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Analysis of Crack in Riveted Joints with the Help of Fracture Mechanics

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ABSTRACT

Aircraft structure contains wide expanses of basic redundant structures, which must be designed with some damage tolerance capability. Despite of all precautions, crack may arise in any of these structural elements, which will reduce the stiffness and the load carrying capacity of the structure. In the built-up structure every element is essential for the functioning of the structure as a whole, hence the possibility of crack occurring in any one of them must be taken into account in the initial design stage. Since the fuselage structure forms one of critical elements in the built-up structure of an aircraft, the damage tolerance analysis (Residual strength and Crack propagation analysis) of the three different crack configurations in stiffened panel was carried out. The finite element models of panel for different crack configurations of different crack length were prepared in ANSYS. The stress intensity factors for different crack length were computed using general-purpose sub-program values. Using these SIF values and rivet loads from finite element analysis, the residual strength of the panels were predicted by analytical approach. The residual strength of the stiffened panel was determined by criteria for stiffener failure and subsequent crack growth analysis was based on analytical methods. The crack arrest capability for the configuration corresponding to crack midway between rivet holes was found to be more as compared to that of crack emanating from rivet hole with middle stiffener either intact or broken.

Key words: *Crack, Fracture Mechanics, Damage tolerance analysis.*

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I. INTRODUCTION

In most of the causes of failures the start of the failure occurs with initiation of crack. A crack is a type of discontinuity brought about by tensile stress the result being that things are no longer held together. This definition establishes that a crack is a sign of impending failure that prompts a course of action when found. A critical survey of aircraft structure shows that most of the failure in aircraft structure design is mainly due to cracking problems and the stress intensity is more sever in case of crack. Experience with structural failures has precipitated significant change in aircraft structural design procedures. Attention is now focused on calculating the residuel life and the ability to arrest a fracture in the place of previous emphasis on initiation of cracks. Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. It uses methods of analytical solid mechanics to calculate the driving force on a crack and those of experimental solid mechanics to characterize the material's resistance to fracture.

Federal Aviation Administration technical center [1] explained fracture mechanics, fatigue crack propagation and Damage tolerance evaluation and requirement. Vlieger [2] concluded that riveted panels of practical design can be dimentionad such that below a certain stress level unstable crack growth of the situated under a stiffener or between two stiffenrs is arrested near the adjacent stiffeners. T. Swift [3] described the role that stiffeners play in reducing the crack tip stress intensity factor to a level which can arrest cracks after rapid propagation. H. Vlieger [4] characterized that cracked built-up structures has the ability to transfer load from the cracked to the intact elements, thus relieving the most critical part of the structure.

M.M. Ratwani and D.P. Wilhem [5] described the importance of fastener flexibility and their influence on crack opening and load transfer in a stiffened structure, Since it will influence the residual strength prediction. Koning [6] proposed a two parameter approch for description initiation and subsequent stable growth of the crack. Pin Tong [7] derived simple formulas to predict the reduction of the residual strength due to the rivet holes in stiffened and unstiffened panels of aircraft structure. He showed that the rivet holes can cause a drastic reduction in residual strength for panels with materials of low yield strength and high fracture toughness. B.R. Seshadri *et al* [8] studied the prediction of stable crack growth behaviour of wide unstiffened panels with a single crack, a single crack with multiple open holes and a single crack with multi site damage at each open hole.

II. PROBLEM STATEMENT

The study carried out in this paper focused on the residual strength of stiffened panels with large damage, such as a two-bay crack. It is an important design parameter for large transport aircraft, typically required to satisfy fail-safety criteria. The crack-stopping role of the stiffeners has long been recognized and utilized for structures with mechanically fastened structure.

Case studies:
Case I: Crack midway between the rivet hole.
Case II: Crack emanating from the rivet hole with middle stiffener intact.
Case III: Crack emanating from the rivet hole with middle stiffener broken.

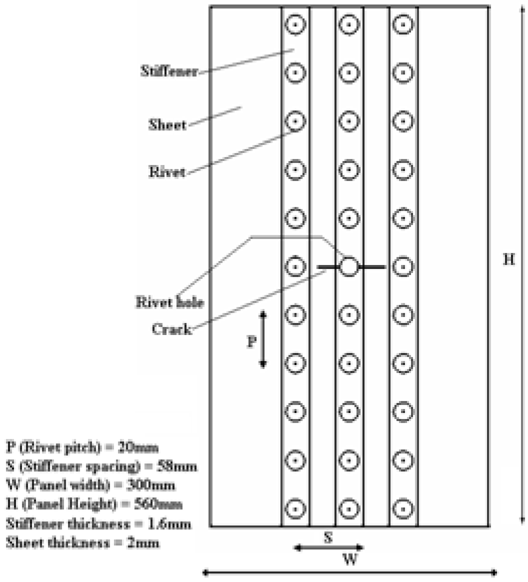

Figure 1: Stiffened panel configuration

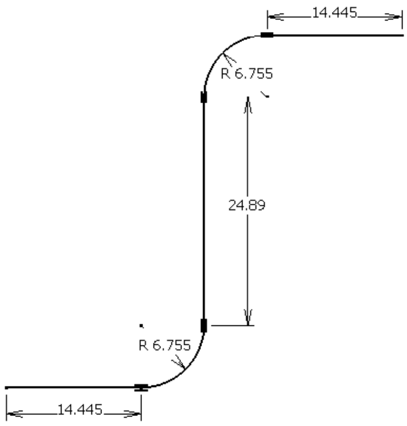

Figure 2: Stiffener dimension

III. DAMAGE TOLERANCE APPROCH

Damage tolerance philosophy was formulated based on the demonstration of structural safety under the assumption that pre-existing damage would be present at critical locations of all structurally significant details. The intent was to ensure that the maximum possible initial damage would not grow to a size that would endanger flight safety during the service life of the aircraft. it is now common practice to consider the damage accumulation process as entirely crack growth, with zero time to initiate the crack. Although this assumption may seem unduly severe, recent studies have shown the approach feasible, of minimal detriment to weight, cost, etc., but most important, the consideration of initial damage in the form of cracks or equivalent damage is absolutely necessary to ensure structural safety.

Figure 3 presents a schematic of typical growth behavior for a crack being observed in a structural element as it moves from an initial damage size to a damage size that causes structural failure. Note that the x-axis measures either the elapsed time (t) during which loading is applied or the number of loading events (N) applied, or the y-axis measures the corresponding length of crack observed in the structure. Typically, the elapsed time is given in operational flight hours and the number of loading events is counted (grossly) by the number of the aircraft's flights.

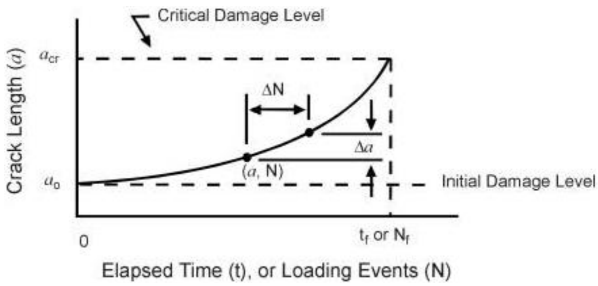

Figure 3 : Typical growth behavior for a crack

When the crack (a) reaches the critical length, the measure of loading (t or N) reaches the structural life limit (t_f or N_f). The structural life limit is a measure of the maximum allowable service time (or number of accumulated service events) associated with driving the crack from its initial length (a_o) to the critical length (a_{cr}). It is the objective of the Damage tolerant requirements to ensure that cracks do not reach levels that could impair the safety of the aircraft during the expected lifetime (t_s or N_s) of the aircraft, i.e., t_f (N_f) must be greater than t_s (N_s). Typically, this relationship between crack length and failure strength level is as shown in Figure 4.The cracked element strength is referred to as the residual strength (σ_{res}) since this represents the remaining strength of a damaged structure.

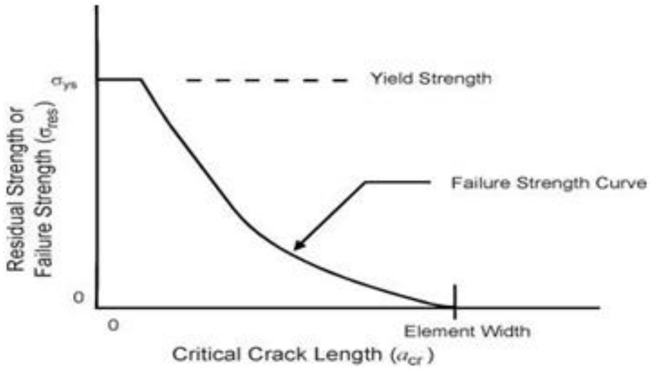

Figure 4: Relationship between failure strength and crack length

The crack length a_o will grow to a_{cr} in some life t_f, and as the crack grows the residual strength capability decreases. Experiments have shown that several parameters affect the crack growth life; the most important of these being the initial crack size, a_o, the load history, the material properties, and the structural properties.

IV MODEL CONSTRUCTION & ANALYSIS

The geometric model of all the three configurations of stiffened panel as mentioned in problem statement is done using ANSYS 8.0. The important points to model all the three configurations of cracked stiffened panel (as mentioned in problem statement) in ANSYS are summarized below:

- To model a crack, there should be two lines at the same location, which represents crack in ANSYS.
- To model a stiffener, line geometry of the stiffener dimension is created and extruded in the third direction up to required length.
- To model a broken stiffener, there should be discontinuity at the point at which it is broken i.e., discontinuity is modeled by two lines at the same locations.

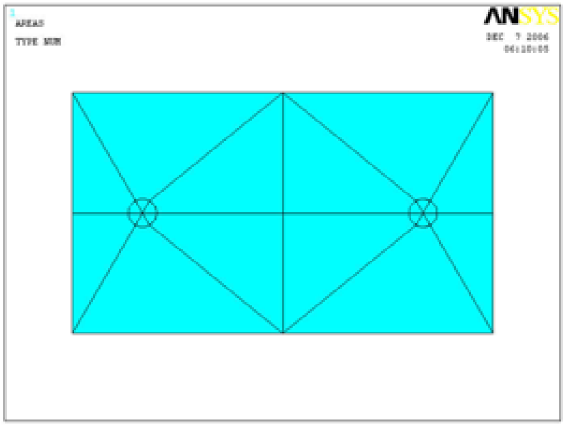

Figure 5: Crack modeling

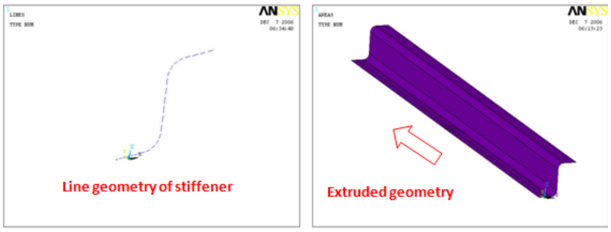

Figure 6: Line and extruded geometry of stiffener

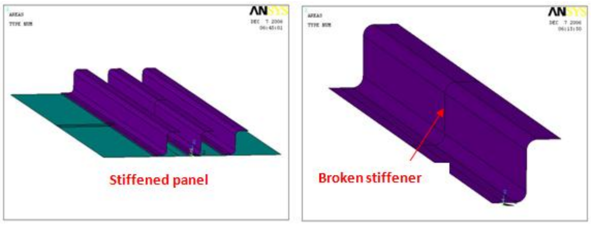

Figure 7: Stiffened panel and broken stiffener

The finite element method is a numerical analysis technique used by engineers, scientists, and mathematicians to obtain solutions to the differential equations that describe, or approximately describe a wide variety of physical (and non-physical) problems. The use of finite element method in fracture mechanics has been quite extensive both in the elastic and elastic-plastic range. The Singular iso-parametric shell elements are used around the crack tips and Curved isoparametric shell element of quadrilateral are used away from crack tip to create finite element model of cracked stiffened panel. Meshing is to discrete the given domain into sub-domains called elements. The singular elements were used to mesh the region around the crack tip and the remaining region was meshed with regular elements. The accuracy of the SIF's is strongly dependent upon the Number of Singular elements (NS) used around a crack tip and the size of the singular element (Δa).

The PREP7 KSCON command (Main Menu > Pre-processor > meshing > size controls > concentrate KPs > Create), which assigns element division sizes around a key point, is particularly useful in a fracture model. It automatically generates singular elements around the crack tip. Other fields on the command allow the user to control the radius of the first row of elements i.e., Δa and number of elements i.e., NS in the hoop direction.

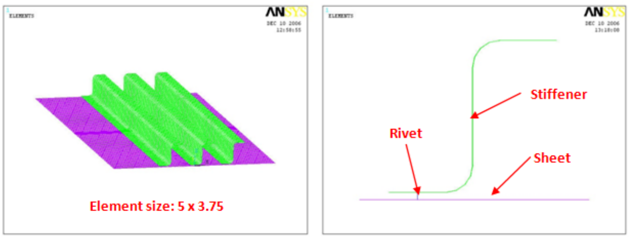

Figure 8: Finite element model of cracked stiffened panel

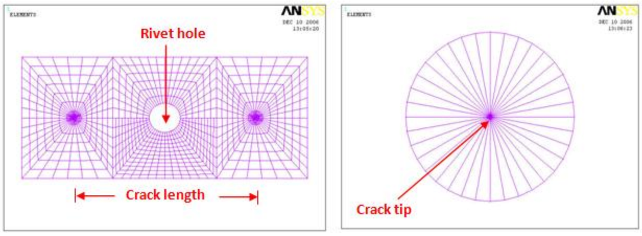

Figure 9: Elements along the crack path and around crack elements

- Number of singular elements around crack tip = 36.
- Size of the singular elements = a/100 (where 'a' is half crack length).
- Material used for modeling sheet, stiffener and rivets is 7075-T6 Aluminum alloy.
- Rivet holes are of diameter = 4.8mm.

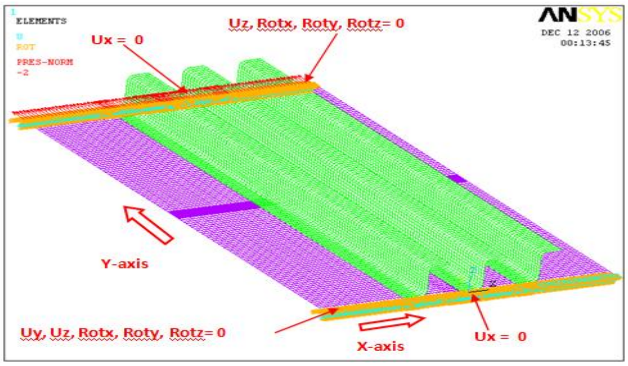

Figure 10: Loads and boundary conditions

V. RESULTS AND DISCUSION

The residual strength of stiffened panels with crack is an important design criterion in the aerospace industry to ensure that the structure is fail-safe. The crack-stopping role of the stiffeners has long been recognized and utilized for structures with mechanically fastened structure.

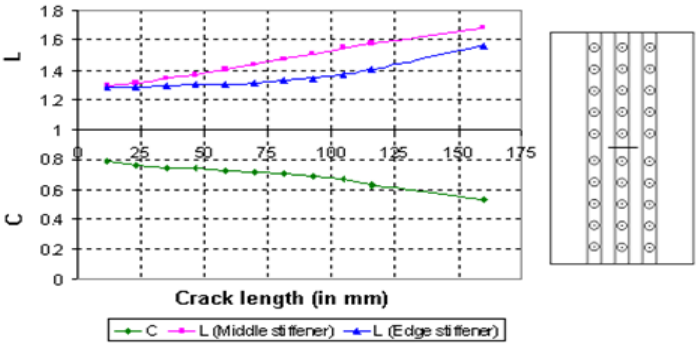

Figure 11: Crack tip stress reduction factor and stiffener load concentration for Case I

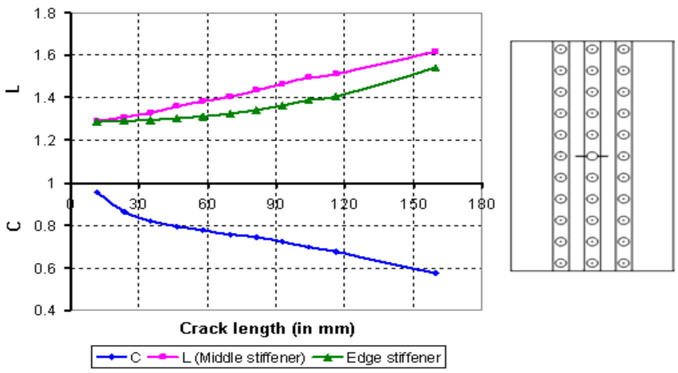

Figure 12: Crack tip stress reduction factor and stiffener load concentration for Case II

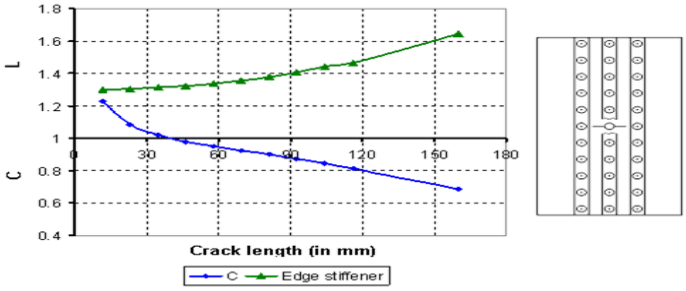

Figure 13: Crack tip stress reduction factor and stiffener load concentration for Case III

From the above Figures, it can be seen as crack length is increasing the stiffener load concentration (L) is also increasing, which indicates that the stiffener is taking more load. The stiffener load increases mainly due to increment in rivet forces. From Figure 11 and 12 it can also be seen that the stiffener load concentration of middle stiffener is higher than the stiffener load concentration of edge stiffener. It can be seen that crack tip stress reduction factor (C) decreases as crack length increases, which shows the stiffening effect of reducing the stress intensity factor as crack approaches towards the stiffener. Generally, crack tip stress reduction factor (C) is less than zero, since stress intensity factor of stiffened panel is less than that of un-stiffened. However, from Figure 13 it can be seen that C is greater than one for smaller crack lengths.

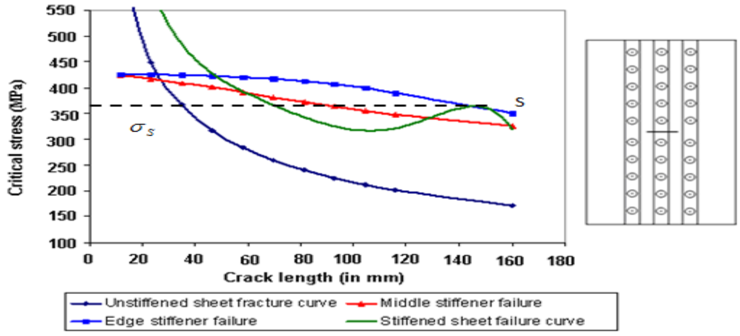

Figure 14: Residual strength plot for Case I

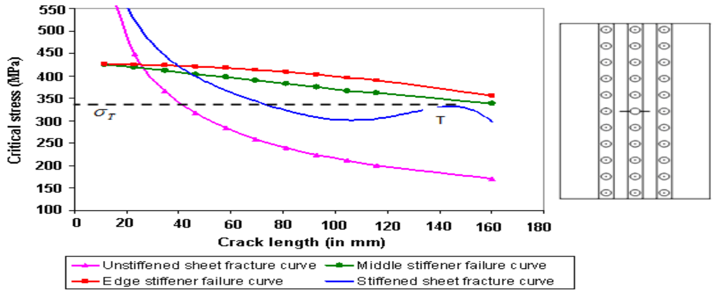

Figure 15: Residual strength plot for Case II

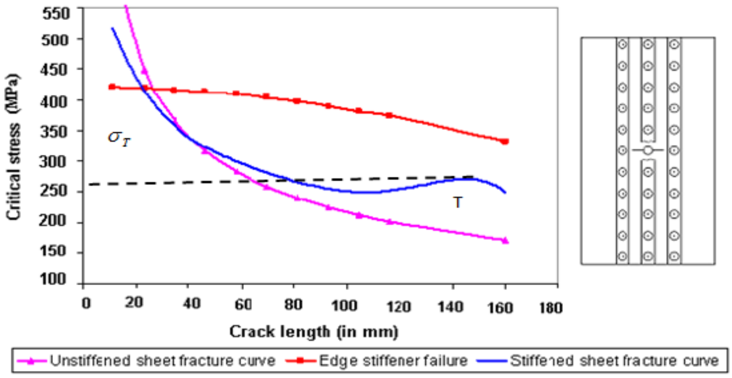

Figure 16: Residual strength plot for Case III

From Figure 14 it is clear that if instability occurs at $\sigma > \sigma_S$ then, the panel will fail without crack arrest. If instability occurs at $\sigma < \sigma_S$ then, after crack arrest, the panel ultimately will fail due to stiffener failure. The failure of this panel configuration may commence either by fracture instability of the skin or due to stiffener failure. From Figures 15 and 16 it is clear that If instability occurs at $\sigma > \sigma_T$ then, panel will fail without crack arrest. If instability occurs at $\sigma < \sigma_T$ then, after crack arrest, the panel ultimately will fail at σ_T. The failure of this panel configuration will always occur due to fracture instability of the skin.

VI. CONCLUSIONS

The stiffener load concentration of middle stiffener is higher than the stiffener load concentration of edge stiffener. This is mainly because of crack under middle stiffener resulting in comparatively higher rivet forces. The failure of this panel in figure 15 configuration may commence either by fracture instability of the skin or due to stiffener failure. The failure of this panel in figure 16 configuration will always occur due to fracture instability of the skin.

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