Assessing the embedded length of epoxy-bonded carbon laminates by pull-out bending tests

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ABSTRACT: To evaluate the embedded length of epoxy-bonded fibre carbon laminates into concrete, pull-out bending tests were carried out. The laminates were embedded into concrete in order to prevent the phenomenon of peeling and to add extra protection against fire, therefore mobilising the potential of reinforcement of this composite material, with high tensile strength and stiffness. The bond-slip relationship obtained at the concrete-laminate interface can be used to define the corresponding constitutive law. This work describes the tests that were performed, and discusses the results obtained in the preliminary experimental program carried out.

1 INTRODUCTION

In Portugal the seismic loading was introduced regularly into the design practice of Civil Engineers only after the seventies. Therefore, a significant number of buildings designed before the seventies may suffer severe damages if a significantly intense earthquake occurs. Apart from these buildings, there are others showing several types of damages, due to design inaccuracies, overloading, unexpected corrosive agents, etc. Insufficiency of capacity on concrete columns is a subject of great concern, since failure of a column may induce a catastrophic building failure.

Before the nineties, concrete columns were retrofitted with steel devices, or by encasing the columns with added reinforced concrete. This kind of reinforcing technique modifies quite significantly the cross-sectional areas of the columns, is very large time consuming to apply and is aesthetically questionable.

Owing to their high strength and stiffness-to-weight ratios, corrosion resistance, potentially high durability and easy application, carbon fibre composite materials are increasingly replacing the steel reinforcing systems in the repair and strengthening of concrete elements (ACI 1993). Recently, carbon composite (CFRP) laminates with a cross section of $9.6\times1.4\ \text{mm}^2$ were embedded into reinforced concrete columns to increase their load bearing capacity when submitted to bending (Barros et al. 2000). This type of reinforcement combines the benefits of fast and easy application with the increasingly reduction on the costs of the reinforcing composite material. Besides, the phenomenon of peeling (Rostasy 1998) was precluded, allowing the full mobilization of the CFRP laminate tensile strength (Ferreira 2001). The resistance to fire is inherently increased, since the embedded of the laminate provides additional protection. However, the concrete confinement and the energy dissipated are not enhanced by the using of this reinforcing technique (Barros et al. 2001), which is a serious drawback for columns submitted to the seismic loading.

To overcome this problem, the reinforcing technique schematically represented in Figure 1 will be studied, constituting the last phase of a research pro-

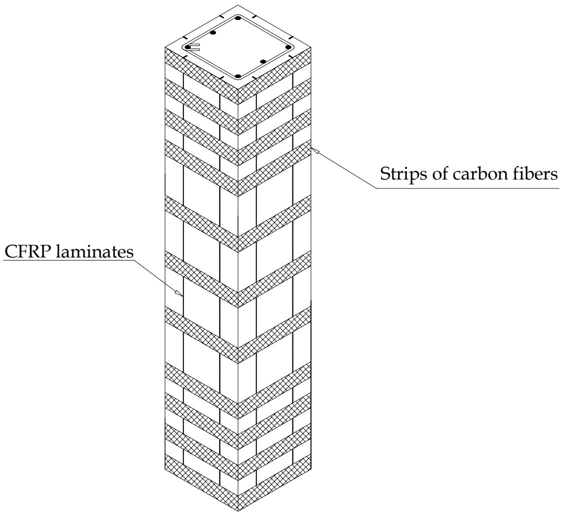


Figure 1. Reinforcing technique for concrete columns.

ject currently under way. The strips of carbon fibres enhance significantly the shear strength and the concrete confinement. Due to the arch effect developed between the strips of carbon fibres (see Figure 2), the concrete confinement provided by this reinforcing solution might be only slightly lower than the one introduced by the full column wrapping, as long as the *s* and *b* values will be correctly evaluated. The strips of carbon sheets reduce the buckling length of the carbon laminates, increasing the efficiency of the latter.

On the other hand, efficiency of the carbon laminates is greatly dependent on its embedded length into concrete, which, as maximum as possible, should be enough to mobilize the tensile strength of the CFRP laminates without occurring the shear/debonding failure. To evaluate the influence of the embedded length of the CFRP laminates into concrete elements, pull-out bending tests were carried out. From the data obtained in these tests the bond (τ)-slip (s) constitutive law to be adopted between the CFRP laminate and the concrete can be estimated.

In the present paper the pull-out bending tests will be presented, and the corresponding results will be discussed. For assessing the behaviour of the materials intervening in the pull-out bending specimens, compression, bending and tensile tests were also performed. The results obtained were analysed.

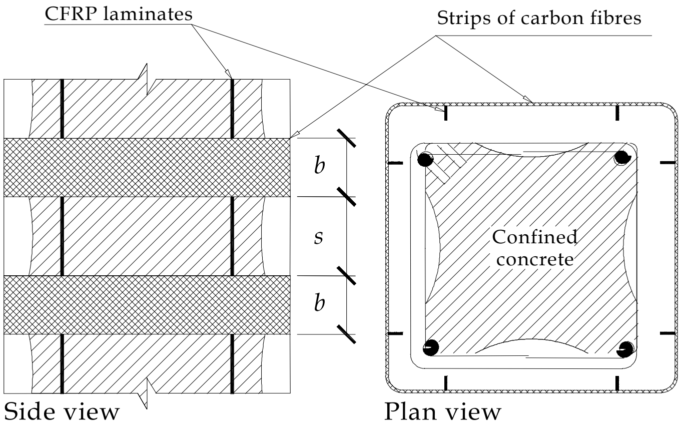


Figure 2. Arch effect provided by the strips of carbon fibres.

2 MATERIALS

2.1 *Concrete*

A concrete class C30/37 (CEB-FIP Model Code 1990) was used for the specimens. Table 1 includes the mix composition of the concrete. To evaluate the workability of the concrete mix slump and VB tests were carried out, with the following results: 85 mm in the slump test and 3 s in the VB test.

Table 1. Concrete mix composition of the specimens.

Component	Content kg/m^3
Sand (0-5 mm)	664
Aggregates (5-15 mm)	1011
Cement	400
Water	200

Compressive tests performed on cylinders (100 mm diameter and 300 mm height) and three-point bending tests with notched beams (RILEM 1985, Barros 1995) were carried out for evaluation of the concrete properties, as documented in Figures 3 and 4. A strength in compression equal to 40.3±1.28 MPa, a flexural tensile strength equal to 3.4±0.30 MPa and a fracture energy equal to 0.140±0.002 N/mm were obtained.

Figure 3. Compressive test.

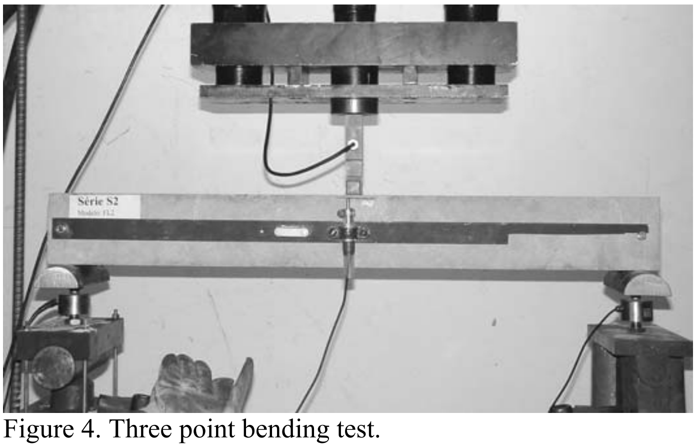


Figure 4. Three point bending test.

2.2 *CFRP laminates*

The CFRP laminates, with a width of 9.59±0.09 mm and a thickness of 1.45±0.005 mm (average values of 15 measures) were provided in rolls. To evaluate the corresponding tensile strength and Young modulus, uniaxial tensile tests were carried out in a servo-controlled test machine (Instron, series 4208), according to the recommendations of ISO 527-5:1997. The overall length was 250 mm, and the distance between grips was 136 mm (see Figure 5).

At the extremities of each specimen, and in both faces, extra CFRP laminate strips were provided to avoid premature ruptures at this location. The displacement rate measured at the controller displacement transducer was 2 mm/min. Strains were measured by means of a 50 mm measuring length clip-gauge, whereas forces were registered from a 100 kN load cell with an accuracy less than 0.1%. From these tests a Young modulus equal to 153 MPa and a tensile strength equal to 1741 MPa were obtained. Figure 6 shows the typical failure mode observed in the tensile tests.

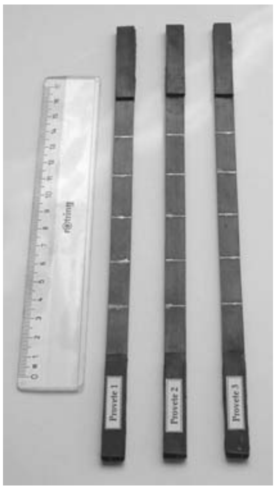


Figure 5. Tensile specimens of CFRP laminates.

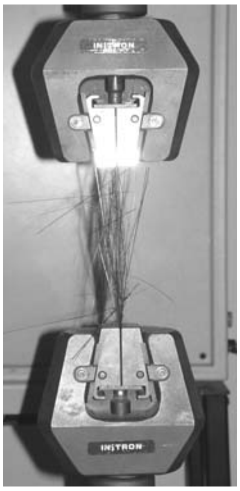


Figure 6. Typical failure mode in the uniaxial tensile tests.

2.3 *Adhesive epoxy compound*

The fixing of the CFRP laminate onto the concrete was performed with an Articol epoxy compound (Biu Internacional 2000), made up of two parts of an epoxy adhesive and one part of a hardening component (proportions in weight).

For assessing the tensile behaviour of the epoxy adhesive, five specimens, depicted in Figure 7, were tested by using the same equipment and measurement devices described for the uniaxial tensile tests performed for the CFRP laminates. These tests were carried out according to the recommendations of ISO 527-3:1997. To increase accuracy in the measurement of the forces, a load cell with 5 kN maximum load bearing capacity was used.

Figure 8 shows the uniaxial stress-strain curve obtained in the tests performed. With an exception for the specimen number 4, the set of specimens exhibited similar uniaxial stress-strain curves. However, in what concerns the tensile strength the differences are significant, which may be related to the spurious voids observed in the fracture surfaces (see Figure 9). In the fracture surface of specimen number 4 imperfections reduced solely to micro-voids, whereas in the fracture surfaces of the other specimens voids with considerable sizes were observed (see Figure 9). A Young modulus equal to 5.09±0.59 GPa was obtained for the adhesive epoxy compound.

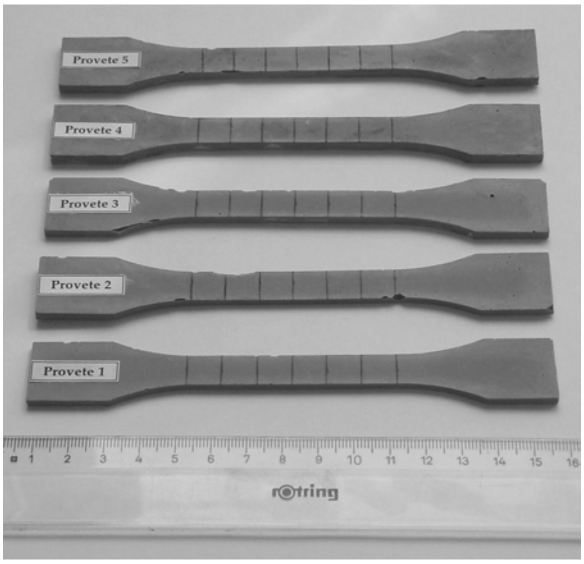


Figure 7. Tensile specimens of adhesive epoxy compound.

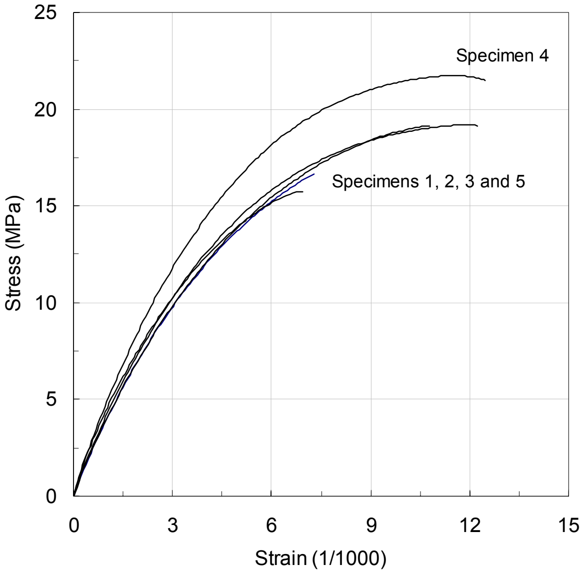


Figure 8. Tensile stress-strain curves for the epoxy adhesive specimens.

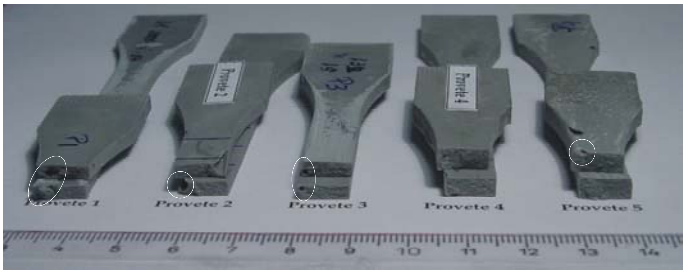


Figure 9. Voids on the fracture surfaces of the epoxy adhesive specimens.

3 EXPERIMENTAL PROGRAM

3.1 *Introduction*

The main purposes of the present test campaign are:

- To evaluate the critical embedded length of carbon laminates, which is assumed as the anchorage length required for mobilizing the ultimate tensile strength of the CFRP laminate;
- To obtain the relationships between the bond stress and the slip displacement for embedded lengths less than the critical one;
- To study the performance of the interface between the CFRP laminate and the concrete under cyclic load conditions, and for different load levels with respect to the ultimate strength of the specimen.

The idealization of the test was based on the beam test proposed by RILEM (1982) for assessing the bond characteristics of conventional steel rebars. Figure 10 shows the layout of this test: the CFRP laminate is fully embedded into the concrete block B, whereas partially embedded into block A along the embedded length, l_b, one of the parameters to be studied. The laminate, with a cross section of 9.59×1.45 mm^2, is inlaid into a saw cut of 15 mm depth and 5 mm width performed on the bottom face of the beam. The CFRP laminate is fixed onto the concrete with the epoxy described in section 2.3. At the centre, the concrete blocks A and B are interconnected by the CFRP laminate (bottom) and by a steel hinged device (top).

Table 2 resumes the test campaign of the present research plan. It is composed by six series of three specimens, each of the latter referenced by indices *a*, *b* and *c*. Three embedded lengths $k_1\phi$, $k_2\phi$ and $k_3\phi$ were considered, with ϕ denoting the diameter of an equivalent circular bar with the same area as the cross sectional area of the CFRP laminate (in the present situation $\phi = \sqrt{4 \times 9.59 \times 1.45/\pi} = 4.21\,\text{mm}$). Nine monotonic and nine cyclic tests compose the experimental research program.

Table 2. Tests performed during the research program.

Embedded length (l_b)	Monotonic tests (M)	Cyclic tests (C)
$k_1\phi$	BS*j*_$k_1\phi$_M	BS*j*_$k_1\phi$_C
$k_2\phi$	BS*j*_$k_2\phi$_M	BS*j*_$k_2\phi$_C
$k_3\phi$	BS*j*_$k_3\phi$_M	BS*j*_$k_3\phi$_C

j = *a*, *b* or *c*.

To define the embedded length corresponding to the mobilization of the tensile strength of the CFRP laminate (i.e., the values of k_1, k_2 and k_3), preliminary tests were carried out. In the present work values of 20, 25 and 30 were assumed for k_1, k_2 and k_3, respectively.

3.2 *Manufacture of the specimens and measuring devices*

After casting specimens were placed into a curing room; 24h later the specimens were demolded and immersed into water. At the age of 20 days the specimens were removed from the water, and the saw cuts were made in the specimens for the pull-out bending tests, as well as in the specimens for assessing the concrete properties through the three-point bending tests. Four days later, the CFRP laminates were glued onto the concrete saw cuts with the epoxy adhesive, the properties of which were already presented in section 2.3. Three days later, i.e., at the concrete age of 28 days, the compressive tests, the three-point bending tests and the pull-out bending tests were carried out.

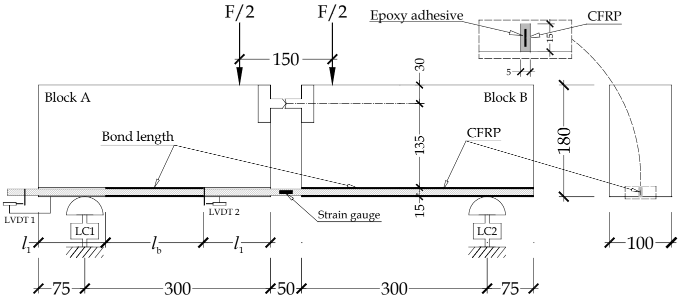
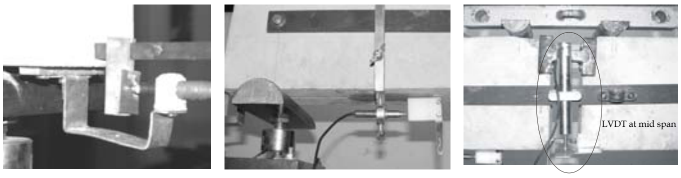


Figure 10. Pull-out bending test specimen and measurement devices.

For measuring the slip displacement two LVDTs, placed according to the arrangement illustrated in Figures 10 and 11 (LVDT 1 and LVDT 2) were used. Strains in the CFRP laminate were assessed with a strain-gauge glued onto the CFRP laminate at the specimen mid-span. A LVDT placed at the specimen mid-span was used for controlling the test (see Figure 11(c)), to be performed at a displacement rate of 15 μm/s. Forces were measured through the load cells LC 1 and LC 2, placed at the supports of the specimen (see Figure 10 and 11), each one with a maximum load bearing capacity equal to 50 kN.



(a) (b) (c)

Figure 11. LVDT 1 (a), LVDT 2 (b) and LVDT for controlling the test (c).

3.3 Pull-out bending test results

The first monotonic pull-out bending test was carried out with a 25ϕ embedded length. In this test a shear failure mode occurred (see Figure 12), owing to the limited shear strength of concrete at the age of 14 days, the age at which the test was performed. In order to make good use of the remainder pull-out bending specimens, already manufactured, it was then decided to glue carbon sheets onto the lateral faces of the concrete blocks, to reduce the risk of a shear failure mode to occur (see Figure 13).

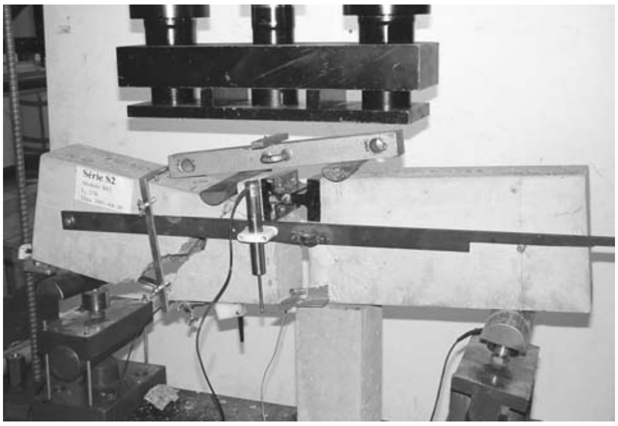


Figure 12. Shear failure mode.

Figure 13. Carbon sheets to increase the shear strength of the specimen.

Figure 14 reproduces the axial stress-strain curve obtained in the CFRP laminate after this reinforcing technique against shear. Stresses were evaluated from the forces registered at the load cell LC 1 (see Figure 10), and taking into consideration that at mid-span the distance between the centre of the steel hinge and the axis of the CFRP laminate is 142.5 mm. Analysing the stress-strain curve reproduced in Figure 14 it is possible to observe that the maximum stress in the CFRP laminate is slightly greater than the tensile strength obtained in the uniaxial tests (see section 2.2), which is probably due to some inaccuracy on the estimation of the internal arm at mid-span. Apart from this fact, the obtained stress-strain curve is practically linear, and the maximum stress registered at the CFRP laminate is similar to the peak strength of 2000 MPa indicated by the manufacturer, which means that for this embedded length the ultimate tensile strength of the CFRP laminate is mobilized. The failure of the CFRP laminate was accompanied by the shear failure of one of the concrete blocks. Furthermore, according to Figure 14 the stress-strain response becomes stiffer as the embedded length is increased. For an embedded length of 20ϕ the slope of the stress-strain curve is a little bit higher than the Young modulus specified by the manufacturer for this composite, indicating such embedded length to be the threshold below which the tensile strength of the CFRP will not be mobilised.

The obtained relationships between the bond stresses and the slip displacements are reproduced in Figure 15. Bond stresses were computed as the ratio between the forces in the CFRP laminate and its contact area with the concrete (i.e., for l_b=20ϕ the contact area is 20×ϕ×(2×9.59+1.45)). The slip displacement was evaluated as the difference between the LVDT 2 and the LVDT 1 measurements (see Figure 10). The obtained curves depicted in Figure 15 are nonlinear for practically the entire range of measurements, putting into evidence that the epoxy adhesive performs nonlinearly under shear, analogously to what was observed in section 2.3 under uniaxial tensile testing.

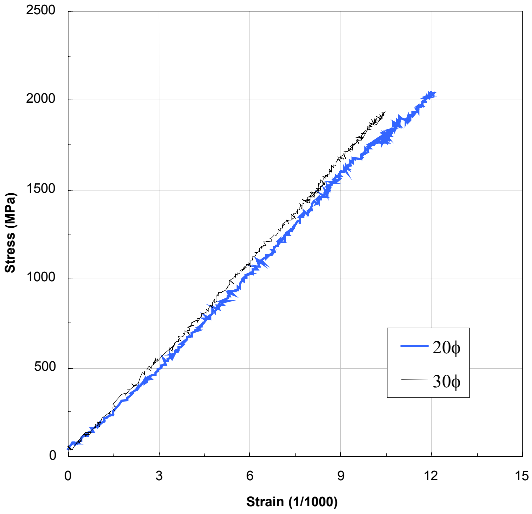


Figure 14. Stress-strain relationship on the CFRP laminate.

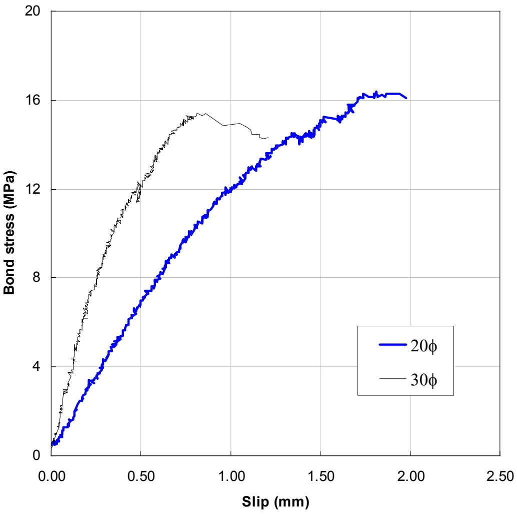


Figure 15. Bond stress-slip displacement curves.

The peak bond stresses observed in Figure 15 are much superior than the usually bond strengths reported for reinforcing techniques based on gluing CFRP laminates onto the external concrete surfaces (Juvandes, 1999), which is an indicator of the improved efficiency of the reinforcing technique proposed in the present work, consisting in inlaying the CFRP laminates into saw cuts.

4 CONCLUSIONS

In previous works a reinforcing technique was proposed, based on the idea that the efficiency of CFRP laminates would be improved by inlaying them into saw cuts made on the concrete cover of the elements to be reinforced.

For safety and economical reasons it is necessary to assess the embedded length of these CFRP laminates, namely the one that assures mobilisation of the carbon fibres tensile strength. To accomplish such a goal a research program is presently under way, within which a series of pull-out bending tests are being performed. From the preliminary results already obtained the following conclusions may be advanced:

- A special care must be devoted to the preparation of the epoxy adhesive, since its tensile strength depends crucially on the voids that can form on its microstructure;
- The bond strength obtained with the proposed technique is much higher than the bond strength reported for the techniques based on gluing CFRP laminates onto the faces of the concrete elements to be reinforced, indicating the former to be a more efficient reinforcing technique;
- For the laminates used in this research plan the embedded length required to mobilize its tensile strength is somewhat below 20ϕ, with ϕ being the equivalent diameter of the cross section of the CFRP laminate.

The results of the forthcoming tests will be used for defining a constitutive law suitable for reproducing the relationship between the bond stress and the slip displacement, necessary for simulating the behaviour of the interface between the CFRP laminates and the concrete.

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