VIRTUAL ASSESSMENT OF A COMPOSITE LAMINATE WITH INTERLEAVED NANOFIBROUS MAT UNDER IMPACT LOADING

G. Giuliese[a*], A. Pirondi[a], E. Furlotti[a], A. Zucchelli[b], R. Palazzetti[c]

[a]*Università di Parma, Industrial Engineering Department, Parco Area delle Scienze 181/A, 43124 Parma, Italy*
[b]*Alma Mater Studiorum – University of Bologna, DIN Department, viale del Risorgimento 2, 40136 Bologna, Italy*
[c]*University of Strathclyde, DMEM Department, 75 Montrose Street, G1 1XJ, Glasgow, UK*
**gregorio.giuliese@nemo.unipr.it*

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Abstract
This paper deals with interleaving a nanofibrous mat between laminate plies to control the interlaminar delamination strength. In previous works, the authors tested delamination toughness and identified the cohesive zone properties of nanomats with varying fiber diameter, fiber arrangement (random, aligned), mat thickness. The results showed that, by varying those parameters, a toughening or an embrittlement of the interface can be obtained. The modification induced by the nanomat can be therefore exploited in order to tailor the interply delamination strength of the laminate. The aim of this work is to simulate the impact strength of a composite laminate with nanomodified interplies of different strength in order to maximize the impact energy absorbed by the composite, in the perspective of optimization for use in impact attenuation.

1. Introduction

Laminated composite materials have several advantages over metals, especially a higher stiffness-to-weight and strength-to-weight ratio, as well as the possibility to vary their structural properties according to the requirements of specific applications. These advantages lead to an increasing use of composite materials for structural components in a number of industrial products, ranging from primary load-bearing members of airplanes to civil constructions and sporting goods.
Laminated composites, however, are usually brittle materials. As a consequence, they do not exhibit phenomena of energy absorption and dissipation through plastic strain after, for example, impact loading. For this reason, energy absorption in composites usually takes place through material damage. In composite laminates, which consist of several plies stacked together to form a single body, damage occurs by matrix and/or fiber cracking followed or accompanied by delaminations between adjacent plies. This kind of damage can be undetectable by visual inspection, but at the same time can significantly decrease the resistance of a laminate.
As in the case of aircrafts, for example, impacts may come from of a variety of objects such as tools, debris, ice or hail, the susceptibility of composites to impact damage has justified an extensive research effort during the last four decades, aimed at understanding both the failure mechanisms and the influence of damage on the mechanical properties of the material. A

great interest still exists in this topic, because while there is a substantial agreement on damage mechanisms, the increasing variety of available materials and upcoming integrity problems (such as low-velocity, high-energy impact between aircraft fuselage and boarding ladder) cannot be considered completely solved.
Pegoretti et al. [1] showed experimentally that it is possible to obtain different delamination strengths within the same laminate by interleaving perforated PET film. In Dzenis and Reneker [2], a nanofibrous mat has been interleaved between laminate plies in order to control the interlaminar delamination strength. Figure 1 shows the nanofibrous reinforce at the laminate's interfaces.

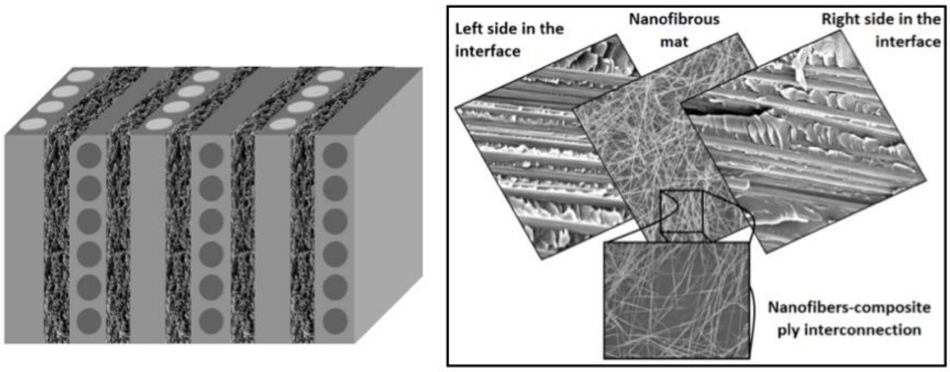


Figure 1. Structure and SEM image of a composite laminate with interleaved nanofibrous mats

In previous works, the authors tested delamination toughness [3] and identified the cohesive zone properties [4, 5] of nanomats with varying fiber diameter, fiber arrangement (random, aligned), mat thickness. The results showed that, by varying those parameters, a toughening or an embrittlement of the interface can be obtained. The modification induced by the nanomat can be therefore exploited in order to tailor the interply delamination strength, hence the absorbed energy.
The aim of this work is to simulate the impact strength of a composite laminate, with nanomodified interfaces in order to maximize the impact energy absorbed by the composite. The idea will be validated in this paper with reference to a literature case [6] where the impact damage was simulated using Finite element Method (FEM) and cohesive elements at the two 0/90 interfaces of the $[0_3/90_3]_s$ cross-ply laminate. Impact damage in this kind of laminate starts due to matrix cracking in the 0° plies at the tensile loaded side during impact, then followed by delamination at the 0/90 interface adjacent to the cracked plies. On the compression loaded side matrix cracking/crushing is very limited, therefore delamination damage develops to a limited extent. In the impact damage simulation performed in this work, the cohesive zone parameters are not the same for the two interfaces, but a lower cohesive energy and strength will be given to the interface close to the impacted (compression loaded) side in order to demonstrate that it is possible to obtain a larger delaminated area and, possibly, a higher absorbed energy by tailoring the interply strength.

2. Modeling

As shown in the work of Aymerich [6], the 65 mm x 87.5 mm composite specimens were simply supported on a rectangular opening of 45 mm x 67.5 mm in size, and impacted by a hemispherical indenter of 12.5 mm in diameter. Because of symmetry, only one quarter of the model was built and analyzed and shown in Figure 2. $[0_3]$ and $[90_3]$ sublaminates were modeled with SC8R reduced integration continuum shell elements, while COH3D8 cohesive elements were inserted at the two interfaces between layers with different orientation (top $0_3/90_3$ interface and bottom $90_3/0_3$ interface).

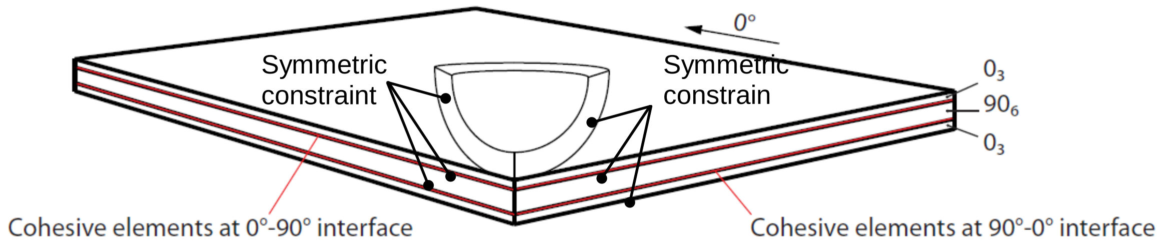


Figure. 2. FE model of the impact specimen.

Symmetry constraints were not placed on the plane parallel to the 0° direction in correspondence of the 0° layers on the tensile side of the plate, in order to simulate the presence of matrix cracking. An element size of 0.2 mm by 0.2 mm (on the laminate plane) was used in the highest density region of the mesh. Accordingly to Aymerich et al. [6], 2.1 J low velocity impacts were simulated using the same Abaqus/explicit solver: simulated mass was 2.3 Kg with a speed at the instant of contact, of 1.351 m/s. The cohesive zone model used in the simulation is represented by a linear damage (triangular) traction-separation law, and is shown in Figure 3, where K is the stiffness per unit area, δ is the separation, σ the strength and Γ the cohesive energy. This latter is usually taken equal to the fracture toughness.

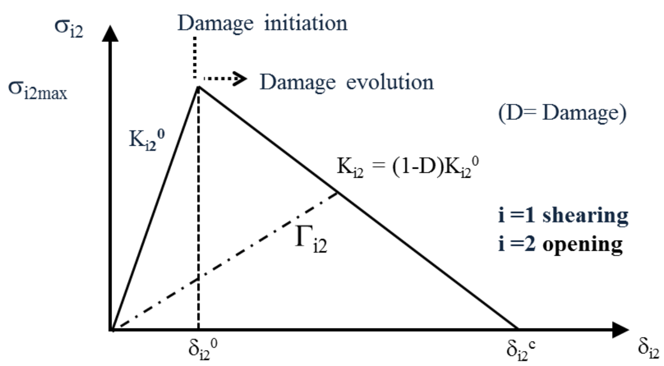


Figure 3. Cohesive law used in the simulation.

A simple quadratic, stress-based damage initiation criterion, Eq. (1), is used.

$$\left(\frac{\langle\sigma_{22}\rangle}{\sigma_{22Max}}\right)^2 + \left(\frac{\sigma_{12}}{\sigma_{12Max}}\right)^2 + \left(\frac{\sigma_{13}}{\sigma_{13Max}}\right)^2 = 1 \qquad (1)$$

It is worth underlining that Aymerich et al. (2008) used a similar criterion but adding a dependence on the value of σ_{22} when compared to $(\sigma_{12}^2 + \sigma_{13}^2)$, which may eventually prevent delamination in case of strong compressive loading with respect to shear loading. This was done in order to simulate mechanical interlocking at the interply under compressive loading. In this work, devoted to a concept feasibility demonstration rather than quantitative simulation, the Eq. (1) available in the Abaqus software is considered appropriate to the scope. The mixed mode equivalent separation is defined by the relationship

$$\delta_{eq} = \sqrt{\langle\delta_{22}\rangle^2 + \delta_{12}^2 + \delta_{13}^2} \tag{2}$$

In case of pure mode I, Eq. (2) yields the value of δ_{22} in case of positive δ_{22}, while it gives 0 in case of negative δ_{22}. This means that compression do not lead to delamination damage. The mixed mode cohesive law is defined in terms of the initial stiffness ($K_{eq,0}$), damage initiation equivalent opening ($\delta_{eq,0}$) and critical equivalent opening ($\delta_{eq,c}$). The equivalent initial stiffness is obtained by equating the equivalent strain energy (U_{EQ}) to the total strain energy (U_{TOT}), which in turn is equal to the sum of the strain energy in mode I (U_{22}), mode II (U_{12}) and mode III (U_{13})

$$U_{TOT} = U_{22} + U_{21} + U_{13} = \frac{1}{2} \cdot \delta_{eq}^2 \cdot K_{eq}^0 = \frac{1}{2} \cdot \langle\delta_{22}\rangle^2 \cdot K_{22}^0 + \delta_{12}^2 \cdot K_{12}^0 + \delta_{13}^2 \cdot K_{13}^0 \tag{3}$$

3. Cases studied

Five simulations have been performed:

- in the first three (named “Case 1”, “Case 2”, and “Case 3”) the properties of top 0/90 interface have been modified taking into account the presence of a nanofibrous mat with the purpose to increase the absorbed energy;
- the last one (named “Case 4”) a nanofibrous layer has been taken into account in the bottom 0/90 interface with the purpose to reduce the delamination, and thus the damage.

As shown in [3], the geometrical configuration of nanofibers affects the mechanical response of the laminated, and it is thus possible to tailor the nanomodification according to specific targets, which, in this case, can be to increase the energy absorption or to reduce the damage. The cohesive zone properties assigned to each of the interfaces are given in Table 1.

Parameter		Reference case		Case 1		Case 2		Case 3		Case 4	
		Top 0/90	**Down 0/90**	**Top 0/90**	**Down 0/90**	**Top 0/90**	**Down 0/90**	**Top 0/90**	**Down 0/90**	**Top 0/90**	**Bottom 0/90**
K_{ij} (GPa/mm)	K_{22}	120	120	120	120	120	120	120	120	120	120
	K_{12}	48	48	48	48	48	48	48	48	48	48
	K_{13}	48	48	48	48	48	48	48	48	48	48
σ_{ij} (N/mm^2)	σ_{22}	20	20	10	20	20	20	10	20	20	30
	σ_{12}	60	60	30	60	60	60	30	60	60	90
	σ_{13}	60	60	30	60	60	60	30	60	60	90
Γ_{ij} (J/m^2)	Γ_{22}	520	520	520	520	260	520	260	520	520	780
	Γ_{12}	970	970	970	970	485	970	485	970	970	1455
	Γ_{13}	970	970	940	970	485	970	485	970	970	1455

Table 1. Cohesive zone parameters, reference case values from Aymerich et al. [6].

In particular:

- for “Case 1” the σ_{ij} of the top interface have been reduced of one-half;
- for “Case 2” the Γ_{ij} of the top 0/90 interface have been reduced of one-half;
- for “Case 3” both the Γ_{ij} and σ_{ij} of the top 0/90 interface have been reduced of one-half;
- for “Case 4” both the Γ_{ij} and σ_{ij} of the bottom 0/90 interface have been multiplied for 1.5.

  In [5] it is shown that the σ_{ij} and Γ_{ij} values of nanomodified specimens can range from 0.23 to about 1.5 times those of virgin specimens. The same factor is then applied here to reference case material.

4. Results and discussion

Force-Time and Force-Displacement impact curves are presented in Figure 4 and Figure 5.

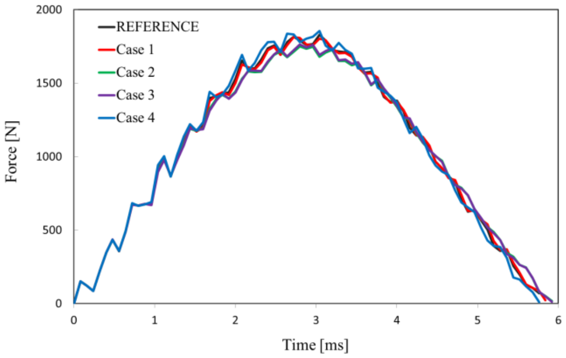


Figure 4. Force vs.Time

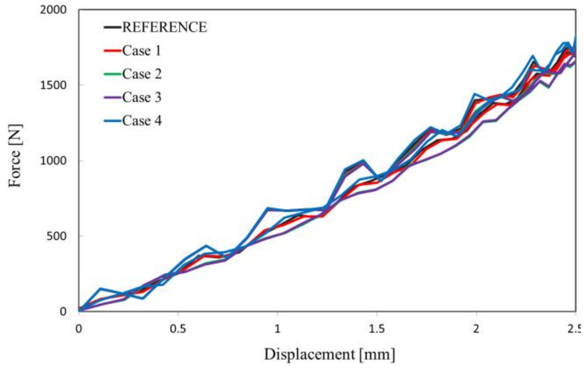
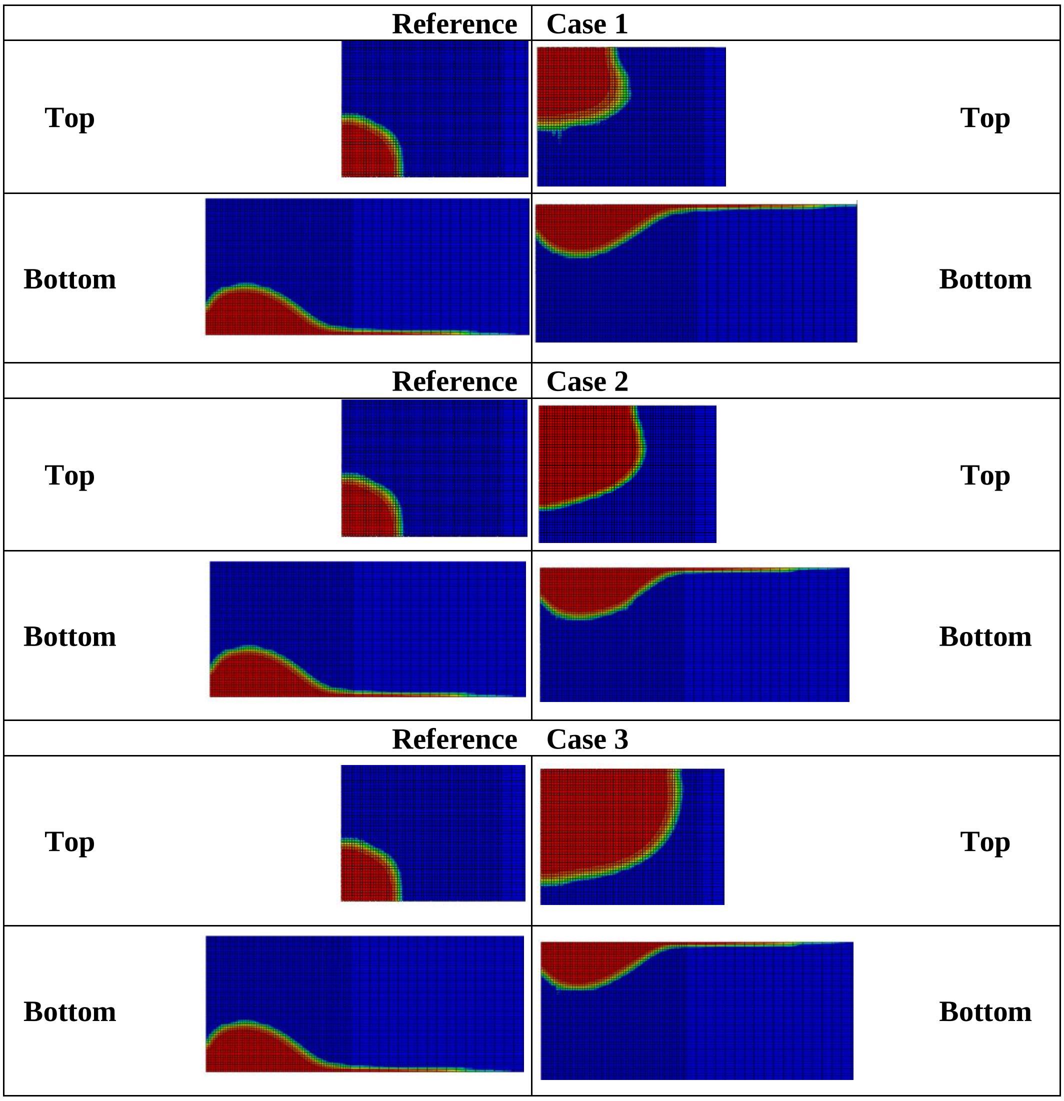


Figure 5. Force vs. Displacement

Simulations also showed damaged areas, presented in Figure 6. Nanomodified cases are reported on the right side and compared with the reference case on the left side of the Figure. Pictures show the 0/90 top and bottom interfaces viewed form the impacted side of the specimen.



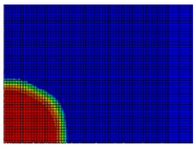
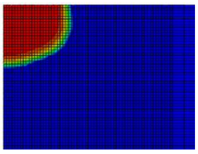
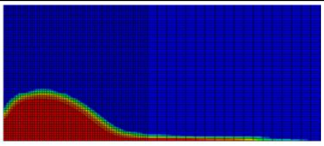
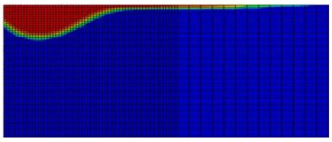
	Reference	Case 4	
Top			**Top**
Bottom			**Bottom**

Figure 6. Delaminated areas (in red) for reference (left) and nanomodified (right) cases.

It is clearly shown that a reduction in cohesive zone parameters causes a significant increase of the delaminated area at the top 0°/90° interface, as expected (Cases 1-3).
The delaminated areas at the bottom 0°/90° interfaces are the same for all cases and do not change compared to the reference case.
Case four, instead, shows the opposite behavior: a reduction of the delaminated area and then a reduction of the damage are clearly presented. In particular, the bottom nanomodified delaminated area is about 18% less than that of virgin sample.
It appears that despite the force history is very similar for all the simulations, the effect on the damage is quite different.
In terms of fracture energy, i.e., delaminated area*cohesive energy, the post-processing of the results is shown in Fig. 7 as a function of the impact point displacement and in Fig. 8 as a function of time. From Abaqus it is possible to extract the Damage Dissipation Energy (ALLDMD), which is the energy used to fracture the surface, which gives an estimation of the damaged induced in the specimen. In Figure 7 and Figure 8 the ALLDMD energy is presented together with the total absorbed energy.

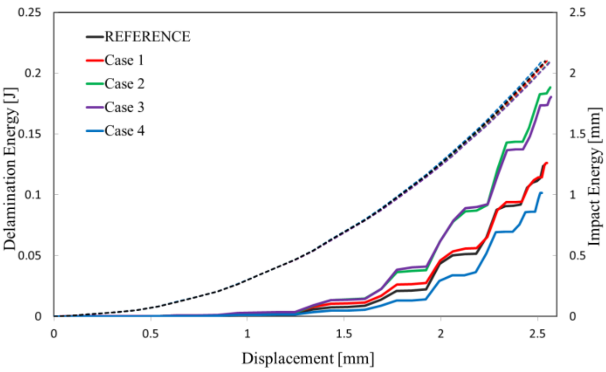


Figure 7. Impact (dashed) and Delamination Energies (continuous) vs. Load Impact Displacement

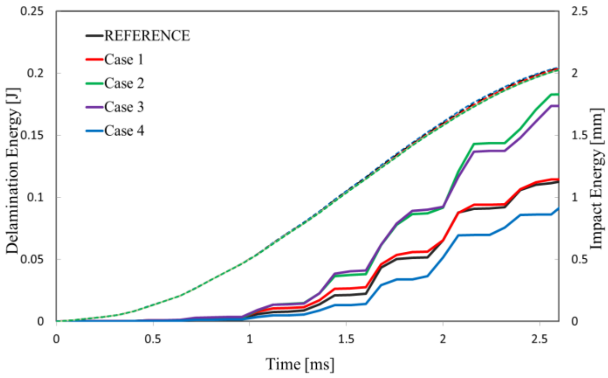


Figure 8. Impact (dashed) and Delamination Energy (continuous) vs. Time

Similarly to the force history, also the absorbed energy history does not present significant differences from a macroscopical point of view among the cases simulated. Instead, the ALLDMD, and thus the damage, presents different situation.

Case 1 does not present significant difference with the reference case, matching with the well-known insensitivity of the cohesive strength only to the damage.

On the other side, Case 2 and Case 3 show that Γ is a sensitive parameter affecting the delamination resistance and thus the delaminated area of the laminate. Case 4 shows as well the nanofibers affect the value of Γ and depending of their configuration, they are either able to increase the delaminated area and thus the absorbed energy (Case 2 and 3) or the delamination resistance, thus reducing the damage (Case 4).

In Table 2 fracture energies have been reported.

	Ref. case	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Total delamination energy [J]	0.126	0.127	0.188	0.181	0.102

Table 2. Delamination energy resulting from the simulations.

5. Conclusion

In this work the impact strength of nanomodified composite laminate was assessed by finite element simulation and compared with the non-nanomodified one. Delamination was modeled using cohesive elements, which properties were selectively modified with respect to a reference case in order to prove that an increase of the absorbed energy is possible by tailoring the interlaminar properties by nanomodification.

Experiments presented in literature show that the configuration of nanofibers has effect on the final behavior of composite. This paper simulates virgin and nanomodified interfaces, with different configuration of nanofibers, achieving different purposes. In two cases nanofibers reduce the fracture resistance of the laminate's interface, showing a larger delaminated area after impact, giving the specimen a greater energy absorption capability.

On the other hand, if nanofibers strengthen the interface, the impact causes a lower delaminated area and the energy absorbed during the impact is reduced as well.

Furthermore the results showed that the increase in absorbed energy is almost proportional to the decrease in the cohesive energy (i.e., delamination fracture toughness), while it is rather insensitive to reduction of the cohesive (delamination) strength.

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