Mathematical & Computational Applications, Vol. 7, No. 1, pp. 73-82, 2002
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TRANSIENT DYNAMIC ANALYSIS OF LAMINATED COMPOSITE PLATE SUBJECTED TO LOW-VELOCITY IMPACT

Züleyha Aslan and Ramazan Karakuzu
Department of Mechanical Engineering, Dokuz Eylül University,
Bornova, İzmir, Turkey

Abstract-This paper concerns with the transient response of composite laminates subjected to low-velocity impact. A drop weight impact tower is used for the low velocity impact study and the contact force during impact is measured with a piezoelectric force transducer. Composite laminates, made of E-glass/epoxy and having $(0/90/0)_s$ stacking sequence, are considered. Numerical results of E-glass/epoxy cross-ply laminates under three different impact velocities (1 m/sec, 2 m/sec and 3 m/sec) and two different impactor masses (135 g and 2600 g) are investigated with 3DIMPACT computer code. Contact force between the impactor and composite laminate, maximum transverse displacement at the center are plotted as functions of time and predicted delamination shapes and sizes are found numerically. The resulting data from the drop-weight tests and computer code provide specific information about the effect of the impactor velocity and impactor mass, all of which have a great influence on the impact response of composite laminates.

1. INTRODUCTION

Engineering structural components made of composite materials are increasing in use in the sporting goods industries, aerospace, automobile, offshore structures, and in marine and civil engineering applications. It is especially important to know how these materials are affected by impact, whether it occurs as part of the intended use of the product, or unintentionally as a result of dropping the product or striking it with another object. Low-velocity impact is one of the most subtle threats to composite materials in aeronautics: owing to the weak bonds between the plies, even small energies imparted by out-of plane loads can result in hardly detectable damages, causing considerable strength losses in tension and, especially, in compression. Therefore, the problem of low velocity impact of laminated composite materials has received much attention in recent years [1-5].

Oguibe and Webb [6] and Besant et al.[7] have studied the finite element modelling of low velocity impact of a laminated composite plate. Kim and Kang [8] developed a new analytical method for predicting the impact force from the dynamic strain of composite plates subjected to transverse impact. They introduced two assumptions in their study. Firstly, the impact force and dynamic strain can be separated into frequency and amplitude. Secondly, the amplitude of the impact force corresponds to that of the dynamic strain at any frequency. Abatan et al. [9] studied analytically and numerically impact resistance modelling of hybrid laminated composite. They evaluated the effect of different pulse shapes on the impact response. Sun and Liou [10] investigated laminated composite plates under impact dynamic loading using a three-dimensional hybrid stress finite element method. They have modelled the contact force between the projectile and the laminated plate with the Hertzian impact law. Chandrashekhara et al. [11] estimated the contact force on composite plates using impact-induced strain and neural networks. Ramkumar and Chen [12] predicted the response of anisotropic laminated plates to low-velocity impact by a rigid object. The contact area was assumed to vary with time, and the complex contact problem was replaced by a loading history that based on available experimental data from instrumented impact tests. Razi and Kobayashi [13] investigated delamination due to low-velocity impact of simply supported graphite/epoxy cross-ply laminate beams and plates.

Choi and Hong [14] proposed a new method for simple prediction of the impact force history on composite laminates subjected to low velocity impact. The impact duration was computed from the eigenvalue analysis of the lumped mass system in which the mass of an impactor was lumped with the plate, and the impulse-momentum conservation law was used with the concept of the spring-mass model. Pierson and Vaziri [15] presented a robust analytical solution technique for the impact response of specially orthotropic rectangular plates.

In the present investigations, a drop weight impact test is used to describe the behaviour of E-glass/epoxy laminated composite plates subjected to the central impact of a hemispherical tip-ended rigid projectile. A numerical investigation into the response of laminated composite plate is carried out using 3DIMPACT transient dynamic finite element analysis code from F.K. Chang. The objective of this research is to determine the influence of impactor velocities and impactor masses on the low-velocity impact response of the clamped laminated plates.

2.EXPERIMENTAL

All the laminates are manufactured from E-glass continues fibers and epoxy resin. A cross-ply lay-up $(0/90/0)_s$ is chosen. For matrix materials, epoxy CY225 and hardener HY225 are mixed in the mass ratio of 100:80. The curing is held on 120 ^{0}C for 4 h under the pressure of 0.2 MPa. The post curing is carried out at 100 ^{0}C for 2 h. It is then cooled to room temperature at the same pressure. The mechanical properties of the laminates are given in Table 1. All of these properties are measured in the mechanical laboratory. The mechanical testing is carried out by Instron-1114 Tensile Testing Machine.

Low velocity impact tests are conducted using a vertical drop weight testing machine developed in the department laboratory. To measure the impact force history Brüel & Kjaer 8201 type piezoelectric force transducer and NEXUS-2692 A OI1 signal-conditioning amplifier are used.

All specimen dimensions are 150 mm by 150 mm and thickness of the laminates 3.4 mm. Prior to impacting, the specimens are tightly clamped on both ends to a target holder, resulting in the 150 mm span. The impact point is on the center of the plate. Impact tests are performed at increasing impact velocities 1 m/sec, 2 m/sec and 3 m/sec and impactor masses of 135 g and 2600 g.

Table 1. Material properties for E-glass/epoxy composite

Symbol	*Value*	*Property*
V_f	57 %	fiber volume fraction
ρ	1.506 gr/cm^3	density
E_1	44 GPa	longitudinal modulus
E_2	10.5 GPa	transverse modulus
G_{12}	3.7 GPa	in-plane shear modulus
ν_{12}	0.36	major poisson's ratio
X_t	800 MPa	longitudinal tensile strength
Y_t	50 MPa	transverse tensile strength
S	60 MPa	in-plane shear strength
X_c	350 MPa	longitudinal compressive strength
Y_c	125 MPa	transverse compressive strength
S_i	35 MPa	interlaminar shear strength

3. FINITE ELEMENT MODELLING

The numerical simulation of E-glass/epoxy composite is carried out by using 3DIMPACT transient dynamic finite element analysis code [16,17]. The model of the impact problem includes a laminated composite plate and a hemispherical tip-ended rigid projectile as shown in Figure 1. The origin of the Cartesian co-ordinate system is located in the middle plane of the laminated plate, and the z-axis is perpendicular to the mid-plane. The contact forces between the impactor and the composite plate as functions of time, transient displacement at the center of the composite plate and a failure analysis for predicting the threshold of impact damage and initiation of delaminations are calculated numerically.

The composite plate is modelled using 8–nodded brick element. A total of four elements are used through the thickness of the laminate. The mesh is made progressively coarser towards the boundary and 768 elements are used in the numerical calculations for generating the results.

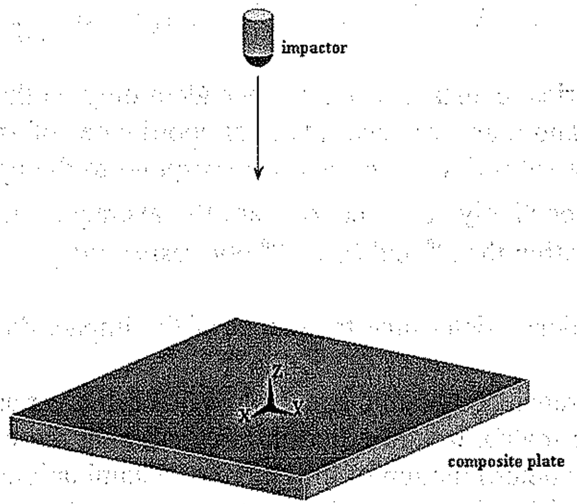


Figure 1. The model of the impact problem.

Gauss quadrature integration scheme is used through the element thickness to account for the change in material properties from layer to layer within the element. The Newmark scheme is adopted to perform time integration from step to step. A contact law incorporated with the Newton-Raphson method is applied to calculate the contact force during impact. The computer code allows evaluation of delamination areas by means of suitable stress analysis and damage criteria. In order to predict the occurrence of the critical matrix cracks, the matrix failure criterion proposed previously by Choi and Chang [17] is adopted at this code; the criterion can be expressed as

$$\left(\frac{{}^{n}\bar{\sigma}_{yy}}{{}^{n}Y}\right)^{2}+\left(\frac{{}^{n}\bar{\sigma}_{yZ}}{{}^{n}S_{i}}\right)^{2}=e_{M}{}^{2} \qquad \begin{array}{l} e_M \geq 1 \text{ Failure} \\ e_M < 1 \text{ No failure} \\ {}^{n}Y = {}^{n}Y_t \text{ if } \bar{\sigma}_{yy} \geq 0 \\ {}^{n}Y = {}^{n}Y_c \text{ if } \bar{\sigma}_{yy} \langle\ 0 \end{array} \tag{1}$$

where the subscripts of x and y are the local coordinates of the n$^{\text{th}}$ layer parallel and normal to the fiber directions, respectively, and z is the out-of plane direction. S_i is the interlaminar shear strengths within the laminate under consideration, and Y_t and Y_c are the ply transverse tensile and compressive strengths, respectively.

Whenever the calculated averaged stresses in any one of the plies in the laminate first satisfy the criterion ($e_M = 1$) during impact, initial impact damage is predicted. It is assumed then that the matrix crack would propagate throughout the thickness of the ply group, which contained the cracked ply. Once a critical matrix crack is predicted in a ply within the laminate, a delamination can be initiated from the crack. Then, the following impact-induced delamination growth criterion for low velocity impact proposed by Choi and Chang [17] is applied at this code.

$$D_a\left[\left(\frac{{}^{n}\bar{\sigma}_{yz}}{{}^{n}S_{i}}\right)^{2}+\left(\frac{{}^{n+1}\bar{\sigma}_{xZ}}{{}^{n+1}S_{i}}\right)^{2}+\left(\frac{{}^{n+1}\bar{\sigma}_{yy}}{{}^{n+1}Y}\right)^{2}\right]=e_{D}{}^{2} \qquad \begin{array}{l} e_D \geq 1 \text{ Failure} \\ e_D < 1 \text{ No failure} \\ {}^{n+1}Y = {}^{n+1}Y_t \text{ if } \bar{\sigma}_{yy} \geq 0 \\ {}^{n+1}Y = {}^{n+1}Y_c \text{ if } \bar{\sigma}_{yy} \langle\ 0 \end{array} \tag{2}$$

where D_a is an empirical constant which is dependent only on the material system used. The subscripts x, y and z are the local material coordinates of an individual ply within the laminate, and the subscripts n and $n + 1$ correspond to the upper and lower plies of the n^{th} interface, respectively. $\bar{\sigma}_{yz}$ and $\bar{\sigma}_{yy}$ are the averaged interlaminar and in-plane transverse stresses within the n^{th} and $(n + 1)^{\text{th}}$ ply, respectively.

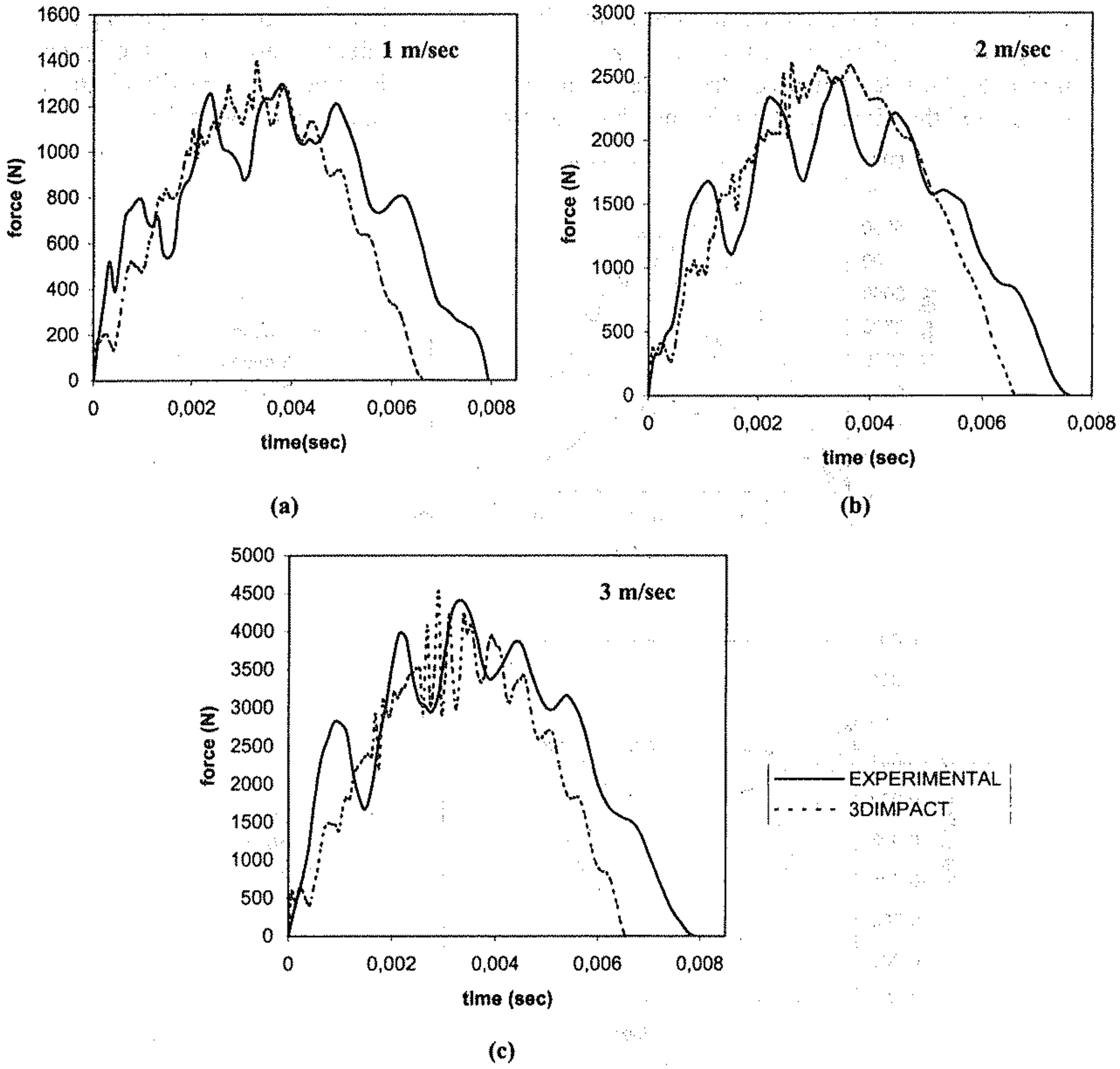
The procedure in order to determine the extent of the impact damage can be described as follows:

1. Calculating transient dynamic stresses within each layer as function of time
2. Applying the matrix failure criterion for predicting the critical matrix cracks in each layer for determination of the extent of delaminations
3. If matrix cracking is predicted in a layer of the laminate, then applying the delamination criterion subsequently in the upper and bottom layer of the interface during the entire period of impact.

4. RESULTS and DISCUSSION

4.1 Constant Mass

With the impactor mass held constant at 2600 g, the velocity is varied for three cases: (a) 1 m/sec,(b) 2 m/sec and (c) 3 m/sec. Figure 2. shows experimentally and numerically the force histories of laminated composite plate (150 mm by 150 mm by 3.4 mm) at three different impact velocity levels. The calculated impact force between the impactor and the composite plate has higher value than that measured by the piezoelectric force transducer. The duration of impact events in the impact test results are more than that from the calculated results. The reason of this discrepancy is that the clamped boundary conditions might not have been completely realized in the impact tests.



(a) (b)

(c)

Figure 2. The force histories for three impact velocities: (a) 1 m/sec, (b) 2m/sec and (c) 3 m/sec.

Effect of impact velocity on contact force and center deflection histories of a laminated composite plate is given in Figure 3. Concerning the effects of projectile velocity on the dynamic response of an impacted laminate, it is found that the impact forces and center deflections are proportional to the projectile velocity. As can be seen, the contact time and deflection duration for the three different impact velocity are the same. The negative displacement of target point indicates a downward movement. The largest deflection (6.3 mm) is obtained at the maximum force. During the contact time, the energy is immediately transmitted to the plate involving high displacements.

Predicted delamination shapes and sizes at the interface containing the major delamination of the laminates are shown in Figure 4. for three different impact velocity levels. The "*", asterisks symbol in the figure indicates the location where the stresses are calculated and satisfied the impact-induced delamination criterion. The area covered by the asterisks gives the estimation of the delamination size. Delamination propagates along the fiber direction at the lower layer. Because major delamination is at the lower interface (the interface away from the impact side) of the laminated composite plate. It is observed that delamination damage increases with increasing impact velocity.

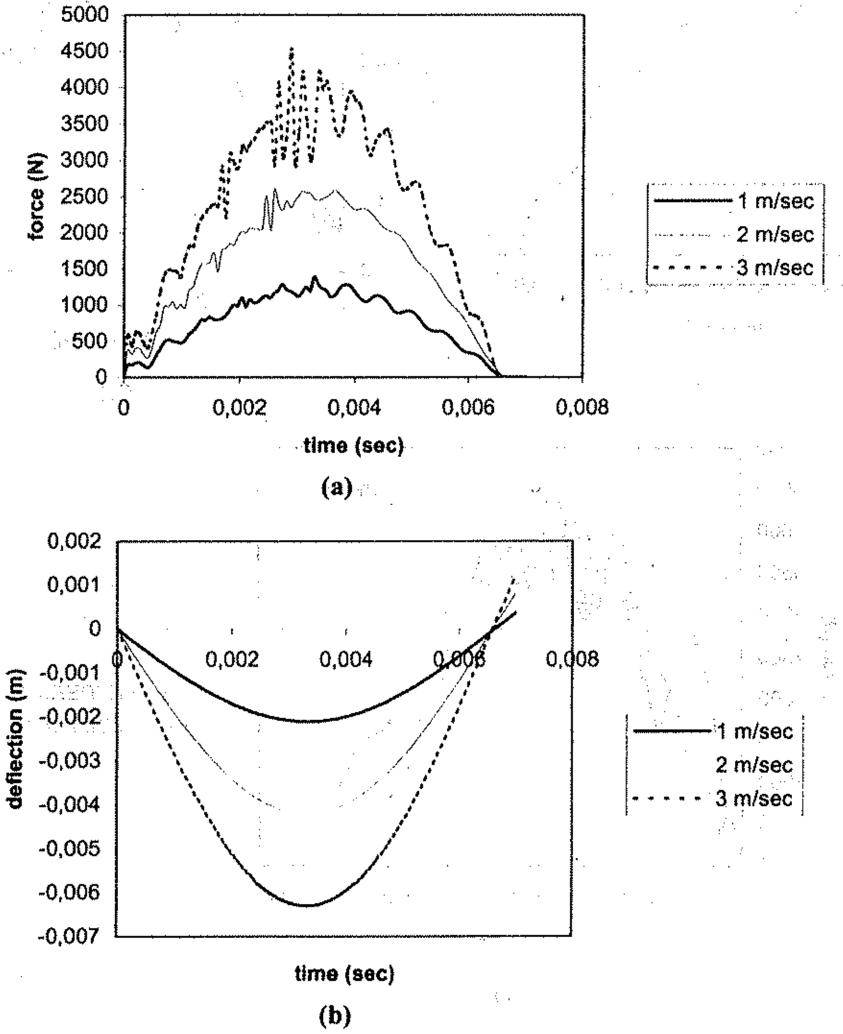


Figure 3. Effect of impact velocity (a) contact force and (b) center deflection histories of a laminated composite plate.

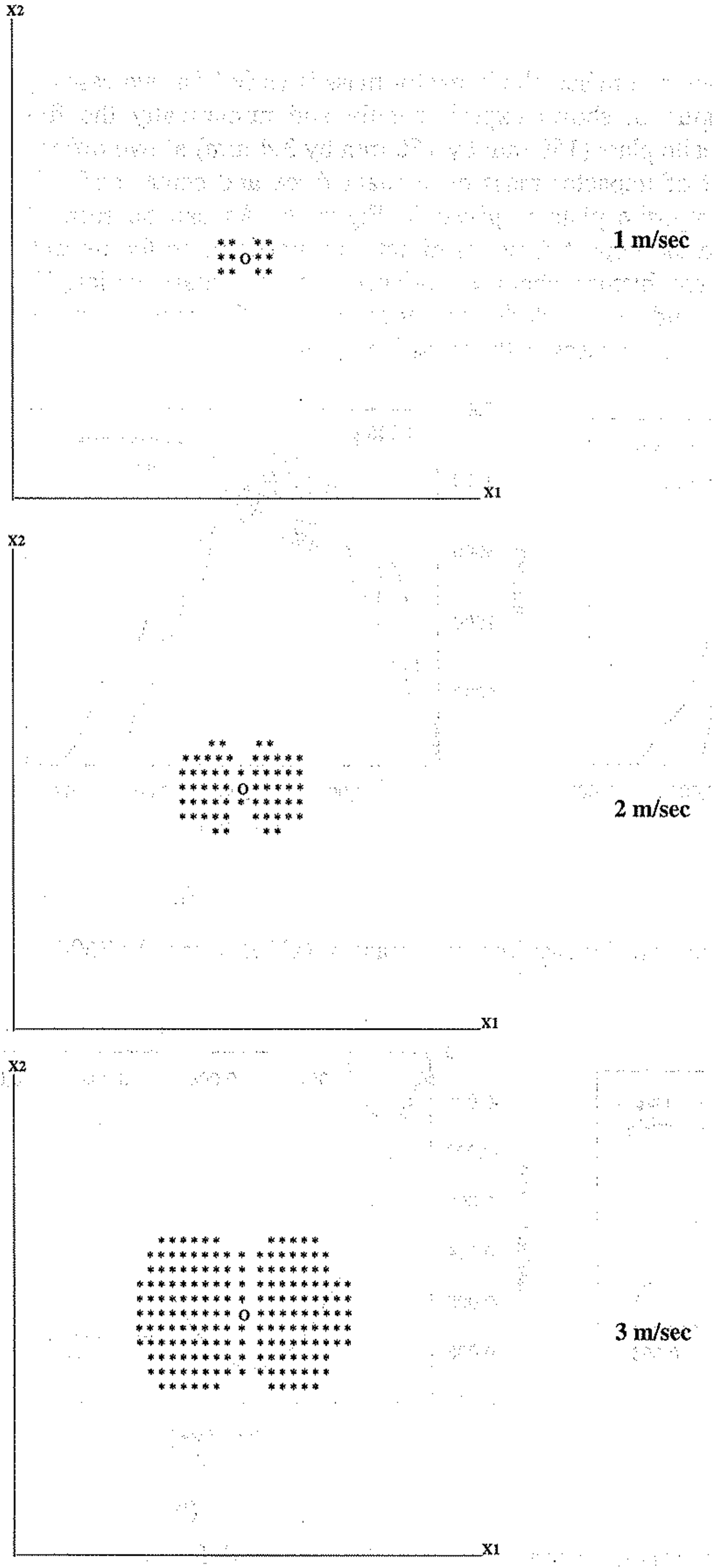
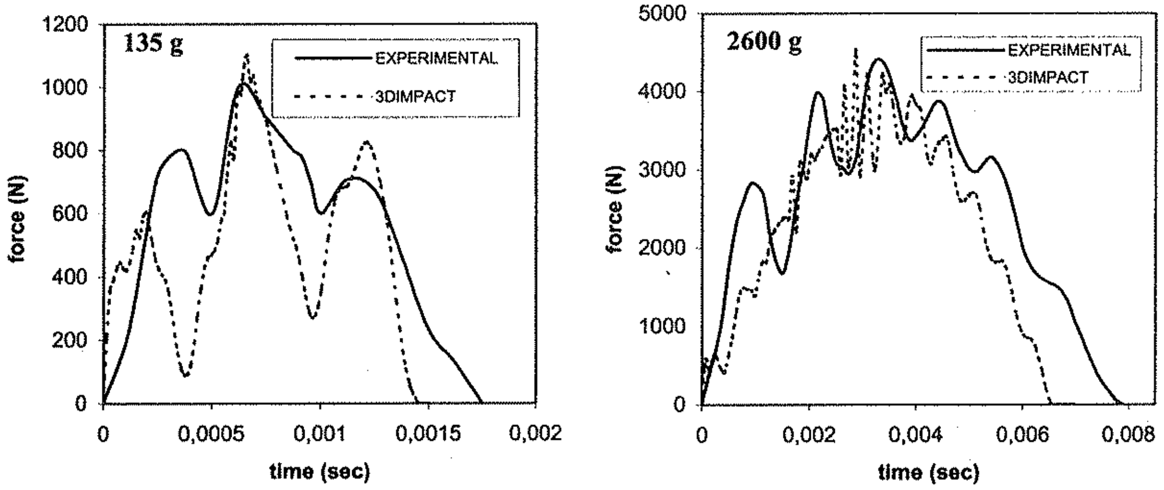


Figure 4. Predicted delamination areas for three impact velocities.

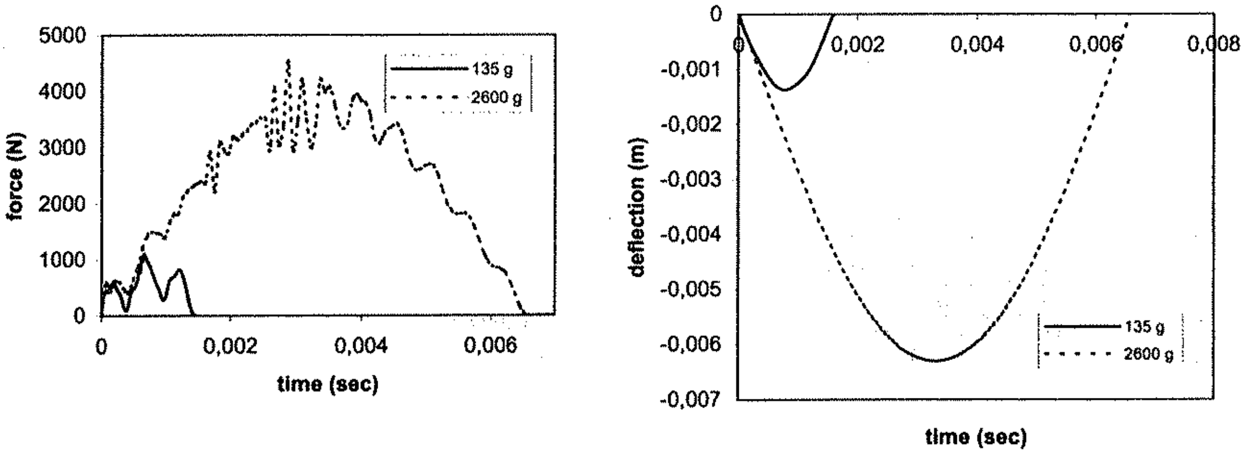
4.2 Constant Velocity

With the velocity held constant at 3 m/sec, the impactor mass is varied for two cases: (a) 135 g and (b) 2600 g. Figure 5. shows experimentally and numerically the force histories of laminated composite plate (150 mm by 150 mm by 3.4 mm) at two different impactor mass levels. Effect of impactor mass on contact force and center deflection histories of a laminated composite plate is given in Figure 6. As can be seen, the magnitude of deflections and the impact forces is directly proportional to the impactor mass. The shape of the force history changes noticeably as the mass varies. The magnitude of impact force and center deflection increases as the mass increases. Similarly the duration of contact increases as the mass increases.



(a) (b)

Figure 5. The force histories for two impactor masses: (a)135 g and (b) 2600 g.



(a) (b)

Figure 6. Effect of impactor mass on (a) contact force and (b) center deflection histories of a laminated composite plate.

Predicted delamination shapes and sizes at the interface containing the major delamination of the laminates are shown in Figure 7. for two impactor mass levels. No delamination is predicted for impactor mass of 135 g. However, the delamination damage for impactor mass of 2600 g is very big and propagates along the fiber direction at the lower layer.

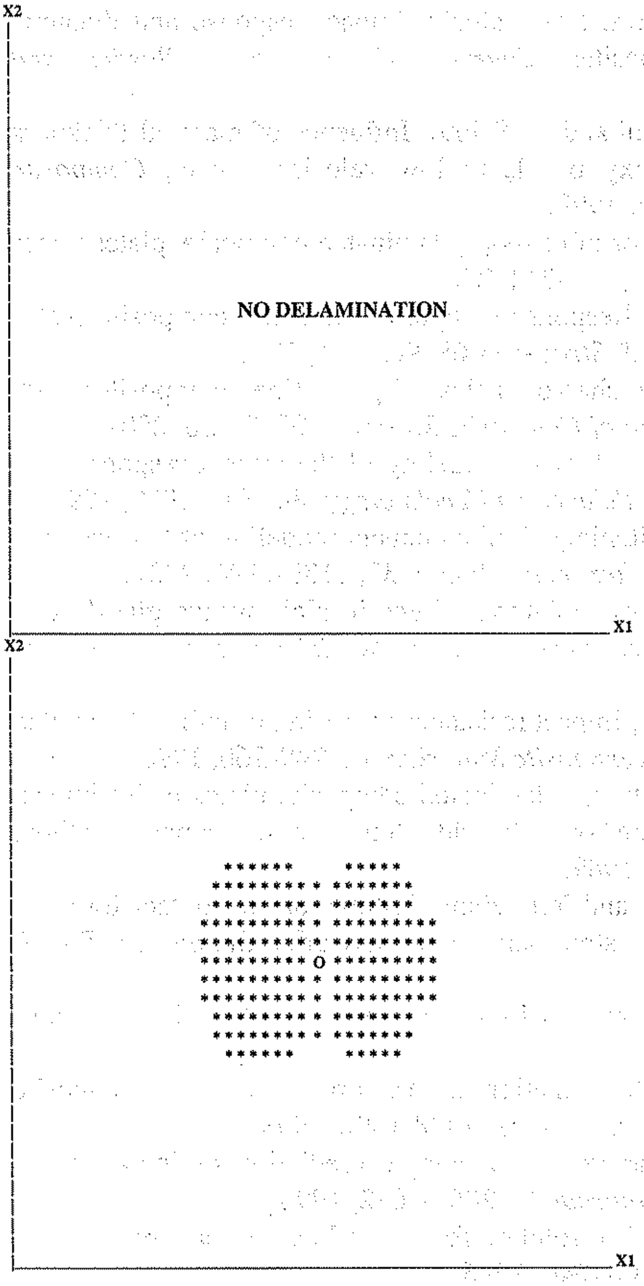


Figure 7. Predicted delamination areas for two impactor masses (135 g and 2600 g).

5. CONCLUSION

In the present investigation, low velocity impact of laminated composite plates is studied. Numerical results and a drop weight impact tower results of E-glass/epoxy laminated composite material are obtained. It is found that the impact forces, center deflections and delamination damage are proportional to the projectile velocity and impactor mass. Duration of contact increases as the mass increases. But while the projectile velocity increases, duration of contact is the same.

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