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Studies on Strength Evaluation of Fiber Reinforced Plastic Composites

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ABSTRACT
Fiber Reinforced Polymer (FRP) composites are extensively used for primary structural components such as wing, empennage and fuselage; and sub-structures such as wing ribs and intermediate spars in new generation aircraft as they give rise to high stiffness and strength to weight ratio. The failure load predictions of such composites are extremely important in order to ascertain the flight safety during its service periods. The stress analysis is a part of failure prediction process, since the failure criterion, in order to predict failure load, requires information about stresses and strains in a structure. In the present investigation, the stress analyses of CFRP composite laminates with and without cut-outs have been carried out by using both analytical and finite element approaches. In analytical approach, a mat lab code has been developed for a flat panel using Classical Laminated Plate Theory (CLPT) and different composite failure theories. MSC.NASTRAN finite element analysis code is used for carrying out finite element analysis. Convergence study has been carried out for the flat composite panel in order to ascertain the best mesh size. Comparison of stress and strain values obtained from both analytical and finite element methods shows that they are in good agreement for flat panel. This further validates the best mesh sizes obtained from the convergence study. This similar mesh sizes are further considered for flat panel with circular and elliptical cut-outs with some mesh refinements around the cut-out regions. Failure load of the flat composite laminate (without cut-out) is determined using four different failure criteria such as maximum stress, maximum strain, Tsai-Hill and Tsai-Wu criteria. The predicted values are compared with experimental results. It is found that the most appropriate theory is Tsai-Wu failure criterion, since the predicted value based on this theory is very closure to experimental failure loads. This theory is used further for predicting the failure loads of composite laminates with cut-outs. The average value of stresses in each lamina has been used for determining the failure indices of the lamina for such cases. The results are compared with experimental failure loads available in the literature. The comparison shows that they are in very good agreement. Tsai-Wu failure criterion best predicts the failure load of a composite laminate with and without cut-outs.
***Keywords* -** circular cut-out, elliptical cut-outs, failure load, flat composite panel, mesh size.

I. INTRODUCTION

Many of the modern technological developments that have taken place in the last few decades are due to the development of new materials and new processing techniques. Among the new materials, composite materials occupy an important place in every important field such as aerospace, defense, automobiles, civil infrastructure, biomaterials as well as sports. These materials originally developed for the use in aerospace applications have now become a part of daily life. The scope of application of composites being unlimited, these materials will dominate the materials field for a long period in the years to come. The aerospace industry needs high strength to weight ratio materials with stringent fatigue tolerance, impact resistance, reparability and now recyclability. But perhaps the defining requirement for aerospace materials is the ability to manufacture multiple copies of the same component all within predetermined structural and dimensional tolerances. Regardless of the advantages of any material, if components cannot be manufactured to these tolerances they will not be certifiable.

The wing, rudder, aileron and nose landing gear doors are made up of carbon fibers reinforced plastic composites. Radom is made up of aramid fiber reinforced plastic composites. Also, wing of the Light Combat Aircraft (LCA), B-2 military aircraft, Tail of the Airbus A300-A340 series is manufactured using carbon-epoxy composites. Various components of space shuttle in space vehicles are also made of composites, thus exploiting the property of low weight to stiffness/strength ratios.

Composite materials used in aerospace applications consist predominantly of stiff continuous carbon, aramid or glass fibers used to reinforce a tough polymer matrix material such as epoxy. Since then the use of composites in aircraft has grown steadily with the demand for more performance from available materials. Although the growth in civil airlines has been steady, the applications of composite materials have, until recently been limited to secondary structural components mainly due to the practical difficulties and resulting costs associated with the manufacture and certification of primary aircraft structures. This trend, however, is set to change with new regulation on carbon emissions and noise pollution. Future aircraft must be lighter, quieter and cheaper to maintain. All of these requirements point to the use of more structurally efficient materials.

II. LITERATURE SURVEY

Improvement in flight performance is one of the most important criteria in the design of aerospace structures. Weight reduction measures, combined with compliance to strength, stiffness and stability requirements are important. Investigators have long been in research of materials that have less weight as well as sufficient strength and stiffness to withstand aerodynamic loads experienced by a structure in various flight conditions. Fiber reinforced composite materials have been found to have promising properties in this regard. These materials are being used extensively in the production of various aircraft components and their usage is increasing day-by-day. This is due to the fact that they have a very high strength to weight ratio higher damage tolerance, better manufacturability and lesser number of joint compared to conventional materials.

In aircraft structures, cutouts are commonly found as access ports for mechanical and electrical systems, or simply to reduce weight. Those structural panels with cutouts are subjected to various kinds of loads and could fail if overloaded. Therefore, the stress variation, failure load etc of those structural panels with cutouts must be fully understood to obtain knowledge for efficient structural design.

Y.X. Zhang and C.H. Yang [2] presented a review of the recent development of the finite element analysis for laminated composite plates. The first-ply failure analysis and the failure were presented clearly.

Generally, the laminated plate theories can be broadly divided into the following two categories:

(a) Equivalent single layer (ESL) theories, including

- Classical lamination theory (CLT)
- The first-order shear deformation theory (FSDT) (referred to as Mid-line Plate theory in some literatures)
- Higher-order shear deformation theories (HSDT)]
- Layer-wise lamination theory (LLT)

(b) Continuum-based 3D elasticity theory

The classical lamination theory (CLT) is based on the Kirchhoff plate theory, it is the simplest theory among others, but the shear deformation effects are neglected.

The first-order shear deformation theories (FSDT) provides a balance between computational efficiency and accuracy for the global structural behavior of thin and moderately thick laminated composite plates, but no accurate prediction for the local effects can be obtained, for example, the Inter laminar stress distribution between layers, de lamination, and etc. Various higher-order shear deformation theories have been developed to overcome the limitations in the classical and first-order shear deformation theory, and the free boundary conditions of the transverse shear stresses on the upper and lower surfaces can usually be satisfied. Layer-wise lamination theory assumes a displacement representation formula in each layer. It can predict accurately the inter-laminar stresses, however layer wise models are computational expensive since the number of unknown functions depends on the number of the layers of the laminates. The 3D continuum- based theory can predict the inter laminar stress of a composite laminate, but the computational cost using 3D models is a major concern.

T.Y Kam and F.M Lai [3] studied the Experimental and theoretical methods for the first ply failure strength of laminated composite plates under different loading conditions. An acoustic emission technique is used to measure the energy released in the plates during the failure process. The first ply failure strength of the plates is then identified via the energy v/s load diagrams which are constructed on the basis of the measured acoustic emissions. A finite element analysis which is constructed on the basis of the layer -wise linear displacement theory and the Tsai-Wu failure criterion are used to predict the first ply failure strength of the plates. The comparison between the experimental and theoretical results shows good agreement.

III. MATH

Hooke's Law for a Two-Dimensional Unidirectional Lamina

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{16} \\ Q_{12} & Q_{22} & Q_{26} \\ Q_{16} & Q_{26} & Q_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix}$$

Stress – Strain Relations

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \nu_{xy} \end{Bmatrix}_k$$

IV. HELPFUL HINTS

A. Figures and Tables

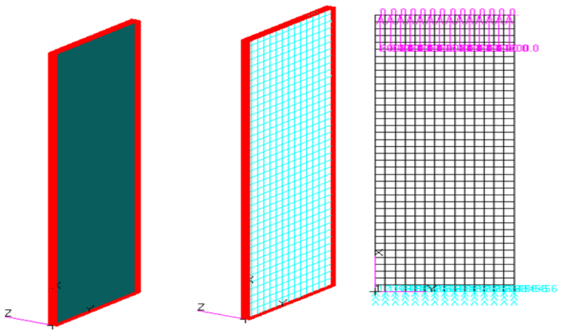

Fig 1: Finite Element Model of the Flat Panel

Abbreviations and Acronyms

AFRP Aramid Fiber Reinforced Plastic
CFRP Carbon Fiber Reinforced Plastic
CLPT Classical Laminated Plate theory
DOF Degree of freedom
FI Failure Index

Equations

Tsai-wu Theory

The theory of strength for anisotropic materials, proposed by Tsai and Wu, specialized to the case of an orthotropic lamina in a general state of plane stress is

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + 2F_{12}\sigma_1\sigma_2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 = FI$$

where,

$$F_1 = \frac{1}{X_t} - \frac{1}{X_c}$$

$$F_2 = \frac{1}{Y_t} - \frac{1}{Y_c}$$

$$F_{11} = \frac{1}{X_t X_c}$$

$$F_{66} = \frac{1}{S^2}$$

S2 and F12 is to be determined experimentally. The magnitude of F12 is constrained by the following inequality that is called the "stability criterion" associated with the theory. The need to satisfy the stability criterion together with the requirement that F12 be determined experimentally from a combined stress-state poses difficulties. The Tsai recommendation is

$$F_{12} = -\frac{I_{xy}}{2}\sqrt{F_{12}F_{22}}$$

In the Tsai-Wu criterion, these values have been supplemented by an interaction term which reflects the interdependence of failure modes due to loading along both the X and Y material directions.

IXY interaction between X and Y directions -1< IXY <1

V. CONCLUSION

The following conclusions may be drawn from the present investigations which are described in preceding chapters.

Stress analysis of a flat composite panel is carried out using both analytical and finite element methods. Convergence study has been carried out for this composite panel considering 6 different meshes. The best mesh is mesh-5 having 560 number of elements and 615 nodes. This mesh sizes are further considered for flat panel with circular and elliptical cut-outs with some mesh refinements around the cut-out region. The mesh refinements are about 1/10th the mesh size of the elements located far from cut-outs. Comparison of stress and strain values obtained by analytical and finite element methods are in good agreement for flat panel. Local stresses and strains developed along fiber direction is maximum in 00 lamina and that of the 900 lamina is minimum for all the three panels (Flat, with circular and elliptical cut-outs). Local stress and strain developed perpendicular to fiber direction is maximum in 900 lamina and that of 00 lamina is minimum. The shear stress and strain in 00 and 900 lamina is zero and +45 and -450 laminas is maximum. The stress analysis results are used for strength prediction of different laminates in the next chapter.

Failure load for flat composite panel has been predicted by both analytical method and finite element methods. These values are in good agreement. The failure loads are obtained using different failure theories such as maximum stress, maximum strain, Tsai-Hill and Tsai-Wu failure criteria. On comparison of these values with experimental failure loads, it is observed that failure load obtained using Tsai-Wu failure criterion is in very good agreement with experimental failure load. This observation concludes that Tsai-Wu failure critessrion is appropriate criterion for predicting the failure of laminated composite panels. For further analysis of composite panel with a circular and elliptical cut-outs in order to predict failure load, Tsai-Wu criterion is used. This failure criterion predicts the failure loads of composite panels with circular and elliptical cut-outs very closely with experimental failure loads. It is concluded that Tsai-Wu failure criterion predicts the failure loads of composite panels with and without cut-outs more accurately.

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