Assessment of load transfer length in textile reinforced cementitious matrix composites

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ABSTRACT: Given their mechanical, environmental and aesthetical properties, textile reinforced cementitious matrix composites (TRCMC) are used on a large scale for the rehabilitation and reinforcement of built heritage and civil engineering structures. The effects of the internal mechanical parameters, such as load transfer mechanisms and fibre-matrix interaction, on the global behaviour are deduced combining surface strain measurements and approaches of continuum mechanics, taking into account damage and fracture characteristics. The direct measurement of these intrinsic parameters (load transfer and crack initiation mechanisms, effective load distribution between components…) is still of major scientific interest.

This paper discusses one of the micromechanical parameters that govern the behaviour of TRCMC under tensile load: the load transfer length. Optical fibres, having a millimetric space resolution, using Rayleigh backscattering principle, were used as linear strain sensors into the core of the TRCMC to measure the load transfer length between the textile and the matrix during uncracked and cracked stages of the composite behaviour.

Two reinforcement ratios were studied: TRCMC with a single layer of textile reinforcement, and with three layers of reinforcement. A general correlation was found between the ratio of reinforcement and load transfer length.

Finally, a comparison between the experimental results and existing models was made, which allowed hypotheses and approaches of continuum mechanics to be analysed and adapted.

KEYWORDS: Cementitious matrix composite; Textile Reinforced Cementitious Matrix Composites; Load transfer length; Optical Fibre; Rayleigh backscatter; strain sensor.

1 INTRODUCTION

Cementitious matrix composite materials are increasingly used for the repair and reinforcement of structural component systems in civil engineering and as building materials. The mechanical behaviour of the TRCMC is obtained through different measurement techniques that focus on the stress and strain field on the surface of the specimens, such as strain gauges, digital image correlation (DIC), linear variable differential transformer, laser extensometry, etc (Promis et al (2011), Caggegi et al (2018)). From these measurements, the internal interactions between the components of these composites are deduced by continuum and fracture mechanics approaches. These allowed the development of hypotheses and models describing the potential micro-mechanical parameters that govern the reinforcement/matrix interaction of a TRCMC, such as the load transfer length (ACK (1971), Cuypers et al (2006)). The latter represents the length along which the load is transferred from the textile reinforcement to the matrix. Experimentally, no study reported a direct local measurement of the evolution of the load transfer length of TRCMCs

subjected to uniaxial tensile loading, which is of critical importance in assessing the accuracy of existing models.
Due to their geometrical and metrological advantages (small size, flexibility, lightweight, precision, millimetric spatial resolution, sensitivity, etc.), the measurement technique based on optical fibre sensors is used in several fields, including civil engineering. It has been used as a tool to assess the health of buildings, and has been the subject of several studies, including their behaviour at the core of concrete structures (Henault (2013)).

Concerning the study of the mechanical behaviour of composites using optical fibre as a strain sensor, it was the subject of several experimental investigations (Bruno (2018)), in particular the Bragg grating system. Textile-reinforced polymer matrix composites, such as FRP and thermoplastic matrix composites, have been studied using optical fibre sensors (De Baere et al (2009)). This measurement technique was used in cementitious matrix composites to verify the reliability of its results and its resistance in a cracking material (Saidi et al (2019)). To the best of the author's knowledge, this technique was applied to TRCMC materials to assess its load transfer length for the very first time.

The aim of this study is to investigate experimentally the internal behaviour of TRCMC composites, based on local measurements at the core of the tested material, and to deduce the evolution of the load transfer length during all the stages of the tensile behaviour. The experimental results obtained are compared with existing models in order to assess their validity. For this purpose, optical fibres based on the Rayleigh backscattering principle (Soller et al (2005)) are used as distributed strain sensors, embedded in the core of TRCMC, to obtain the behaviour of the matrix and the textile reinforcement, and to deduce the load transfer length from it.

2 EXPERIMENTAL WORK

2.1 *Experimental device*

2.1.1 Tensile testing machine

The tensile tests were performed using a Zwick universal testing machine as shown in Figure 1, which has a maximum capacity of 65kN. It is equipped with force and displacement sensors having an accuracy of 0.01 N and 0.01 mm, respectively, and the system is connected to a computer governed data acquisition system that allows the test parameter set-up and data recording. The tensile tests were controlled in displacement, with a velocity of 0.1 mm/min. The TRCMC specimen was clamped by two ball-joint loading heads to reduce the effects of parasitic bending due to the eventual geometrical imperfections of the specimens.

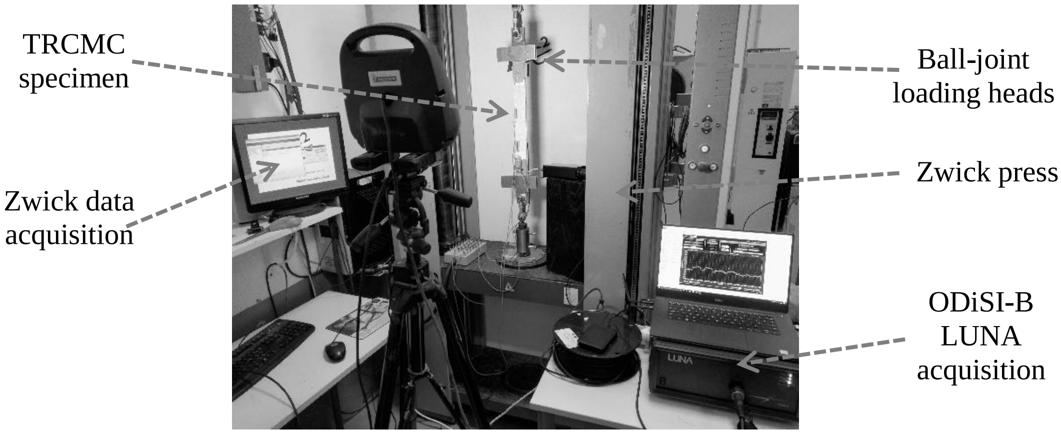


Figure 1: Experimental protocol for the tensile test of TRCMCs with optical fibre

2.1.2 Optical data acquisition

In this work, the ODiSI-B LUNA (Optical Distributed Sensor Interrogator) device is used to acquire the strain measured by the optical fibre. The measurement is based on the OFDR-Rayleigh principle. The optical fibre can be calibrated at the beginning of the test to eliminate residual strain, as well as to instantly visualise the results. For our study, the spatial resolution is 2.6 mm over the entire range of the optical fibre (2 m), with an acquisition rate of 2 Hz.

2.2 Specimen

2.2.1 Materials

- Matrix

In order to facilitate the preparation of specimens, to minimise the geometrical defects of the TRCMC specimens and to prevent the damaging of the optical fibre, an ettringite, liquid and self-placing cementitious matrix was used. These properties allowed good handling and ensured a good coating of the textile reinforcement by the cementitious matrix. The mechanical properties of the cementitious matrix were synthesised in Table 1.

- Textile reinforcement

The reinforcement textile used in this study was a grid-type alkali resistant (AR) glass textile with a surface weight of 525 g/m² and an inter-axis opening mesh of 5×5 (mm²). The yarns of the grid have a weight of 2400 Tex in the weft direction, and of 272 Tex in the warp direction. Table 1 shows the main geometrical and mechanical characteristics of this textile measured in the laboratory using standard methods.

Table 1. Mechanical properties of the cementitious matrix and the textile reinforcement

Component	Parameter	σ_{ultime} compression (MPa)	σ_{ultime} tension (MPa)	ε_{ultime} compression (µm/m)	ε_{ultime} tension (µm/m)	E_c compression (MPa)	E_t tension (MPa)
Matrix	Average	40	4.5	3000	400	13000	14000
	Standard deviation	1.57	0.36	230	34	507	492
Textile	Average	-	520	-	1.5	-	35000
	Standard deviation	-	48	-	0.12	-	3180

2.2.2 TRCMC specimen preparation

In order to measure the internal strain of the TRCMC, the 2m long optical fibre was placed in six different positions in the core of the composite. For this purpose, an effective measuring length of 20 cm has been set for the six positions, with 5 external loops of 10 cm each, as shown in Figure 2.

The shape of the studied TRCMCs is rectangular parallelepipedic with approximate dimensions of 600 × 50 × 10 mm3 (±1 mm) (length × width × thickness). This shape was chosen based on common case studies of the rehabilitation of civil engineering structures using this type of composite, as well as to scientific studies concerning TRCMC (Caggegi et al (2018)).

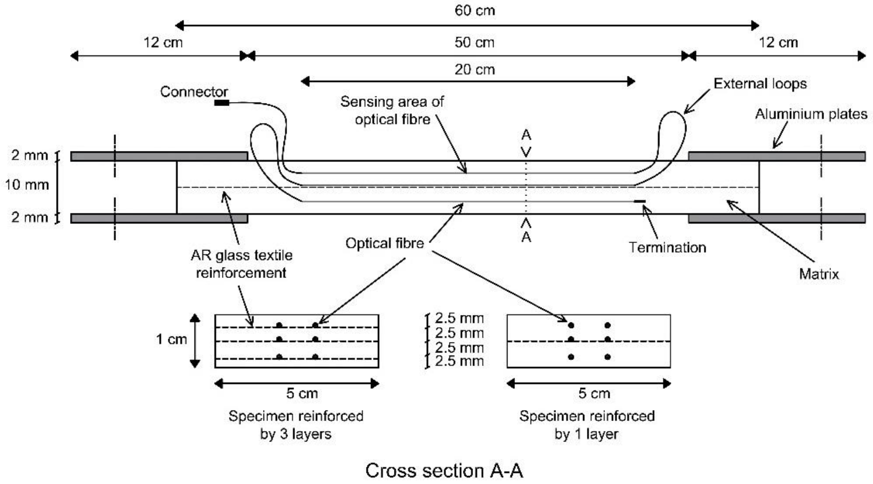
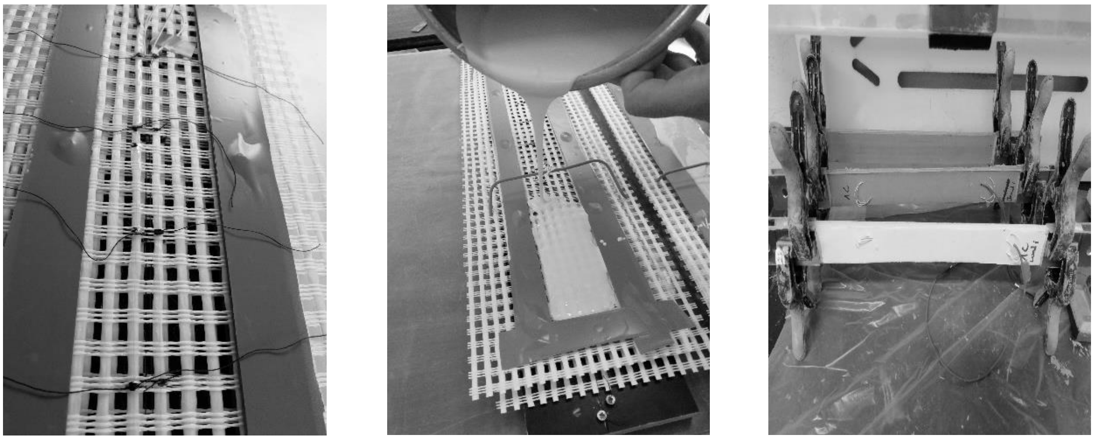


Figure 2: Schematic diagram of a specimen and the positioning of the optical fibre.

For this purpose, a mould was prepared by superposing 4 layers of polyvinyl chloride (PVC) plastic, each 2 mm thick. This superposition allowed us to place and centre both the textile reinforcement and the optical fibre in the different positions. Indeed, between each two superposed plastic plates, and depending on the number of reinforcement layers, either a layer of textile reinforcement was applied, or a 0.7 mm sewing thread was stretched. For the strain measurement of the textile, the segments of the optical fibre were bonded on the textile, and for the measurement in the matrix, the segments were punctually attached using knots every 5 cm (Figure 3-a). Note that to form a loop, the optical fibre was removed from the mould, and protected with a plastic sleeve.



a b c

Figure 3: Preparation steps for TRCMC specimens: a) installation of the textile and optical fibre; b) casting of the cementitious matrix; c) glueing of the aluminium plates after demoulding

Once the mould prepared and the positioning of the optical fibre done, the matrix was prepared and then poured into the moulds (Figure 3-b). A slight manual vibration was made during and after pouring to evacuate any air bubble in the matrix.

Once casted, the TRCMC specimen was covered with a plastic film to facilitate the cement hydration, and then cured at room temperature. After demoulding, two aluminium plates were bonded by epoxy resin to each of the two ends of the specimen (Figure 3-c).

3 RESULTS AND DISCUSSION

3.1 *Experimental measurement of the load transfer length*

Figure 4 and Figure 5 present the distribution of the strain along the optical fibre during the loading of the specimen. Before cracking the strain in the textile and the matrix is the same (Figure 4-a and Figure 5-a). When a crack occurs, the strain in the textile reaches its maximum value, while in the matrix the strain decreases to zero. In the vicinity of the crack, the matrix strain gradually increases from zero until it becomes equal to the strain of the textile reinforcement. This distance where the strain increases from zero to its nominal value can be assimilated to the "load transfer length", noted δ_o (Figure 4 and Figure 5).

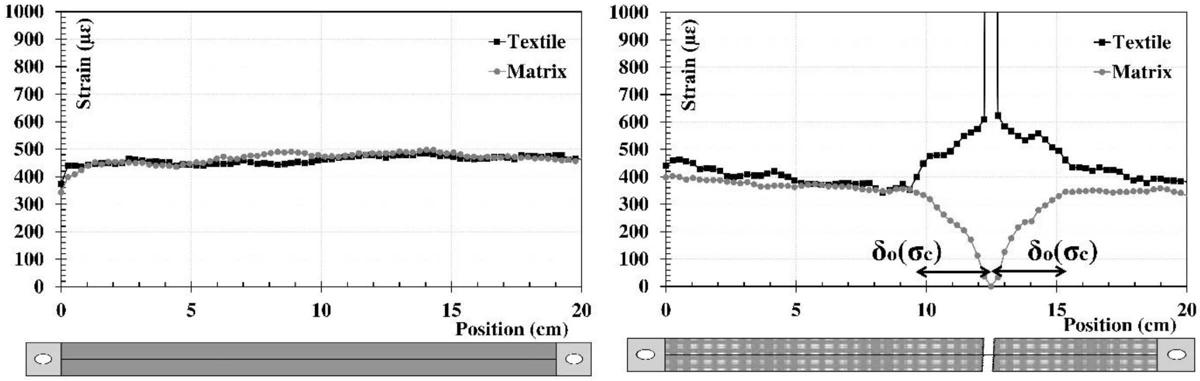


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Figure 4: Distribution of the strain in the matrix and the textile reinforcement of the TRCMC reinforced with a single textile layer: a) before cracking; b) after cracking

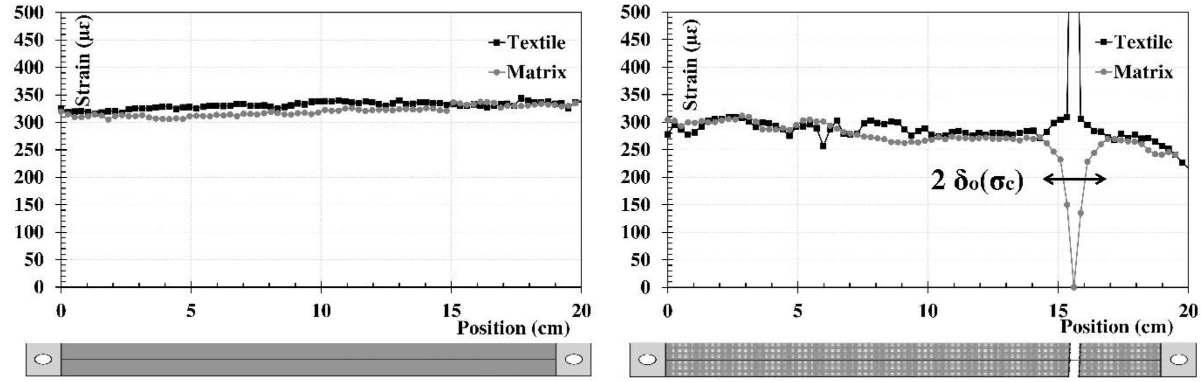

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Figure 5: Distribution of the linear strain of the matrix and the textile reinforcement of the TRCMC reinforced with three textile layers: a) before cracking; b) after cracking

A crack occurs in the matrix when the ultimate matrix strain is reached, and therefore over the length δ_o, the strain is lower compared to the rest of the matrix (Figure 4-b and Figure 5-b). This implies that, by increasing the applied load, the ultimate strain of the matrix will be reached in the area outside the δ_o length, induced by the previous crack. Based on this analysis, the crack spacing cannot be less than δo and not more than 2 δ_o, which shows that this parameter controls the cracking pattern of the TRCMC.

Thanks to optical fibre measurement, an accurate measurement of the δ_o values during the loading of the specimen is possible. To do this, once the first crack appears, δ_o is measured by taking the average of the two load transfer lengths at both sides of the crack. Then, the evolution of this quantity is measured as a function of the applied load. The results are presented in Figure 6.

On the one hand, we notice that δ_o evolves almost linearly with the increase of the applied load, expressed in terms of the stress in the composite (calculated as the applied load divided by the cross-sectional area of the composite specimen). This proves that the load transfer length is not constant after cracking, unlike the ACK (1971) model, which considers that this length is fixed. On the other hand, the load transfer length of the three-layer reinforced TRCMC is smaller than that of the single-layer reinforced TRCMC. This observation shows that this parameter is strongly related to the reinforcement ratio and that it decreases with the increase of this ratio. This result also explains the observation found in Figure 7 and in the literature, which note a decrease in crack spacing with the increase of the reinforcement ratio of TRCMC composites.

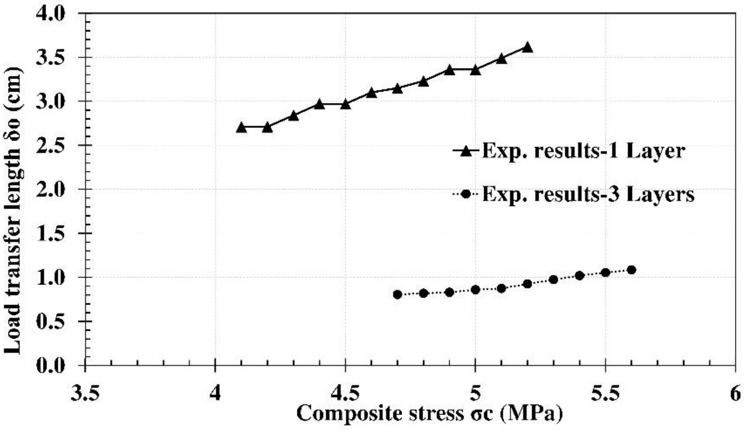

Figure 6: Evolution of the load transfer length of TRCMCs composites as a function of the stress in the composite

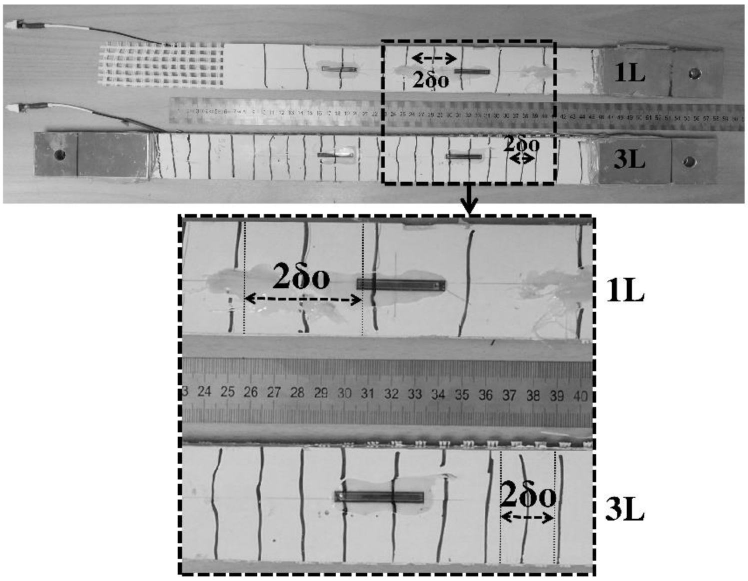

Figure 7: Cracking diagram of the TRCMC specimens after the tensile test, with the indication of the initial load transfer length measured by the optical fibre, compared to the smallest crack spacing. (L= Layer)

3.2 Confrontation with existing models

The load transfer length has been the subject of several theoretical models, which attempted to estimate this parameter from the mechanical characteristics of the matrix and the textile. In this section, two models are confronted with experimental results: ACK model (1971) and Cuypers et al (2006).

3.2.1 Model presentations

The first model is that of ACK (1971), which assumes that the load transfer length is constant and depends on the ultimate stress of the matrix (the stress of the appearance of the first crack):

$$\delta_o = \frac{(1-V_f).r}{2.V_f.\tau_o}\sigma_{um} \qquad (1)$$

The second model is that of Cuypers et al (2006), who estimate that the load transfer length is linearly related to the stress in the composite:

$$\delta_o = \frac{r}{2.\tau_o}\;\frac{(1-V_f).E_m}{V_f.E_{c1}}\;\sigma_c \qquad (2)$$

With: "r" radius of the cross section of a reinforcement fibre, "V_f"' reinforcement ratio, "E_{c1}"' composite modulus before cracking, "E_m"' matrix modulus,"σ_c"' stress in the composite, "σ_{um}"' ultimate matrix stress, "τ_o"' shear stress at the fibre-matrix interface.

The shear stress at the interface τ_o is determined by pull-out tests (Homoro et al (2019)), it corresponds to the maximum stress divided by the lateral section of the textile. In our case, it is equal to 1.4 MPa.

3.2.2 Comparison of models with experimental results

Figure 8 presents a comparison of the ACK (1971) and Cuypers et al (2006) models with the obtained experimental results.

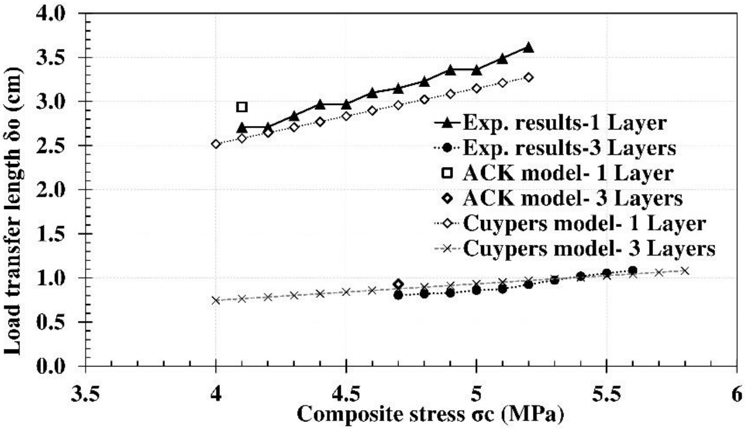

Figure 8: Confrontation of experimental results of the load transfer length of TRCMCs composites with existing models: ACK model (1971) and Cuypers et al model (2006)

These results show that the ACK model (1971) gives an approximative estimate of the load transfer length at the instant of cracking, but it remains limited at this point, while the Cuypers et al (2006) model gives a better estimate of this value δo either in terms of the evolution according to the applied stress, or in terms of the reinforcement ratio.

Thus, these results show the advantage of optical fibre measurement, and the possibility of obtaining results at the core of the materials, which will allow both to understand the behaviour of these composite materials and to evaluate, refine and validate existing theoretical models.

4 CONCLUSION AND OUTLOOK

Thanks to optical fibre measurement, the distribution and evolution of the strain in the matrix and textile of the TRCMC in tension is identified. The main results are listed below:

- After the appearance of the first crack, the "load transfer length δ_o" parameter, which controls the number and areas of crack occurrence, was identified and measured during the test.
- The load transfer length δ_o depends linearly on the stress in the composite and decreases with the increase of the reinforcement ratio.
- The ACK model (1971) is limited to estimating the value of δ_o at the time of the crack's appearance.
- Cuypers et al (2006) model gives a better approximation of δ_o by taking into consideration the applied composite stress and the reinforcement ratio.

These results show the interest of characterising the mechanical behaviour of TRCMCs by optical fibre, which leads us to deepen this study further, to identify the role of the matrix and the textile by making a parametric experimental study, and to improve the existing models.

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