Influence of Stress State, Strain Hardening and Load Ratio on Plasticity-induced Fatigue Crack Closure

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ABSTRACT

A center-crack panel subjected to cyclic loading has been analyzed using a finite difference program. The influence of stress state (plane stress or plane strain), strain hardening capacity of the material and the load ratio on plasticity-induced fatigue crack closure has been studied. The results show that the crack opening load is highly dependent upon residual stress distribution behind the crack tip. The evolution of crack opening load in different conditions is obtained from numerical calculations.

KEYWORDS

Fatigue crack closure; crack tip plasticity; residual stresses.

INTRODUCTION

Crack closure during fatigue crack propagation is dependent upon the material microstructure and test environment as well as upon the mechanical properties of the material and loading conditions. While the influence of the former factors has been experimentally evaluated, the latter ones may be analyzed by numerical simulations. Studies about the influence of mechanical properties on plasticity-induced crack closure have been performed using finite element programs with implicit solution schemes (Newman, 1976; Newman, 1981; Nakagaki *et al.*, 1979; Blom *et al.*, 1985; Fleck, 1986). All of them include specific algorithms to propagate the crack during the analysis and to solve contact problems between the crack faces. Recently, the authors have shown that calculation programs based on the finite difference method and explicit solution schemes may be used for a simple analysis of crack closure. Using sophisticated procedures to simulate the crack propagation and the contact problems are not required (LLorca *et al.*, 1988).

In the case of programs with explicit schemes, convergence is ensured if Courant´s condition is fulfilled. Mechanically, such condition requires that the integration time interval must be shorter than the time elapsed by the pressure wave travelling between the two closest nodes of the mesh (the equations of motion are then uncoupled). In the zone close to the crack tip, the mesh must be fine enough to simulate accurately the high stress gradients and thus the integration times are quite reduced. On the other hand, the achievement of reliable values of the crack opening load (P_{op}) involves the analysis of crack propagation during several loading cycles. Therefore, the utilization of high frequencies (between 100 and 1000 Hz) is necessary to achieve valid results using reasonable computation times. Although such frequency values are quite high for laboratoty tests, there are many industrial devices (airplane engines, turbines, etc.) where frequencies between 100 and 500 Hz are often observed.

A computation program of this kind has been used to analyze plasticity-induced fatigue crack closure in a center-crack panel in both plane stress and plane strain conditions, with different values of the load ratio $R = P_{min} / P_{max}$ and elastic-plastic materials with different strain hardening capacity.

THE FINITE DIFFERENCE MODEL.

Calculations have been performed with a 2-dimensional finite difference general program, named PR2D (Principia, 1987). The program utilizes a lagrangian mesh and takes into account non-linearity due to large strains; constitutive equations of the material simulated are displayed in Fig. 1.

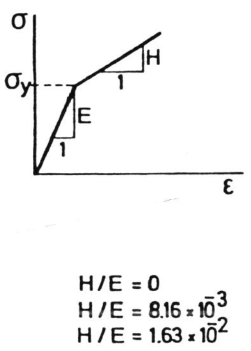

Fig. 1. Constitutive equations

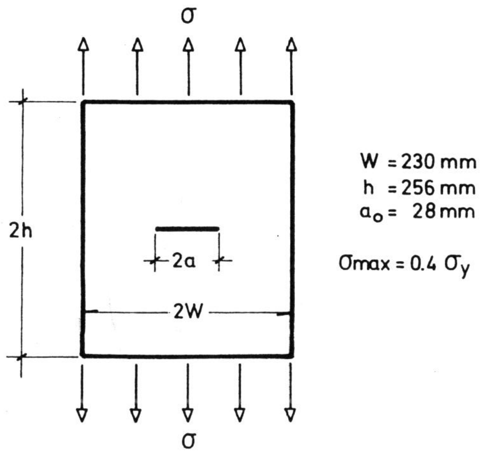

Fig. 2. Center-crack panel.

Yield stress σ_y is 350 MPa and Young´s modulus E is 70 GPa both in tension and in compression. Those values have been chosen, being usual for high strength aluminum alloys of series 2000. Three different materials have been simulated with different plastic behaviour. The first one is elastic-perfectly plastic while the other two exhibit linear strain hardening. The stress wave has frequency of 400 Hz and triangular shape. For all calculations, the maximum stress applied was 40% of yield stress. For such values of the stress and frequency, the strain rate is about 4 s^{-1}, not so high to produce meaningful changes on the mechanical properties of the material.

Figure 2 illustrates the general dimensions of the center-crack panel used in the analysis. The initial crack length a_0 was 28 mm. Figure 3 illustrates the mesh used. Due to the symmetry of the problem one fourth of the body has been modelled. The mesh includes 85 nodes and 131

elements. Elements used were triangles of constant strain. Element size near the crack tip was 0.5 mm. Convergence analysis carried out with finer meshes (Newman, 1976; Llorca *et al.*, 1988) allow to conclude that such element size is fine enough for accurately modelling crack closure for the maximum stresses applied while keeping computation times into acceptable ranges.

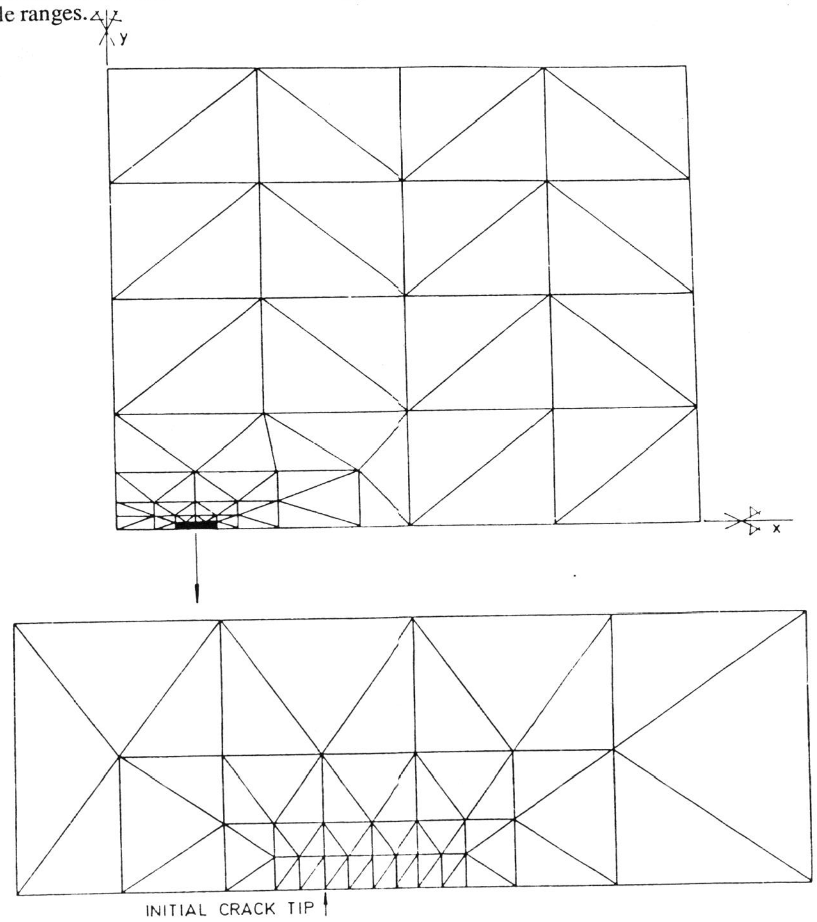

Fig. 3. Finite difference mesh used for the analysis.

In plane strain calculations, a mixed discretization procedure was utilized to avoid the problem of plane strain locking, which might occur when triangles of constant strain are used (Martí *et al.*, 1982).

Crack propagation was simulated by releasing the node placed in front of the crack tip when reaching the maximum load in each cycle. When a node was released, the corresponding reaction decreases rapidly to zero and the crack opens very fast. At the begining of the unloading slope, the crack starts its closing. When a compressive reaction is produced in the node released, crack closure is taking place, giving the value of P_{cl}. When the external load is increasing again, after reaching the minimum value, the magnitude of the reaction at the node diminishes. Crack opening is detected when the reaction vanishes and P_{op} is thus achieved.

Considering those two values (P_{cl} and P_{op}), P_{cl} is mainly determined by the size of the element placed in front of the crack tip, the smaller is the element size, the greater is P_{cl} (Fleck, 1986; Llorca *et al.*, 1988). On the contrary, the crack opening load P_{op} lead to a constant value when the elements placed near the crack front are small enough to adequately simulate the high stress and strain gradients (Newman, 1976). Therefore, the parameter utilized to represent the magnitude of crack closure is Pop.

Contact problem between crack faces is solved by introducing the requirement that nodes cannot penetrate into the region x < 0 (Fig.3). Such type of condition is easy to implement in programs with explicit integration (Principia , 1987).

INFLUENCE OF STRESS STATE

Figure 4 illustrates the curves crack opening load P_{op} vs crack length increment for plane stress and plane strain conditions. In the same figure, the results of Fleck (1986) for plane strain and Newman (1976) for plane stress with the same body geometry (center-crack panel) have been plotted. In all cases, materials used are elastic-perfectly plastic with no strain hardening and load ratio equal to zero. As can be seen, P_{op} increases with crack propagation, achieving a stationary value when the crack has grown about 2 mm for plane stress and 1 mm for plane strain.

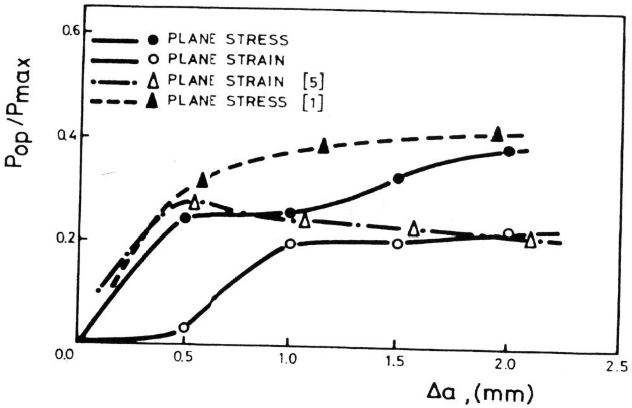

Fig. 4. P_{op} load *vs* crack increment. R = 0.

Figure 5 illustrates crack opening displacement at maximum load for two different cases: when the initial crack length is a=30 mm and when the crack has propagated by fatigue from an initial value a_0=28 mm up to that value of 30 mm. The striped area between both curves represents the residual plastic strain produced in the material placed over the crack. Such residual strains are produced during unloading of the material placed in that region when the crack propagates. Figure 6 shows similar curves for plane strain conditions.Therefore, it can be concluded that crack closure is controlled by the magnitude of plastic strains ahead of the crack tip. When higher values of plastic strain are achieved, the period of the stress cycle for which the crack remains closed is longer.

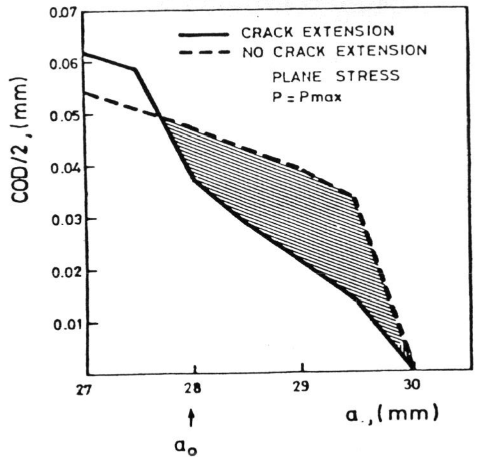

Fig. 5. Displacements distribution behind crack tip. Plane stress.

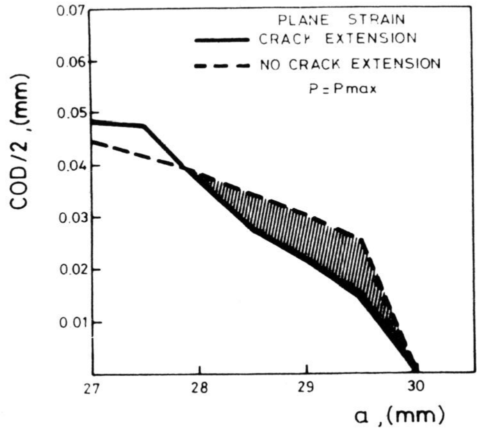

Fig. 6. Displacements distribution behind crack tip. Plane strain.

Plastic strain produced near the crack tip in plane stress is about 10%, while in plane strain is about 3%. Such difference gives an explanation of the results shown in Fig.4, where higher values of the opening load in plane stress are observed. From the point of view of numerical analysis, it is necessary to compute accurately plastic strains near the crack front. This requirement involves that the ratio between element size and plastic zone size must be reduced. In our analysis such ratio is 0.11 and the results obtained are similar to those obtained by other authors using more refined meshes. On the other hand, when the maximum stress in a cycle is increased (and thus the plastic zone is greater) coarser meshes may be used and viceversa.

Figure 4 shows also that the crack opening load P_{op} increases from zero for Δa equal to zero up to a stationary value for Δa about 1 mm in plane strain and about 2 mm for plane stress. It can be seen in Fig. 5 and 6 that residual plastic strains are highest in a zone placed some 1 mm apart from the crack tip in plane strain and 2 mm in plane stress. Such results show that crack closure is concentrated on a small area placed backwards of the crack tip. The same conclusions have been derived by other authors from experimental results (Breat *et al.*, 1983; Minikawa *et al.*, 1983).

Although the P_{op} values determined for plane strain and plane stress are different, the mechanism controlling crack closure is the same for both loading conditions. During unloading, the crack closes progressively, starting at the zone near the crack tip. During the next loading step, the crack opens following the reverse path of the preceding closing.

INFLUENCE OF STRAIN HARDENING

Three calculations in plane stress and three calculations in plane strain have been performed with materials whose stress-strain curves are sketched in Fig.1. The load ratio was zero, and the maximum stress in a cycle $0.4\sigma_y$. Figure 7 illustrates the results of P_{op} vs. crack length increment. In plane stress, the strain hardening has a great influence on P_{op} while in plane strain the three curves are nearly coincident.

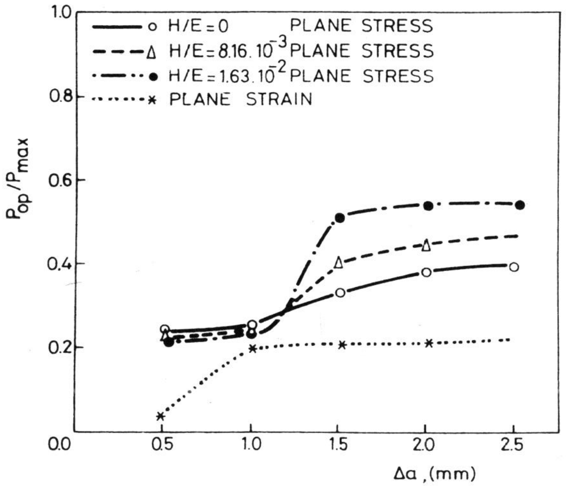

Fig. 7. P_{op} load *vs.* crack increment. Materials with different strain hardening.

For material with higher strain hardening capacity, plastic strains near the crack tip are lower. Therefore, according to the results outlined above, materials with higher strain hardening slope H, must show a less pronounced crack closure. However, the results illustrated in figure 7 show the opposite in plane stress and no influence in plane strain. Such different behavior might be explained if the factors influencing the opening load P_{op} are analyzed deeply.

Figures 8 and 9 illustrate compressive residual stresses produced on the crack face after unloading in plane stress and plane strain respectively. Thereafter, loading starts again. The crack will open when the applied load reaches the value for which the stress intensity factor due to the combination of external load and residual stresses is zero (Llorca *et al.*, 1987).

Consequently, the crack opening load P_{op} will be higher when the length of the zone affected by compressive residual stresses will be greater and the magnitude of such residual stresses is higher. For a material with no strain hardening (H/E=0), the zone affected by residual stresses and their magnitude is only dependent on residual plastic strains. For a material with strain hardening, residual plastic strains are lower and the zone affected by compressive residual stresses is smaller. However, during unloading, compressive yielding may occur for the material placed backwards of the crack tip (for instance, in plane stress) and in that case the strain hardening capacity would produce higher compressive residual stresses (Fig.8). For such cases the crack opening load will be higher. In plane strain, however (Fig.9) compressive yielding during unloading is not reached and the magnitudes of residual stresses are thus quite similar for all materials studied. Therefore, crack opening load P_{op} is fairly independent on strain hardening capacity of the material for a load ratio R=0. For negative values of the stress ratio, when compressive yielding takes place, the behavior in plane strain is expected to be similar to that in plane stress.

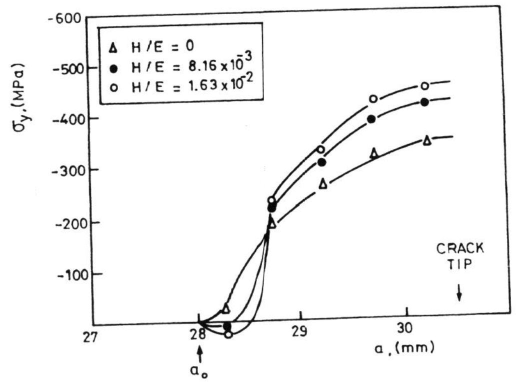

Fig. 8. Residual stresses behind crack tip. P = 0

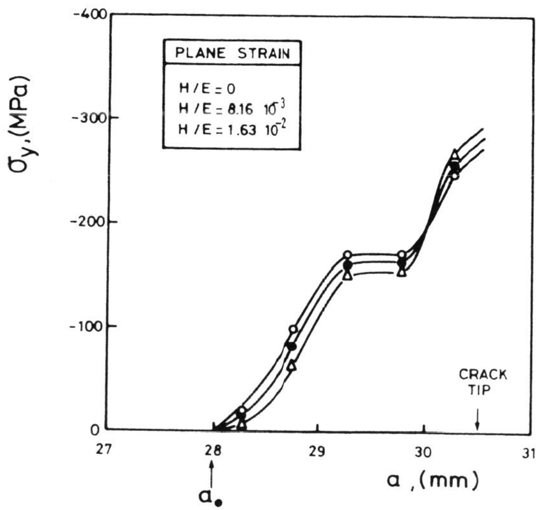

Fig.9. Residual stresses behind crack tip. P = 0

INFLUENCE OF LOAD RATIO

To analyze the influence of load ratio R on crack closure, three calculations in plane stress and three calculations in plane strain have been carried out with load ratio values of 0, 0.3 and 0.5. In all cases the elastic-perfectly plastic material was chosen for the analysis. Table 1 shows the stationary values of the crack opening load P_{op} for all calculations performed. The non-dimensional quantity U, effective amplitude of the stress intensity factor, has also been included in the table. This quantity is defined as follows:

$$U = \frac{\Delta K_{eff}}{\Delta K} = \frac{K_{max} - K_{op}}{K_{max} - K_{min}} = \frac{P_{max} - P_{op}}{P_{max} - P_{min}} \quad (1)$$

Table 1. Evolution of opening load and effective amplitude of the stress intensites factor with load ratio.

	Plane stress			Plane strain		
Load ratio R	0.00	0.30	0.50	0.0	0.30	0.50
P_{op} / P_{max}	0.39	0.55	0.62	0.23	0.36	< 0.50
U	0.61	0.66	0.75	0.77	0.92	1.00

The results achieved show that in plane stress the stress intensity range is affected by crack closure even for R values over 0.5. On the contrary, in plane strain crack closure has little influence for R values over 0.3 and vanishes for R=0.5. These results are quite similar to those obtained by Blom and Holm with compact specimens (Blom *et al.*, 1985) (Fig.10).

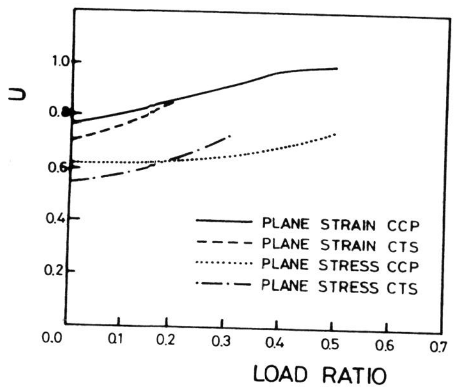

Fig.10. Influence of load ratio on effective stress intensity factor range.

CONCLUSIONS

A dynamic analysis of plasticity-induced fatigue crack closure has been performed. The influence of stress state, strain hardening capacity of the material and the load ratio on the crack opening load has been analyzed.

The results obtained lead to the conclusion that crack closure is produced by residual plastic strains produced in a region placed backwards of the crack tip when the crack propagates. The phenomenon is more pronounced in plane stress than in plane strain because plastic strains are higher. Strain hardening has no influence on crack opening load in plane strain. On the contrary, in plane stress, the crack opening load increases for higher strain hardening capacity. Finally, the influence of load ratio on the effective stress intensity range has been evaluated, both in plane stress and in plane strain.

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