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# A three-dimensional failure analysis of singly-curved composite shells subjected to impact loading

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***Abstract:*** *This paper presents a numerical study on the impact behaviour of curved composite panels subjected to impact loading. The model has been developed using ABAQUS finite element code. A nonlinear three dimensional failure model including irreversible strains, damage and strain rate effects have been used for this purpose. The model incorporates a viscoplastic damageable constitutive law for the inplane shear dominated failure mode. In order to account for delamination failure modes a single cohesive layer was placed at the midplane of the laminate. The results indicate that delamination has a significant influence on the dissipated energy of curved laminates when subjected to impact loading.*

***Keywords:*** *impact, composite laminate, damage mechanics, finite elements*

## 1. INTRODUCTION

Composite materials exhibit different failure modes such as fibre failure in tension/compression, matrix cracking in tension/compression, shear cracking and delamination. The coupling between these different failure modes is not fully understood yet. For this reason there is a clear need for the development of reliable theories which enable not only the prediction of damage initiation but also damage progression in composite laminates, mainly when these structures are subjected to multiaxial stresses induced severe loadings (Donadon *et al*, 2009; Yokoyama *et al*, 2010; Iannucci and Willows, 2006; Kärger *et al*, 2009).

Aktas *et al* (2009) studied experimentally the compression after impact behaviour of laminated composite plates subjected to low velocity impact using cross-ply and quasi-isotropic laminates. Donadon *et al* (2008) proposed a 3-D failure model for predicting the dynamic material response of composite laminates under impact loading. Their model was implemented into LS-DYNA explicit finite element and experimental tests were carried out to validate the failure model. The results of the numerical model showed a good agreement with the experimental results. Heimbs *et al* (2009) investigated numerically and experimentally the low velocity impact induced damage in composite plates pre-loaded in compression. The failure methodology proposed by the authors took into account intralaminar and delamination failure modes. The authors used an iterative failure criteria proposed by Chang and Chang (1987). Their results showed a good agreement with the experimental results and a great dependence on the simulation parameters like size of mesh and number of shell layers.

## 2. DAMAGE MODEL FORMULATION

The formulation of the damage model used in this paper combines Continuum Damage Mechanics (CDM) and fracture mechanics approaches within an unified way by using a smeared cracking formulation. Details on the model formulation may be found in Donadon *et al* (2009).

The model accounts for fibre failure in tension/compression, matrix cracking in tension/compression and in-plane shear cracking by using the following stress based failure criteria,

*Fibre failure in tension:*

$$F_1^t(\sigma_1) = \frac{\sigma_1}{X_t} \geq 1 \tag{1}$$

*Fibre failure in compression:*

$$F_1^c(\sigma_1) = \frac{|\sigma_1|}{X_c} \geq 1 \tag{2}$$

*Matrix cracking in tension/shear:*

$$F_2^t(\sigma_2, \tau_{23}, \tau_{12}) = \left(\frac{\sigma_2}{Y_t}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 \geq 1 \tag{3}$$

*Matrix cracking in compression*

$$F_2^c(\sigma_{nn}, \tau_{nl}, \tau_{nt}) = \left(\frac{\tau_{nl}}{S_{23}^A + \mu\sigma_{nn}}\right) + \left(\frac{\tau_{nt}}{S_{12} + \mu\sigma_{nn}}\right) \geq 1 \tag{4}$$

*In-Plane Shear Failure:*

$$F_{12}(\tau_{12}) = \frac{|\tau_{12}|}{S_{12}} \geq 1 \tag{5}$$

where $X_t$ and $X_c$ are the longitudinal strengths in tension and compression, respectively, $Y_t$ is the transversal strength in tension, $S_{12}$ and $S_{23}$ are the in-plane shear and out-of-plane shear strengths, respectively; $\sigma_{nn}, \tau_{nl}, \tau_{nt}$ are the normal and shear stresses acting on the potential fracture plane (Puck and Shurmmann, 2002). $S_{23}^A$ is effective shear strength of the material in the potential fracture plane. When one of the criteria presented above is met, damage start to grows according to the linear-polynomial damage evolution law proposed by Donadon *et al* (2009).

## 3. DELAMINATION MODELING

The failure modes associated with delamination were modelled using a cohesive model. The cohesive model was implemented into ABAQUS as a user defined material model within solid elements. This model enables the prediction of the mixed mode delamination without knowing *a priory* the mixity ratio between different delamination modes. The constitutive law is written in terms of the following relationship between interfacial stresses and interfacial relative displacements,

$$\begin{Bmatrix} \sigma_I \\ \sigma_{II} \\ \sigma_{III} \end{Bmatrix} = \begin{bmatrix} K_I(1-d(\bar{\delta})) & 0 & 0 \\ 0 & K_{II}(1-d(\bar{\delta})) & 0 \\ 0 & 0 & K_{III}(1-d(\bar{\delta})) \end{bmatrix} \begin{Bmatrix} \delta_I \\ \delta_{II} \\ \delta_{III} \end{Bmatrix}$$

with

$$d(\bar{\delta}) = 1 - \frac{\bar{\delta}_0}{\bar{\delta}}\left[1 + \left(\frac{\bar{\delta} - \bar{\delta}_0}{\bar{\delta}_f - \bar{\delta}_0}\right)^2 \left(2\left(\frac{\bar{\delta} - \bar{\delta}_0}{\bar{\delta}_f - \bar{\delta}_0}\right) - 3\right)\right]$$

where $K_I$, and $K_{II}$ and $K_{III}$ are the interfacial stiffnesses associated with mode I, II and III, respectively. $\sigma_I$, $\sigma_{II}$, $\sigma_{III}$ are the interfacial stresses and $\delta_I$, $\delta_{II}$ and $\delta_{III}$ are the respective relative displacements associated with mode I, II and III. $\bar{\delta}_0$ is the equivalent displacement at damage onset obtained from a quadratic stress based criterion. $\bar{\delta}_f$ is the final displacement when damage $d(\bar{\delta}) = 1$ and the stresses are equal to zero obtained from the energy based failure criterion. Details on the model formulation may be found in (Donadon and Almeida, 2010)

## 4. NUMERICAL SIMULATIONS

The purpose of this paper is to study numerically the influence of the delamination on the amount of dissipated energy of curved plates subjected to impact loading. For this purpose two types of simulations were carried out: (i) plate model with a cohesive layer at the middle plane of the curved plate and (ii) model without the cohesive layer. The degradation of the material is considered in the simulation by using an "*user defined material model*" which was implemented into solid elements available in *ABAQUS 6.5-1 Dynamic Explicit*. The impact energies applied were 12 J and 24 J. The Table 1 depicts all the simulations performed in this paper.

**Table 1. Simulated cases**

| Name | Impact Energy (J) | Cohesive Layer |
|---|---|---|
| Case 1 | 12 | No |
| Case 2 | 12 | Yes |
| Case 3 | 24 | No |
| Case 4 | 24 | Yes |

The curved plate has the displacements in the radial direction constrained. The striker has only the displacement in vertical direction free (impact direction). Also the laminate has the displacements in the other two directions constrained into the eight nodes on the vertices of the plate (two in each one) in order to avoid the rigid body movement. The elements used in the curved plate and on the striker were an 8-node linear brick with reduced integration and hourglass control. The material properties were taken from the literature and they are listed in Table 2. The properties of the cohesive layer are presented in Tab. 3. The contact between the striker and the curved plate was assigned using the nodal erosion contact option available in ABAQUS.

**Table 2. Mechanical properties of a typical woven ply**

| Mechanical Properties | |
|---|---|
| $E_{11}$ (GPa) | 60.8 |
| $E_{22}$ (GPa) | 58.25 |
| $G_{12}= G_{13}$ (GPa) | 4.55 |
| $\nu_{12}= \nu_{13}$ | 0.07 |
| $\nu_{23}$ | 0.4 |

**Table 3. Mechanical properties of a cohesive layer**

| Mechanical Properties | |
|---|---|
| $E_{33}$ (GPa) | 2.97 |
| $G_{12}= G_{13}$ (GPa) | 1.08 |
| $S_{12}=S_{13}$ (MPa) | 100 |
| $G_{IC}$ | 585 |
| $G_{IIC}=G_{IIIC}$ | 2500 |

The dimensions of the curved plate are 85 mm × 145 mm × 4.6 mm, 200mm of curvature radius with lay-up $[(0/\pm45/90)_2/(0)_2]_s$ .The thickness of each layer is 0.23 mm. The thickness of the cohesive layer is 1/10 of the lamina thickness. The total thickness of the laminate was kept the same for both cases. The impact energies for each case were set through a velocity field assigned to the hemispherical striker with a diameter of 12.7 mm and 1.5 kg of mass. The impact resistance of the laminates was measured by the dissipated energy, which was obtained from the integration of the curve Contact Force × Displacement for each case.

## 5. RESULTS AND DISCUSSIONS

The simulations showed consistent results for the laminates with and without cohesive layer. The impact resistance including the delamination effects was evaluated through the amount of dissipated energy for each impact case. Figure 1 shows a comparison in terms of contact force between the cases including and neglecting delamination failure modes (Cases 1 and 2, respectively). It is clear that the delamination plays an important rule in the impact resistance of composite curved plates and it must be taken into account in the analyses. Figure 2 shows the load-displacement curves for both models with and without delamination modelling. This figure also confirms that a great amount of impact energy is dissipated through delamination induced failure modes.

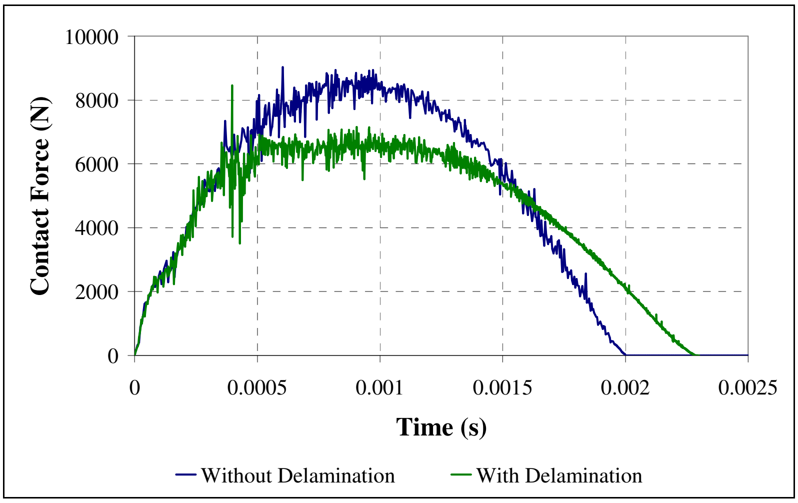

**Figure 1. Contact Force × Time**

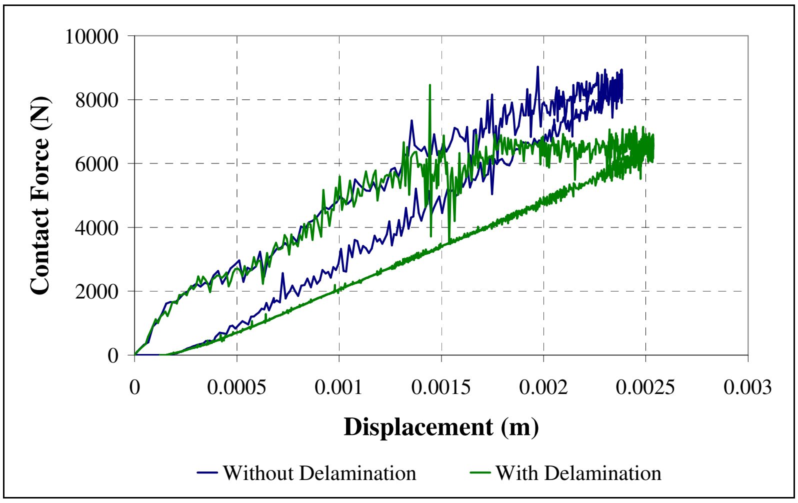

**Figure 2. Load-Displacement curves**

Figure 3 shows the amount of dissipated energy obtained by each the impact energy for the laminate with and without cohesive layer. The results show a variation of the dissipated energy for the laminates with and without cohesive layer for same impact energy.

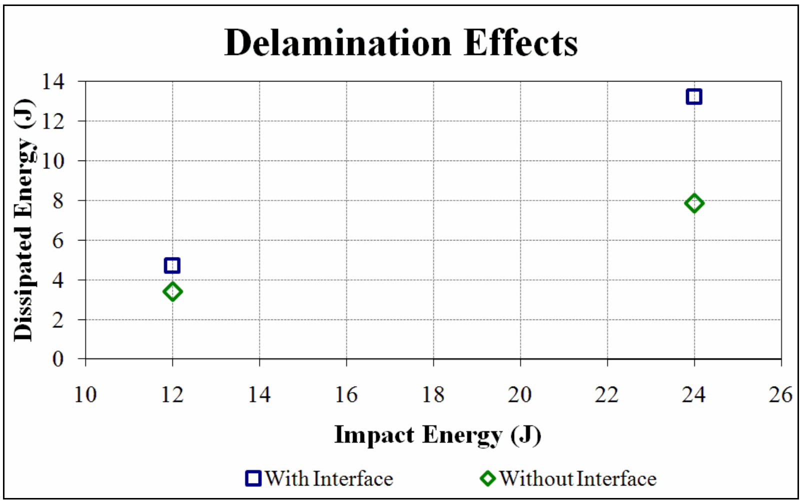

**Figure 3. Delamination effects on the impact resistance.**

In the Table 4 are listed the failure modes predicted by the simulations with and without cohesive layer. The Case 4(impact energy of 24 J) indicated a fibre failure mode in tension leading to partial perforation on the bottom face of the laminate. This effect was not observed in model which not include delamination (Case 3).The Case 2, impact energy of 12 J and cohesive layer, shows a fibre failure mode in compression and a in-plane shear failure which was not observed in Case 2 that is, same impact energy but without cohesive layer.

**Table 4. Failure modes**

| | **Impact Energy 12 J** | | **Impact Energy 24 J** | |
|---|---|---|---|---|
| | **Case 1** | **Case 2** | **Case 3** | **Case 4** |
| **Fiber Failure in Tension** | no | no | no | yes |
| **Fiber Failure in Compression** | no | yes | yes | yes |
| **Tensile Matrix Cracking** | yes | yes | no | yes |
| **Compression Matrix Cracking** | no | no | no | no |
| **In-plane Shear Failure** | no | yes | no | no |
| **Delamination** | yes | - | yes | - |

Figure 4 shows the predicted shape and extent of the delamination at the midplane interface for the impact energy of 12 J, where the failed element has been removed from the mesh.

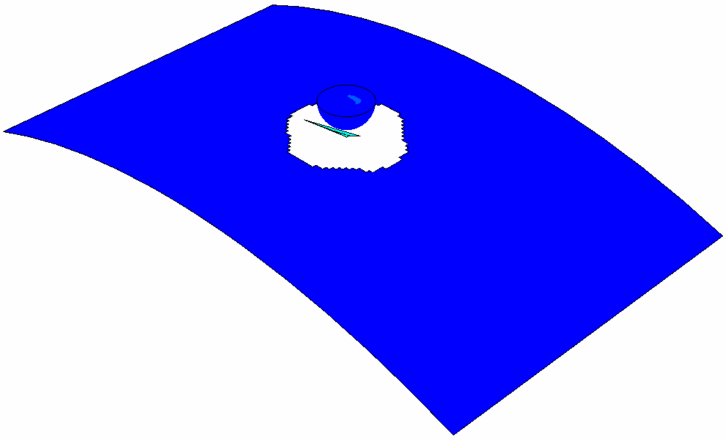

**Figure 4. Delamination extent for Case 2**

## 6. CONCLUDING REMARKS

This paper presented a numerical study of the delamination effects on the impact resistance of composite curved plates. The numerical results indicated that the delamination considerably affects the amount of dissipated energy in curved composite plates subjected to impact loading. The results indicate that delamination plays an important rule on the impact behaviour of composite curved plates. Thus such an effect must be taken into account in the design and analysis of composite structures. An experimental programme will be carried out to validate the numerical models presented in this paper.

## 7. ACKNOWLEDGMENTS

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