Stress analysis of laminated E-glass epoxy composite plates subject to impact dynamic loading

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ABSTRACT

The transient response of an E-glass epoxy laminated composite plate impacted by a steel circular cylinder is analyzed. The analysis is performed by using a three dimensional hybrid stress finite element program. The contact force between the projectile and the laminated plate is modeled by the Hertzian impact law. The transverse deflection at the center of the laminated plate agrees with the deflection determined experimentally. The displacement and stress distributions are plotted as a function of time to show the transient response of the laminated plate when impacted by a projectile. The effects of projectile velocity and laminate thickness on the impacted stress distributions and the central transverse deflection are also investigated.

INTRODUCTION

The transient response of laminated plates subject to local impact loadings has been of significant concern in many advanced engineering structures and components. For example, the leading edge of an aircraft wing or blades in a jet engine may be hit by foreign objects such as stones, nuts, bolts or birds. In these cases the impact resistance of laminated plates must be known in order to design the laminated plates which meet aircraft safety requirements.

Impact problems with energies far below the penetration levels can cause significant damage to components made of composite materials, since delamination often occurs at energy levels which are an order of magnitude below those causing penetration [1]. The analysis of the plate impact problems has been concerned for a long time history. Goldsmith [2] provided a detailed discussion for impact on isotropic beams and plates. Chow [3] investigated the transient response of a rectangular laminated plate subject to a concentrated impact loading by using shear deformation theory [4]. Chen [5] applied a Hertzian contact law to analyze the response of impact on anisotropic materials. The dynamic response of laminates impacted by spherical impactors was discussed by Greszczuk and Chao [6] using Hertzian contact theory.
Concerning the plate impact experiments, a systematic experimental study of failure mechanisms on impact of laminated plates was conducted by Takeda [7]. In the experiments, a small steel cylinder was fired from a gas gun at subperforation velocities. It indicated that the flexural wave propagation was the principal response mode of moderately thin and thick plates subject to central local impact and it led to delamination failure propagation. The effect of impactor mass and velocity, and ply orientation on laminated plate delamination was investigated by Takeda et al. [8,9].

In the present investigation, a hybrid stress finite element program is applied to predict the displacement and stress distributions in an E-glass epoxy laminated composite plate subject to a local impact loading. The accuracy and versatility of the hybrid stress finite element method have been validated by many investigators [10,11,12], they have proven that the hybrid stress finite element model is a useful tool in attacking complicated structure analysis problems. The detailed formulation of this model can be found in these references.

The analysis herein is concerned only with the time that the laminated plate remains elastic, and that delamination has not yet occurred. The damping in the laminated plate is assumed to be negligible. The stresses and central transverse deflections are presented to show the transient response of the laminated plate when impacted by a projectile. Knowledge of where and when the stresses are maximum should be helpful in determining where, when, and how the delamination failure occurs.

IMPACT MECHANISM AND LAMINATE CHARACTERISTICS

In the present investigation, a blunt-ended steel circular cylinder with 2.54 cm (1 in) in length and 0.9525 cm (3/8 in) in diameter is used as a projectile. The mass of the projectile is 14.175 gm (1/2 ounce). The target plate is a square E-glass epoxy laminated composite plate with a side length of 14 cm (5.5 in). The target plate is clamped around the four edges. The projectile dimensions and mass, and plate dimensions and boundary conditions are the same as those used in the experimental works conducted by Takeda [7].

The material of the laminate is the Scotchply 1002 E-glass epoxy with the following material properties for each lamina,

\[
\begin{align*}
E_L &= 40.0 \text{ Gpa} \\
E_T &= 8.27 \text{ Gpa} \\
G_{LT} &= 4.13 \text{ Gpa} \\
G_{TT} &= 3.03 \text{ Gpa} \\
v_{LT} &= v_{TT} = 0.26 \\
\rho &= 1.90 \text{ gm/cm}^3,
\end{align*}
\]

where \(\rho\) is the density of the lamina, with units of mass per unit volume.

Due to the laminate geometry, boundary conditions, and loading are symmetric with respect to the axes through the center of the laminate, it is sufficient to analyze only one quarter of the laminate. The clamped boundary conditions for the present model are shown in Figure 1, where the shaded area is the impact area.
HERTZIAN IMPACT LAW AND FORCE DISTRIBUTION ON IMPACTED PLATE

In the present hybrid stress finite element model, equivalent nodal forces are required in the computation. However, when a laminate is impacted by a projectile only the velocity of the projectile can be observed. The actual force distribution between the projectile and the laminate during impact is unknown. An elastic impact including indentation of the laminate surface by the projectile is used to simulate the force distributions of the projectile on the laminated plate. The force between the projectile and the laminate during impact is assumed to be governed by the Hertzian theory in the form of

\[ F = H(r - w)^p, \]  

(2)

where \( F \) is the applied force of the projectile on the laminate during impact, \( H \) is a material constant, and is set equal to 100,000,000 N/m\(^{1.5}\), \( r \) is the displacement of the projectile, \( w \) is the displacement at the point of impact, i.e. the transverse displacement of the center of the laminate, and \( p \) is an exponent and equals to 1.5. Both displacements are measured from the surface of the undeformed laminate. The Hertzian contact law was used successfully by Petersen [13] in the investigation of transient response of laminated plates subject to dynamic impact loading. In his study, \( p \) was set equal to 1.5, and the corresponding value of \( H \) was set equal to 100,000,000 N/m\(^{1.5}\), which were found to be appropriate. The contact behavior is mathematically modeled and incorporated into the hybrid stress finite element program to perform the dynamic analysis of a square laminated plate subject to impact of a steel circular cylinder.

After the establishment of the hybrid stress finite element model and the Hertzian impact law, the transient response of the E-glass epoxy laminated composite plate impacted by a steel circular cylinder projectile is investigated. The central transverse deflection and stress distributions as functions of time are presented in the next section.

E-GLASS EPOXY LAMINATES SUBJECT TO A LOCAL IMPACT

In this section, the central transverse deflection and stress distributions of an E-glass epoxy cross-ply laminate subject to impact loading are examined. Equal thickness is assumed in each layer. The laminate and projectile dimensions are as described in the previous section. The boundary conditions of the finite element model are given in Figure 1. The force distribution between the projectile and the laminated plate during impact is governed by the Hertzian impact law, which allows the projectile to indent the laminate and rebound.

Figure 2 contains plots of the central transverse deflection of a 3-layer cross-ply (0/90/0) E-glass epoxy laminate impacted by a circular cylinder projectile as a function of time determined experimentally and by the hybrid stress finite element method. The laminate thickness is 4.29 mm and the projectile velocity is equal to 22.6 m/sec. The deflection predicted by the hybrid stress finite element method agrees with the deflection determined experimentally for time interval less than 300 μsec. As time increases, the computed and experimental deflections do not agree closely because that the delamination failure is initiated at the interface of the laminate and the material stiffness changes after the delamination failure occurs. The other reason is that the
boundary conditions for the experimental work are not truly clamped around the four edges. The metal frame which holds the impacted laminate will allow the laminate to move in the horizontal direction and rotate a small amount. These effects cause that the effective side length of the laminated plate is larger than the distance between the supports.

In the following investigations, the effort will be concentrated on the numerical analysis. A perfect clamped boundary condition is assumed around the edges and the side length will be set equal to 140 mm in the computation. The central transverse deflection of a 3-layer cross-ply (0/90/0) E-glass epoxy laminate as a function of time with Hertzian impact is shown in Figure 3, where the laminate thickness is equal to 3.81 mm and the projectile velocity is equal to 22.6 m/sec. After impact, the center point deflects from zero to a maximum about 1.7 mm at 300 μ sec. As time increases, the plate starts to rebound. The period of the dynamic response is longer than Figure 2, where the thickness is equal to 4.29 mm, it indicated that the thickness of the laminate has effect on the period of the dynamic response. The applied force between the projectile and the laminate computed from the Hertzian impact law is also included in Figure 3. The first impact occurs from 0 to approximately 260 μ sec, at which time, the projectile loses contact with the laminate. The projectile recontacts the laminate at approximately 530 μ sec. These observations agree with the results of experimental works.

The transverse deflections along the x axis and the y axis of the same laminate under Hertzian impact for time from 40 to 200 μ sec are shown in Figures 4 and 5. The results show the flexural wave motion along the x axis and the y axis from the center to the edge of the laminate. Since $E_l$ is greater than $E_r$, the bending stiffness $D_{ll}$ is greater than $D_{rr}$ for a 3-layer cross-ply (0/90/0) laminate. This difference in bending stiffness causes the flexural wave to move faster in the x direction than in the y direction. For example, observe the deflection at time equal to 80 μ sec, the distance from the center to the nearest point of zero deflection is 36 mm in the x direction and 28 mm in the y direction. At a particular time, the transverse deflection is larger at a specified point along the x axis than at a point at the same distance along the y axis. The difference between them is owing to the anisotropy exhibited by a 3-layer cross-ply laminate.

The normal stress, $\sigma_x$, transverse normal stress, $\sigma_y$, and transverse shear stress, $\tau_{xy}$, along the x axis in the 3-layer cross-ply laminate are shown in Figures 6, 7, and 8 for time from 20 to 100 μ sec. The normal stress, $\sigma_x$, which is evaluated at the upper surface of the 90° layer (2/3 laminate thickness above the bottom of the laminate) along the y axis for time from 20 to 100 μ sec are shown in Figure 9. As the observation for the transverse deflection, in which the flexural wave moves faster in the x direction than in the y direction, the stress wave is also noticed moving in a similar fashion. The maximum value of the normal stress, $\sigma_x$, along the x axis is greater than the maximum value of the normal stress, $\sigma_y$, along the y axis. The transverse normal stress (Figure 7), $\sigma_y$, which is evaluated at the top surface of the laminate is dependent on the contact force computed from the Hertzian impact law (Figure 3). Outside the impact region, the transverse normal stress approaches to zero.

Figure 10 contains plots of the central transverse deflection versus time for a 3-layer cross-ply (0/90/0) laminate under three different projectile velocities, 20 m/sec, 40 m/sec, and 60 m/sec,
respectively. The central transverse deflection increases with increasing projectile velocity and is almost proportional to the projectile velocity, but the period of the dynamic response remains the same. It is seen that the projectile velocity does not have an effect on the period of laminate response.

CONCLUSIONS

The deflection and stress distributions of laminated E-glass epoxy composite plate subject to impact of a steel circular cylinder projectile have been investigated and presented graphically. The contact force between the projectile and the laminated plate during impact was modeled by the Hertzian impact law. The contact force distribution was incorporated into the hybrid stress finite element program to perform the analysis. The central transverse deflection of the laminated plate predicted by the finite element method agreed with the deflection determined experimentally. The force distribution between the projectile and the laminated plate computed from the Hertzian impact law showed that the projectile impacted the laminated plate, lost contact, and then recontacted, which agreed with the experimental observations.

The stress distributions along the x axis and the y axis of a laminated plate when impacted by a projectile showed evidence of flexural wave motion. The flexural wave started from the center of impact and propagated outwardly. For an anisotropic laminated plate, the flexural wave propagated faster in the direction in which the bending stiffness is the greatest. Higher stresses were also existed in the direction having higher stiffness. The transverse normal stress and shear stresses were dependent on the history of the contact force. After the time when the projectile separated from the laminated plate, these stresses decreased significantly.

For a thicker laminated plate, the central transverse deflection and the period of the dynamic response were smaller. Laminate thickness also had an influence on the flexural wave velocity. The flexural wave propagated faster in the thicker laminate than in the thinner laminate. The deflections and stresses were proportional to the projectile velocity.

The deflection and stress analysis for the present impact problems was based on the assumption of linear elasticity and the damping in the laminated plate being neglected. It was assumed that no failures will occur within the structure. However, experimental studies of impact by Takeda et al. [9] showed that delamination usually existed at the interface between layers. They observed a delamination crack beginning near the point of impact and propagating outwardly.

The present hybrid stress finite element model is capable of providing predictions of the interlaminar stresses which actually cause delamination cracks at the interfaces [14]. It is hoped that the interlaminar stresses can be incorporated into a suitable failure criterion to examine the failure envelope and investigate the initiation of the delamination crack and the characteristics of the delamination mechanism at a particular interface.

REFERENCES


Figure 1. Clamped boundary conditions for a quadrant of the laminate.

Figure 2. Transverse deflections of the center vs time for a 3-layer laminate determined experimentally and by using hybrid stress finite element method, h=4.29 mm, v=22.6 m/sec.
Figure 3. Transverse deflection of the center vs time for a 3-layer laminate under Hertzian impact, \( h=3.81\ \text{mm} \), \( v=22.6\ \text{m/sec} \).

Figure 4. Transverse deflection along the x-axis under Hertzian impact for time from 40 to 200 \( \mu\) sec, \( v=22.6\ \text{m/sec} \).
Figure 5. Transverse deflection along the y-axis under Hertzian impact for time from 40 to 200 µsec, v=22.6 m/sec.

Figure 6. Normal stress along the x-axis under Hertzian impact for time from 20 to 100 µsec, v=22.6 m/sec.
Figure 7. Transverse normal stress along the x-axis under Hertzian impact for time from 20 to 100 μ sec, v=22.6 m/sec.

Figure 8. Shear stress along the x-axis under Hertzian impact for time from 20 to 100 μ sec, v=22.6 m/sec.
Figure 9. Normal stress along the y-axis under Hertzian impact for time from 20 to 100 μsec, \(v=22.6\) m/sec.

Figure 10. Transverse deflections of the center vs time for a 3-layer laminate under Hertzian impact with three projectile velocities, \(h=3.81\) mm.