STRENGTHENING CFRP CHALLENGE at UM

Competition for the prediction of the behaviour of a CFRP strengthened reinforced concrete beam

SC@UM

CHARACTERISTICS OF THE MATERIALS

Contents

1. Introduction

This document provides a brief description of the materials used in the production of the reinforced concrete T-beams, which are the object of this competition. The T-beams were cast on job-site and cured at open air, remaining exposed to the weather. During the first week and especially in the first three days the weather was rainy. The temperature varied approximately between 6ºC (lowest at night) and 16ºC (during the day). The concrete mixture was composed of Portland cement, sand, limestone gravel, water and super-plasticizer. The maximum aggregate size was approximately 15 mm. The considerable variability and indeterminacy of all the parameters involved in this experiment meet the spirit of this competition, by simulating the uncertainty typically encountered in real cases of structural strengthening interventions.

a. b. c. d.

Figure 1. Verification of the dimensions and geometry of the mould (a. and b.), spacers employed to guarantee the concrete cover (c.) and verification of the positioning of the reinforcing bars (d.).

Before casting, the geometry of the moulds, the positioning of the reinforcement and all concrete covers were verified (Figure 1). A maximum deviation of +/- 1 mm between the final geometry and the initial drawings was found. The positioning of all reinforcement bars was also checked and a maximum deviation relatively to the drawings of +/- 2 mm was found. Specific plastic reinforcement spacers were employed to guarantee the predefined concrete covers during casting. The file ***Tbeam.pdf*** details the final geometry of all relevant elements.

In the following sections the main properties of the concrete matrix, the steel reinforcement, the CFRP laminates and the adhesive are described. In addition, to favour the development and differentiate the more refined models and their capability to consider the entire loading history of the beam element, the load-displacement response obtained while imposing the serviceability conditions (pre-loading) to the T-beam are also presented.

2. Concrete

Twelve concrete cylinders were cast and cured in the same conditions as the T-beams. Eight of these cylinders were tested at 190 hours (four cylinders) and at 28 days (four cylinders) after casting. The remaining 4 cylinders will be tested at 90 days, simultaneously with the final testing of the CFRP strengthened T-beam until failure. As shown in Figure 2.a, the cylinder specimens are in direct contact with the upper and lower steel plates, therefore some degree of transverse confinement at the top and bottom ends of the specimen should be considered. In Figure 2 the test setup used to determine the Young's modulus is shown. The prescriptions of [1,2] were adopted. Initially one of the cylinders was used to estimate the compressive strength of the concrete. Afterwards, each of the three cylinders was first used to determine the Young's modulus [1,2] and then used to characterise the entire load-displacement response, including the post-peak stage, according to [3]. The results obtained at 7 and 28 days after casting are presented subsequently in sections 2.1 and 2.2.

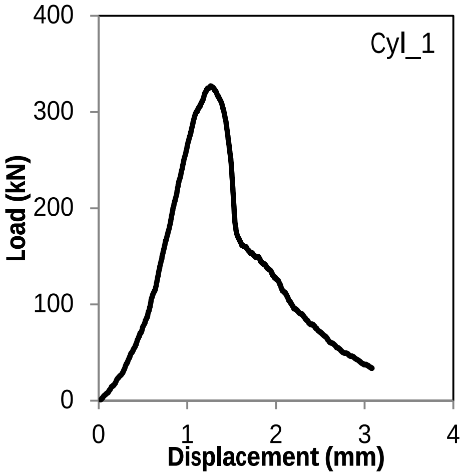
a. b.

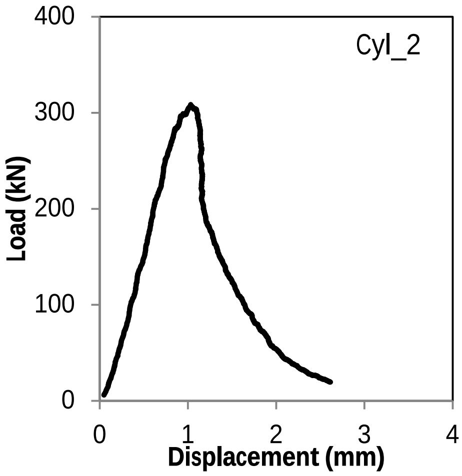
Figure 2. Compressive testing: a. determination of the overall load-displacement response; b. determination of the Young's modulus .

2.1. Compressive behaviour at 190 hours:

Specimen	dimensions (mm)	E_c (GPa)	f_{cu} (MPa)
Cyl_1	150 x 300	26.09	18.52
Cyl_2	150 x 300	29.02	17.45
Cyl_3	150 x 300	24.71	18.68
X_m	-	26.61	18.22
CoV	-	8.3%	3.7%

Note: E_c = Concrete Young's modulus; f_{cu} = concrete compressive strength; X_m = average value; ***CoV*** = coefficient of variation.





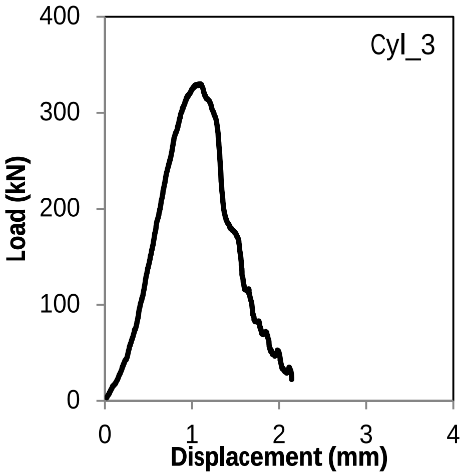
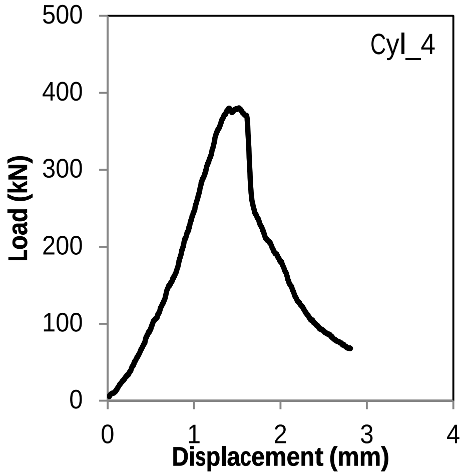


Figure 3. Young's modulus and compressive load-displacement response obtained for the three cylinder specimens tested at 190 hours after casting.

2.2. Compressive behaviour at 28 days:

Specimen	dimensions (mm)	E_c (GPa)	f_{cu} (MPa)
Cyl_4	150 x 300	38.40	21.52
Cyl_5	150 x 300	34.52	26.06
Cyl_6	150 x 300	34.39	25.95
X_m	-	35.77	24.51
CoV	-	6.4%	10.6%

Note: E_c = Concrete Young's modulus; f_{cu} = concrete compressive strength; X_m = average value; ***CoV*** = coefficient of variation.



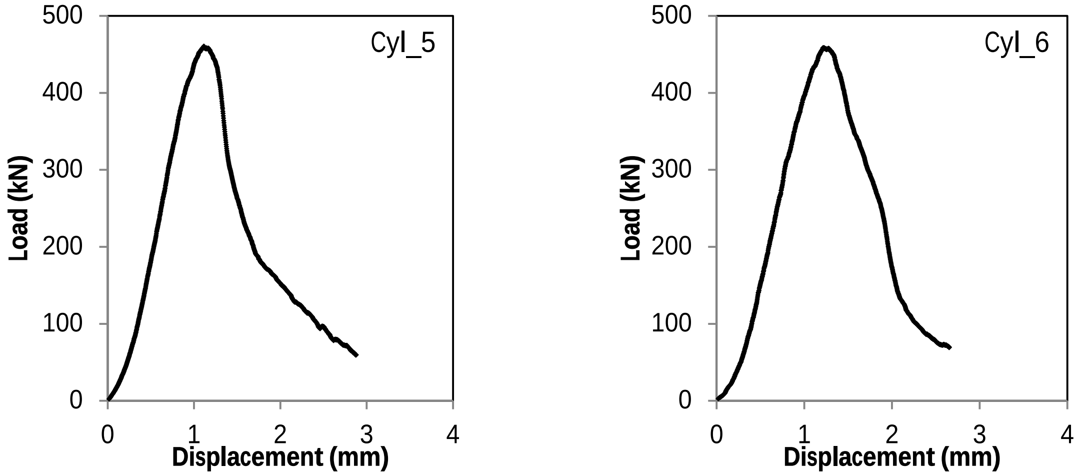


Figure 4. Young's modulus and compressive load-displacement response obtained for the three cylinder specimens tested at 28 days after casting.

3. Steel

The steel reinforcement of the T-beam was assembled and 4 samples of each type of steel bar were collected. Subsequently, these steel bar specimens were tested in direct tension at an increasing tensile load with the rate of approximately 0.25 kN/s (for the 6 mm steel bars), 0.70kN/s (for the 10 mm steel bars) and 2.0 kN/s (for the 16 mm steel bars). The entire loading sequences took approximately 80 s.
As shown in Figure 5, one clip gauge was used to measure the deformation of the steel bar during the initial stage of the loading sequence. The purpose was to obtain the net deformation of the steel bars, that is, the deformation free from the influence of the deformation of the loading frame and of the slippage occurring at the top and bottom clamped ends of the bars during testing. These results were subsequently used to estimate the entire tensile stress-strain response and the Young's modulus of all steel bars. The testing procedures followed the prescriptions of [4,5] The dimensions of all steel bars are summarized on Table 1.

Table 1. Geometry of the steel bar specimens tested.

f 6 (diameter = 6 mm)		f 10 (diameter = 10 mm)		f 16 (diameter = 16 mm)	
Specimen	Length (mm)	Specimen	Length (mm)	Specimen	Length (mm)
6_1	603	10_1	597	16_1	613
6_2	605	10_2	600	16_2	611
6_3	605	10_3	601	16_3	606
6_4	605	10_4	604	16_4	618

Figure 5. Setup of the direct tension tests in the steel bars. One clip gauge (gauge length = 50 mm) was used to measure the deformation of the steel bars in the early stage of the loading sequence.

In the following sections 3.1 to 3.3 the entire tensile stress-strain responses of the steel bar specimens are presented in Figures 6 to 8. In Tables 2 to 4 the main results are summarised. The responses shown are decoupled from the effects of the deformation of the loading frame and of the slippage occurring at the bar clamped ends during testing.

3.1. Tensile behaviour of steel bars with 6 mm of diameter:

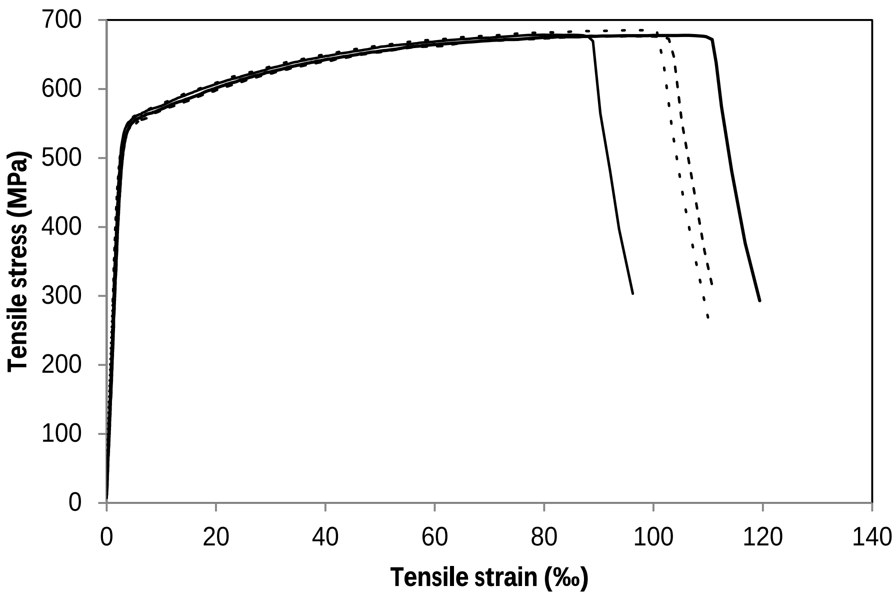


Figure 6. Tensile stress-strain response of the steel bar specimens with a diameter of 6 mm.

Table 2. Mechanical properties of the steel bar specimens with 6 mm of diameter.

Specimen	E_s (GPa)	f_{sy} (GPa)	f_{su} (GPa)
6_1	213.86	557.75	685.34
6_2	215.44	545.62	676.64
6_3	199.94	551.41	677.82
6_4	220.87	555.57	678.76
X_m	212.53	552.59	679.64
CoV	4.2%	1.0%	0.6%

Note: E_s = steel Young's modulus; f_{sy} = steel yield stress; f_{su} = steel tensile strength; X_m = average value; ***CoV*** = coefficient of variation.

3.2. Tensile behaviour of steel bars with 10 mm of diameter:

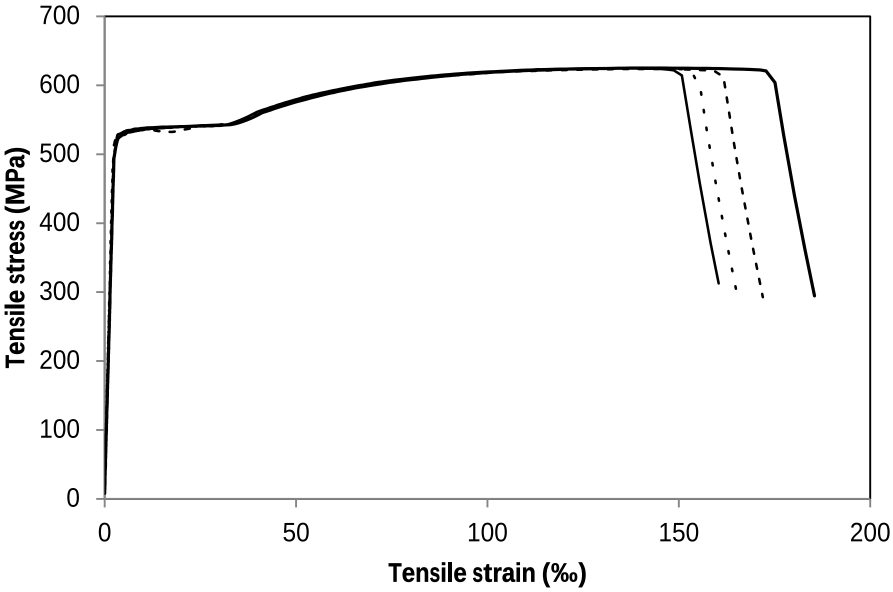


Figure 7. Tensile stress-strain response of the steel bar specimens with a diameter of 10 mm.

Table 3. Mechanical properties of the steel bar specimens with 10 mm of diameter.

Specimen	E_s (GPa)	f_{sy} (GPa)	f_{su} (GPa)
10_1	203.66	531.84	624.81
10_2	215.10	525.88	623.71
10_3	200.02	528.04	625.15
10_4	204.44	531.66	624.64
X_m	205.81	529.36	624.58
CoV	3.2%	0.5%	0.1%

Note: E_s = steel Young's modulus; f_{sy} = steel yield stress; f_{su} = steel tensile strength; X_m = average value; ***CoV*** = coefficient of variation.

3.3. Tensile behaviour of steel bars with 16 mm of diameter:

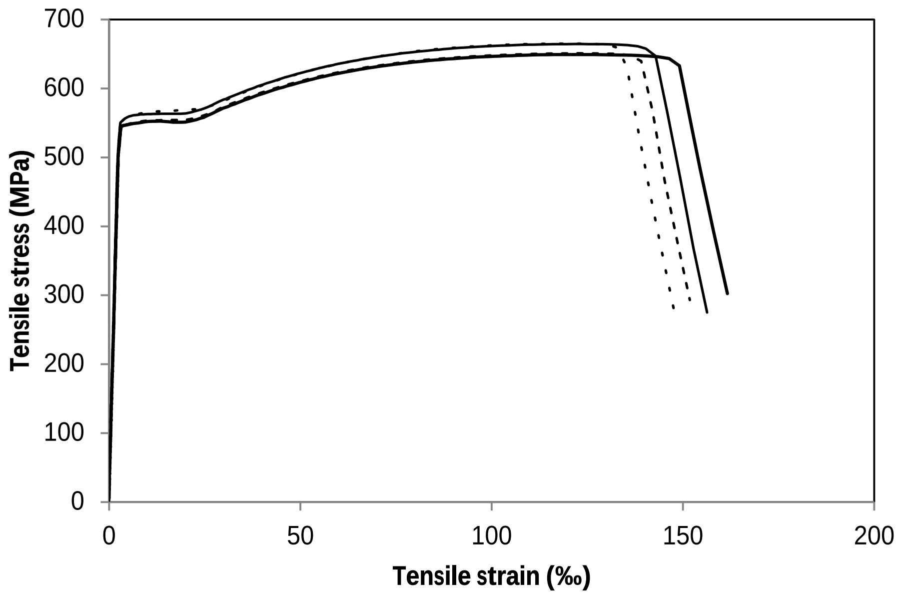


Figure 8. Tensile stress-strain response of the steel bar specimens with a diameter of 16 mm.

Table 4. Mechanical properties of the steel bar specimens with 16 mm of diameter.

Specimen	E_s (GPa)	f_{sy} (MPa)	f_{su} (MPa)
16_1	200.17	558.21	665.07
16_2	210.06	547.85	650.98
16_3	203.60	547.19	649.29
16_4	214.91	557.78	664.44
X_m	207.19	552.76	657.45
CoV	3.2%	1.1%	1.3%

Note: E_s = steel Young's modulus; f_{sy} = steel yield stress; f_{su} = steel tensile strength; X_m = average value; ***CoV*** = coefficient of variation.

4. CFRP laminates

Considering that the response of the CFRP laminates in tension is elastic until the tensile strength is reached and that failure is purely brittle, the tensile response is entirely described by the Young's modulus and the tensile strength. In Figure 9 the test setup used to characterise the tensile response of the 1.4×20 mm CFRP laminates is shown. As before, one clip-gauge (measuring length = 50 mm) was used to measure the deformation of the CFRP laminates during most of the initial stage of testing. This measurement allowed to exclude the influence of the loading frame deformation and of the slippage at the CFRP clamped ends on the axial deformation of the laminates. The experimental procedure was based on [6]. The results obtained are summarised in Table 5.

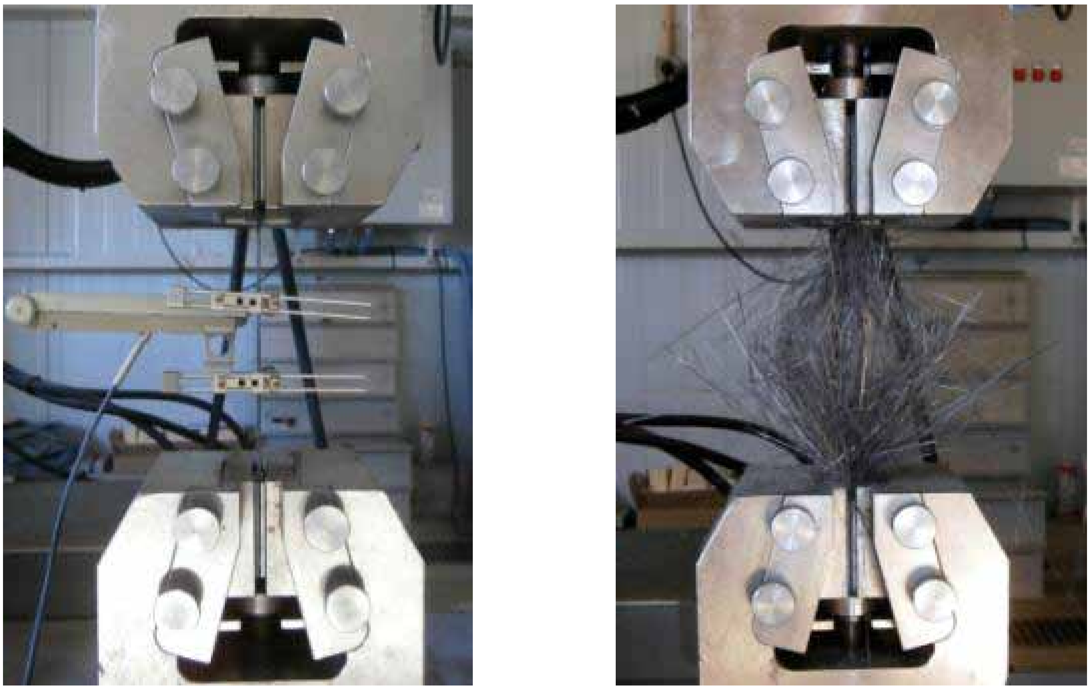


Figure 9. Test setup used to characterise the tensile response of the CFRP laminates.

Table 5. Geometrical and mechanical properties of the CFRP laminates.

Sample	Length (mm)	Young's modulus (GPa)	Tensile strength (MPa)	Strain at peak stress (‰)
C_1	250	167.04	2571.28	15.39
C_2	250	179.22	2482.19	13.85
C_3	250	175.36	2566.53	14.64
C_4	250	165.48	2549.66	15.41
C_5	250	171.04	2500.48	14.62
X_m	-	171.63	2534.03	14.78
CoV	-	3.3%	1.6%	4.4%

Note: X_m = average value; ***CoV*** = coefficient of variation.

5. Adhesive

The reference of the adhesive to be used is ***S&P Resin 220 epoxy adhesive***. The batch was not tested yet. However, previous studies by [7] to characterise the tensile response of the adhesive after curing at different temperatures have shown that no significant differences occur between the mechanical properties obtained from different batches. According to [7] the tensile tests were performed on dogbone-shaped specimens after 7 days of curing at 20ºC. The results obtained are summarised in Table 6.

Table 6. Mechanical properties of the adhesive [7].

Specimen	E_a (GPa)	f_{au} (MPa)
.1	7.65	19.87
.2	7.63	21.44
.3	7.74	22.97
.4	7.96	18.35
.5	7.77	23.63
.6	7.21	18.03
X_{min}	7.21	18.03
X_m	7.66	20.72
X_{max}	7.96	23.63
CoV	3.1%	9.9%
X_k	-	18.25

Notes: X_{min}= Minimum value; X_m= Average value; X_{max}= Maximum value; **CoV**= Coefficient of variation; X_k= Characteristic value.

6. Pre-loading of the reinforced concrete T-beam before strengthening

As described in the competition rules, to simulate the typical case of an existing structure that needs to be strengthened at a certain stage of its life cycle, the T-beam is pre-cracked and loaded up to a certain level considered equivalent to the hypothetical serviceability conditions. In the present case a deflection of L/350 at mid span was prescribed, which approximately leads to the initiation of yielding in the longitudinal reinforcement at the loading section.

In total, 5 linear variable displacement transducers (LVDTs) were used to describe the deformed shape of the T-beam during testing. The deflection at the loaded section was measured using the LVDT 3 (in blue, see Figure 10). LVDT 3 was also used to control the testing sequence, and the deformation of the beam was performed at a constant displacement rate of 20 mm/s. After reaching a deflection at mid span of *L/350* the movement of the loading cross-head was stopped for 10 minutes, and subsequently the T-beam was unloaded. The 5 LVDTs used (Figure 10) were longitudinally supported by a 5.8 m long aluminium beam (black beam in Figure 10), which in turn was fixed (pinned connection) on the lateral face of the T-beam, at the barycentre of the T-beam cross-section and in the vertical alignment of the left and right supports. The two steel rods used as supports of the T-beam had a diameter of 50 mm.

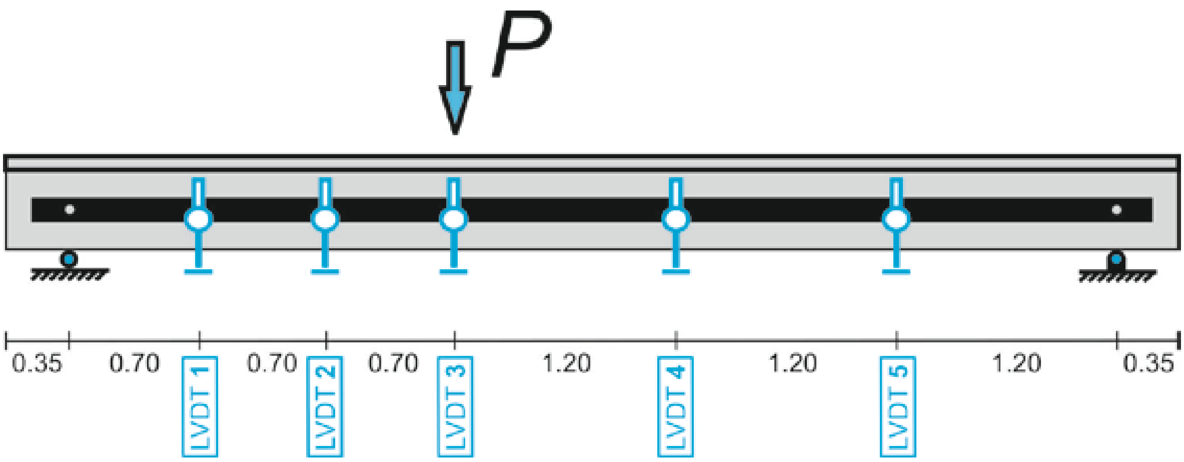


Figure 10. Test setup used to characterise the load-displacement response of the T-beam.

The overall load-displacement response obtained is shown in Figure 11. The vertical displacement refers to the data recorded from LVDT 3. All the data recorded during testing is included in the file ***Tbeam.xlsx***.

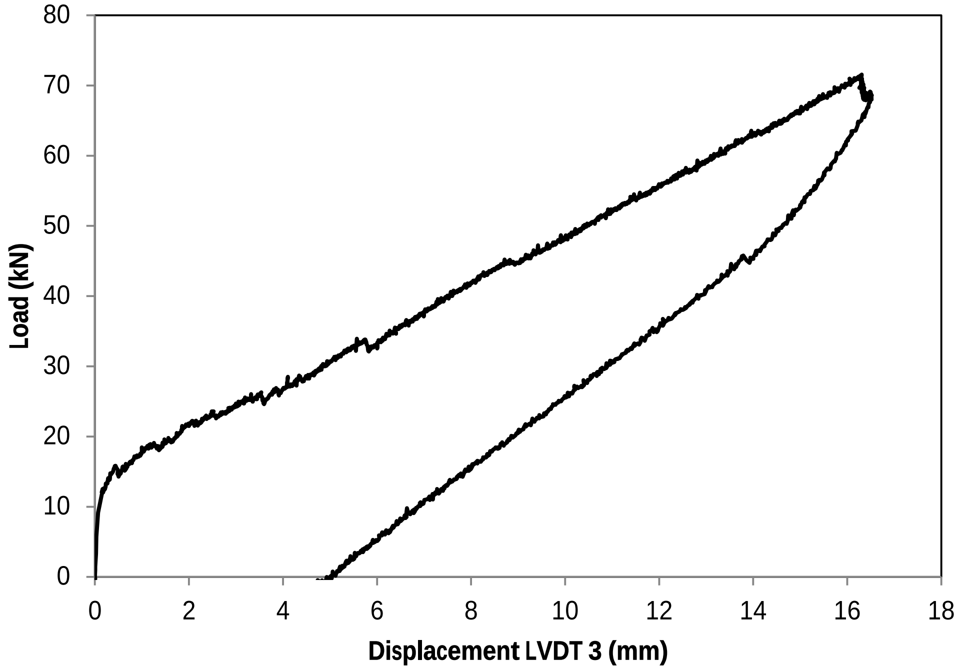


Figure 11. Overall load-displacement response of the reinforced concrete T-beam.

References:

[1] RILEM TC14-CPC8. “Modulus of elasticity of concrete in compression: final recommendation.”. Materials and Structures, 6(30): 25–7 (1975).

[2] LNEC E397-1993:1993. “Concrete - Determination of the elasticity modulus under compression.” Portuguese specification from LNEC.

[3] NP EN 12390-3:2011. “Testing hardened concrete. Part 3: Compressive strength of test specimens.” IPQ - Instituto Português da Qualidade, Caparica.

[4] ISO 15630-1. Steel for the reinforcement and prestressing of concrete - Test methods -Part 1: Reinforcing bars, wire rod and wire. International Standard, First edition, April, 2002.

[5] NP EN 10002-1:1990 “Metallic materials. Tensile testing. Part 1: method of test (at ambient temperature).” IPQ - Instituto Português da Qualidade, Caparica, 34 pp.

[6] ISO 527-5:1997. “Plastics — Determination of tensile properties — Part 5: Test conditions for unidirectional fibre-reinforced plastic composites.” International Organization for Standardization – ISO, Genève, 11 pp.

[7] Sena-Cruz, J.M.; Michels, J.; Czaderski, C.; Motavalli, M.; Castro, F. (2012) “Mechanical behavior of epoxy adhesives cured at high temperatures”, Report no. 880163, Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland, 40 pp.