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RESEARCH ARTICLE

Effect of Weaving Type on Damage Behaviour of Carbon/Epoxy Laminate under Low Velocity Impact Loading

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Abstract

The main purpose of the present investigation was to determine the damages generated by the low velocity impact by mean of the finite element method. The commercial transient finite element package LS-dyna used to model the effect of slug impactor induced damage in composite material subjected to low velocity impact. Four types of weaving were considered; serge (2/2), serge (0/30/-30/0), serge (0/45-45/0) and taffeta. The Texgen package was used to build the laminate pattern weaves. The composite material was subjected to stainless steel slug impactor in the transverse direction dropping the composite laminate at the center with a velocity about of 15m/s. The analysis was carried out using the model 001-ELASTIC for matrix, 002-ORTHOTROPIC_ELASTIC for fibersand a rigid body model MAT20 for the slug impactor. The contact automatic single surface has been used between the yarns and the automatic_surface_to_surface between the matrix and the impactor and the contact automatic_surface_to_surface_tiebreak between the matrix and yarns and the contact automatic_surface_to_surface_tiebreak between layers.

The impact load, energy, displacements were reported as function of impact time. The delamination area was represented at the layer interfaces for each material.

Keywords

Ls-dyna, low velocity, 2D weavings, Texgen, slug impactor, delamination

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1 Introduction

The fibrous composites are being increasingly used in load bearing structures due to number of advantages over conventional materials: high specific strength and stiffness, good fatigue performance and corrosion resistance. A serious obstacle to more widespread use is their sensitivity to impact and static loads in the thickness direction. As composites have demonstrated to be very venerable to out of plane impact, which cause barely visible impact damage (BVID) reportedly contributes up to 60% loss in structures' compressive strength and major reason of catastrophic failures. The energy absorbed during impact is mainly dissipated by a combination of matrix damage, fibre fracture and fibre-matrix de-bonding, which leads to significant reductions in the load carrying capabilities. In ballistic impacts the damage is localized and clearly visible by external inspection, while low velocity impact involves long contact time between impactor and target, which produces global structure deformation with undetected internal damage at points far from the contact region. For such reasons the low velocity impact are often simulated by simple static indentation-flexure tests, neglecting the influence of dynamic effects. It is also suggested the complete model to take into account the full dynamic behaviour of the laminates. Composite design optimization typically consists of identifying the optimal configuration that would achieve the required strength with minimum over heads. The possibility to achieve an efficient design that fulfills the global criteria and the difficulty to select the values out of a large set of constrained design variables makes mathematical optimization a natural tool for the design of laminated composite structures [1].

Zhi-gang Hu et al. [2], used a continuum damage mechanics (CDM) meso-model to model the behaviour at the transverse low velocity impact in both intraply and modelled by 2D woven-fabric composite laminate. The numerical results are in agreement with those of experimental counterparts, verifying the progressive failure model of a woven composite laminate. The proposed model will enhance the understanding of dynamic deformation and progressive failure behaviour of composite laminate structures in the low velocity impact process.

Kwansoo Chung et al. [3] have studied the impact behaviour of woven composite subjected at high strain rates by mean of a constitutive equation to describe the nonlinear, anisotropic/ asymmetric. The results were compared with experiments, showing that the current constitutive equation including the characterization technique. P. V. Cavallaro [4] investigates the effect of weaving and crimp gradient of the damage tolerance of woven fabric reinforced polymer composites. The study was to determine the mechanisms failure between fibre/matrix, matrix cracking and fiber bridging. The composite used was a Kevlar/ epoxy of 20 layers with three different weaving styles. The composite was subjected to ballistic impact. The experimental results demonstrated that weave style selections and CGs can positively influence the spatial and temporal distributions of stress resulting from severe loading events and that the fiber/ matrix cohesive zone stresses that often lead to delaminations can be reduced. V. Lopresto et al. [5] investigate the behaviour of composite materials at dynamic loading taking account the thickness, stacking sequences and weaving fiber architecture. The analysis highlighted the importance of the penetration energy. An elastic solution available for circular isotropic plates loaded at the centre was modified to model the indentation and applied to the prediction of the load-displacement curve necessary to know the energy that cause the first failure. Interestingly, the force required for damage initiation under form of delamination was found to increase at the increasing of the composite thickness, following a power law whose exponent is very close to 1.5 of the contact law. Harpreet Singh [6] investigate the numerically and experimentally the behaviour of E glass/epoxy composite at low velocity impact. N.K. Naik et al. [7] conducted a finite element research on the behaviour of woven composite materials under transverse central low velocity impact. They used two impact velocities (1m/s and 3m/s) with an impactor of mass 3mg.

M. A. Kounain et al. [8] conducted a drop weight impact tests at different impact energies were performed to investigate the effect of ply stacking sequence and thickness in plain weave glass fiber reinforced composite laminates with 0° and 0/90° ply orientations. They conclude that the stacking sequence did not significantly affect the impact behaviour of the composite laminates. The peak load increased with increase in the number of plies.

J. A. Artero-Guerrero et al. [9], have conducted an experimental study on the effect of mass impactor on the behaviour at low velocity impact of composite made of epoxy reinforced by woven carbon fiber. They used a drop weight tower in range of energies from 10 to 110 J with three different impactor masses.

1.1 Nomenclature

Xc : Longitudinal compressive strength, a-axis (positive value).
Xt : Longitudinal tensile strength, a-axis
YC : Transverse compressive strength, b-axis (positive value).
Yt : Transverse tensile strength, b-axis
Z_t : Normal tensile strength c-axis.
σ_i : Principal stress in direction 1, 2,3
σ_{ij} : Principal stress in plan 23; 13; 12
Sba : In plane shear strength.
Sca : Transverse shear strength.
Scb :Transverse shear strength.

2 Laminate and impactor

The studied was carried out on four woven composite materials of epoxy matrix reinforced with carbon fibers in 2D weaving form (serge and taffeta), see Fig. 1. The serge weaving sequences were (0/30/-30/0) and (0/45/-45/0), see Fig. 1c and 1d. The laminate specimens were formed of four layers with the dimensions of 10×10×0.88 mm^3, and a ply thickness was about 0.22 mm. The fiber volume fraction was about of 33%. They were manufactured rectangular laminate panels using moulding conditions included a temperature of 315°C and a pressure of 2 Bar for 15 min followed by the same temperature with 20 Bar for 20 min, and finally 10 min for 20 Bar at 140°C. The slug impactor targeted the plate by the hemispherical front head. Specimens were tested according to ASTM D7136/ D7136M-05 [20] at ambient temperature of 20°C.

In Table 1, we present the mechanical properties of woven composite laminate and the slug impactor which targeted the

Table 1 Mechanical properties of the composite material and the impactor [1]

Fibers	Density Kg/mm^3	E11 GPa	E22 GPa	E33 GPa	v21
1.628e-6		186.8	3.5	3.5	0.0016
v31		v32	G GPa		
0.0016		0.4	14.37	14.37	14.37
Matrix		Density Kg/mm^3	E GPa	v	
		1.144.10^{-6}	2	0.3	
Impactor		Density Kg/mm^3	E GPa	v	
		7.85.10^{-6}	207	0.3	

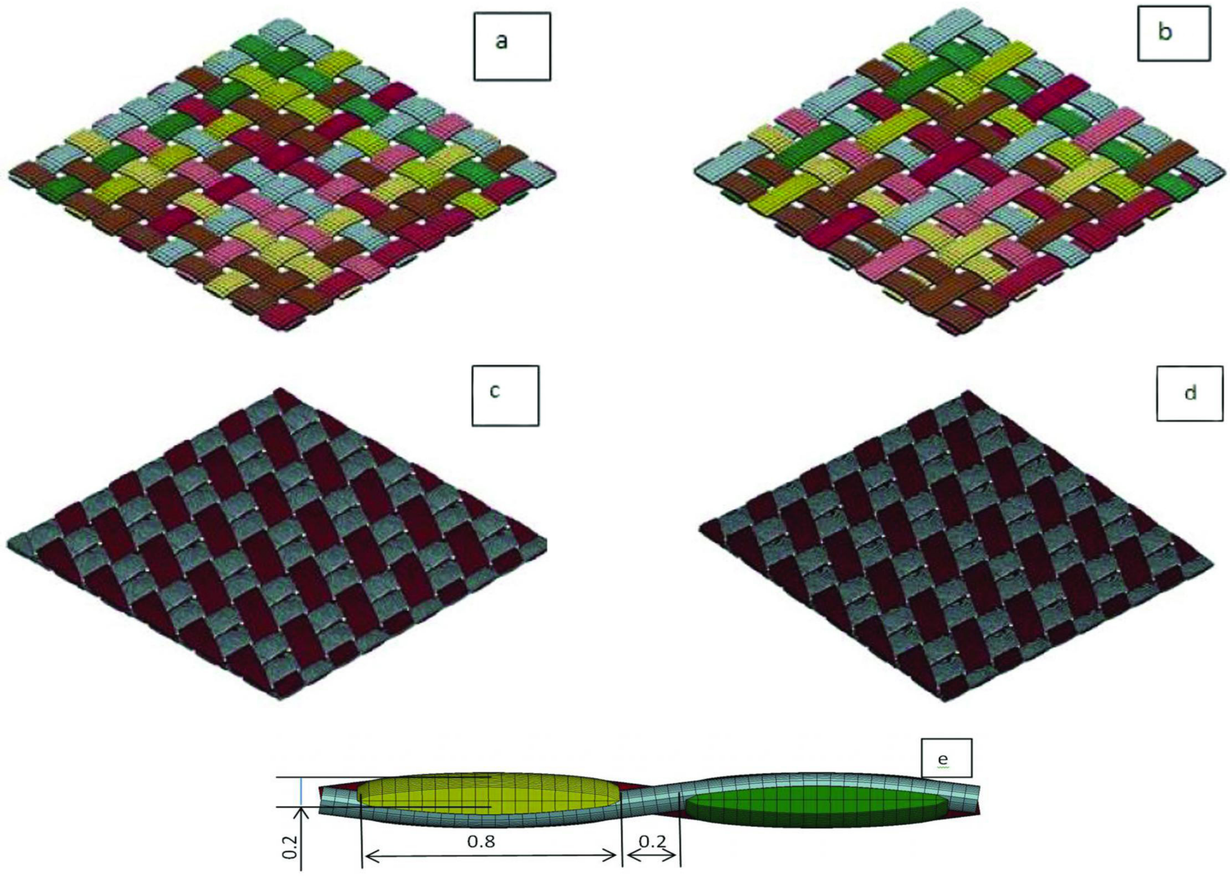


Fig. 1 2Dweaving patterns: a) Serge (2/2), b) Taffeta, c) Serge (0/30/-30/0), d) Serge (0/45/-45/0), e) Fiber bundle geometry

plate at the center by the hemispherical front head. The Texgen [10] package was used to build the weaving pattern model. The finite element model has been built in the FE code Ls-dyna using the solid element formulation. The analysis was carried out using 001-ELASTIC for matrix, 002-ORTHOTROPIC_ELASTIC for fiber and a rigid body model Mat-20 for hemispherical head impactor (slug); in boundary conditions all the laminate sides were clamped, Fig. 3. Eight nodes element usedwith three degrees of freedom at each node and one integration point at the middle of layer laminate, see Fig. 3. The total number of solid elements used was 21576, while the number of solid element nodes was about 44365 and the end time simulation was 2ms. The contact automatic single surface has been used between the yarns and the automatic_surface_to_surface between the matrix and the impactor and the contact automatic_surface_to_surface_tiebreak between the matrix and yarns and the contact automatic_surface_to_surface_tiebreak between layers.

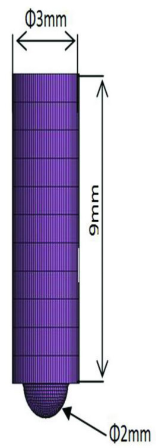


Fig. 2 Slug impactor geometry

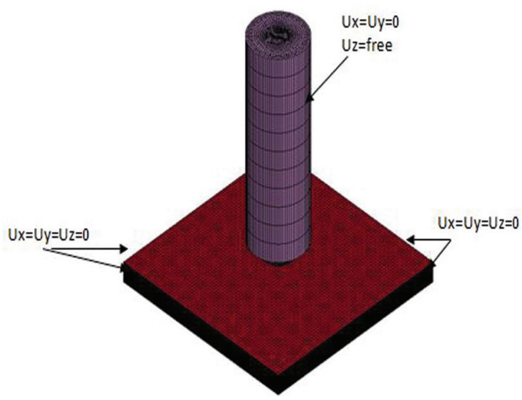


Fig. 3 Mesh scheme and boundary conditions of the composite under drop weight impact

3 Failure criteria

Weight, cost and structure minimization of composite structures necessarily involves strength constraints, because decreasing number of load carrying plies eventually leads to failure. The structure must be able to withstand the imposed loads without suffering any failure.

Thru-Thickness shear failures

- Longitudinal ($\sigma_{11} > 0$)

$$\left(\frac{\sigma_{11}}{X}\right)^2 + \left(\frac{\sigma_{13}}{S_1}\right)^2 \geq 1 \qquad (1)$$

- Transverse ($\sigma_{22} > 0$)

$$\left(\frac{\sigma_{22}}{Y}\right)^2 + \left(\frac{\sigma_{23}}{S_2}\right)^2 \geq 1 \qquad (2)$$

Delamination failures

$$\left(\frac{\sigma_{23}}{Z}\right)^2 + \left(\frac{\sigma_{13}}{S_1}\right)^2 + \left(\frac{\sigma_{23}}{S_2}\right)^2 \geq 1 \qquad (3)$$

Compressive failures

a. Longitudinal compressive failure (if the following is met:

$$\left(\frac{\sigma_{11}}{X_c}\right)^2 \geq 1 \qquad (4)$$

Transverse compressive failure occurs if the following is met

$$\left(\frac{\sigma_{22}}{S_{12}+S_{23}}\right)^2 + \left(\left(\frac{Y_c}{S_{12}+S_{23}}\right)^2 - 1\right)\frac{\sigma_{22}}{IY_c} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{23}}\right)^2 \geq 1 \qquad (5)$$

$$\left(\frac{\sigma_{33}}{S_{13}+S_{23}}\right)^2 + \left(\frac{Z_c}{S_{13}+S_{23}}\right)^2 - 1)\frac{\sigma_{33}}{IZ_c} + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 + \left(\frac{\sigma_{23}}{S_{13}}\right)^2 \geq 1 \qquad (6)$$

4 Numerical modeling

Many factors such as lay- up configuration, impactor size and shape, mechanical properties of composite, environment, presence of notch and cracks, impact velocity can affect the impact behavior and damage pattern. The impact tests were simulated using the commercial finite element code LS-DYNA Version 971, and were run in double precision mode. Since one of the scopes of the analysis was the prediction of damage development, a 3D model of the ply was selected, to obtain a more accurate description of the stress distribution along the ply thickness. Each ply was modeled through a single layer of three-dimensional eight nodes finite elements. In contrast, parts that are relatively thin in one direction are generally modeled with shell elements. To model a thin part with solids can be expensive since the smallest dimension of a solid will control its time step, and generally two or more solid elements through the thickness are required to produce an accurate response. For solid elements, the corresponding element formulations exist with more options if shear locking is for example present. If eight-noded brick elements are to be used, the recommended element formulations are either the default formulation with one integration point, denoted as “ELFORM=1” or the fully integrated solid formulation, denoted as “ELFORM=2” [11] which provides eight integration points on the element surface. The biggest disadvantage to one-point integration is the need to control the zero energy modes, which arise, called hourglassing modes. Undesirable hourglass modes tend to have periods that are typically much shorter than the periods of the structural response, and they are often observed to be oscillatory. However, hourglass modes that have periods that are comparable to the structural response periods may be a stable kinematic component of the global deformation modes and must be admissible. One way of resisting undesirable hourglassing is with a viscous damping or small elastic stiffness capable of stopping the formation of the anomalous modes but having a negligible effect on the stable global modes. Ply element deleting criterion was added by using ADDEROSION card, which allows elements to be deleted from the calculation.

4.1 Numerical results and discussion

The impactor was modeled as a hemispherical rigid body with rigid LS-DYNA material model (MAT-RIGID). Its initial velocity and mass were set depending on the energy level considered. Contact between the impactor and the whole laminate was simulated using the AUTOMATIC-SURFACE-TO-SURFACE penalty based contact algorithm, with the interface parameters listed below:

- ERATEN =7.65e-4KN/mm3: Normal energy release rate used in damage calculation
- ERATES=0.00125KN/mm3: Shear energy release rate used in damage calculation
- NFLS=0.06 GPa Normal failure stress
- SFLS= 0.06 GPa Shear failure stress

Particular attention will be given to the impact energy, contact load and delamination area in the composite laminate. Fig. 4, presents the contact load. In the initial stage, the contact force increases linearly due to elastic deformation of the carbon fiber and resin matrix. Intense oscillations occurring near the peak force value indicate initiation of damage. After the peak load, the crack of resin matrix gradually occurs and fiber tows appears to be damaged. The serge (2/2) and taffetas present more or less the same value about of 0.22KN. The other laminates the serge (0/30/-30/0) provide a value of 0.213 KN and the serge (0/45/-45/0) give a value of 0.175 KN.

All this induce the load decreasing gradually. During the impact event the impactor’s kinetic energy is transferred to the composite plate once contact is made, until it reaches in equilibrium. Part of this energy is stored as elastic strain-energy and part is absorbed. The absorbed component results from the sum of the contributions given by non-conservative forces and the energy dissipated due to the failure mechanisms. Finally, the stored elastic energy is transferred to the impactor. The absorbed energy increases slowly in the early stage. Along with the increase of the displacement, resin crack and fiber breakage lead. The Fig. 5 presents the displacement histories as function of the impact time. The displaced values were reported at the surface contact of the laminate-impactor. We note that the serge (2/2) and the taffetas present the same displacement value about of 0.46mm during an impact time of 0.05ms. The serge (0/30/-30/0) provides a displacement value of 0.42mm. The minimal displacement value was provided by serge (0/45/-45/0) about of 0.11mm during aduration of 0.02ms.

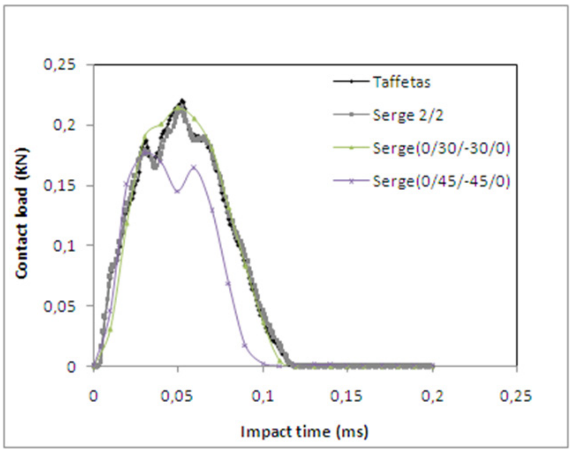


Fig. 4 Contact load histories

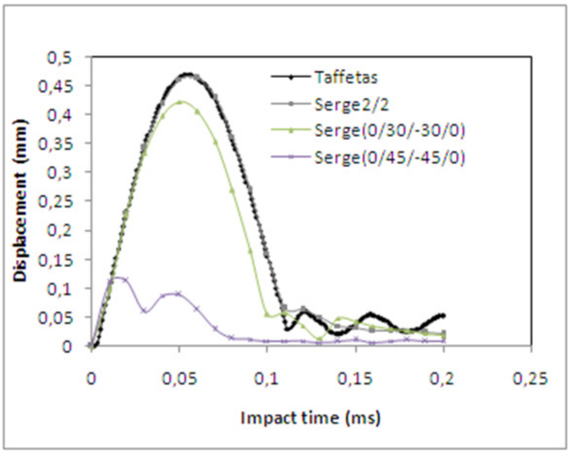


Fig. 5 Displacement histories as impact time

From Fig. 6, we appreciate that the three woven laminates present more or less the same impact energy value about of 0.036J during a time of 0.05 ms. The lowest impact energy was given by laminate serge (0/45/-45/0) about of 0.026J.

4.2 Delamination area

Delamination damage was implemented in the simulation model through the use of a contact_automatic_surface_to_surface_tiebreak between the layers surface-to-surface tiebreak algorithm based on the knowledge of the interlaminar properties of the material in terms of normal and shear strengths with law option 6 [12] was adopted between separate solid elements modeling solid plies. Using this approach, each ply is modeled as a solid layer of elements, but the nodes between plies initially in contact are tied together, inhibiting sliding motions, until a failure criterion is reached, corresponding to delamination onset. In particular, the nodal stress is monitored throughout the analysis and implemented in the interface strength-based failure criterion, Eq. (7).

$$\left(\frac{|\sigma_n|}{NFLS}\right)^2 + \left(\frac{|\sigma_s|}{SFLS}\right)^2 \geq 1 \quad (7)$$

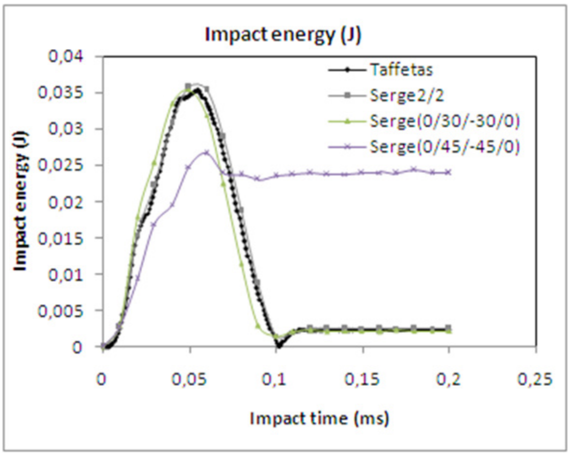


Fig. 6 Impact energy histories

The delamination in laminates is an important phenomena conducting to a catastrophic failure of the components. In Fig. 7, we present the maximum delamination area for the four laminates at the layer interfaces. The taffetas laminate, present a delamination area at interlayer 1-2 about of 5.57 mm^2, and while at the interlayer 3-4 this value increase reaching the 7.95 mm^2. In the case of serge (2/2), at interlayer 1-2, delamination area was 4.51 mm^2, and 9.22 mm^2 at interlayer 3-4. In the serge (0/30/-30/0), the interlayer's 1-2 and 3-4 provide more or less the same value about of 4.81 mm^2. The maximal value was obtained at interlayer 2-3 about of 7.55mm^2. The serge (0/45/-45/0) no present any delamination areas at interlayer's this is due to the lowest contact load.

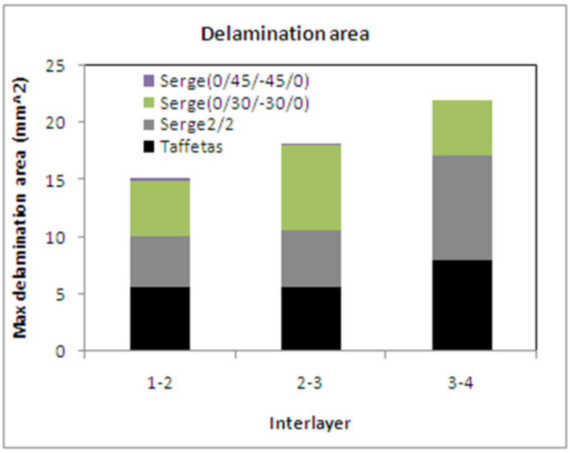
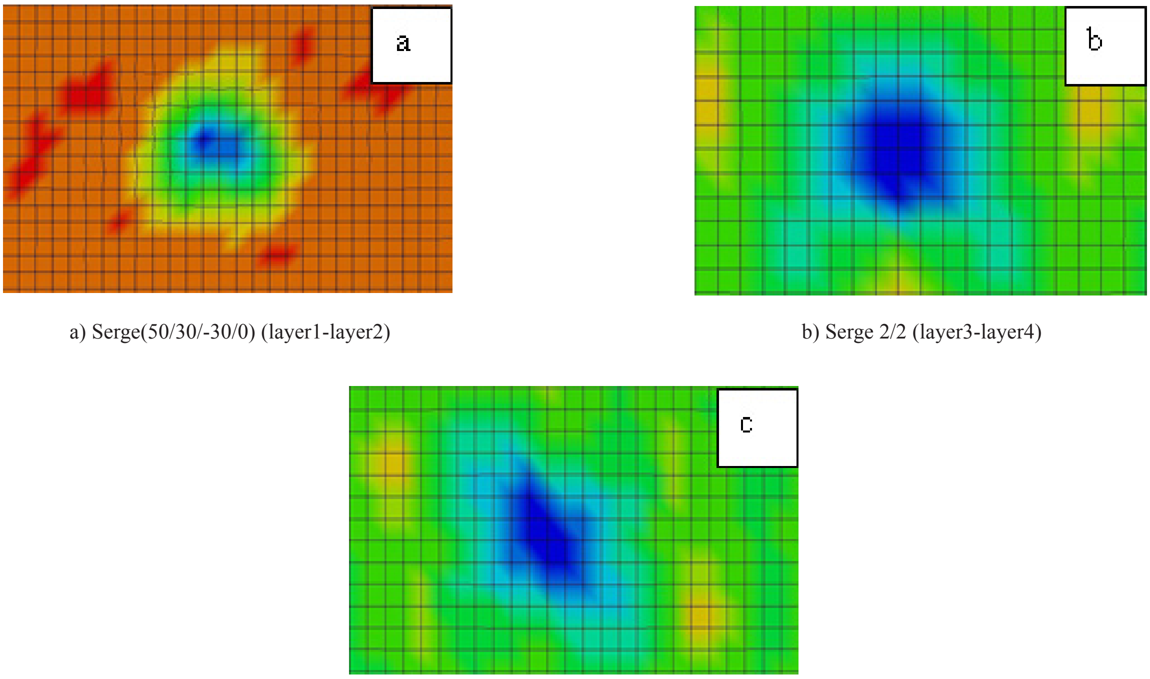


Fig. 7 Maximum delamination area

In Fig. 8, we report the maximal delamination areas at the layer interface. The serge (0/30/-30/0) present a maximal delamination between layer 1and 2.



a) Serge(50/30/-30/0) (layer1-layer2)

b) Serge 2/2 (layer3-layer4)

c) Taffetas (laye3-layer4)

Fig. 8 Maximal interlayer delamination

5 Conclusion

In this study the low velocity impact behavior of four 2D weave fabrics were modeled by mean of the Ls-dyna transient finite element package. The pattern weave was billed by Texgen package. The laminates were targeted at the center by a hemispherical stainless steel slug impactor with a velocity about of 15m/s. The results showed that the taffetas and the serge 2/2 laminates, present more or less the same contact load and displacement.

On the other hand, the serge (0/45/-45/0) presents a lower contact load. The weave fabrics serge (0/30/-30/0) and serge 2/2 presents different delamination area values. The laminate (0/45/-45/0) shows a less delamination area due to the lowest contact load.

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