CORRELATION BETWEEN BEAM AND BARCELONA TESTS FOR FRC QUALITY CONTROL FOR STRUCTURAL APPLICATIONS

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Abstract

The efficacy of the use of fibre reinforced concrete (FRC) for the production of segmented-lining tunnels is already demonstrated. Thousands of segments are fabricated for a tunnelling construction and, therefore, a good program for the quality control of the material should be established. Regularly the structural parameters of FRC are controlled by a flexural test where the limit of proportionally and residual strength are measured (EN 14651:2088). On the other hand, the Barcelona test is also able to evaluate the flexural tensile strength and it requires simpler equipment and smaller samples optimizing the quality control process. However, the constitutive equations used in the majority of the tunnel projects are based on the EN 14651:2008 parameters; therefore, this condition complicates the use of the Barcelona test to perform the quality control. In that sense, this study presents a methodology to correlate the EN 14651:2008 results with the Barcelona ones. Therefore, the fundamental parameters of the EN 14651:2008 test results (f_{LOP}, f_{R1m}, f_{R2m}, f_{R3m} and f_{R4m}) may be obtained using the values of load and energy (toughness) achieved from the Barcelona test.

Keywords: post-cracking behaviour, flexural tensile strength, correlation, beam test, Barcelona test, quality control

1. Introduction

Studies and projects carried out recently demonstrate the efficacy of using fibre reinforced concrete (FRC) for the production of segmented-lining tunnels constructed with TBM [1, 2]. The use of fibres leads to a partial or a total elimination of the conventional reinforcement leading to logistical and economic advantages [3, 4].

As thousands of segments are fabricated during these constructions, a good program of quality control of the material should be established to avoid structural failures and damages. In that sense, the control process should focused on both transitory (production, demoulding, stoking, transporting and colocation) and service stages [5]. Considering the

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use of FRC, the most important parameter to be controlled is the tensile strength, which is defined by the limit of proportionally (f_{LOP}) and the residual tensile strength (f_{Rm}) [6].

Currently, the most important test in Europe to obtain structural parameters for FRC is the one described in the European standard EN 14651:2007+A1 [7]. It is important to remark that, instructions and recommendations such as the Model Code 2010 [6] and the RILEM TC 162-TDF [8] calculate and control FRC structures based on the results of this test. However, this test presents some disadvantages such as the dimension of the samples (150x150x550 mm), their preparation (performing the notch) and the high scatter of results [9, 10]. These drawbacks complicate establishing a wide quality control of the FRC in large constructions such as tunnels. On the other hand, a new test is proposed to facilitate this aim: the Barcelona test [11]. Developed by researchers of the Universitat Poltècnica de Catalunya, this test evaluates the flexural tensile strength of the FRC and requires simpler equipment and smaller samples, facilitating and optimizing the material quality control process. However, the constitutive equations used in the majority of the current tunnel projects are based on the EN 14651:2007+A1 parameters (f_{R3m} and, f_{R1m} and f_{R4m}, for the Model Code 2010 and the RILEM TC 162-TDF, respectively). So, that condition complicates the use of the Barcelona test as a regular test for the quality control process of the FRC segments.

In that context, the objective of the present study is to demonstrate that is possible to achieve correlations between the results obtained performing the EN 14651:2007+A1 test with the Barcelona test ones. In that sense, an experimental program was followed considering one mix of FRC and the results were analysed. Finally, equations were proposed in order to obtain fundamental parameters of the EN 14651:2007+A1 test results (f_{LOP}, f_{R1m}, f_{R2m}, f_{R3m} and f_{R4m}) using the values of load and energy (toughness) obtained from the Barcelona test.

2. Methodology

2.1 Materials

2.1.1 Cement, water, aggregates and additives

One type of cement was used: CP-V ARI RS (Brazilian denomination). This was considered by project specifications due to the early strength of the concrete in order to permit rapid demoulding of the elements. The strength class of this cement entails 45 MPa at an age of 28 days.

Potable water, fine and coarse sand (0-2 and 0-4 mm, respectively) and two different limestone gravels (4-12 and 12-20 mm) were used in the mixes. Finally, a polycarboxylatic based superplasticizer was used in order to achieve the fluidity requirements established in the project.

2.1.2 Fibres

Two types of fibres were used in the same mix with different objectives: avoid explosive spalling and improving of mechanical properties. Regarding the first one, Neomatex polymeric fibres were introduced in the mixes (1.5 kg/m^3). These did not have any structural contribution and therefore, they were not considered in this study. On the other hand, structural steel fibres Dramix 80/60 BN supplied by Bekaert were used. This is a fibre widely used for FRC, which have a length (L) and an aspect ratio (L/D) equal to 60 mm and 80, respectively. The fibre content considered was 40 kg/m^3, which is a typical value for FRC applied in tunnel construction [12, 13].

2.2 Mix design

The reference mix used in this study entailed 434 kg/m^3 of cement and the water to cement ratio adopted was 0.38. The amount of fine and coarse sand and gravels 4-12 and 12-20 were 540, 279, 205 and 808 kg/m^3, respectively. The amount of superplasticizer was 0.66% by weight of cement. The water in the aggregates was taken into account to correct the amount of water added to the mix as usual in the job site. Finally, the fibres were introduced in the mixing that was carried out by five minutes in order to guarantee the homogeneity of the material.

2.3 Test methods

2.3.1 Beam test

Currently, the more accepted test in Europe to characterize the FRC post-cracking behaviour is the three-point beam test with notch as described by the European standard EN 14651:2007+A1 [7]. During the test (Fig. 1.a), the load (F) is controlled and the crack width ($CMOD$) and/or the vertical displacement (δ) are measured. In this study, the curve F - δ was obtained (Fig. 1.b). Using the Equation 1, this result may be converted to a curve F - $CMOD$, which is eventually used to achieve the loads (F_{Ri}) linked to the residual flexural tensile strength (f_{Rim}) described in the standard. These are calculated using the Equation 2, which depends on the length (L), the width (b) and the height of the sample considering the notch (h_{sp}). In this study, 4 samples were tested using an Instrom testing machine at an age of 28 days. A typical result obtained using this method is presented in Fig. 1.a.

$$\delta = 0.85 \cdot CMOD + 0.04 \qquad (1)$$

$$f_{Rim} = \frac{3 \cdot F_{Ri} \cdot L}{2 \cdot b \cdot h_{sp}} \qquad (2)$$

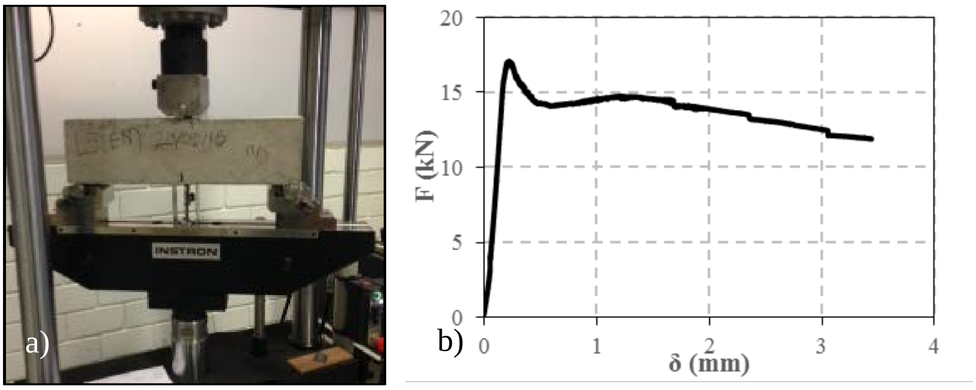

Fig. 1: Three-point beam test a) and test result b)

2.3.2 Barcelona test

An alternative test method was presented by researchers of the Universitat Politècnica de Catalunya based on the double punch test developed by Chen (1970) [14]. The Barcelona test is now a standardized method according to UNE 83515:2010 [11]. The cylindrical FRC specimen used presents a diameter and a height of 150 mm. During the test, it is located between two steel cylindrical rod punches located at the centre of the top and at the bottom surfaces as presented in Fig. 2.a). The steel rod punches have a height of 24 mm and a diameter of 37.5 mm.

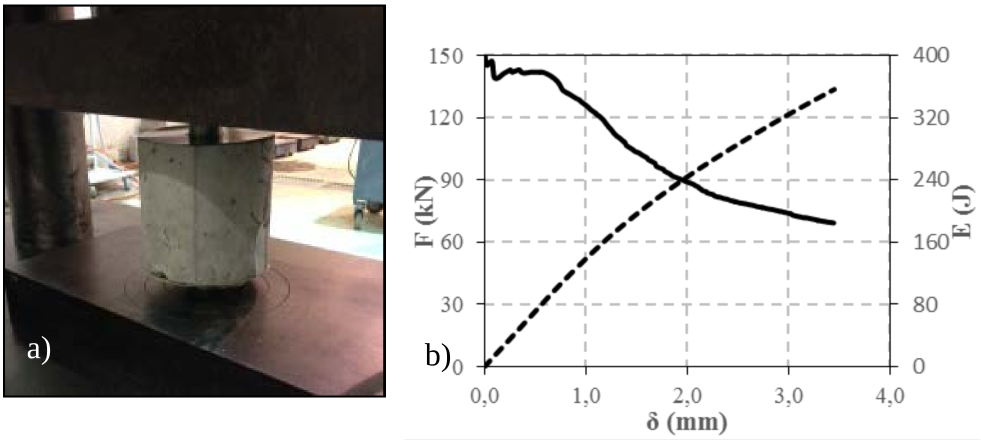

Fig. 2: Barcelona test sample a) and typical test results c)

This test is characterized by the appearance of radial cracks (from two to four). At the beginning, the test was controlled by measuring the total crack opening displacement (TCOD) with a circumferential extensometer placed at half-height of the specimen as described in the standard. The fact that a circumferential extensometer was necessary to measure the TCOD restricted the widespread use of the Barcelona test. In order to overcome such drawback, an analytical correlation between the axial displacement and the TCOD was proposed [15] leading to perform the test considering the axial displacement and eliminating the circumferential extensometer. This change facilitates performing the test rising its potential to be used for FRC quality control.

Then, considering this last setting, 4 samples were tested using a Shimazu testing machine at an age of 28 days. The curve load (F) – vertical displacement (δ) was obtained for each sample and their energies were calculated as the integral of the curve. Figure 1.b presents an example of the results obtained.

2.3.3 Comparison between the beam and the Barcelona tests

The beam test is a relatively simple test method and the use of a notch intends to lead to a significant decrease of the results variation. However, the FRC characterization by means of this method is a labour demanding process that requires important efforts of time and material. The test involves prismatic samples (150x150x500 mm) entailing 13.50 litres of concrete and a weight of about 30 kg per sample. Considering that a minimum of three samples are required to obtain reliable results, 54 litres of concrete are needed to perform a single evaluation of FRC.

On the other hand, the Barcelona test presents lower variations than the ones of the beam test [10]. Furthermore, the cylindrical samples used to perform the test are 150x150ϕ mm entailing only 2.70 litres of concrete and a weight of 6.60 kg. Hence, if three cylindrical specimens were used to perform the test, the residue produced in the process will be reduced in 80%. Therefore, the Barcelona test could also allow testing a higher number of samples leading to a more robust analysis of the data and a more representative evaluation of the average results, although this option will reduce the savings in the residue volume. This is especially important for FRC due to the inherit dispersion of the mechanical properties of the material. Finally, the Barcelona test leads to the possibility of testing extracted cores bored from the real structural elements, which could be necessary in some evaluations or other applications such as sprayed concrete [17].

3. Results and analysis

3.1 Beam and Barcelona results

The results obtained performing the beam test are presented in Table 1. This shows the values of limit of proportionality (f_{LOP}) and residual flexural tensile strength (f_{im}) considering the CMOD defined by the standard EN 14651:2007+A1. Furthermore, the table presents the average (*Av*) of the results and their variances (*CV*).

Tab.1: Results of tensile strength (f_{LOP}) and residual tensile strength (f_i) obtained (Results in MPa)

Parameter	**Sample**				***Av***	**CV (%)**
	1	**2**	**3**	**4**		
f_{LOP}	5.47	6.27	4.88	5.79	5.60	10.37
f_{R1m}	4.58	4.27	3.81	5.39	4.51	14.70
f_{R2m}	4.70	4.50	3.99	5.93	4.78	17.27
f_{R3m}	4.38	4.36	3.74	5.29	4.44	14.38
f_{R4m}	4.00	4.05	3.31	4.78	4.04	14.86

The results presented lower variation for the flexural strength (f_{LOP}) than the ones presented by the residual flexural strengths (f_{Rim}). As the first depends on the geometry and the strength class of the concrete [6], the higher variation presented by the f_{Rim} is naturally due to a variation of the fibre content of the samples and at crack as a consequence.

On the other hand, Table 2 presents the results obtained performing the Barcelona test. These are the cracking loads ($F_{BCN,cr}$), the residual loads depending on the vertical displacement ($F_{BCN,\delta}$) and the energies obtained for each residual load ($E_{BCN,\delta}$). The vertical displacements (δ) considered in this study are: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 mm. Furthermore, the table presents the average (*Av*) and the (*CV*) of the results.

As observed in the beam test results, the cracking loads ($F_{BCN,cr}$) present a lower variation demonstrating a uniformity of the geometry and the concrete used to produce de samples. Even though, a possible variation of the fibre content in the mixes entailed a higher variation of the residual loads depending on the vertical displacement ($F_{BCN,\delta}$). Then, the real fibre content, and not the one considered in project, will be take in to account in future studies.

Tab.2: Cracking loads ($F_{BCN,cr}$), residual loads ($F_{BCN,\delta}$) and energy for different residual loads ($E_{BCN,\delta}$) obtained (Load and Energy results in kN and J, respectively)

Parameter	**Sample**				***Av***	***CV*** **(%)**
	1	**2**	**3**	**4**		
$F_{BCN,cr}$	165.14	152.52	163.98	155.71	159.34	3.88
$F_{BCN,0.5}$	106.25	141.87	111.61	94.79	113.63	17.68
$F_{BCN,1.0}$	84.63	125.95	79.14	77.84	91.89	24.92
$F_{BCN,1.5}$	77.99	103.35	65.34	65.39	78.02	22.95
$F_{BCN,2.0}$	70.78	88.94	58.52	59.57	69.45	20.34
$F_{BCN,2.5}$	63.70	79.17	53.87	55.34	63.02	18.42
$F_{BCN,3.0}$	59.35	73.93	52.32	50.97	59.14	17.79
$F_{BCN,3.5}$	54.74	69.30	49.98	47.90	55.48	17.39
$E_{BCN,0.5}$	64.03	71.17	61.04	54.66	62.73	10.93
$E_{BCN,1.0}$	110.50	138.69	108.48	97.48	113.79	15.43
$E_{BCN,1.5}$	151.13	195.91	143.70	132.82	155.89	17.78
$E_{BCN,2.0}$	188.50	243.75	174.63	164.07	192.74	18.39
$E_{BCN,2.5}$	221.75	285.43	202.64	192.72	225.64	18.46
$E_{BCN,3.0}$	252.32	323.74	229.20	219.37	256.16	18.40
$E_{BCN,3.5}$	280.90	355.51	254.78	244.02	283.80	17.71

3.2 Correlation between tests

In this section, a methodology to correlate the results of the beam and the Barcelona tests is presented. This allows obtaining the fundamental parameters of the EN 14651:2007+A1 (f_{LOP}, f_{R1m}, f_{R2m}, f_{R3m} and f_{R4m}) using the results obtained from the Barcelona test. The methodology considers both the flexural tensile strength and the residual flexural tensile strength.

3.2.1 Flexural tensile strength

The concrete strength achieved when the concrete starts cracking is called flexural tensile strength ($f_{ct,fl}$). This strength is equal to the one obtained with the maximum value of load got from the beam test (F_{LOP}). Furthermore, the strength $f_{ct,fl}$ is directly related with the tensile strength of the concrete (f_{ct}) using the Equation 3 [6], which depends on the total edge of the section in metres (h = 150 mm).

$$f_{ct,fl} = f_{LOP} = f_{ct} \cdot (1.6 - h) \tag{3}$$

Considering the Spanish standard UNE 83515:2010, the strength f_{ct} is estimated performing the Barcelona test and using the Equation 4. This depends on the maximum load obtained during the test ($F_{BCN,cr}$), the punch diameter (a) and the height of the sample (H).

$$f_{ct} = \frac{4 \cdot F_{BCN,cr}}{9 \cdot \pi \cdot a \cdot H} \qquad (4)$$

Then, f_{LOP} may be related with the cracking load $F_{BCN,cr}$ obtained by means of the Barcelona tests using the Equation 5, which is the result of combining the Equation 2, the Equation 3 and the Equation 4.

$$f_{LOP} = \frac{3 \cdot F_{LOP} \cdot L}{2 \cdot b \cdot h_{sp}} = \frac{4 \cdot F_{BCN,cr}}{9 \cdot \pi \cdot a \cdot H}(1.6 - h) \qquad (5)$$

Considering the experimental values (V_{exp}) presented in Table 1 and Table 2, using the Equation 5 estimated values (V_{est}) of the tensile strength (f_{LOP}) could be calculated. In that sense, Table 3 presents these results and the relative error (E_r) between the V_{exp} and the V_{est}.

Tab.3: Estimation results and relative errors using the correlation equation

Sample	**V_{exp} (MPa)**	**V_{est} (MPa)**	**E_r (%)**
1	5.47	6.02	10.05
2	6.27	5.56	11.27
3	4.88	5.98	22.46
4	5.79	5.68	1.94

The correlation proposed for the flexural tensile strength, which is described in the standard UNE 83515:2010, presents a non-significant relative error. Only the value of the sample 3 presents an error slightly higher than 20%. The average of the relative errors is equal to 10%. Considering that the higher number of samples that would be tested in order to apply the methodology proposed, these relative error values might be reduced; therefore, the methodology would present better results.

3.2.2 Residual flexural tensile strength

To correlate the loads ($F_{BCN,\delta}$) and the energies ($E_{BCN,\delta}$) obtained with the Barcelona test and the residual tensile strength parameters of the beam test, a similar multi-parametric analysis as the one performed by the authors of this study was performed [16]. In that sense, the parameters of the Barcelona test that shown better correlation with the beam test parameters were: the load $F_{BCN,0.5}$, the cracking load ($F_{BCN,cr}$) and the energy $E_{BCN,0.5}$.

The values of the parameters were used to obtain an equation that related them through a non-linear regression using the experimental data curve fitting software (LAB Fit). The best fitting was obtained with Equation 5:

$$f_{R,i} = \frac{E_{BCN,0.5}}{\left[A + B \cdot \left(F_{BCN,0.5} \middle/ F_{BCN,cr} \right)\right]} + C \qquad (6)$$

The proposed equation considers three parameters: A, B and C. These adjust the results considering the crack width (CMOD). To calibrate these parameters a Levenberg-Marquardt algorithm was used. Parabolic laws considering the CMOD of the residual tensile strength that needs to be evaluated are used to estimate the parameters A, B and C using Equation 7, 8 and 9, respectively (Fig.3).

$$A = -1148.93 \cdot CMOD^2 + 473.72 \cdot CMOD - 2165.34 \tag{7}$$

$$B = 1889.31 \cdot CMOD^2 - 791.03 \cdot CMOD + 3617.56 \tag{8}$$

$$C = -0.14 \cdot CMOD^2 + 0.48 \cdot CMOD + 3.80 \tag{9}$$

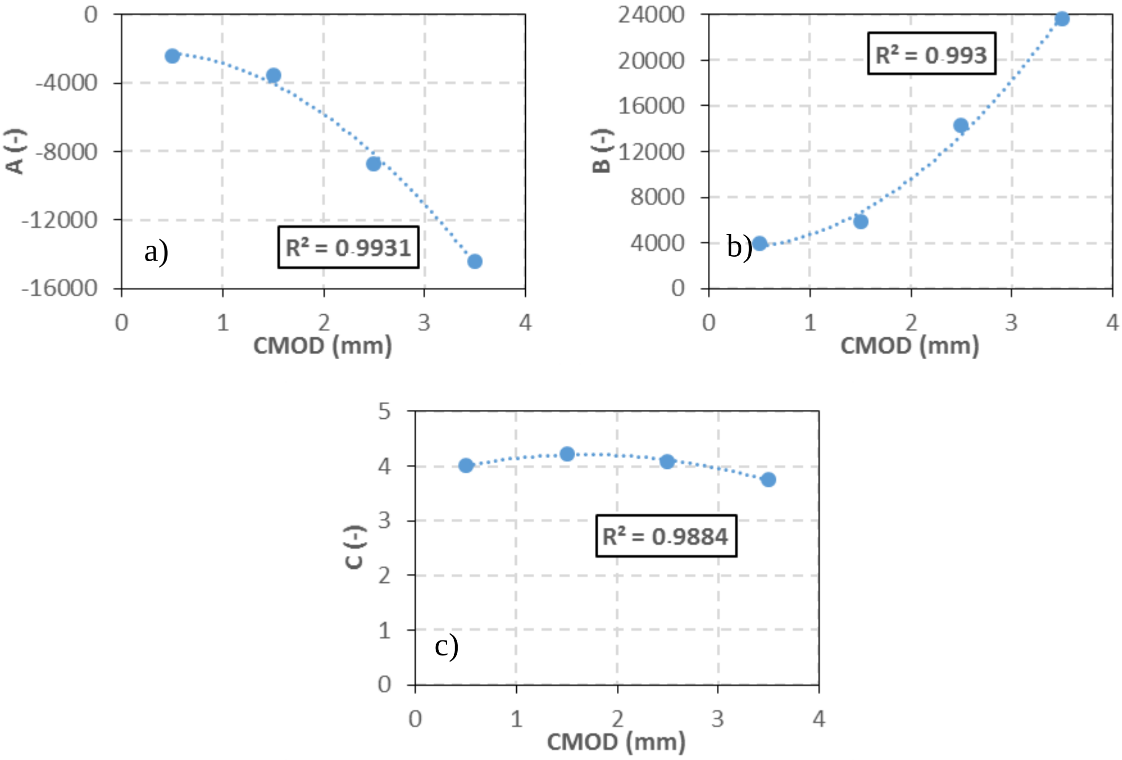

Fig. 3: Parabolic correlation of the parameters A, B and C related to the CMOD

Then, considering the results obtained in the present experimental program, the method is validated. Fig. 4 presents the relationship between the experimental and the estimated values of residual tensile strength (V_{exp} and V_{est}, respectively).

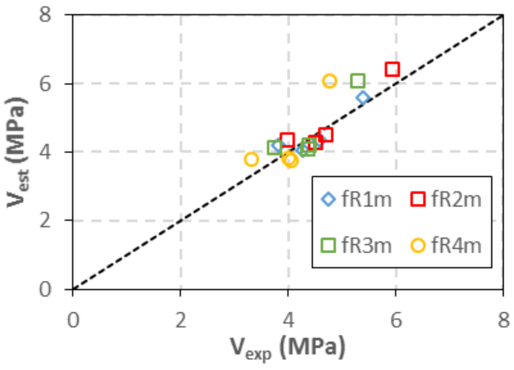

Fig. 4: Relation between V_{exp} and V_{est} using the proposed method

The correlation coefficient R^2 obtained between the V_{exp} and V_{est} was equal to 0.74. However, the R^2 value is reasonably correct considering the low number of samples tested, a minimum value of 0.85 should be guaranteed to apply the method for the quality control in a real construction. In that sense, this value is readily achievable if the number of samples is widened. So, further studies will be performed in order to verify that condition. For instance, the first results obtained during the control production of the FRC, used in an actual construction, could be used to increase the number of values analysed and re-calibrate the method presented

4. Conclusions

The following conclusions are drawn from the findings of this study:

- Regarding the results obtained performing the beam and the Barcelona tests the variation was higher than expected. This may be due to the variation of the actual volume of fibre in the sample number and the position of fibres presented in the crack. Both parameters affects the post-cracking flexural strength that shown greater variation than the presented by the peak-load that depends only on the matrix characteristics. Therefore, the method proposed could be improved considering the real fibre content in each sample using non destructive tests such as the inductive method [17].
- Based on the results and the analysis conducted, a methodology to correlate the results of the beam and the Barcelona tests was presented. Furthermore, it was validated with a short number of samples. In that sense, even though the method may be applied for different types of FRC (different concretes and different types and content of fibres), the equations and parameters presented in this study only can be used for the concrete considered.

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References

[1] di Prisco, M., Plizzari, G., Vandewalle, L. 2009 Fibre reinforced concrete: New design perspectives. In: RILEM Materials and Structures 42 (9). p. 1169-1171.

[2] Plizzari, G.A., Tiberti, G. 2006 Steel fibres as reinforcement for precast tunnel segments. In: Tunnelling and Underground Space Technology 21 (3-4). p. 438-439. Special Issue: Safety in Underground Space (CD-ROM Proceedings of the ITA-AITES 2006 World Tunnel Congress and 32nd ITA General Assembly).

[3] de la Fuente, A., Blanco, A., Pujadas, P., Aguado, A. 2012 Experiences in Barcelona with the use of fibres in segmental linings. In: Tunneling and Underground Space Technology 27 (1). p. 60-71.

[4] Hilar M., Vítek P., 2012. Experimental loading tests of steel fibre reinforced and traditionally reinforced precast concrete segments for tunnel linings. Tunnel 21(4), pp.: 54-65.

[5] Liao, L. et al., 2015. Design of FRC tunnel segments considering the ductility requirements of the Model Code 2010. Tunnelling and Underground Space and Technology. 47, 200-210.

[6] fib Bulletin 65, 2010, Model code 2010 Final Draft. fédération internationale du béton (fib), Lausanne, Switzerland.

[7] EN 14651, 2007. Test method for metallic fibered concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual).

[8] RILEM TC 162-TDF 2000 Test and design methods for steel fibre reinforced concrete: bending test, Materials and Structures, 33, pp. 3-5.

[9] Stroband, J. 1998 Standardisation of test methods for Steel Fibre Reinforced Concrete, Laboratory report no. 25.5.98-14, Delft University of Technology, Netherlands.

[10] Saludes, S. 2007 Ensayo de doble punzonamiento aplicado al hormigón reforzado con fibras. Tesina de especialidad, Universitat Politècnica de Catalunya, Barcelona.

[11] UNE 83515:2010, 2010 Hormigones con fibras. Determinación de la resistencia a fisuración, tenacidad y resistencia residual a tracción. Método Barcelona. Asociación Española de Normalización y Certificación Madrid.

[12] Kasper, T. et al. 2008 Lining design for the district heating tunnel in Copenhagen with steel fibre reinforced concrete segments. Tunnelling and Underground Space Technology 23 574–587

[13] Caratelli, A. et al. 2012 Design according to MC2010 of a fibre-reinforced concrete tunnel in Monte Lirio, Panama. Structural Concrete 13 (2012), No. 3

[14] Chen, W.F. 1970 Double punch test for tensile strength of concrete. ACI Materials Journal, 67(2), pp. 993-995.

[15] Pujadas, P. 2013 'Caracterización y diseño del hormigón reforzado con fibras plásticas'. PhD Thesis. ETSECCP. Universitat Politècnica de Catalunya. Barcelona, Spain.

[16] Galobardes, I. 2013 'Characterization and control of wet mix sprayed concrete with accelerators'. PhD Thesis. ETSECCP. Universitat Politècnica de Catalunya. Barcelona, Spain.

[17] Cavalaro, S.H.P., López, R., Torrents, J.Mª. and Aguado, A. 2015 'Improved assessment of fibres content and orientation with inductive method in SFRC'. Materials and Structures, 48, Issue 6, pp.:1859-1873. 2015. DOI: 10.1617/s11527-014-0279-6