EQUIVALENT CO_2 EMISSIONS OF TRC AND F/TRC STRENGTHENING SOLUTIONS

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Abstract. The construction industry is among the main contributors to global CO_2 emissions, accounting for more than 30% of the total emissions. Within the framework of the current environmental crisis, such impact is unsustainable, yet the construction sector is an essential activity for both the economy and the welfare of people. In order to reduce its influence on the environment, existing structures need to be enabled to exhibit a longer service life, thus leading to a reduction of demolishing and rebuilding operations. To do so, innovative materials are continuously being developed and tested in strengthening applications. In this article, several RC beams were strengthened with TRC or F/TRC materials. Their environmental impact was evaluated and compared to newly built solutions with the same performance. The results of this case study clearly show how strengthening existing elements can result in a strong reduction of equivalent CO2 emissions of the construction sector.

Keywords: Environmental impact, RC beams, TRC, F/TRC

1 INTRODUCTION

Aging and degradation of concrete constructions are important phenomena that can significantly affect their performance. In 2004, 55% of European railway bridges were between 20 and 50 years old while 16% were between 50 and 100 years old [1]. In 2013, 11% of US bridges were structurally deficient while 25% functionally obsolete [2]. To maintain acceptable levels of performance retrofitting and upscale interventions are unavoidable operations. Textile Reinforced Concrete (TRC) and Fibre/Textile Reinforced Concrete (F/TRC) materials are viable solutions for strengthening existing Reinforced Concrete (RC) structures [3]–[7]. Little information is, however, available on their environmental impact. A case study is presented, dealing with equivalent CO_2 emissions (CO_2e) of such strengthening solutions applied on RC beams tested in bending, which results were discussed in previous publications [6], [7]. The results are compared to the CO_2e of rebuilt beams with performances comparable to the strengthened ones. The results show how strengthening with TRC and F/TRC elements can strongly reduce the environmental impact of construction activities necessary to guarantee the performance of existing structures.

2 EXPERIMENTAL ACTIVITY

Thirteen RC beams, eleven of which were strengthened by mean of TRC or F/TRC solutions, were tested. Each beam was 2.5 m long and had a cross section of 220x450 mm. The internal reinforcement consisted of 2∅20 rebars in the tensile zone, 2∅10 rebars in the compression zone and 20∅10 stirrups spaced at 125 mm. C40/50 concrete and B 550B steel were used to produce the beams. A schematic representation of the geometry can be found in Figure 1a.

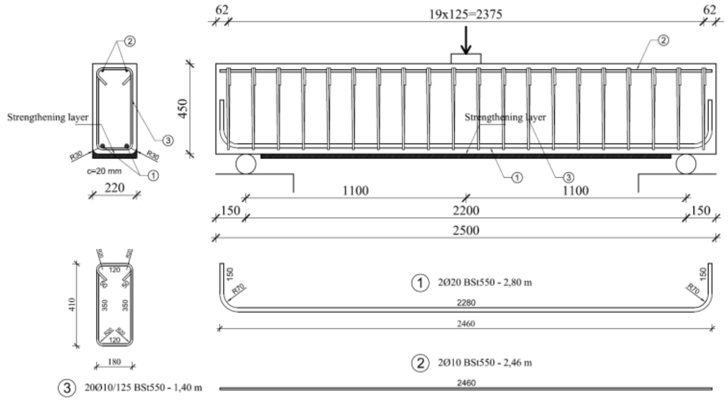
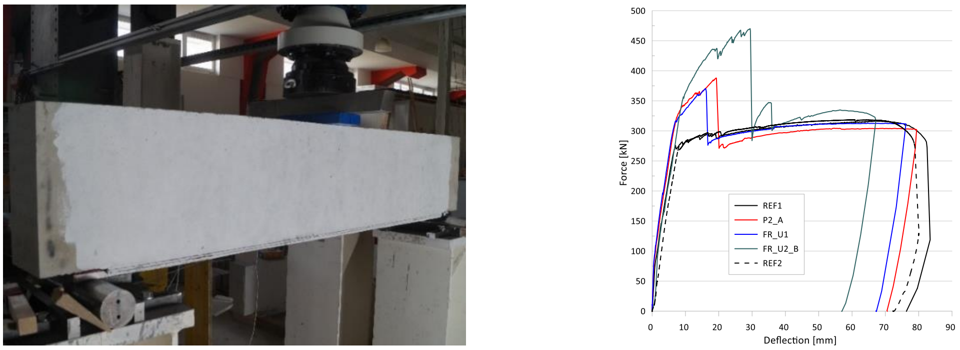


Figure 1. Geometry and application of strengthening elements of the tested beams

The strengthening solutions consisted of layers of TRC or F/TRC applied in the tensile zone of the beams. Each solution consisted of alternate layers of cementitious matrix (≈ 5 mm) and epoxy impregnated carbon textile covered by an additional 5 mm thick cementitious cover. Two different cementitious materials were employed in this study: the first one was a High Performance Concrete (HPC) premix suitable for these type of applications via lamination [8], [9], while the second one was a self-developed Ultra High Performance Concrete (UHPC), which was further developed based on previous results [10], characterized by a self-compacting behaviour and suitable for pumping applications. Furthermore, when F/TRC strengthening elements were produced, 2.5 vol% of short, dispersed steel fibres were admixed to the matrix (HPFRC and UHPFRC). Such fibres were characterized by a length of 5 mm and a diameter of 0.15 mm (aspect ratio: 33.3). The cube compressive strength of the cementitious materials was tested on 100x100x100 mm cubes and resulted in 86.5 MPa, 89.7 MPa, 184.4 MPa and 164.7 MPa for HPC, HPFRC, UHPC and UHPFRC, respectively. The textile reinforcement consisted of a bidirectional carbon fabric characterized by 25 mm spaced fully epoxy-impregnated rovings with a cross sectional area of 3.62 mm². According to the data provided by the manufacturer the tensile strength was 3100 MPa and 3300 MPa for the longitudinal and transversal rovings, respectively [11]. Two types of mechanical anchorages were employed in some of the strengthening solutions. Such anchorage elements were placed in three different configurations: A – four 62 mm long threaded studs embedded 37 mm and positioned at 380 mm for each end of the beam; B – two 220 mm long bonded anchors embedded 160 mm in the substrate concrete and positioned at 270 mm for each end of the beam; C – two bonded anchors as in configuration B and continuously distributed threaded studs along the rest of the beam (see a summary of the tested strengthening solutions and the achieved maximum loads in Table 1). The strengthening layers were applied by lamination when HP(FR)C was employed and by pumping in the case of UHP(FR)C. The only exception is specimen FR-U1-M, where the cementitious material was manually poured.

Table 1. Tested strengthening solutions

ID	N° of layers	Matrix typology	Anchors	Maximum load [kN]	Failure mode
REF1 / REF2	-	-	-	317 / 319	-
P1 / P2	1 / 2	HPC	-	338 / 368	Interlaminar shearing
P2-A/P3-A	2 / 3	HPC	A	388 / 417	Interlaminar shearing
FR-U1-M/FR-U1	1	UHPFRC	-	370 / 370	Debonding / Textile rupture
FR-U2-A	2	UHPFRC	A	370	Textile pullout
U1	1	UHPC	-	362	Textile rupture
FR-P2-B/FR-U2-B	2	H-/UHPFRC	B	447 / 470	Textile pullout
P2-C	2	HPC	C	447	Textile pullout



a) Test setup *b) Selected Force-Deflection curves*

Figure 2. Experimental activity

The specimens were tested in a three-point-bending setup with a span of 2.2 m. The measurements were performed using a Digital Image Correlation (DIC) system consisting of four high resolution cameras arranged in a two-systems stereo setup. The deflection was also monitored using a LVDT placed at mid-span. Figure 2 presents a view of the test setup and the force-deflection curves of selected tests. For more detailed information about the test results, please refer to [6], [7].

3 ENVIRONMENTAL IMPACT

An analysis of the Global Warming Potential (GWP) of the tested strengthening solutions was performed. To highlight the benefits that strengthening existing structures can have on the present environmental crisis, the equivalent CO_2 emissions originating from the tested strengthening solutions were compared to the emission of rebuilding the same beam with increased internal reinforcement. The increase in internal reinforcement for the "rebuilt" solution was calculated multiplying the cross-sectional area of the longitudinal tensile reinforcement by the ratio between the maximum load of each strengthening solution and the average maximum load of the reference beams. The equivalent CO_2 emissions were calculated in terms of Embodied Carbon (EC) and the data was collected from the Inventory of Carbon and Energy (ICE) database (http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html). The only exception was the data for the carbon textile, which was assumed to be 27.5 $kgCO_2e/kg$, in accordance with *Das [12]*. A summary of the EC for the different materials can be viewed in Table 2. It is important to mention that such analysis only takes into account the impact associated to the production of the elements. Other activities, such as demolition, transport, pre-treatment, etc. were not considered.

Table 2. CO_2 equivalent outputs of the used materials

Material	**Embodied Carbon [$kgCO_2e/kg$]**
C40/50	0.159
HPC	0.176
UHPC	0.332
Rebar	1.99
Fibres	2.53
Anchorage	2.53
Carbon textile	27.5

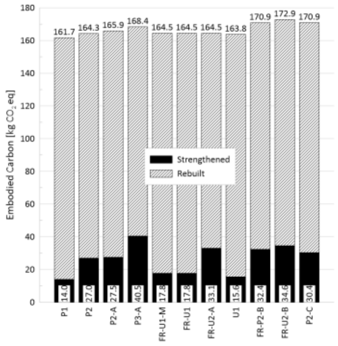


Figure 3. CO_2-Comparison rebuilt vs strengthened

The results can be viewed in Figure 3. All the strengthening solutions result in significantly lower CO_2 emissions when compared to rebuilt solutions, with a CO_2 reduction ranging between 76% and 91%. Concerning the rebuilt solutions, it can be seen that the main factor accounting for their emissions is concrete, principally due to its relative high volume compared to the internal steel reinforcement. Focusing on the strengthened solutions, the main contributing factor is the number of layers (mainly due to the high emission associated with carbon textiles). The presence of short dispersed fibres, as well as the use of the two different matrix typologies, play a non-negligible, yet not particularly relevant role. The presence of the anchorage could be ignored without significantly affecting the results.

4 CONCLUSION

An experimental study on reinforced concrete beams strengthened by mean of TRC and F/TRC solution was performed. The equivalent CO_2 emission of the tested strengthening solutions was calculated and compared to a rebuilding strategy in which the internal reinforcement was increased to match the performance of the strengthened beams. The results show that strengthening existing structures is a viable way of reducing the carbon footprint of the construction sector, enabling a reduction of equivalent CO_2 emissions up to more than 90%.

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6 REFERENCES

[1] B. Bell and Network Rail, “European Railway Bridge Demography,” WP1-02-T-040531-R-Deliverable D 1.2, 2004.
[2] American Society of Civil Engineers, “Report Card for America’s Infrastructure,” 2013.
[3] F. Bencardino, C. Carloni, A. Condello, F. Focacci, A. Napoli, and R. Realfonzo, “Flexural behaviour of RC members strengthened with FRCM: State-of-the-art and predictive formulas,” *Composites Part B: Engineering*, vol. 148, pp. 132–148, 2018.
[4] L. N. Koutas, Z. Tetta, D. A. Bournas, and T. C. Triantafillou, “Strengthening of Concrete Structures with Textile Reinforced Mortars: State-of-the-Art Review,” *J. Compos. Constr.*, vol. 23, no. 1, p. 03118001, 2019.
[5] E. Rossi, N. Randl, P. Harsányi, and T. Mészöly, “Experimental study of fibre-reinforced TRC shear strengthening applications on non-stirrup reinforced concrete T-beams,” *Engineering Structures*, vol. 256, p. 113923, 2022.
[6] E. Rossi, N. Randl, T. Mészöly, and P. Harsányi, “Effect of TRC and F/TRC Strengthening on the Cracking Behaviour of RC Beams in Bending,” *Materials*, vol. 14, no. 17, Art. no. 17, 2021.
[7] E. Rossi, N. Randl, T. Mészöly, and P. Harsányi, “Flexural Strengthening with Fiber-/Textile-Reinforced Concrete,” *ACI Structural Journal*, vol. 118, no. 4, 2021.
[8] Pagel Spezial-Beton, “TF10 TUDALIT FINE CONCRETE Technical Data Sheet.”
[9] Deutsches Institut für Bautechnik, “Verfahren zur Verstärkung von Stahlbeton mit TUDALIT (Textilbewehrter Beton).” 2016.
[10] N. Randl, T. Steiner, S. Ofner, E. Baumgartner, and T. Mészöly, “Development of UHPC mixtures from an ecological point of view,” *Construction and Building Materials*, vol. 67, pp. 373–378, 2014.
[11] “solidian GRID Q142/142-CCE-25 Technical Data Sheet.”
[12] S. Das, “Life cycle assessment of carbon fiber-reinforced polymer composites,” *Int J Life Cycle Assess*, vol. 16, no. 3, pp. 268–282, 2011.