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Finite Element Analysis of Low Velocity Impact on Composite Laminates

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Abstract: ***To analyse a low velocity impact on a laminated composite plate using nonlinear explicit finite element software LS-DYNA and calculates the contact force . The present finite element model is verified by analyzing impact-loaded laminated composite plate structures that have previously been studied through experimental or other numerical procedures. Here parametric studies were carried out by varying the mass and velocity of impactor. Analytical formulation for low velocity impact on a laminated composite plate impacted by steel sphere. The predictive capability of the present numerical and analytical approach is successfully demonstrated through comparisons between experimentally-measured force-time histories for impact of carbon fiber-reinforced plastic (CFRP) plates.***

Keywords: Laminated composite plates, impact, large deflections, L S Dyna

1. Introduction

Composite laminates are used in many engineering applications Advance fiber reinforced material with high stiffness and high strength such as carbon/epoxy graphite/epoxy and Kevlar/epoxy are now widely used in as structural material in aerospace industries and material transport purpose. The classical kirchoff-law laminate theory for thin elastic plates and shells and the von karman large deflection relations are adopted in the governing finite element formulation. **[7]**.The Newmark-β method and the Newton-raphson iterative scheme are used for the time integration and solution of the set of non-linear equation within each time step **[7].** The contact force is calculated, according to the loading and unloading processes. During the loading the contact force follows the Hertzian contact law, and an expression proposed by Tan and Sun for the unloading phase[**3**], The impact response and the resulting damage of laminated composite shell objects by a metallic impactor are studied by means of the finite-element method Here the study also includes prediction of damage in the finite element code for appropriate reductions in lamina stiffness as the solution progresses[**6**]**,** Depending on the intensity of the impact loads, varying levels of internal damage are induced which can result in significant degradation of the structural stiffness and strength. To improve the performance of composite materials under impact and utilize them to their full advantage, it is crucial to have a good understanding of their impact response.

2. Impact Dynamics

During the life of a structure impact by foreign objects can be expected to occur during manufacturing, service and maintenance operations. An example of in service impact occurs during aircrafts takeoffs and landing. During the manufacturing process or during maintenance tools can be dropped on the structure, in this case the impact energy is small, laminated structures are more susceptible to impact damage often cannot be detected by visual inspection. This internal damage can severe reductions in strength and further reductions occur under the load. Therefore the effects of foreign object impact on composite structure must be understood and proper measures should be taken in the design process to account for expected events. Concerns about the effects of impact on the performance of composite structures have been a factor in limiting the use of composite materials. For these reasons the problem of impact has received considerable attention in the literature.

3. Geometrical Modeling of a Steel Sphere and Laminated Composite Plate

Figure 1 shows the geometric modeling of a laminated composite plate of carbon fiber reinforced plastic plate and a steel sphere the simulation is carried out by varying the mass and velocity of the impactor. The size of the plate is 127x76.2x4.65mm and radius of the sphere is 6.35mm. the 2D modeling is done in AUTO CAD 2007.

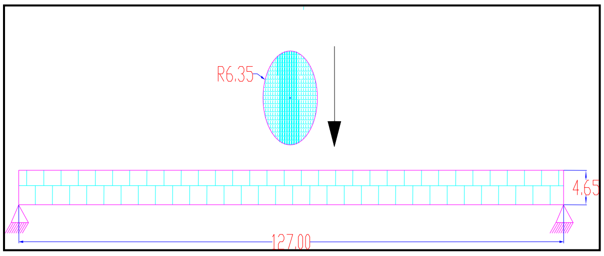

Figure 1 Geometric model of steel impactor and CFRP plate

Figure 1 shows a square plate length 127mm,width 76.2mm, and thickness 4.65mm made of a contineous fiber reinforced organic matrix laminated composite. The plate consists of 24 plies or lamine ply orientation is arbitaray and need not be symmetric with respect to the mid surface of the plate perfect bonding between each ply is asumed. The plate is supported with a simply supported boundary condition. The mass of the impactor is varied as 6.14Kg and 0.314Kg and velocity is varied as 1.76 and 2.68mm/ms for 6.14Kg mass and 7.7 and 11.85mm/ms for 0.314Kg mass.

Table 1: Material Properties of Composite plate

Material Property for plate	*Symbol (unit)*	*Value*
Young's modulus in fibre direction	E_{11} (Gpa)	32.062
Young's modulus in transverse direction	E_{22} (Gpa)	10.789
Young's modulus	E_{33} (Gpa)	10.789
Shear Modulus	G_{12} (Gpa)	11.92
Shear Modulus	G_{13} (Gpa)	11.92
Shear Modulus	G_{23} (Gpa)	4.68
Poisson's Ratio	γ_{12} (Gpa)	0.344
Poisson's Ratio	γ_{13} (Gpa)	0.344
Poisson's Ratio	γ_{23} (Gpa)	0.344
Density	ρ (kg/mm^3)	1.796e^{-6}

3.1 Low velocity impact on carbon fiber reinforced plastic by varying the mass and velocity of impactor

To validate the predictive capability of the present approach, numerical results are Compared with instrumented impact test data reported in Delfosse etal[8].The properties of the target plate used here are listed in table 1 The numerical simulations were conducted using the linear geometry option and a uniform 4 x 4 mesh for a quarter plate. In this 24 layer laminate, a single Gauss point per layer was used for the through-thickness integrations. Here the impact analysis carried out by low velocity-large mass and high velocity- small mass of impactor as shown in figures below.

3.2 Low velocity impact with impactor mass 6.14kg and velocity of 1.76mm/ms

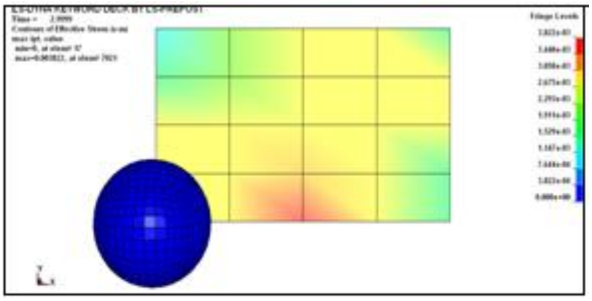

Figure: 2 Stress plot for CFRP plate at velocity of 1.76mm/ms

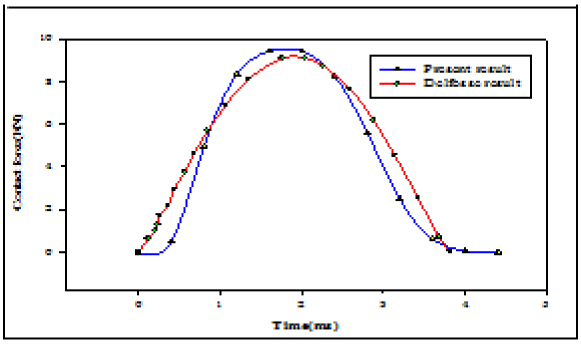

Figure: 3 Comparison force vs time of Present result with Delfosse[19]

Figure 2 illustrate the damage caused to the laminated composite plate due to an impactor with velocity of 1.76mm/ms. The red region shows the maximum stress condition at time 3ms. The nature of graph obtained by fem matches closely with that of experimental test for impact load vs time. As seen from the Figure 3 the maximum contact force for plate of 4x4 mesh size with mass of 6.14kg and velocity of 1.76mm/ms is 9.7kN at time 2.1ms. Due to continuous loading beyond this point there is a continuous progression of damage to the structure and thus reduction in the contact force. Therefore the major mode of failure for this impact loading scenario was due bending stress produce in the bottom laminate which is carried to the delamination which in turn there is reduction in the strength of laminated composite plate which in turn causes reduction in load carrying capacity of the plate. The damage in structure started with Matrix cracks since the strength properties of matrix were much less than Carbon fibers.

3.3 Low velocity impact with impactor mass 6.14kg and velocity of 2.68mm/ms

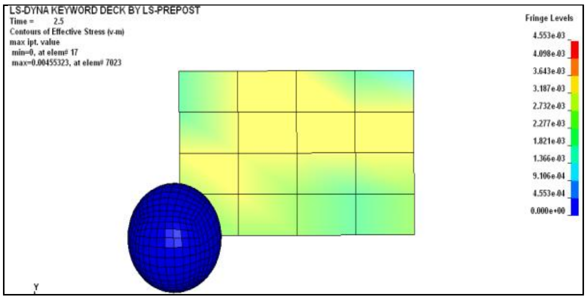

Figure 4: Stress plot for CFRP plate at velocity of 2.68m/ms

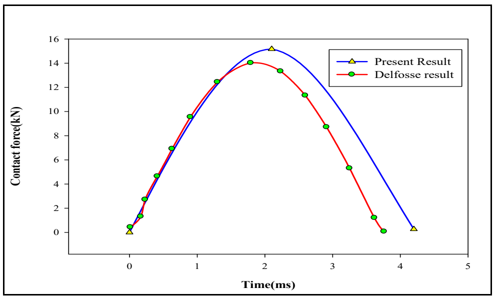

Figure 5: Comparison force vs time of Present result with Delfosse[8]

Figure 4 illustrate the damage caused to the laminated composite plate due to an impactor with velocity of 2.68mm/ms. The red region shows the maximum stress condition at time 2.5ms. Figure shows the nature of graph from fem matches closely with that of experimental test for impact load vs time. A similar laminated composite plate of 4x4 mesh size with different impactor velocity but with same mass of 6.14kg, the maximum contact force is 15.16kN at time 2.1ms(appox),as shown in Figure 5. It can be seen that the contact force is directly proportional to the impact velocity while the duration of contact is insensitive to it similarly for different mass and different velocity.

3.4 Low velocity impact with impactor mass 0.314kg and velocity of 7.7mm/ms

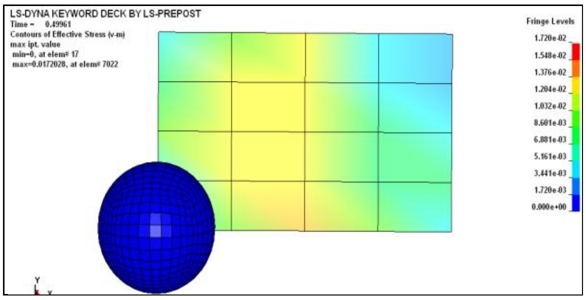

Figure 6: Stress plot for CFRP plate at velocity of 7.7mm/ms

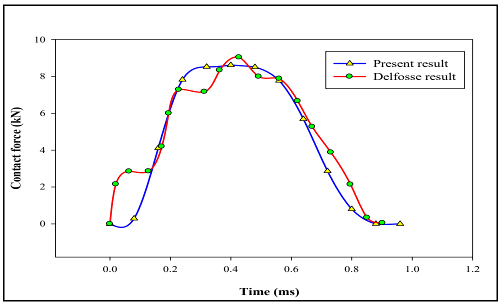

Figure 7: Comparison force vs time of Present result with Delfosse[19]

Figure 6 illustrate the damage caused to the laminated composite plate due to an impactor with small mass of 0.314kg and high velocity of 7.7mm/ms. The yellow region shows the maximum stress condition at time 0.4ms. Figure 7 shows The nature of graph from fem matches closely with that of experimental test for impact load vs time. In this case the mass of the impactor is 0.314kg and impactor velocity is 7.7mm/ms the contact force obtained is 8.61kN at time 0.5ms(approx). So it can seen if mass of impactor is small but the velocity is high then also it effect the damage process of laminated composite plate. And it can also be seen that impact duration for low mass and high velocity is less than as compared to high mass and low velocity of impactor and curve obtained from low mass and high is velocity is linear bell shape but it has some spikes due the high velocity of impactor.

3.5 Low velocity impact with impactor mass 0.314kg and velocity of 11.85mm/ms

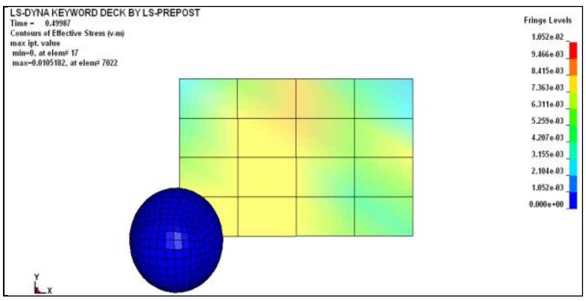

Figure 8: Stress plot for CFRP plate at velocity of 11.85mm/ms

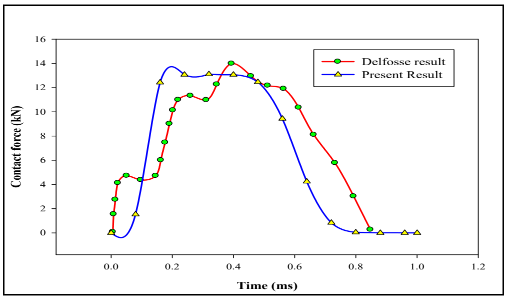

Figure 9: Comparison of contact force vs time of Present result with Delfosse[19]

Figure 8 illustrate the stress plot for CFRP plate with mass of impactor as 0.314kg and 11.85mm/ms velocity. The yellow region in the figure shows the maximum stress condition. Figure 9 shows the nature of graph from fem matches closely with that of experimental test for impact load vs time. In this case velocity of impactor is increased to 11.85mm/ms keeping the same mass as 0.314kg. The contact force obtained is 13.1kN at time 0.5ms(approx) as shown in Figure 9. So it can be concluded that the mass and velocity of impactor is proportional to each other increase in any one of the parameter increases the contact force. With the high velocity and low mass it is found that impact duration is less than that of large mass and low velocity. Figure 9 shows the spikes were due to noise component present due to breakage of fibres. The noise component affected the peak values of the stress significantly. The damage in the structure started with epoxy damage such as matrix cracks since the strength properties of matrix were much less as compared to the carbon fibers.

The trend of the predicted contact force histories are seen to be in fair agreement with the experimental results for both the low-velocity/large mass and high-velocity/ small mass.

3.6 Deformation of laminated composite plate after impact with a mass of 6.14kg and different velocities of 1.76 and 2.68mm/ms

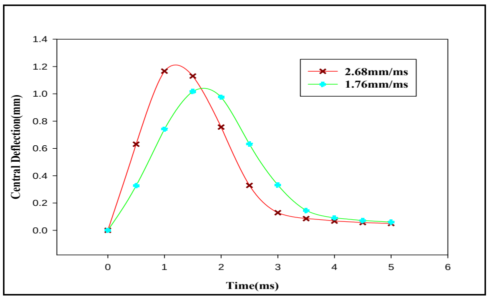

Figure 10: Comparison of Central deflection of plate with impactor mass of 6.14kg and velocity of 1.76 and 2.68mm/ms

Figure 10 shows the comparison of displacement result obatined with different velocities of impactor but keeping the mass of impactor constant as 6.14kg it is observed that the maximum displacement occurred at time 1.1ms(approx) when plate is impacted with a velocity of 2.68mm/ms and the displacement occurred at time 1.3ms(approx) when plate is impacted with the velocity of

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1.76mm/ms. It is found that as the velocity of impactor increases the maximum displacement is occurred. So it can be said that the velocity of impactor is prapotional to displacement of laminated composite plate.

3.7 Deformation of laminated composite plate after impact with a mass of 0.314kg and different velocities of 7.7 and 11.85mm/ms

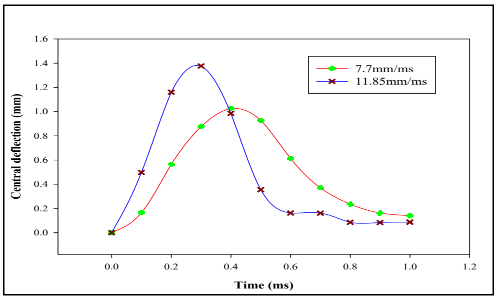

Figure 11: Central deflection of plate with impactor mass of 0.314kg and velocity of 7.7 and 11.85mm/ms

Figure 11 shows the comparison of displacement result obatined with different velocities of impactor but keeping the mass of impactor constant as 0.314kg it is observed that the maximum displacement occurred at time 0.3ms(approx) when plate is impacted with a velocity of 11.85mm/ms and the displacement occurred at time 0.5ms(approx) when plate is impacted with the velocity of 7.7mm/ms. It is found as the velocity of impactor increased the maximum displacement is occurred. So it can be said that the velocity of impactor is prapotional to displacement of laminated composite plate.

Table 2: Comparison of FEM and Experimental peak force by varying the impactor velocity

Mass of the impactor kg	*Velocity of impactor mm/ms*	*FEM Simulation Peak impact load (kN)*	*Experimental Result Peak Impact Load (kN)*	*Analytical Result(kN)*
6.14	1.76	9.7	8.16	9.6
6.14	2.68	15.1	14.0	15.44
0.314	7.7	8.61	9.15	9.48
0.314	11.85	13.1	14.0	15.9

4. Analytical Method

The analytical solution to the analysis is carried out as shown below

$$\frac{1}{2}MV^2 = \int_0^{\delta_{max}} F d\delta + \int_0^{\alpha_{max}} F d\alpha - \ 1$$

Where M and V are the mass and velocity of the impactor and δ and α represent the plate center displacement and contact indentation, respectively. The center deflection of the plate, and can be related to the contact force F by the linear equation

$$F = K\delta \ - 2$$

Where K is an stiffness of conatct is defined as relationship between the force and the displacement

$$K = 2aE^* \ - 3$$

Where $E^* = \frac{E}{(1-\gamma^2)}$

E*=Effective modulus of elasticity

a= contact radius

$$a = \sqrt{Rd}$$

R is the Radius of impactor γ_r is the Poisson's ratio of impactor, E is the Young's modulus of composite laminate and d is the indentation depth

Since K is determined from a static analysis, the plate is assumed to deform in a static mode shape. Similarly, the contact indentation, α is related to the contact force by Hertz's Law

$F = n'\alpha^{3/2} \ - 4$ Where n' is the Hertzian contact stiffness which can be approximated by the expression

$$n' = \frac{4}{3}R^{1/2}E_2 \ - 5\ (5.5)$$

Where R is the radius of the indenter and E_2 is the modulus transverse to the fiber direction.

By substituting (5.2) and (5.4) into (5.1) and integrating, the energy balance equation can be rewritten as

$$\frac{1}{2}MV^2 = \frac{1}{2}\frac{F_{Max}^2}{K} + \frac{2}{5}\frac{F_{Max}^{5/3}}{n^{2/3}} 6$$

Furthermore, the indentation and plate center deflection can be calculated through the use of (5.2) and (5.4) once Fmax is known.

5. Conclusion

The numerical simulations were carried out for varying mass and velocity of impactor. The simulation is conducted using the linear geometry option and a uniform 4 x 4 mesh for a quarter plate. In this 24 layer laminate, a single Gauss point per layer was used for the through-thickness integrations. The mass and velocity of impactor is varied from the simulations it has been observed that the results show that the contact force is proportion to the impactor velocity.as the mass or velocity of impactor is increased the contact force is also increased. However, the contact period is dependent on the stiffness of the laminated structure such as the curvature and boundary condition. The obtained results were well matched with the existing expremental results.

Parameters such as different lay-up sequences different impactor material properties different boundary conditions on laminated composite plate angle difference between the consecutive laminas and impactor with different velocities was done which affects the impact damage process. It was found that configuration with more number of interfaces and less difference between the consecutive laminas yield higher peak loads for given loading conditions which means that particular configuration is more resistant to applied loading. Also the boundary conditions on the laminated composite plate affect the impact load distribution. All of the parametric results were also correlated with the research work done by various researchers in the literature who mainly looked at the computational and experimental studies of individual parameters. The result obtained from FEM simulation for different parameters shows approximately same results observed by the researchers.

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