Delamination mechanisms in fiber-reinforced composites structures tested at different loadings

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Abstract: *Composite materials are a special class which has some advantages like low weight, high strength and stiffness. For a composite system they are very suitable for aerospace, marine and auto applications due to the low density. Among all the synthetic fibers, carbon fibers are now considered the first material to be used for reinforcement due to their proper cost, as compared to aramid, and better mechanical and physical properties. This paper is an experimental work and presents the preliminary results regarding the evaluation of CFRP prepreg based on M18/1 carbon fiber prepreg developed by manual lay-up/autoclave curing. The obtained materials were tested at different mechanical loads and the failure mode was analyzed with the aim of evaluating their performances. The mechanism by which the fibers are delaminated in the composite system is assessed. To verify if the structure has defects that can interfere with the delamination process, ultrasonic nondestructive testing has been used. Also, for a better understanding of the delamination mechanism, the numerical simulation was used.*

Key Words: *delamination, composite materials, autoclave, mechanical testing, NDT testing, optical microscopy, prepreg*

1. INTRODUCTION

Composite materials are a special class which has some advantages like low weight, high strength and stiffness. For a composite system they are very suitable for aerospace, marine and auto applications due to their low density.

The laminates have a high specific strength and stiffness, but are very sensitive to the delamination mechanism.

The manufacture technology and operational loadings could be incriminated for the materials weakness.

Ply interfaces in CFRP composite laminates are susceptible to initial damage due to their inherent low peel strength and toughness as compared to nominal strength of the plies [1]. The occurred defects during use can significantly affect the stiffness and strength of the structural elements of laminates [4]. Delamination mechanism is an interesting topic nowadays, being analyzed to highlight how it contributes to the failure of fiber-reinforced composites. Various studies have considered thickness failure due to interlaminar stresses and the effect of delamination on impact and compression after impact [2]. Important aspects in this topic have been shown concretely in examples of loaded cvasi-isotropic laminates [2], where the delamination mechanism is caused by the high interlaminar stress combined with the thickness strength.

Delamination is a critical failure mechanism in laminated fiber-reinforced polymer matrix composites, and one of the key factors differentiating their behavior from that of metallic structures [2]. The delamination onset is analyzed from the stress level, and the common scenario for delamination mechanism is when the interlaminar bonding strength is lower than interlaminar peeling stress [7].

Some theory claim that delamination frequently leads to failure initiation and has a decisive role in determining the strength [2]. Interlaminar stresses can be another cause of delamination in laminate, produced indirectly as a result of the geometry of the structure [2].

On the other hand, when a composite experiences impact, the composite strength and stiffness are reduced since the internal damage is made and expanded around the impact area [5]. In this case, the first type of failure is matrix cracking [5] followed by delamination, fiber crack and pull-out. Crack is the most obvious form of discontinuity [2] like delamination during the manufacture or events such as impact or compression. These cracks produce stresses at ply interface which may cause delamination in the punctual area.

The results presented in this paper is part of a larger study focused on CFRP materials - design and testing.

The extended study refers to the evaluation of CFRP materials developed by manual lay-up/autoclave curing, regarding the mechanical properties, the evaluation of the wettability of the resin to the fiber and the delamination mechanism occurring in the CFRP system at different mechanical loads.

The main objective of this paper is to study the CFRP system obtained by manual processing and polymerization in the autoclave.

The obtained compositions are mechanically tested, and the fracture mode of the tested specimens is evaluated by optical microscopy. These data are very important in the applicability of these materials in the aerospace industry.

2. EXPERIMENTS

Materials

For this study was used prepreg M18/1 Hexcel, the parent plate was manufacture by autoclave technology. The specification of the material is shown in the table below.

Table 1. M 18/1 characteristics

M 18/1 characteristics	**Value**	**Unit**
Density	1.22	g/cm^3
Glass Transition Temperature Tg Dry	196	˚C
Fiber density	1.78	g/cm^3
Fiber areal weight	160	g/m^2

HexPly® M18/1 is a high performance, self-extinguishing, tough epoxy matrix for use in primary aerospace structures.

It exhibits low moisture absorption at saturation [3]. The laminate has a staking sequence [0/90] with quasi-isotropic characteristics.

Methods and Instrumentation

To evaluate the mechanical properties, the composite laminates were subjected to mechanical testing using INSTRON 5982 machine.

It were performed 3-point bending, interlaminar shear stress (ILSS) and in-plane shear (IPS) method tests for a minimum of 5 specimen per test, according to DIN EN ISO 14125, Class IV at 2 mm/min speed rate [9] for 3-point bending test, DIN EN ISO 14130 at 2 mm/min speed of test [8] on rectangular specimens for ILSS and BS EN ISO 14129 at 1 mm/min speed [10] of test for IPS.

The manufacture process was evaluated through ultrasounds technique using EPOCH 6LT from Olympus.

The delamination process was analyzed through microscopy, morphological analysis was registered with optical microscopy using MEIJI 8520 microscope and it was performed in the fracture cross-section of the tested specimens.

To better understand the delamination process and predict this mechanism, the finite element method was used in order to reproduce the laboratory tests. We use the software MSC PATRAN and the analysis was computed using the linear static SOL 101 from MSC NASTRAN.

3. RESULTS AND DISCUSSIONS

Ultrasounds nondistructive testing (NDT)

To verify if the structure has defects that can interfere with the delamination process, ultrasound nondestructive testing has been used.

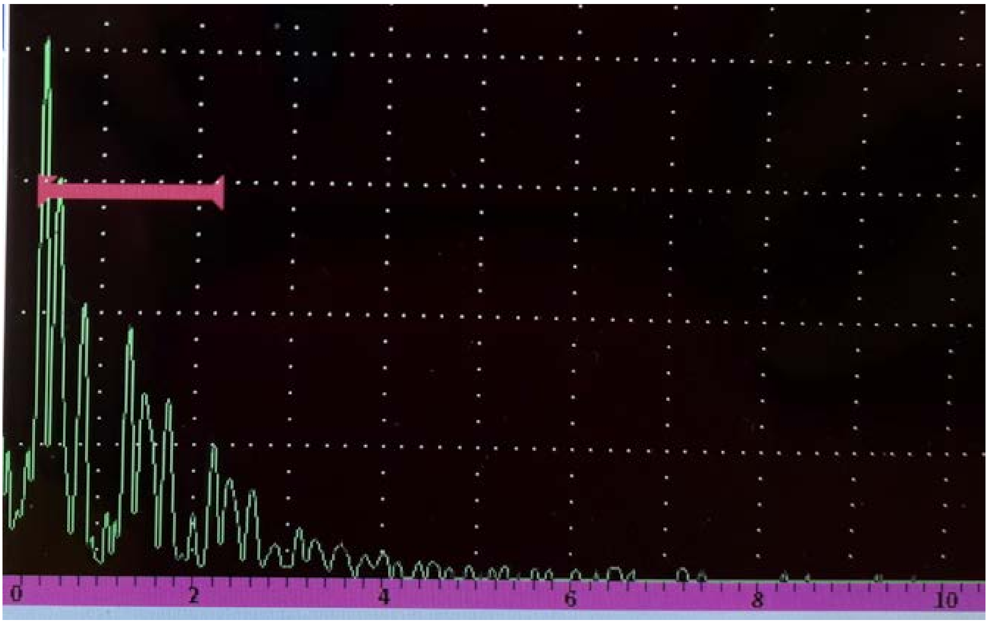

Fig. 1 Ultrasound nondestructive analyse in composite materials

After the manufacturing process, the ultrasound nondestructive testing is needed. This analyze highlights a uniform structure before mechanical testing, with some discontinuities from the small defects in the structure of the sample.

Delamination analyses and mechanical behavior

In order to analyze the mechanical resistance, mechanical tests were chosen to be able to have a clearer picture of their behavior at stresses and to observe the mechanism of delamination at different mechanical loads.

They were analyzed morphologically to observe how failure occurs.

Table 2. The results of the mechanical tests

Tests	Strength [MPa]		Modulus [MPa]		Apparent interlaminar shear strength [MPa]		in-plane shear stress at Maximum Load [MPa]
3-point bending	0	918.92	0	39.62	-		-
	90	986.50	90	34.96			
Short beam shear	-		-		0	58.98	-
					90	57.94	
In-Plane shear	-		-		-		76.6

Those samples that failed in the grip area were not considered as valid breaks, and were not taken into account for the mediation of mechanical results.

For **3-point bending** tests, a number of 5 samples were tested according to the international standard DIN EN ISO 14125, Class IV, applying speed test 2mm / min until preload 0.1N [9].

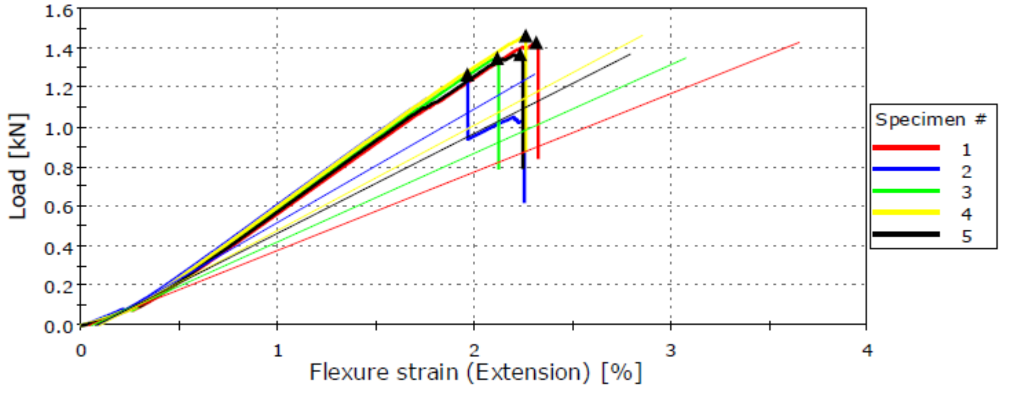

Fig. 2 Stress-strain curves during 3-point bending tests of specimens cut in the 90° plane

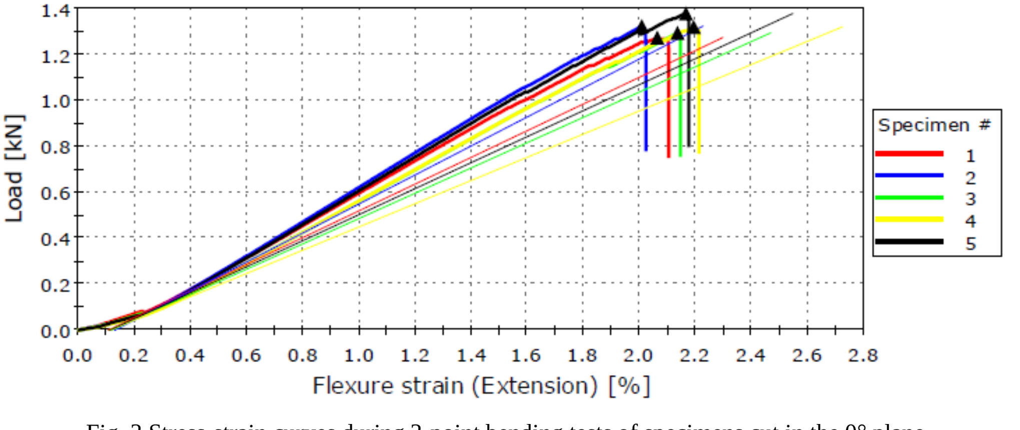

Fig. 3 Stress-strain curves during 3-point bending tests of specimens cut in the 0° plane

To complete the information on the behavior of the mechanically tested specimens, they were analyzed using optical microscopy.

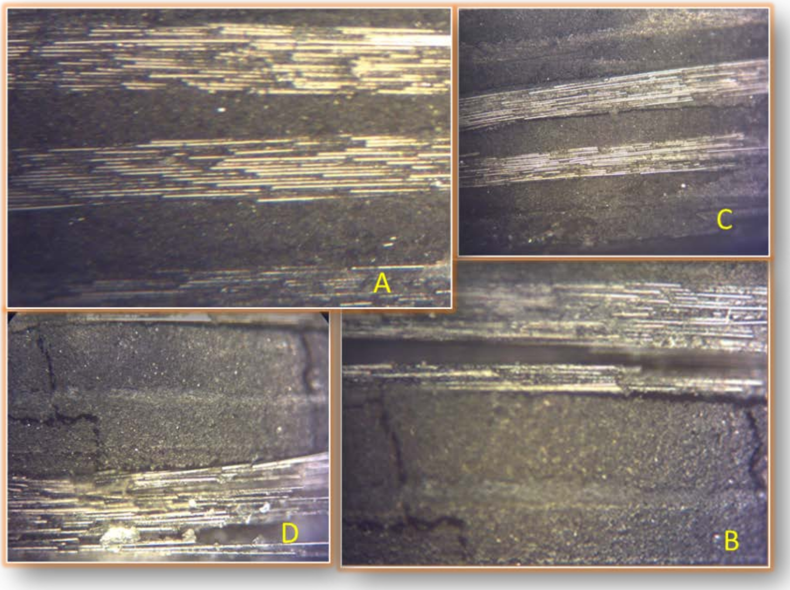

Fig. 4 Optical microscopy on 3-point-bending samples:(a) before testing, (b-c-d) after testing

It can be seen that the specimens failed both by detaching the fibers and by delamination at the fiber interface (Fig. 4. b), d)).

In the case of specimens that have not been visibly broken (fig. 4. (c)), the optical microscopy images illustrate that they have yielded structurally, yielding taking place inside the laminated structure, in the matrix.

This failure mode is very dangerous, because it is difficult to detect and difficult to repair; besides this, the behavior of this kind is unpredictable and difficult to evaluate.

A complementary explanation could be that the phenomenon arises because the fibers are lying in the plane of the laminate and do not provide the reinforcement through thickness, so that the composite relies on the relatively weak matrix to carry loads in that direction. This is exacerbated by the fact that matrix resins are typically quite brittle.

For the **Interlaminar shear stress (ILSS) test**, the short beam shear (SBS) method 5 samples were tested according to the international standard DIN EN ISO 14130, applying speed test 2mm/min until preload 10N [8].

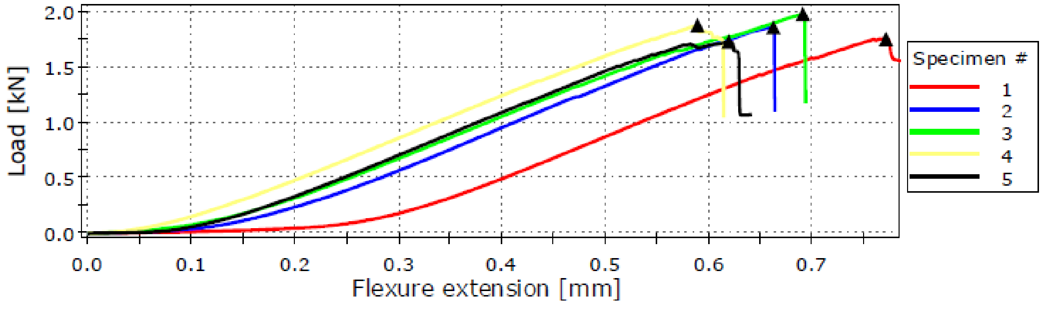

Fig. 5 Stress-strain curves during short beam shear tests of specimens cut in the 0° plane

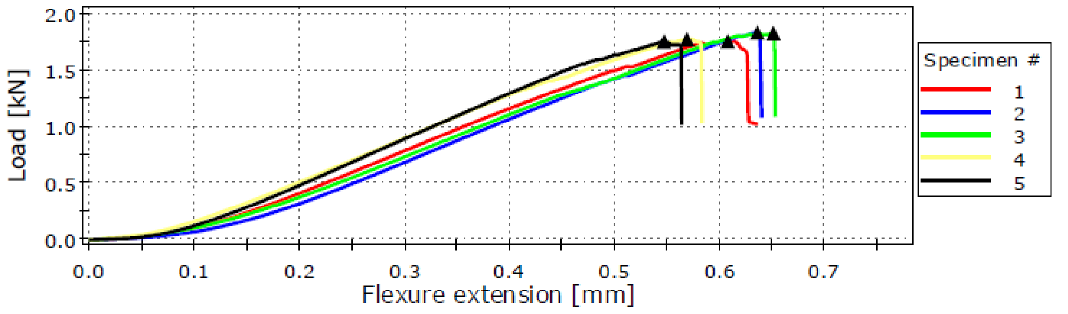

Fig. 6 Stress-strain curves during short beam shear tests of specimens cut in the 90° plane

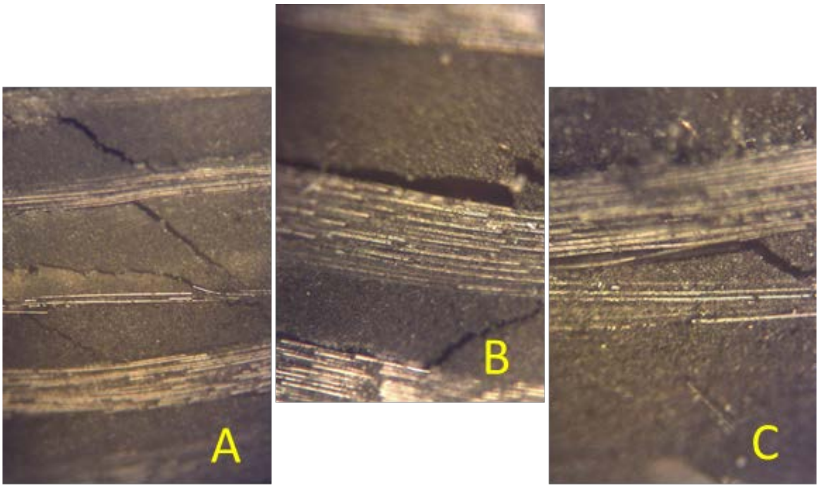

Fig. 7 Optical microscopy on ILSS tested samples: (a) sample no. 1, (b) sample no. 2, (c) sample no. 3

Optical microscopy illustrates that the crack propagates inward into the fracture area, with propagation in adjacent areas. The delamination process is highlighted at the interface between fibers and resin in case of sample no. 2 (Fig. 7 b)). Both in the case of sample no. 2 and no. 3 a crack propagation is observed in the cross section of the laminate, with delamination areas at the ply/resin interface.

For the **In-Plane shear (IPS) method** was tested a number of 5 samples according to the international standard DIN ISO 14129, applying speed test 1mm/min until preload 5N [10].

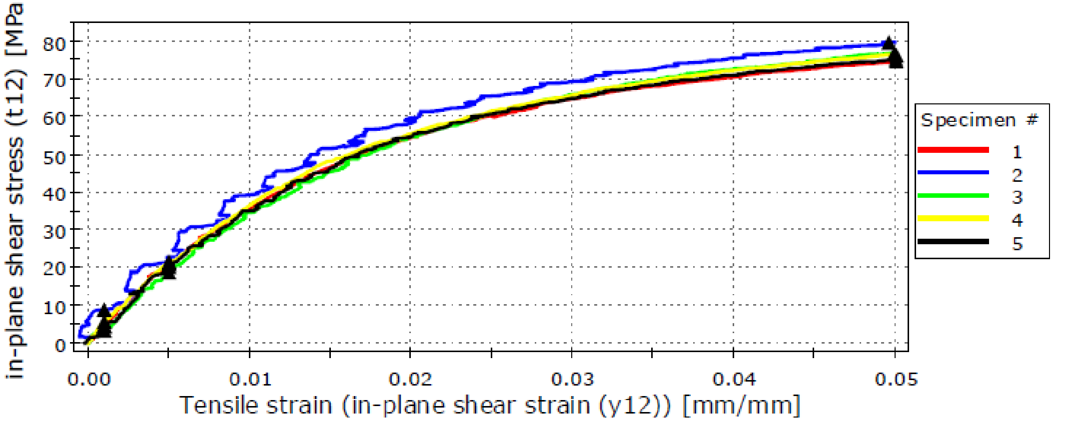

Fig. 8 Stress-strain curves during in-plane shear tests of specimens

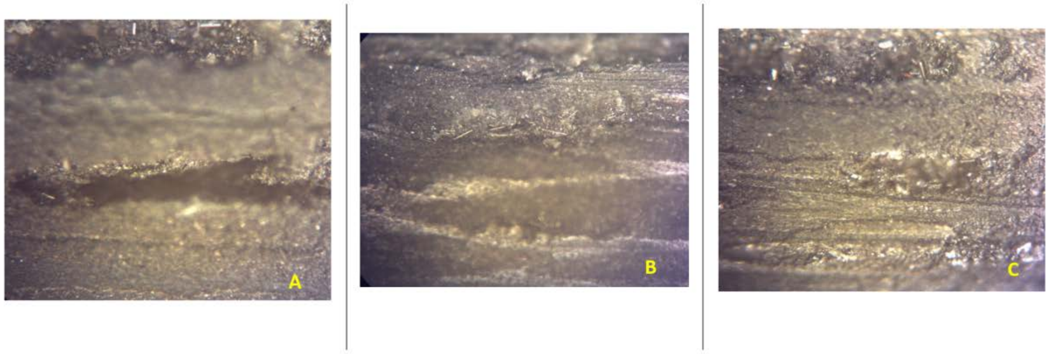

Fig. 9 Optical microscopy on IPS tested samples: (a) sample no. 1, (b) sample no. 2, (c) sample no. 3

The microscopic analyses highlight that an interlaminar stress and delamination mechanism occur in case of sample no. 1 without propagation in adjacent areas. The cracks are an obvious form of discontinuity in this case.

In case of sample no. 3, it is observed a tension which generates interlaminar normal stress with crack propagation into resin structure.

This pointed stress in matrix doesn't generate the delamination mechanism in the sample.

In the IPS samples, cut or discontinuity plies caused by ply joins (case of sample no. 2) produce interlaminar stress without delamination mechanism.

Numerical simulation

An analysis with FEM was made to simulate the delamination phenomenon by using the SOL 101 from MSC NASTRAN.

The delamination due to the interlaminar shear occurs in the area of the boundary conditions (simply-supported).

The highlighted results presented in the picture below show the area of the maximum strength ratio (Tsai-Wu failure theory [6]). By using this analysis, we can predict the areas where the first delamination initiates.

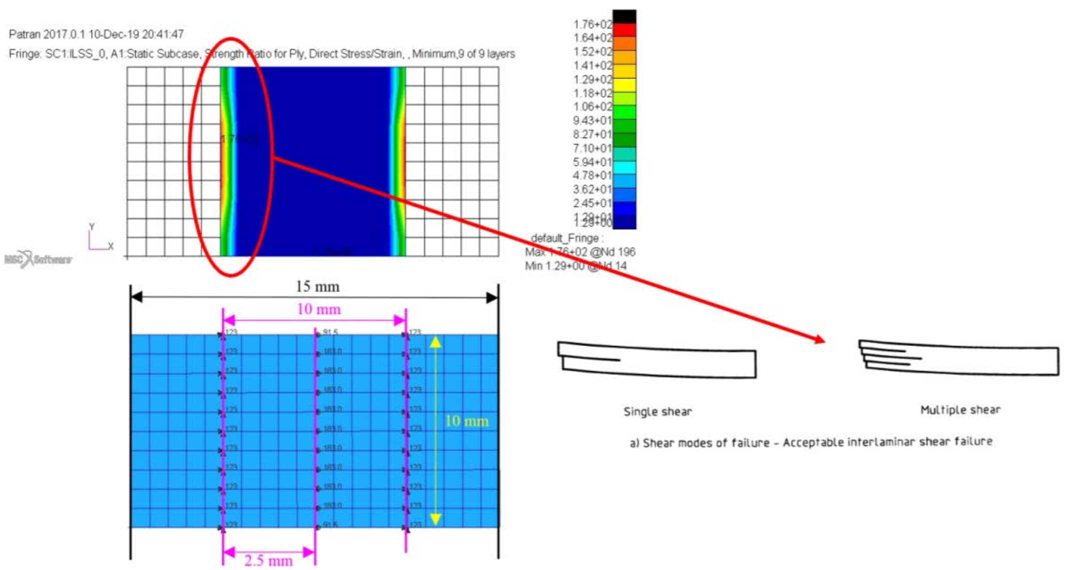

Fig. 10 FEM results for ILSS delamination prediction

4. CONCLUSIONS

The present work presents partial results on the type of samples made from CFRP prepreg by the autoclave forming method.

The specimens were subjected to 3-point bending mechanical tests, ILSS and IPS and their behavior was evaluated at different mechanical loads, type of rupture and delamination methods. The NDT testing showed some defects in the structure of the composite material. The appearance of interlaminar stresses, highlights that the resistance in the plane is affected which leads to the premature initiation of failure. The initiation of the delamination behavior of the coupons can be predicted with success by using FEM for this type of material and offers the possibility to predict the failure also in composite parts of the aerospace structures.

Considering the results of the experimental studies, it should be mentioned that the manufacturing process and the geometry may interfere in the delamination process.

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