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CHARACTERIZATION OF THE BOND BEHAVIOUR BETWEEN GLASS AND GFRP

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Abstract: In this study the bond behavior between glass fiber reinforced polymers (GFRP) and glass is studied. The GFRP is used to compensate for the brittle behavior of glass and the corresponding reduced strength under tensile stresses. In this paper, a numerical study is presented based on data collected from experimental tests conducted by the authors. The finite element method is used to model the bond between glass and GFRP pultruded laminates by means of an epoxy resin. For this purpose, a discrete crack approach based on non-linear fracture mechanics is adopted. The bond between glass and GFRP is modeled by means of zero thickness interface elements. The material properties that characterize the interface, namely the shear stiffness, the cohesion and the mode-II fracture energy, are evaluated from a parametric study performed with the objective of approximating the experimental results obtained from testing double lap joints in tension. The obtained parameters, describing the bond-slip law between glass and GFRP, are used to model a glass beam strengthened with GFRP. The obtained results are compared with experimental data. This work is expected to contribute to a better understanding of the stress transfer mechanisms between the glass and GFRP, particularly with respect to the qualitative and quantitative definition of mode-II fracture.

1 INTRODUCTION

In recent years, composite materials have increasingly been applied to the external reinforcement of structural elements. In

particular, carbon fibre reinforced polymers (CFRP) bonded to a concrete substrate are frequently adopted. This study is focused on the bond behaviour between glass fibre reinforced polymers (GFRP) and a less common material used for structural purpose: glass. In this case, the GFRP is not used for strengthening, rehabilitation or retrofitting; instead, the GFRP is introduced to overcome the brittle behaviour of glass and the corresponding reduced strength under tensile stresses [1].

In this paper, a numerical study is presented based on data collected from experimental tests conducted by the authors. The model was originally applied to describe the behaviour of externally reinforced concrete specimens. The finite element method is used to model the bond between glass and GFRP pultruded laminates by means of an epoxy resin. For this purpose, a discrete crack approach based on Non-linear Fracture Mechanics is adopted. The bond between glass and CFRP is modelled by means of zero thickness interface elements. The material properties that characterize the interface, namely the shear stiffness, the cohesion and mode-II fracture energy, are obtained from a parametric study performed with the objective of approximating the experimental results obtained from testing double lap joints in tension. The obtained parameters, describing the bond-slip law between glass and GFRP, are used to model a glass beam strengthened with GFRP. The numerical beam response is compared to experimental data collected from four-point bending tests [2]. This work is expected to contribute for a better understanding of the stress transfer mechanisms between the glass and GFRP, particularly with respect to the qualitative and quantitative definition of mode-II fracture.

2 EXPERIMENTAL TESTS

Double lap joints in tension are tested to support the quantification of the bond behavior between glass and GFRP pultruded laminates by means of numerical analysis.

In addition, the data collected from a four-point bending test on a glass beam strengthened with GFRP [3] is used to validate the numerical model presented in this work.

2.1 Experimental Setup

The double lap joints considered in this work consist of specimens composed by two external layers of glass bonded to an inner layer of GFRP pultruded laminate, by means of epoxy resin. The specimens are subjected to a tensile load as shown in Figure 1.

Figure 1: Double lap joint specimen during tensile test.

The specimens tested have a rectangular cross-section of 12mm by 50mm and 10mm by 50mm, for glass and GFRP, respectively. Both materials, glass and GFRP laminates, are

350mm long. The bond length and thickness are 100mm and 2mm, respectively. The geometric properties of the double lap joint specimens are shown in Figure 2.

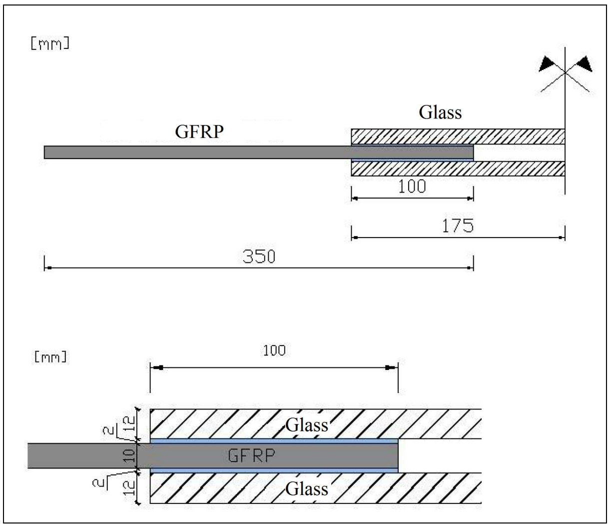


Figure 2: Double lap joint geometry [3].

To measure the axial strain distribution along the bonded splices, ten strain gauges are bonded on one side of the composite adherend as shown in Figure 3. These gauges have dimensions of $6\times11mm^2$. An additional control gauge is used outside the overlap region.

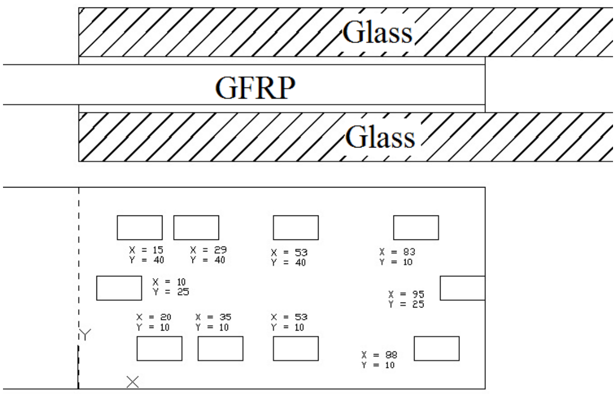


Figure 3: Strain gauge arrangement on 100mm overlap (dimensions in mm).

The bending test conducted is briefly presented in this paragraph. Further information related with the four-point bending tests on a glass beam strengthened with GFRP can be found in [3]. Figure 4 illustrates the geometry, reinforcing scheme and the boundary conditions, considering GFRP laminate.

The four point bending beams had a $12\times100mm^2$ glass cross section with a 1.50m span. The laminate was bonded, by means of epoxy resin, at the bottom of the beam along its length. One GFRP layer of t_f=10mm thickness and b_f=12mm width was adopted.

Figure 4: Configuration scheme of the bending tests on a glass beam strengthened with GFRP [3].

2.2 Material properties

According to [4], the glass can present a Young's modulus, a tensile strength and a Poisson's ratio of 70GPa, 45-50MPa and 0.25, respectively. The tensile strength value adopted is 45MPa.

Table 1 summarizes the main mechanical properties of the GFRP laminate, determined from tests [5].

Table 1: GFRP Mechanical Properties [5]

Mechanical Properties	Bending	Tension	Longitudinal Compression
σ_{fu} [MPa]	624.6±26.9	475±25.5	375.8±67.9
E_f [GPa]	26.9±1.3	32.8±0.9	26.4±1.9
ε_{fu} [10^{-3}]	24.9±1.3	15.4±1.5	17.0±2.5
υ_f [-]	-	0.28	-

In Table 1 σ_{fu} is the tensile strength, E_{fu} is the Young's modulus, ε_{fu} is the ultimate tensile strain and υ_{fu} is the Poisson ratio of the GFRP laminate.

In this work, the following values are adopted: σ_{fu} = 457MPa (in tension), σ_{fu} = 375.8MPa (in compression), E_{fu} = 29.7GPa and υ_{fu} = 0.28. The Young's modulus adopted, although above the values presented in Table 1, is defined according to the experimental data obtained, in particular from the strain value in the GFRP outside the overlap zone in the double lap joint tests.

The commercial epoxy resin Sikadur-330 was used in all experimental tests.

3 NUMERICAL MODELING

3.1 Material Model

The glass-epoxy-GFRP assemblage is modelled using interface elements with null initial thickness. In these interfaces, mode-II fracture is assumed, characterized by the cohesion, c, the shear stiffness, k_s, and the mode-II fracture energy, G_F^{II}. The adopted bond law presents an ascending linear branch and bilinear softening branch.

Cracks in the beam model are modeled by discontinuities embedded inside the finite elements. The displacement jumps are obtained at additional degrees of freedom, located at the embedded crack. In the model adopted, which is designated as discrete strong discontinuity approach (DSDA) [6], these degrees of freedom are global, giving rise to continuous displacement jumps across element boundaries. Cracking in the bulk is modelled according to mode-I fracture, in which a linear softening law is adopted.

3.2 Numerical Implementation

The numerical analysis is performed using the finite element method. Two node truss elements are used in the double lap model for both glass and GFRP. The bond behavior is modeled by four node linear interface elements.

The specimen response is determined using an incremental, iterative procedure.

To model the glass beam strengthened with GFRP laminates, bilinear four node isoparametric elements are used for both glass and GFRP. The bond behavior is again modeled by four node linear interface elements. The finite element mesh adopted is presented in Figure 5.

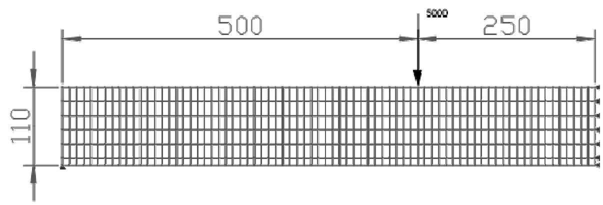


Figure 5: Finite element mesh adopted in the beam model (dimensions in mm).

Since the central zone of the beam is subjected to a constant bending moment, the glass tensile strength is numerically attained simultaneously in all elements located at the bottom of this zone. As a consequence, a large number of micro-cracks will initially form, although only some will localize and continue to evolve, whereas the others will close. This localization phenomenon is very difficult to capture numerically, being the main reason why the use of iterative schemes, like the Newton-Raphson method, usually fail to converge. Here, a non-iterative energy based method is used [7-8]. The following nonlinear phenomena are taken into account: (i) mode-I fracture of glass; (ii) mode-II fracture behavior of the assemblage formed by glass-epoxy-GFRP.

4 RESULTS

As aforementioned, the constitutive relationship of the interface glass-GFRP is defined by three parameters: the elastic shear stiffness, k_s, the cohesion, c, and the fracture energy in mode II, G_F^{II}. The influence of each one of these parameters on the specimen response is studied.

The data collected from the double lap joint tests is used to quantify the bond behavior between glass and GFRP. In addition, based on a sensitivity study carried out in [9], in which each parameter was varied independently with respect to a reference solution, it is possible to bring some enlightenment concerning those parameters. Thus it is possible to observe, predominantly, an elastic behavior. In this situation, the elastic shear stiffness and the cohesion have an important role in the structural response, as opposed to G_F^{II}. A value of 500MPa/mm is adopted for the shear stiffness. Regarding the cohesion it is not possible to come to a final conclusion yet, although it was observed that a value higher than 19MPa should be used to guarantee the elastic response of the specimen. However, from the bending tests a cohesion value of 23MPa gives rise to a good agreement between experimental and numerical results. Thus the proposed value for the cohesion in the interface glass-epoxy-GFRP is 23MPa. Assuming a predominantly elastic behavior, fracture energy in mode-II is considered small when comparing to the concrete-CFRP case. The adopted value is 0.01N/mm.

The double lap specimen response is shown in Figure 6, in terms of load-elongation, and in Figures 7 and 8, concerning the axial strains distribution along the overlap. The maximum load obtained is 36.8kN. It is possible to observe a very good agreement between experimental and numerical curves.

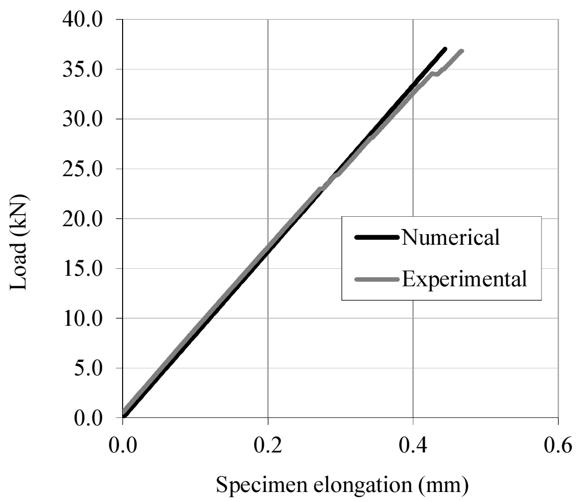


Figure 6: Load-elongation curves of double lap joint specimens.

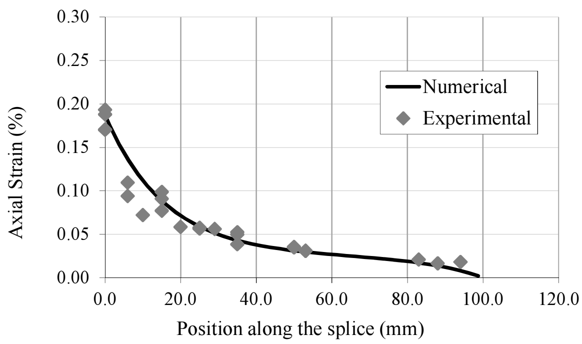


Figure 7: Axial strains at 28kN along bonded splice.

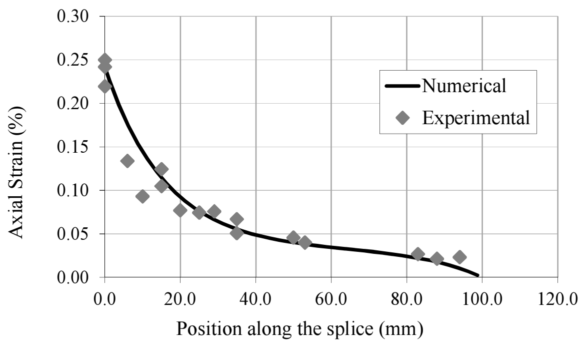


Figure 8: Axial strains at 36kN along bonded splice.

The numerical response of the glass beam strengthened with GFRP, by adopting the aforementioned values for the materials used, is shown in Figure 9. Considering the extreme brittle behavior which characterizes glass elements, it is possible to notice once more a very good agreement between numerical and experimental results.

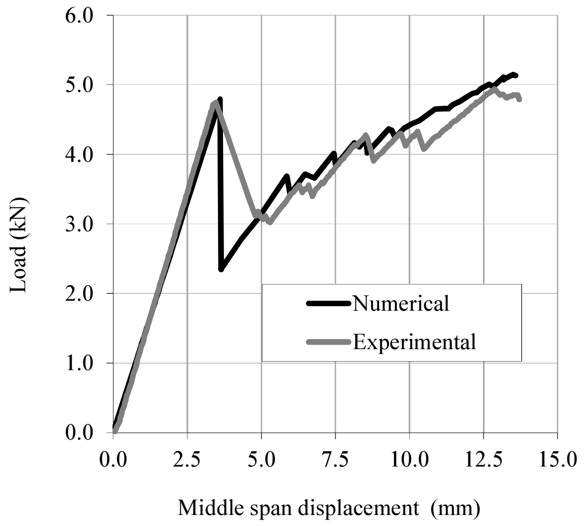
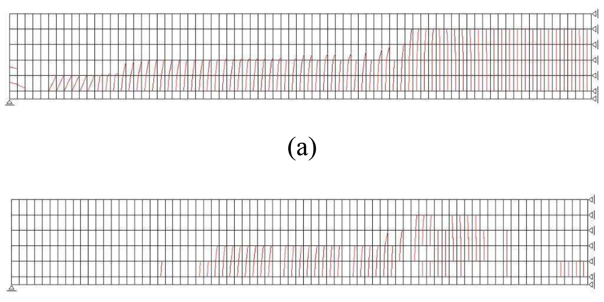


Figure 9: Load displacement curve of the glass beam strengthened with GFRP.

The crack pattern obtained from both solutions, experimental and numerical, is also compared. First, all numerical micro-cracks are shown in Figure 10(a), whereas in Figure 10(b) only the active cracks are depicted. From Figures 10 and 11, it is shown that a good agreement is found between numerical and experimental crack patterns.



(a)

(b)

Figure 10: Crack pattern of the glass beam strengthened with GFRP: (a) all micro-cracks are shown; (b) only the active cracks are depicted.

Figure 11: Beam crack pattern [3].

6 CONCLUSIONS

The characterization of the bond behavior between glass and GFRP is achieved by the quantification of the relevant material properties under mode-II fracture, namely the shear stiffness, the cohesion and the mode-II fracture energy.

A parametric study is performed to approximate the experimental results obtained from testing double lap joints in tension.

The elastic behavior of the bond law is found to be determinant in accordance to the extreme brittle behavior exhibited by structures involving these materials. A value of 500MPa is proposed for the elastic shear stiffness. The cohesion presents high values when compared to the usual values adopted for CFRP-epoxy-concrete interfaces. From the first shear test, it is clear that the cohesion should be higher than 19MPa. In fact, from the results obtained with the bending model, a cohesion value of 23MPa is found appropriate.

The fracture energy in mode-II plays a less important role when compared to the bond between concrete and CFRP. The adopted value for G_F^{II} in this study is 0.01N/mm.

Using the parameters mentioned above to model the glass beam strengthened with GFRP, it is possible to observe a very good agreement between the numerical and experimental results, both in the load-displacement curves and in the crack patterns. As a consequence, it seems that a good approximation for the referred parameters has been achieved. However, more experimental and numerical tests are needed to support these conclusions.

Considering the high non-linearity and brittleness of the studied behavior, it is possible to conclude that the use of a non-iterative energy based method has proved extremely efficient and valuable, without which it would have been impossible to obtain these results.

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