Acta Polytechnica CTU Proceedings **33**:309–315, 2022
https://doi.org/10.14311/APP.2022.33.0309

INNOVATIVE STRENGTHENING OF RC COLUMNS USING A LAYER OF A FIBRE REINFORCED CONCRETE

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Abstract.

Reinforced concrete structures that are influenced by degradation, overloading, the thawing and freezing cycles, abrasive damage and corrosion of reinforcement, should be repaired or strengthened. Each of those mentioned situations lead to decreasing the load-carrying capacity of the construction. The damage of a structure or its member causes exceeding the serviceability limit states and ultimate limit states. For this reason, for further use of the structures, they have to be strengthened to increase the load-carrying capacity and to extend the remaining lifetime. A new method for strengthening the vertical members, e.g., columns, is using the fibre reinforced concrete layer and its increased tensile strength in comparison to common RC concrete. This article deals with the theoretical design of dimensioning the columns using a layer of fibre concrete around a column (wrapping). In this case, it is necessary to calculate the residual strength of fibre concrete, which is a crucial factor for the tensile strength of the element.

Keywords: Columns, experimental measurements, fibre reinforced concrete, numerical modelling, reinforced concrete, strengthening.

1. Introduction

Typical way how to strengthen the member, as the beams and columns, is e.g. using the FRP materials [1–5]. The fibre reinforced concrete (FRC) is mostly used on concrete floors [6], but recent researches are also focused on use of the FRC to strengthen columns [7, 8]. The type of fibres has a huge influence on the load-bearing capacity of the fibre reinforced concrete. Therefore, a parametric study of that effect on column strengthening is presented in the article. The theoretical calculation is experimentally and numerically verified on a group of columns. Use of the fibre reinforced concrete changes not only its load-bearing capacity, but its behaviour and the nature of failure, as well [9]. An iteration diagram is the most often used for assessment of members subjected to combination of normal force and moment like columns, which is derived from selected material (concrete, reinforcement) and geometric assumptions. The curve of the iteration diagram represents points, which are derived from the limit deformations, based on conditions of the balance of forces and deformation of the corresponding design value of the relative deformation of a material. The cross-section is stressed by the bending moment and a normal force; these forces must be in balance. The internal cross-sectional forces refer to the centre of gravity of the element. It is also assumed that the compatibility condition of relative deformation ε, depending on the used working diagrams, is fulfilled [10–12].

The design bearing capacity of the cross-section is expressed by ultimate force N_{Rd} and ultimate moment M_{Rd}:

$$N_{Rd} = F_c + \sum F_{si} \tag{1}$$

$$M_{Rd} = F_c \cdot z_c + \sum F_{si} \cdot z_{si} \tag{2}$$

where:

- F_c is the compression force in the concrete [kN],
- F_s is the tensile force in the reinforcement [kN],
- z_c is the length of the internal force distance from the centre of gravity of the cross-section to the compressive force [m],
- z_{si} is the length of the internal forces distance from the centre of gravity of the cross-section to the forces in reinforcement.

To construct an iteration diagram of a strengthened cross-section using the fibre reinforced concrete (FRC), it is necessary to know the tensile force of the fibre reinforced concrete. Since FRC has a higher tensile strength than the plain concrete, this material can be applied to strengthening the column. In the cases, where we are limited by the cross-section and it is not possible to use the concrete reinforcement due to non-compliance with requirements for covering the

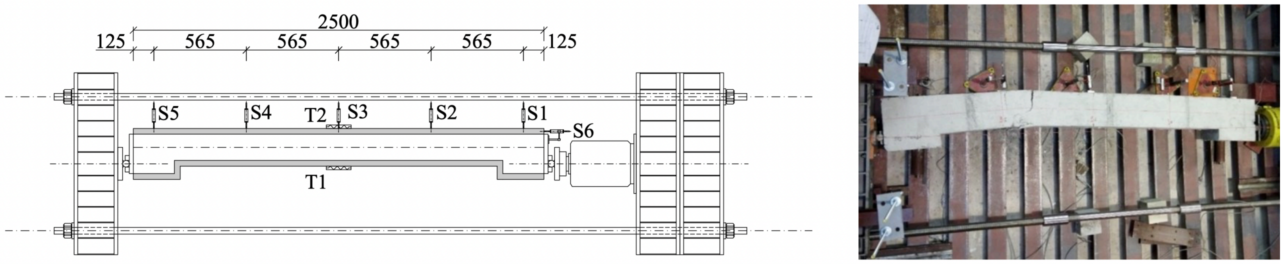

Figure 1. Experimental program, a) load of a sample, b) sample after loading.

reinforcement, it is a suitable way to use a layer of fibre reinforced concrete [13]. By adding a new layer of fibre concrete and its increased strength, it is possible to expand the iteration diagram and thus achieve the required load-bearing capacity, which would comply with the Ultimate Limit State (ULS).

2. Experimental program

To construct and verify the analytical calculation, it was necessary to start from a real experimental measurement. Basic dimensions of the reinforced concrete column cross-section 160 × 160 mm were chosen, which was used for strengthening by the fibre concrete wrapping. The column was reinforced with 4 ⌀10 mm. The class of concrete C16/20 and the reinforcement B500B were used. Axial distance of stirrups was 100 mm and diameter of stirrups was 8 mm. Detailed reinforcement and description of materials' characteristic are presented in [14]. For the strengthening was used the Dramix 3D fibres of a length 35 mm. The volume of fibres in the concrete mixture was 0.5 %, which represented 40 kg/m^3 of fibres. Concreting of the reinforced column was carried out horizontally by placing the column in the formwork and consisted of two steps. The first step was the concreting of the lower part, which had a thickness of 35 mm and spacer washers were used to ensure an even thickness of the cladding. The second step was to insert the unreinforced column into the fresh concrete mix from step one and then concrete the fibre concrete. Two samples of columns were tested. The contact between the original and the newly added FRC was made on a smooth surface and was not specially treated. The samples were loaded eccentrically, the value of eccentricity was 100 mm.

Reinforced columns strengthening with the FRC carried 410.62 kN (S3_SV_01) and 359.34 kN (S3_SV_02). Figure 2 shows the relation between the load and deformation in the middle of the column (sensor S3). Sample SV_02 carried about 51.28 kN less than sample SV_01, which may be due to uneven distribution of fibres in the concrete mix. The bending moment was determined from the normal force, namely 41.06 kNm and 35.93 kNm. From these values, point 2 was determined, which are ultimate bending moment and ultimate normal force. More information is given in [14].

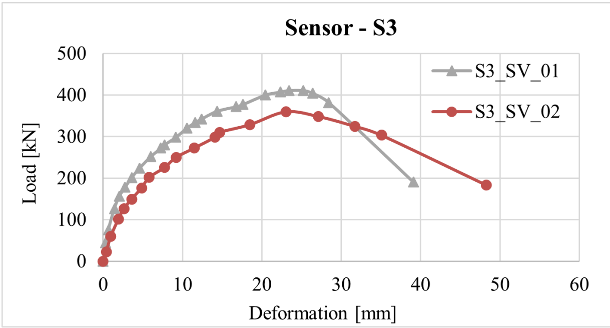

Figure 2. Relationship Load - deformation, sensor S3.

To verify the shear resistance, three samples of push-tests were made. The samples consisted of a core and encasement. Dimension of samples of cross-section were the same as dimension of a column. The surface was considered smooth, which was cleaned and moistened before concreting [15]. Samples after hardening, i.e., after 28 days, were tested by the axial force. The deformation between the core and the encasement was measured. After dismantling the sample, it was clear that in some places the new concrete "overgrown" with the old concrete, which could be caused by hydration of the concrete. A large number of air cavities can also be seen in the samples, which weakened the shear surface. Using the fibre concrete, one or two major longitudinal cracks were formed at the time of the shear resistance. After reaching the maximum shear force, cracks were formed and opened. Detailed information is provided in [16].

In order to construct an iteration diagram, it was necessary to determine the material characteristics of the fibre reinforced concrete. A 3-point bending test was performed (Figure 3c). The size of the test beam was $150 \times 150 \times 700$ mm with a notch. Three samples were tested, where the average value was calculated from the 3-point bending test. The average force of the crack mouth opening displacement (CMOD) was 10.8 kN.

3. Analytical calculation

An interaction diagram is a great tool for designing vertical elements. Using the iteration diagram, it

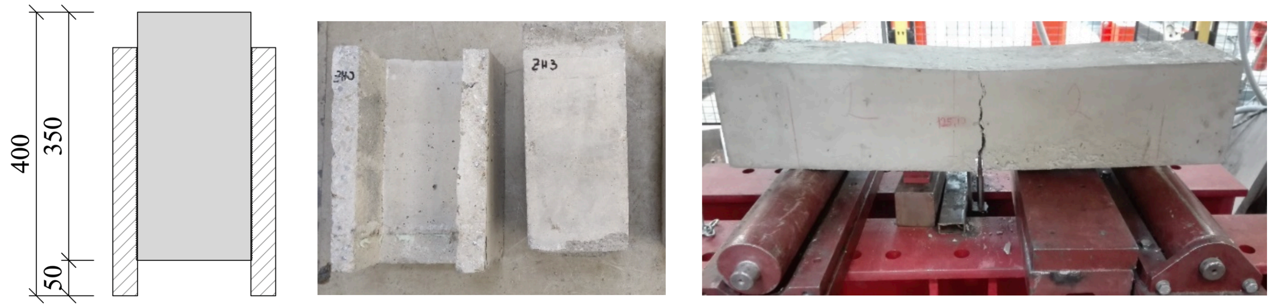

Figure 3. Push test and 3-point bending test, a) dimension of a push test, b) push test after the loading, c) sample after the 3-point bending test.

is possible to calculate the cross-sectional resistance. When designing the reinforcement of the column, it is necessary to combine the bearing capacity of the original cross section and the bearing capacity of the new layer of fibre concrete. However, in order to determine the load-bearing capacity of the reinforced column, using the fibre-reinforced concrete, it was necessary to implement the knowledge from the calculation of fibre-reinforced concrete and combine it with the calculation of the interaction diagram. The basics of calculation, are given in STN EN 1992-1-1 [17]. The calculation of the residual strength of the fibre reinforced concrete can be performed according to the FIB MODEL CODE [18] or according to RILEM TC 192 [19]. In this article, the calculation was done according to RILEM TC. The work procedure according to RILEM is based on the results of the 3-point bending by determining the values at certain widths of the opening. From the width of the cracks, it is possible to determine the stresses that describe the tensile behaviour of the fibre reinforced concrete at certain degrees of the FRC (Fig. 4).

To calculate the stresses [20], it is necessary to determine the residual strength of the fibre reinforced concrete for the crack opening displacement of 0.5 mm, 2.5 mm and 3.5 mm according the equation

$$f_{Ri} = \frac{3 \cdot F_i \cdot l_z}{2 \cdot b \cdot h_{sp}^2} \tag{3}$$

According to Löfgren [21], it is necessary to compensate the random location and orientation of the fibres by the dimensional factor k_h:

$$k_h = 1.0 - 0.6\,\frac{h - 12.5}{47.5}, \tag{4}$$

where h is the height of members [mm].

Calculation of individual stresses of the diagram from the tensile strength of fibre reinforced concrete was done as follows, [**?**]:

$$\sigma_2 = 0.45 \cdot f_{R1,\,b} \cdot k_h \tag{5}$$

$$\sigma_3 = 0.37 \cdot f_{R3,\,b} \cdot k_h \tag{6}$$

$$\sigma_1 = 0.7 \cdot f_{ctm} \cdot (1.6 - d) \tag{7}$$

The neutral axis x_{tot} (ratio factor) for the tensile stress area is given as:

$$x_{tot} = \frac{A_1\,x_1 + A_2\,x_2 + A_3\,x_3 + A_4\,x_4 + A_5\,x_5}{A_{tot}} \;[-] \tag{8}$$

where:

- A_i is the individual areas of the FRC tensile stress blocks [mm^2],
- x_i is the length to center of gravity of individual tensile areas of FRC [$-$],
- A_{tot} is the total stress of the tensile stress block of FRC [m^2].

The resulting stress in the fibre reinforced concrete is given by:

$$\sigma_m = A_{tot} \tag{9}$$

In calculation of the iteration diagram, for point 2 of the resistance line, it is assumed that the limit relative deformation ε_{cu3} is achieved in the compressed fibres (edge) of concrete and the yield strength is reached in the steel reinforcement (Figure 4) [17].

It follows that the height of the compressed part x of the concrete is equal to the limit height x_{lim}. The calculation of the reinforcement deformation is based on assumptions of achieving the limit deformation in concrete

$$\varepsilon_{s2} = \frac{\varepsilon_{cu3}}{x_{lim}}\,(x_{lim} - d_{2a}) > \varepsilon_{yd} = 2.5‰ \tag{10}$$

$$\varepsilon_{s1} = \frac{\varepsilon_{cu3}}{x_{lim}}\,(d_a - x_{lim}) > \varepsilon_{yd} = 2.5‰ \tag{11}$$

The following equations are used for calculation of tensile forces F_{si}, the compressive force of the concrete F_c, the compressive force of the fibre reinforced concrete F_{fci} and the tensile force of the fibre reinforced concrete F_{fti}, respectively:

$$\begin{aligned} &\text{a) } F_{s1} = A_{s1} \cdot \sigma_{s1} \\ &\text{b) } F_{s2} = A_{s2} \cdot \sigma_{s2} \end{aligned} \tag{12}$$

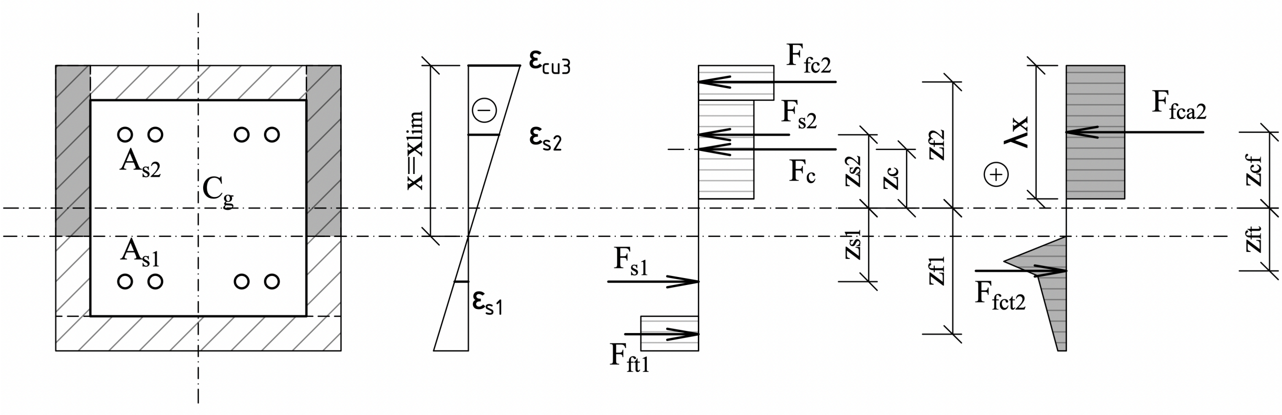

FIGURE 4. Iteration diagram - point 2.

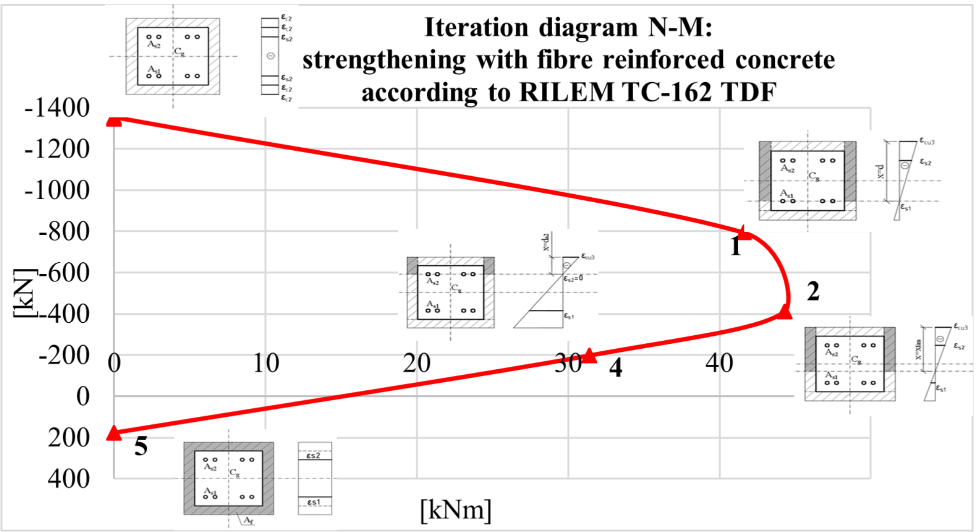

FIGURE 5. Iteration diagram - point 2.

$$F_c = b \cdot \lambda \left(x_{lim} - a \right) \cdot \sigma_{cf} \tag{13}$$

$$F_{fa2} = 2 \cdot a \cdot \lambda \cdot x_{lim} \cdot \sigma_{cf} \tag{14}$$

$$\begin{array}{c} \text{a)} \;\; F_{ft1} = a \cdot b \cdot \sigma_3 \\ \text{b)} \;\; F_{ft2} = a \cdot b_a \cdot \sigma_{cf} \end{array} \tag{15}$$

$$F_{fct2} = 2 \cdot \sigma_m \left(h_a - x_{lim} \right) \cdot a \tag{16}$$

where:

- a is the thickness of strengthening,
- b is the width of original column,
- b_a is the width of new cross-section (strengthened),
- h_a is the height of new cross-section (strengthened),
- σ_c is the compressive stress in concrete,
- σ_{cf} is the compressive stress in the fibre concrete.

The internal forces arms for fibre reinforced concrete are calculated as follows

$$\begin{array}{r} \text{a)} \;\; z_c = \dfrac{h}{2} - \dfrac{\lambda \left(x_{lim} - a \right)}{2} \\ \text{b)} \;\; z_{cf} = \dfrac{h_a}{2} - \dfrac{\lambda \cdot x_{lim}}{2} \\ \text{c)} \;\; z_{ft} = \left| \dfrac{h_a}{2} - x_{lim} \right| + x_{tot} \left(h_a - x_{lim} \right) \end{array} \tag{17}$$

The resulting internal forces are calculated according to the equilibrium conditions

$$N_{Rd,2} = -F_c - F_{fc2} - F_{fca2} - F_{s2} + F_{ft1} + F_{s1} + F_{fct2} \tag{18}$$

$$\begin{aligned} M_{Rd,2} = {} & F_c z_c + F_{fc2} z_{f2} + F_{fca2} z_{cf} + \\ & F_{s2} z_{s2} + F_{ft1} z_{f1} + F_{s1} z_{s1} + \\ & F_{fct2} z_{ft} \end{aligned} \tag{19}$$

According to the calculation presented above, the other points of the iteration diagram were derived (Figure 5). A detailed calculation is given in [22].

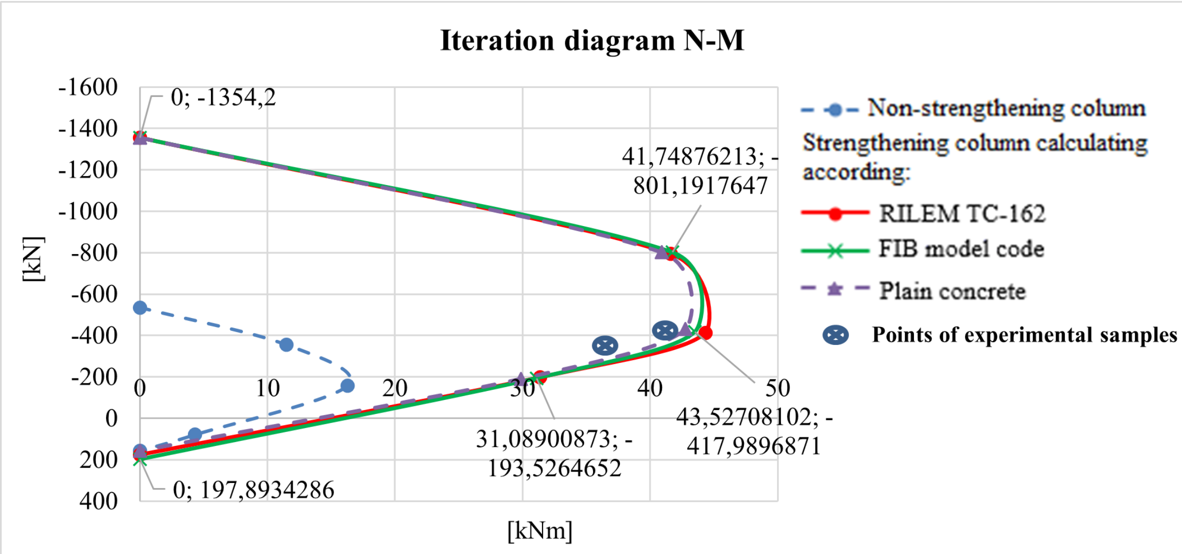

Figure 6. Iteration diagrams for individual methods of calculation - comparison.

	RILEM TC-162		FIB MODEL CODE		Plain concrete		RILEM -PC		FIB -PC	
	N_{Rd}	M_{Rd}	N_{Rd}	M_{Rd}	N_{Rd}	M_{Rd}	N_{Rd}	M_{Rd}	N_{Rd}	M_{Rd}
0	−1354.2	0	−1354.2	0	−1354.2	0	0.00 %	0.00 %	0.00 %	0.00 %
1	−794.07	41.59	−801.19	41.748	−801.19	40.90	0.90 %	1.67 %	0.00 %	2.03 %
2	−412.22	44.32	−417.99	43.52	−430.91	42.77	4.53 %	3.49 %	3.09 %	1.73 %
4	−198.22	31.39	−193.52	31.08	−190.3	29.87	4.00 %	4.85 %	1.67 %	3.92 %
5	176.18	0	197.89	0	157	0	10.89 %	0.00 %	20.66 %	0.00 %

Table 1. Comparison of bending moment and normal forces for various methods of calculating.

4. Analytical parametric study

In both experimental and analytical studies, an iteration diagram of the strengthened column was constructed using the FIB MODEL CODE [19] and RILEM TC-162 [20]. To determine the utilized of fibres compared to plain concrete, an interaction diagram of the strengthening column by using the plain concrete was also created. The reason for comparison of these methods is to determine the contribution of fibres in the strengthening for different areas of the bending moment and the normal force combination (Figure 6).

In Table 1, is presented a comparison of the individual points calculated according to RILEM and FIB MODEL CODE and the associated increase in internal forces. The results of the work can be applied to strengthening of the substructures of bridges and footbridges, such as columns of pillars [23–29]. In that case, it would certainly be necessary to investigate the effect of the chloride ions penetration into the cross section and its influence on degradation of concrete and corrosion of steel fibres [30–33].

5. Conclusions

When comparing these methods, it is necessary to take into account that the effect of the fibre reinforced concrete (FRC) has a great influence on the load-bearing capacity, namely, the FRC softening or hardening and how many fibres bridge the crack. In the performed experiment, the composite has softened, i.e., the main crack is formed and the fibres are pulled out due to increase of the load. The given experiment shows that the calculation methods differ from each other only minimally. The largest increase in fibres is observed in the area of plain tension where in comparison to the unreinforced concrete by 10.89 % for the calculation procedure according to RILEM and by 20.66 % for the calculation procedure according to FIB. A comparison of the calculation procedures in point 2, which is also verified by the experimental program, shows that the increment from the FRC for RILEM was 4.53 % for normal force and 3.49 % for bending moment. The analytical calculation according to FIB in point 2 transferred smaller values for a normal force of 3.09 % and a bending moment of 1.73 %. As can be seen from the experiment, the increase in the load-bearing capacity, due to the FRC, is influenced by the number of fibres, the orientation of the fibres in the crack and also by the length of the fibre. Using the DRAMIX 3D, only slight increase of the load-bearing capacity was achieved. However, the given analytical calculation was confirmed by an experiment, as well as by a numerical model, where it correctly captured the achieved bearing capacity of the given cross-section.

Acknowledgements

This research was supported by the Slovak Research and Development Agency under contract No. APVV-14-0772 and by Research Project No. 1/0306/21 and Project No. 1/0045/19 of the Slovak Grant Agency.

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