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DYNAMIC FAILURE ANALYSIS OF LAMINATED COMPOSITE PLATES

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ABSTRACT

A developed finite element analysis investigation into the failure behavior of laminated composite plates subjected to impulsive loads was undertaken using ANSYS. The study presents the effects of pulse duration and pulse shapes on the predicted critical static and dynamic failure modes as well as free vibration, for several layer configurations. These studies include the effects of parameters like size of plates, boundary conditions and fiber orientation angles. Extensive studies on convergence and validity of results based on available data have been carried out prior to the presentation of salient results of this analysis. The normal mode superposition technique is used for the analytical solutions of dynamic response. The failure analysis of the plates was calculated based on the material failure of the facings predicted from Tsai-Wu theory. The pulse shapes considered are, rectangular and half-sine.

Key words: Composite Laminates, FEM, Static & Dynamic Failure, Pulse Shape, ANSYS

1. INTRODUCTION

The high specific strength, superior stiffness to weight ratio and other desirable properties of fiber reinforced composites make them candidates for a number of structural applications. These applications frequently necessitate design of structural composite members like plates to withstand high dynamic stresses. In such applications suitable prediction methods must be developed to evaluate failure strength and failure modes of these structures. Most of the research work in the area of failure analysis of composite structures, especially of plates, has been devoted to determining the static failure mode. A. Bogdanovich et al. [1] employed the theoretical prediction of the initial failure and ply-by-ply failure processes in laminated composite structures under dynamic loading. A static and transient dynamic finite element computational procedure is presented for failure analysis of pretwisted rotating plates subjected to center point transverse load by A. Karmakar et al. [2, 3]. Resently, Kyoung Sik Chun et al. [4]

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developed the higher-order shear deformation theory is used to study the response of graphite/epoxy laminated composite non-prismatic folded plates subjected to impact loads. Progressive failure analysis of laminated unstiffened and stiffened composite panels has been carried out in the present investigation. The laminated panels under transverse static loadings in the linear elastic range have been investigated using the finite element by B. G. Prusty [5].

To the best of author's knowledge, finite element analysis is not available for prediction of dynamic failure response of plates. Hence for this reason, the performance of a three -dimensional finite element analysis using the developing ANSYS [6] program, was used to provide some understanding of static, free vibration and dynamic failure response of plates subjected to impulsive loading to initiate and sustain failure in a structure.

2. THE ANALYSIS PROCEDURES

The objective of finite element analysis is to accurately represent the behavior of the physical structure being analyzed. The degree of success in achieving this objective depends largely on the modeling techniques and assumptions employed in the analysis. The general purpose finite element analysis program ANSYS, was used for the analysis. This program offers a family of layered elements to analyze structural models. The element formulation is based on the standard isoparametric element is similar to that given by Ahmad et al. [7]. The element used denoted by Shell99, in the analysis has four corner nodes and four middle side nodes with six degrees freedom at each node, viz., translations (u, v, w) in nodal x, y and z directions and rotations (θ_x, θ_y, θ_z) about the x, y and z axes. These are connected by quadric shape functions which describe both the original shape and displacements of the element. This shown in (Fig. 1). A 3-D quadratic failure criterion Tsai-Wu which includes interaction among the stress or strain components, used with Shell99 element, has been applied as the failure criterion to predict the ultimate failure strength of the laminated composite plates under static and dynamic distributed loads.

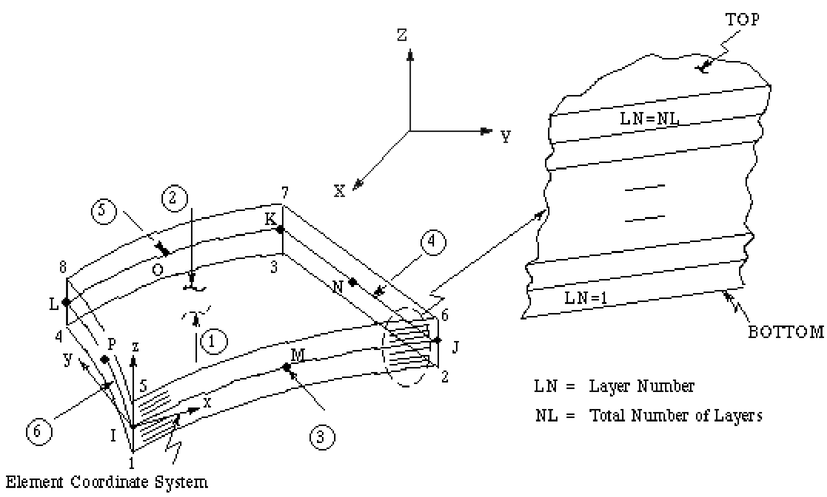

Fig. 1. A laminated plate

3. SOLUTION PROCEDURE

3.1 Static Analysis

The strength of a material is an important property in the design of any structure that uses that material. All design procedures involve a comparison of the actual stress field with the allowable stress field. The idea of "Failure theory" or "Failure criterion" has been introduced to predict the strength of materials under multi-axial loading conditions using strength data obtained from uni-axial tests. The failure criterion, being a function of stresses, encloses all the stress states that the material can sustain without failure. In the case of orthotropic materials the strength changes with direction and the direction of principal stress may not coincide with the direction of maximum strength. Thus the highest stress may not be the stress governing the design process. In-plane failure of laminates can generally be classified into matrix failure and fiber breakage. Each of these failure mechanisms are cased by a uni-axial stress or combined stresses. To identify the failure mechanism and to trace the path of the failure propagation, failure criteria are used. The failure modes such as fiber breakage and matrix damage are predicted using different failure theories.

The present work uses two types of failure theories for the static analysis. First the elements are analyzed by Tsai-Wu [8] failure criterion using the ANSYS and then they are analyzed by Tsai-Hill failure theory using the numerical method for comparison of the results. By using stress transformation equation, the stress along the principal material axes in each lamina is checked for the appropriate failure theories. Once the failure has been identified, the failed layer of the elements is made inert by making the modulus take on a very low value. This is to avoid the [D] matrix becoming singular. The over-all stiffness matrix is updated and analysis is continued for the next load increment. If there are no failures in a load step, then the applied load is incremented until failure occurs. This procedure is continued till the failure propagates across the width of the laminate and causing the ply to fail.

3.2 Modal Analysis

The modal characterizations are determined through a mode frequency analysis, resulting in eigenvalue - eigenvector extraction procedures. In the present analysis, a reduced procedure is adopted. In this procedure, the system of equation is first condensed down to those degrees-of-freedom associated with the defined master DOFs by a Guyan reduction. This technique preserves the potential energy of the system but modifies, to some extent, the kinetic energy. The number of master DOFs selected should be more than twice the number of frequencies of interest. The extraction technique employed is the Householder Bisection Inverse iteration technique.

A vibration technique is utilized for the prediction of the extent of failure in layered composite plates. The natural frequency decreases with the increase in layer failure due to the reduction in stiffness of the laminated. The measurement of the frequencies of the plates before and after the lamina failure, due to static load, therefore, offers the possibility of predicting the change in frequencies of the system. For the present analysis, two methods have been proposed to account for the failed lamina on the subsequent behavior of the laminate [9] to checking the frequencies after the each lamina failure.

Total Discount Method (TDM): In this method, zero stiffness and strength are assigned to the failed lamina in all directions (D11 = D12 = D16 = D22 = D26 = D66 = 0).

Limited Discount Method (LDM): In this method, zero stiffness and strength are assigned to the failed lamina for the transverse and shear modes if the lamina failure is in the matrix material (D11 = D12 = D16 = D26 = D66 = 0).

3.3 Transient Analysis

The transient dynamic equation of interest for a linear structure is given by:

$$[M]\{\ddot{u}\} + [K]\{u\} = P(t) \quad (1)$$

Three methods of solution are available in the code, viz., full reduction and mode-superposition. In the present analysis the mode superposition method was adopted. The mode superposition method sums factored mode shapes from a modal analysis to calculate the structure's response. The main advantage is that it is faster than the other two methods. However the time step is constant throughout the transient response. In the present study, plates are subjected to impulsive loading to initiate and sustain failure beast upon the static failure response.

4. NUMERICAL RESULTS AND DISCUSSIONS

The static, free vibration and impulsive response of five lay-ups i. e. (0, 90), (45,-45), (30, -30, -30, 30), (0, 30, 60, 90) and (45,-45, 45,-45) with varying boundary condition are investigated to study the effect of layer failure under the step and half sinusoidal impulsive loading. In the present study, ANSYS, a general purpose finite element method program was employed to evaluate the results. Computations were carried out in double precision arithmetic, with a PC – P4 computer. Preliminary studies indicated that for all the ranges of the length ratio, very good convergence was obtained for an equal number of elements in both directions. It was established that 64 elements with unit aspect ratio provided acceptable convergence and this has been used in this study. The thickness and material properties are taken to be equal for all layers. As typical composites for engineering application, a fiber-reinforced (unidirectional) layer T300/5208:

$$E_{11} = 154\ GPa \qquad E_{22} = 10.8\ GPa$$

$$G_{12} = 5.7\ GPa \qquad \upsilon_{12} = 0.28 \ \ \rho = 1600\ Kg/m^3$$

$$\sigma_{xt} = 1470\ MPa \qquad \sigma_{xc} = 1400\ MPa\ \ \sigma_{yt} = 43\ MPa$$

$$\sigma_{yc} = 147\ MPa \qquad \sigma_{zt\,\&\,zc} = 91\ MPa$$

$$a = b = 1.27\ m \qquad z = a/20\ m \quad h = 0.0254\ m \qquad t_d = 4\ ms$$

having different degrees of orthotropy is considered.

A simple convergence study for the non-symmetric angle-ply (0, 30, 60, 90) laminated plate for second layer subjected to a static load, is shown in (Fig. 2). The failure factors of the plate show that, there is not much variation as the number of elements goes on increasing. (Fig. 3, 4) shown the effect of ply failure using two failure theories. From these figures it can be seen that, as the load increase, variation between both the theories become more. For lay-ups (45,-45 & 0, 90), Tsai-Hill failure criterion take place faster than Tsai-Wu criterion and the slope of the load curve also, is steeper.

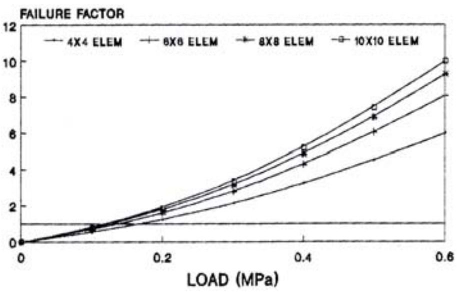

Fig. 2a. Convergence study of layer 4, (0,30,60,90), under static load, B.Cs (CC-CC)

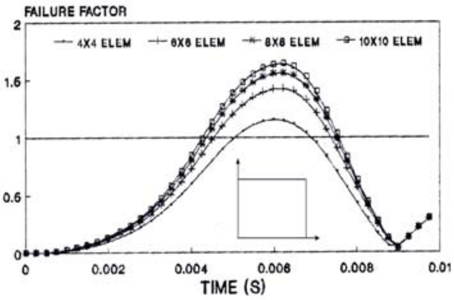

Fig. 2b. Convergence study of layer 4, (0,30,60,90), dynamic load, P=0.13 Mpa, B.Cs (CC-CC)

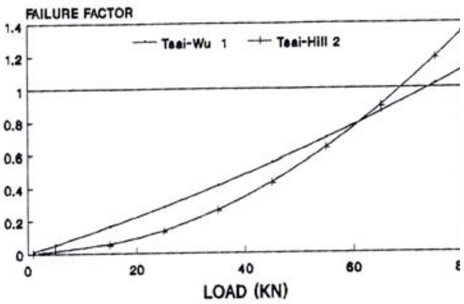

Fig. 3a. Comparison Tsai-Wu & Tsai-Hill for layer 1, (0, 90), B.Cs (CC-CC)

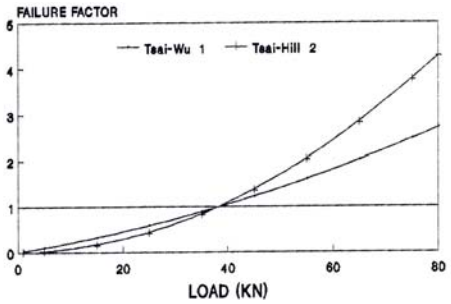

Fig. 3b. Comparison Tsai-Wu & Tsai-Hill for layer 2, (0, 90), B.Cs (CC-CC)

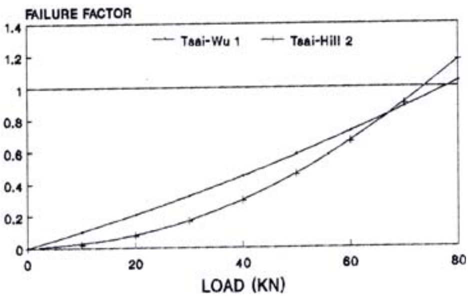

Fig. 4a. Comparison Tsai-Wu & Tsai-Hill for layer 1, (45,-45), B.Cs (CC-CC)

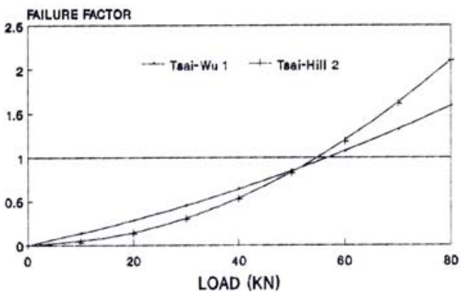

Fig. 4b. Comparison Tsai-Wu & Tsai-Hill forlayer 2, (45,-45), B.Cs (CC-CC)

The Tables 1 and 2, show the first eight frequencies parameters $\lambda_i = (\rho h \omega^2 a^4 / D_0)^{1/2}$ of laminated (30,-30,-30, 30) with two different boundary condition, for before and after failure occurs in the layers under static loads by using the Limit and Total Discount

Methods. For both boundary conditions, the frequencies obtained from TDM are lower than LDM. In fact, the frequencies parameters decreases with the increase in the sustain loads due to reduction in stiffness of the laminate.

Table 1: Frequencies parameter $\lambda_i = (\rho h \omega^2 a^4 / D_0)^{1/2}$ *before and after failure of laminated (30,-30,-30,30) square plate, B.C's (CC-CC)*

Mode No.	Before Failure FEM Analysis	After Failure Limit Discount Method			After Failure Total Discount Method		
	$(30,-30)_s$	Layer 4	Layer 3	Layer 1	Layer 4	Layer 3	Layer 1
1	21.57	13.24	9.890	8.513	11.18	5.762	2.633
2	33.86	26.12	15.90	10.47	18.94	9.955	4.006
3	50.76	27.06	23.09	14.64	25.61	13.13	6.119
4	52.00	39.07	25.83	20.87	30.56	16.35	6.520
5	64.47	46.30	28.19	22.17	34.19	17.74	8.322
6	74.12	47.82	37.05	23.43	44.77	24.05	8.958
7	86.37	57.44	40.42	26.51	46.77	24.56	11.31
8	91.73	60.13	42.87	28.31	48.01	24.93	12.27

Table 2: Frequencies parameter $\lambda_i = (\rho h \omega^2 a^4 / D_0)^{1/2}$ *before and after failure of laminated (30,-30,-30,30) square plate, B.C's (SS-SS)*

Mode No.	Before Failure FEM Analysis	After Failure Limit Discount Method			After Failure Total Discount Method		
	$(30,-30)_s$	Layer 1	Layer 4	Layer 3	Layer 1	Layer 4	Layer 3
1	12.17	8.891	5.799	4.125	8.354	5.479	1.831
2	23.03	18.24	12.46	5.918	14.75	12.17	2.796
3	35.21	22.97	17.83	10.27	22.07	16.37	4.597
4	38.72	29.89	21.00	14.62	24.90	19.92	4.606
5	48.93	38.08	26.77	15.65	31.34	26.39	6.354
6	58.23	44.59	30.64	15.84	37.14	29.39	6.696
7	69.77	45.70	37.48	18.96	44.46	34.00	8.817
8	71.29	55.68	41.61	21.68	45.24	39.09	9.510

The results for the impulsive response under the uniform external pressure loading acting on the top surface of the plates and time step ($1/40 \times T_5$), are shown in (Fig. 5 through 9). They are meant to illustrate the following aspects: (i) effects of pulse duration, (ii) effects of edge conditions, (iii) effects of pulse shapes, (iv) effects of fiber orientations, (v) effect of number of stiffeners, on the transient response particularly on critical failure factor (e = 1).

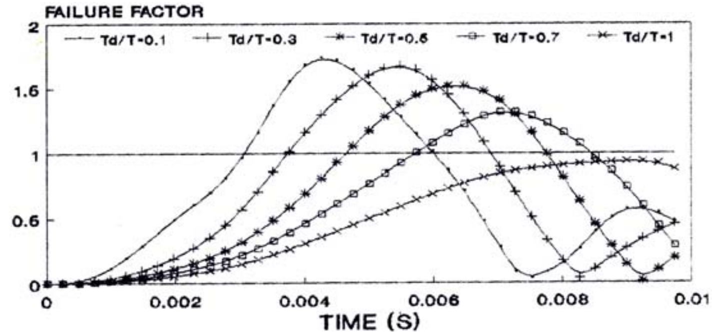

Fig. 5. Effect of td / T for layer 4, (0, 30 ,60, 90), Step pulse, B.Cs (CC-CC)

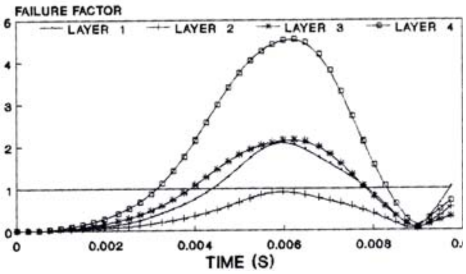

Fig. 6a. Effect of load, P=0.27 Mpa, (0,30,60,90)

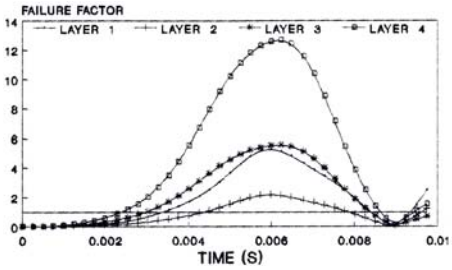

Fig. 6b. Effect of load, P=0.5 Mpa, (0,30,60,90)

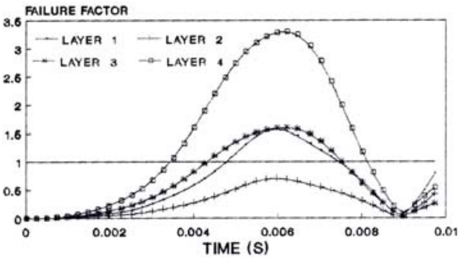

Fig. 6c. Effect of load, P=0.22 Mpa, (0,30,60,90)

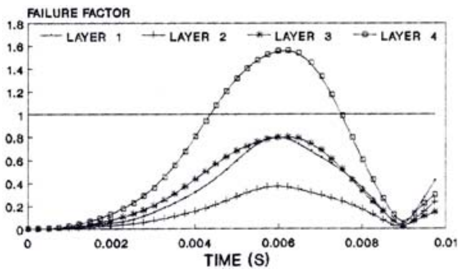

Fig. 6d. Effect of load, P=0.13 Mpa, (0,30,60,90)

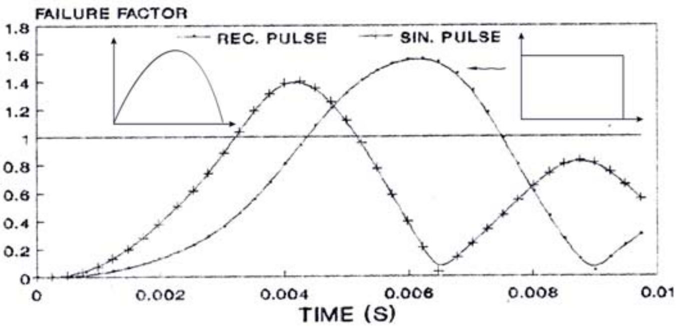

Fig. 7. Effect of pulse shape (Step & Sin) for layer 4, (0. 30, 60, 90), B.Cs (CC-CC)

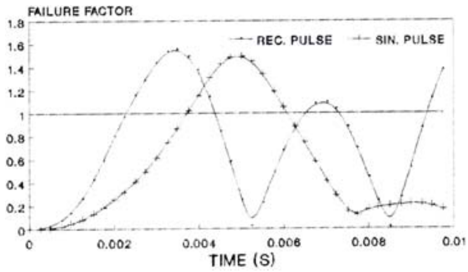

Fig. 8a. Effect of pulse shape for layer 4, (30,-30,-30,30), B.Cs (CC-CC)

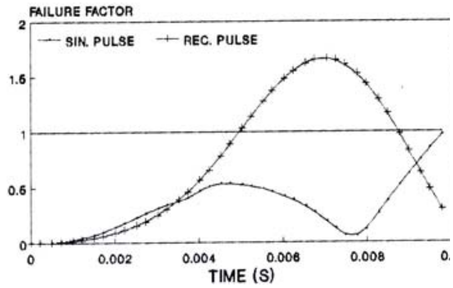

Fig. 8b. Effect of pulse shape for layer 4, (30,-30,-30,30), B.Cs (SS-SS)

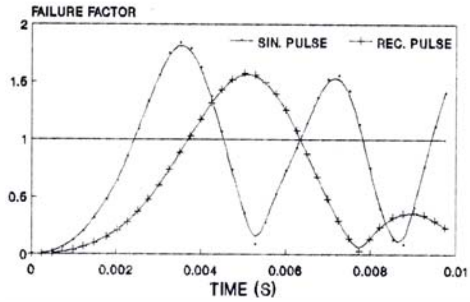

Fig. 9a. Effect of pulse shape for layer 4, (45,-45,-45,45), B.Cs (CC-CC)

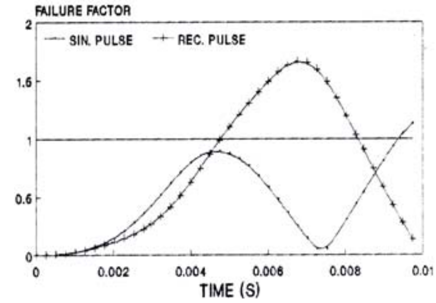

Fig. 9b. Effect of pulse shape for layer 4, (45,-45,-45,45), B.Cs (SS-SS)

A simple study of effect of the pulse duration ($t_d / T = 1$ through 0.1) for the fourth layer of non-symmetric (0,30,60,90) laminated plate subjected to step pulse, is shown in (Fig. 5). From the figure it can be seen that, with a increase of t_d / T , the critical failure factor (e = 1) decreases. (Fig. 6) depicts the failure factor variations of each layer versus the impulsive loads for (0, 30, 60, 90) lay-up under distribution step pulse. These loads are corresponding to the static loads for each layer, that cause failure, in the laminated plate. The results in the figures indicates that the characterization of dynamic failure in layers, same as static failure, i.e. if under static load (0.13 MPa) only layer 4 failed, in the dynamic analysis also layer 4 failed. But, for Layer 3 under (0.22 MPa) load, failure also occurs in layer 1 addition to layer 3 (because of, both sustain load are very close). It has been observed that, the failure ratio (Dynamic/Static) for each layer is $\cong 1.5$.

For equal input impulses, (Fig. 7 - 9) show the effect of various pulse shapes and stacking arrangements of same total thickness (0, 30, 60, 90), (30,-30,-30, 30) and (45,-45, 45,-45) with different boundary conditions. It is noted that, in this study, all applied loads are the loads corresponding to the layers which fails earliest. For all clamped edges layer 4 first reach to e = 1 and for all simply supported layer 1 first to e = 1.

Comparisons of results of both pulse shapes (step & sin) for non-symmetric (0, 30, 60, 90) laminated plate shows that, failure factor due to sin pulse reaches critical value (e = 1) earlier than step pulse. The same pattern has been observed for symmetric laminated (30,-30,-30, 30). For anti-symmetric angle-ply (45,-45,45,-45) critical failure factor for step pulse is reached earlier for case of layer 4 alone, but for other layers the results are similar to the other cases. This is due to the large time duration of step pulse. However, for all the cases, depending upon which first layer failed due to lower load, both pulse shapes create of critical failure to same layer.

5. CONCLUSION

This Paper seeks to provide some understanding of prediction of critical failure of laminated composite plates with different boundary condition, arbitrary stacking sequence and pulse shapes subjected to static and dynamic pressure loads, based upon the finite element analysis procedures using the ANSYS. Due to the lack of results from published literature, no comparison for dynamic failure factor using the finite element methods is possible. Vibration measurement of plates, before and after the introduction of failure, gives useful information about the extension of failure in the plates. To reduce of failure factors further stiffeners provided in the centre of plates.

Nomenclature

$a = b = h$	Dimension of the plates
D_{ij}	Stiffness modulus
e	Failure factor
$E_{ij}, G_{ij}, \upsilon_{ij}$	Young's modulus, Shear modulus and Poisson ratio
$[K], [M]$	Stiffness and Mass matrices
$P(t)$	Normal dynamic pressure load
T	Fundamental period
T_5	Fifth fundamental period
t	Total time duration
t_d	Time duration of pulses
λ_i	Frequency parameters
$\sigma_{xt\,\&\,xc}$	Ultimate strength for tension and compression in the X direction
$\sigma_{yt\,\&\,yc}$	Ultimate strength for tension and compression in the Y direction
$\sigma_{zt\,\&\,zc}$	Ultimate strength for tension and compression in the Z direction
CC-CC, SS-SS	All edges are clamped and simply supported

Step Pulse $P(t) = P_0 \quad if \quad 0 \le t \le t_d \quad \& \quad P(t) = 0 \quad if \quad t > t_d$

Half Step Pulse $P(t) = P_0 \sin(\pi t / t_d) \quad if \quad 0 \le t \le t_d \quad \& \quad P(t) = 0 \quad if \quad t > t_d$

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