FACTORS AFFECTING THE FATIGUE LIFE OF WELDED JOINTS

I. Cole*, C. Pietrosanti*, O. Vittori*

A model for the prediction of fatigue life of welded joints is presented. The model is biphasal using a local stress/strain approach to estimate crack initiation life and a linear elastic fracture mechanics model to estimate crack propagation life. In combination with a Montecarlo simulation the model is used to predict the effect of the variation of weld geometry on fatigue life. Comparisons are made with experimental results. The implications of the results to fabricators, designers and steel suppliers are detailed.

INTRODUCTION

Due to the limitations of traditional design practice a great deal of interest is being focussed on fracture mechanics based methods of life prediction. Such methods may both increase the accuracy and reliability of life estimates (reducing the required design safety factors) and allow an assessment of the various factors influencing the life of a structure. While there is a general consensus that growth of long cracks can be modelled by linear elastic fracture mechanics (L.E.F.M.) no such consensus exists for crack initiation and short crack growth. In fact modelling techniques range from corrected L.E.F.M. with relatively large initial defects to a local stress/strain approach assuming a uncracked notch. In this paper the validity of the latter approach to initiation and of the L.E.F.M. to crack propagation is assessed. Further, the model is used to evaluate life variations produced by scatter in weld geometries (particularly at the local weld toe). The problem is, of course, of direct relevance to fabricators (and code writers thereof) but is also of critical interest to both designers and material suppliers as it has implications for defining design curves and in the comparative assessment of materials.

*C.S.M.-ILVA, Rome, Italy

LIFE PREDICTION MODEL

The model has been designed to predict the initiation life (up to a crack depth of 0.5 mm) and propagation life of cracks forming at the weld toe of plate to plate and tubular joints while incorporating the effect of local weld geometry.

Crack Initiation

Verreman et al(1) have demonstrated that in the case of welded plate joints early crack growth is controlled by notch plasticity and that the initial defect size has little influence on "initiation life".Thus crack initiation can be modelled by the local stress/strain approach as applied to crack free blunt notches. The model based on Neubers Law and the Manson-Coffin relation follows the formulation of Bhuyan and Vosikovsky(2) but also includes the Morrow(3) mean stress modification in order to evaluate the effect of residual stress. Full details being given in previous references (4,5), here it need only by noted that through the elastic stress concentration factor, K_t, and the fatigue reduction factor, K_f, the model incorporated a dependance on local weld geometry (Fig.1).

Crack Propagation

Crack propagation is modelled by a linear elastic fracture mechanics approach, following the broad methodology of the revised British Standard P.D.6493. Thus the crack is assumed to grow according to Paris´s Law.

$$da/dN = C\left(\Delta K_{eff}\right)^m \qquad (1)$$

where ΔK is given by

$$\Delta K = \left(M_{Km}\, M_m\, \Delta\sigma_m + M_{Kb}\, M_b \Delta\sigma_b\right) \frac{\sqrt{\pi a}}{\phi} \qquad (2)$$

The model modifies the standard in four distinct areas:
1) Effect of local weld geometry on the weld S.C.F. (M_K) factor; 2) Effect of residual stress; 3) Crack Shape Development; 4) Load distribution during crack propagation.
While the standard incorporates some dependencies of M_K on weld geometry (on a/t, L/t) the work of Dijkstra et al(5) is used to introduce into M_K a dependence on (θ, ρ). The effect of residual stress on propagation is incorporated by modifying the effective R value. Given the complexity of determining the residual stresses in a structure after the development of a defect, a simple model is proposed.

$$\sigma_r = \sigma_Y/2 \quad a/t \leq 0.2 \;; \quad \sigma_r = 0 \quad a/t > 0.2 \qquad (3)$$

The maximum value of σ_R is an extrapolation of the work of Portergoff et al.(6). Crack formation at welds is associated with multi-crack initiation and coalescence and in the model this process is approximated by constraining the crack aspect ratio (a/c) to follow a predetermined forcing function (for T-butts that of Vosikovsky et al(7) and for X-joints that of Bignonnet et al(8)); However, the formulation of Vosikosky et al is changed subtly to incorporate a dependence on local weld geometry. Thus while originally

$$a/c = e^{-Ga} \text{ where } \quad G = G_{ref} \left(\frac{\Delta\sigma}{\Delta\sigma_{ref}}\right)^2 \left(\frac{t}{t_{ref}}\right)^{0.5} \qquad (4)$$

in the new formulation the nominal stress is replaced by the stress concentration factor (with "a" tending to zero) so that when the formulation is rearranged using equation 2.

$$G = G_{ref} \left(\frac{\Delta\sigma}{\Delta\sigma_{ref}}\right)^2 \left(\frac{M_K}{M_{Kref}}\right)^2 \left(\frac{t}{t_{ref}}\right)^{0.5} \qquad (5)$$

Experimental and theoretical evidence suggests that, for tubular joints, with the propagation of the crack the load carried by the cracked section decreases (load shedding). An empirical formula has been derived to model this effect.

$$\Delta\sigma_{HS} = \Delta\sigma_{HS(m)} + f\Delta\sigma_{HS(b)}\,; \quad \begin{array}{ll} f=1 & C \leq 120 \\ f=2-X/126 & 126 < C < 252 \end{array} \qquad (6)$$

APPLICATION OF MODEL

A detailed knowledge of geometry of the welds of the modelled structures (T-butts and X-joints) is a necessary input into the model. In order to determine the parameters defining the weld geometry a large number of weld profiles were measured both on plate to plate (up to 180) and tubular joints (up to 80), multiple measurements being taken on each specimen. Statistical analysis indicated that the distribution of the parameters ρ, Θ, was best modelled by a log normal distribution, further that while ρ (local weld radius) and Θ (weld angle) were independent, ρ and α (local weld angle) were dependent. In table 1 the parameters defining the distribution of ρ and Θ are reported.

SPECIMEN	MODELLED VARIABLE	MEAN	STANDARD DEVIATION	ACTUAL VARIABLE	MEAN	STANDARD DEVIATION
T-Butt	Log θ	1.664	.047	θ	46.2	5.3
	Log ρ	0.122	0.160	ρ	1.32	0.59
X-Joint	Log θ	1.633	.053	θ	49.4	6.2
	Log ρ	0.191	0.230	ρ	1.78	0.98

TABLE I - Distribution of LogΘ and Logρ

Further analyses which studied the distribution of the most severe weld parameters on any given specimen indicated that such critical parameters always fell at least one standard deviation (S.D.) away from the mean. Thus

$$\rho_{cric} = \rho_m - 1\,S.D. \quad ; \quad \theta_{cric} = \theta_m + 1\,S.D. \qquad (7)$$

a) Prediction of mean life. The model has been used to assess the life of T-butts (main plate thickness 32 mm) tested in fatigue under four point bending in seawater with cathodic protection (-850 mV). The simulation models the conditions of an actual experimental program(9) on joints fabricated from the steel Euronorm FE510, or TMCP steels of equivalent strength. It was established that the performance of all steels were equivalent(9) and thus in the experimental data no distinction is made between steel type. Material parameters for the initiation model are taken from Bhuyan and Vosikovsky(2) (steel type E355) and the paris law coefficients for propagation from Booth et al(10) (for BS 4360 50D). Critical and mean weld geomtry parameters were used for in the initiation and propagation models respectively. In Fig.2 the predicted and the experimental results are presented.

b) Prediction of scatter in life. The expected variation in life that arises due to scatter in weld geometry was assessed for tests on both T-butts and X joints in C.P. The X-joint (chord wall thickness 32 mm, brace wall thickness 16 mm) is tested in inplane bending with the stress range being defined by the hot spot stress (σ_{HS}) according to the definition of the european working group on fracture. A finite element study indicates that at the hot spot the components of stress are.

$$\sigma_{HS} = 0{\cdot}2\,\sigma_{HS(m)} + 0{\cdot}8\,\sigma_{HS(b)} \qquad (8)$$

where m and b signify membrane and bending components. To generate a large number (2000) of weld parameter values from the distributions of the same, a Montecarlo simulation was used. For model of crack propagation the total distributions given previously were used, excluding only nonphysical values those greater than three standard deviations from the mean. In contrast for the model of crack initiation only weld parameters with values more extreme that the critical values (as previously defined) were of interest so that the distributions in the simulation were truncated. In Fig. 3 and 4 the theoretical variation in total life are compared to the observed experimental scatter for T-butt and X-joint tests respectively. However while in both cases the scatter bands are defined at one standard deviation in the case of the experimental deviation the same is calculated with respect to the regression line assuming that the scatter is the same at all stress ranges.

DISCUSSION AND CONCLUSIONS

It is apparent that not only does this biphase model give reasonable agreement with experimental data (Fig. 3 and 4), but so do its component initiation and propagation submodels (Fig. 2). This implies that the assumption that a significant initial defect exists is not necessary, at least for modelling crack initiation from weld toes of limited radius. Although the L.E.F.M. model of crack propagation was very sensitive to the constants selected, i.e. paris law coefficients, the value of residual stress, the factors defining controlled crack shape development if such factors are well defined (by studies such as this one) accurate predictions are possible. Thus this type of model offers the possibility of predicting joint life of complex or large scale joints where fatigue testing is either impractical or uneconomic.

It has been shown that a significant part of the experimental scatter in fatigue lifes may arise from variations in local weld geometry. This has significant implication in the fields of design and material comparison. The present design curves are based on mean curves and standard deviations derived from massed data where no specific control was made on local weld geometry. It is concievable that a large extent of the scatter in such compilations may be associated with weld geometry variations. As such the connection between scatter in test results and that likely in service may need to be reassesed. Further the analyse demonstrates that as significant scatter in experimental results is inevitable, valid comparisons of different materials on the basis of S-N curves are only possible using a statistical approach.

REFERENCES

(1) Verreman Y., Bailon J., Masounave, E.G.F. Publication 1 The Behaviour of Short Fatigue Cracks, 1986, MEP, London, pp.387-404.

(2) Bhuyan G. and Vosikovsky O., Int. J. Fatigue, No.3, 1989, pp.153-159.

(3) Glinka G., Dharmavasan S. and Dover W., SIMS, TS19, 1987.

(4) Cole I. and Fabrizi F., I.G.F.90, 1990, p.225.

(5) Dijkstra O., Snijder H. and van Straalen I., OMAE 89, pp.137-145, 1989.

(6) PorterGoff R., Free J., Tsiagbe W., Fatigue of Offshore Structures, London, 1988, pp.285-297.

(7) Vosikovsky O., Bell R., Burns D., Mohaupt U., Behaviour of Offshore Structures, Amsterdam, 1985.

(8) Bignonnet A., Lieurade H., Siscon Y., Lebrun J., Fatigue 84, 1984.

(9) Cole I., Vittori O., Final Report ECSC Convention 7212-KG/401, 1990.

(10) Booth G.S. and Dobbs S.J., The Welding Institute Research Bulletin, pp.293,27, 1986.

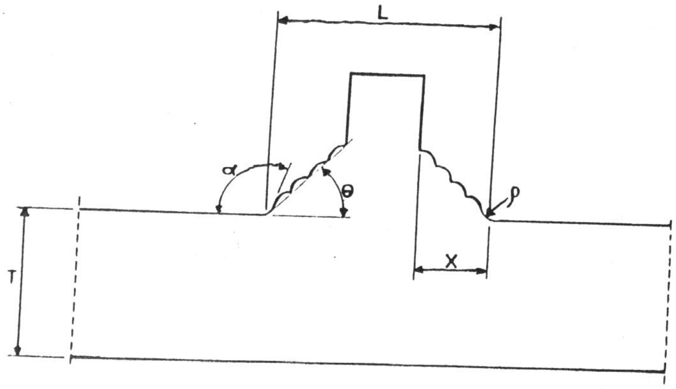

Fig.1 Parameters defining weld geometry.

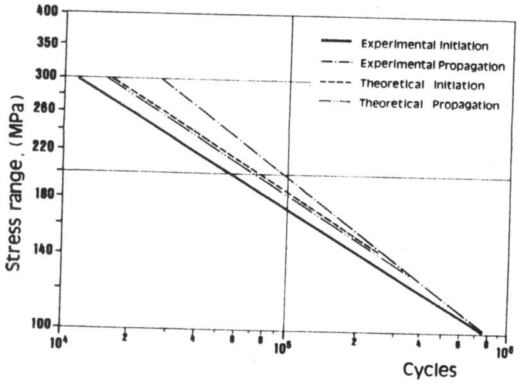

Fig. 2 Initiation and propagation lifes for T Butts.

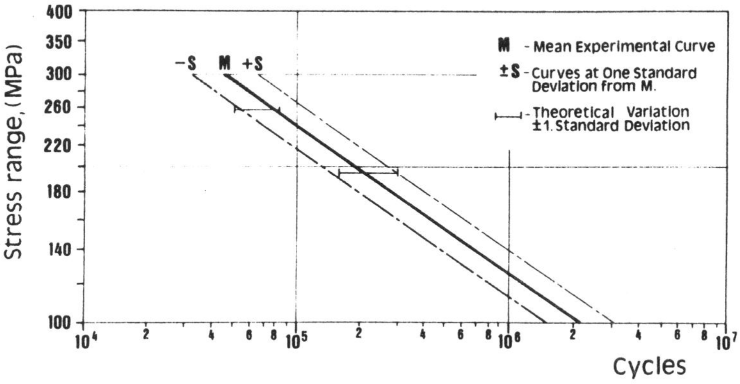

Fig. 3 Total lifes and scatter for T Butts.

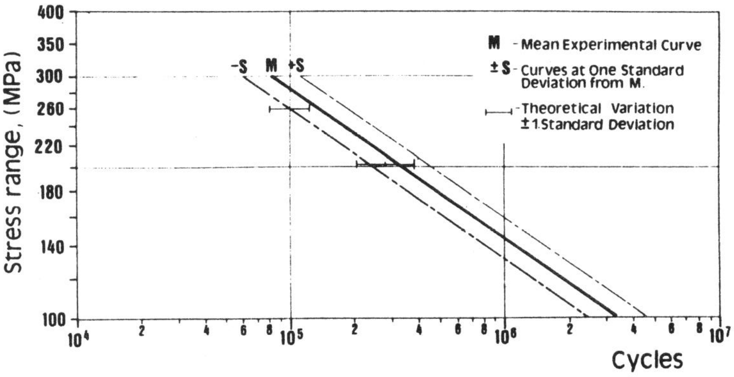

Fig.4 Total lifes and scatter for X joints.