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Numerical Analysis of Low Velocity Impact on Laminated Composite Plates

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Abstract

A numerical investigation is performed to study the behaviour of a composite plate under low velocity impact. The finite element simulation is performed to investigate the stress distribution during the impact on the laminated composite plate. The effectiveness of the developed numerical model is investigated by comparing the results in terms the transverse-deflection and stress, longitudinal stress and impact duration with those of available literature. Various parametric studies are performed to study the effect of boundary conditions, thickness of the laminate, impactor mass and velocity and composite lay-up sequence on stress variation of the composite laminate. It is concluded that the stresses are distributed symmetrically along the bottom and top layers irrespective of the boundary conditions. Furthermore, it is shown that the maximum tensile stress is yielded at the bottom layer while the maximum compressive stress is yielded at the top layer of the laminated composite plate. Symmetric variation in in-plane shear stress distribution is also observed. It is also shown that the thickness of the composite plate plays an important role on the deflection of the plate. It is further shown that depending on the boundary conditions considered, the significant variation of shear stress is observed along the shear plane with respect to the mass and velocity of the impactor and the lay –up configuration.

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Keywords: Composite; Low velocity impact; In-plane shear stress; Laminated compoiste analysis;

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1. Introduction

Fiber - reinforced composite laminates are widely used in many engineering fields, owing to their high strength-to-weight and stiffness-to-weight ratios. These structures are fabricated with tailoring properties in a required direction. They have been increasingly used in load-bearing structures such as aircraft and automobile industries. However, they are liable to damage due to low velocity impact loading during in service. This impact loading can cause extensive sub-surface damage that may not be visible on the surface but can lead to a significant reduction in the strength of composite laminates. It can create internal defects in the form of delamination, matrix failure and fiber breakage which yields reduction in the residual strength and stiffness of the structure [1].

The resistance to impact depends on several factors of the laminate such as interlaminar strengths, stacking sequence, impacting object size, velocity and mass of the impactor. The dynamic behaviour of the composite laminates is very complex due to their many concurrent phenomena under impact load. Fiber breakage, delamination, matrix cracking and plastic deformations due to contact are few effects, which should be considered when a structure made from composite material is impacted by a foreign body [2].

Pradhan and Kumar [3] have investigated the low-velocity impact behaviour and impact induced damages in graphite /epoxy laminates through a three dimensional finite element and transient dynamic analysis to evaluate the time-varying displacements, forces, strains and stress throughout the laminate resulting from transverse impact. Approximate three- dimensional failure criteria are used to predict the occurrence of the matrix cracking and extent of delamination after impact. Scarponi et al [4] evaluated tensile strength reduction of angle plies composite laminates due to low velocity impact. A correlation between the amount of delamination areas and the impact energy has been determined. Sutherland et al [5] investigated the effects of specimen thickness, impactor kinetic energy and velocity of impact in laminates. Furthermore, the damaged area was observed for various magnitudes of impact energies. Found and Howard [6] concluded that the impact force rather than the impact energy preside over the initiation of failure for single impact.

Kwon and Liu [7] presented the numerical modeling technique to simulate and predict progressive damage in a composite structure subjected to external loading. A macro/micro mechanical approach was proposed along with the damage mechanics. Park et al [8] have presented an experimental technique for time resolved characterization of the mechanical response and induced damage of fiber–reinforced composite laminates during low-velocity, transverse impact. The relationship between the amount of energy absorbed by the laminates and the post-impact tensile strengths of the materials are studied.

Hosseinzadeh and Mahmood [9] investigated the damaged area of the various fiber-reinforced composite plates such as thin glass fiber reinforced plastic (GFRP) plates, thick GFRP plates, carbon fiber reinforced plastic (CFRP) plates and carbon glass fiber reinforced plastic (CGFRP) plates under impact loading. It is concluded that CFRP plates show the best structural behavior under low velocity impacts while CGFRP plates show suitable behavior under high impact energy.

Anil Kumar and Shivanand [10] investigated the impact response of different composite panels made up of glass/epoxy and graphite/epoxy. The various failure modes, failure mechanisms, and energy absorbing characteristics of those composite laminates were studied systematically. It was concluded that the energy absorbed by a composite panel made of graphite/epoxy was about 15% - 40% more than that of the energy absorbed by glass/epoxy combination.

Kersys et al [11] investigated the impact response of woven carbon/epoxy and E-Glass / epoxy composite systems employed on vehicle body structures by considering energy profile diagrams and force-displacement curves. The energy introduced to a composite specimen and the energy absorbed by it through the impact event is considered to assess impact response of the composite structures. It is established that by increasing the impact energy elastic deformation of woven E-glass / epoxy composite systems is 1.5 times higher than that of carbon/ epoxy composite systems that defines the formation of smaller areas of damage.

Setoodeh et al[12] conducted low velocity impact analyses of general fiber reinforced laminated composite plates using three-dimensional elasticity based approach coupled with layer-wise laminated plate theory. Transient dynamic response of laminated composite plates due to transverse low velocity impact was studied by employing user developed code IMPLW3D. The responses of laminated plates with various stacking sequence and boundary conditions under impact loading are studied with the effects of impact mass, initial velocity of the impactor, laminate thickness and multiple impacts on the impact response. The effects of the impact velocity, mass of the impactor, anisotropic material properties on the impact response are examined.

Kranthi Kumar and Lakshmana kishore [13] studied the damage generated on fiber-glass laminates subjected to low velocity but larger impactor mass. Finite element analysis was performed in terms of drop tower test using ANSYS/LS-DYNA. Furthermore, the analysis was extended to thick laminates and various parametric studies were performed in terms of various impact velocity and mass. Critical stress was also identified during the impact.

Ma and Xu [14] proposed a composite damage model including the damage initiation to predict the composite intralaminar damage under impact loading. Numerical simulation was performed using subroutine VUMAT and ABAQUS software to investigate the low-velocity impact on various composite laminates. A good agreement was also observed between the results obtained in terms of delamination shape and area, the contact force and the deflection of the impactor the numerical experimental investigations.

Olsson [15] reviewed impact damage in textile based laminates. Different failure mechanisms such as local and global buckling, compressive failure, and delamination growth were identified around the damage zones. The constitutive behaviour of damage zones were studied experimentally and compared with those obtained using FE models of generic impact damage. It was concluded that analytical and computational models predict the resulting strength of impacted laminates.

Ashish and Naik [16] have presented an analytical model for the response of symmetric woven fabric and unidirectional composite laminates, simply supported on all four sides subjected to low-velocity impact at the midpoint of the plate. The plate is impacted by an impactor with a hemispherical tip. Contact forces at the impact point, lateral displacements and velocities of the plate and the impactor and the stress state within the plate have been determined using modal solution technique. In-plane and interlaminar failure functions have also been determined using quadratic failure criteria. Based on failure functions, damage initiation in the form of yarn/fiber breakage has been predicted and it is observed that overall failure function is lower for woven fabric composites than for unidirectional laminates. It is evident from the above literature review that most of the studies have concentrated on impact damage generated on the composite laminates. However, the effect of longitudinal, transverse and in-plane stresses in the laminates have not yet been explored in detail.

In the present work, a numerical analysis to study the behavior of a composite plate under low velocity impact is performed. A composite plate with as isotropic impactor is modeled using the commercial finite element analysis software ANSYS® and the impactor is considered to be in contact with the composite plate under low velocity. The finite element simulation is performed to investigate the stress distribution during the impact. The effectiveness of the developed numerical model is investigated by comparing the results in terms the transverse- deflection and stress and longitudinal stress with those of available literature. Furthermore, the impact duration using the current finite element analysis is also compared with those available in literature. Various parametric studies are also performed to study the effect of boundary conditions, thickness of the laminate, impactor mass and velocity and composite lay-up sequence on stress variation of the composite laminate.

2. Numerical Modeling in ANSYS

A woven fabric composite plate having stacking sequence of $[0_{12}]_S$ with 0.25 mm ply thickness and dimensions of 150 mm × 150 mm x 6 mm is considered for the impact analysis using commercial available software ANSYS®. The various material properties of the composite plate assumed for the analysis are presented in Table 1 [16]. The hemispherical tip impactor with radius of 6.5 mm is considered to be made up of steel with a mass of 4.7 kg. The various material properties of the impactor are: Young's modulus, E = 210 GPa, Poisson ratio, v = 0.3, density, ρ = 7800 kg/m^3. The composite plate is meshed using SHELL 163 having 4 nodes and 12 degrees of freedom at each node. The degrees of freedom are translation, accelerations and velocities at each node in three perpendicular axes and rotational degrees of freedom about those axes. Furthermore, the impactor is meshed using SOLID 164 element having eight nodes and 9 degrees of freedom at each node [17].

The ANSYS LS-DYNA/Explicit dynamic analysis is selected to perform the low-velocity impact test on composite laminates with various loading and boundary conditions. Furthermore, the contact between the impactor and plate were defined by the general contact algorithm available in ANSYS /Explicit to generate the contact forces.

Table 1: Materials properties and ultimate strength along three perpendicular directions, *X*, *Y* and *Z* of E-glass/epoxy woven fabric composite lamina

Young's modulus (GPa)			Shear modulus(GPa)			Poisson's ratio			Volumetric fraction, Vf (%)	ρ (Kg/m^3)
E_{11}	E_{22}	E_{33}	G_{12}	G_{23}	G_{13}	ν_{12}	ν_{13}	ν_{23}		
36.3	36.3	31.1	4.47	4.68	4.68	0.173	0.279	0.279	0.4	1750
Tensile strength (MPa)			Shear strength (MPa)			Compressive strength (MPa)				
X_T	Y_T	Z_T	S_{12}	S_{13}	S_{23}	X_C	Y_C	Z_C		
330	330	35	35	35	35	320	320	500		

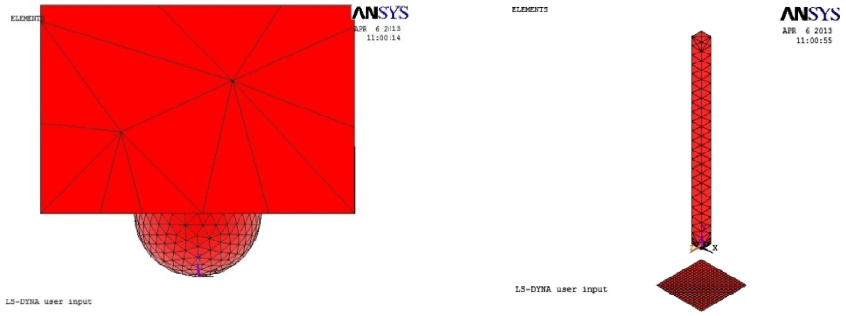

Fig. 1. Schematic representation of impactor and plate

3. Validation

The validity of the developed numerical modeling and analysis is demonstrated by comparing the results in terms of deflection, longitudinal (σ_x) and transverse (σ_y) stresses at the centre of the bottom layer of the composite plate and impact duration obtained using the current finite element formulation with analytical results available in literature [Ref. 16]. The simulation is performed by considering the impactor mass of 4.7 kg with a velocity of 1.68 m/s impact on a composite plate. The plate having identical dimensions as mentioned in section 2 are considered to be simply supported at four edges (S-S-S-S). The impact energy yielded on the plate is 6.63 J. The results are presented in Table 2. A very good agreement was observed between the results obtained using the current finite analysis and the analytical solution available in Ref. [16]. Furthermore, the distribution of longitudinal stresses (σ_x) in the composite plate during the impact is shown in Fig. 2. It can be seen that the maximum stress is developed at the bottom layer of the composite plate and yields the maximum deflection of 2.604 mm as presented in Table 2. Simulation is also performed to investigate the variation of longitudinal (σ_x) and transverse (σ_y) stresses distribution at X= 75 mm along L_y in bottom and top layers of the composite laminate and the results are illustrated in Fig. 3. Similar trend is also observed in Ref. [16]. It can be seen that the maximum longitudinal and transverse stresses occur at the centre of the laminate. This can be attributed to the fact that as the impact load is applied at the centre of the plate, the maximum stress is developed at the same location.

Table 2: Comparison of longitudinal and transverse stresses, deflection at bottom layer of the plate and impact duration evaluated using current FE formulation and Ref. [16].

Method of analysis	Longitudinal Stress, σ_x (MPa)	Transverse stress, σ_y (MPa)	Maximum deflection (mm)	Impact duration (μs)
Ref. [16] (Analytical)	300	306	2.6	5124
Current FEA	304	305	2.604	5000
% deviation	-1.330	0.326	-0.153	2.419

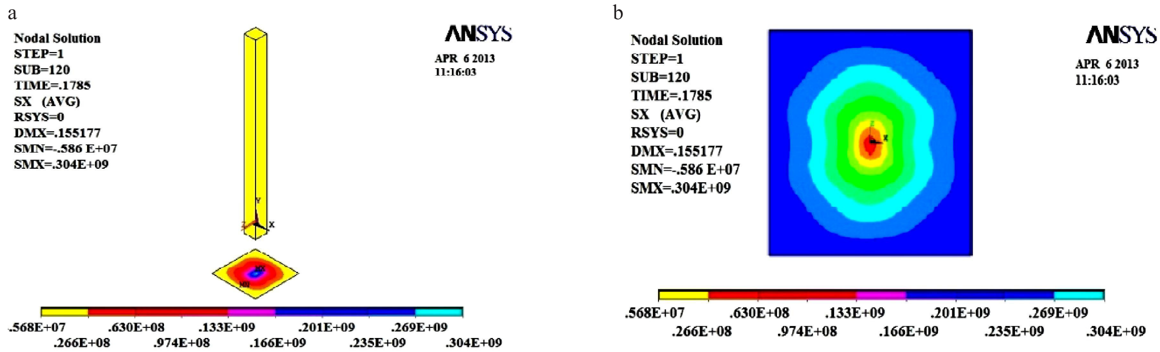

Fig. 2. a) and b) Longitudinal stress distribution of$[0_{12}]_S$ plates at the centre of the bottom layer under S-S-S-S

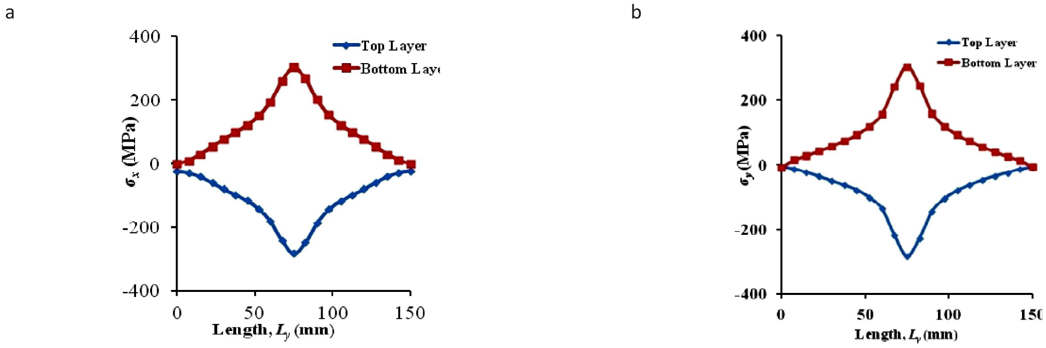

Fig. 3. Variation of a) longitudinal (σ_x) and b) transverse (σ_y) stresses distribution at X= 75 mm along L_y in bottom and top layers of the composite laminate under simply supported end condition at all the four edges

4. Parametric study

The damage mechanism of the composite laminates under low velocity impact depends on several factors of the laminate, such as strengths, stacking sequence, velocity and mass of the impactor, boundary conditions and the thickness of the laminates. The proposed FEM model is used to perform the various parametric studies to investigate the effect of those parameters on the variation of longitudinal, transverse and in-plane shear stresses along the laminate. The various materials and geometric properties considered for the simulation are identical to those of used in the previous section.

4.1. Effect of boundary conditions on the stress distribution

The effect of boundary conditions on the variation of stress distribution along the laminate is studied by performing the low velocity impact simulation under various boundary conditions. The boundary conditions considered are i) Clamped at four edges (C-C-C-C); ii) Clamped-Simply supported-Clamped-Simply supported (C-S-C-S); iii) Clamped-Free-Clamped-Free (C-F-C-F); iv) Simply supported- Free- Simply supported- Free (S-F-S-F);v) Clamped-Free-Free-Free(C-F-F-F);vi)Clamped-Simply supported-Free-Simply supported (C-S-F-S).

The stacking sequence of the laminate and the impact energy are assumed respectively as $[0_{12}]_S$ and 6.63 J. Figs. 4-7 illustrate the variation of the longitudinal (σ_x) and transverse (σ_y) stresses distribution at X= 75 mm along L_y in bottom and top layers of the composite laminate under C-C-C-C, C-S-C-S, C-F-C-F and S-F-S-F respectively. Symmetric distribution of stresses is observed along the bottom and top layers irrespective of the boundary conditions. Similar trend is also observed in Ref. [16] under simply supported at all edges of the laminate. This can be attributed to the symmetric boundary conditions of the laminate. Furthermore, it has been observed that the maximum stress and deflection yield at the centre of the laminate which is due to the consequence of the application of the impact load at the centre of the laminate. The maximum deflection is also evaluated at the centre of the laminate under all the boundary conditions considered and are given by: 1.57 mm, 1.922 mm, 1.95 mm and 3.378 mm under C-C-C-C, C-S-C-S, C-F-C-F and S-F-S-F respectively. It can be seen that C-C-C-C and S-F-S-F yield the lowest and highest deflections, respectively. This can be attributed to the laminates highest and lowest stiffness's under C-C-C-C and S-F-S-F.

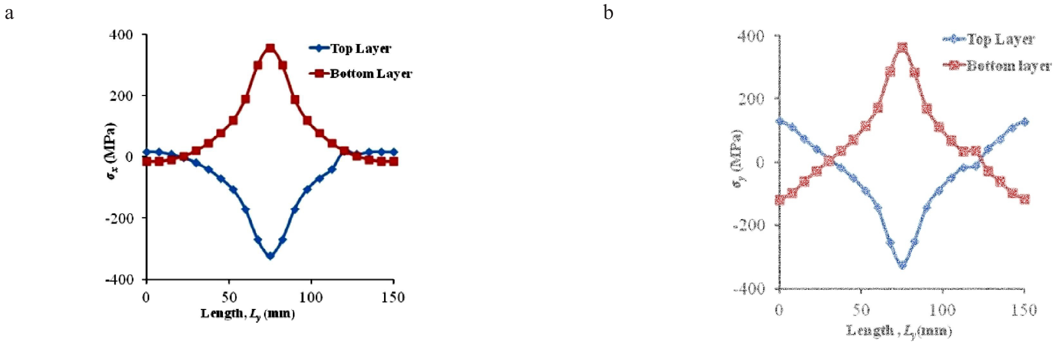

Fig. 4. Variation of a) longitudinal (σ_x) and b) transverse (σ_y) stresses in the laminate along L_y at X= 75 mm under C-C-C-C.

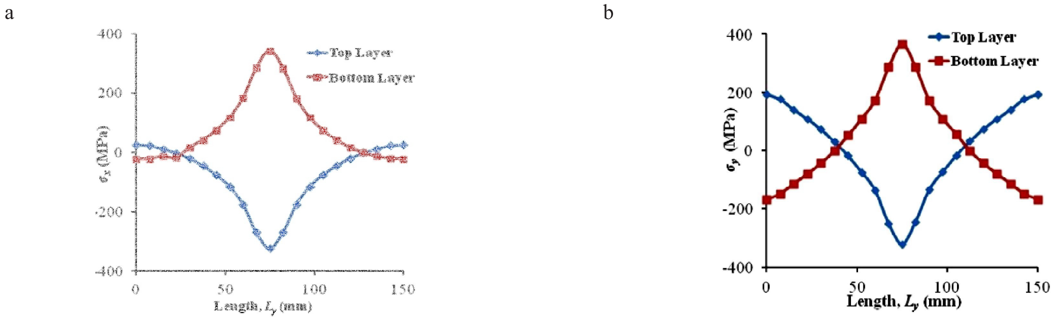

Fig. 5. Variation of a) longitudinal (σ_x) and b) transverse (σ_y)stresses in the laminate along L_y at X= 75 mm under C-S-C-S.

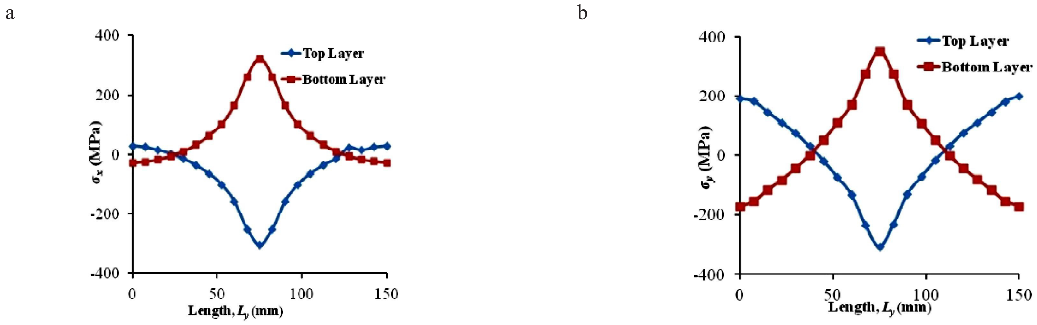

Fig. 6. Variation of a) longitudinal (σ_x)and b) transverse (σ_y) stresses in the laminate along L_y at X= 75 mm under C-F-C-F.

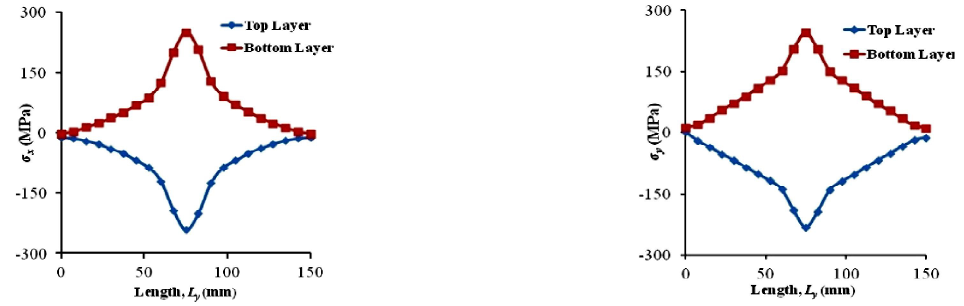

Fig. 7. Variation of a) longitudinal (σ_x) and b) transverse (σ_y) stresses in the laminate along L_y at X= 75 mm under S-F-S-F.

Fig. 8.shows the variation of in-plane shear stress (τ_{xy}) in the laminate along L_y at X=75 mm under S-S-S-S and C-C-C-C respectively. It can be observed that the bottom layer of the plate under S-S-S-S yields higher in-plane shear stress (τ_{xy}) compared to that of top layer. However, the similar trend couldn't be observed under C-C-C-C conditions. The top layer of the plate yields higher in-plane shear stress. This can be attributed to the fact that the shear force at the simply supported end is maximum. Symmetric variation of shear stress along XY plane is also observed which can be related to the symmetric boundary conditions at the four edges.

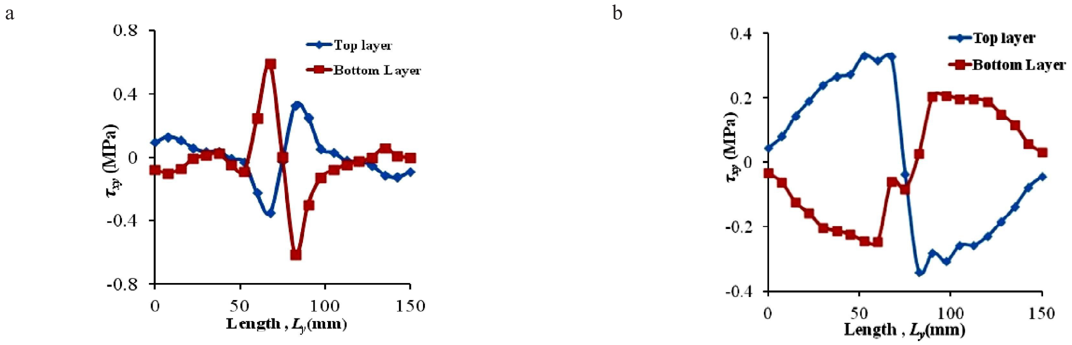

Fig. 8 Variation of in-plane shear stress (τ_{xy}) in the laminate along L_y at Y=75 mm under a) S-S-S-S and b) C-C-C-C

Figs. 9 and 10 illustrate the variation of the longitudinal (σ_x) and transverse (σ_y) stresses distribution at Y = 75 mm and X= 75 mm along L_x and L_y, respectively in bottom and top layers of the composite laminate under C-F-F-F. It can be seen that the maximum tensile stress is yielded at the bottom layer while the maximum compressive stress is yielded at the top layer. Symmetric variation in stress distribution along the XY plane is also seen.

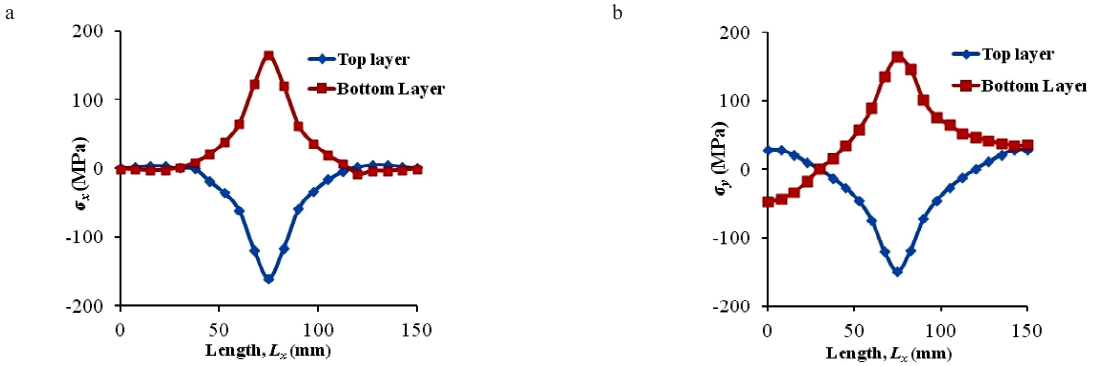

Fig. 9. Variation of a) longitudinal (σ_x) and b) transverse (σ_y) stresses in the laminate along L_x at Y = 75 mm under C-F-F-F.

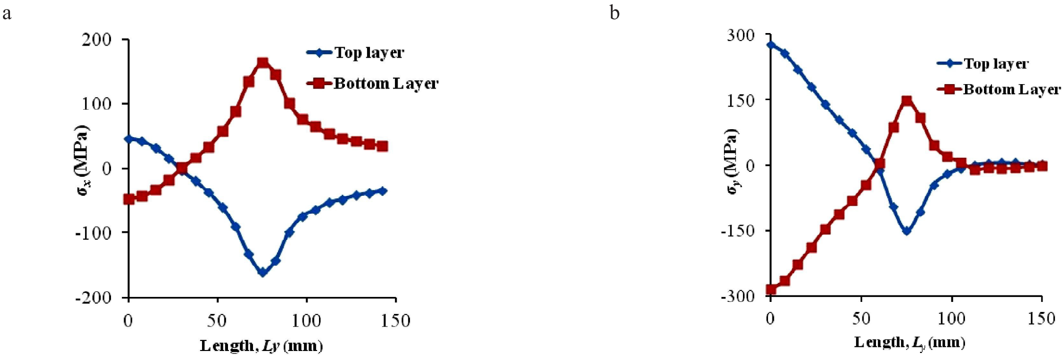

Fig. 10 . Variation of a) longitudinal (σ_x) and b) transverse (σ_y) stresses in the laminate along L_y at X= 75 mm under C-F-F-F

Fig.11 illustrates the variation of the shear stress (τ_{xy}) distribution at X= 75 mm along L_y in bottom and top layers of the composite laminate under C-F-F-F. It is observed that due to the unsymmetrical boundary conditions of laminate along LY , the stress distribution is minimized along free supported edges.

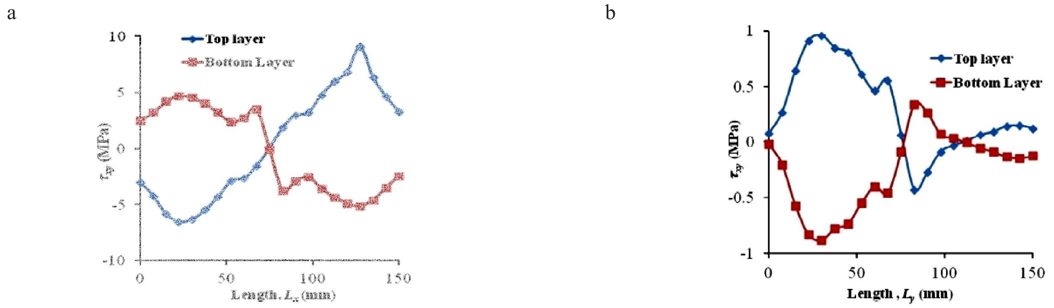

Fig. 11. Variation of in-plane shear stress (τ_{xy}) in the laminate a) along L_x at Y= 75 mm and b) along L_y at X= 75 mm under C-F-F-F.

4.2. Effect of variation of thickness on laminate stresses

The effect of the variation in the thickness of the laminate on the variation of longitudinal (σ_x) and transverse (σ_y) stresses in the laminate is studied. The simulation is performed with stacking sequences of $[0_8]_s$, $[0_{12}]_s$ and $[0_{16}]_s$, with the identical layer thickness of 0.25 mm under S-S-S-S and C-F-F-F. Figure 12 and 13 represent the distribution of longitudinal (σ_x) stresses at X= 75mm along L_y in top and bottom layers of $[0_8]_s$, $[0_{12}]_s$ and $[0_{16}]_s$, composite laminates under S-S-S-S and C-F-F-F respectively. Symmetric distribution is also observed in top and bottom layers and $[0_8]_s$ plate yields the maximum stresses whereas $[0_{16}]_s$ yields minimum stresses in both boundary conditions. The maximum deflection is evaluated at the centre of the laminate under S-S-S-S and are given by: 4.78 mm, 2.62 mm and 1.69 mm for $[0_8]_s$, $[0_{12}]_s$ and $[0_{16}]_s$ respectively. The maximum deflection is also evaluated at the centre of the laminate under C-F-F-F and are given by: 13.36 mm, 6.03 mm and 4.97 mm for $[0_8]_s$, $[0_{12}]_s$ and $[0_{16}]_s$ respectively. It can be observed that the $[0_8]_s$ and $[0_{16}]_s$ yield highest and lowest deflections respectively under S-S-S-S and C-F-F-F. This can be attributed to the lowest and highest stiffness's of $[0_8]_s$ and $[0_{16}]_s$ plates respectively.

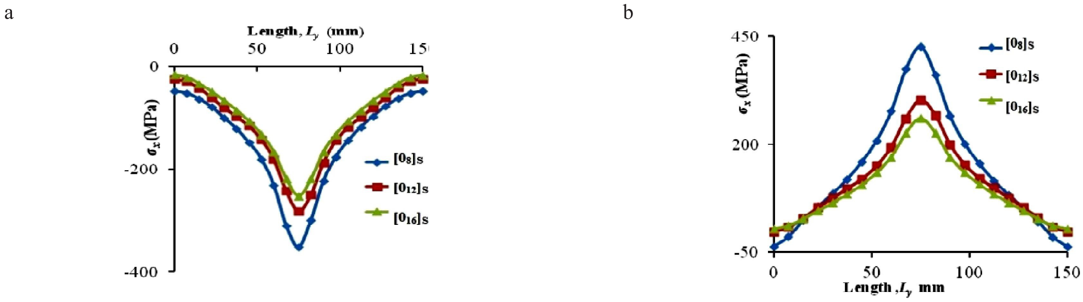

Fig. 12. Variation of longitudinal (σ_x) stresses in a) top layer and b) bottom layer of laminate with $[0_{16}]_s$, $[0_{12}]_s$ and $[0_8]_s$ stacking sequence along L_y at X= 75 mm under S-S-S-S

Fig. 13. Variation of longitudinal (σ_x) stresses in a) top layer and b) bottom layer of laminate with $[0_{16}]_s$, $[0_{12}]_s$ and $[0_8]_s$ stacking sequence along L_y at X= 75 mm under C-F-F-F

4.3. Effect of variation of impact mass and velocity on the laminate in-plane shear stresses

The effect of impactor mass and velocity on the variation of stress distribution along the laminate is studied by performing the low velocity impact simulation under various conditions. The various mass and velocity conditions considered are i) Mass of 2.7 kg with velocity of 2.21m/sec (2.7kg). ii) Mass of 4.7 kg with velocity of 1.68 m/sec (4.7 kg) iii) Mass of 6.7 kg with velocity of 1.4m/sec (6.7 kg). The impact energy is considered to be identical for all the cases as 6.63 J. The variation of in-plane shear stress in the laminate with the change in the impactor mass and velocity is studied. The simulation is performed with stacking sequences of $[0_{12}]_s$ with the identical layer thickness of 0.25 mm under S-S-S-S and C-S-F-S. Figure 14 represents the distribution of in-plane shear stresses (τ_{xy}) stresses at X= 75mm along L_y in bottom layers of $[0_{12}]_s$ composite laminate under S-S-S-S and C-S-F-S respectively. It is seen that depending on the boundary conditions considered, the significant variation of shear stress is observed along XY plane with respect to the mass and velocity of the impactor.

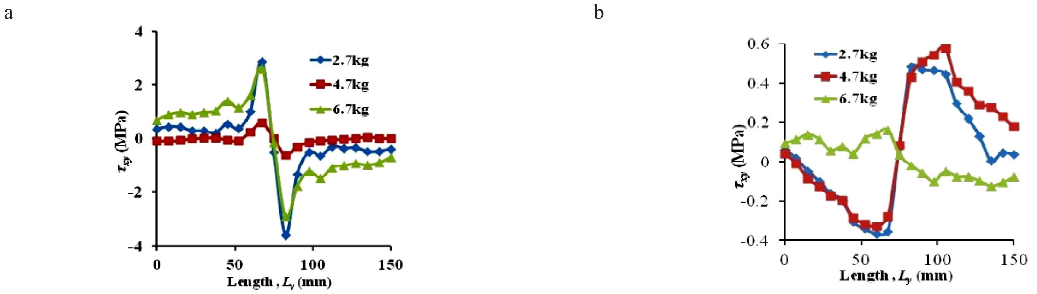
a
b

Fig. 14. Variation of in-plane shear stress (τ_{xy}) stresses in $[0_{12}]_S$ laminates along L_y at X= 75 mm under a) S-S-S-S and b) C-S-F-S

4.4. Effect of variation of lay-up sequence on the laminate in-plane shear stresses

The variation of in-plane shear stresses in the laminate with the change in the lay-up sequence of laminate is studied. The simulation is performed with two stacking sequences of $[+45_3/0_3/-45_3/90_3]_S$ (Lay-up A) and $[+45/0/-45/90/+45_2/0_2/-45_2/90_2]_S$ (Lay-up B) [Ref.18] with the identical layer thickness of 0.25 mm under C-C-C-C and C-S-F-S. Figs. 15-16 illustrate the variation of the in-plane shear (τ_{xy}) stresses distribution at X= 75 mm along L_y in bottom and top layers of Lay-up A and B composite laminate under C-C-C-C and C-S-F-S respectively. It can be seen that Lay-up B configuration yields higher in-plane shear stress in both top and bottom layers irrespective boundary conditions considered.

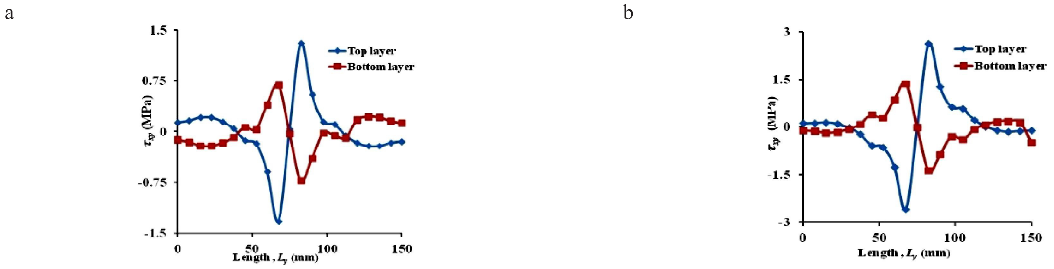
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Fig. 15. Variation of in-plane shear stress (τ_{xy}) stresses in a) Lay-up A and b) Lay-up B laminates along L_y at X= 75 mm under C-C-C-C

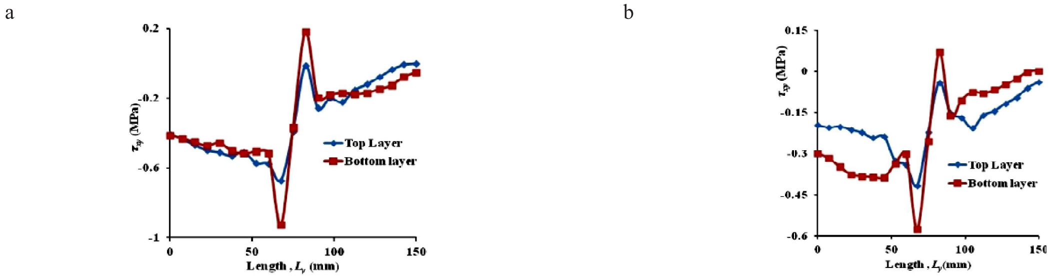
a
b

Fig. 16. Variation of in-plane shear stress (τ_{xy}) stresses in a) Lay-up A and b) Lay-up B laminates along L_y at X= 75 mm under C-S-F-S

5. Conclusions

A numerical analysis is performed to study the behavior of a composite plate under low velocity impact using the commercial finite element analysis software ANSYS®. The effectiveness of the developed numerical model is investigated by comparing the results in terms the transverse- deflection and stress and longitudinal stress, impact duration with those of available literature. Various parametric studies are also performed to study the effect of boundary conditions, thickness of the laminate, impactor mass and velocity and composite lay-up sequence on stress variation of the composite laminate. It is concluded that the stresses are distributed symmetrically along the bottom and top layers irrespective of the boundary conditions. It can be shown that C-C-C-C and S-F-S-F yield the lowest and highest deflections, respectively under identical impact energy. It is also observed that the bottom layer of the plate under S-S-S-S yields higher in-plane shear stress (τ_{xy}) compared to that of the top layer. Furthermore, it is shown that the maximum tensile stress is yielded at the bottom layer while the maximum compressive stress is yielded at the top layer. Symmetric variation in stress distribution along the *XY* plane is also observed. It is also shown that the thickness of the composite plate plays an important role on the deflection of the plate. It is further shown that depending on the boundary conditions considered, the significant variation of shear stress is observed along *XY* plane with respect to the mass and velocity of the impactor and the lay–up configuration.

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