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Comparative investigation of mode I and II fracture toughness of directly cured CFRP and co-cured bonded CFRP joints

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Abstract

Adhesive bonding is the elective joining system between Carbon-Fiber Reinforced Polymer (CFRP) parts because, with respect to fastening, it allows a large connection area, no additional parts (hence weight saving) and no need to drill holes into the composite, that is always detrimental for the strength due to the possibility of developing damage. However, the choice of bonding CFRP should be evaluated as alternative to direct curing in terms of strength and durability, compared to cost and manufacturing time and complexity. In this work, a comparison between directly cured and co-cured, bonded CFRP is done with respect to mode I and mode II fracture toughness, in order to understand whether bonding guarantees the same performance of a co-cured composite part.

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Keywords: Carbon-Fiber Reinforced Polymer; bonded joints; fracture toughness

1. Introduction

The joining of composite laminates is generally made by mechanical fastening or bonding, as testified from the large number of studies performed on the topic (Camanho and Tong, 2011; Vassilopoulos, 2015), while welding is confined to applications when composite matrix is of thermoplastic nature. Fastening ensures the possibility of decoupling and it is easier to inspect with respect to bonding, however it requires the drilling of a hole through the composite, as a result it generates fiber discontinuity, affecting bearing and shear strength of the component. On the

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other hand, when composite laminates are joined by bonding and/or co-curing, the joint strength is typically limited by the onset of debonding and/or delamination. The knowledge of the joint performance with respect to fracture toughness is therefore of utmost importance for the design of the connection, but also in order to compare different design solutions in terms of strength versus cost,manufacturing time and complexity. In this paper CFRP adherents are either co-cured or bonded with a structural adhesive film and tested with respect to mode I and mode II fracture toughness, in order to understand whether bonding guarantees the same performance of a co-cured composite part.

2. Experiments

2.1. Materials and specimen manufacturing

The materials used in this work include C280 T1100 12K satin-weave (5H) carbon fiber, pre-impregnated with 2573 epoxy resin (38% resin content) supplied by Toray with a ply nominal thickness of 0.3mm and 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 (from supplier datasheet if not differently specified).

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	-
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 appication), then pre-preg plies were laid over the adhesive and the resulting layup was consolidated by a cure cycle, always 130°C for 120 min in a vacuum bag and applied external pressure of 6 bars.

2.2. Fracture toughness testing

The experimental plan includes the following tests:
- 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;
- 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

For the sake of brevity, only fracture tests are described and the results used for comparison between bonded solutions and directly cured composite laminate. The nominal geometry of DCB and ENF specimens is shown in Fig. 1. Each adherent is 19 plies thick, all of them aligned along 0° direction of the fiber.

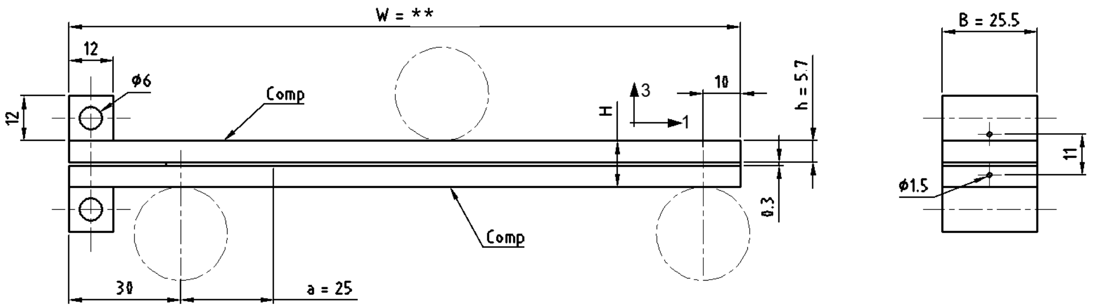

Fig. 1. Nominal dimensions of DCB specimens. *W = 150 (DCB) or 180 mm (ENF). Dashed-dotted circles represent the ENF supports and load application points.

The specimens are prepared by inserting a sheet of non-stick material to create the initial defect. In this way, however, the tip radius of the crack depends on the thickness of the non-stick sheet. In order to create a natural crack, fatigue precracking is performed in mode I to propagate the defect a few millimeters. The fracture tests are performed in displacement control at a loading speed of 2.5 mm/min. The test is conducted with partial unloadings to allow for crack length monitoring from the value of unloading compliance and, in turn, 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 value of G_I, G_{II} are evaluated at each unloading point by FEM analysis. Also the crack-length vs. compliance relationship is evaluated numerically by FEM (Finite Element Modelling). Since in ENF test the crack is not open and the compliance is less sensitive to crack length changes than in DCB tests, DIC (Digital Image Correlation) was used to detect the crack tip position on the specimen side at unloading points during the test. The crack length was then evaluated by matching DIC values with and the values of crack length evaluated by inverse FE analysis of the unloading compliance. However, in ENF no R-curve was detected due to unstable crack propagation from the initial length to below the loading point. Directly cured composite specimens are manufactured with the same dimensions and methodologies but without using the film adhesive and except the total thickness that is 13 mm instead of 5.7x2=11.4 mm due to a small excess of resin in the laminate. Test conditions for mode I or mode II delamination are the same as in the case of bonded joints. At least three repetitions were done for each kind of test.

3. Results and discussion

Results will be presented scaled with respect to the mode I or mode II fracture toughness, respectively, of the directly cured CFRP for the sake of confidentiality. Therefore, diagrams show normalized values denoted as G_{I_norm} and G_{II_norm}. For analogous reasons, the value of force in force-opening diagrams is normalized with respect to the maximum force of the same test, F_{max}.

3.1. Co-cured CFRP delamination

An example of Force vs. opening behavior and fracture surface of DCB tests is shown in Fig. 2. In some 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 Fig. 3: for all three specimens propagation begins at about the same G_I.

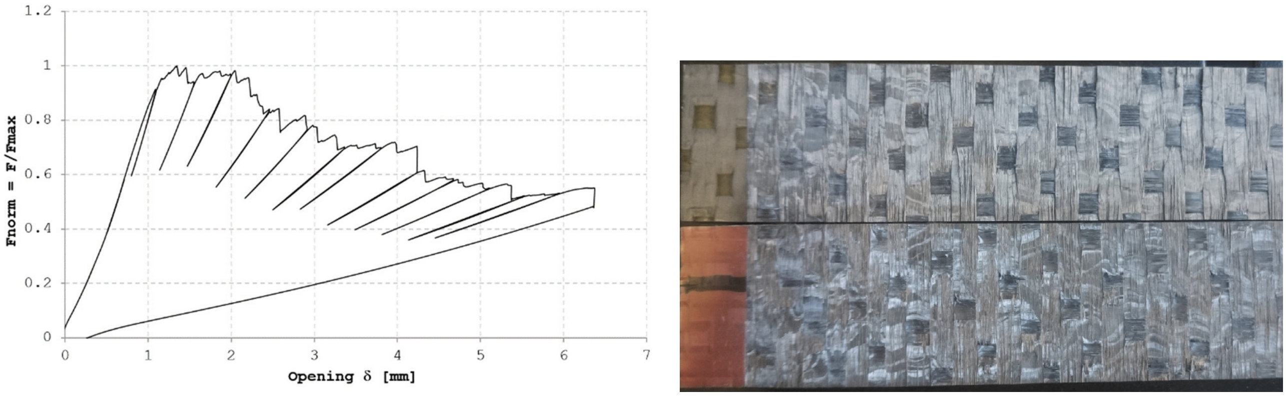

Fig. 2. Example of force vs. opening behavior and fracture surface of massive CFRP DCB tests.

Next, for the specimen DCB_CC_C01_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.

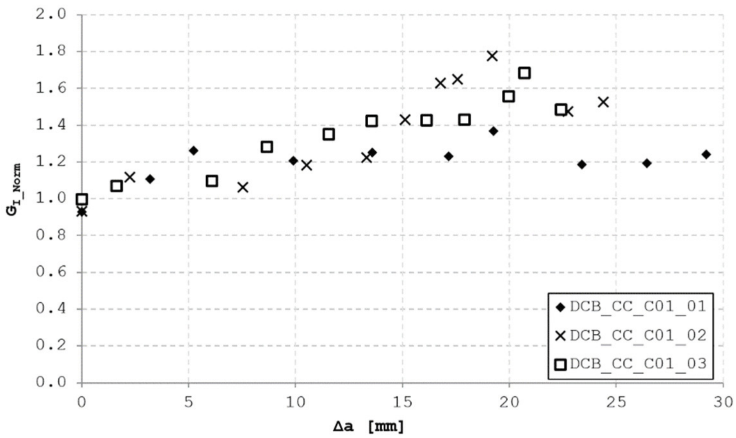

Fig. 3. Mode I R-curve of co-cured CFRP tests.

An example of Force vs. opening behavior and fracture surface of ENF tests is shown in Fig. 4. In this case, only one test was available at the time of writing this article.

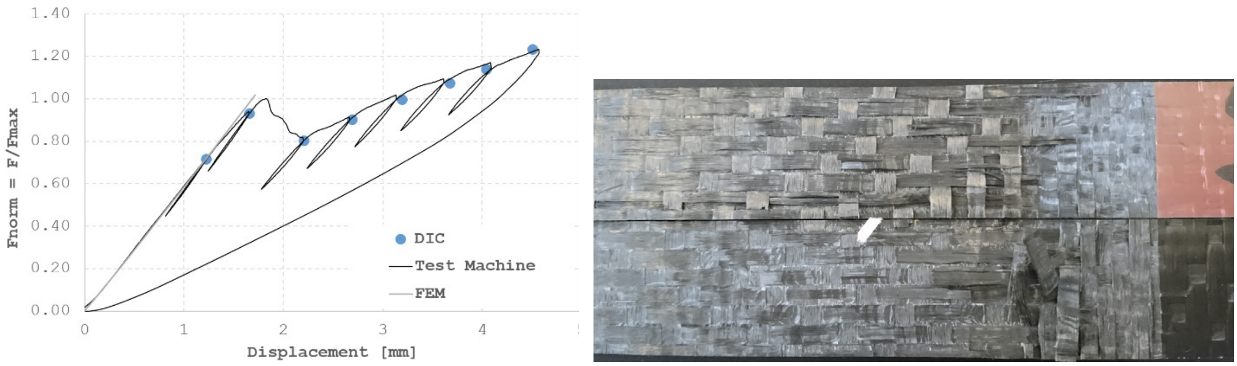

Fig. 4. Example of force vs. opening behavior and fracture surface of co-cured CFRP ENF tests.

3.2. CFRP-CFRP bonded joint

An example of Force vs. opening behavior and fracture surface of DCB tests is shown in Fig. 5Fig. 2.

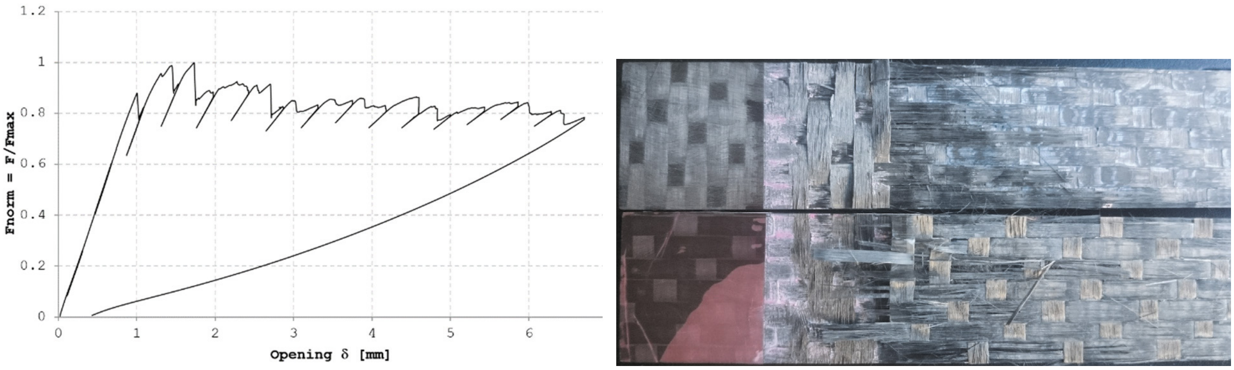

Fig. 5. Example of force vs. opening behavior and fracture surface of CFRP-CFRP bonded joint DCB tests.

By analyzing the fracture surfaces it is possible to notice how the propagation of the defect starts in the adhesive and then jumps between composite plies, possibly with multiple delaminations. 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 Fig. 6. The value of G_{Ic} and, in general the trend of the R-curve, are lower than those of directly cured CFRP specimens.

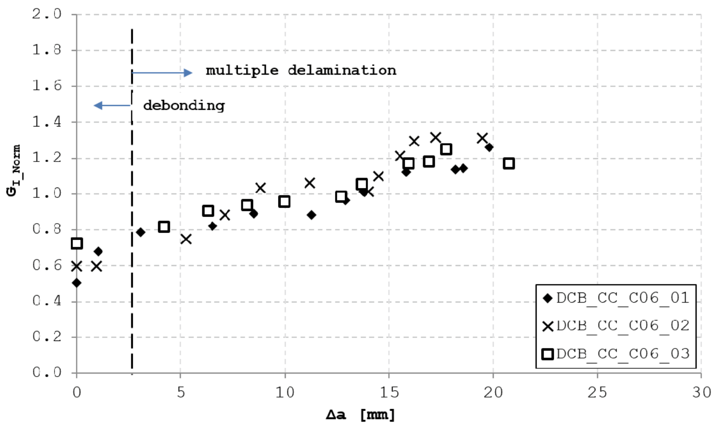

Fig. 6. Mode I R-curve of CFRP-CFRP bonded joints.

An example of Force vs. opening behavior and fracture surface of ENF tests is shown in Fig. 7Fig. 4. The adhesive is visible both at the beginning (fatigue precracking) and during the propagation phase. However, due to instability of the propagation phase, only the value of G_{IIc} could be evaluated, being 2.25 times the value found in directly cured CFRP specimens. Therefore, the presence of adhesive yields a higher fracture toughness since the crack is constrained within the adhesive layer differently from DCB test, where it runs away in the plies soon after initiation.

The reason of the different behavior in mode I and II can be related to the competition between composite resin and adhesive 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 a bonded joint of 56.6 ± 2.06 MPa, while the same test on directly cured CFRP (TRAZ_CI) gave 47.1 ± 2.64 MPa. Therefore, under mode I loading the weakest region is the ply-to-ply interface and the adhesive cannot fully exploit its higher strength and (probably) fracture toughness with respect to the composite epoxy resin. On the other hand it is not yet fully understood why mode I CFRP delamination in bonded joint (see Fig. 6) occurs at G_I slightly lower than in the co-cured CFRP. A first guess hypothesis is that the stress state in the delaminating plies at the crack tip region in the directly cured and co-cured, bonded specimens are not exactly the same, due to presence of a compliant adhesive layer. The presence of a small resin excess in directly cured CFRP and the possible mixing of pre-preg resin and adhesive during cure cycle in bonded joints are also factors that may contribute to that difference. Further investigation, including micrographic analysis is foreseen to highlight reasons of this behavior.

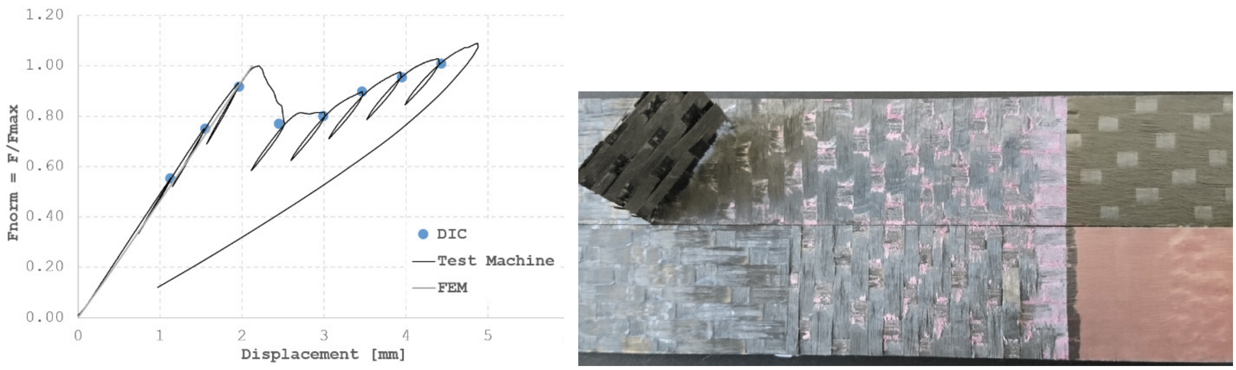

Fig. 7. Example of force vs. opening behavior and fracture surface of massive CFRP-CFRP bonded joint ENF tests.

4. Conclusions

When comparing to mode I and mode II fracture toughness co-cured and CFRP joints bonded with a structural film adhesive, the following conclusions can be drawn:

- mode I fracture toughness of co-cured 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.

References

Camanho, P.P., Tong, L., Eds., 2011. Composite Joints and Connections. Woodhead Publishing, Cambridge, UK.
Vassilopoulos, A.P., Ed., 2015. Fatigue and Fracture of Adhesively Bonded Composite Joints, Woodhead Publishing, Cambridge, UK.