

A Global–Local Numerical Model for the Prediction of Impact Induced Damage in Composite Laminates

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Abstract Delamination and other damage mechanisms, such as matrix cracks, fibre-matrix debonding and fiber failure can appear as a consequence of impact events with foreign objects under in service conditions and maintenance operations. These phenomena are seldom analyzed together without discussing how the interferences between the different damage mechanisms can influence their evolution under different loading conditions. The present work is focused on the development of a specific numerical procedure, able to take into account the failure modes interaction in composite laminated structures subject to a low velocity impact. As a matter of fact, a very fine mesh refinement is required to correctly evaluate the stress state where the impact induced damage onsets. Hence, in order to reduce the computational cost without compromising the accuracy of results, a global/local approach, characterized by a very refined mesh in the critical impact region interacting with a coarser mesh in the rest of the geometrical domain, has been implemented in the FE model. In the present work, Multi-Point-Constraints (MPC) has been used to link the refined local domain to the coarse global domain without using transition meshes. The implementation and the analyses have been performed in the ABAQUS® FE environment.

Keywords Composites · Low velocity impact · Finite element analysis · Damage · Global–local analysis

1 Introduction

The impact damage influences the residual strength of composite materials, which are generally constituted by components (such as fiber and matrix) whose stiffness and strength-to-failure can be extremely different. Composites are characterized by several interacting failure modes such

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as matrix breakage, fiber failure and delaminations. These failure modes, which can be simultaneously induced by low velocity impacts [1], can be very difficult to be detected by visual inspections of the structure. Hence, time and cost consuming non-destructive techniques, such as ultrasound based techniques, must be adopted for the inspection of composite materials.

Due to the technical difficulties which can arise during the application of non-destructive techniques, aeronautical structures are designed assuming the presence of preexisting non visible impact damages, which can determine a drastic reduction of composites structure's nominal strength, leading to a significant increase in weight of the whole structure. The allowables of damaged structure are determined through long and expensive experimental tests. In order to reduce the costs associated to the experimental campaigns, it's very important to integrate experimental tests with numerical tools able to investigate the structural behavior of complex composite components under impact loading conditions.

The aim of this work is to propose a Global–local based modeling technique able to accurately predict, with reasonable computational time and costs, the damage onset and evolution in composite materials, arising as a consequence of low velocity impacts. The modeling technique is able to simulate simultaneously the initiation and propagation of both inter-laminar and intra-laminar damage.

In section 2 the theory behind the proposed numerical approaches for the prediction of the intra-laminar and inter-laminar failures onset and evolution, is introduced. In section 3 the numerical applications are reported. A first application on a small laminated composite plate under a low velocity impact is introduced to validate the implemented damage approach against literature experimental results. A second application on a stiffened composite panel under a low velocity impact is presented to assess the interaction between inter-laminar and intra-laminar failure mechanisms.

2 Composites Failure Modeling

Inter-laminar and intra-laminar failure mechanisms are simultaneously taken into account in the proposed numerical model implemented in the Abaqus Explicit® FE environment. Intra-laminar damages, such as the breaking of the fibers, the matrix cracking and the interface damages between fibers and matrix (debonding), are generally caused by in-plane layer stresses and can arise in each single layer [2, 3]. While, the inter-laminar damage, such as the

Fig. 1 constitutive relation adopted for each failure mode

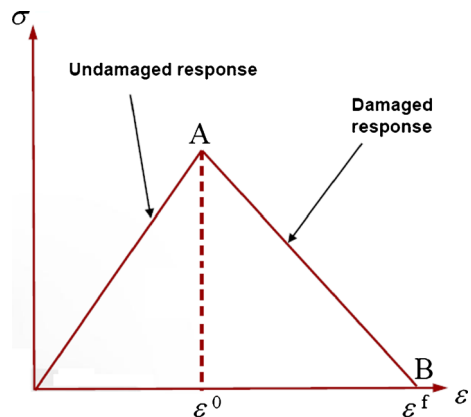


Table 1 Hashin’s failure criteria

Failure criteria	Failure modes
$\left(\frac{\sigma_{11}}{X_t}\right)^2 + \alpha\left(\frac{\tau_{12}}{S_t}\right)^2 = 1$	Fiber tensile failure
$\left(\frac{\sigma_{11}}{X_c}\right)^2 = 1$	Fiber compressive failure
$\left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S_t}\right)^2 = 1$	Matrix tensile failure
$\left(\frac{\sigma_{22}}{2S_t}\right)^2 + \left[\left(\frac{Y_c}{2S_t}\right)^2 - 1\right]\left(\frac{\sigma_{22}}{Y_c}\right) + \left(\frac{\tau_{12}}{S_t}\right)^2 = 1$	Matrix compressive failure

delaminations between the layers, is generally (but not always) caused by out-of-plane stress components. Intra-laminar and inter-laminar damage mechanisms can onset and propagate independently, or may interact each other [4].

The intra-laminar damage onset and propagation is taken into account by stress based failure criteria and material degradation rules. The delamination onset and propagation is modeled by means of “cohesive elements” approach. These two different approaches are briefly described hereafter.

The progressive damage method for intra-laminar damage onset and propagation, as implemented in the Abaqus code, offers a general capability of modeling progressive damage in fiber-reinforced composites in terms of fiber and matrix failures. Four different failure modes are considered: fiber rupture in tension and compression and matrix cracking under transverse tension and compression. The constitutive relation adopted for each failure mode is graphically shown in Fig. 1.

An initialization (undamaged) phase and a propagation (damaged) phase can be distinguished; the undamaged constitutive behavior is defined as orthotropic linear elastic. When the element stress exceeds a limit value, the element is considered partially damaged and the damage propagation starts. Hence, the point A in Fig. 1 is representative of the initiation of the stiffness degradation. The damage initiation criteria for fiber reinforced composites are based on Hashin’s theory [5, 6] (Table 1).

The path A-B describes the rate of degradation of the material stiffness once the initiation failure criterion is satisfied. For the damage propagation, a linear evolution law has been considered. The law is based on the energy dissipated during the process. An element is removed once the damage parameters for all failure modes at all material points in the element reach the maximum degradation value.

A similar damage evolution criteria, based on the fracture energy, is used in the cohesive elements theory for the simulation of delamination growth [7].

Table 2 Material properties

Property	Value	Property	Value
Longitudinal tensile modulus	165.1 GPa	Longitudinal tensile strength	2594.0 MPa
Longitudinal compression modulus	135.2 GPa	Longitudinal compressive strength	1120.9 MPa
Transverse tensile modulus	8.3 GPa	Transverse tensile strength	81.0 MPa
Transverse compression modulus	8.4 GPa	Transverse compressive strength	223.2 MPa
Poisson ratio 12	0.27	Interlaminar shear strength	114.0 MPa
Poisson ratio 13	0.25	Poisson ratio 23	0.41

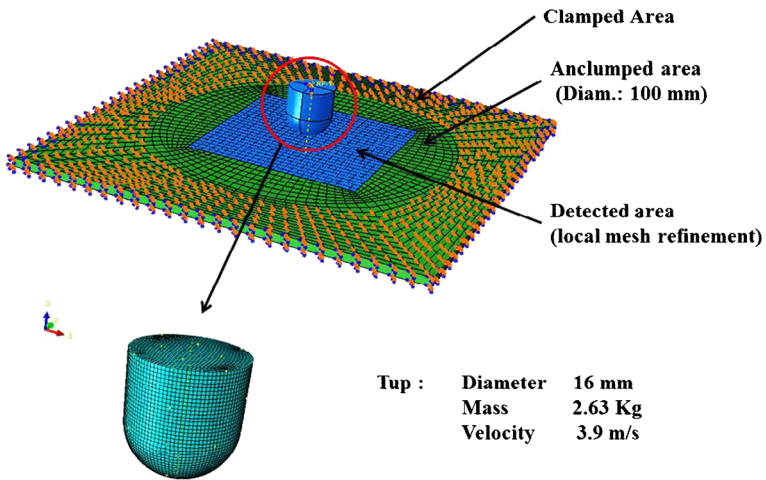


Fig. 2 Boundary conditions and impactor properties

The constitutive model of cohesive elements for delamination damage is based on a traction-separation law which is characterized by an initial damage phase, a damage evolution phase and by the possibility to remove full damaged elements. The cohesive damage evolution phase, representing the post-damage initiation response, is based on two criteria (energy criterion and displacement criterion). Hence, the total fracture energy must be specified when the energy criterion is used, while the post-damage ultimate displacement at failure of the element must be defined for displacement criterion. The fracture energy is defined as the area under the constitutive response curve. The failure displacement is the last possible displacement before the cohesive element is totally damaged. In this work the damage evolution based on the fracture energy criterion has been adopted.

3 FE Modeling and Analysis

In the frame of the present work the progressive damage approaches described in the previous section are used to numerically predict the damage onset and propagation in a typical aeronautical stiffened panel subjected to a low velocity impact [8] simulated by means of a rigid impactor of fixed kinetic energy.

However, a preliminary validation of the proposed progressive damage model has been carried out by comparisons with literature experimental results [5] on a small laminated composite specimen under low velocity impact. The full-scale panel FE model has been built

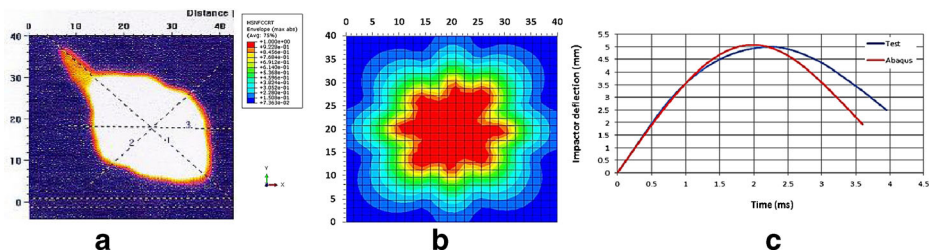


Fig. 3 a Experimental damage area; b Numerical damage area; c time-deflection

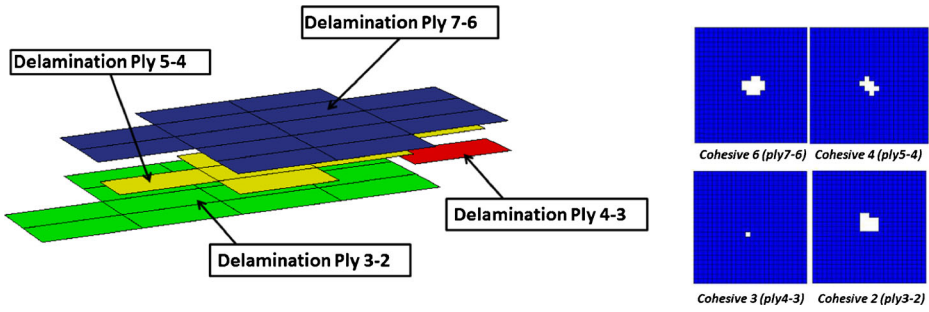


Fig. 4 Delaminations distribution along the thickness

by means of the Pre/Post Abaqus CAE®. The Shell Continuum (SC8R elements from the ABAQUS elements’ library) and the Cohesive elements (COH3D8 elements from the ABAQUS elements’ library) have been used for the model, as explained in the next subsection.

3.1 Validation of the Progressive Damage Model

The reference experimental test used to preliminary validate the proposed progressive damage model is reported in [5]. The test-case consists in a low velocity impact on a clamped plain panel. The impactor is modeled as an analytical rigid surface with a body diameter of 16 mm, a mass of 2.63 kg and a constant impact velocity of 3.9 m/s (impact energy value equal to 40 J). The total thickness of the plate is 3 mm. The lamina material properties for the considered material system are shown in Table 2.

In order to reduce the computational time, without losing accuracy of results, a Global–local approach is used to create the finite element model of the composite plain panel. A refined local finite element model of the impact area has been linked to a coarser global model of the rest of the panel by adopting a multi-point-constraints approach (tie constraints from the abaqus element library). This technique allows matching all degrees of freedom of a surface to the ones of another surface [9–11]. In this case the “node to surface” contact algorithm is used. The refined FE model is characterized by one continuum shell element per ply, with cohesive elements placed at each interface between two consecutive plies. Contact elements are used between shell continuum elements and cohesive elements to allow the

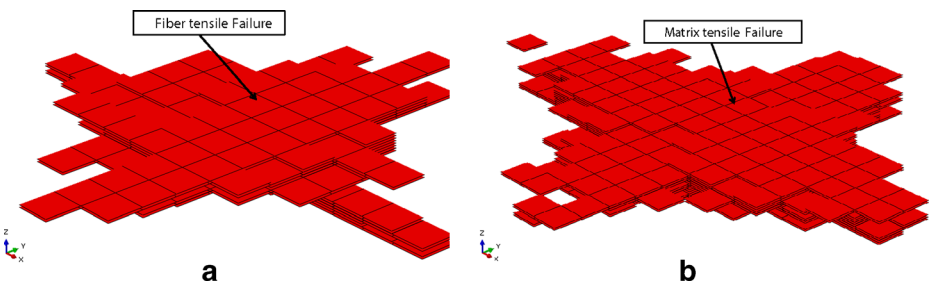


Fig. 5 a Fiber tensile failure; b Matrix tensile failure

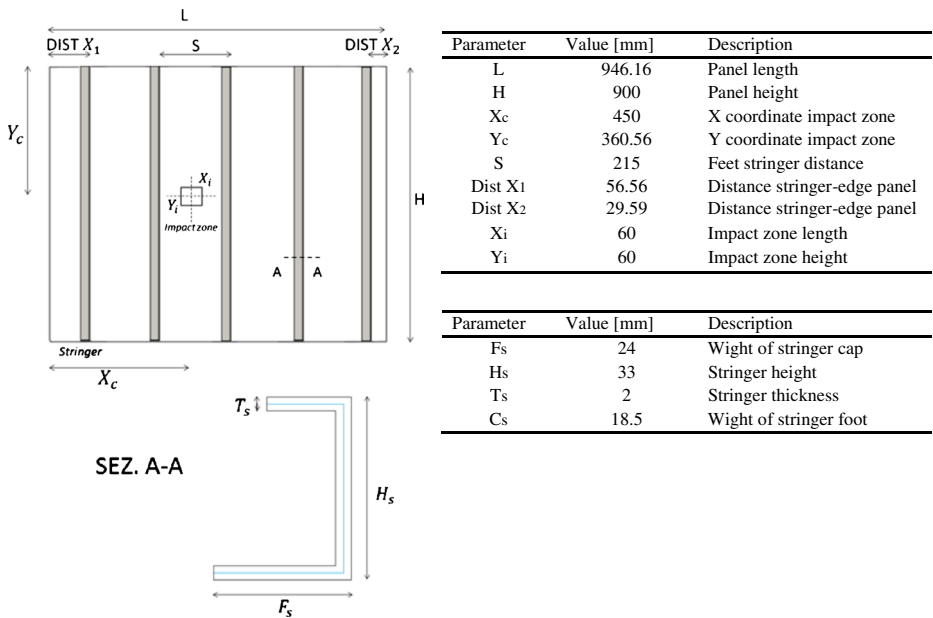
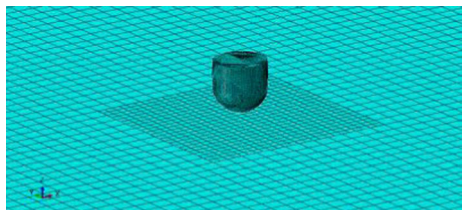


Fig. 6 Stiffened panel subjected to a low velocity impact – geometrical description

right connection between separated layers. The plate is composed by 24 plies, $[(-45,+45,90,0)_3]_{s_s}$, and 23 layers of cohesive elements between each couple of plies; these cohesive layers allowed to model inter-laminar damage onset and propagation. The thickness of each cohesive layer is set to 0.001 mm in order to avoid significant changes in the total thickness of the plate. The boundary conditions applied to the panel simulate the impact machine fixtures. Clamping conditions ($U_x=U_y=U_z=0$) have been imposed to the panel nodes which are placed outside the 100 mm diameter ring fixture. Between impactor and plate, surface to surface contact algorithms have been used. Figure 2 shows the FE boundary conditions and the impactor properties.

In reference [5] the reported experimental damaged area is the global projection of the damaged areas at different plies on a plane parallel to the plane of the specimen, without showing the different types of failure (delaminations, matrix cracks, fiber fracture) occurred; hence the numerical-experimental correlation on the projected damaged area is presented in Fig. 3a and b.

Fig. 7 Global–local fem model



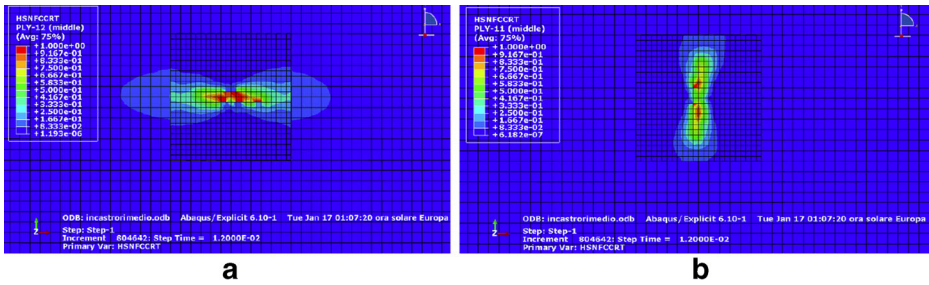


Fig. 8 a Ply 12 - fiber compressive failure b Ply 11 - fiber compressive failure

The numerical results illustrated in Fig. 3b show in red the elements which have failed (at least in one ply) according to at least one of the failure criteria.

The numerical results, compared with the experimental C-scan (Fig. 3a), show an acceptable agreement in terms of damaged area (experimental value: 481.2 mm² vs. numerical value 470.6 mm²).

In Fig. 3c the numerical-experimental comparison in terms of impactor deflection vs. time curves is shown. Also in this case a very good agreement between numerical and experimental results is obtained.

In Fig. 4 the delaminations distribution along the thickness is shown. The different delaminations, with peanuts shape, arising at the interfaces between plies as a consequence of the low velocity impact event are clearly appreciable [12].

In Fig. 5 the intra-laminar damage distribution along the thickness is shown. The fibre and matrix failure in each ply as a consequence of the low velocity impact event can be appreciated.

The accuracy of the numerical predictions obtained in the frame of this preliminary application, demonstrates the effectiveness of the proposed progressive damage model.

3.2 Stiffened Panel Test-Case

Figure 6 schematically shows the geometrical description of the composite stiffened panel, subjected to a low velocity impact, investigated in the present study as second numerical application.

The panel is 900 mm wide and 946.16 mm length, with a skin thickness of 2 mm (each ply 0.167 mm thick). A Global–local approach, likewise the preliminary test-case, is used to

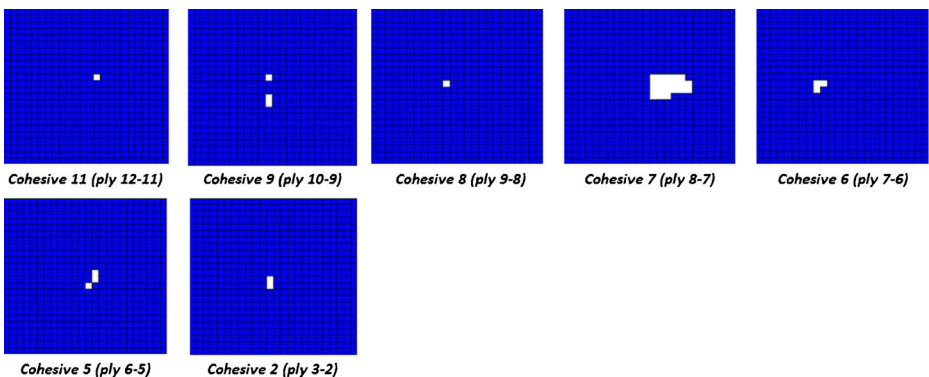


Fig. 9 Delamination distribution along the thickness

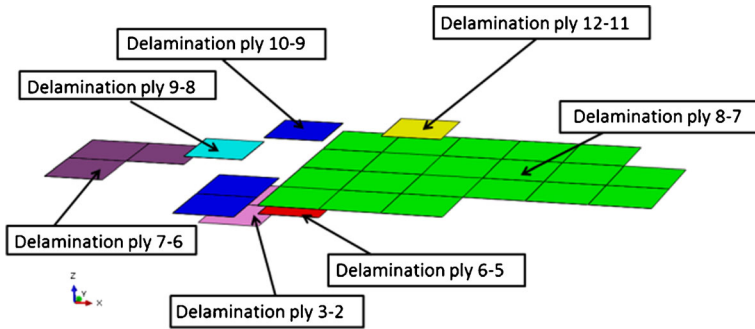


Fig. 10 Cohesive elements failure

model the stiffened composite panel. A refined model in the impact zone and a coarser one for the rest of the panel have been considered. In Fig. 7 a detailed view of the local area representing the impact zone (60×60 mm) in the FE model is shown.

The panel skin is composed by 12 plies disposed according to the stacking sequence $[90,0,+45,90,-45,0]_s$ and 11 layers of cohesive elements between each couple of plies to model inter-laminar damage. The thickness of cohesive elements is 0.001 mm. The stringers are modeled with conventional shell elements, with the same stacking sequence of the skin. A Dynamic Explicit structural analysis has been performed for the simulation of the impact event on the stiffened panel and both intra-laminar and inter-laminar failure mechanisms have been considered in the frame of the performed analysis. Boundary conditions are modeled by means of clamping conditions ($U_x=U_y=U_z=0$) at stringer feet. From the numerical simulation it is possible to appreciate the areas where each ply fails with respect to the Hashin criteria (Intra-laminar failure). In Fig. 8a and b, the indexes for fiber compressive failure obtained for the Ply 12 and 11 (ply 12 is the first ply on the impactor side), at the last impact time step (just before the end of the contact phenomenon between the impactor and the plate), are, respectively, shown.

In Fig. 9 the delaminations distribution in the impacted area along the thickness is shown. In Fig. 10 the same delaminations are shown in a 3D view

In Fig. 11, the delaminations are shown in a cut view showing a quarter of the skin at impact location.

Figure 12 shows the displacement and the reaction force of the impactor as a function of the time.

The following considerations can be deduced from the above results:

- The proposed model is able to predict both the intra-laminar and inter-laminar damage propagation. This feature can be of relevant interest for many aeronautical applications.

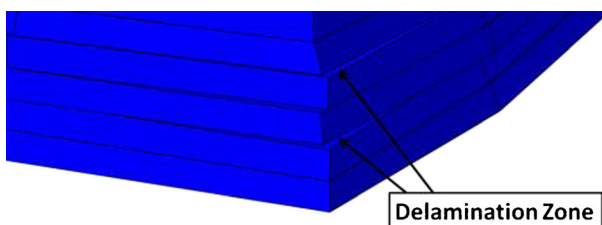


Fig. 11 Delaminated zone between the plies

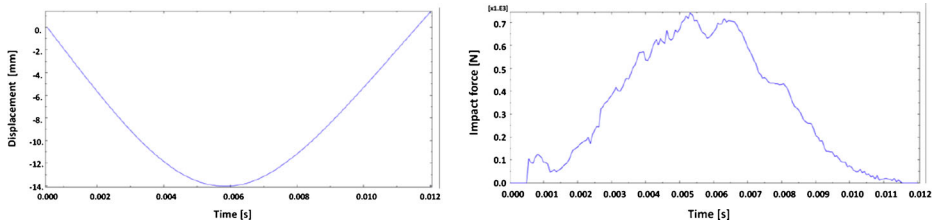


Fig. 12 Displacement of the impactor and impact force as a function of the time

- The considered FEM analysis methodology allows to evaluate the impact damage accurately even in the presence of very complex structure by means of the effective global local modeling approach.

4 Conclusions

In this paper an effective progressive damage model is introduced. The model is able to predict with a good accuracy the damage onset and propagation due to an impact event on complex composite structures. The implemented failure criteria allow to predict simultaneously delamination growth (cohesive element criterion) and intra-laminar damage onset and propagation. A Global–local Approach is used to effectively link separated models built for the impact area (refined model) and for the rest of the panel (coarse model), obtaining advantages in terms of computational costs without losing results accuracy. A preliminary validation has been performed on a simplified test case. Numerical results have been compared to literature experimental data obtaining a very good agreement in terms of impact induced damage area and impactor deflection-time curve.

By means of a numerical application on a stiffened composite panel, the proposed approach has been demonstrated able to accurately predict the damage propagation and able to integrate experimental activities on low velocity impacts by improving the understanding on the inter-laminar and intra-laminar damage phenomena in impact zones for composite structures.

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