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Influence of material and manufacturing technology on the failure behavior of composite laminate bonded joints

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Abstract

The purpose of this work is to evaluate the influence of co-lamination vs. co-bonding on the failure behavior, and namely the fracture toughness, of carbon fibre reinforced (CFR) composite laminate joints in order to assess comparatively their performance. Since the strength of the laminate and ply texture are parameters affecting the strength of the joint, the comparison is extended to two different types of CFR pre-preg fibers, a satin T1100 with 2573 Nanoalloy® epoxy resin supplied by Toray and a twill T700 with ER450 toughened epoxy resin supplied by CIT, Toray group, representative of two different fields of application, racing and automotive, respectively.

Keywords: Carbon-Fiber laminate joints; co-lamination; co-bonding; fracture toughness

1. Introduction

Bonding is the elective joining techniques for composite laminates, as testified from a large number of studies performed on the topic (see e.g. the collections edited by Camanho and Tong, 2011 and Vassilopoulos, 2015), while mechanical fastening is applied for high damage-tolerant applications where the structural redundancy offered by fasteners is preferred or when rapid/easier dismantling is foreseen. Bonding is mostly preferred over fastening because of weight saving and to avoid the drilling of a hole through the composite that generates fiber discontinuity,

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affecting bearing and shear strength of the component. On the other hand, the strength of bonded joints is limited by the onset of debonding and/or delamination. Delamination or debonding fracture toughness is therefore a fundamental parameter for the design of the connection, but it is also important as a mean to compare different design solutions in terms of strength versus manufacturing time and cost.

Bonding of composite laminate parts can be done following different manufacturing routes, in particular by co-laminating, co-bonding or cold-bonding. The technology is generally chosen according to the final product purpose and complexity. In the automotive field for instance, co-lamination and co-bonding can be found in monocoques of racing cars, while cold-bonding is present in parts with complex geometry such wings, fairings and bottom plate.

The purpose of this work is therefore to evaluate the influence of co-lamination vs. co-bonding on the failure behavior, and namely the fracture toughness, of carbon fibre reinforced polymeric (CFRP) laminate joints in order to assess comparatively their performance. Since the strength of the laminate and ply texture are parameters affecting the strength of the joint, the comparison is extended to two different types of CFRP pre-pregs, representative of two different field of application, racing and automotive, respectively.

1.1. Materials and specimen manufacturing

The carbon fiber pre-pregs used in this work include C280 T1100 12K satin-weave (5H) and a T700 twill-weave supplied by Toray, pre-impregnated with 2573 Nanoalloy® epoxy resin (38% by weight) with ER450 toughened epoxy resin (40 % by weight) supplied by CIT (Toray group), respectively. The ply nominal thickness is 0.3mm for T1100 and 0.42 mm for T700.

Co-bonding was done with AF 163-2U Scotch-Weld thermosetting modified epoxy, unsupported structural film adhesive from 3M with a 0.15 kg/m^2 mass and 0.14 mm nominal thickness. Mechanical properties from the suppliers technical datasheets are reported in Table 1.

Table 1. Properties at environmental temperature of the materials used in this work (T1100 CF + 2573 and AF 163 from supplier datasheet; T700 CF + ER 450 from internal tests).

Material		Modulus of elasticity (GPa)	Tensile Strength (MPa)	Yield strength (MPa)
T1100 CF + 2573 epoxy resin adherent	0° tensile	89	1900	-
	90° tensile	87	1740	-
	0° compressive	76	800	-
	90° compressive	80	740	-
	0° Flexural	75	1060	-
	0° ILSS	-	74	-
	90° ILSS	-	73	-
T700 CF + ER450 epoxy resin adherent	0° tensile	61	860	-
	90° tensile	57	815	-
	0° compressive	-	615	-
	90° compressive	-	550	-
	0° Flexural	59	930	-
	0° ILSS	-	75	-
	90° ILSS	-	-	-
AF 163 film adhesive		1.1	48	-

Composite parts were cured a 130°C for 120 min in a vacuum bag and applied external pressure of 6 bars. In the case of bonded joints, the film adhesive was placed on a cured CFRP adherent (sandpapered and carefully cleaned with acetone before application), then pre-preg plies were laid over the adhesive and the resulting layup was consolidated with the same cure cycle described above.

1.2. Fracture toughness testing

The fracture toughness testing includes:
- 3PB: three-point bending test for the identification of the flexural and shear modulus of the composite adherent, to use in DCB (Double Cantilever Beam) and ENF (End Notched Flexure) tests;
- DCB: mode I delamination/debonding test
- ENF: mode II delamination/debonding test

The nominal geometry of DCB and ENF specimens is shown in Figure 1. Each adherent is comprised of 19 plies in the case of T1100 and 15 plies in the case of T700, all of them aligned along 0° direction of the fiber.

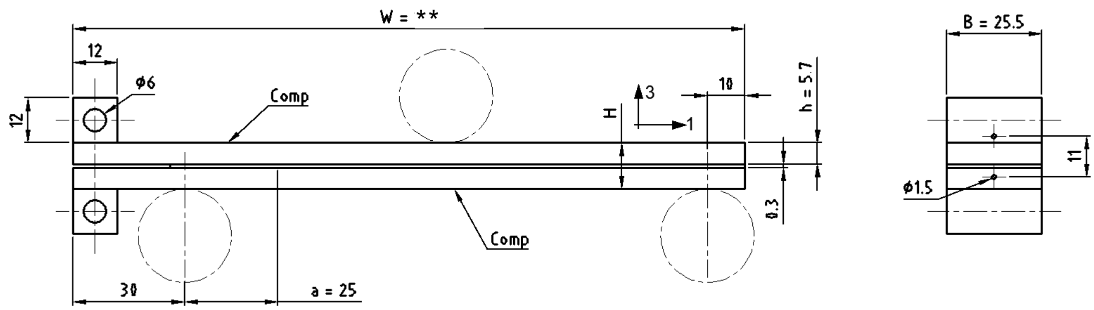


Figure 1. Nominal dimensions of DCB specimens. *W = 150 (DCB) or 180 mm (ENF). Dashed-dotted circles represent the ENF supports and load application points.

A non-sticking material insert is placed between adherent at one side of the specimens in order to create the initial defect. A delamination/debonding crack of a few millimeters is then created by fatigue loading in mode I. The fracture tests are performed in displacement control at a loading speed of 2.5 mm/min. Partial unloadings are done to evaluate the compliance, hence crack length, during the test so the value of G_I, G_{II} (strain energy release rate under mode I or mode II loading) as a function of crack length (R-curve). The values of G_I, G_{II} are evaluated at each crack length by FEM (Finite Element Modelling). Also the crack-length vs. compliance relationship is evaluated numerically by FEM. Additionally, DIC (Digital Image Correlation) was used in ENF test to detect the crack tip position at the specimen side during the test since the crack is not open and the compliance is less sensitive to crack length changes than in DCB tests. The crack length was then evaluated by matching DIC measurements with crack lengths evaluated by inverse FEM of the unloading compliance. However, R-curve was not detected in ENF due to unstable crack propagation from the initial length to below the loading point, that is a common feature of this test. Co-laminated joints are manufactured with the same nominal dimensions and methodologies of co-bonded ones but without using the film adhesive. Test conditions for mode I or mode II delamination are the same of bonded joints. Three repetitions were done for each kind of test.

Other tests, not reported here because outside the scope of the paper but helpful for a thorough understanding of the strength behavior are:
- TRAZ-BJ: tensile test on butt-bonded cylindrical joints, in order to extract the average tensile strength of the adhesive used in a joint;
- TRAZ-CI: tensile test on cylinders of CFRP, stressed in direction 3 (perpendicular to the lamination plane) in order to extract the ILTS (InterLaminar Tensile Strength);
- TRAZ-CE: tensile test on cylinders of composite material, stressed in direction 3 (perpendicular to the lamination plane) in order to extract the elastic module in the 3 direction of the laminate;
- SLJ-CC: lap shear strength of CFRP-CFRP joint;

2. Results and discussion

Results will be presented scaled with respect to the mode I or mode II fracture toughness, respectively, of the co-laminated CFRP because of confidentiality. Therefore, normalized values are denoted as G_{I_norm} (normalized with respect to the average of the first propagation values of the co-laminated T1100+2573 DCB specimens) and G_{II_norm}. (normalized with respect to the average of the values of the co-laminated T1100+2573 ENF specimens). For the same reason, in force-opening diagrams force is normalized (F_{norm}) with respect to the maximum force of the corresponding test, F_{max}.

2.1. Co-laminated joints

An example of Force vs. opening behavior and fracture surface of DCB tests is shown in Figure 2 for the two different materials.

(a)

(b)

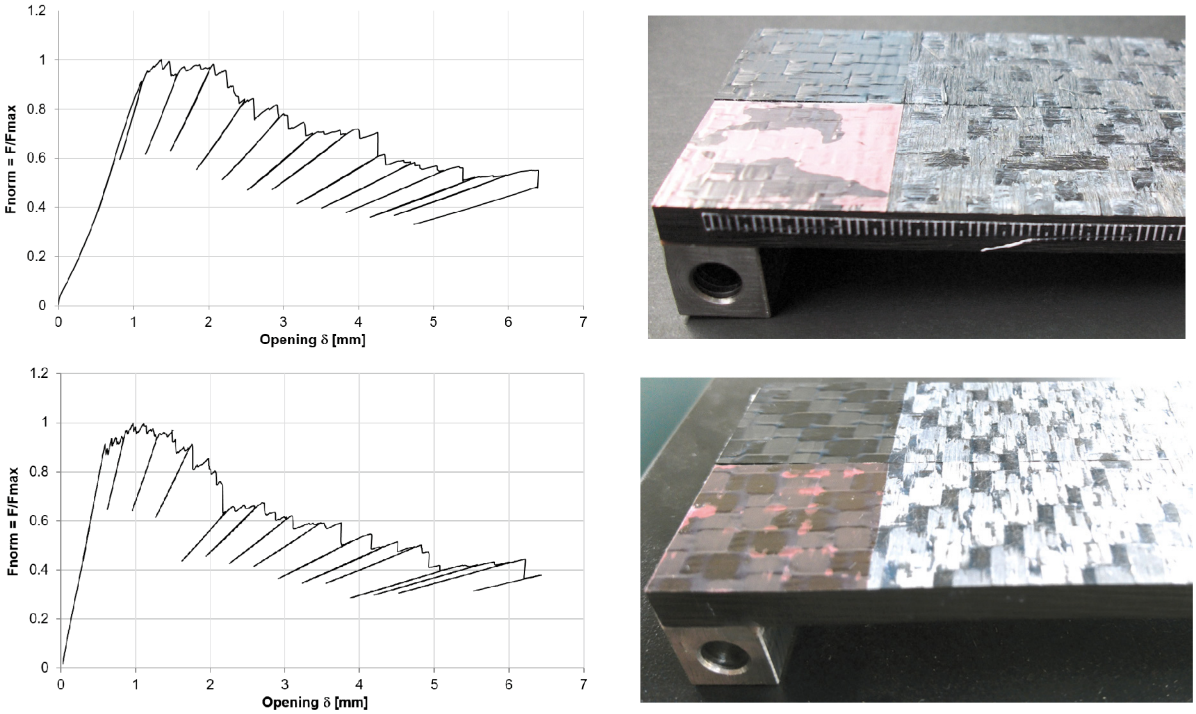


Figure 2. Example of force vs. opening behavior and fracture surface of: (a) T1100+2573 resin; (b) T700+ER450 resin co-laminated DCB tests.

In some T1100 specimens it is possible to identify also a marked bridging phenomenon with the initiation and propagation of more delaminations.

This phenomenon requires a greater amount of strain energy release, as visible in the diagram of Figure 4a: for all three specimens propagation begins at about the same G_I but, for the specimen T1100_01, the value of G_I grows slightly and stabilizes around a 20% higher value, while for the other two samples G_I shows a more marked increase. The initial fracture toughness of T700 co-laminated joints is just about 20% of that of T1100, highlighting the large performance gap of a "standard" CFRP system like T700/ER450 with respect to the high performance T1100/2573. The value of G_{I_norm} increases with crack propagation becoming about 50% greater than the initial one but remaining much lower than that of T1100/2573. The three test show a similar increase from the initial value to the stabilized one since multiple delaminations were not detected in this case, differently from T1100/2573.

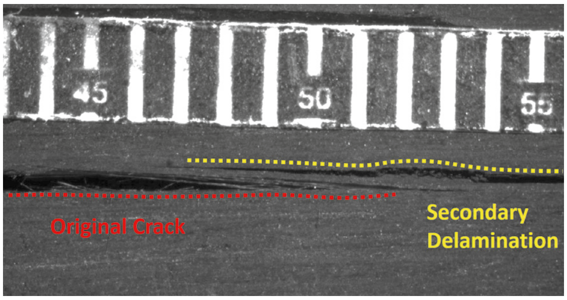
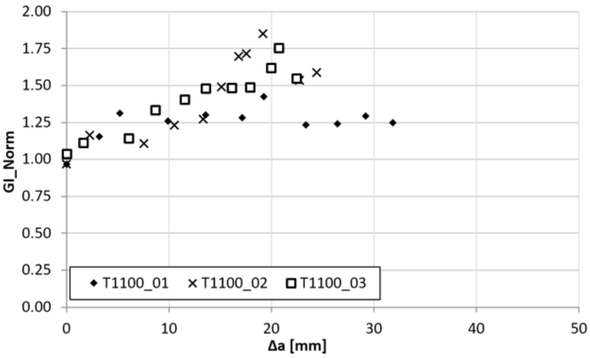
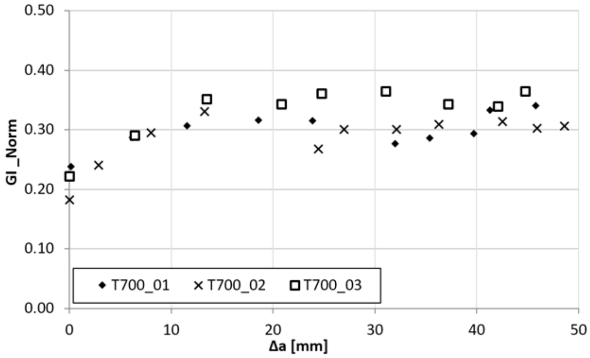


Figure 3. Example of secondary delamination in a DCB test (T1100_03 specimen).



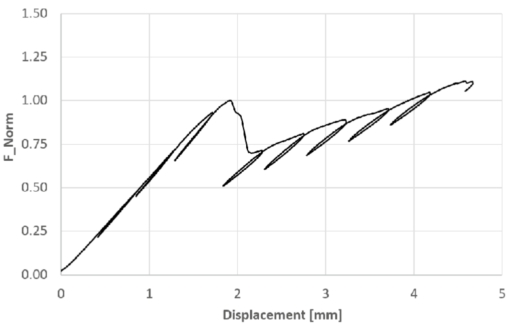
(a)

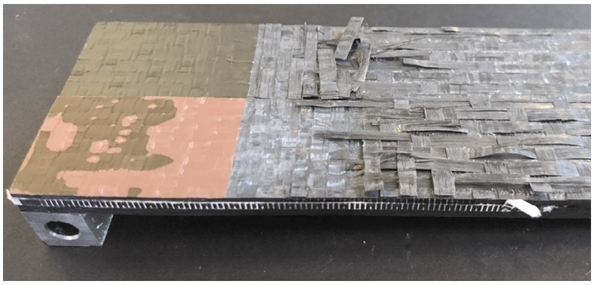


(b)

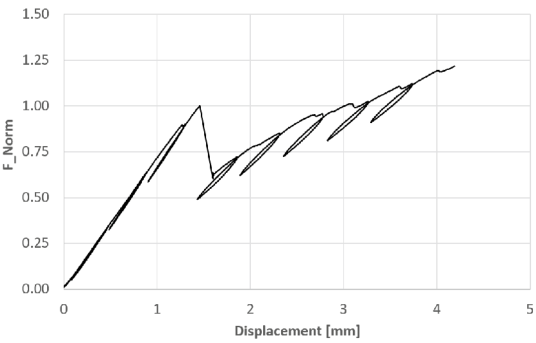
Figure 4. Mode I R-curve of: (a) T1100+2573 resin; (b) T700+ER450 resin co-laminated DCB tests.

(a)





(b)



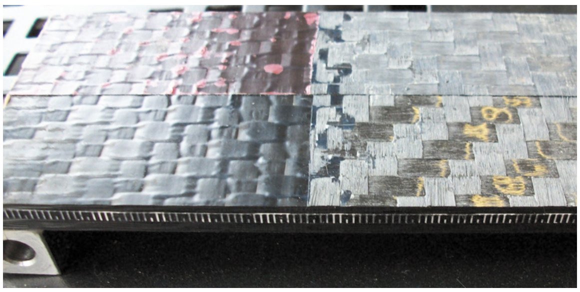


Figure 5. Example of force vs. opening behavior and fracture surface of: (a) T1100+2573 resin; (b) T700+ER450 resin co-laminated ENF tests.

An example of Force vs. opening behavior and fracture surface of ENF tests is shown in Figure 5. Due to the unstable fracture propagation in ENF specimens, only the value of normalized G_{II}, G_{II_norm}, at the beginning of propagation is reported in Table 2 in terms of average value of the three tests and standard deviation.

Alike mode I fracture toughness, the T700/ER450 CFRP shows a much lower value than T1100/2573. being the average value only 59% of the more performing material. The standard deviation of T700/ER450 is instead higher than T1100/2573 but it keeps anyway within a reasonable value with respect to the average, meaning that the manufacturing process is properly set to yield a good reproducibility of results.

Table 2. Normalized G_{II_norm} (average and standard deviation) resulting from ENF tests on co-laminated specimens.

Configuration	G_{II}_norm (average)	G_{II}_norm (std. dev)
T1100 CF + 2573 (co-laminated)	1.00	0.016
T700 CF + ER450 (co-laminated)	0.59	0.029

2.2. Co-bonded joints

An example of Force vs. opening behavior and fracture surface of DCB tests is shown in Figure 6.

(a)

(b)

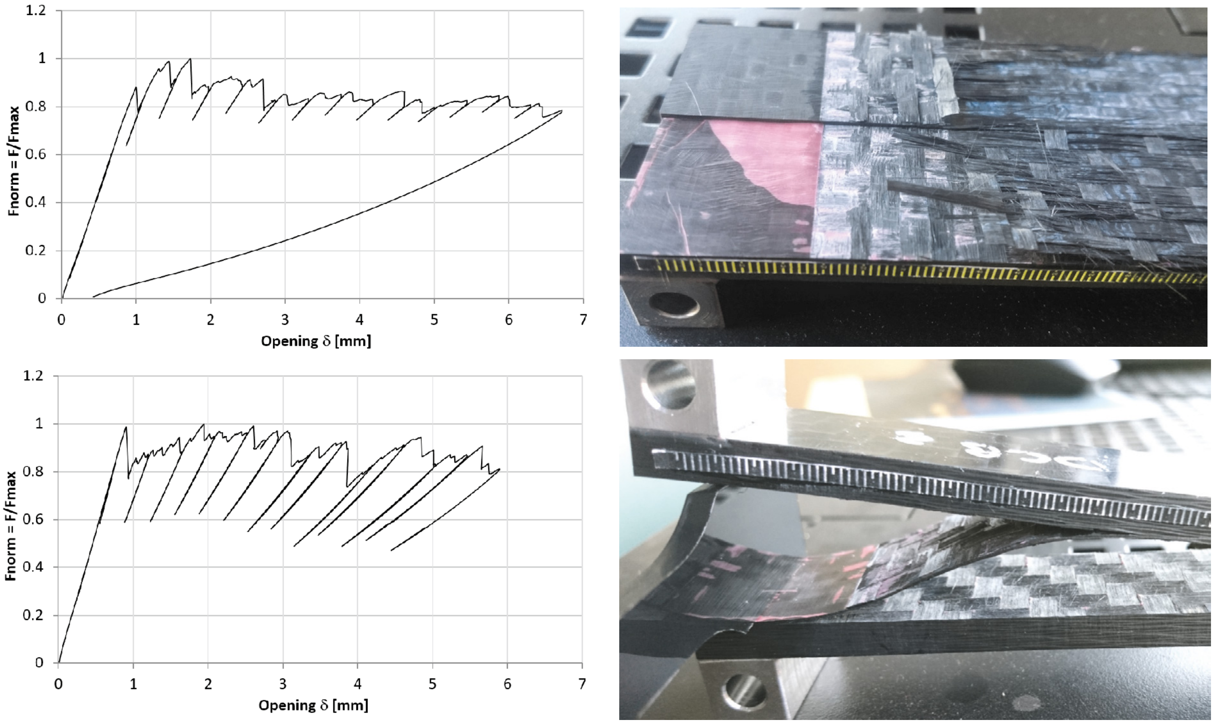


Figure 6. Example of force vs. opening behavior and fracture surface of: (a) T1100+2573 resin; (b) T700+ER450 resin co-bonded DCB tests.

By analyzing the fracture surfaces it is possible to notice how the propagation of the defect in T1100 joints starts in the adhesive and then jumps between composite plies, possibly with multiple delaminations (Figure 7).

For this reason, by associating the images of the fracture surfaces and the experimental results, one can distinguish the peaks relative to propagation inside the adhesive from those related to propagation inside the composite material, see Figure 8. The value of G_{Ic} and, in general the trend of the R-curve, are lower than those of co-laminated CFRP joints.

The fact that the T1100 co-bonded joint fail by delamination as the co-laminated one, can be related to the competition between composite resin and adhesive strength in determining the failure behavior. In fact, the TRAZ_BJ test (see Sect. 2.2 for definitions) yielded a nominal tensile strength of the adhesive in an aluminum-to-aluminum bonded joint of 56.6 ± 2.06 MPa, while the out-of-plane tensile strength test on the CFRP only (TRAZ_CI) gave 47.1 ± 2.64 MPa. Therefore, the ply-to-ply interface under mode I loading the weakest region and the adhesive cannot exploit its higher strength and fracture toughness. On the other hand, it has still to be fully understood why mode I delamination in co-bonded joint (see Figure 8a) occurs at G_I slightly lower than in the co-laminated CFRP (Figure 4a). A first hypothesis is that the stress state in the delaminating plies at the crack tip may be altered in co-bonded joints due to the presence of a compliant adhesive layer. Also the presence of a small resin excess in co-laminated joints and the possible mixing of pre-preg resin and adhesive during cure cycle in co-bonded joints are contributing factors.

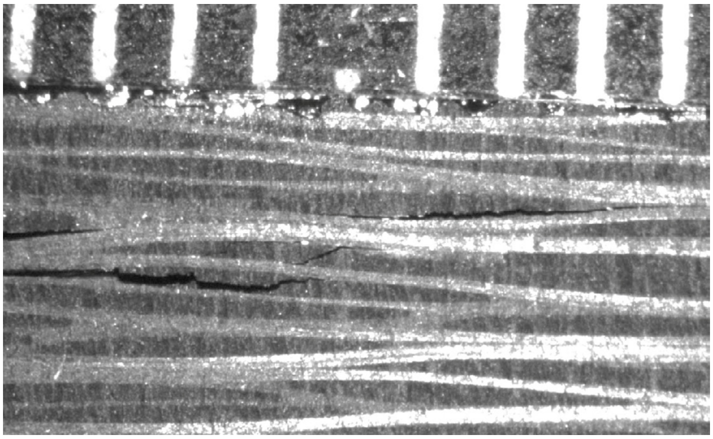
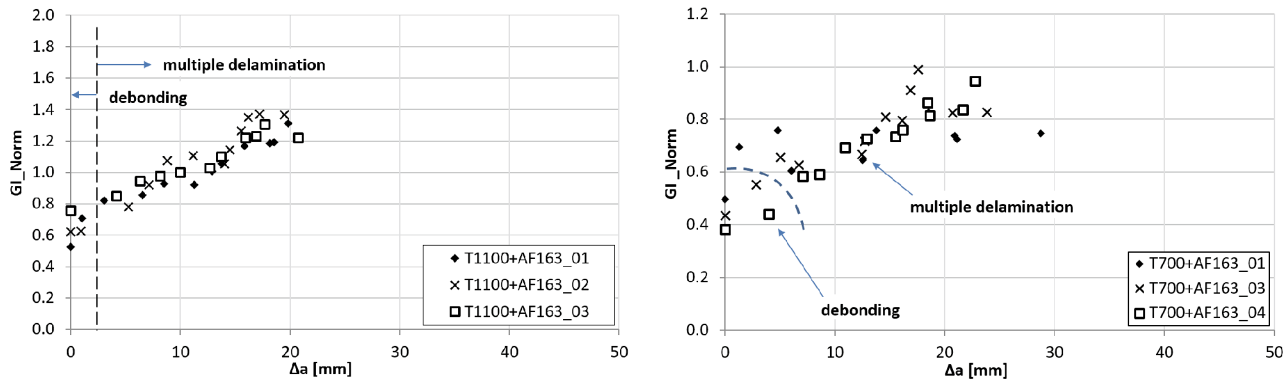


Figure 7. Example of multiple delamination in a DCB test (T700+AF163_01 specimen).



(a) (b)

Figure 8. Mode I R-curve of: (a) T1100+2573 resin; (b) T700+ER450 resin co-bonded DCB tests.

A situation similar to T1100 is recorded also for T700 co-bonded joints, where initial debonding is followed by delamination (Figure 6b) and therefore the value of G_{II_norm} steadily increases with crack propagation. On the other hand, by comparing Figure 4b and Figure 6b it is possible to notice that the fracture toughness of co-bonded joint is consistently higher (about twice) the one of the co-laminate material. The reason for this result can be different depending on the type of fracture, viz. debonding or delamination. Taking into account that T700 co-laminated joints failed by a single delamination crack, in co-bonded joints:

- when the crack starts to propagate by debonding, the adhesive yields a higher fracture toughness than a single delamination, as expected;

- as soon as the crack jumps into the composite, multiple delaminations occur, requiring more energy than a single delamination to propagate.

The reason why multiple delaminations develop in co-bonded joints while a single delamination was present in the co-laminated ones cannot be ascertained but some hypothesis can be done. In particular, the higher fracture toughness developed at the beginning in co-bonded joints may cause damage to several ply interfaces, that subsequently evolves into multiple delaminations.

An example of Force vs. opening behavior and fracture surface of T1100 ENF tests is shown in Figure 9aFigure 5. The adhesive is visible both at the beginning (fatigue precracking) and during the propagation phase, therefore the propagation is cohesive in the adhesive. In the case of T700, the adhesive seems to be located predominantly on one surface, but some pink spots are visible also on the other surface. Since the propagation is unstable, only the initial value of G_{IIc} could be evaluated and the average and standard deviation of G_{II_norm} are summarized in Table 3. For both materials, the value is about twice that of co-laminated CFRP joints. In this case, the propagation of the crack within the adhesive yields a higher fracture toughness differently from DCB test, where it jumps between the plies soon after initiation.

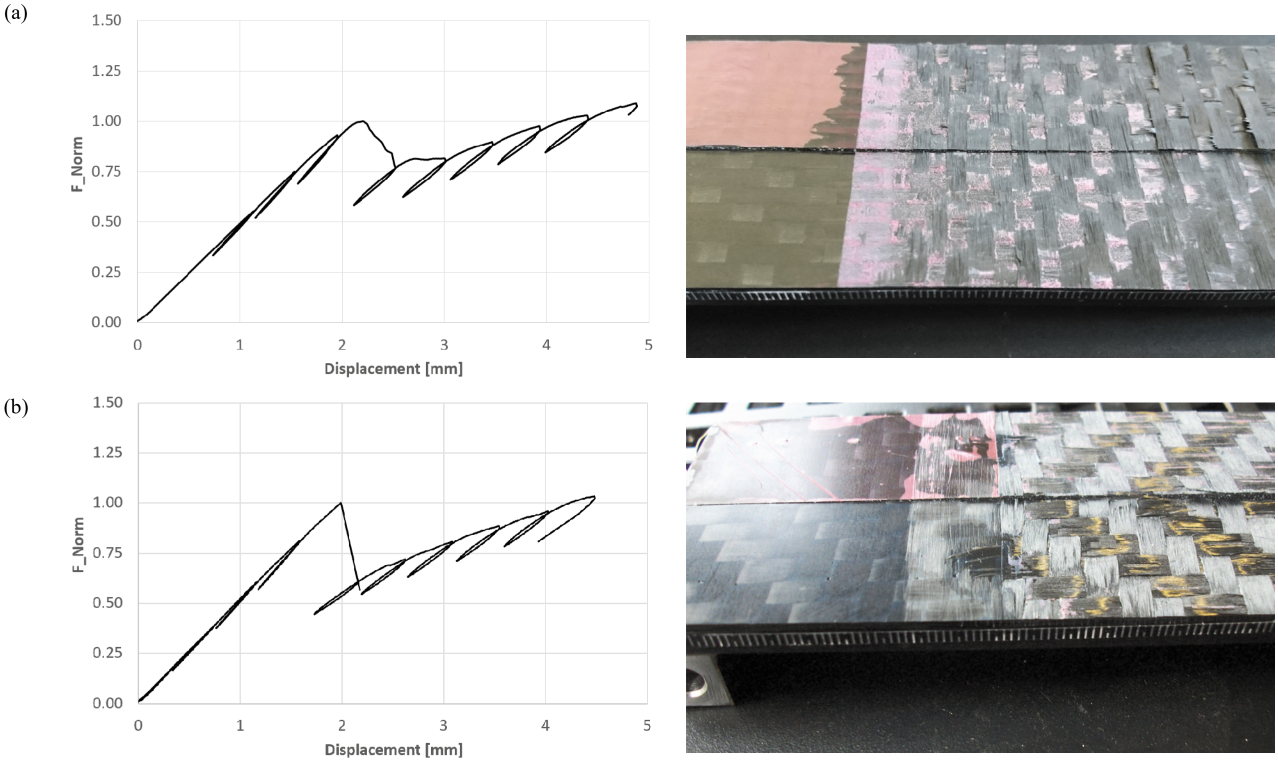


Figure 9. Example of force vs. opening behavior and fracture surface of: (a) T1100+2573 resin; (b) T700+ER450 resin co-bonded ENF tests.

Table 3. Normalized G_{II_norm} (average and standard deviation) resulting from ENF tests on co-bonded specimens

Configuration	GII_norm (average)	GII_norm (std. dev)
T1100 CF + 2573 + AF 163(co-bonded)	2.02	0.203
T700 CF + ER450 + AF 163(co-bonded)	1.22	0.035

3. Conclusions

When comparing to mode I and mode II fracture toughness co-laminated and co-bonded and CFRP joints, the following conclusions can be drawn concerning the T1100+2573 resin system:

- mode I fracture toughness of co-laminated joints is higher than bonded joints and so the R-curve trend. In both joints the increasing R-curve is related to the development of multiple delaminations.

- the competition between composite resin and adhesive in determining the mode I failure behavior is determinant. Tensile tests in the direction normal to the joint showed that under mode I loading the weakest region can be located at the ply-to-ply interface and, therefore, the adhesive cannot fully exploit its higher strength and (probably) fracture toughness with respect to the composite epoxy resin since the crack runs away from the adhesive layer soon after initiation;

- mode II fracture toughness of bonded joints is more than twice that of co-cured joints since the crack is constrained in this case within the adhesive layer differently from mode I loading.

Regarding instead the T700+ER450 resin:

- the performance in terms of fracture toughness is always lower than T1100+2573, certifying that this latter may be a better choice for highly-demanding applications;

- mode I fracture toughness of co-laminated joints is lower than that of co-bonded joints, where multiple delaminations have been recorded that were not present in the case of co-laminated joints.

- mode II fracture toughness of bonded joints is about twice that of co-laminated joints also in this case, since the crack runs mainly within the adhesive layer differently from mode I loading.

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