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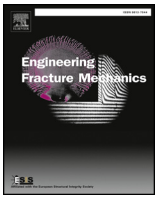

# An experimental-finite element method based on beach marks to determine fatigue crack growth rate in thick plates with varying stress states

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ABSTRACT

The relation between the fatigue crack growth rate and stress state is significant for fatigue life estimation, especially for thick-welded structures with complex stress states. This paper proposes a hybrid Experimental-Finite Element Method aimed to obtain the fatigue crack growth rate corresponding to plane stress and plane strain states. A static load marking method is proposed to mark a series of crack fronts in a single edge notched bending specimen at known numbers of cycles, which is analysed by nonlinear finite element method to evaluate the stress state by a local constraint factor. Stress intensity factor at the center of the thickness and the surface position where plane strain and plane stress states approximately exist and remain unchanged with crack propagation, is calculated by the 1/4-node displacement method with consideration of non-orthogonal mesh influence. The *J*-integral method and the virtual crack closure technique are also applied to check the performance of the methods in dealing with the actual cracked body problem. Crack length increments are determined based on the crack front profiles. The $da/dN$-$\Delta K$ curves of plane strain and plane stress states are determined and compared with the results from normal fatigue crack growth rate tests according to Chinese standard: GB/T 6398-2000. The fatigue crack growth behavior of a semi-elliptical surface crack located at the weld toe of a T-plate welded joint subjected to cyclic tension loading is assessed based on the curves and the analytical results are compared with the experimental results. The asymptotic crack shape observed in experiments is successfully predicted by using the curves determined by the hybrid method.

## 1. Introduction

Nowadays, steel plates over 30–40 mm thick are widely used in marine structures. Plate thickness is regarded as one of the parameters that control the Fatigue Crack Growth Rate (FCGR) [1–4]. With the thickness increasing, the FCGR accelerates [1,5], and the acceleration becomes significant when the load is random [6]. Therefore, it is necessary to investigate the FCGR in thick plates for the fatigue strength assessment on thick-welded structures under the action of random sea waves.

Some researchers have investigated the effect of specimen thickness on the FCGR. Liu [7] pointed out that the FCGR should be implicitly represented by the range of stress intensity factor, $\Delta K$, stress ratio, $R$ and thickness, $B$, where $\Delta K$, $R$ could represent the cyclic stress and strain around the crack tip, if the plate is thick enough to keep the crack in plane strain state. Schijve [8] attributed

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**Nomenclature**

| | |
|---|---|
| $a$, $a_0$ | crack length (crack depth for surface cracks), initial crack depth |
| $\delta a$, $\Delta a$ | difference of crack lengths at surfaces, crack length increment |
| $a/c$ | crack aspect ratio |
| $B$, $S$, $W$ | thickness, span, width of the specimen |
| $c$, $c_0$ | half of the surface crack length, initial crack length |
| $C$, $m$ | material constants of Paris law |
| $d$ | crack front shape parameter, Fig. 16 |
| $E$, $G'$, $\mu$ | elasticity modulus, shear modulus, Poisson's ratio |
| $J$, $G$ | $J$-integral, elastic energy release rate |
| FCGR | fatigue crack growth rate |
| $\Delta K$, $K_{max}$, $\Delta K_{th}$ | SIF range, maximum SIF, fatigue crack growth threshold |
| $\Delta K_{eq}$, $\Delta K_{FEM}$ | SIF calculated by equation, FEM |
| $N$ | number of cycles |
| $P$, $P_{\min}$, $P_{\max}$ | applied load, minimum load, maximum load |
| $r_p$ | plastic zone size |
| $r_{1/4}$ | distance between the 1/4-node and the crack front |
| $R$ | load ratio |
| SE(B) | single edge notched bending specimen |
| SIF | stress intensity factor |
| $t$, $w$ | plate thickness, width of the welded joint |
| $u_{1/4}$ | displacement of 1/4-node normal to the crack surface |
| $x$, $y$, $z$ | Cartesian coordinates |
| $\alpha$ | $a/W$ |
| $\alpha_g$, $\alpha_l$ | global, local constraint factor |
| $\theta$, $\rho$ | weld toe angle, radius |
| $\sigma_y$, $\sigma_{ys}$, $\sigma_u$ | stress normal to crack surface, yield stress, ultimate stress |
| $\Delta\sigma_n$ | nominal stress range |

the thickness effect to the difference of plastic zone sizes in thin and thick specimens under similar $K$ conditions, and suggested that the FCGR should be obtained with specimens of similar thickness as used in the structure. All the above studies on thickness effect concern with the stress state around the crack tip, and the stress state associated with specimen thickness has a major influence on fatigue crack growth behaviour [9].

The fatigue crack growth mechanism in different stress states was originally studied by FCGR data from a series of specimens with different thickness, in which the plane stress state is achieved with thin specimens, and the plane strain state is achieved by increasing the specimen thickness. However, for a through-thickness crack, the plane stress state exists near the surface and the plane strain state dominates in the interior region [9]. Moreover, the stress state along the crack front changes with the load level and crack propagation [4,10,11]. As a result, complex stress state always exists for practical crack, making it difficult to evaluate the stress state effect on the FCGR, if the crack is considered as a whole. In order to overcome the difficulty, a new approach is proposed, which consists of marking a series of three dimensional crack fronts to determine the $da/dN$ of different stress states, evaluating the stress state quantitatively along the crack front during the crack propagation and computing the driving forces, $\Delta K$ of different stress states.

Marking crack fronts are essential for three-dimensional crack growth behavior analysis. Branco et al. [12] proposed a 3-step reverse engineering technique to determine Paris law constants in round bars from beach marks on fracture surface and the experimental beach marks are obtained by reducing the fatigue load to one-half for several cycles. Putra et al. [13] developed a crack opening stress measurement technique based on the load sequence through electron fractography, and the marking load which has the same $P_{\max}$ as in the crack propagation phase and a higher $R$ ($R = 0.9$) was applied. In the present study, a static load marking method is proposed and eleven crack fronts were marked. The crack growth direction is defined as normal to these crack fronts, which is widely applied in many three-dimensional crack growth simulations [9,12,14,15], and thus the increments at any region along crack fronts could be obtained based on the profile of crack fronts.

To achieve plane strain conditions, specimens were usually machined on each side with a groove along the fatigue crack path [16]. Branco et al. [9] proposed a notched middle tension specimen with lateral side grooves to reduce the size dominated by plane stress at surface regions. The ratio of the out-of-plane stress component to the sum of the other in-plane stresses, which is called constraint factor, was usually used to represent the degree of plane strain in literature. Kwon and Sun [17] obtained the degree of plane strain distributions near the through-the-thickness crack front after elastic three-dimensional finite element analyses based on the factor. Two-dimensional crack global constraint factor ($\alpha_g$) to evaluate the stress state effect was proposed in the modified strip yield model of Newman [2]. The $\alpha_g$ is defined as the ratio of the averaged normal stress to yield stress in the plastic region. Elastic-plastic finite element analysis of through-thickness crack in finite thickness plates for an elastic-perfectly plastic material was carried out and the $\alpha_g$ equation was fitted [4]. Shen and Guo [18] proposed an effective thickness, which could be used to calculate the local constraint factor at different positions of the crack front based on the $\alpha_g$ equation developed by Guo et al. [19]. In this study, a local constraint factor $\alpha_l$, which is the ratio of the averaged normal stress to yield stress ratio at local plastic region along the crack front, is proposed and applied to evaluate the local stress state.

For three-dimensional cracks, the stress state should be assumed in the Stress Intensity Factor (SIF) calculation. Two commonly used assumptions are: plane stress for the free surface, plane strain for the non-surface [12,14,15], and plane strain for the whole crack front [20]. If the stress state along crack fronts can be determined quantitatively, the stress state assumption is unnecessary. In the present study, the local stress state is evaluated by local constraint factors, and then various methods including the 1/4-node displacement method, $J$-integral method and the virtual crack closure technique are used to calculate the SIF. The results are compared to check the performance of the methods in dealing with the actual cracked body problem.

One of the most common applications of the FCGR curves of different stress states may be the analyses of surface crack growth behaviour. The variation in fatigue resistance along crack front due to the variation in stress state should be taken into account, because it has a major impact on the crack shape and fatigue life [21]. A classical approach to consider this effect was proposed by Newman and Raju [22]. The surface cracks are assumed to be semi-elliptical and the surface point and deepest point that control the