A NUMERICAL INVESTIGATION OF THE PRESSURE AND CURVATURE EFFECTS ON THE IMPACT RESISTANCE OF COMPOSITE LAMINATES

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Abstract. *This paper presents a numerical study of the pressure and curvature effects on the impact resistance of composite shell laminates. For this purpose composite shells with four different curvatures subjected to two pressures levels each were analysed. The pressure levels were chosen based on real in-flight conditions typically experienced by the aircraft fuselage. In addition to the pressure and curvature effects the influences of the stacking sequence and shell thickness on the impact resistance were also analysed. The model has been developed using ABAQUS 6.5-1 FE code. The analyses account for failure modeling by using a newly developed in-plane damage model. The damage model has been implemented into ABAQUS as a user defined material model within shell elements.*

***Keywords**: Impact , Composite Laminates, Damage mechanics, Finite elements*

1. INTRODUCTION

The use of composite laminates in the aeronautical industry has increased in the last years due to the superior mechanical properties of these materials compared to conventional metals, such as higher strength stiffness per unit of mass. In this paper we present a numerical study of the pressure and curvature effects on the impact resistance of composite shell laminates. The pressure levels were chosen based on real in-flight conditions typically experienced by the aircraft fuselage. Many works has been developed in order to evaluate and validate numerically the behavior of composite shells laminates subjected to impacts loading (Aktas *et al*, 2009; Ballère *et al*, 2008; Choi, 2008; Donadon *et al*, 2008a). These studies include the impact on low, medium and high velocities as well as the initiation, propagation and extent of damage in the structure and the influence of factors such as thickness, curvature, stacking sequence and boundary conditions.

Aktas *et al* (2009) investigated experimentally the effects of the stacking sequence on the impact response of composite panels made of glass/epoxy under different impact energies levels. They found that quasi-isotropic laminates showed better results in terms of impact resistance compared to cross-ply laminates. Johnson *et al* (2001,2006) studied numerically and experimentally the behavior of composite panels when subjected to low velocity impact damage. Using numerical damage models validated for experimental tests. In their works the influence of delamination on the impact resistance of composite panels were studied was assessed. In this paper the influence of stacking sequence and shell thickness on the impact resistance is also numerically analysed. For this purpose two different stacking sequences were chosen. The shell laminates have a quasi-isotropic lay-up with stacking sequence of $[0/\pm45/90]_{2s}$ e $[0/\pm45/90]_s$. The thickness of each individual layer is $t = 0.286mm$.

Zhao *et al* (2007) also analysed the influence of stacking sequence and laminate thickness on the damage initiation in composite shells subjected to impact loading. They concluded that the stacking sequence has a great influence on low velocity impact events, and the smaller the thickness greater is the damage for composite shells with the same curvature. Tita *et al* (2008) studied the low velocity impact damage in carbon/epoxy thin laminates using a user defined material model. Their model was implemented into ABAQUS within shell elements and it was used to simulate the failure mechanisms caused by quasi-static indentation tests in composite plates. In their study, it was also found that the stacking sequence and impact energy levels affect the dynamic behavior of the composite plates. Other authors have used the Tsai-Wu quadratic failure criterion to predict impact damage in composites. In these models the failure mode is identified by using the maximum stress criteria (Ganapathy, 1998). This paper presents an in-plane damage model based on the smeared cracking formulation, considering damage evolution laws for each failure mechanism, non-linear rate dependent in-plane shear model and stress degradation procedure as described in the following topic.

2. NUMERICAL MODELING OF DAMAGE

The damage model has been implemented into a FORTRAN subroutine using a methodology that combine stress based CDM (Continuum Damage Mechanics) and fracture mechanics approaches within an unified way by using a smeared cracking formulation (Donadon *et al*, 2008b). The approach consists of applying a set of stress based failure criteria to detect damage initiation as well as predict the main failures modes within each ply of the laminate (Donadon *et al*, 2008b). Similar approaches have been reported elsewhere (Iannucci *et al* ,2005) where the authors presented a damage model based on the energy for woven carbon composites under high strain loading. The numerical results were validated experimentally in a subsequent work, Iannucci *et al* (2007).

For shell elements the non-linear finite element formulation uses an orthotropic stress-strain relationship and the local material behavior is derived in terms of the second Piola-Kirchhoff stress S_s and the Green-St.Venant strain E_s for plane stress element (Donadon *et al*, 2008b). The failure criteria used in the formulation to detect damage initiation is based on the maximum stress criteria, given as follows,

Tensile fibre failure mode:

$$F_f^t(\sigma_{11}) = \frac{\sigma_{11}}{X_t} \tag{1}$$

Compression fibre failure mode:

$$F_f^c(\sigma_{11}) = \frac{\sigma_{11}}{X_c} \tag{2}$$

Tensile matrix cracking mode:

$$F_m^t(\sigma_{22}) = \frac{\sigma_{22}}{Y_t} \tag{3}$$

Compression matrix cracking mode:

$$F_m^c(\sigma_{22}) = \frac{|\sigma_{22}|}{Y_c} \tag{4}$$

In-plane shear failure mode:

$$F_m^s(\tau_{12}) = \frac{|\tau_{12}|}{S_{12}} \tag{5}$$

where X_t, X_c, Y_t and $Y_c$are the tensile and compression strengths in the fibre and matrix directions, respectively, and S_{12} is the in-plane shear strength.

The model formulations also incorporates damage evolution laws relating the specific or volumetric energy with the strain energy release rate of the material. To calculate the damage evolution law, the model uses the intralaminar fracture toughnesses (G_f^t and G_f^c , G_m^t and G_m^c), the maximum strains prior to catastrophic failure in tension and compression ($\epsilon_{1,0}^t$ and $\epsilon_{1,0}^c$, $\epsilon_{2,0}^t$ and $\epsilon_{2,0}^c$), for the fibre failure and matrix cracking, respectively. For in-plane shear failure the damage evolution law is defined in terms of inelastic strain at failure ($\gamma_{12,0}^{in}$) and the in-plane shear intralaminar fracture toughness (G_s). The Figure 1 shows an example of the material model behavior at element level.

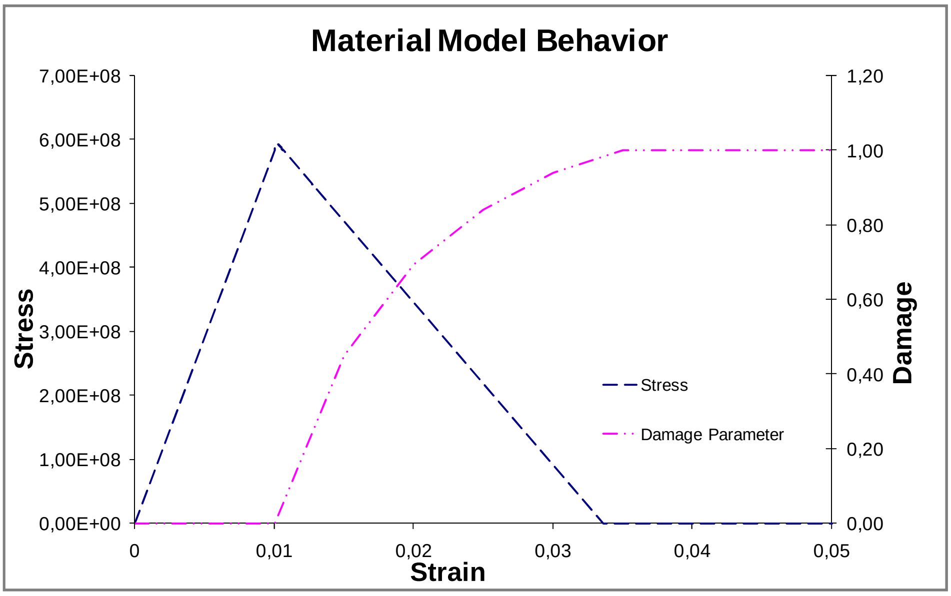

Figure 1. Material model behavior in tension in the matrix direction

3. NUMERICAL SIMULATIONS

The purpose of this paper is to verify the influence of the pressure and stacking sequence in the energy dissipated by the specimen after an event of impact. For this purpose two types of simulations were carried out: (i) The first with $P_1 = 0atm$, which was used a single step for the application of impact, (ii) The second with $P_2 = 0.58atm$ (pressure based on real in-flight conditions), in which was used two steps, one step for the application of pressure (Figure 2) followed by the application of the impact loading. Both simulations were performed using *ABAQUS 6.5-1 Dynamic Explicit*. The specimen had all displacements constrained on the four edges and the striker had only the displacement on the direction 2 free.

The laminate was modeled using shell elements type S4R available in ABAQUS and the striker using analytical rigid elements. The damage model development was based on the Theory of Reissiner-Mindlin for shell elements. Thus, shear correction factors (K_{11} and K_{22}) are required in this model. The expressions for K_{11} and K_{22} are respectively given by:

$$K_{11} = \frac{5}{6} G_{13} \times t \tag{6}$$

and

$$K_{22} = \frac{5}{6} G_{23} \times t \tag{7}$$

where

$$t = \sqrt{12 \times [(D_{44} + D_{55} + D_{66}) \times (D_{11} + D_{22} + D_{33})]} \tag{8}$$

D_{ii} are the elements in the main diagonal of the bending stiffness matrix for the laminate. G_{13} and G_{23} are the out-of-plane shear modulus.

The simulations were carried out for four different types of shell laminates with curvature radius of 100mm, 125mm, 200mm and a plane plate, respectively. The laminate dimensions are 119x209mm with thickness values of t_1=4.58mm and t_2=2.29mm. The material for the shell laminate is a graphite/epoxy tape. The chosen values for the impact velocities depend on the stacking sequences of the laminate, ranging from 1.63m/s (impact energy of 2J) to 5.16m/s (impact energy of 20J), assuming a hemispherical striker with a diameter of 12,7mm and 1.5Kg of mass. Two different stacking sequence were investigated: $[0/\pm45/90]_s$ and $[0/\pm45/90]_{2s}$. To verify the influence of the curvature and pressure on the amount of energy dissipated due the damage we used two types of simulation for each stacking sequence. Table 1 describes the impact energies used for this purpose. Table 2 describes the impact energies used to evaluate the effects of pressure and thickness on the amount of energy dissipated due the damage.

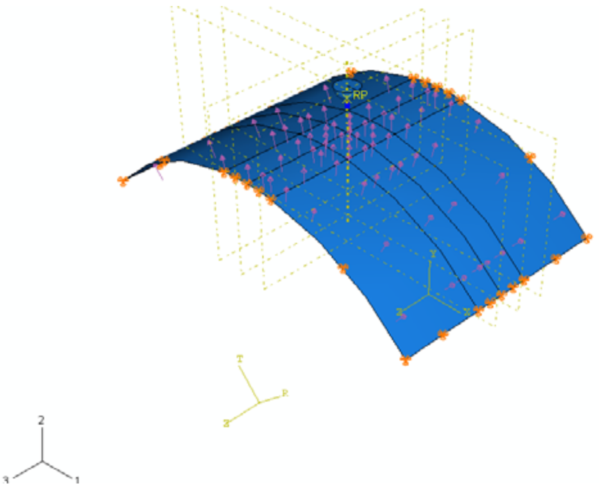

Figure 2. The application of pressure in the model.

Stacking Sequence	Impact Energies
$[0/\pm45/90]_s$	6, 8 and 10 *(J)*
$[0/\pm45/90]_{2s}$	4, 8, 12, 16 and 20 *(J)*

Table 1. Impact energies chosen for each stacking sequence to verified the influence of the curvature on the amount of energy dissipated due to damage.

Stacking Sequence	Impact Energies
$[0/\pm45/90]_s$	2, 4, 6, 8, 10, 12, 16 and 20 *(J)*
$[0/\pm45/90]_{2s}$	2, 4, 6, 8, 10, 12, 16 and 20 *(J)*

Table 2. Impact energies chosen for each stacking sequence to verify the pressure and thickness influence on the amount of energy dissipated due the damage.

The impact resistance of the laminates was measured in terms of the energy dissipated during the impact event. The amount of dissipated energy was obtained by the difference of areas under the curves of load versus displacement during loading and unloading, respectively, defined during the contact duration between the striker and the laminate (Figure 3).

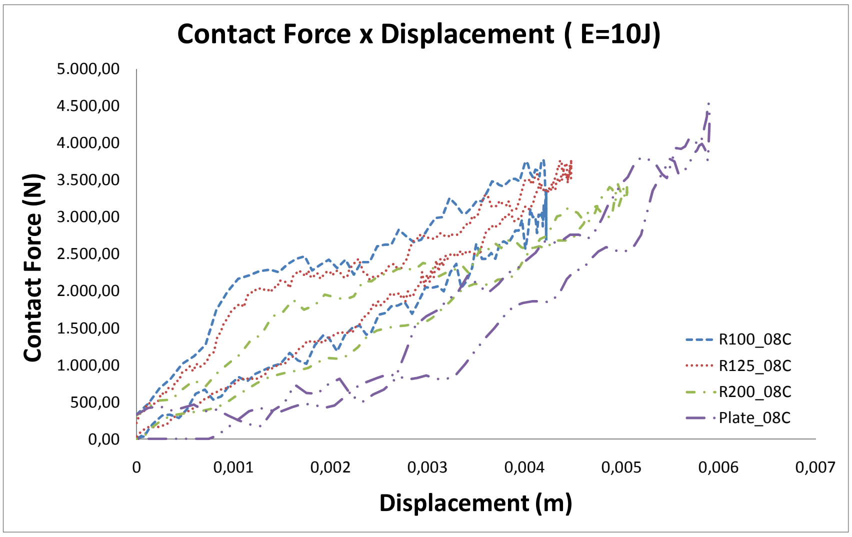

Figure 3. Contact force versus displacement for the impact energy of 10(*J*) for the four specimens with P_1=0,00atm and lay-up $[0/\pm45/90]_s$.

3. RESULTS AND DISCUSSIONS

The simulations showed consistent results, maintaining a trend in behavior. An example of the results obtained from simulations in terms of contact force versus displacement of the striker for all cases with $P_1 = 0atm$ and $P_2 = 0.58atm$ is shown in the Figure 3. From these data the dissipated energy can be calculated.

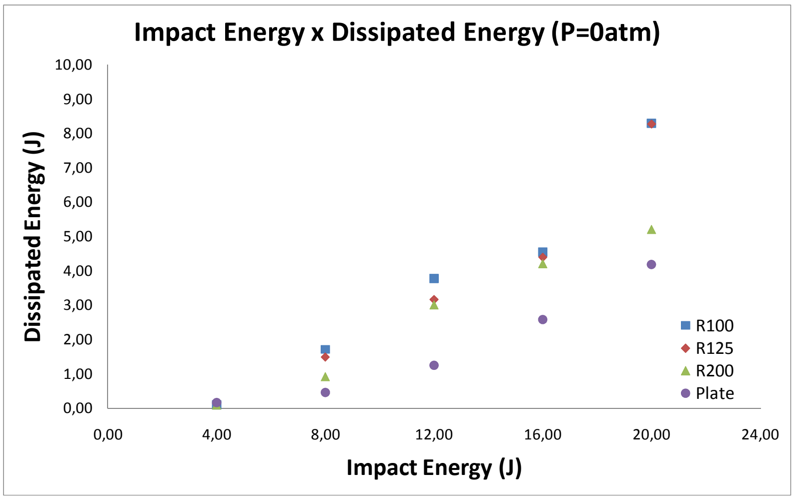

Figure 4. Impact energy versus energy dissipated to the four specimens with lay-up $[0/\pm45/90]_{2s}$ and $P_1 = 0atm$

Figures 4, 5, 6 and 7 show the relation between the impact energy versus dissipated energy due to damage for the different cases studied in this work. Figures 4 and 5 allow us to visualize the effects of the curvature on the amount of energy dissipated due to damage for the $[0/\pm45/90]_{2s}$ laminates. It is clear from these figures that for both values of pressure ($P_1 = 0atm$ and $P_2 = 0.58atm$) the greater the curvature the greater is the amount of dissipated energy due to damage for the same impact energy level. Figures 6 and 7 shows the behavior of the laminates with lay-up of $[0/\pm45/90]_s$, which also confirm this trend. Thus, the curvature has a great influence on the damage extent of laminates when subjected to impact loading combined with internal pressure effects.

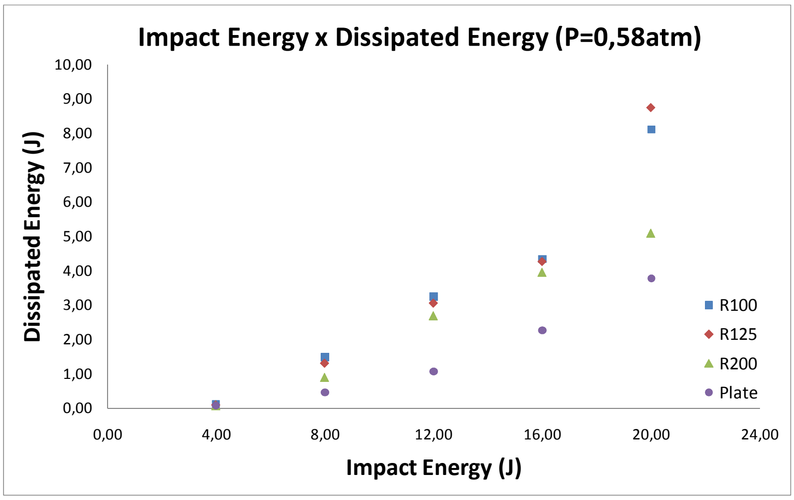

Figure 5. Impact energy versus energy dissipated for the four specimens with lay-ups of $[0/\pm45/90]_{2s}$ and $P_2 = 0.58atm$

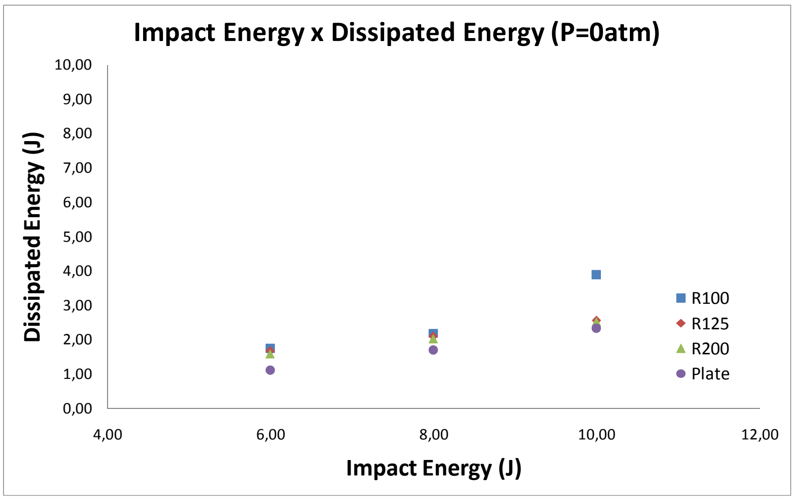

Figure 6. Impact energy versus energy dissipated for the four specimens with lay-up $[0/\pm45/90]_s$ and $P_1 = 0atm$

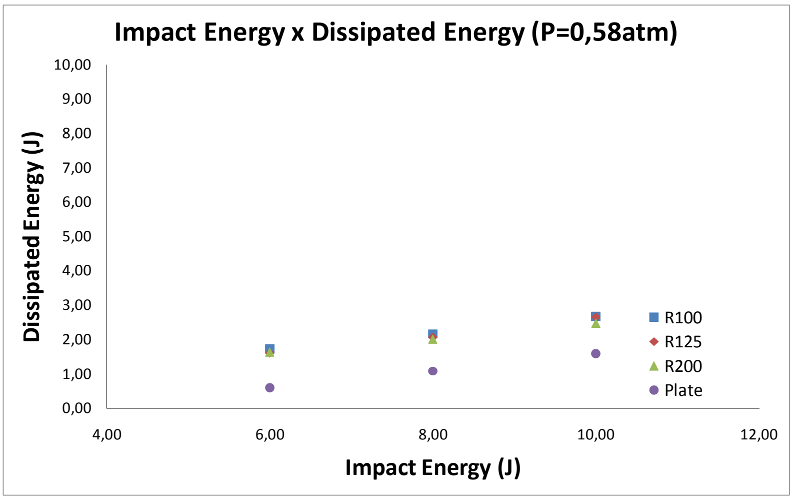

Figure 7. Impact energy versus energy dissipated for the four specimens with lay-ups of $[0/\pm45/90]_s$ and $P_2 = 0.58atm$

For the purpose of evaluating the influence of the pressure and laminate thickness, simulations were performed for the impact energies ranging from 2 to 20 (*J*), for both lay-ups ($[0/\pm45/90]_s$ and $[0/\pm45/90]_{2s}$). Figure 8 relates the dissipated energy with the variation of thickness where we find that the smaller the thickness the greater the damage of the laminate for the same impact energy, showing a reduction up to 88% for the laminate with curvature radius of 125mm thickness of 4,56mm. Other authors have also investigated the influence of stacking sequence and the total thickness of the laminate (Tiberkak *et al*, 2008) on the impact response, finding that 90° layers increase the value of the contact force. The laminates also presented a regular behavior in most of simulations where the value of energy dissipated increases as the curvature increases. The pressure effects on the amount of dissipated energy are shown in the Figure 9. From Figure 9 we can see that the dissipated energy decreases with pressure.

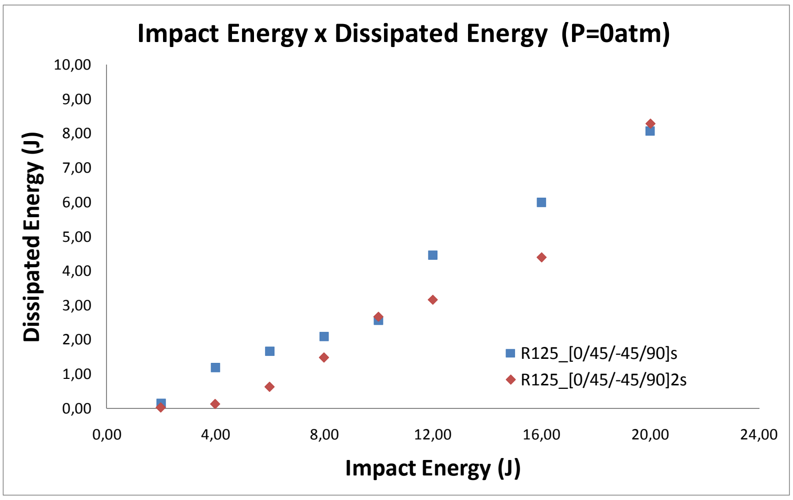

Figure 8. Impact energy versus dissipated energy for the laminate with curvature radius of 125mm and both lay-ups with $P_1 = 0atm$

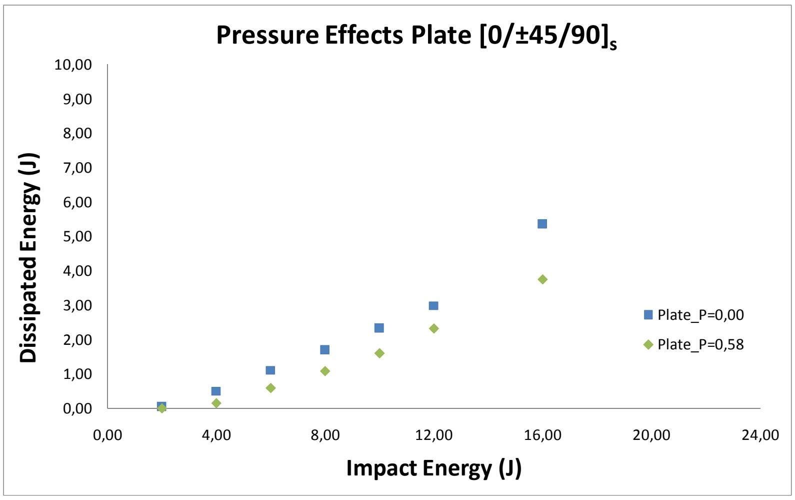

Figure 9. Impact energy versus dissipated energy for the plate with and without pressure effects.

After the simulations it was clear the great influence of thickness, lay-up and pressurization in the damage extent in composite laminates under impact loading. For more conclusive results, laminated composite shells should be tested experimentally in the same conditions presented in this paper to validate these simulations.

4. CONCLUDING REMARKS

This paper presented a numerical study of the pressure and curvature effects on the impact resistance of composite laminates. The numerical results indicated that thickness, lay-up and pressurization level significantly affects the damage extent in composite laminates under impact loading. The concluding remarks drawn from this study can be summarized as:

- The damage extent in composite laminates under impact loading decreased when combined with internal pressure effects;
- The greater the curvature the greater is the amount of the dissipated energy of the shell laminate with and without internal pressure effects;
- And the greater the thickness the lower the damage extent of the shell laminate with and without internal pressure effects.

5. ACKNOWLEDGEMENTS

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