Experimental investigation on confinement of columns with TRC: a comparison between basalt and carbon textile fabrics

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Abstract

The use of Textile Reinforced Concrete (TRC) is a promising solution in the confinement of RC columns. Based on an experimental campaign on 15 short cylindrical RC columns, this work aims to get a better understanding about the performance of basalt textile in the confinement of short RC columns by comparing basalt and carbon TRC. Furthermore, the impact of mixing short steel fibers in the TRC concrete matrix (F/TRC) is investigated. The test results show that columns confined with basalt textile and carbon textile are, in terms of strength and, to some extent, post-elastic behaviour, comparable. Basalt textile seems to be a valid alternative to carbon, without significant loss of performance, and it provides less environmental impact. Columns reinforced with F/TRC show that adding 2.5 Vol.-% of short steel fibers has a beneficial effect in the confinement.

1 Introduction

Ageing, deterioration of steel and concrete materials, change in structural layout or purpose, increase in loads, and accumulation of damage are phenomena that lead to the necessity of structural retrofit. When the intervention involves the retrofitting of Reinforced Concrete (RC) columns, jacketing is a common practice [1], [2]. The best known techniques used to retrofit columns are: reinforced concrete/mortar jacketing, steel jacketing and Fibre Reinforced Polymer (FRP) jackets [3]–[5]. Lately, the most common technique to retrofit columns is by wrapping FRP sheets around the column. The success of this technique is mainly due to the high strength to weight ratio of the material and the minimal impact on the original geometry [1], [6]. However, there are some drawbacks on the FRP, which are mainly related to the organic matrix: rather poor behaviour at high temperature and on wet surfaces and potential incompatibility with certain substrate materials [1]. More recently, also to overcome such limitations, the organic matrix was replaced by an inorganic one in combination with textile fabrics, which ultimately led to the development of a new material called Textile Reinforced Concrete (TRC). In literature TRC is also named Fabric Reinforced Cementitious Matrix (FRCM) or Textile Reinforced Mortar (TRM) [1], [7], [8].

The most common textile fabrics used in TRC retrofitting are made of carbon, glass, PBO, steel and basalt fibres. The mechanical performances and the low environmental impact of basalt fibres compared to those of the more common materials such as carbon and glass are some of the main reasons for the interest showed on this material. Basalt fibres are also characterized by good resistance in alkaline environment [9] and resistance at high temperature [10].

Recent studies investigated about the influence of admixing short fibres in the cementitious matrix of TRC reinforcement [11]–[23] leading to a new material called Fibre/Textile Reinforced Concrete (F/TRC). Compared to traditional TRC, which performances are limited by the relatively low tensile strength of the matrix, this material is capable of achieving better performances.

Application of Basalt-Textile Reinforced Concrete (B-TRC) has already been investigated on retrofitting of non-reinforced concrete columns (i.e. concrete cylinders) by Garcia et al. [11] and on masonry columns by Yilmaz et al. and Wang et al. [24], [25]. However, to the best of the Authors' knowledge, the effect on the compressive capacity of RC columns retrofitted with B-TRC and Basalt-F/TRC (B-F/TRC) has not been investigated yet. In the present work, an experimental investigation through axial compressive tests on 15 columns is carried out. The variables considered are: type of textile fabric (basalt and carbon) and presence of short steel fibres in the cementitious matrix.

2 Experimental program

2.1 Test specimens

Short cylinder columns are characterized by circular cross section with a diameter of 200 mm and a length of 675 mm. The longitudinal and transversal steel reinforcement is made by 4Ø12 rebars, and Ø8 stirrups spaced at 170 mm, respectively. In order to prevent premature failure in the load application zone two additional stirrups, spaced by 40 mm, are situated on top and on bottom of the columns. The concrete cover is 20 mm on all surfaces.

The 15 columns are distinguished according to the type of retrofitting: 3 reference columns without TRC reinforcement, 3 columns retrofitted with two layers of Carbon-Textile Reinforced Concrete (C-TRC), 3 columns retrofitted with two layers of Carbon-Fibre/Textile Reinforced Concrete (C-F/TRC), 3 columns retrofitted with two layers of B-TRC and 3 columns retrofitted with two layers of B-F/TRC. Since the columns differ only on the type of retrofitting, the ID specifies the type of retrofit: B or C indicate the material of the textile fabric (C for carbon and B for basalt), P indicates the cementitious matrix without steel fibres and Pf indicates a cementitious matrix with steel fibres. The last numbers (1,2 or 3) are to distinguish the three columns characterized by the same retrofitting. For example, the ID BP-1 indicates the first column of three identical specimens retrofitted with Basalt-TRC.

2.2 Mechanical characteristics

The reinforcement is made by a B550 B grade steel, with a characteristic yield strength of 550 MPa and a mean value 10% higher, namely 600 MPa. The concrete strength class is C20/25, and besides the cast of the columns, 150x150x150 mm cubes and 150x300 mm cylinders were cast to test the concrete compressive strength, 100x100x400 mm prisms to test the elastic modulus and 100x200 mm cylinders to determine the concrete tensile strength through a splitting tensile test. The average compressive cube strength obtained from tests is 32,41 MPa (standard deviation 1,1 MPa). From tests on cylinders, the average compressive strength is 28,1 MPa (standard deviation 0,7 MPa). From splitting tests the average tensile strength derived on concrete is 3,0 MPa (standard deviation 0,3 MPa). The average elastic modulus of the concrete is 25181,4 MPa (standard deviation 1437,8 MPa). These values of mechanical properties of the concrete were obtained by tests performed on specimens at the beginning and at the end of the test campaign, which means the age of the concrete was 132 and 206 days. The age of the concrete core and the cementitious matrix of the retrofit of the tested columns was between 139 and 190 days and between 58 and 70 days, respectively. The cementitious matrix employed in this research consisted in a fine-grained premix [26] which received a technical approval in Germany for being used to produce TRC strengthening solutions [27]. The matrix was mixed with short steel fibres with 2,5% by vol. to produce F/TRC. The short steel fibres are 5 mm long and with a diameter of 0,15 mm with an aspect ratio of 33,3. From compressive test on 100x100x100 mm cubes the average compressive strength of the TRC cementitious matrix is 103,8 MPa and 94,6 MPa with and without fibres respectively. The textile fabrics used in both TRC and F/TRC reinforcement are made of carbon [28] or basalt [29] fibres. The grid opening and the reinforcement cross section area per meter of the rovings are: 22 mm and 71 mm^2 for the carbon textile and 20 mm and 65 mm^2 for the basalt textile. The choice of these textile fabrics is mainly based on the availability in the market. The grid size was chosen also in order to allow the cementitious matrix admixed with short steel fibres to get between the rovings of the textile fabric. Mechanical performances of the TRC and F/TRC layer are obtained through uniaxial tensile tests. Three identical specimens, 15 mm thick, 120 mm wide and 600 mm long composed by one layer of textile fabric inserted in the middle of a layer of cementitious matrix, were tested for each combination of basalt and carbon textile fabric embedded in a cementitious matrix with and without short steel fibres. The tensile strength of this layer is 5,8 MPa, 4,9 MPa, 5,4 MPa and 2,9 MPa for C-F/TRC, C-TRC, B-F/TRC and B-TRC respectively.

2.3 Retrofit and test procedure

24 hours after the cast, columns and accompanying specimens were removed from their formworks. In order to improve the bond between the substrate and the strengthening material, the lateral surface of the columns was roughened via water-jetting. The top and bottom faces of the columns have been made

as parallel and smooth as possible to reduce accidental eccentricity and to increase the uniformity of the load application. To do so, a smooth and thin layer of rapid setting grain concrete was applied on the surfaces. The column retrofit procedure presented here was adopted in order to best simulate the in-situ procedure. Therefore, during all the process, columns were placed vertically on a support. The lateral surface of columns, which is covered by the retrofit layers, was sprayed with water in order to avoid that capillary absorption remove reaction water from the cementitious matrix of the TRC retrofit. The retrofit of the columns consists in the application of a layer of cementitious matrix with a thickness of 6 mm, then the textile fabric, which is assumed to be 3 mm thick, is applied to the cementitious matrix and wrapped around the column. The next step is to repeat the operation by applying another 6 mm thick layer of cementitious matrix on the textile and then continuing to wrap the textile around the cementitious matrix. Finally, a 6 mm thick layer of matrix is applied as a cover. The TRC retrofit is applied along all the height of the columns except for the last 10 mm both on top and bottom (Fig.1a, Fig.1b). This was done in order to ensure that the vertical load would not be directly applied to the TRC layers but only to the concrete core of the column. This would make the TRC reinforcement principally subjected to the lateral expansion of the RC columns induced by vertical deformation.

(a) (b)

Fig. 1 Retrofitting of a column with B-TRC (a) and detail of a B-F/TRC retrofitted column (b).

The overlap length of the textile is 150 mm and 250 mm for carbon and basalt textile fabrics, respectively. Both values are obtained by increasing the overlap length suggested by the producers by 50 mm. For every column retrofitted, additional 100x100x100 mm cubes of cementitious matrix were cast to measure the cube compressive strength and were tested the same day of the relative column. The age of the concrete core and the cementitious matrix of the columns during the test campaign was between 139 and 189 days and between 58 and 70 days, respectively.

Tests are done in displacement control, with a speed of 0,5 mm/min. The displacement of the machine is measured by two laser sensors placed in two diametrically opposed positions at the base of the test machine.

3 Results and discussion

In Figure 2 force-displacement curves of the tested columns are shown. Table 1 summarizes the following parameters: average of maximum load, average of displacement at the maximum load and average of index of inelastic displacement μ. This index is the ratio between the equivalent yielding displacement δy, and the ultimate displacement δu. Due to phenomena such as the nonlinear behaviour of materials as concrete or the possibility to have the yield of reinforcements in different positions of the structure, values of δy and δu may not be clearly distinguishable on the force-displacement curve. In this study, the equivalent yielding displacement δy corresponds to that of an equivalent elasto-plastic system, characterized by a secant stiffness at 75% of the maximum force and ultimate displacement δu as the post-peak displacement corresponding to a decrease of 20% of the maximum load as defined in [30].

From Figure 2 it is possible to observe how retrofitted columns behave differently compared to reference columns. The elastic branch of the force-displacement curve is stiffer on retrofitted columns from the beginning of the test until approximately 1 mm of axial displacement, showing an effect of the TRC and F/TRC layers from the beginning of the test. Subsequentely TRC retrofitted columns show a rapid decrease of stiffness, while F/TRC retrofitted columns showed a more gradual decrease of stiffness.

The difference, in terms of average of maximum loads, between TRC and F/TRC retrofitted columns is about 200 kN. Columns retrofitted with B-F/TRC and B-TRC reached 1352 kN and 1145 kN respectively, while on columns retrofitted with C-F/TRC and C-TRC 1368 kN and 1177 kN are reached respectively.

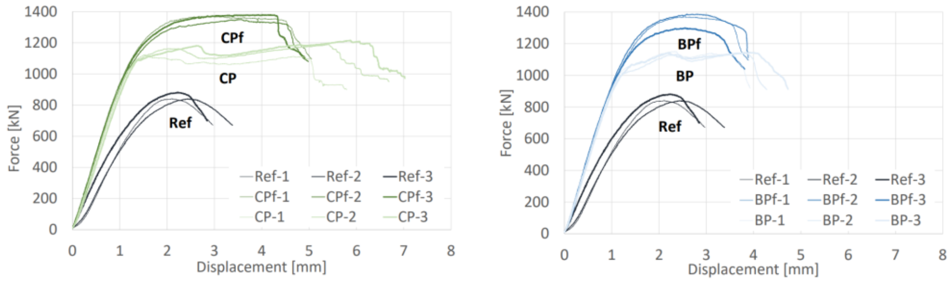

Fig. 2 Force-displacement behaviours for carbon retrofitted specimens (on the left) and basalt retrofitted specimens (on the right).

Furthermore, a different shape of the plateau is observed between TRC and F/TRC retrofitted columns. Columns with F/TRC retrofit are characterized by one load peak, while TRC retrofitted columns are characterized by two. This different behaviour could be explained by the presence of short steel fibres in the cementitious matrix which distribute more uniformly stresses around the retrofit. However, this behaviour of these TRC retrofitted columns needs to be investigated more deeply. Difference of less than 3% are observed between the average maximum load reached by columns retrofitted with carbon and basalt textile fabric in both TRC and F/TRC retrofit. Therefore, taking into account the strength and the cross-sectional ratio of basalt and carbon textile fabrics, it can be said that the contribution of the basalt fabrics to the specimens performance is comparable to that of the carbon fabrics. The retrofitting of columns affects also the index of inelastic displacement μ. In fact, μ increases of 162%, 73%, 85% and 38% for columns retrofitted with C-TRC, C-F/TRC, B-TRC and B-F/TRC respectively. Such higher values of μ for TRC retrofitted columns may be consistent with the crack pattern at failure. In fact, these columns, compared to the F/TRC retrofitted columns, present a greater number of thin cracks around the columns that may justify larger deformation before the failure. However, more investigations are needed in order to validate or contradict this hypothesis.

Table 1 Maximum load, displacement at the maximum load and ductility of the tested columns.

Column ID	Average Max Load [kN]	Average Displacement [mm]	Average μ
Ref	854,8	2,3	1,9
BP	1145,4	3,3	3,5
BPf	1352,9	2,6	2,6
CP	1177,1	4,3	4,9
CPf	1367,8	3,5	3,2

4 Analytical formulation

Through analytical expressions it is possible to estimate the maximum load F attained by the columns during the tests. For the reference columns, F is defined by the equation (1) whose first term represents the contribution of the confined core, and the second term represents the contribution of the longitudinal reinforcement.

$$F = f_{cc} \cdot (A_c - A_s) + f_{ys} \cdot A_s \tag{1}$$

Where f_{cc} is the confined concrete compressive strength, A_c is the area of the core section enclosed by the center lines of the perimeter stirrup, f_{ys} is the yield strength and A_s the area of this reinforcement.

The contribution of the concrete cover is not considered since it is assumed that it would spall off when the maximum load is reached. Consequently, the load carrying capacity of the concrete cover would not affect the maximum load *L*. In order to calculate f_{cc}, the formulations proposed by Mander, Priestley and Park [31] are used. The calculated theoretical maximum load is 830 kN, which is 2,9% lower than the average maximum load, 854,8 kN, obtained from the tests. The load capacity of the retrofitted columns is estimated by the following equation.

$$F' = f'_{cc} \cdot (A_{tot} - A_s) + f_{ys} \cdot A_s \tag{2}$$

Where *F'* is the maximum load, f'_{cc} is the concrete confined compressive strength of the retrofitted column and A_{tot} is the concrete cross section area of the inner column, including the concrete cover. From literature f'_{cc} can be estimated through the following relationship [32].

$$\frac{f'_{cc}}{f_{co}} = 1 + k\left(\frac{f_l}{f_{co}}\right)^{\alpha} \tag{3}$$

Where f_{co} is the concrete strength without confinement, f_l is the lateral pressure and k and α are numerical constants. In this work two formulations with different values of these constants are used. The first formulation, named "Th.A", is proposed in [33] for RC columns confined by FRCM and provides k=2,6 and α=2/3. The second formulation, named "Th.B", is proposed in [32] for concrete cylinders confined by basalt fibres preimpregnated with epoxy resin and then bonded with a cement-based mortar and used in [34] to estimate the compressive strength of confined masonry columns with TRC, which provides k=3,35 and α=0,85. It is important to point out that the formulation from CNR [33] makes use of design values of concrete compressive strength, while in this work values of average strength from compressive tests on 150x300 mm concrete cylinders are used. Furthermore, the value of the lateral pressure f_l is obtained with equation (4), which might differ from the expressions used in the formulations from [32], [33]. Equation (4) is obtained by the equilibrium of the half TRC subjected to internal pressure equal to f_l.

$$f_l = \frac{2 \cdot f_{TRC} \cdot t_{TRC}}{D} \tag{4}$$

Where f_{TRC} corresponds to the 85% of the ultimate strength of the TRC [35] obtained from uniaxial tensile tests on both TRC and F/TRC specimens, and t_{TRC} is the thickness of the overall TRC retrofit. It is relevant to point out that multiplying the tensile strength of the TRC by a thickness different from the one used in the uniaxial tensile test could lead to an underestimation of the TRC contribution. Results from the two formulations are reported in Table 2 which also reports in the last two columns the values of the maximum load obtained by using design values of the concrete compressive strength and the yield tensile strength in accordance with the Eurocode 2, the values in brackets represent the percentage difference between the calculated and measured values [36].

Table 2 Comparison between experimental, theoretical and design maximum load (values in kN).

Col. ID	Average Max Load	Th.A k=2,6; α=2/3	Th. B k=3,35; α=0,85	Th.A-Design k=2,6;α=2/3	Th.B-Design k=3,35; α=0,85
CPf	1367,8	1453,4 (6,3%)	1374,5 (0,5%)	874,9 (-36,0%)	839,8 (-38,6%)
CP	1177,1	1421,7 (20,8%)	1344,8 (14,2%)	850,2 (-27,8%)	813,2 (-30,9%)
BPf	1352,9	1439,3 (6,4%)	1361,2 (0,6%)	864,0 (-36,1%)	827,9 (-38,8%)
BP	1145,4	1339,9 (17,0%)	1272,4 (11,1%)	786,2 (-31,4%)	748,4 (-34,7%)

Figure 3 shows a comparison between the average maximum load of the tested columns reported in Table 2 and the maximum loads calculated with the theoretical formulations. From Table 2 and Figure 3 the formulation Th B [32] shows the lowest difference between experimental and theoretical values. This formulation is more accurate on columns retrofitted with F/TRC (CPf and BPf), with differences of 0,5% and 0,6% compared to the experimental values. The difference between theoretical and experimental values on columns retrofitted with TRC are higher and equal to 14,2% and 11,1% respectively on CP and BP specimens. This could be explained by the different behaviour of the concrete matrix with and without the short steel fibres. In fact, the columns reinforced by the concrete matrix with these fibres show a crack pattern different from that of columns with matrix without fibres. In absence of fibres, many poorly opened cracks appear at the failure, while, in the presence of fibres, fewer cracks appear. These different crack patterns outline that in the presence of the two different type of mortar different distributions of stresses and deformations arise. Results obtained with design values for concrete and steel reinforcement show an underestimation of the maximum load about 30% lower than the experimental values, which can be considered adequately on the safe side.

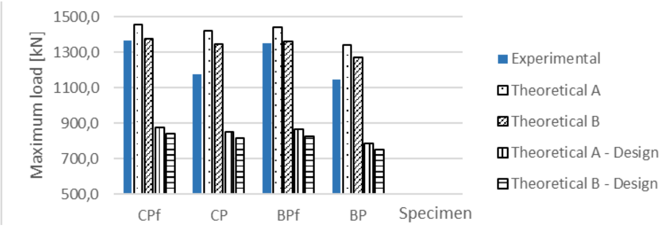

Fig. 3 Comparison of average maximum load between experimental and theoretical results.

5 Conclusions

In this work, the retrofitting of short RC columns with Textile Reinforced Concrete (TRC) and Fibre/Textile Reinforced Concrete (F/TRC) is investigated through an experimental test campaign. The variables considered herein are the type of textile fabric (carbon and basalt) and the presence of short steel fibres mixed in the cementitious matrix. A method to predict the retrofitted column strength is proposed. From the analysis of the experimental test' results and the obtained numerical predictions, the following conclusions can be drawn:

- TRC and F/TRC provide improvement in the post-elastic displacement and maximum load capacities of the columns. Increase up to 162% and 38% of the average index of inelastic displacement are observed, respectively. The increase of the average maximum load is between 34% and 38% for TRC retrofitted columns and between 58% and 60% for F/TRC retrofitted columns.
- Admixing short steel fibres in the cementitious matrix improves the performances of the retrofitted columns in terms of average maximum load. An increase of about 18% between columns retrofitted with B-F/TRC and B-TRC and about 16% between columns retrofitted with C-C/TRC and C-TRC are observed in this work.
- Basalt is a valuable alternative to carbon in retrofitting structural elements. In this work, the performance in terms of average maximum load reached by retrofitted columns differs less than 3% between basalt and carbon textile reinforcement.
- The analytical expressions used to estimate the maximum load reached by columns without retrofit (reference columns) prove to be accurate. Indeed, a difference of less than 3% is attained between experimental and theoretical values.
- The proposed equilibrium equation and the formulations “Th.A” and “Th.B” are valuable tools to estimate the maximum load of retrofitted columns. Indeed, the difference between theoretical and experimental results is lower than 1% for F/TRC retrofitted columns and 15% for TRC retrofitted colums, by using formulation “Th.B”. The difference is lower than 6,5% and 21% for F/TRC and TRC retrofitted columns, respectively, by adopting formulation “Th.A”.
- The use of design strength values for concrete and steel in the analytical expressions “Th.A” and “Th.B” lead to safe predictions of the columns load carrying capacity. Indeed, the maximum loads predicted by these formulations are between 27,8% and 38,8% lower than the experimental results.
- Formulations used in this work estimate the maximum load reached by F/TRC retrofitted columns with a better accuracy than the load reached by TRC retrofitted columns. Future studies on these analytical expressions may better investigate the influence of presence or absence of short steel fibres on the cementitious matrix.

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