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Dynamic Response of Glass/Epoxy Laminated Composite Plates under Low-velocity Impact

J. Anish Jafrin Thilak*[a], P. Suresh[b]

[a] *Department of Mechanical Engineering, Mepco Schlenk Engineering College, Sivakasi, India*
[b] *Department of Mechanical Engineering, Muthayammal Engineering College, Namakkal, India*

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ABSTRACT

In the presented paper, the phenomenon of impact response of glass/epoxy laminates of thickness 5, 7, 10 mm subjected to impact energy of 50, 100, 150 J were numerically analyzed using the commercially available finite element software LS-DYNA. To predict the energy absorption capability and damage response, a finite element model was developed. The impact response was assessed in terms of maximum displacement, contact force at the event of an impact and energy absorption. Laminates with higher thickness showed better results in deformation and contact force generation when compared with thin laminates. The numerical results in terms of displacement and contact force are validated with experimental studies in the literature. Moreover, there is a good agreement between numerical results and experimental studies. In this study chang chang failure criteria were considered for predicting the impact response at low-velocity impact. Based on the observed numerical results, the energy absorption capability and the perforation resistance of the laminated composite structure were revealed. These results can be further referred to in the design and modelling of the composite laminated structure subjected to impact loadings. A grid independent study has been performed in this paper, which will be helpful for the researchers to select an optimized element size to reduce the computational time. In addition, the finite element analysis reasonably predicted the impact load–displacement responses and the perforation energies of laminated plates.

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1. INTRODUCTION

Glass/epoxy laminated composites are valued for their strength and stiffness concerning their density and are preferable to traditional materials in various applications where weight plays a major role, like aircraft panels, rocket structures. Whereas, the resistance to transversal loads of these materials is poor, especially dynamic loads. Many attempts have been made endlessly in search of materials with relatively high quality and performance. Synthetic fiber-reinforced composites, especially glass/epoxy laminated composites have gained substantial importance in aerospace and defense applications due to their high specific strength, damage tolerance and maturity in processing [1]. Fiber-reinforced polymer (FRP) composites have better fatigue and corrosion resistive performance superior to metals, which in turn reduce the maintenance cost. Moreover these materials have been recognized as effective energy-absorbing materials in impact related applications [2]. But still many researchers have extensively studied laminated composites' performance since an out of plane impact can initiate damage even at very low impact energies [3]. In FRP structures with impact, the damage is one of the major concern in aerospace industries since it can accidentallly happen from dropped tools, hailstone impact, bird strikes and so on [4]. This research work addresses the imapact damage caused either by low-velocity sources like collisions between cars, cargo, maintenance damage, dropped tool or high velocity sources like runway debris, hail, bird strike and having some ballistic impact in military aircraft. The influence of diameter and boundary conditions on low-velocity impact response of CFRP circular laminated plates has

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*Corresponding author email: jafrinthilak@gmail.com (J. Anish Jafrin Thilak)

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been investigated [5]. Their results indicate that the higher target stiffness results in more energy absorption and delamination. Recently, the behavior of continuous fiber composite sandwich core plates under low-velocity impact was studied [6]. They revealed that the multi-cell composite corrugated core has increased the energy absorption capacity because of the fibers between adjacent cells. Impact damage detection is a key factor to maintain the structural integrity of composite structures used in the aerospace industry. Impact loads are always considered a threat to laminated structures since it reduces the load bearing capability. The effects of impactor mass, velocity and energy on the contact force, energy absorption and overall damage area of laminates were also investigated [7]. Researchers have also employed active thermography techniques and image processing technology. The pattern and area of the damage zone were determined by the Vibro thermography method [8]. It was established that a flat nose striker causes no crucial damage to the composite laminate, when compared to a conical and spherical nose impactor. In addition, the stiffness behavior [9] of hybrid laminated composites with surface crack has been investigated. Energy balance modeling [10] of high-velocity impact effect and damping response [11] in fabric reinforced composite plate structures were also studied by researchers in the last decades.

Eventually, the results of the low impacts results in a drastic reduction of stiffness and strength of laminates, therefore investigating the material's stiffness and strength at the time of impact is essential. Even though the impact behavior of laminate structures has been investigated by various researchers very few works reported the comparison study on the response on different laminate thickness and impact velocities. In this study, the low-velocity impact response behavior of glass/epoxy composite laminates was numerically investigated with the help of LS-Dyna, commercially available explicit finite element software. The effect of laminate thickness and impact energy on the response behavior was studied.

2. EXPERIMENTAL INVESTIGATION

In this section, the materials used in the sample preparation for material characterization and impact tests were discussed. In addition the experimental test procedures implemented for the low velocity impact testing was also discussed.

2. 1. Materials and Sample Preparation

The materials needed for the preparation of the laminates are glass fiber, epoxy resin and hardener. In the recent studies about composite materials performance the widely used resin and hardener are LY556 and HY951. At room temperature the composites having a density of 1100 kg/m^3 and 1000 kg/m^3, respectively. E-glass plain woven fabric having a thickness of 0.25 mm, 360 GSM was selected as the reinforcement material. Samples were prepared aacording to ASTM D3039 standard and the obtained mechanical properties were used in the finite element modelling of impact response of glass/epoxy laminated composites.

2. 2. Experimental Impact Testing Procedure

The low velocity impact tests were performed using instrumented drop weight impact tester [12]. The glass/epoxy laminates were exposed to low velocity impact using a hemispherical tip steel impactor of 16mm diameter. The ballistic limit velocity of hemispherical tip projectiles was found to be highest as compared to the other shapes such as flat, ogive and conical [13]. In order to measure the force exerted by the laminate on the impactor at the time of impact a transducer of 45 KN capacity was equipped with the striker. By varying the dropping height of the impactor the required impact energies were obtained [14]. The complete results of these experiments such as failure behavior, deformation and energy absorption were taken from literatures and were used in this study for the correlation with numerical results. In order to avoid further damage due to rebound of the impactor it was seized by the catcher system. Moreover piezoelectric sensors were incorporated to record the impact time-histories which provides force versus time plots.

3. FINITE ELEMENT MODELLING

3. 1. Failure Modelling–Theoretical Background

The low velocity impact response of the glass reinforced epoxy composite laminates was performed in the LS-DYNA explicit finite element analysis software. Composite lamina failure theories for can be categorized into three distinct groups namely: Non-interactive or limit theories, Interactive theories and Failure mode based theories. Whereas, the interaction between various stress/strain components in a laminate is accounted by Interactive theories; Tsai-Wu and Tsai-Hill, Tsai-Wu and Chang-Chang failure criterion falls under this category. The damage behavior of composite materials can be easily simulated using LS DYNA. Various material models like MAT_22, 54/55, 58/158, 59, 138, 261, 262, 161/162, are available to simulate intra and inter-laminar behavior of composite materials. Material model MAT_54/55 is the most commonly used which uses the Chang-Chang and Tsai-Wu failure criteria to model composite failure and it is only valid for thin shell elements. Failure can happens by any one of the following ways:

- If DFAIL (maximum strain for fibre tension) = 0, tensile fibre mode failure occurs if the Chang-Chang failure criterion satisfies.
- If DFAILT > 0, failure occurs when the tensile strain > DFAILT or strain < DFAILC (Maximum strain for fibre compression).
- If EFS (Effective failure strain) > 0, failure occurs in the laminate.
- If TFAIL (time step size criteria for element deletion) > 0, failure occurs based on the respective element's time step.

As soon as the failure happens in through-thickness integration points of a composite laminate, the element gets removed. And the elements which shares the nodes with abolished elements will start to lose the strength namely XT, XC, YT, YC in accordance to the SOFT parameter (constant). Where XT, YT are the tensile strength in longitudinal and transverse direction, XC and YC compressive strength in longitudinal and transverse directions respectively.

3. 2. FE Modelling of Glass/Epoxy Layers

The method of modelling laminated composites depends on the scope of the simulation and the time required to run the analysis. Usually laminates can be modelled as a one shell element where all the layers can be defined using a single shell element and the second method is using layers of solid elements where the connection between layers can be node to node or using cohesive elements or TIEBREAK contact or by physically modelling adhesive. The last method is using layers of shell elements, in which the connection between layers can be done as the second method.

Here we have used one shell element modelling approach to assess performance of the composite laminates in terms of failure behavior, energy absorption and maximum displacement, so that the computational time can be reduced. [15] used this approach to minimize the complexity of analysis and to reduce the computational time. In this paper laminates of 5, 7 and 10mm thickness were modelled with a layer thickness of 0.25mm. The glass/epoxy finite element impact assembly model is shown in Figure 1. An impactor in the shape of a sphere was modelled as a solid part and solid brick elements were used for the mesh. The comparison parameters used in this study is given in the Table 1.

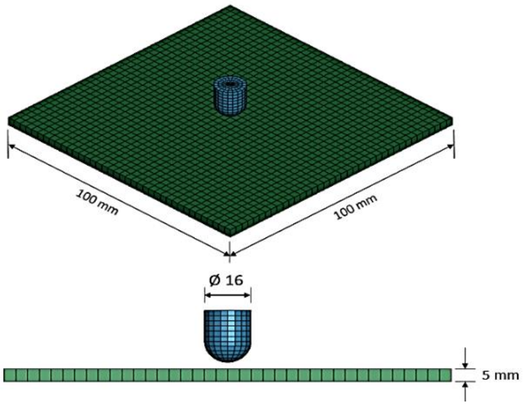


Figure 1. Finite element model of laminate and impactor

TABLE 1. Comparison parameters used in this study

Parameters	Units	Values
Thickness of the laminate	mm	5,7,10
Impact energy	J	50, 100, 150

3. 3. Material and Contact Definition

In LS-Dyna laminated composite shell elements material properties were defined using MAT 54/55 card and the MAT20 card was used for the impactor.

Since we have modelled only the tip of the impactor, its density has been intensified. The material properties this present study is given in Tables 2 and 3. The contact between the laminate and the impactor was defined by AUTOMATIC SURFACE TO SURFACE card in Ls-

TABLE 2. Material properties glass/epoxy lamina

Property description	Notation	Units	Value
Longitudinal elastic modulus	EA	MPa	32636.45
Transverse elastic modulus	EB	MPa	30326.93
Poisson's ratio	PRBA	--	0.22
In-plane shear modulus	GAB	MPa	2849.50
Tensile strength in longitudinal direction	XT	MPa	360.67
Tensile strength in transverse direction	YT	MPa	348.07
Compressive strength in longitudinal	XC	MPa	244.56
Compressive strength in transverse	YC	MPa	238.23
In-Plane shear strength	SC	MPa	64.00
Maximum strain for matrix failure	DFAILM	mm/mm	0.0115
Maximum in-plane shear strain	DFAILS	mm/mm	0.0225
Maximum strain for fibre tension	DFAILT	mm/mm	0.0111
Maximum strain for fibre compression	DFAILC	mm/mm	0.0221

TABLE 3. Material properties of the rigid solid impactor

Property description	Notation	Units	Value
Density	RO	Kg/m^3	7860
Young's Modulus	E	GPa	200
Poisson's ratio	PR	--	0.32

Prepost. Using this approach the impactor penetrates into the modelled shell elements considering the actual thickness of 5, 7, 10 mm, respectively in each case. It is assumed that the laminate exists in a dry form and a static friction coefficient of 0.2 is applied for the interaction between them.

3. 4. Mesh and Boundary Conditions

The accuracy of the simulation results depends on the mesh quality and size. In order to find the optimum element size, a mesh sensitivity analysis is also performed since the mesh size is inversely proportional to the computational time. The impact performance of the laminate was analyzed by fixing the edges of the laminate using SPC card as shown in Figure 2 and a linear velocity is applied to the impactor corresponding to the impact energy. In this study three different energy values 50, 100 and 150J respectively were used and this can be achieved by dropping the impactor from a predefined height. However, to reduce the computational time here we have varied the impact velocity rather changing the height of the impactor. The impact test characteristics was based on the principle of energy conservation where the potential energy of the impactor head before impact is assumed equal to the kinetic energy after impact event [16]. The velocity can be calculated from the equation:

$$v = \sqrt{2gh}$$

where v, h and g are the impact velocity, height from which the impactor is dropped and g is the acceleration due to gravity.

4. RESULTS AND DISCUSSION

The acquired results of the low-velocity impact response analysis are presented in this section. The numerical results are divided into three main categories: contact force histories, the effect of laminate thickness and impact energy on damage behavior.

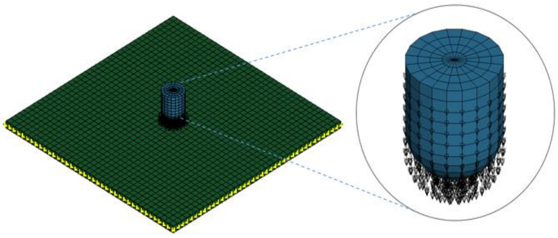


Figure 2. Boundary condition for the low velocity impact setup

4. 1. Force– Displacement

Many researchers have studied the history of contact force during impact, since it can yield significant information about damage initiation and growth on composite laminates. Studies have recorded the occurrence of matrix cracking, matrix breakage and a minor delamination growth that happened as soon as the impactor hit the specimen. When the specimen gets impacted matrix cracking happened, so that there is a drop in the transverse stiffness as shown in Figures 3, 4 and 5. The curve continues to increase further and reaches the maximum peak force Fp. Fiber failure and delamination happens at the maximum peak force. The mass and velocity of the impactor, laminate thickness affect the critical failure load. The force-time, deflection-time and force-deflection plots shown in Figures 3, 4 and 5 reveal the characteristic behaviour of glass/epoxy laminates under low velocity. The maximum displacement and contact force at the time of impact are provided in the Table 4. Figure 6 reveals the typical contact force-deflection curve patterns of composites subjected to low velocity impact [17]. With the help of these curve patterns we can confirm whether the impact event is elastic, or impactor is penetrating or perforating into the laminate. In this study contact force increases with laminate deflection, so rebounding occurred. Moreover, the force-displacement curves can be categorized as three distinct zones A, B and C based on the behaviour of laminate during the time of impact. Zone A represents an elastic state, whereas in Zone B damage initiates and extends further to the peak where the deflection and contact forces are maximum. In general longer the zone B portion higher will be the energy absorption and damage tolerance of the laminates. Zone C is an unloading region where the deflection and contact force reach a minimum value.

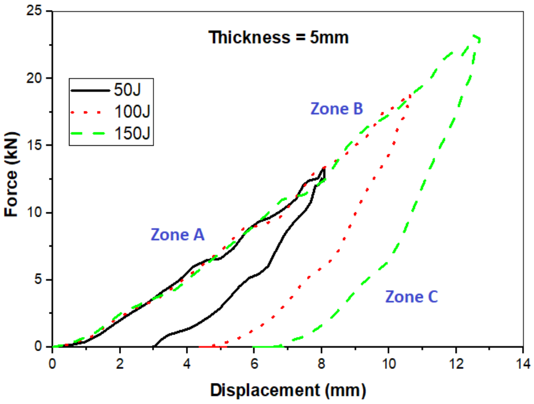


Figure 3. Force - displacement plot of 5 mm thick laminate at different energy

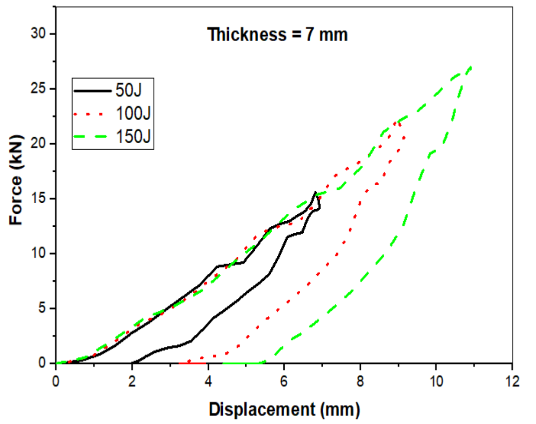


Figure 4. Force - displacement plot of 7 mm thick laminate at different energy

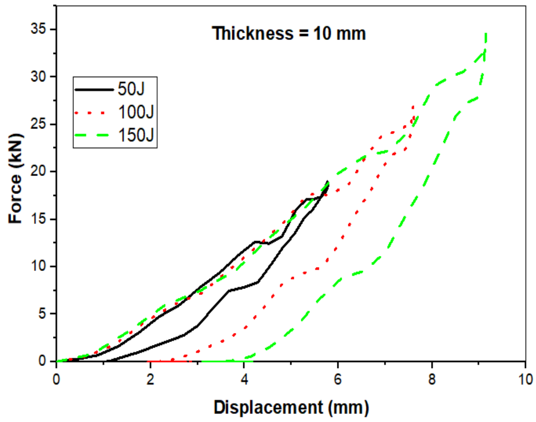


Figure 5. Force - displacement plot of 10 mm thick laminate at different energy

TABLE 4. Maximum deformation and contact force at the time of impact

Thickness (mm)	Max deformation (mm)			Contact Force (kN)		
	50J	**100J**	**150J**	**50J**	**100J**	**150J**
5	8.08	10.6	12.7	13.3	19	23.5
7	6.93	9.15	10.9	15.7	22.5	28.2
10	5.79	7.64	9.15	19.3	27.6	34.6

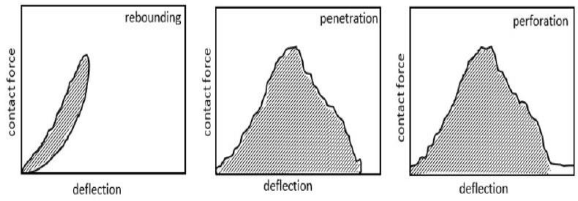
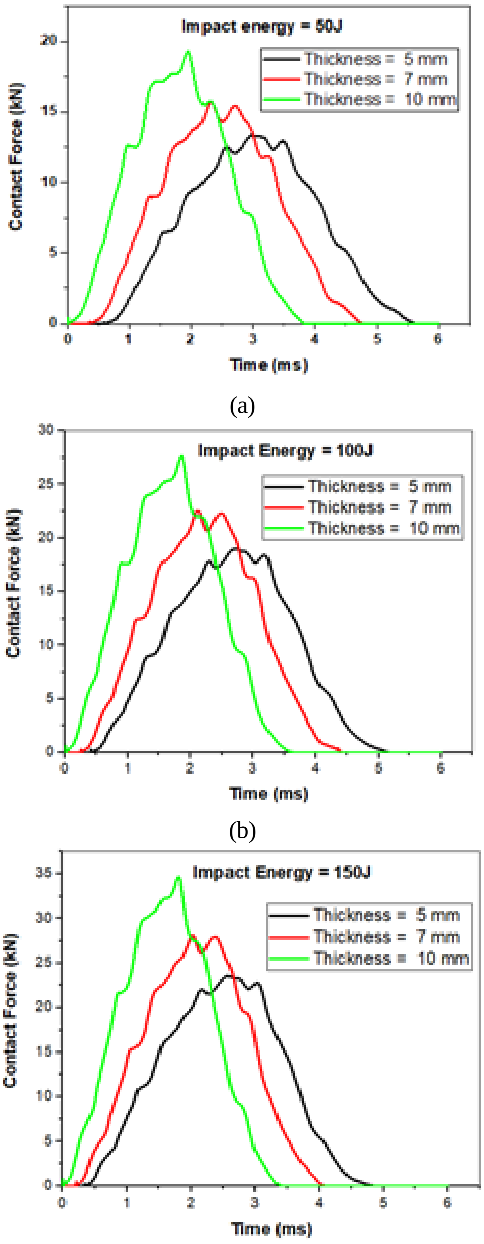


Figure 6. Typical contact force-deflection curves of composites subjected to low velocity impact

4. 2. Effect of Laminate Thickness on Damage Behaviour

The results of numerical simulation as shown in Figures 7 (a-c) and 8 (a-c) reveals the behavior of glass/epoxy laminate at different ply thickness. It is identified that the prominent factors for damage mechanism are indentation, surface cracking, bending of laminates and fiber breakage [17]. The area of damage and the energy absorption for the different ply thickness and impact energy configuration are summarized in Table 5.

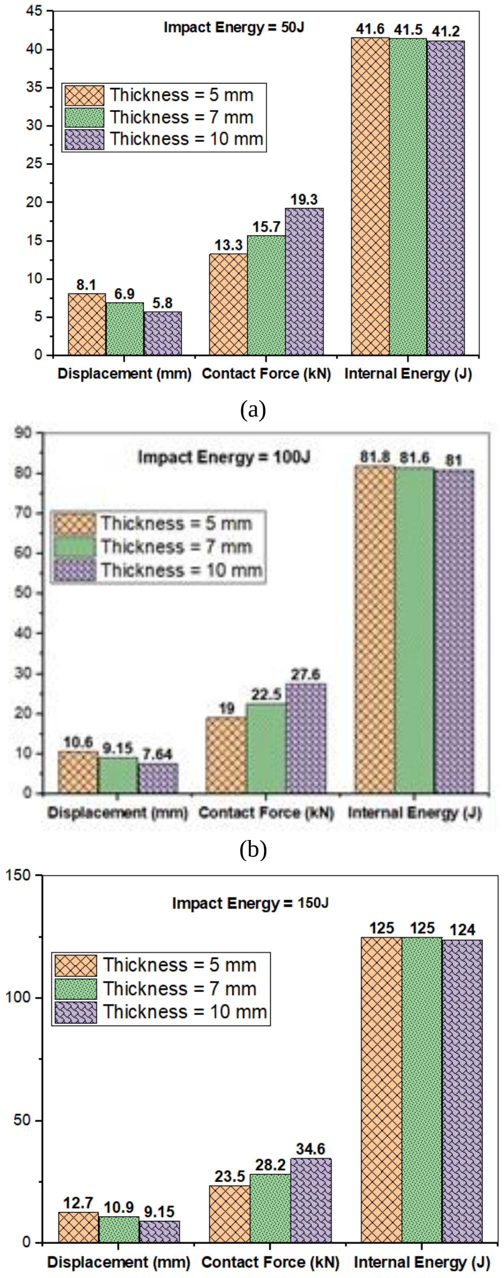


(a)

(b)

(c)

Figure 7. a, b, c Contact force history plots at impact energies 50, 100 and 150 J



(a)

(b)

(c)

Figure 8. a, b, c Comparison of displacement, contact force and internal energy at 50, 100 and 150J

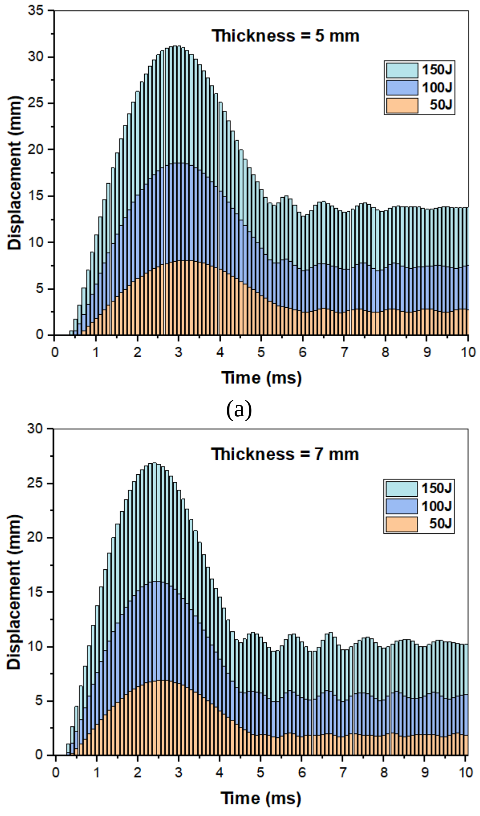
TABLE 5. Energy absorption and area of damage at the time of impact

Thick	Internal energy (J)			Damage area (kN)		
(mm)	50J	100J	150J	50J	100J	150J
5	41.6	81.8	125	2688.35	2850.52	3697.72
7	41.5	81.6	125	2679.71	2801.69	3240.50
10	41.2	81.0	124	2568.50	2768.34	2996.51

It is revealed that the area of damage is directly proportional to impact energy and inversely proportional to the laminate thickness. For instance, the area of fiber breakage for 5, 7 and 10 mm thick laminates were found to be 3697.72, 3240.50, 2996.51 mm^2 respectively, when impacted with 150 J energy. Whereas the contact force at the time of impact is keep on increasing with the ply thickness.

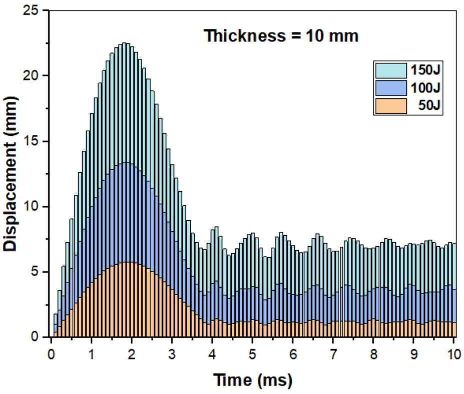
4. 3. Effect of Impact Energy on Damage Behaviour

The energy history curves of all the laminates impacted at 50J, 100 J and 150J are shown in Figure 9 (a-c). In genera,l the energy absorbed the specimen is the maximum value in internal energy history plot and the rebound energy or elastic energy is the difference between energy at flat portion and peak. The obtained results show that the rebound energy has increased at higher impact energies. Also whenever the absorbed energy is equal to the impact energy of the striker complete perforation occurs. In this study, there is no perforation but there is a slight traces of penetration occurred since around 75% of the impact energies were absorbed by the glass/epoxy laminates. Moreover, it is perceived the energy absorption rate has been decreased for thick laminates because of the stiffness and damage resistance increased.



(a)

(b)



(c)

Figure 9. a, b, c Energy history plots of laminates of thickness 5, 7, 10 mm

4. 4. Correlation of Experimental and Numerical Results

The obtained results of this numerical study showed a higher compliance with the experimental results as shown in Tables 6 and 7. At higher thickness of the glass/epoxy laminates the numerical results are not correlated accurately because here the impact of laminated plates are modelled using thin shell element in order to reduce the computation time. But the model has shown better correlation at lower thickness in terms of deformation and contact force. In addition, if the setup was modelled using sold elements integrated cohesive zone elements or TIE_BREAK elements in LS-Prepost more accurate results would have obtained but the computational time should have increased. Usually Cohesive zone elements or TIE_BREAK elements are used to model the delamination or interlaminar interactions between plies, but here our intention is to study the impact response.

TABLE 6. Experimental versus numerical results for displacement

Laminate Thickness (mm)	Displacement (mm) at 100J		% Error
	Experimental	Numerical	
5	10.62	10.6	0.18
7	7.64	9.15	16.5
10	5.36	7.64	29.84

TABLE 7. Experimental versus numerical results for contact force

Laminate Thickness (mm)	Contact Force (kN) at 50J		% Error
	Experimental	Numerical	
5	14	13.3	5.26
7	16	15.7	1.91
10	21	19.3	8.81

5. CONCLUSIONS

Glass/epoxy laminated composite plates, which are subjected to low-velocity impact were numerically analyzed in this study. In-depth analyses were carried out in the aspect of assessing the damage initiation, energy absorption, rebounding or penetration of the impactor. A finite element impact analysis model was set up using a combination of shell and solid elements. The impact behavior was studied on the glass/epoxy laminate of different thicknesses 5, 7, 10 mm subject to impact energy of 50 J, 100 J and 150 J, respectively. The following decisions were attained from this study:

- The deformation of the glass/epoxy laminate was decreased at higher thickness because a large number of plies improved the stiffness and damage tolerance.
- Contact force generated at the event of impact is directly proportional to laminate thickness. And the energy absorption rate has slightly dropped for the increase in thickness.
- Moreover, for the selected set of impact parameters in this study the force-displacement curve behavior is completely rebounding with small traces of penetration and there is no perforation observed.

It is established that there is a decent agreement amongst experimental and numerical results even if the percentage of error is 29% at higher impact energy. This results can be improved by modeling the plies using solid elements integrated with cohesive elements and a good computational capacity.

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Persian Abstract

چکیده

در مقاله ارائه شده، پدیده پاسخ ضربه لایه‌های شیشه/اپوکسی با ضخامت‌های ۵، ۷، ۱۰ میلی‌متر تحت تأثیر انرژی ضربه‌ای ۵۰، ۱۰۰، ۱۵۰ ژول با استفاده از نرم‌افزار اجزای محدود تجاری LS-DYNA مورد تجزیه و تحلیل عددی قرار گرفت. برای پیش‌بینی قابلیت جذب انرژی و پاسخ آسیب، یک مدل المان محدود توسعه داده شد. پاسخ ضربه از نظر حداکثر جابجایی، نیروی تماس در صورت ضربه و جذب انرژی ارزیابی شد. ورقه های با ضخامت بالاتر در مقایسه با ورقه های نازک نتایج بهتری در تغییر شکل و ایجاد نیروی تماسی نشان دادند. نتایج عددی بر حسب جابجایی و نیروی تماس با مطالعات تجربی در ادبیات تایید شده‌اند. علاوه بر این، تطابق خوبی بین نتایج عددی و مطالعات تجربی وجود دارد. در این مطالعه معیارهای شکست چانگ چانگ برای پیش‌بینی پاسخ ضربه در ضربه با سرعت پایین در نظر گرفته شد. بر اساس نتایج عددی مشاهده شده، قابلیت جذب انرژی و مقاومت سوراخی ساختار کامپوزیتی چند لایه نشان داده شد. این نتایج را می‌توان در طراحی و مدل‌سازی سازه چند لایه کامپوزیتی تحت بارهای ضربه‌ای اشاره کرد. یک مطالعه مستقل از شبکه در این مقاله انجام شده است که برای محققان در انتخاب اندازه عنصر بهینه برای کاهش زمان محاسباتی مفید خواهد بود. علاوه بر این، تجزیه و تحلیل اجزای محدود به طور منطقی پاسخ های بار-جابجایی ضربه و انرژی های سوراخ شدن صفحات چند لایه را پیش بینی کرد.