International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 - 5161

Available at http://inpressco.com/category/ijcet

Research Article

Design and Analysis of Crack Stopper

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Accepted 10 January 2014, Available online 01 February 2014, **Special Issue-2, (February 2014)**

Abstract

One of the fail-safe design features is the two-bay crack arrest capability of the airframe. In particular two-bay longitudinal and two-bay circumferential crack arrest feature is the main aspect of design for damage tolerance of the pressurized fuselage cabin. Under fuselage pressurization load cycles fatigue cracks develop at location of maximum tensile stress. There are locations on the airframe which are favorable for the initiation of longitudinal cracks and other locations for circumferential cracks. This investigation identifies one such location from where a longitudinal crack can initiate and studies the fast fracture and crack arrest features under the action of uni-axial hoop stress. The main crack arresting features are the bulkheads and crack stopper straps. A finite element modeling and analysis approach will be used for a realistic consideration of bulkheads and crack stopper straps and their role in the two-bay crack arrest capability of the aircraft. In particular through a stress analysis at a hoop stress corresponding to the design limit load, the load carrying ability of the bulkheads and the crack stopper straps will be assessed. For a realistic representation of two-bay cracking scenario it will be examined under what condition a two-bay crack can be arrested. For the evaluation of crack arrest capability of bulkheads in the stiffened panel with and without the presence of tear strap is studied. The SIF(stress intensity factor) value for different crack length is calculated by analytical (FEM) method.

Keywords: *Damage tolerance, circumferential crack, fracture, bulkhead, tear strap, Finite element analysis, fail-safe design.*

Introduction

The basic functions of an aircraft's structure are to transmit and resist the applied loads; to provide an aerodynamic shape and to protect passengers, payload systems, etc., from the environmental conditions encountered in flight. These requirements, in most aircraft, result in thin shell structures where the outer surface or skin of the shell is usually supported by longitudinal stiffening members and transverse frames to enable it to resist bending, compressive and torsional loads without buckling. Such structures are known as semi-monocoque, while thin shells which rely entirely on their skins for their capacity to resist loads are referred to as monocoque.

The load-bearing members of these main sections, those subjected to major forces, are called the airframe. The airframe is what remains if all equipment and systems are stripped away. In most modern aircrafts, the skin plays an important role in carrying loads. Sheet metals can usually only support tension. But if the sheet is folded, it suddenly does have the ability to carry compressive loads. Stiffeners are used for that. A section of skin, combined with stiffeners, called stringers, is termed a thin-walled structure.

The main body structure is the fuselage to which all other components are attached. The fuselage contains the cockpit or flight deck, passenger compartment and cargo compartment. While wings produce most of the lift, the fuselage also produces a little lift.

A bulky fuselage can also produce a lot of drag. For this reason, a fuselage is streamlined to decrease the drag. We usually think of a streamlined car as being sleek and compact - it does not present a bulky obstacle to the oncoming wind. A streamlined fuselage has the same attributes. It has a sharp or rounded nose with sleek, tapered body so that the air can flow smoothly around it.

As a result of the investigations into the accidents in the 1950's, aircraft manufacturers began to incorporate into their fuselage designs features which would increase the ability of the aircraft to sustain damage caused by fatigue cracking; i.e., a damage tolerant design philosophy. A reinforced doubler on the inside of the fuselage skin, termed tear strap, crack stopper strap, or fail-safe strap, is commonly employed. Tear straps are simply strips of material attached circumferentially to the skin of the fuselage which capitalize on the advantage of flapping. A tear strap locally reduces the hoop stress thus causing the bulge stress to become greater than the hoop stress for an axial crack length that is less than the axial crack length for flapping the un-stiffened cylinder. Properly designed

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tear straps are able to induce flapping and contain the damage between two tear straps.

These tear straps are made up of aluminum alloy and are placed between the bulkhead and skin and they run below the bulkhead as shown in the figure1

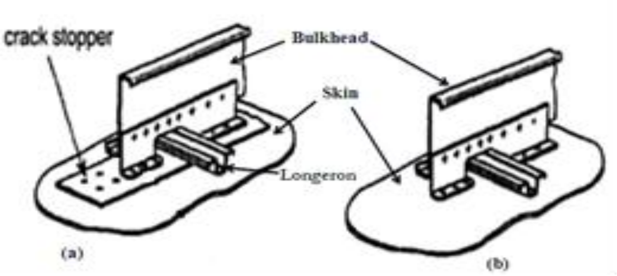


Figure.1 (a) Frame with Crack stopp (b) Frame without Crack stopper

The problem

Stiffened panels are the most generic structural elements in an airframe. Currently large transport airplanes are being developed with Large damage tolerance capability as a design goal. An important concept in the design of the pressurized fuselage of large transport aircraft is the provision of crack stopper straps to arrest the fast fracturing of a crack.

Objective of the present work

In this project the role of the crack stopper strap in the fail-safe design of the fuselage is investigated. As a first approximation a stiffened flat panel with a center longitudinal crack is considered. The strength of this cracked panel is investigated as a function of crack length in the absence of crack stopper straps. Crack stopper straps is then introduced at the locations of stiffeners perpendicular to the crack line and strength of the cracked flat panel is investigated as a function of crack length in the presence of crack stopper straps. The failure criteria that is used in this study are

The skin crack will have a fast fracture when the maximum stress intensity factor becomes equal to the fracture toughness of the skin material at that thickness

1. There is no rivet failure
2. There is no failure of the stiffener normal to the crack line

A Finite element analysis approach is followed in this investigation. Industry relevant data is used in this investigation .Geometrical dimensions representative of actual aircraft in service is considered. The material is taken as 2024-T3 sheet aluminum alloy.

A panel strength diagram is derived from the stress analysis of this cracked stiffened panel. This diagram illustrates the strength of the skin and the stiffener as function of crack length.

Material Properties

The material considered for the structure is Aluminum Alloy – 2024-T351, with the following properties.

Young's Modulus, E = 70,000 N/mm^2

Poison's Ratio, μ = 0.3

Ultimate Tensile Strength, σ_u = 420 N/mm^2

Yield Stress, σ_y = 350 N/mm^2

The following table shows the composition of the material considered.

Table.1 Chemical composition of AA 2024-T351 aluminum alloy

M	Wt. %	M	Wt. %
Al	90.7-94.7	Mn	0.3-0.9
Cr	max. 0.1	Si	max. 0.5
Cu	3.8-4.9	Ti	max. 0.15
Fe	max. 0.5	Zn	max. 0.25
Mg	5.2-5.8	Others	max. 0.15

A small part of fuselage is taken, which is rectangular stiffened panel as shown in the Figure 2 and relevant loads and boundary conditions are applied and analyzed. The stiffened panel consists of, Skin, Bulkhead, Crack stopper strap (tear strap), Longerons (stringer) Fasteners (rivets).

Figure.2 Detailed view of fuselage part

All the components of the stiffened panel are assembled together by riveting with the rivet pitch 25mm and diameter of the rivet is 5mm. The following Figure.4 show the details about the finite element mesh generated on each part of the structure using MSC PATRAN.

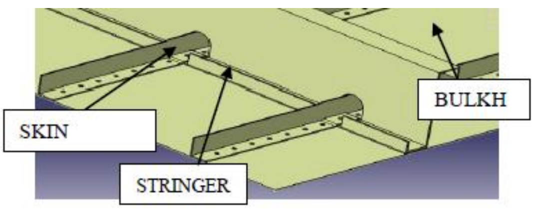


Figure 3:Close up view of stiffened panel

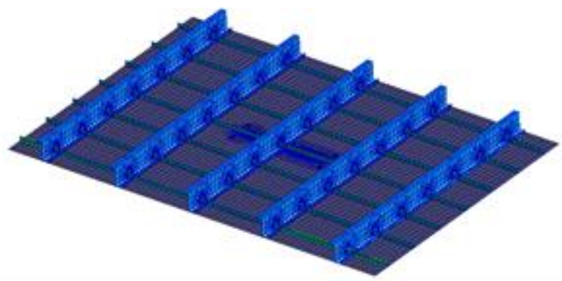


Figure.4 Complete finite element mesh on stiffened panel

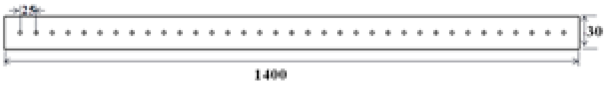


Figure.5 Geometric dimensions of tear strap (crack stopper)

In the Finite element meshing of tear strap nodes are placed at calculated distance so that the riveting could be carried out in a proper way. The tear straps are placed on the skin and the rivet nodes are aligned so that the riveting could be carried out once the rest of the components are ready. These tear straps are placed in between the skin and bulkhead and runs below the bulkhead in the circumferential direction and perpendicular to the longitudinal crack. The close up view of the meshed tear strap is shown in Figure.6.

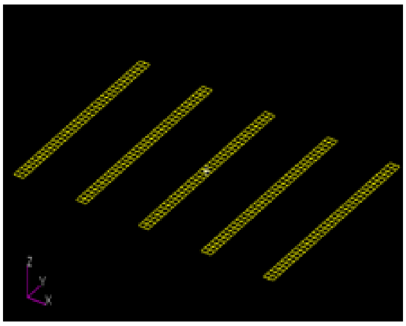


Figure.6 Finite element mesh on Tear strap

Loads and boundary conditions

A differential pressure of 9 psi (0.062066MPa) is considered for the current load case. Due to this internal pressurization of fuselage (passenger cabin) the hoop stress will be developed in the fuselage structure. The tensile loads at the edge of the panel corresponding to pressurization will be considered for the linear static analysis of the panel.
Hoop stress is given by

$\sigma_{hoop} = \frac{p*r}{t}$

Where
Cabin pressure (p) = 9 psi= 0.062066MPa
Radius of fuselage(r) = 1500 m
Thickness of skin (t) = 1.5mm
After substitution of these values in (Eq6.1) we will get
σ_{hoop} =6.327 N/mm^2

We know that
$\sigma_{hoop} = \frac{P}{A}$

Above equation can be written as
P = σ_{hoop} *A ------ Eq.1

Load on Tear strap
Here

P_{ts}=Load on skin
σ_{hoop} =6.327 Kg/mm^2
A=Cross sectional area of each Tear strap in mm^2
i.e. Width *Thickness(30*1.5)
Substituting these values in the Eq.1 we get
P_{ts}=1423Kg On each Tear strap
Uniformly distributed load on Tear strap will P_{ts} =9.4905Kg/mm

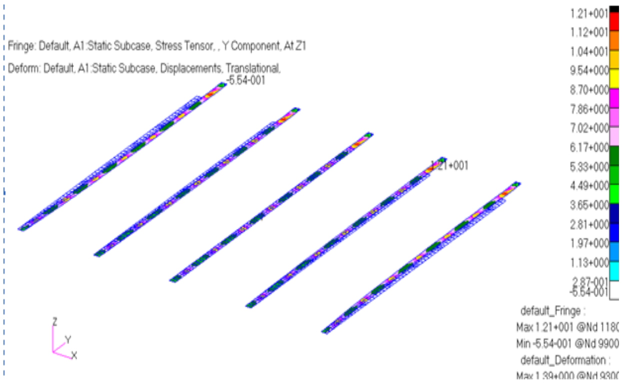


Figure 7.Stress counter for tear strap

Figure shows the stress contour on the tear strap from global analysis results. It is clear that the maximum stress on tear strap is at the rivet location where the rivets are used to fasten tear strap, bulkhead and longeron on skin.

Stress intensity factor (SIF) approach

There are different methods used in the numerical fracture mechanics to calculate stress intensity factors (SIF). The Virtual Crack Closure Technique (VCCT) originally proposed in 1977 by Rybicki and Kanninen, is a very attractive SIF extraction technique because of its good accuracy, a relatively easy algorithm of application capability to calculate SIF for all three fracture modes. The VCCT has a significant advantage over other methods, it has not yet been implemented into most of the large commercial general-purpose finite element codes.

The detail calculation of the energy release rate is,

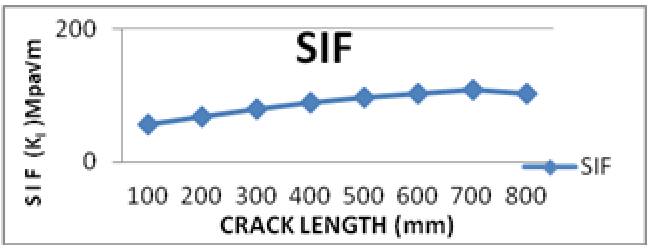
$G=\frac{F\,u}{2\,\Delta c\,t}$ ------Eq.2
Where
G=Strain energy release rate
F=Forces at the crack tip in kg or N
Δc=change in virtual crack length in mm
t= thickness of skin in mm
Then the SIF is calculated by FEM method by substituting Eq.2 in below Eq.3
$K_I=\sqrt{GE}$ --MPa $\sqrt{m}$ -----Eq.3

Where,
K_I= stress intensity factor (SIF)
E =young's modulus =7000Kg/mm^2 = 68670 Mpa
G=Strain energy release rate
Theoretically SIF value is calculated by
$K_I = \sigma_{hoop}\sqrt{\pi * a} * f(\alpha)$ ---MPa$\sqrt{m}$ --- (Eq.4)
And

$$f(\alpha) = \frac{1+0.326(a/b)^2-0.5\frac{a}{b}}{\sqrt{1-\frac{a}{b}}} \qquad \text{---(Eq.5)}$$

Where

a = Crack length in mm
$f(\alpha)$ =Correction factor
b=Width of the plate (1500mm)



SIF (stress intensity factor) has been calculated by FEM (by using VCCT technique). SIF values are obtained analytically(FEM) by using EQUATIONS 2 AND 3 for un-stiffened panel having same dimension as skin in stiffened panel by applying boundary conditions which are discussed earlier. SIF values are also obtained for stiffened panel using FEM.

From the table 2 it is clear that SIF values obtained by using FEM (by using VCCT technique) for un-stiffened panel agrees with the SIF values calculated theoretically.Therefore FEM (by using VCCT method) for finding SIF value is valid.

Table 2 that SIF values obtained by using FEM

Crack length mm	SIF by Theoretical in MPa√m	SIF by FEM Analytical in MPa√m
50	26.1	26.53
100	36.92	37.59
150	45.25	46.13
200	52.30	53.39
250	58.54	59.85
300	64.23	65.75
350	69.50	71.25
400	74.46	76.45
450	79.16	81.39
500	83.68	86.16
550	88.04	90.78
600	92.28	95.28

For the evaluation of effect of tear strap (crack stopper strap) for crack arrest capability, as a first approximation a stiffened flat panel with a center longitudinal crack is considered. The SIF value of this cracked panel is investigated as a function of crack length in the absence of crack stopper straps. Crack stopper straps are then introduced at the locations of stiffeners perpendicular to the crack line. The SIF Values of the cracked flat panel is investigated as a function of crack length in the presence of crack stopper straps. In the parametric study the thickness is varied. The SIF values obtained for stiffened panel without tear strap and stiffened panel with tear strap are compared with the critical stress intensity factor K_{Ic} (Fracture toughness of the material)

If SIF (K) at the crack tip approaches or exceeds an upper limit of stress intensity factor (K_{Ic}), then the crack will zip through leading to catastrophic failure of the structure. The upper limit is known as critical stress intensity factor (Fracture toughness of the material) which is the material property and is usually denoted by K_{Ic}. Graph 1. sif vs cracklength

The stress intensity factor is a parameter to measure severity of stress at the crack tip but critical stress intensity factor is the limit on SIF such that if SIF exceeds beyond the critical stress intensity factor, the crack will grow rapidly leading to the final failure.

When the crack stress intensity factor due to remote loading reduces below the fracture toughness of the material then a crack will get arrested.

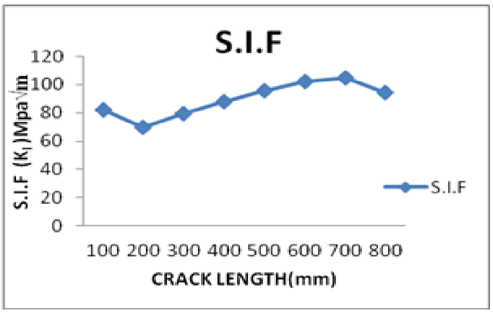
We know that aluminum maximum yield strength is 35 kg/mm^2. The structure is normally designed in such a way that the maximum stress developed at design limit load will be equal to the yield strength of the material. By using incremental ratio, which is ratio of aluminum yield strength to the obtained maximum stress.

$$\sigma_{\text{incremental}} = \frac{\sigma\ \text{yeild}}{\sigma\ \text{obtained}} = \mathbf{1.35}$$

So we can increase the stress to 1.35 times the originally obtained values. Those values are calculated and tabulated below.

Table 3 Comparison of K_I FEA values with tear strap and without tear strap of stiffened panel for actual loads and boundary conditions. S.I.F as a function of crack length without tear strap

Crack length (a) in mm	K_I FEA without Tear strap (MPa√m)	K_I FEA with Tear strap (MPa√m)
100	56.06	82.35
200	68.58	69.57
300	78.92	79.21
400	88.74	88.12
500	96.43	95.40
600	103.63	101.97
700	108.37	104.71
800	102.80	94.44



Graph 2 S.I.F as a function of crack length with tear strap

From the results it is clear that the SIF value increases as crack length increases, as the crack approaches near to the stiffening member (bulkhead and tear strap) SIF decreases because near the stiffener region the load gets transferred from skin to the stiffener. Therefore the SIF in the skin reduces. When the crack is propagated beyond the bulkhead position, there will be an increase in SIF because the load shared by the skin increases gradually. The increasing trend in the curve is observed as the crack moves away from the bulkhead position. So by using the tear strap we can control the crack growth rate (k_I) within the two-bay structure.

Conclusion

1. A stiffened panel which is generic structural element of the fuselage structure is evaluated analytically for its crack arrest capability.
2. Finite element analysis (FEA) approach is used for structural analysis of the stiffened panel.
3. Stress analysis is carried out to identify the maximum tensile stress location in the stiffened panel. The magnitude of maximum tensile stress in loading direction is 23.3 Kg/mm^2 (228.59 MPa) which is in the bulkhead at the stringer cut-out. The maximum stress locations are the probable locations for crack initiation. Invariably these locations will be at stringer cut-out locations in the bulkhead.
4. There are other possibilities of crack initiation at different locations in the stiffened panel due to discrete source of damage. It may be due to bird hit, foreign object hit. For the analysis centre cracked stiffened panel with central broken bulkhead and tear strap is considered which is due to discrete source of damage.
5. Modified virtual crack closure technique (VCCT) along with FEA analysis results are used for calculation of stress intensity factor (SIF). The effect of tear strap in arresting two-bay crack is studied.
6. Tear straps (crack stopper straps) with thickness 1.5 mm shows that a two bay crack is arrested it the stiffened panel.
7. These results were obtained for the rivet pitch of 25mm in the bulkheads by varying the pitch of the rivet may alter the crack arrest capability of the stiffened panel.

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