack traverses the weld. In case of a part-through crack the magnification factor in the presence of weld is lower.

The differences between the crack growth rate results of weld, HAZ and base metal

As has been reported the residual stresses influence the growth rate in welded specimens with a varied degree depending on the orientation and type of notch geometry. The results therefore were categorised in terms of specimen geometry, as one type experienced compressive residual stress and the other tensile ahead of its crack-tip. Some authors have used the distribution pattern of these stresses to calculate the resultant stress intensity factor, K_R, by means of either a simplified function, or in terms of a complicated expression. In this study the values of K_R are derived using the assumption that the residual stresses act as a distributed pressure on part or whole of the area of the crack surfaces, where these stresses are defined in terms of:

$$\sigma(x) = \frac{P(x)\ a}{\pi x [x^2 - a^2]^{1/2}} \qquad (1)$$

where P(x) is point force per unit thickness; x is the distance of a point (a-x) from the crack-tip. The variation of the stress $\sigma(x)$ across the thickness is negligible (plane stress case). Thus, in the case of Griffith crack of length of 2a, K due to $\sigma(x)$ is:

$$K = \frac{P(x)\ \sqrt{a}\ dx}{\sqrt{\pi}\quad [x^2\ \ a^2]^{1/2}} \qquad (2)$$

$$K_R = \frac{2\sqrt{a}}{\sqrt{\pi}} \int_o^a \frac{P(x)\ dx}{(a^2 - x^2)^{1/2}} \qquad (3)$$

By knowing the distribution of P(x) which describes the variation of the residual stresses, K_R can be evaluated. A similar approach has been carried out by Glinka, 1979 and others.

EXPERIMENTAL PROCEDURE

The fatigue crack-growth rate of weldment of BS4360-50D steel under CA loading has been examined by Moghadam et al., 1984. The purpose of the present work is to provide information on the crack-growth response in weld and HAZ under random loading. Both CT and SCB specimens were used for this investigation. The preparation of the specimens and the welding process were identical to that reported by Moghadam et al., 1984, and Foroughi and Radon, 1988. Manual arc welding and wide-weave techniques were employed for the manufacture of butt-welded specimens. The c/Mn electrode was of the type BS639 (1976) : E4311R21. CT specimens were produced by the butt-welding of two plates, each 50mm wide and 95mm long. The joint preparation was a double "Vee" with a 2-mm root gap.

Four SCB specimens were produced, two for weld tests and two for HAZ. The joint preparation for the weld SCB specimens was the same as that for the CT specimens, while for HAZ specimens K-type joint-preparation with a root gap of 2mm was chosen. This type of joint allowed the crack-growth to stay within the HAZ during the entire test period. The SCB specimens were made of two plates 120mm wide and 260mm long, with the transverse butt-weld joint being along the width. This type of welding resulted in some angular distortion with one side under compressive stress and the other under tensile stress. The surface notches were made on the tensile side by a spark-erosion technique for the parent plate specimens, and had the same dimensions i.e., 2c and a equal to 31 and 6.2mm respectively. The welds were ground flat and the surfaces were polished to allow the monitoring of crack growth.

The two butt-welded CT specimens of 25mm thickness were tested under a random load of a frequency range of 0-15 Hz and Q factor of 8 (ratio mean/rms). Two different spectra were used for the loading, broad band BB and triple-peaked spectrum BP. The load system for the CT specimens was supported on a 100 KN Mayes fatigue machine.

The SCB specimens of weld and HAZ were tested under pure bending by means of the Dartec fatigue machine. The frequency-bandwidth and Q factor were the same as above. For both weld and HAZ test-pieces, one specimen was tested under a flat broad band signal and the other under a BP spectrum load. The monitoring of crack growth was done with the same equipment used for the parent-plate tests. The experiments were all conducted in laboratory air conditions at normal room temperature of 22°C. The results were analysed in the same way as for the base metal data.

RESULTS AND DISCUSSION

From the experimental work it is clear that crack growth along the weld line in transverse butt-welded joints demonstrates the most deleterious effect when compared with the results of the base metal under similar conditions. Therefore, it was decided to examine the crack growth behaviour of the two crack-geometries in transverse butt-welded joints. First to be examined was crack propagation in a CT specimen, in which, under CA loading, it has been shown, that the propagation rates accelerate faster although compressive residual stresses prevail around the crack-tip which results in a slower growth rate at low ΔK values with respect to those of the parent plate. Secondly, SCB specimens were used which produced a faster growth rate due to the tensile residual stresses ahead of the crack tip, as has been observed in CCT specimens (Ohta, 1982).

Fatigue crack growth response in butt-welded CT specimens under random loading

The CT specimens were tested at a Q factor equal to 8. The reason for this choice was that Moghadam *et al.*, 1984 reported CA loading test results such, that at R equal to 0.08, the crack propagation rate in weldment was slower than that in 50D steel, while at R equal to 0.7, the data curves crossed such, that the weldment results had a larger Paris exponent and were faster at higher ΔK values and slower at low ΔK in contrast to those of the base metal. The slope of the weld results did not change under different stress ratios. Thus it was necessary to see whether at high mean loads a similar trend could be observed under random loading.

The crack growth rate results for two welded CT specimens are shown in figure 1, which is a plot of growth rate, da/dt in units of mm/second versus K_{rms} (MN/m$^{3/2}$). The spectrum shapes of the signal for the two tests were of BB and BP type with a bandwidth 0 - 15 Hz. The BP spectrum data do not cover the same range of growth rate as the BB data; however, the results appear to be similar which indicates, that no influence due to the spectrum shape was present in the frequency bandwidth of 0 - 15 Hz. The same kind of conclusion was observed from the base metal CT specimen tests under identical load and environmental conditions. In the case of through crack geometries when the bandwidth is large, the shape of the spectrum does not appear to be significant as long as the frequency ranges are the same and the rms of the two load types are equal.

Fatigue resistance of weld and HAZ in SCB specimens

The crack propagation results of two butt-welded SCB specimens tested under BB-and BP-spectrum loadings of frequency range of 0-15 Hz are shown in figure 2. The dc/dt data of this figure (where c is half crack length of a surface crack) demonstrate that the growth rate in weldment under the BP signal is slightly faster than that due to the BB-spectrum loading. A similar behaviour, due to the two spectrum shapes, was observed in the parent plate data under similar conditions; however, this difference is not very significant in the weldment results and at K_{rms} values of 4MN/m$^{3/2}$ or above, there is no difference in the results. The da/dt data where a is depth of a surface crack, (see Foroughi and Radon 1988), correlate very well but indicate that under small K_{rms} values the slope of the growth-rate curve becomes very steep as has been repeatedly pointed out, the scatter in the da/dt data does not allow a reliable judgement to be made on the crack growth behaviour at the maximum depth of the part-through crack of the present study. Nevertheless, an assessment of the influence of the residual stresses on the crack growth behaviour at the deepest point of the crack front is crucial.

Comparison of HAZ, weld and base metal data

The crack propagation data of HAZ, weld and base metal of 50D steel tested under BB- spectrum loading are shown in figure 3. The dc/dt data shown here illustrate that under the same loading the growth rate at the surface-intersection points in the weld is greater than in both HAZ and base metal. However, the growth rates were the same in HAZ and the parent plate. The tensile residual stresses ahead of the crack tip are responsible for the increase in the growth rate in weldment. Under high mean stresses the crack tip is open at the load minima and, as discussed earlier, the increase in K_{max} by K_R may activate new crack growth micromechanisms. Areas of fracture by microvoid coalescence mechanism have been observed from the CA and CT specimens of weldment (Moghadam and Radon, 1984). However, under a CA frequency of 30 Hz the SCB specimen results for the load ratio of 0.7 showed that the weld and HAZ had similar fatigue resistance, while the parent plate had slightly more fatigue resistance than the other two materials. The tensile transverse residual stresses are present in both HAZ and weld specimens and the resultant K_R seems to have affected the growth rate in both materials. The random load dc/dt data of weld, HAZ and the base metal of 50D steel, can be fitted in a narrow scatter band, as the influence of the tensile residual stresses seems to be smaller than that reported under CA loading.

The dc/dt results due to the BP-spectrum loading (not shown here) demonstrated a larger scatter in contrast to the BB signal test results. The major portion of the scatter was due to the base metal results. However, the trend was similar to that shown in figure 3 with the weld showing the least resistance to the crack growth, and the base metal and HAZ behaving virtually in the same manner except at large K_{rms} values, where HAZ seemed to show slightly more resistance to crack growth; however this difference was small. The random load data for weld and HAZ have been presented in terms of K_{rms} and are shown in figure 4. The CA data of the surface crack bend specimen tested under a load ratio of 0.7 is also presented in this figure. From these results it may be concluded that under random loading the crack growth in weld and HAZ is much faster than in the base metal under CA loading.

CONCLUSIONS

1. The influence of the residual stresses has been seen to have an effect on the crack propagation rates of weldment and HAZ specimens, but different effects could be induced depending on the type of specimen notch geometry. In edge-notched specimens compressive residual stresses increase the fatigue resistance of the weldment, while in centrally notched specimens, contrary to the above case, the tensile stresses enhance the growth rate. The influence of microstructural changes manifests itself when large stress intensity factors are present, or the crack growth rate is outside the mid-range regime.

2. The crack growth rate at the surface intersection points of the SCB specimens in weld were greater than those in the base metal. The fatigue resistance of HAZ in the same geometry was similar to that of the base metal.

3. The crack growth rate results for the SCB specimen of weld, HAZ and parent metal at the surface intersection points fall into a narrow scatter band, with the weldment results being the fastest at high K_{rms} values and parent plate data the slowest. HAZ results generally lie between the weld and the base metal data.

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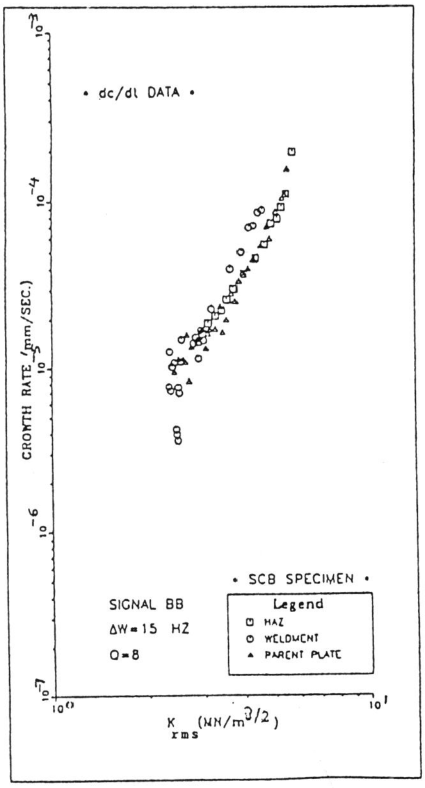

Fig 3. Comparison of surface-crack growth results of HAZ, weld and 50D steel (at surface intersection points).

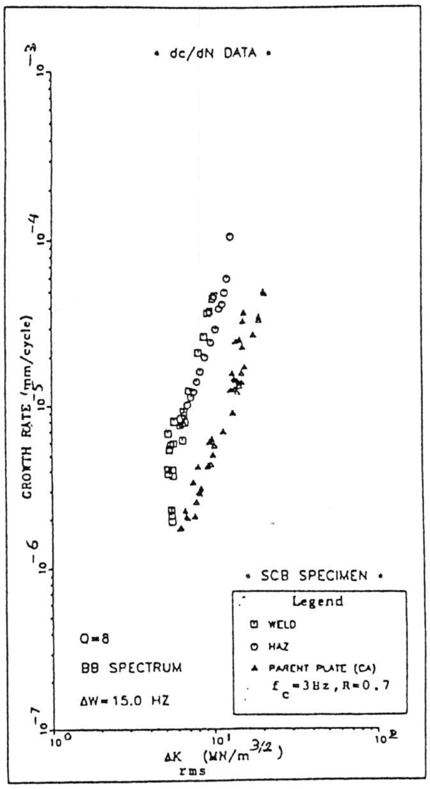

Fig 4. Comparison of random-load surface-crack growth results of weld and HAZ with the constant amplitude crack growth data of 50D steel (at surface intersection points).

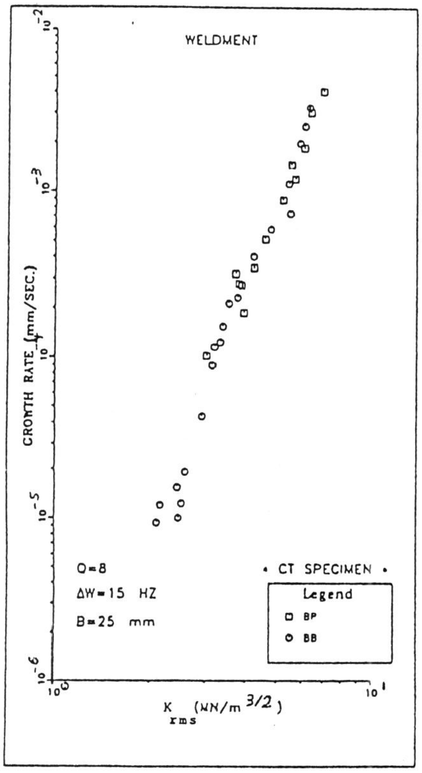

Fig 1. Crack growth results of welded CT specimens tested in air under random loads of different spectrum shape.

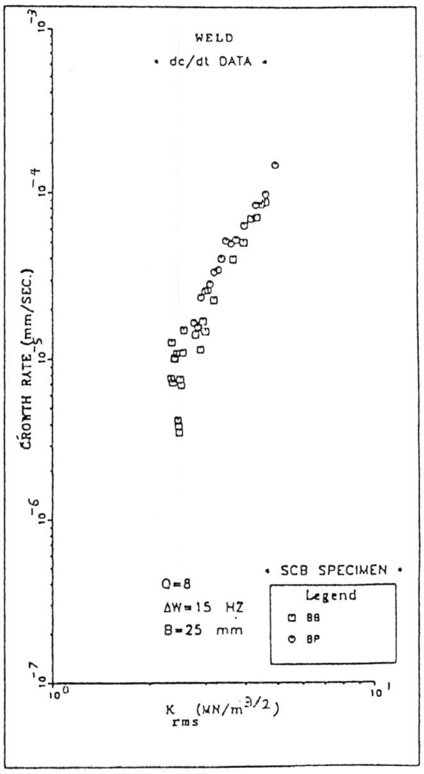

Fig 2. Surface-crack growth results of welded SCB specimens tested in air under random loads of different spectrum shape (at surface intersection points).