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FATIGUE BEHAVIOUR OF STRUCTURAL COMPONENTS AT THRESHOLD

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ABSTRACT

The present paper investigates the influence of several variables on the fatigue behaviour of cracks at therashold. Variables considered are crack size, mean stress, crack closure and type of loading. Several fracture mechanics models are developed to simulate the effects of such parameters on the fatigue therashold. The accuracy of these models were tested using wide range of experimental data. The present work plays an important rule in design against long life fatigue of structural components.

1. INTRODUCTION

The fatigue limit as a tool for design of structural components subjected to cyclic loading has been most successful. However, in circumstances where defects preexist or are created in service a somewhat different approach is required. This can involve the concept of an arrested crack or a crack with an extremely low growth rate. If the crack is in a well defined stress field then a threshold stress intensity range, ΔK_{th}, can be a assigned to the crack such that ΔK_{th} must be exceeded for substantial crack growth to occur as shown in Fig.1.

A fair amount of research has been devoted to the near threshold regime. The need for such studies has been motivated by the fact that, the concept of fatigue threshold is utilised in design or for fracture control procedures such as in analyses of bridges, nuclear plants, ships, airoplanes, cars,etc. There are now exist in the literature results on the near threshold fatigue crack growth behaviour of a wide range of engineering materials, including observations on the specific role of such variables as load ratio, crack size, microstructure, geometry, crack closure, type of loading and cyclic

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material properties.

It is the objective of the present paper to discuss the significance of some of the above mentioned variables on the fatigue behaviour of structural components at threshold. The use of fatigue threshold concept in design is also described.

EFFECT OF CRACK SIZE ON THERASHOLD

Therashold behaviour of the material as measured by $\Delta\sigma_{th}$ or ΔK_{th} was found to be dependent on the size of the crack (1), i.e. ΔK_{th} that describe therashold level is only unique for any value of therashold stress range ($\Delta\sigma_{th}$) for long cracks. However for cracks smaller than certain size, for a given material and stress conditions, therashold stress intensity range (ΔK_{th}) was found dependent of crack size. Such behaviour is well represented in fig.2 for variety of steels collected from literature (2). In this figure the therashold value for a given crack size is normalized by dividing by the crack therashold value for certain crack size with the constant long crack therashold value. The calculation of therashold values was based on the following equation:

$$\Delta K_{th} = F\ \Delta\sigma_{th}\sqrt{\pi \ell} \qquad (1)$$

where F : geometry dependant factor (= 1)

$\Delta\sigma_{th}$: therashold stress range at a given crack size

ℓ : crack size.

This figure indicates that for longer cracks (larger than 1mm) the therashold level is constant. However for shorter cracks the therashold value decreases as crack size decreases. This indicates that crack growth behaviour for short cracks is different from long cracks. In fact short cracks was found to grow faster than long cracks for the same nominal ΔK value. In view of this, one of the authors (1) have modified equation (1) to account for the behaviour of short cracks by introducing a material constant (ℓ_o) into equation (1) as follows:

$$\Delta K_{th} = F\ \Delta\sigma_{th}\sqrt{\pi(\ell + \ell_o)} \qquad (2)$$

For steels a value of ℓ_o equal to 0.24mm was quoted and a result of this small value, ℓ_o can be ignored for long cracks. However for small cracks ℓ_o leads to higher ΔK values than the nominal values in equation (1).

The therashold stress at a very short crack length is shown to approach the fatigue limit of the material ($\Delta\sigma_e$) based on smooth specimen tests (1), and from equation (2) the therashold stress intensity can therefore be obtained by:

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$$\Delta K_{th} = F\, \Delta\sigma_e \sqrt{\pi \ell_o} \qquad (3)$$

or

$$\ell_o = \frac{1}{\pi F} \left(\frac{\Delta K_{th}}{\Delta\sigma_e}\right)^2 \qquad (4)$$

at any crack length ℓ, the therashold stress is then obtained through equation (2) as

$$\Delta\sigma_{th} = \frac{\Delta K_{th}}{F\sqrt{\pi(\ell + \ell_o)}} = \frac{\Delta\sigma_e}{F}\sqrt{\frac{\ell_o}{\ell + \ell_o}} \qquad (5)$$

Fig.(3) represents experimental results (3) obtained for mild steel compared with predictions based on equation (5). Such prediction adequately describes the influence of crack size on therashold stress. For crack sizes smaller than 1 mm the term ℓ_o constitutes an increasingly important fraction of the effective crack length, resulting in an increasing deviation of the therashold stress range from the more usual prediction of equation (1) without ℓ_o as clearly indicated in figure 3. Data presented in fig. (2) could be modified based on equation (2) and the expected result is constant ΔK_{th} to be independent of crack size due to the incooperation of the term ℓ_o that accounts for short crack behaviour.

LONG AND SHORT CRACK BEHAVIOURS

The term ℓ_o which modifies the stress intensity appears to account for the differences in behaviour between short and long cracks. Such differences could be summarized as:

a- Crack Front Geometry.

Front of short cracks are generally straight or slightly curved lines but for long cracks the front is slightly irregular and the length of crack front is relatively larger, as a result the material resistance to cracking increases.

b- Resistance to Slip.

Short cracks usually have low resistance to slip due to the effect of free surface. However, resistance to slip for long cracks is more difficult due to the present constraints in the bulk of the material. It should be also noted that the number of active slip systems required for short cracks is only one, but for longer cracks, at least two active slip systems are needed and in this case more resistance to slip is available.

c- Plasticity in the Wake of the Crack.

For short cracks such plasticity is limited, however, it is relatively large for long cracks. As a result crack closure will be limited in case of short cracks and evident for long ones.

Therefore the effective stress intensity is always larger for the short cracks compared with longer ones.

d. Fracture Surface Topography.

Unfortunately no much information in the literature documents the fractography of short cracks, however, fracture surfaces for long cracks are not flat and contains rough topography that facilitates crack closure and reduces the effective stress intensity resulting a slower fatigue crack growth. As yet there is no analytical method for combining the above effects as well as aspects of material inhomogenity (as elastic anizotropy, inclusions, grain boundaries and material surface layer conditions on the behaviour of short cracks). The imperical calculation of the term ℓ_o (equation 4) provides an accurate predictions of crack propagation behaviour.

Since ℓ_o is dependent on the values of therashold stress range and the fatigue limit, therefore, factors which may influence these parameters may also affect the magnitude of ℓ_o as follows:

a- Strength level of the material
b- Mean stress
c- Stress history

These three factors will be discussed in details in the following sections:

Effect of Strength Levels on Therashold Behaviours.

Recent observations have shown that (1,4) material strength and the scale of microstructure can influence the therashold stress intensity and near therashold crack propagation rates as well as the fatigue limit. An increase in therashold values has been observed in lower strength steels as the yield stress decreases. Other investigators have shown that the therashold level for low carbon steels and titanium alloys increases with grain size (1). This increase in therashold level with grain size is the reverse in the decrease in yield stress and fatigue limit with grain size. To investigate the effect of strength on therashold levels and fatigue limits, SAE 1010 mild steel was subjected to different cold rolling levels (5). The annealed steel was cold rolled to three levels correspond to a reduction in thickness of 22, 56 and 76%. The resulted Brinnel hardness numbers (BHN) were 122, 160 and 195 respectively as compared with BHN of 86 for the annealed steel. Table I summarizes the therashold stress intensity range for the annealed and cold rolled specimens. These results clearly indicate that ΔK_{th} decreases and fatigue limit increases simultaneously with cold working. The therashold behaviour of the preexisting crack in a cold rolled metal can be described using equation (5). In fig.4 this equation is plotted for materials A and D. Also shown for each metal condition are therashold data for long cracks and for a crack approaching zero length (fatigue limit). Equation (5) predicts the thera-

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shold data very well. If a small preexisting crack in the order of 0.001 mm was present in both metals a higher therashold stress would be required for near therashold crack propagation in metal D than in metal A. In fact, metal D would provide a greater therashold stress resistance to crack propagation so long as the preexisting crack size did not exceed 0.2mm. However, for crack sizes greater than 0.2mm metal A would provide a higher therashold stress resistance to crack propagation. These results are significant in the manufacture of components to resist high cycle fatigue since the optimum level of cold rolling will depend upon whether the design is to be based on crack initiation or propagation of preexisting flaws.

EFFECT OF MEAN STRESS AND STRESS HISTORY ON THERASHOLD BEHAVIOUR.

Effect of Mean Stress:

Several investigations have been conducted to study the effect of mean stress and stress ratio on fatigue therasholds. Fig.5 presents data published by various investigations on therashold stress intensity factor values of structural steels (6, 7). The figure indicates that as cyclic stress ratio(R) increases, ΔK_{th} decreases substantionally. The data show that concervative estimates of ΔK_{th} for steels can be predicted from

$$\Delta K_{th} = \Delta K_{th(R=0)} \; (1-0.85R) \qquad (6)$$

where $\Delta K_{th(R=0)}$ is the therashold value of the stress intensity range at R=0.

Effect of Compressive Overloads:

In a recent study ΔK_{th} is shown to depend on the type of random loading (8). It is shown that compressive overload may decrease the steady state therashold level and accelerate crack growth for subsequent small cycles. Overload crack growth results presented in fig.6 indeed varify this postulation. This figure shows that at low growth rates, accelerated crack growth and a lower therashold stress intensity presist for a large number of zero-tension cycles following a single compressive overload of a magnitude about one half the yield strength of the material. Even after 200,000 cycles therashold values still greatly reduced. These results suggest that current methods of estimating crack growth rates in variable amplitude fatigue may be sericely unconservative when the load history contains large numbers of small cycles. Conditions in which short cracks grow out of connections are often accompanied by high compressive stress cycles which can accelerate crack growth during many subsequent small tensile stress cycles. Similarly, it appears largely nonconservative to neglect small cycles in damage calculations when considering variable amplitude load histories. Because test results shown in fig.(6) indicate that these small cycles well below the constant amplitude stress intensity therashold can cause crack growth following compressive overloads.

As K_{max} increases the effect of compressive overloads becomes less important. For concervative design procedure, curve corresponding to n=1 shown in fig.6 should be considered. Fig. (7) shows the effect of compressive overload (n=1) on the therashold behaviour of G40.11 structural steel (8). As S_{min} increases in compression, the maximum therashold stress intensity decreases. The same phenomena is also presented in fig. (8). This phenomena can be best explained interms of crack closure. As S_{min} increases in compression the opening stress of the crack decreases. This lead to a larger value of the effective stress intensity.

$$\Delta K_{eff.} = \Delta K_{applied} - \Delta K_{opening} \qquad (7)$$

The above mentioned phenomena could be also explained if the applied stress (or maximum stress intensity) at therashold is plotted vers the applied minimum stress as shown in fig. (9). Such plot is analogous to the known Goodman diagram for fatigue. In the present figure (9) actual data on mild steel were plotted where two regimes exists; the first when ($R \geq 0$) represents tensile mean stress effect; where the second ($R < 0$) crack closure phenomena domenate the behaviour. Generally the boundary between these two regimes is not necessary located at zero minimum stress; in many cases it was reported (9) that crack closure may be extended to values of R larger than zero. The effect of the tnesile mean stress was described by equation 6, could also be described by a better model (10) as follows:

$$S_{eff} = \Delta S \sqrt{\frac{1-R}{1+R}} \quad \text{at therashold}$$

$$\text{for } R > 0 \qquad (8)$$

Such equation fits the data well as shown in fig.9. Other models describe this field may also be located in reference (6).

When crack closure is possible, not all of the applied stress is effective in propagation cracks. As was discussed above there is clear evidence that some fraction of the compressive part of the stress cycle is contributing to crack propagation. An assumption is needed to predict the opening stress level as a function of the minimum stress level. It was proposed that such level is one third the minimum stress level (10) as shown in fig.(9). It is interresting to notice that the opening line based on the above mentioned proposal is parallel to the maximum stress line for the presented mild steel data which indicates that the effective stress range is constant and independent of the minimum stress level. The effective stress range $\Delta S_{eff.}$ can therefore be predicted using the following

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equation:

$$\Delta S_{eff.} = \sqrt{\frac{1 - \frac{1}{3} R}{1-R}} \cdot \Delta S \qquad (9)$$

The above mentioned model assumes that crack closure only occurs at negative values of the stress ratio R. More data is certainly needed to varify such assumptions and determine the point on the diagram (fig.9) where crack closure is possible. Certainely the proposed one third assumption of the opening stress is not expected to be always true for different materials. More work is needed along this idea to varify such assumption.

CONCLUSIONS

Several variables affecting fatigue therashold behaviour was discussed. Fracture mechanics model was developed to simulate such effects as mean stress, crack size, crack closure and type of loadings.

Table I: Effect of cold rolling on hardness, fatigue limit ΔK_{th} and ℓ_o for SAE 1010 mild steel.

Material Designation	A	B	C	D
% Cold work	0	22	56	76
BHN	86	122	160	195
$\frac{\Delta\sigma_e}{2}$ (MPa)	177	207	269	303
ΔK_{th} (MPa $\sqrt{m}$)	12	-	8	4
ℓ_o (mm)	0.8	-	0.08	0.02

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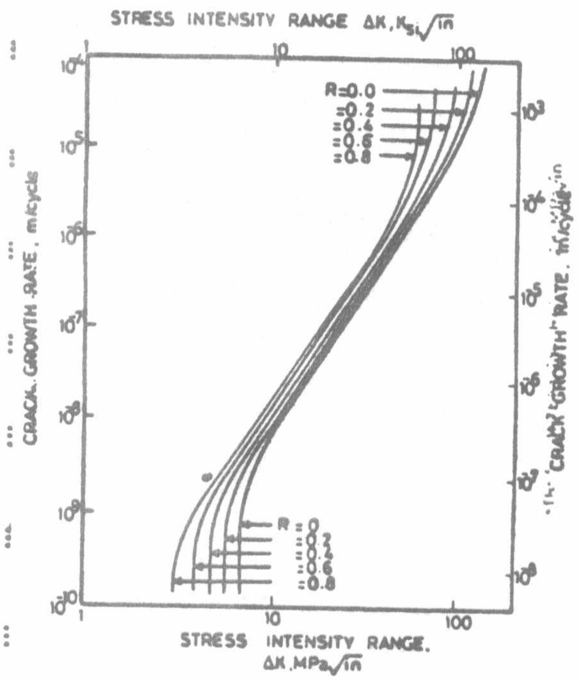

Fig.1. Dependency of crack growth rate on the applied stress intensity and mean stress.

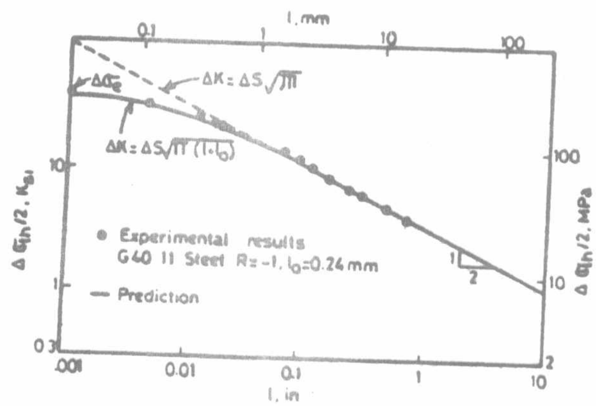

Fig.3. Influence of crack size on the therashold stress range.

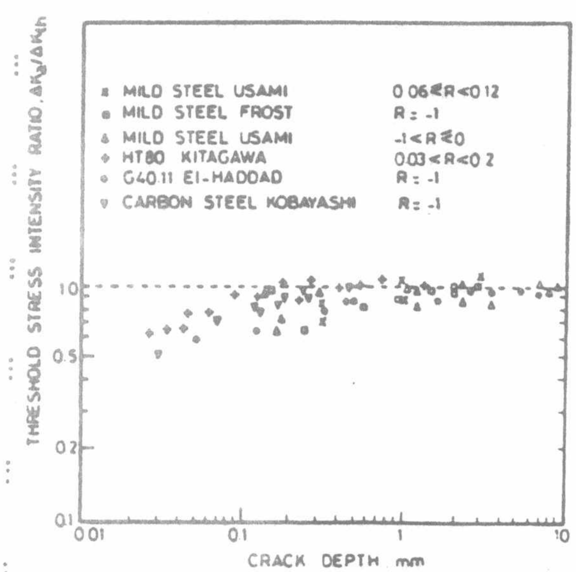

Fig.2. Relationship between crack depth & therashold stress intensity ratio $\Delta K_a/\Delta K_{th}$.

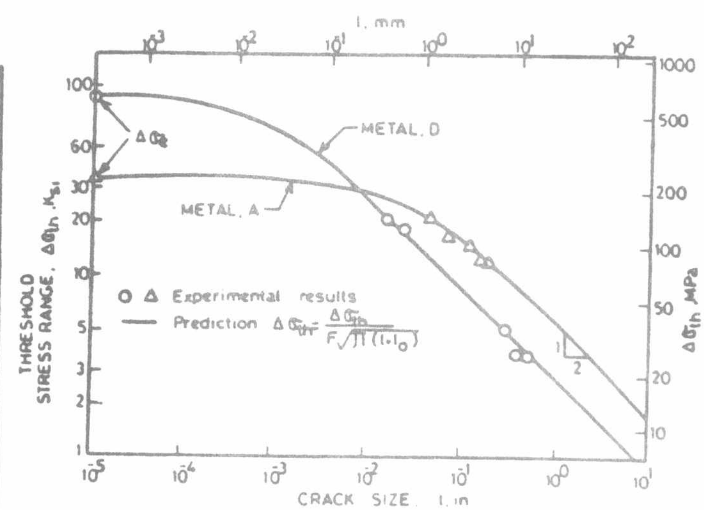

Fig.4. Dependency of therashold stress range on crack size for annealed(A) and cold rolled (D) ASE 1010 mild steel.

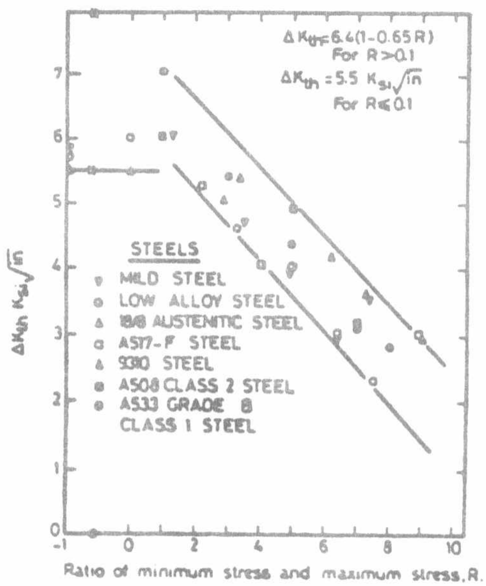

Fig.5. Effect of stress ratio on ΔK_{th}.

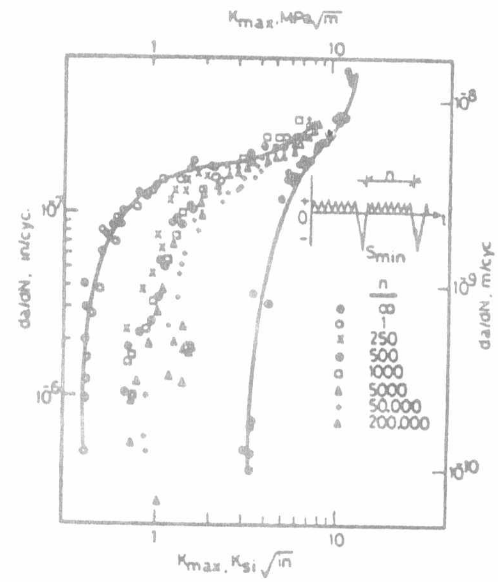

Fig. 6. Effect of compression cycles on crack growth behaviour of G40.21 steel.

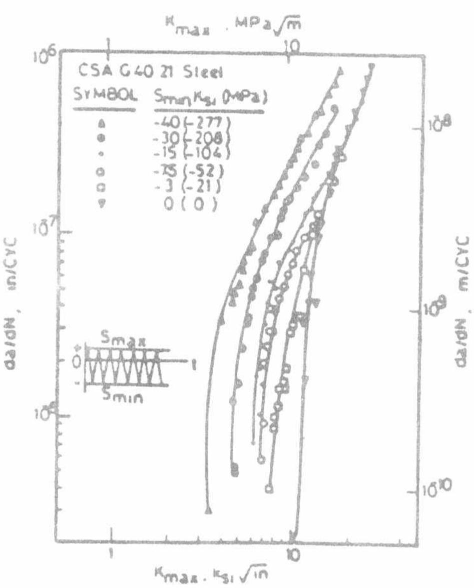

Fig.7. Effect of comparessive stress level on therashold behaviour of G40-21 steel.

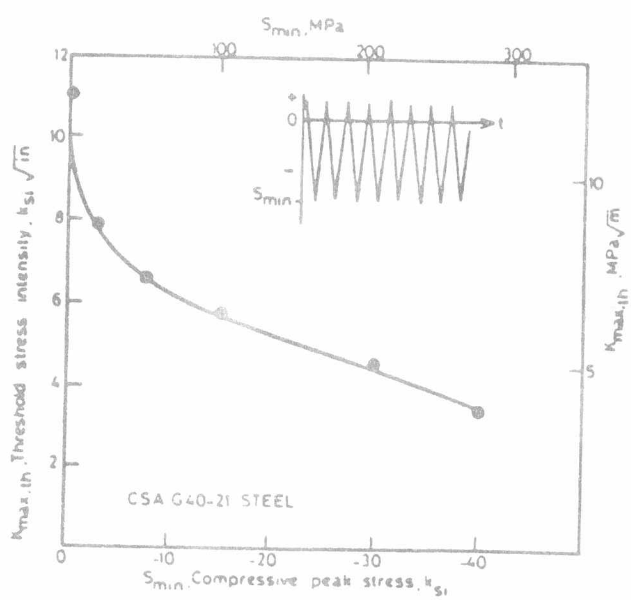

Fig.8. Relationship between S_{min} and $K_{max,th}$ for G40.21 steel.

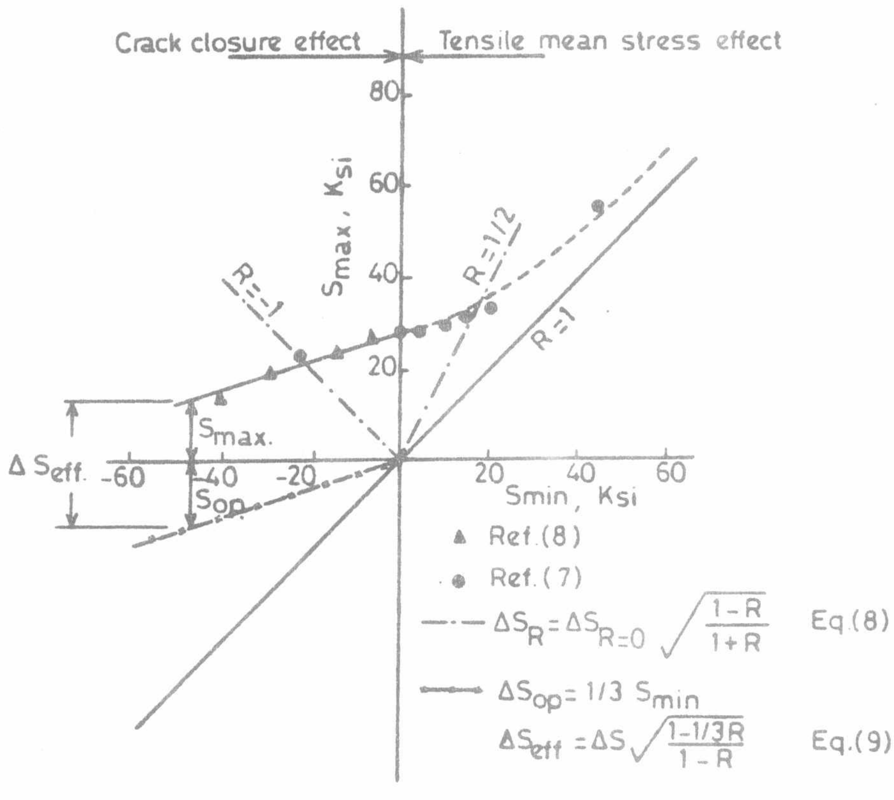

Fig.9 Relation between ΔS_{eff} and mean stress.