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PREDICTION OF FAIL-SAFE STRENGTH OF REALISTIC STIFFENED SKIN AIRCRAFT STRUCTURES

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INTRODUCTION

An aircraft structure mainly consists of plain sheet or built-up sheet structures. During the operational life of the aircraft cracks may arise in these structural elements. Due to service loadings these cracks may extend to a considerable size and even lead to failure of a component. However, in spite of the presence of cracks or partial failures a safe operation of the aircraft must be warranted. To achieve this a number of precautions can be taken. First of all, the structural design can be made such that the damage can be detected with a certain amount of certainty during regular inspections. Further, it can be demanded that when the damage still remains undetected at a certain inspection, during the subsequent inspection interval the crack either will not progress to a critical (= unstable) size due to fatigue loading or peak loads or will be arrested by adjacent elements if unstable crack growth occurs. A structure that meets these requirements is called fail-safe.

The designer of a fail-safe structure has the task, apart from designing easily inspectable structures, to evaluate in the design stage of the aircraft the merits of potential designs as to their crack growth (stable and unstable) and crack arrest properties in order to fulfil the airworthiness requirements. Further, a specified fail-safe strength has to be demonstrated by the designer. The present paper discusses how the fail-safe properties of a realistic stiffened skin structure can be predicted. The effect of yielding of stiffeners and fasteners is accounted for.

FAIL-SAFE STRENGTH OF STIFFENED PANELS

The behaviour of a stiffened panel as a function of crack length is illustrated qualitatively in Figure 1 for a panel configuration with a stiffener spacing, s, and a central crack of length, 2a.

With increasing crack length, the remaining strength of a structure (= residual strength) will gradually decrease. Fracture mechanics usually assumes that the residual strength of an unstiffened panel with a crack is governed by the value of the crack tip stress intensity factor, K, which is defined as

$$K = \alpha \cdot \sigma \sqrt{\pi a} \tag{1}$$

where α is a factor accounting for finite panel size. Fracture instability is assumed to occur then, when K attains a critical value usually denoted by the symbol, K_c. This implies that the residual strength curve of the

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unstiffened panel will have the shape shown by the dashed curve in Figure 1 (the effect of plasticity on the shape of this curve [1] has been ignored here).

In the case of a cracked stiffened panel, in the cracked region load will be transferred from the sheet to the stiffeners, resulting on the one hand in a reduction of the stress intensity factor and on the other in a higher local load in the stiffeners. For a certain panel configuration the effectivity of this sheet-stiffener interaction will increase with decreasing distance of crack tip to stiffening element. Assuming that both in the stiffened and in the unstiffened panel fracture instability occurs at the same stress intensity value and that a stiffener fails when its maximum stress attains the ultimate strength of the stiffener material, the foregoing implies that the residual strength properties of the stiffened panel are determined by curves of the shape shown in Figure 1 by the solid lines. The lower curve dictates the behaviour of the stiffened sheet and the upper curve that of the central stiffener. The stress level, $\bar{\sigma}$, corresponding to the intersection of both curves (point A) has a special meaning. It was shown in [2] that if at any stress level below $\bar{\sigma}$ fracture instability of a skin crack extending across the central stiffener might occur, then the unstably growing crack will be arrested at the adjacent stiffeners (see crack growth history of crack a_o, due to peak stress, σ_{peak}, in Figure 1). Fracture instability due to peak loads can be expected for crack lengths in the range between $a = \bar{a}$ and $a = s$. For crack lengths smaller than $\bar{a}$ fracture instability will never occur when the stress level in the structure does not exceed $\bar{\sigma}$. Thus, the stiffened panel will be fail-safe when the design stress level is chosen equal to or lower than $\bar{\sigma}$.

For a more detailed discussion on the residual strength of stiffened panels, the reader is referred to [2]. The effect that unstable crack growth has on the time that is available for inspection is discussed in [3].

SHEET-STIFFENER INTERACTION

It was shown in the previous section that, apart from the residual strength properties of the unstiffened panel, the sheet-stiffener interaction plays an important part in predicting the residual strength properties of cracked stiffened panels. In literature on this subject [4 - 6] the sheet stiffener interaction usually is expressed in terms of the "tip stress correction factor", C and the "stiffener load concentration factor", L. The factor C is defined as the ratio of the stress intensity factors of the stiffened and the unstiffened panel at the same crack length, or

$$C\ (a) = \frac{K_{stiffened}}{K_{unstiffened}} \qquad (2)$$

The factor L is defined as the ratio of the maximum stiffener load in the region of the crack and the stiffener load remote from the crack, or

$$L\ (a) = \frac{F_{max}}{F_{remote}} = 1 + \frac{\sum_{i=1}^{n} P_i}{\sigma_{st} A_{st}} \qquad (3)$$

where P_i are the fastener loads, n is the number of fasteners per stiffener half and σ_{st} and A_{st} are the stiffener end-stress and cross-sectional area, respectively.

Elastic values of C and L can be readily calculated. An analytical procedure for such a computation is discussed in [2]. By performing this computation for different crack length values, plots of C, L versus a can be obtained. Results obtained in this manner are given in Figure 2. However, by using these elastic results one may easily come to wrong conclusions concerning the residual strength properties of a certain panel configuration. This is illustrated qualitatively in Figure 3. The dash-dot curves in this figure are based on elastic results. However, due to the high load concentration in the stiffeners, yielding of fasteners and stiffeners may occur at relatively low external loads. This means that the stiffeners henceforth will behave less stiffly than was assumed, implying a less pronounced increase of the stiffened sheet curve and an upward shift of the stiffener failure curve. Apparently, in the case shown in Figure 3 this implies that the crack arrest and residual strength properties of the stiffened panel will be overestimated considerably when they are based on purely elastic computations of C and L. However, the effect of yielding is appraised here only on the basis of qualitative considerations. In the next section a quantitative prediction will be made of the residual strength diagram of a realistic stiffened skin structure in which yielding occurs.

PREDICTION OF RESIDUAL STRENGTH

By considering the sheet-stiffener interaction (as expressed by the values of C and L) in combination with the residual strength of the unstiffened sheet (as given by K_c) and the mechanical properties of the stiffeners, a quantitative prediction of the complete residual strength diagram of a stiffened panel can be given [2]. In the case of a panel with riveted stiffeners the values of C and L can be readily calculated when the interacting rivet forces are known. The rivet forces can be computed analytically be separating the stiffened panel and the loads on it into its composite parts and generating the equations that govern the rivet point displacements due to the different load systems. Equating the displacements in corresponding rivet points of sheet and stiffeners will yield the unknown rivet forces. To generate and solve the set of displacement equations the computer programme ARREST was developed. In this computer programme the effect of yielding of rivets and stiffeners was incorporated in the displacement equations. Reference [7] gives a detailed description of the computer programme and of the execution of it in determining the residual strength diagram of cracked stiffened panels.

Using ARREST the complete residual strength diagram was determined for a panel configuration with Z-stiffeners and a central skin crack initiating from a rivet hole. The material of sheet and stiffeners is 7075-T6. The results of the computation are plotted in Figure 4. The stiffened-sheet curve and the central stiffener failure curve that were obtained using elastic values of C and L (see Figure 2) are shown. When the skin crack is assumed to pass through rivet holes of the adjacent stiffeners, crack arrest and subsequent panel failure will occur at a crack length of 2a = 2s + d, as indicated by the vertical line in Figure 4. This implies that, based on elastic computations, panel failure after crack arrest would occur at point A (see further [2]). However, as shown in Figure 4, the elastic failure curve of the central stiffener is located above the boundary for elastic computations, implying that, prior to failure, yielding of the stiffener will occur. Based on elastic-plastic computations the failure curve will move upwards and panel failure will occur then at point B. Also shown in Figure 4 are experimental data from residual strength tests on panels of the same configuration. Comparing the computed results with the experimental data it is apparent that the elastic results considerably underestimate the crack arrest and residual strength properties, whereas the elastic-plastic computations slightly overestimate these properties.

CONCLUSIONS

1. Elastic computations do not suffice to predict the crack arrest and residual strength properties of cracked stiffened panels. They may easily lead to wrong conclusions concerning these panel properties (see Figure 3 and Figure 4).

2. In appraising the fail-safe properties of stiffened panels drawing of the complete residual strength diagram as given in Figure 4 provides more information than do plots of C and L versus crack length (see Figure 2). Therefore the procedure followed in Figure 4 is to be recommended for determining the fail-safe properties in the design stage.

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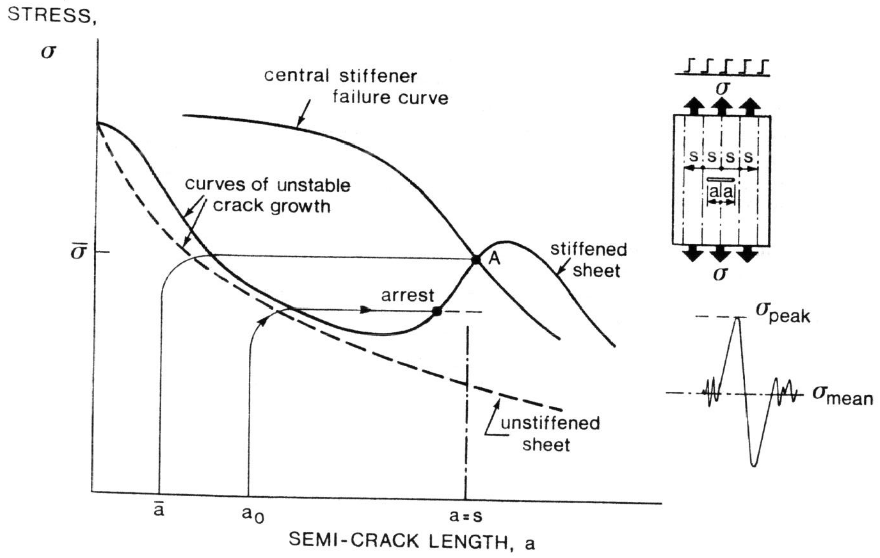

Figure 1 Residual Strength Diagram of Cracked Stiffened Panel (Schematic)

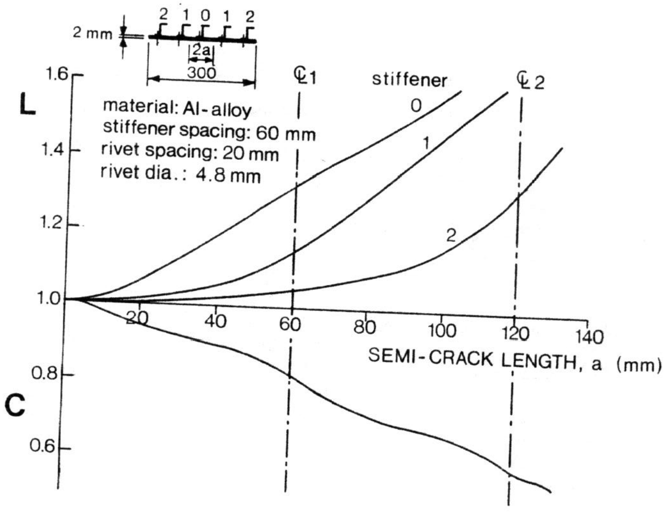

Figure 2 Plots of C and L versus a (elastic values) for a Riveted Panel with a Central Crack, Initiating from a Rivet Hole. Ratio of Stringer Stiffness to Total Panel Stiffness if .5

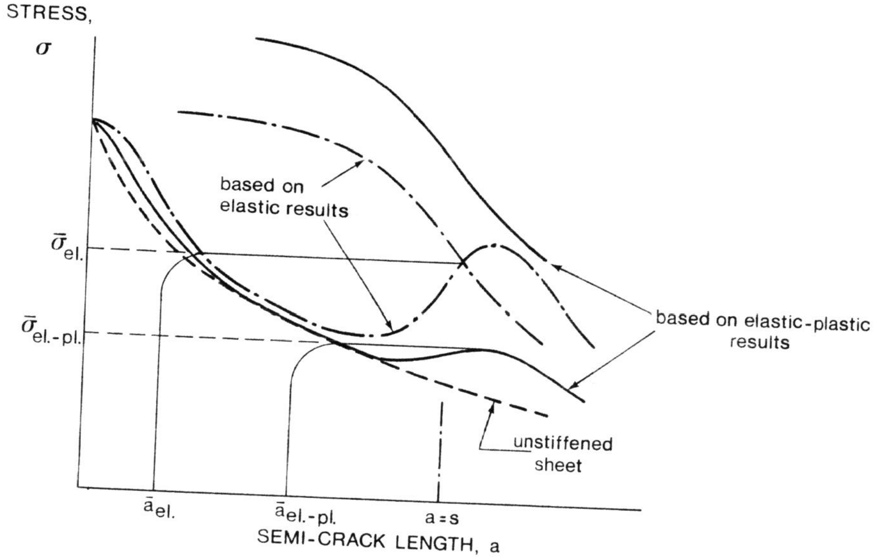

Figure 3 Effect of Yielding of Rivets and Stiffeners on Behaviour of Stiffened Panel (Schematic)

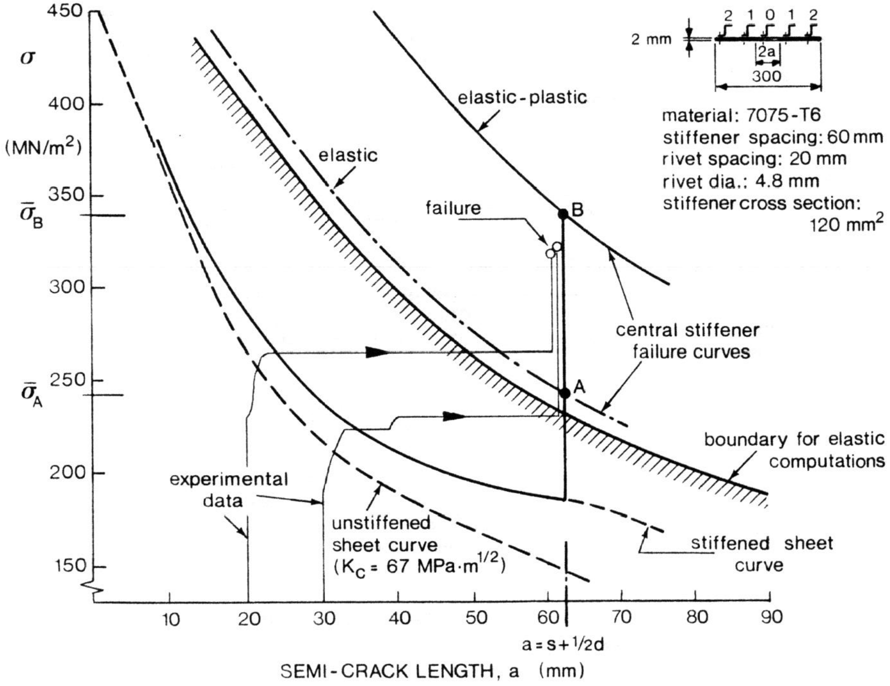

Figure 4 Residual Strength Diagram of Stiffened Panel, Based on Elastic-Plastic Computations