NUMERICAL ANALYSIS OF LOW VELOCITY IMPACTS ON 5HS WOVEN COMPOSITE LAMINATES

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Keywords: Low velocity impact test, FEM modelling, satin woven CFRP laminates, Continuum Damage Approach

Abstract
This work proposes a numerical methodology, carried out in an explicit commercial finite element code, to model the response of AGP 280-5H carbon/epoxy satin woven laminates under low velocity impacts. Numerical simulations will be validated with a set of experimental tests performed also by same authors in accordance to ASTM standards; in which it is studied the influence of thickness, ply sequence and ply clustering. The material model for the woven laminate takes into account different intralaminar failure mechanisms, such as fiber failure or in-plane shear, based on a Continuum Damage Approach; in addition the use of cohesive interactions allows reproducing the inter-lamina damage.

1. Introduction

Aeronautic and aerospace industries are continuously increasing the use of composite materials, which nowadays represent more than 50% of aircraft structures weight. High strength-to-weight and stiffness-to-weight ratio of these materials allow optimizing the structures and reducing significantly the weight.

Due to the use of these materials in primary structures they usually are exposed to occasional impacts. Moreover, it is known the poor out-of-plane properties of composite laminate which increase the impact vulnerability of composite structures. Therefore it is necessary to understand how composites behave when they are subjected to these types of events. It has been observed that the response of CFRP panels is quite different depending on the impact velocity, thus this type of events can be classified into high and low velocity impacts. Concerning to low velocity impact, drop-weight tower is the most used experimental test for analyzing the behavior of laminates. The impact induces different failure mechanisms such as matrix cracking, delamination and fiber failure [?]. This effect has been studied experimentally and numerical mainly on tape CFRP laminates [? ?]. Also it has been analysed the influence of different laminate parameters, such as stacking sequence or ply clustering, in damage extension [? ?]. Concerning to woven CFRP laminates, there is a lack of works in which the influence of previous laminate parameters is addressed together, using both experimental and numerical approaches.

This work proposes a numerical methodology, carried out in an explicit commercial finite element code ABAQUS v.6.14, to model the response of AGP 280-5H carbon/epoxy satin woven laminates under low velocity impacts. Numerical simulations will be validated with a set of experimental tests performed also by same authors in accordance to ASTM standards [?]; in which it is studied the influence of thickness, ply sequence and ply clustering. The material model for the woven laminate takes into account different

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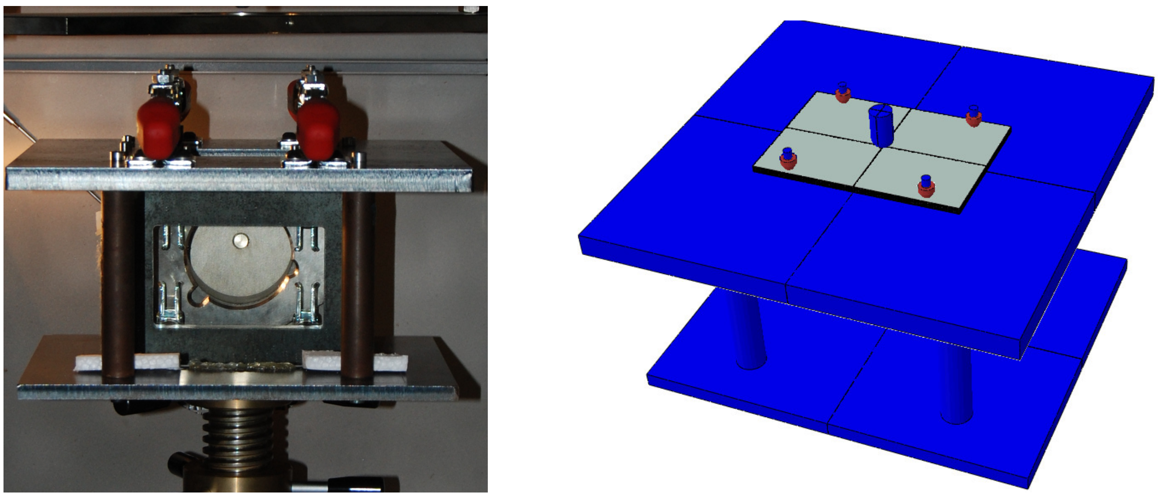
intralaminar failure mechanisms, such as fiber failure or in-plane shear, based on a Continuum Damage Approach; in addition the use of cohesive interactions allows reproducing the inter-lamina damage.

2. Numerical modeling

Experimental tests has been performed to study the influence of thickness, ply sequence and ply clustering in the response of AGP 280-5H carbon/epoxy satin woven laminates under low velocity impacts. Three configurations of thickness ($(0/90)_{4s}$ corresponding to a thickness $t = 2.3$ *mm*, $(0/90)_{6s}$ $t = 3.5$ *mm* and $(0/90)_{8s}$ $t = 4.6$ *mm*), stacking sequence ($(0/90)_{8s}$ and $(\pm45)_{8s}$, all of them corresponding to $t = 4.6$ *mm*) and ply clustering ($[(\pm45)/(0/90)]_{4s}$, $[(\pm45)_2/(0/90)_2]_{2s}$ and $[(\pm45)_4/(0/90)_4]_s$, all of them corresponding to $t = 4.6$ *mm*) have been selected.

In order to reproduce the experiment tests, the drop-weight impact has been modelled using the commercial explicit finite element software Abaqus/Explicit v6.14, Fig. 1. The model has been divided in three different parts: impactor, laminate and rigid base. The impactor and the rigid base were made of steel, and due to its strength no plastic deformation has been observed after the impacts. For this reason a linear elastic behaviour was chosen for the simulations, with the following properties: $E = 210\,GPa$ and $\nu = 0.3$. In this model only a fraction of the impactor was modelled in order to reduce the computational costs, so the density of this part was increased to get the total impactor mass.



(a) (b)

Figure 1. Experimental set-up and numerical model developed in Abaqus/Explicit v6.14.

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The composite laminate of woven carbon/epoxy takes into account the intralaminar and interlaminar failure. The intralaminar failure has been modeled using the “Abq Ply Fabric” Vumat subroutine, available in Abaqus v6.14; while cohesive interaction is used for the interlaminar failure. The material properties used for each ply are described in Table 1. One continuum shell element for each ply was used to simulate the laminate layup. The intralaminar material model uses a Continuum Damage Approach to simulate the degradation of the material properties during the impact. The material model defines different failure criteria for the fibre damages, distinguishing between tension, compression and shear damage. The onset of damage is detected by the following equations.

- Fibre tension $d_f = \frac{\sigma_{11}}{X_{iT}}$

- Fibre compression $d_f = \frac{\sigma_{11}}{X_{iC}}$
- In-plane shear $d_S = \frac{\sigma_{12}}{S}$

being X_{iT} the tensile strength of the ply in the i direction of the fibre, X_{iC} the compressive strength of the ply in the i direction of the fibre and S the in-plane shear strength.

Table 1. Intralaminar material properties for AGP 280-5H carbon/epoxy satin woven.

Density	1570 Kg/m^3
Elastic Properties	$E_{11} = 67\ GPa$; $E_{22} = 66\ GPa$; $G_{12} = 5.5\ GPa$; $\nu_{12} = 0.3$
Strength	$X_{1T} = 876\ MPa$; $X_{1C} = 800\ MPa$; $X_{2T} = X_{2C} = 924\ MPa$; $S = 79\ MPa$
Fracture Toughness	$G_{1T} = G_{2T} = G_{1C} = G_{2C} = 48.9\ KJ/m^2$

The damage evolution will degrade the material stiffness coefficients until the energy dissipated is equal to the fracture toughness (G_i [J/m^3]), once this point is reached the material is considered fully damaged. The inter-laminar damage is modelled through a cohesive surface interaction. The cohesive behaviour is based on a traction-separation law, in which is necessary to define a damage initiation criteria and a damage evolution law, Table 2. In order to reduce the computational costs the symmetries of the problem are applied, thus only one quarter of the model was simulated, with an appropriate element size to avoid snap-back effects [**?**].

Table 2. Interlaminar material properties for AGP 280-5H carbon/epoxy satin woven.

Elastic Properties	$K_{nn} = 44000\ N/mm^3$; $K_{ns} = 40000\ N/mm^3$
Strength	$T = 50\ MPa$; $S = 65\ MPa$
Fracture Toughness	$G_I = 0.28\ KJ/m^2$; $G_{II} = 0.79\ KJ/m^2$

3. Validation and study of laminate parameters

In the following section it is presented the validation of the numerical model performing a comparison between experimental and numerical results. Through this validation has been study the influence of the laminate thickness, stacking sequence and ply clustering.

3.1. Validation

In Fig. 2 it is shown the force time history data obtained from the experimental test and the numerical simulations for an impact at 15 J for the laminate composed by 12 plies $(0/90)_{6s}$. As it can can be seen in the figure, the numerical model reproduces faithfully the force exerted in the experimental test regarding elastic slope, peak force and impact duration. Moreover, in order to validate the numerical modelling it has been selected four different time points (Frame A, B, C and D) in which it has been related the force time history and the behaviour of the laminate. In the experimental tests, in order to record the effect of the impact in the laminate a mirror is placed below the plate; also the laminate is painted in white to highlighted the apparition of failures. Numerically, the same area of the back face of the laminate is shown to compare the effects; the magnitude of the damage in direction of the fibre parallel to the

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smallest length of the plate is represented in the figures. Corresponding to the elastic regime (Frame A), no damage can be seen in the experimental nor numerical images. Nevertheless, when the first drop of the force appears (Frame B), a fibre failure is generated in the experimental test, and also in the numerical simulations. After this point, the force increases very slowly while the fibre failure and the damage continues increasing in both, experimental test and numerical model (Frame C). Finally, in Frame D the fibre failure reaches its maximum length in the experimental test. The failure only appears perpendicular to the smallest length, phenomenon well reproduce by the numerical model. This is explained because the BCs induce higher stresses in the fibre parallel to the smallest dimension of the plate, so the failure develops normally to this direction. In the numerical model, damage does not increase, being smaller than the experimental one. This could explain why the contact time, related with the laminate stiffness [**?**], is higher for the experimental case. It can be concluded that the numerical model reproduce accurately not only the force time history, but the behaviour of the laminate and its main failure mechanisms.

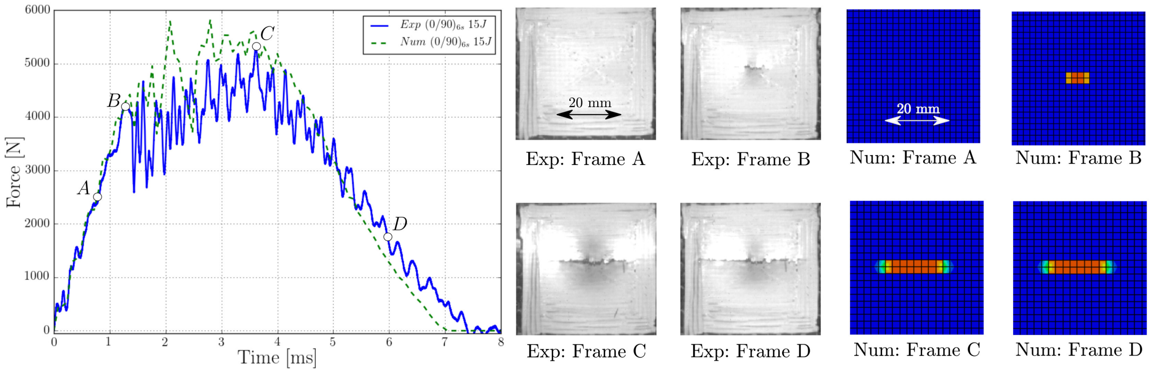

Figure 2. Experimental and numerical force time history for the 12 plies laminate $(0/90)_{6s}$ subjected to a 15 J impact. Experimental failures in the laminate and numerical fibre damage predicted for time points corresponding to Frame A, B, C and D

3.2. Influence of the laminate thickness

In order to analyse the influence of the thickness, Fig. 3 shows the time force history of an impact at 10 J to the 8 plies $(0/90)_{4s}$ laminate and the 16 plies $(0/90)_{8s}$ laminate. In order to have information about the response of the laminate, it is included a detail of the failure in the laminate once the test is performed that is compared with the numerical damage obtained in the same laminate area. The variable which is plotted combine the damage of the fibre in both directions and it is defined as $d_F = \sqrt{d_{f1}^2 + d_{f2}^2}$. For the thinner laminate, Fig. 3 (a), the force curve shows an elastic regime that ends in a sudden drop that corresponds to the apparition of fibre failure. Then the force continues increasing, but with a lower slope, as failure grows. Experimentally and numerically, it can be noticed a failure in the two fibre direction, because stresses are higher enough to promote failure in both directions, and not as the previous case shows, Fig. 2. Nevertheless the failure is always higher in the direction perpendicular to smallest dimension of the plate. It can be seen how as the thickness increases the damage decreases, Fig. 3 (b). The force curve its similar to a sinusoidal curve, but the drop in the force means that the fibre failure appears. The failure presented in both experimental test and numerical model is only a small slit in the direction perpendicular to the smallest dimension.

In Fig. 4, force time history and failures correspond to a case in which the nominal impact energy is the same, defined as $\frac{E_i}{p}$ [**?**], being E_i the impact energy and p number of plies. For this case, it is used

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$\frac{E_i}{p} = 2.5J/plies$ that means 20 J for the 8 plies laminate and 40 J for the 16 plies laminate. If the cases are compared with previous Fig. 3, it can be seen that as the impact energy increases, damages increases, appearing a cross type fibre failure for both laminates. For both cases contact duration increases which is related to the damage produced in the laminate. Attending to the comparison between experimental and numerical results, it can be also concluded that the numerical model reproduce same trends concerning to influence of impact energy and thickness, but as it was previously stated, numerical model slightly underestimated the damaged area.

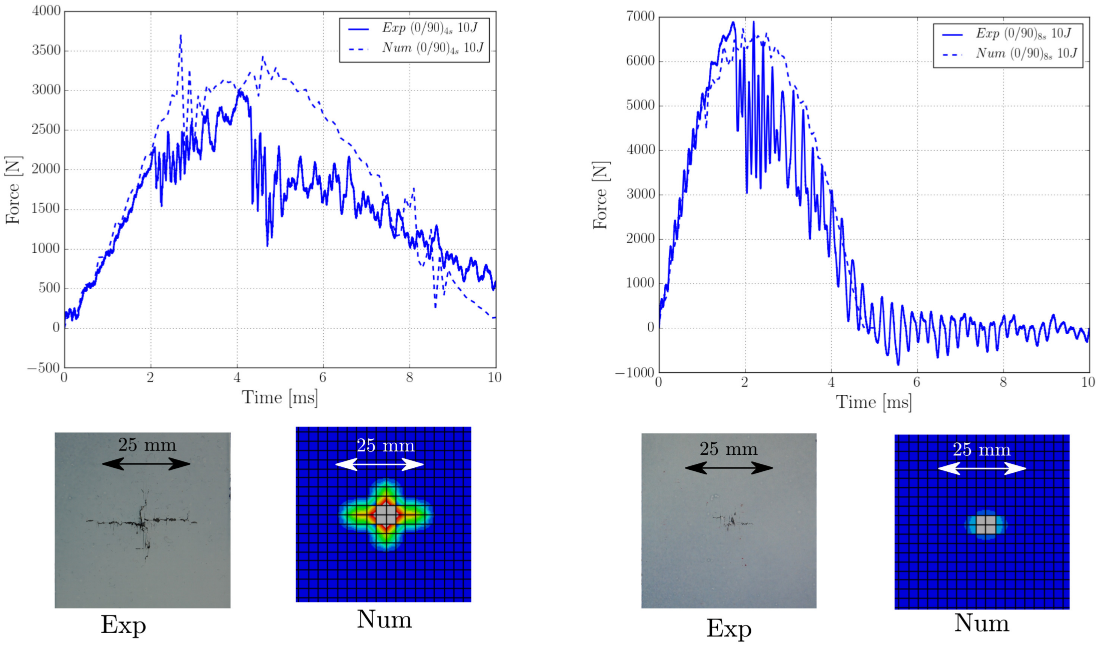

Figure 3. Experimental and numerical force time history for a equinergetic impact to $(0/90)_{4s}$ and $(0/90)_{8s}$ laminates. Experimental failures in the laminate and numerical fibre damage predicted.

3.3. Influence of the stacking sequence

To uncover the influence of the ply sequence it has been compared the behaviour of the laminate when subjected to an impact at 40 J for the laminate $(0/90)_{8s}$ and the laminate $(\pm 45)_{8s}$. In Fig. 5 it is plotted the Coefficient of Restitution (COR) obtained experimentally and numerically for both laminates. The COR is a measure of the damage induced by the impact and it is obtained by the following equation $COR = \sqrt{\frac{E_i - E_{abs}}{E_i}}$ [?]. It can be seen small differences in this parameter between both laminates. It is included also the experimental failure of the laminate in the back face and the value numerically predicted for the damage in both fibre directions previously explained. It can be noticed clearly how the damage in both cases follows the fibre direction, so rotated 45^o in the $(\pm 45)_{8s}$ case. As it was previously said, in the case of the $(0/90)_{8s}$, the impact induces higher stresses in the direction parallel to the smallest plate dimension due to the particular BCs and therefore promotes an higher failure length perpendicular to the smaller plate dimension. Nevertheless, in the $(\pm 45)_{8s}$ case the BCs affects similarly for both fibre directions which explains why fibre failure dimension is the same for both directions. The numerical model is able to reproduce the failure pattern appeared experimentally but the COR values are underestimated due to the damaged extension is not accurately reproduced, as previously was showed.

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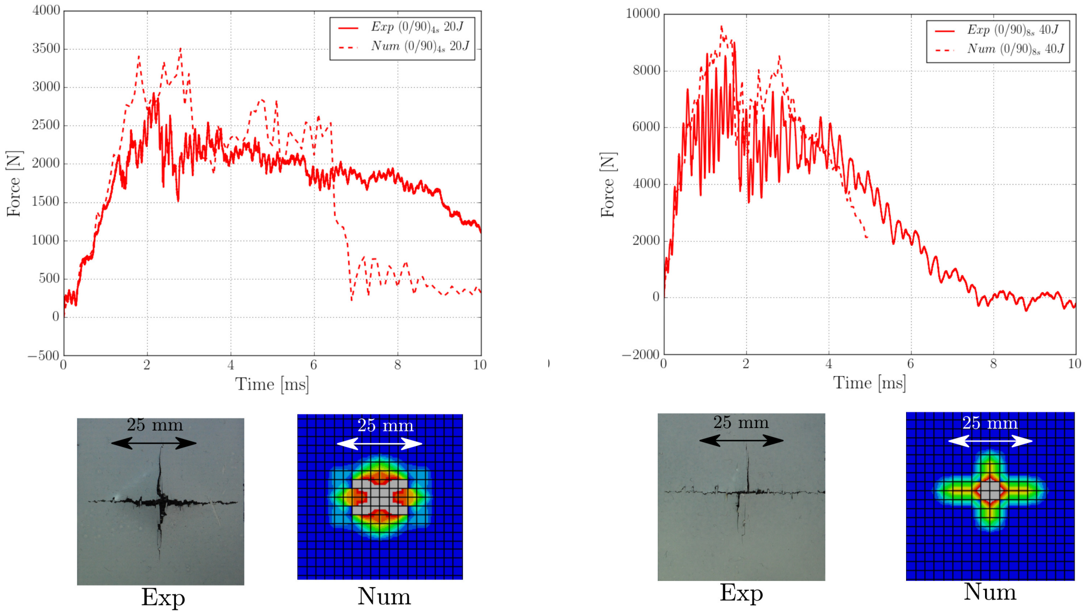

(a) 20 J $\frac{E_i}{p}$ = 2.5 $J/plies$ $(0/90)_{4s}$ (b) 40 J $\frac{E_i}{p}$ = 2.5 $J/plies$ $(0/90)_{8s}$

Figure 4. Experimental and numerical force time history for same nominal impact energy to $(0/90)_{4s}$ and $(0/90)_{8s}$ laminates. Experimental failures in the laminate and numerical fibre damage predicted.

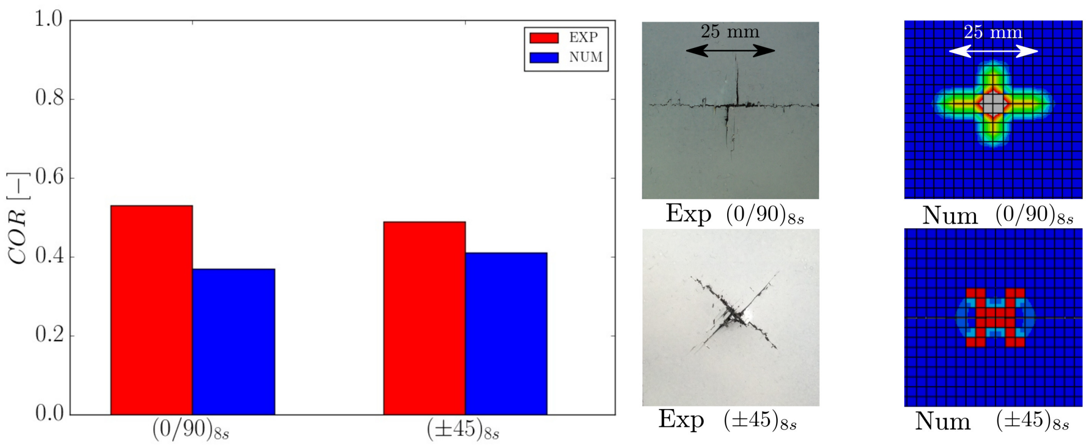

Figure 5. COR values obtained experimentally and numerically for the 16 plies laminates $(0/90)_{8s}$ and $(\pm45)_{8s}$ subjected to a 40 J impact.Experimental failures in the laminate and numerical fibre damage predicted.

3.4. Influence of the ply clustering

Fig. 6 helps to understand the effect of the the ply clustering, showing the COR parameter obtained experimentally and numerically for an impact at 40 J for the laminates $[(\pm45)/(0/90)]_{4s}$, $[(\pm45)_2/(0/90)_2]_{2s}$

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and $[(\pm45)_4/(0/90)_4]_s$. The ply clustering will provide information about the relation of the number of interfaces with dissimilar angle and the appearance and extension of delamination. Therefore, it is also included the delaminated area obtained numerically to study this effect. Comparing the three cases, it can not be seen important differences for both COR values and delaminated area. As it is already said, the numerical model underestimates the COR value.

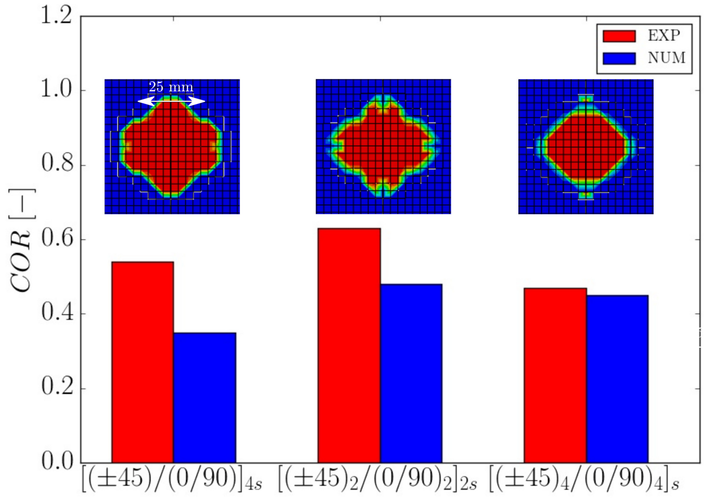

Figure 6. COR values obtained experimentally and numerically for the 16 plies laminates $[(\pm45)/(0/90)]_{4s}$, $[(\pm45)_2/(0/90)_2]_{2s}$ and $[(\pm45)_4/(0/90)_4]_s$ subjected to a 40 J impact. Predicted delaminated area is included in the graph for each case.

4. Conclusion

In this work, numerical simulations have been carried out to model the response of AGP 280-5H carbon/epoxy satin woven laminates under low velocity impacts. It has been studied the influence of laminate thickness, stacking sequence and ply clustering.

- The numerical model has been validated using the experimental test carried out. The model predict faithfully the time force history curves and the generation of the main failure mechanisms. Nevertheless the model has to be improved to reproduce better the failure dimensions.
- Concerning to the influence of the thickness, as it increases the damaged area is reduced in equienergetic impacts. Additionally, it has been shown that when the nominal impact energy is the same, the damaged area is similar for laminates with different thickness.
- Concerning to the analysis of the stacking sequence, it has been found that the shape and the dimension of the fibre failure is clearly influenced by the direction of the fibre. Nevertheless, COR parameter, that is related to absorbed energy and so the damage, is almost constant for both laminates.
- No important differences has been found in the COR parameter and the delaminated area for different laminate in which the ply clustering is varied.

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Acknowledgments

This research was done with the financial support of the Spanish Ministry of Economy and Competitiveness under Project reference DPI2013-41094-R.

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