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Progressive Failure Analysis of Composite Plate using FEA

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ABSTRACT

Due to advantages of high stiffness and low strength to weight ratio composite materials are widely used in space applications.Some applications undergoes thermal load which causes to generation of thermal stresses. This stresses are responsible to failure. In this paper by considering this problem as need analysis of glass fiber reinforced polymer (GFRP) plate has been analyzed. Basically this failure is termed as thermo mechanical failure (TMF).Some important examples of TMF are wings of commercial aircrafts exposed to sun irradiation. Load carrying structure of advanced propulsion component, Boillers, High temperature furnaces etc.In In all cases stress must be preceded by an accurate thermal analysis, which is to provide the temperature input data required for the stress analysis. Progressive failure analysis of composite laminates(FRP) for critical thermal (uniform and linear) and thermo-mechanical loads is reported here. The objective of this work is to carry out a theoretical as well as FEA investigation of composite plates under thermo-mechanical loads. The analytical investigation involved certain mathematical preliminaries, a study of equations of orthotropic elasticity for classical laminated plate theory (CLPT),Looyeah and Jihan model (Thermomechanical), and numerical analysis (Finite element method), FEA of plate is carried out with the help of ABAQUS.

Keywords:- TMF, FRP, ABAQUS, FEA, UMAT, Coefficient of thermal expansion, Hashins, T sai Wu criterion.

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I. INTRODUCTION

Among the other structural materials, composites have become popular because of their high strength and stiffness-to-weight ratio. As the enthusiasm for using composite materials in marine, aerospace and automobile structures is increasing, designers are trying to understand the damage mechanisms under compressive, tensile and combined loading i.e Thermal and Mechanical conditions and damage propagation and modes. For predicting the failure modes, damage propagation and failure loads in fibre-reinforced composite structures ,progressive failure analysis methodology has been implemented in finite element analysis codes.Numerous finite element programs such as ABAQUS ,NASTRAN and ANSYS are currently available for carrying out progressive failure analysis. Damage modes such as fiber breakage in tension and compression, matrix cracking and delamination are generally observed in composite structures. Fiber breakage and matrix cracking are called as intra-laminar damage and delamination damage mode is called as called inter-laminar damage. These intra-laminar and inter-laminar damages can lead to major strength reduction in the post-damage performance of the structure. In general, A laminate failure may not be catastrophic under thermal, environmental and mechanical loads. The layer which fails first is called as the first ply failure (FPF)[2] and that the composite continues to take more loads until all the plies fail, the layer which fails at last is called as the Last ply failure (LPF)[2]. Failed plies may still contribute to the stiffness and strength of the laminate. The degradation of the stiffness and strength properties of each failed lamina depends on failure criteria followed by the designer. To predict the failure of the laminated composites, there are two categories of failure criteria (i)Failure criteria associated with failure modes such as Tsai-Wu, Tsai-Hill, Modified Tsai- Wu and Hoffman
(ii) Failure criteria not associated with failure modes such as

Maximum stress, Maximum strain, Hashin and Puck criteria.

After the stress distribution in the laminate has been determined, a failure criterion is used to determine if the laminate has failed at a certain point. To predict the failure load and failure propagation, failure criteria should be used in conjunction with progressive failure analysis. New strength properties will be assigned failed elements according to the degradation rule and the failure mode until the final failure.

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Classical Laminated Plate theory (CLPT)

The displacement field of CLPT contains only three dependent variables

$$u(x,y)=u_o(x,y)+z\emptyset_x(x,y)$$
$$v(x,y)=v_o(x,y)+z\emptyset_y(x,y)$$
$$w(x,y)=w_o(x,y)$$

Where:Φx and Φy , denote rotations about y and x axes respectively, and u ,v ,w denote the displacement components along (x,y,z) directions respectively and α is coefficient of thermal expansion of a point on the mid-plane(i.e..z=0)

$$\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \gamma_{xy}\end{Bmatrix}=\begin{Bmatrix}\varepsilon_{xx}^{(0)}\\ \varepsilon_{yy}^{(0)}\\ \gamma_{xy}^{(0)}\end{Bmatrix}+z\begin{Bmatrix}\varepsilon_{xx}^{(1)}\\ \varepsilon_{yy}^{(1)}\\ \gamma_{xy}^{(1)}\end{Bmatrix}=\begin{Bmatrix}\frac{\partial u_0}{\partial x}-\alpha_x T_0\\ \frac{\partial v_0}{\partial y}-\alpha_y T_0\\ \frac{\partial u_0}{\partial y}+\frac{\partial v_0}{\partial x}-\alpha_{xy} T_0\end{Bmatrix}+$$
$$z\begin{Bmatrix}\frac{\partial \emptyset_x}{\partial x}-\alpha_x T_1\\ \frac{\partial \emptyset_y}{\partial y}-\alpha_y T_1\\ \frac{\partial \emptyset_x}{\partial y}+\frac{\partial \emptyset_y}{\partial x}-\alpha_{xy} T_1\end{Bmatrix}$$

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \sigma_{xy}\end{Bmatrix}_k=\begin{bmatrix}\bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16}\\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26}\\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66}\end{bmatrix}_k\begin{Bmatrix}\varepsilon_{xx}-\alpha_x\Delta T\\ \varepsilon_{yy}-\alpha_y\Delta T\\ \gamma_{xy}-2\alpha_{xy}\Delta T\end{Bmatrix}$$

where

$$Q_{11}^0=\frac{E_{11}}{1-\nu_{12}\nu_{21}};\ Q_{22}^0=\frac{E_{22}}{1-\nu_{12}\nu_{21}}$$
$$Q_{12}^0=Q_{21}^0=\frac{\nu_{12}E_{22}}{1-\nu_{12}\nu_{21}}=\frac{\nu_{21}E_{11}}{1-\nu_{12}\nu_{21}}$$
$$Q_{66}^0=G_{23}$$

Failure criteria

1.Hashin failure criterion

The Hashin failure criteria [8] are also interacting failure criteria as the failure criteria use more than a single stress component to evaluate different failure modes. The Hashin criteria were originally developed as failure criteria for unidirectional polymeric composites, and hence, application to other laminate types or non-polymeric composites represents a significant approximation. Usually the Hashin criteria are implemented within a two-dimensional classical lamination approach for the point-stress calculations with ply discounting as the material degradation model. Failure indices for the Hashin criteria are related to fiber and matrix failures and involve four failure modes. Additional failure indices result from extending the Hashin criteria to three-dimensional problems wherein the extensions are simply the maximum stress criteria for the transverse normal stress components.

In these failure criteria, lamina strength allowable values for tension and compression in the lamina principle material directions (fiber or 1-direction and matrix or 2-direction) as well as the in-plane shear strength allowable value are denoted by *XT*, *XC*, *YT*, *YC*, and *S12*, respectively, *ZT* and *ZC* are the transverse normal strength allowable values in tension and compression, respectively, and *S13* and *S23* are the transverse shear strength allowable values. The failure modes included with the Hashin criteria are:

- Tensile fiber failure – for $\sigma_{11} \geq 0$

$$\left(e_1^t\right)^2=\left(\frac{\sigma_{11}}{X_T}\right)^2+\frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2}=\begin{cases}>1 & \text{failure}\\ \leq 1 & \text{no failure}\end{cases}$$

- Compressive fiber failure – for $\sigma_{11} < 0$

$$\left(e_1^c\right)^2=\left(\frac{\sigma_{11}}{X_C}\right)^2=\begin{cases}>1 & \text{failure}\\ \leq 1 & \text{no failure}\end{cases}$$

- Tensile matrix failure – for $\sigma_{22}+\sigma_{33}>0$

$$\left(e_2^t\right)^2=\frac{\left(\sigma_{22}+\sigma_{33}\right)^2}{Y_T^2}+\frac{\left(\sigma_{23}^2-\sigma_{22}\sigma_{33}\right)}{S_{23}^2}+\frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2}=\begin{cases}>1 & \text{failure}\\ \leq 1 & \text{no failure}\end{cases}$$

- Compressive matrix failure – for $\sigma_{22}+\sigma_{33}<0$

$$\left(e_2^c\right)^2=\left[\left(\frac{Y_C}{2S_{23}}\right)^2-1\right]\left(\frac{\sigma_{22}+\sigma_{33}}{Y_C}\right)+\frac{\left(\sigma_{22}+\sigma_{33}\right)^2}{4S_{23}^2}$$
$$+\frac{\left(\sigma_{23}^2-\sigma_{22}\sigma_{33}\right)}{S_{23}^2}+\frac{\sigma_{12}^2+\sigma_{13}^2}{S_{12}^2}=\begin{cases}>1 & \text{failure}\\ \leq 1 & \text{no failure}\end{cases}$$

- Interlaminar normal tensile failure – for $\sigma_{33}>0$

$$\left(e_3^t\right)^2=\left(\frac{\sigma_{33}}{Z_T}\right)^2=\begin{cases}>1 & \text{failure}\\ \leq 1 & \text{no failure}\end{cases}$$

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2.Tsai-Wu Failure Polynomial

The Tsai-Wu failure polynomial is an interacting failure criterion since all stress components are used simultaneously to determine whether a failure at a material point has occurred or not. The three-dimensional form of the Tsai-Wu failure polynomial for three dimensional problems is written as

$$\phi=F_1\sigma_{11}+F_2\sigma_{22}+F_3\sigma_{33}+F_{11}\left(\sigma_{11}\right)^2+F_{22}\left(\sigma_{22}\right)^2+F_{33}\left(\sigma_{33}\right)^2$$
$$+2F_{12}\sigma_{11}\sigma_{22}+2F_{23}\sigma_{22}\sigma_{33}+2F_{13}\sigma_{11}\sigma_{33}$$
$$+F_{44}\left(\sigma_{13}\right)^2+F_{55}\left(\sigma_{23}\right)^2+F_{66}\left(\sigma_{12}\right)^2$$

In this expression, the linear terms (*Fi*) account for the sign of the stresses and the quadratic terms (*Fij*) define an ellipsoid in the stress space. The values of the polynomial coefficients, *Fi* and *Fij*, are dependent on the material ultimate strength allowable values as given by

$$F_1=\frac{1}{X_T}-\frac{1}{X_C};\quad F_2=\frac{1}{Y_T}-\frac{1}{Y_C};\quad F_3=\frac{1}{Z_T}-\frac{1}{Z_C}$$
$$F_{11}=\frac{1}{X_T X_C};\quad F_{22}=\frac{1}{Y_T Y_C};\quad F_{33}=\frac{1}{Z_T Z_C}$$
$$F_{44}=\frac{1}{(S_{13})^2};\quad F_{55}=\frac{1}{(S_{23})^2};\quad F_{66}=\frac{1}{(S_{12})^2}$$
$$F_{12}=-\frac{1}{2}\frac{1}{\sqrt{X_T X_C Y_T Y_C}};\quad F_{13}=-\frac{1}{2}\frac{1}{\sqrt{X_T X_C Z_T Z_C}}$$
$$F_{23}=-\frac{1}{2}\frac{1}{\sqrt{Y_T Y_C Z_T Z_C}}$$
$$\phi=\phi_1+\phi_2+\phi_3+\phi_4+\phi_5+\phi_6=\sum_{i=1}^{6}\phi_i=\begin{cases}\le 1\ldots\text{No failure}\\ >1\ldots\text{Failure}\end{cases}$$

From this we can say that if value of polynomial is greater tan one then composite is going to fail.

USER SUBROUTINE UMAT

The ABAQUS/CAE is a nonlinear finite element analysis tool. Abaqus/CAE provides a complete interactive environment for creating Abaqus models, submitting and monitoring analysis jobs and viewing and manipulating simulation results. But the more distinguishing feature of ABAQUS is that it not only provides a library for materials, loading conditions, friction contacts, elements, flow and all other features, but also it has a provision to define a user defined entity if none of those given in ABAQUS are able to simulate the behaviors as expected by the user.

Hence, if a user wants a special entity (say element) with a distinguished behavior for his analysis but the desired behavior is not exhibited by any of the elements provided by ABAQUS[9], so the user has a provision to define his own element with desired features and behavior and carry out the analysis. But the behavior of this entity has to follow the fundamentals of FEA. So this distinguishing feature is rendered by ABAQUS by the implementation of Subroutines that can be executed in conjunction with ABAQUS analysis[9]. The subroutines are codes programmed in FORTRAN77 programming language which interact with ABAQUS to provide required behaviour of entity for a given input from ABAQUS to the subroutine[10]. In short, ABAQUS provides users with an extensive array of user subroutines that allow them to adapt ABAQUS using UMAT[10] to their particular requirements.

- Simple **UMAT header** shown below

```
      SUBROUTINE UMAT(STRESS, STATEV, DDSDDE, SSE, SPD, SCD, RPL,
     1 DDSDDT, DRPLDE, DRPLDT, STRAN, DSTRAN, TIME, DTIME, TEMP, DTEMP,
     2 PREDEF, DPRED, CMNAME, NDI, NSHR, NTENS, NSTATV, PROPS, NPROPS,
     3 COORDS, DROT, PNEWDT, CELENT, DFGRD0, DFGRD1, NOEL, NPT, LAYER,
     4 KSPT, KSTEP, KINC)
C
      INCLUDE 'ABA_PARAM.INC'
C
      CHARACTER*8 CMNAME
C
      DIMENSION STRESS(NTENS), STATEV(NSTATV), DDSDDE(NTENS, NTENS),
     1 DDSDDT(NTENS), DRPLDE(NTENS), STRAN(NTENS), DSTRAN(NTENS),
     2 PREDEF(1), DPRED(1), PROPS(NPROPS), COORDS(3), DROT(3, 3),
     3 DFGRD0(3, 3), DFGRD1(3, 3)
```

The following quantities are available in UMAT:
– Stress, strain, and SDVs at the start of the increment
– Strain increment, rotation increment, and deformation gradient at
the start and end of the increment
– Total and incremental values of time, temperature, and user-defined field variables
–Material constants, material point position, and a characteristic element length
– Element, integration point, and composite layer number (for shells and layered solids)
– Current step and increment numbers

II. PRESENT STUDY

In this study, progressive failure analysis of symmetrically laminated composite plate [0°/+45°/-45°/90°]2s with circular cutout under uniform axial compression loading is carried out using FEA method. Furthermore, orientation of circular cutout, size of circular cutout, thickness of plate on ultimate failure load are investigated. The width and length of the composite plate are 100mm and 200mm, respectively. Each layer thickness of this composite plate is 0.125mm and the thickness of the composite plate is “t”. In the present work the circular cutout placed in the centre of the rectangular composite plate. Briefly ,progressive failure analysis is performed for different sized circular sections.In table 1, graphite/epoxy composite material properties are listed.

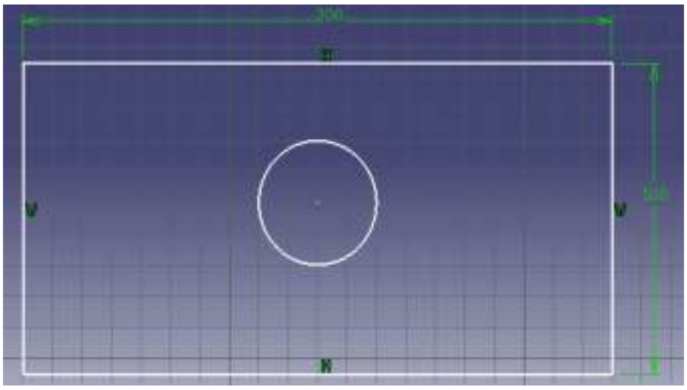

Fig 1 Part modelling

Finite element modeling

In the present study, progressive failure analysis for predicting the ultimate failure load of a rectangular composite plate with a circular cutout is carried out using ABAQUS software .Using Hashin failure criterion[8] ultimate failure loads are predicted. The plates are modelled using eight-node shell elements (S48R). As per the our problem finite element meshing for composite plate with circular cutout as shown in figure. composite plate has two boundary conditions i.e left hand edge and right hand edge are fixed and two upper and lower edges are free. The applied loading conditions includes mechanical as well as thermal load. Thermal load is in terms of temperature. As per the literature review I have considered 180^0 C temperature as a thermal load. Coefficient of thermal expansion for this material is 0.02μm/m/c For this procedure we can use temperature-displacement step or predefined field option in ABAQUS. Important steps in this analysis are thermal loading from this we can get thermal stresses in next step mechanical load is applied.There are so many criterios available to predict composie failure out of which Hashin, T sai wu ,T sai hill criteria’s are widely used.Out of which we have developed UMAT code[10] of T Sai Wu criterion for predicting failure using FORTRAN language. Along with T sai wu criteria hashin failure criteria is used.

Property	Unit	T300H/3900-2
E_1	[GPa]	181
$E_2 = E_3$	[GPa]	10.3
$G_{12} = G_{13}$	[GPa]	7.17
G_{23}	[GPa]	1.23
$v_{12} = v_{13}$	—	0.28
v_{23}	—	0.28
X_T	[MPa]	1500
X_C	[MPa]	1500
$Y_T = Z_T$	[MPa]	40
$Y_C = Z_C$	[MPa]	246
S_{12}	[MPa]	68

Table 1- Material properties(Graphte/epoxy cmposite)[11]

In above table
E- Young's modulus of elasticity in different direction.
G-Modulus of rigidity, υ- Poissons ratio
Xt,Xc-Strength of lamina in tension and compression
S-Shear strength of lamina

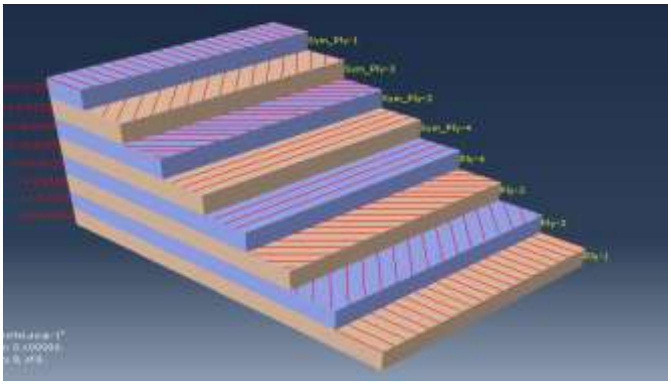
Fig 2 Part Modeling (Composite layup)

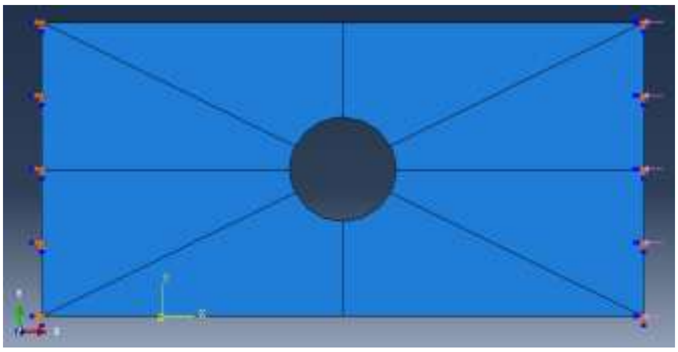
Fig 3 Loading and Boundary conditions

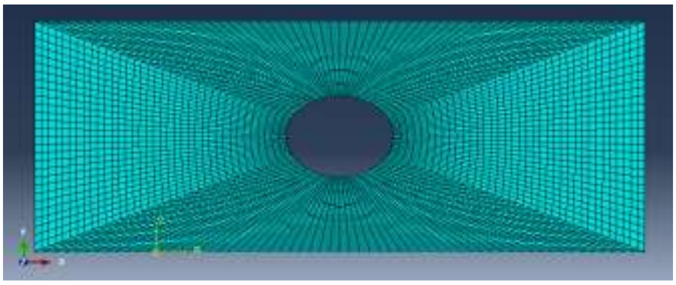
Fig 4 Finite element mesh for composite layup

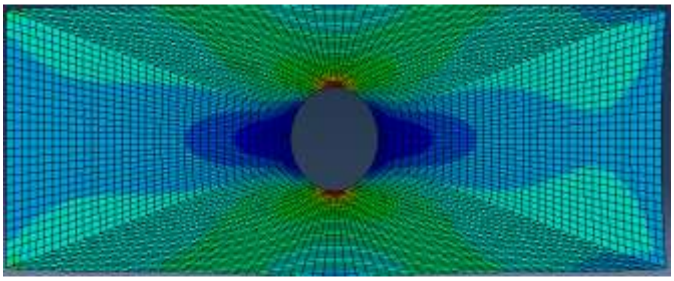
Fig 5 Stress distribution(Failure Initiation)

In fig 2 part modeling has shown which shows orientation of fibers. We have used orientation [0°/+45°/-45°/90°]2s.In fig 2 loading and boundary conditions has shown .In our problem we have fixed vertical edges and compressive load is applied on one of edge. In fig 4 finite element meshing has been carried out. For meshing to get accuracy we have to do partitions which takes all curvatures in to consideration. In Fig 5stress distribution has shown and failure initiation has started.Failure initiation is coming as per the experimental results which has ben carried by Liu G[7].

III. RESULTS and VALIDATION

Reference	Exprimental (Ultimate failure strength MPa)	In Present study ABAQUS(Ultimate failure strength MPa)
Liu et al [7]	397.1	390

As investigated by Liu's et al.[7], the Experimental ultimate failure strength is 397.1Mpa and In present study ultimate failure strength obtained by using ABAQUS software were 390Mpa which gives 1.78% variation from the experimental ultimate failure strength.

IV. CONCLUSION

By using UMAT defined in ABAQUS manual, code has been generated for T Sai wu failure criteria using FORTRAN.Failure initiation of composite plate has been observed at particular temperature (180^0c) and mechanical load.

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