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CHALLENGES OF VIRTUAL TESTING FOR THE COMPREHENSION OF IMPACT PHENOMENA

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Abstract: *Delamination is one of the most critical damage mechanisms taking place in composite structures. Its modeling is challenging and its observation even more. Numerical modeling allows us to study these phenomena in a new way and make it possible to study the influence of different parameters on the damage mechanics taking places during an impact loading. In this article, we propose to use virtual testing of complex composite structures subjected to low and high velocity impact loading and to study the effect of different mechanisms on the damage induced in the composite.*

Keywords: Impact modeling; Delamination; Virtual testing; Cohesive zone modeling

1. Introduction

Composite materials are widely used in aeronautics for their high strength coupled with their low density. Such materials can mainly be found in the fuselage, the wings and the tailplanes. These structures will be subjected, throughout their entire life cycle, to a certain number of impacts. These impacts, ranging from low velocity and low energy (e.g., tool drop, hail) to high velocity and high energy (e.g., birds, debris from the track), can cause significant damage. Among the major damage types appearing in composite laminates, delamination is the most critical for low velocity and low energy impacts [1,2]. Indeed, such damage can then reduce drastically the residual compression strength of the structure [3].

Studies on the behavior of the interface under varying loading rates showed very mixed results. Some authors noticed an increase in the critical energy release rate G_c when the loading rate increased [4-7]. Their explanation for this behavior is that the fracture surfaces of the samples tested seemed to have absorbed more energy when the loading rate increased [7]. Others noticed a decrease of the G_c [8-12], attributing it to smoother rupture profiles and a lesser number of shear cusps. Finally, some did not notice any effect of the strain rate on the G_c [13-14]. This discrepancy between the results seems partly due to the complexity of the phenomena studied, of the tests and of the analyses.

In order to understand and characterize these effects, the tests are chosen so that such effects are amplified. However, composite structures chosen for industrial purposes are chosen to minimize the possible damages. A question comes then to determine how these effects translate to such complex laminates. This is an important question as some models can require several parameters that will require extensive testing and analysis to calibrate it.

In this study, we focus on a few simple aspects of numerical models of composite layups. We studied the influence of impactor velocity and layup on delamination using a simple model with elastic plies. We then looked at the influence of friction between the plies on delamination and stability.

2. Material properties

2.1 Ply

The ply is considered purely elastic in this first study. The properties chosen are that of T700/M21 as presented in Table 1. E_l and E_t represent the longitudinal and transverse modulus respectively, ν_{lt} and ν_{tt} , represent the Poisson coefficients, G_{lt} is the shear modulus and ρ is the density. An improved material law will later be used to implement fiber rupture, matrix damage and strain rate effects.

Table 1: Ply properties (T700/M21)

E_l [MPa]	E_t [MPa]	ν_{lt} [-]	ν_{tt} [-]	G_{lt} [MPa]	ρ [kg/mm ³]
115000	8500	0.28	0.4	4500	1.58×10^{-6}

2.2 Interface

Cohesive zone modeling is used for the interface behavior with a simple bilinear law, as represented in Figure 1. The law chosen is an elastoplastic bilinear cohesive law called CONNECT (MAT59) available in the Radioss solver. In this law, both modes (normal and shear) are defined separately by an initiation displacement δ_0 and a critical displacement δ_c . When δ_0 is reached, stress is reduced as displacement increases through a negative hardening plasticity. A coupling is then introduced for the rupture of the element based on a power law for the displacement as presented in Eq. 1:

$$\frac{\delta_N}{\delta_{cN}} + \frac{\delta_S}{\delta_{cS}} = 1 \quad (1)$$

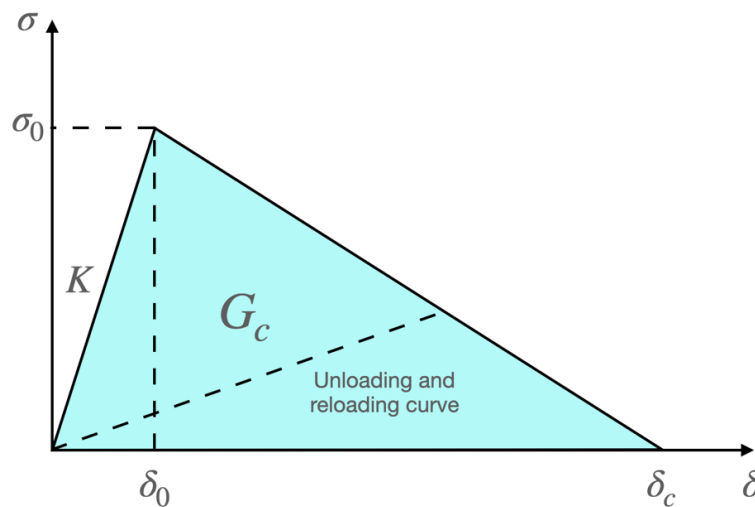


Figure 1. Bilinear law

The properties chosen for the interface are presented in Table 2.

Table 2: Interface properties

K [MPa/mm]	σ_{ON} [MPa]	σ_{OS} [MPa]	G_{Ic} [J/m ²]	G_{IIc} [J/m ²]
10^5	45	75	400	1200

3. Simulations

The impact simulations were based on an experimental setup found in [14]. A 16 plies composite is supported by two cylinders. The hemispherical impactor is dropped on the composite with an energy of 10 J. The different layups and impactor velocities used in the simulations are presented in Table 3.

Table 3: Layups and impactor velocities

Layups				
$[0_{16}]$	$[90_{16}]$	$[0_5/90_6/0_5]$	$[(45/90/-45/0)_2]_s$	$[(0/-45/90/45)_2]_s$
Impactor velocities (m/s)				
1.7	3.5	8.9		17.7

Supports were modeled by blocking nodes displacement ($u_z = 0$) along two lines, representing the cylinders, set parallel to the fiber in the 0° direction. The numerical model used for the simulations is represented in Figure 2.

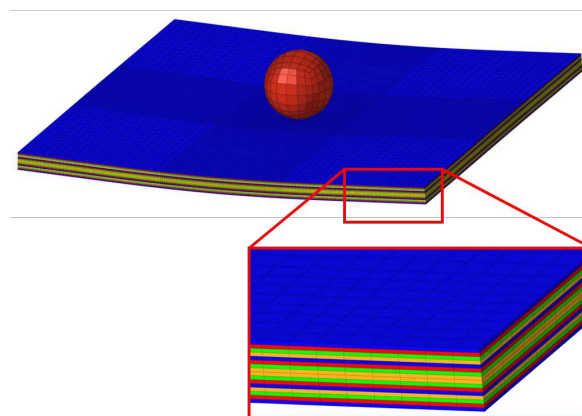


Figure 2. Numerical model for the impact simulations

A fine mesh was used for elements in the center of the model (where most of the delamination takes place) and became coarser further from the center. This mesh size was determined by approximating the cohesive zone length, which corresponds to the size of the process zone where damage occurs. An approximation presented in [15] was used and displayed in Eq.2.

$$l_{cz} = \frac{E_t G_{Ic}}{\sigma_0^2} \quad (2)$$

In this equation, l_{cz} is the cohesive zone length, and with our values for E_t , G_{Ic} and σ_{0N} , we obtain a cohesive zone length of 1.67 mm. It is recommended to have a mesh size at least three times smaller than this value, leading to a sufficient mesh size of 0.5 mm. This value was confirmed after conducting a sensibility analysis.

4. Results

4.1 Influence of impactor velocity and layup

The influence of impactor velocity and layup on delamination was first studied. This was done so that it could be isolated in further studies where strain rate effects will be implemented. Looking at the results on each layup for the different impactor velocities, a clear trend appears for the dissipated energy in the interfaces due to delamination: as the impactor velocity increases, the dissipated energy increases too. This is clearly visible for unidirectional layup as shown in Figure 3. This is however not the case for quasi-isotropic layups where the total delaminated area stayed almost constant over the range studied, as seen in Figure 4.

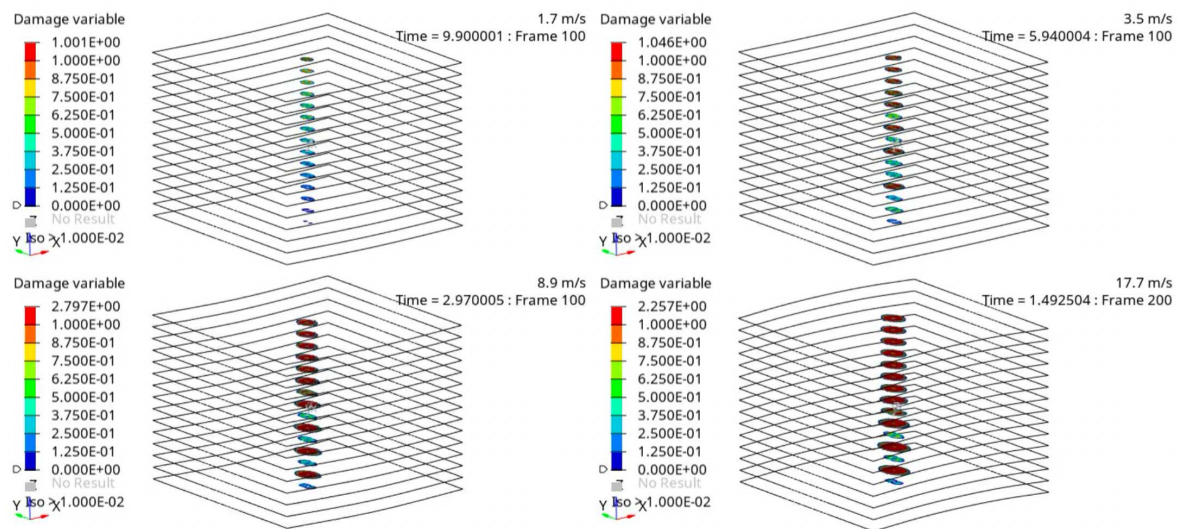


Figure 3. Delamination on a $[0_{16}]$ composite with increasing impactor velocity

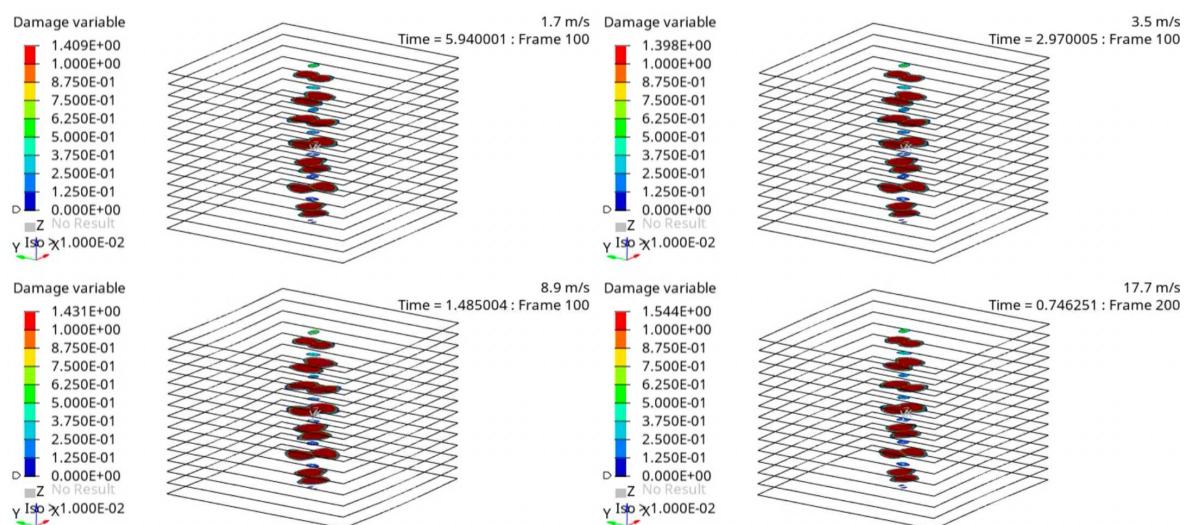


Figure 4. Delamination on a $[(45/90/-45/0)_2]_s$ composite with increasing impactor velocity

The layup also has a strong influence on delamination. Based on the orientation of the plies, the delamination orientation and shape changes. But it has also been observed that when the layup rigidity increases, so does the dissipated energy. This tendency is clearly visible in Figure 5.

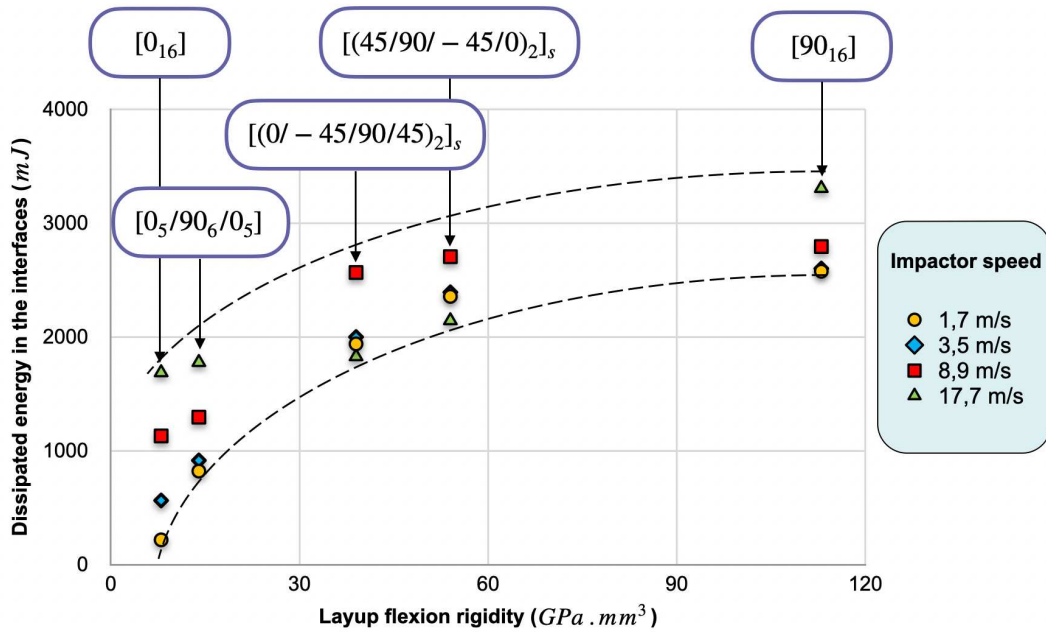


Figure 5. Impactor velocity and layup influence on delamination

4.2 Influence of friction between the plies

A second law based on the work of Camanho and Dávila [16] was implemented in a User Subroutine to be then used in the explicit solver Radioss. This law implements better coupling definition for mixed modes loading as well as introducing damage instead of plasticity.

The initiation displacement δ_0 (indicating the start of damage) is determined through a quadratic formula (Eq. 3), with indices N and S corresponding to normal and shear loading respectively:

$$\left(\frac{\sigma_N}{\sigma_{0N}}\right)^2 + \left(\frac{\sigma_S}{\sigma_{0S}}\right)^2 = 1 \quad (3)$$

The final displacement δ_c , corresponding to rupture of the interface, is then deduced through a power law criterion defined in Eq. 4:

$$\left(\frac{G_I}{G_{Ic}}\right)^\alpha + \left(\frac{G_{II}}{G_{IIc}}\right)^\alpha = 1 \quad (4)$$

Damage evolution is then given by:

$$d = \frac{\delta_c}{\delta} \cdot \frac{\delta - \delta_0}{\delta_c - \delta_0} \quad (5)$$

Finally, the stresses can be computed:

$$\sigma = K(1 - d) \cdot \delta \quad (6)$$

Using this new law, delaminations appeared to become asymmetrical. This was unexpected, considering every component of the model (mesh, boundary conditions) are all symmetrical. Adding a general surface/surface contact with penalty and a Coulomb friction coefficient showed a strong influence on delamination symmetry. Increasing the friction coefficient brought symmetry to the delaminations as shown in Figure 4.

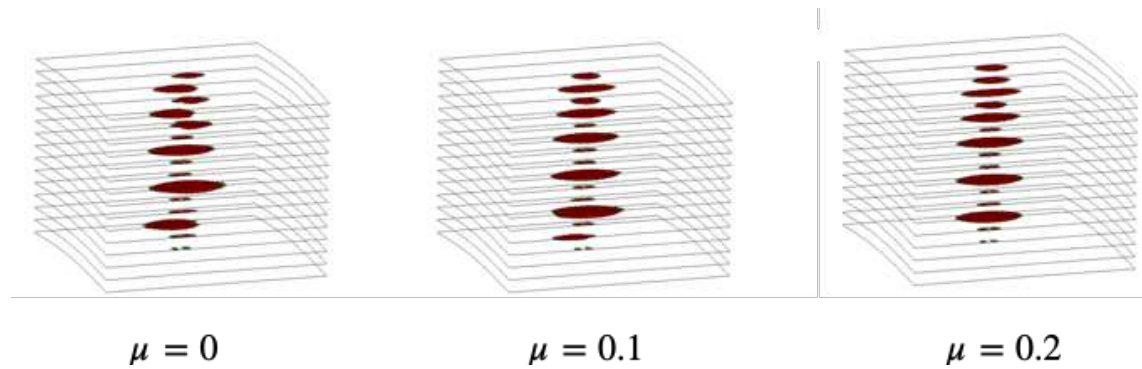


Figure 6. Influence of friction coefficient μ on delamination on a $[0_{16}]$ layup

On top of gaining symmetry, friction also changes the delamination shapes, which has also been noted by other authors [17]. This result led us to believe the use of friction between plies could help with instabilities, as well as give better results.

5. Conclusion

The main goal of this study was to isolate effects of impactor velocity and strain rate before introducing strain rates in the material laws. It has been shown that layup greatly changes how the impactor velocity influences the delamination. Moreover, a difference appears between quasi-isotropic layups and the other layups. This behavior remains however to be seen when a more realistic ply behavior is introduced. Two different ply models are being implemented in our simulations: an elastoplastic model available in Radioss (COMPSH) and a viscoelastic model with damage developed at ONERA called OPFM [18] (ONERA Ply Failure Model). Comparison between these models and with the current results are our primary focus. Strain rate effects will then be introduced in both the ply and the interface models.

Friction influence on simulation stability and delamination shape is obvious in the results obtained. An improvement currently in the works is the inclusion of friction in the cohesive law. A formulation based on the work of Alfano and Sacco [19, 20] is currently studied and its influence will be covered in future work.

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