DAMAGE ARREST ASSESSMENT OF SUPERSONIC TRANSPORT COMPOSITE SANDWICH PANELS WITH INTEGRAL TEAR STRAP REINFORCEMENTS

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SUMMARY: In this study, composite sandwich panels with crack-like damage are analyzed for application in subsonic and supersonic transport fuselage structures. To assess the effect of curvature and reinforcements due to tear straps and circumferential frames, the panel can be (i) either flat or cylindrical, (ii) either reinforced or unreinforced by tear straps, and (iii) either stiffened or unstiffened by circumferential frames. A composite sandwich test panel under axial tension will be analyzed. The panel consists of two facesheets and a core. The facesheets are made of polyimide composite prepreg tape and the core is made of titanium honeycomb. Five tear straps are built into the facesheets by interweaving plies. The panel is stiffened by three J-section frames which are made of two-dimensional orthotropic triaxially braided composites. The commercial finite element code ABAQUS with layered shell sections is employed for stress analysis. A quantitative estimate of residual strength in panels reinforced by straps is provided by this study.

KEYWORDS: fracture, composite laminates, finite element method (FEM), tear strap.

INTRODUCTION

A rational design of composite structures for transport aircraft wing and fuselage components must rely on efficient and accurate methods for evaluating stress, strain, and deformation states at critical structural details. Examples of critical wing and fuselage structural details include damage arrestment straps which can provide for fail-safety under penetrating damage scenarios. This type of detail is characterized by severe stress and deformation gradients, and designs have traditionally relied on conservative approaches in order to avoid elaborate analyses. The severe weight requirements for subsonic and supersonic transport aircraft structures necessitate a more judicious analysis that will use the most accurate available methods to obtain weight-efficient designs.

Traditionally, fail-safe aircraft designs have relied on several different approaches to the analysis of structural components. Fail-safe metallic skin-stringer structures were investigated by Poe[1,] and Swift[2,3]. Fracture criteria and energy release rate for a cylindrical fuselage stiffened by longerons and frames were analyzed by Huang *et al*[4]. The design challenge for damage arrestment features for a highly loaded transport fuselage is to determine the optimum distribution of graphite and glass fibers that can bring about a minimum weight fail-safe structure. The minimum weight design must also incorporate features capable of carrying load as well as arresting large cracks.

In this study, our focus will be on the development of a finite element based methodology for analyzing composite sandwich panels reinforced and unreinforced by tear straps with crack-like damage. The panel is treated as a laminated layered shell. The commercial finite element code ABAQUS with layered shell sections is employed for computation. The panels in our analysis can be either stiffened or unstiffened by frames. Our objective is to provide data for a quantitative estimation of residual strength in those panels reinforced by tear straps. In this study, panels without tear straps are also analyzed for purpose of comparison with the reinforced panels to assess the damage arrestment effect. Results of stress intensity factors for different cases are provided to insure a confident and weight-efficient design.

MODEL FOR COMPUTATION

A representative composite fuselage test panel will be used in this study. As shown in Figure 1, the test panel is basically a cylindrical composite sandwich panel with two facesheets and a core. The facesheets are made of polyimide composite prepreg tape and the core is made of titanium honeycomb. Five tear straps are built into the facesheets by interweaving plies. The panel is stiffened by three J-sectional frames. The frames are made of a 2-D orthotropic triaxially braided composites. The sections of the panel are shown in Figures 2 and 3 respectively. The detail of the frame structure is shown in Figure 4. The panel is modelled as a shell. Geometrical dimensions of the cylindrical panel are:

Radius of mid-surface	R = 75.32 in.
Length	L = 74.00 in.
Width (arc length)	W = 50.00 in.
Tear strap spacings	S = 6.00 in.
Thickness of facesheet, layup 1	t_f = 0.066 in.
Thickness of facesheet, layup 2	t_f = 0.022 in.
Thickness of tear strap, layup 1	t_t = 0.165 in.
Top width of tear strap, layup 1	w_t = 1.5 in.
Bottom width of tear strap, layup 1	w_b = 2.5 in.
Thickness of tear strap, layup 2	t_t = 0.055 in.
Top width of tear strap, layup 2	w_t = 1.5 in.
Bottom width of tear strap, layup 2	w_b = 2.5 in.
Thickness of core	t_c = 1.0 in.

Frames are treated as space beams. Geometrical properties of the cross-section of the frames are:

Cross-sectional area	A_f = 0.97 in^2.
Moment of inertia about bending axis	I_{f1} = 3.206 in^4.
Moment of inertia about other axis	I_{f2} = 0.3192 in^4.
Product of inertia	I_{f12} = 0.3303 in^4.

Torsional rigidity $J_f = 0.00573$ in^4.
Distance of bending axis to bottom surface of panel $y_f = 2.102$ in.

The subscripts 1 and 2 represent the local x_1-axis and x_2-axis of the beam section respectively. The local x_1-axis is parallel to the mid-surface of the panel and the local x_2-axis is perpendicular to the mid-surface of the panel as shown in Figure 4. The intersection of the x_1-axis and the x_2-axis is the centroid of the cross-section of the beam.

The panel is subjected to a pure axial tension. Since the in-plane elastic constants of the core are zero, all tractions are therefore applied on the facesheets. The tensile traction is given as stress component $\bar{\sigma}_z$ on the boundaries of the facesheet z = ±L/2 as shown in Figure 1. In our computation, $\bar{\sigma}_z$ is considered to be uniformly distributed on both ends of the panel with the value $\bar{\sigma}_z = 1000$ psi. It is be noted that since the thickness of the reinforced facesheet is non-uniform, the corresponding section force per unit arc length $\bar{N}_z$ on the boundary of the facesheet is therefore also non-uniform. In the interval of $-2.5S < y < 2.5S$, facesheet thickness is represented by a smeared thickness

$$t_s = t_f + \frac{0.5(w_t + w_b)(t_t - t_f)}{S} \,. \tag{1}$$

In the intervals $y < -2.5S$ and $y > 2.5S$, the facesheet thickness is t_f. From the point of view of weight-efficient analysis, it is more reasonable to prescribe $\bar{\sigma}_z$ than $\bar{N}_z$.

In the computation, the following cases of panel structures are analyzed:

Case 1-1: Flat panel without tear straps, unstiffened.
Case 1-2: Flat panel with tear straps, unstiffened.
Case 2-1: Cylindrical panel without tear straps, unstiffened.
Case 2-2: Cylindrical panel with tear straps, unstiffened.
Case 3-1: Cylindrical panel without tear straps, stiffened by frames.
Case 3-2: Cylindrical panel with tear straps, stiffened by frames.
Case 4 : Flat panel with one facesheet reinforced.
Case 5-1: Unstiffened cylindrical panel with only top facesheet reinforced.
Case 5-2: Unstiffened cylindrical panel with only bottom facesheet reinforced.

Note that case 3-2 as shown in Figure 1 is the most essential for engineering practice. Results of stress intensity factors for these cases will be provided and compared with each other. In case 5-1 and case 5-2, the top facesheet is on the convex side of the panel and the bottom facesheet is on the concave side of the panel.

COMPUTATIONAL METHOD

For cases of unstiffened panels (cases 1-1, 1-2, 2-1, 2-2, 4, 5-1 and 5-2), the crack is assumed to be located at the center of the panel with the central tear strap severed. Due to structural symmetry, only a quarter of the panel need to be analyzed. For cases of stiffened panels (cases 3-1 and 3-2), the frames divide the panel into two bays, and the crack is assumed to be located at the center of one bay with the central tear strap severed as shown in Figure 1. Due to structural symmetry, only half of the test panel need to be analyzed. Half-crack length, as denoted by a, varies from 1.0 in. to 5.0 in. When a = 1.0 in., the crack tip is at the mid-point of the ramp of the central tear strap. When a = 5.0 in., the crack tip is at the mid-point of the ramp of the tear strap next to the central tear strap. When a = 2.0-4.0 in., the crack tip is within the range between the central tear strap and its neighboring tear strap.

The finite element mesh for cases of unstiffened panels are shown in Figures 5 and 6. Thirteen layers of the spider's web shaped elements are employed in the vicinity of the crack tip. Each layer contains 12 elements which are focused at the crack tip with a 15° central angle. The element size increases gradually from the crack tip to the outer boundary of the spider's web element region. According to the ABAQUS manual, the crack tip is modeled as a small key hole with radius r_k = 0.0025 in. as shown in Figure 6(b). The finite element mesh for cases of stiffened panels are shown in Figures 7 and 8. Here thirteen layers of spider's web shaped elements are also employed in the vicinity of the crack tip. However, the 90° annular region on the right of the crack tip in each layer contains 7 elements. Hence, each layer of the spider's web element contains 25 elements. The eight-point isoparametric shell elements, identified as S8R in ABAQUS, are used for the panel. It is noted that this type of elements include transverse shear deformation which can relax the constraint of Kirchhoff's assumption in thin shell theory. The nodal points of the beam elements for the frames coincide with the nodes of the shell elements. The beam elements themselves also coincide with the sides of the shell elements. The 3-node quadratic spaced beam elements, identified as B32 in ABAQUS, are used for the frames.

Since the loading system is symmetric, for cases of unstiffened panels, the constraint conditions on the planes xoy and xoz are also symmetrical. To suppress the rigid body motion of the panel, the right point of the key hole at the crack tip is constrained in the normal direction. For cases of stiffened panels, the constraint condition on the plane xoz is symmetrical. To suppress the rigid body motion of the panel, the points at y = 0 and z = ±L/2 are constrained in the axial direction and the right point of the key hole at the crack tip is constrained in the normal direction.

Each facesheet consists of several layers of tapes. Fracture of the facesheet initiates at the top or bottom surface layer. To study the critical condition for fracture, each surface layer is singled out for in-plane stress analysis. Since each layer of the facesheet is thin, the variation of stress through the thickness of the layer due to bending of the panel can be neglected. Thus the problem of fracture analysis can be approached based on a 2-D model of the surface layer of the facesheet. In this study, stress intensity factors are calculated for determining the critical condition of crack initiation on the surface of the facesheet, and for assessing the capability of crack-like damage arrestment of the tear straps. Since the material is anisotropic and the expressions for displacements in the vicinity of the crack tip are not available, the stress intensity factor for an opening mode under a symmetrical load condition is determined according to its definition based on the tangential component of stress on the line of crack extension, i.e.

$$K_I = \lim_{r \to 0} \sigma_\theta (r,0)(2\pi r)^{1/2}, \qquad (2)$$

where r and θ are the radius and the polar angle respectively . The origin of the polar coordinates is set at the crack tip and the coordinate line θ = 0 is chosen in the direction of the crack extension. Hence, the stress intensity factors can be calculated from the stress σ_θ at either the nodal points or the centers of the elements on the extension of the crack. The value of K_I as r approaches zero can be determined by extrapolation of the K_I versus r curve back to the crack tip.

COMPUTATIONAL RESULTS

Stress intensity factors are computed in both dimensional and dimensionless forms. The former shows the damage arrestment capabilities of the tear straps. The latter can be used to find various combination factors for establishing empirical equations. In the following, we only provide explanation for the results of dimensional stress intensity factors.

Stress intensity factors plotted against crack length are presented in Figures 9-16. From these figures, some general conclusions can be drawn. For panels without tear strap, stress intensity factor increases monotonically with the increasing crack length. However, for panels reinforced by tear straps, stress intensity factor K_I is small for short cracks a < 1.0 inch. For 1.0 inch < a < 2.0 inches, the value of K_I increases rapidly. For 2.0 inches < a < 4.0 inches, the K_I increment becomes so slow that it is essentially a constant. For 4.0 inches < a < 5.0 inches, the value of K_I decreases rapidly. It is found that for 4.0 inches < a < 5.0 inches, the crack-like damage initiated from the severed strap (the central strap) can be arrested by the adjacent straps. It is also seen from these figures that for panels without straps, the dimensionless stress intensity factor K_I increases monotonically with the increasing crack length. However, for panels reinforced by tear straps, the value of K_I decreases monotonically with the increasing crack length.

Figure 9 shows the curves of the stress intensity factors versus the half-crack length for flat composite sandwich panels (cases 1-1 and 1-2). It is found that the stress intensity factor K_I has only a small change in the interval a = 2.0-4.0 inches and appears to have a maximum value at a = 3.0 inch. Figure 10 shows curves of the stress intensity factors versus the half-crack length for cylindrical composite sandwich panels, represented by case 2-1 for panels without tear strap and case 2-2 for panels reinforced by tear straps. It is found that in case 2-1, the stress intensity factor in the top facesheet is larger than that in the bottom facesheet. In case 2-2, the stress intensity factor in the top facesheet is smaller than that in the bottom facesheet. Figure 11 shows the curves of the stress intensity factors versus the half-crack length for the case of cylindrical composite sandwich panels stiffened by frames, represented by case 3-1 for panels without tear strap and case 3-2 for panels reinforced by tear straps. It is found that for case 3-1, the stress intensity factor in the top facesheet is larger than that in the bottom facesheet for long cracks and is smaller than that in the bottom facesheet for short cracks. The stress intensity factors in both facesheets are equal to each other when the half-crack length a = 3.45 inches. Stress intensity factors versus half-crack length for case 3-2 are also plotted in Figure 11. It can be found that the stress intensity factor in the top facesheet is smaller than that in the bottom facesheet. Figures 12-14 show the curves of the stress intensity factors versus the half-crack length for cases 1-1, 1-2, 2-1, 2-2, 3-1 and 3-2 respectively for plies layup 2. These curves behave similar to those in cases for plies layup 1.

Figure 15 shows the curves of the stress intensity factors versus the half-crack length for case 4. Figure 16 shows the curves of the stress intensity factors versus the half-crack length for cases 5-1 and 5-2. It is seen in Figure 15 that in the unreinforced facesheet, the value of K_I increases monotonically with the increasing crack length. But in the reinforced facesheet, the value of K_I increases gradually with the increasing crack length in the interval a = 1-4 inches and decreases in the interval a = 4-5 inches. Hence, there is no damage arrestment in the unreinforced facesheet although the other facesheet is reinforced by tear straps. Similar behaviors can also be found in Figure 16 for cases 5-1 and 5-2. In comparison with cases of unstiffened panels as shown in Figures 9 and 11, it is found that if only one facesheet is reinforced, the stress intensity factor in the unreinforced facesheet is smaller than that in the corresponding case without tear strap. However, the stress intensity factor in the reinforced facesheet is larger than that in the corresponding case with both facesheets reinforced by tear straps. Since damage arrestment is not observed in panels with only one facesheet reinforced by tear straps, this type of structure is not recommended for design purpose.

CONCLUSIONS

In this study, a methodology for numerical analysis of composite sandwich panels with crack-like damage is developed. The following conclusions can be drawn from our investigation:

(1) For the panel without tear strap, the stress intensity factors in both facesheets increase monotonically with increasing crack length. For panel reinforced by tear straps, the stress intensity factors increase rapidly when the initial crack severing the central tear strap starts to grow. The stress intensity factors vary slightly when the crack tip is in the region between the central tear strap and the adjacent strap. The stress intensity factors decrease rapidly when the crack tip approaches the adjacent strap. Hence the tear straps have damage arrestment capabilities.

(2) For the panel with only one facesheet reinforced by tear straps, the stress intensity factor in the unreinforced facesheet increases monotonically with the crack length. However, the stress intensity factor in the reinforced facesheet increases initially with the crack length and decreases when the crack tip approaches the adjacent strap. Hence, only the reinforced facesheet has damage arrestment capability. Since the entire panel cannot arrest crack propagation, this type of panels is not recommended for use. In certain situations, if only one facesheet has crack-like damage and this facesheet is reinforced, the panel with only one reinforced facesheet may still be considered as an economic structure for design purpose. This type of problem will be studied in future investigations.

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