

Research Article

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Effect of the reinforcement ratio on the mechanical behaviour of textile-reinforced concrete composite: Experiment and numerical modeling

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Abstract: Over the past decade, the textile-reinforced concrete (TRC) composite was gradually used to replace the fibre-reinforced polymer in the strengthening or repairing of existing reinforced-concrete structures, thanks to many criteria of sustainable development. The reinforcement ratio of textiles within TRC composites emerges as a crucial factor significantly impacting their reinforcement effectiveness, altering the material's mechanical behaviour and properties. This study presents both experimental and numerical findings concerning the tensile behaviour of carbon TRC composites, exploring reinforcement ratios ranging from 0.5 to 1.5%. As experimental results, the carbon TRC specimens exhibited a strain-hardening behaviour with the cracking phase. The ultimate strength improved by 95 and 146% compared to that of non-reinforced specimens, respectively, with the reinforcement ratio of 0.92 and 1.32%. As numerical results, the model reached the strain-hardening curve with three distinct phases when the reinforcement ratio was higher than a critical value (0.7%). The effect of reinforcement ratio ranging from 0.5 to 1.5% on the mechanical behaviour and properties of carbon TRC was also highlighted and analysed.

Keywords: carbon textile, textile-reinforced concrete, mechanical behaviour, reinforcement ratio, numerical modeling

1 Introduction

Over the past decade, with the development of reinforcement methods, there has been a growing demand for strengthening or repairing existing reinforced-concrete (RC) structures that decreased their mechanical performance or cracked on their service life. This method ensures sustainability in the field of construction engineering [1,2]. Thanks to the development of material composite for construction, it could satisfy the high-quality requirement in mechanical properties. Among them, textile-reinforced concrete (TRC) and fibre-reinforced polymer (FRP) composites were commonly used for strengthening or repairing works [3,4]. The main difference between both composites is the nature of the matrix used, in which the polymer-based matrix is used for FRP, and the cement-based matrix is used for TRC. Then, the TRC satisfies several requirements of sustainable development than the FRP composite. Therefore, the TRC composite was gradually used to replace the FRP in the strengthening and/or repairing of RC members [5,6].

Literature showed several experimental and numerical studies on TRC composite at both material and structural scales. At the material scale, previous studies aimed to characterize the tensile or flexural behaviour and the mechanical properties of the TRC specimen. Nearly all findings demonstrate strain-hardening behaviour in TRC, marked by a cracking phase distinguished by stress drops. TRC's behaviour could be divided into different phases depending on several factors belonging to the constitutive materials, interface bonding strength, and environmental conditions [7–10]. At structural scales, previous authors have performed structural tests on RC member strengthening with TRC composite withstands various loading cases. These studies aim to identify the reinforcement efficiency of TRC composite on the RC member compared with FRP. As a result, the TRC composite offered remarkable advantages for strengthening works in several special loading conditions such as earthquakes, elevated temperature, repetitive loading, *etc.* [11–14].

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An important factor that could greatly influence the reinforcement efficiency of TRC composites on RC members is the number of textile layers used for strengthening. This factor involves the reinforcement ratio of textiles in the TRC composite leading to the change in the TRC's mechanical behaviour and properties. Previous studies showed the enhancement of shear and flexural performances of RC member strengthening with TRC composite depending on the number of textile layers [15,16]. However, this evolution trend was not linear because it was still affected by the thickness of the cementitious matrix on TRC properties.

The effect of the number of textile layers and the cementitious matrix thickness on TRC's mechanical behaviour and tensile properties has been investigated in previous studies [17–19]. Rambo *et al.* [20] have performed the tensile tests on basalt TRC specimens in which the number of basalt textile layers varied from 0, 1, 3, and 5 for a cementitious matrix plate with dimensions of 400 mm × 60 mm × 13 mm in length × width × thickness. The results showed that TRC's mechanical behaviour was strongly influenced by the reinforcement ratio as well as, in comparison with the un-reinforced cementitious matrix, the TRC's ultimate strength improved 1.01, 1.2, and 2.6 times, respectively, for 1, 3, and 5 reinforcement layers. The explanation for this effect could be understood by the effective thickness of the cementitious matrix for one reinforcement layer. It means that each layer of the cementitious matrix with an effective thickness together works with the reinforcement textile inside. This mechanism is essentially based on two main factors: the bonding strength of the textile/matrix interface and the shear stiffness of the cementitious matrix to transfer the internal force [21]. TRC composite has optimization characteristics if the matrix thickness per one textile layer is designed based on the effective thickness.

According to ACI Committee 549 [22] and ACI Committee 434 [23], the principle mechanical properties of TRC (or FRCM [fabric reinforced cementitious matrix]) used for flexural strengthening design are ultimate tensile strength (f_{fu}) and strain (ϵ_{fu}). Both values are highly influenced by the reinforcement ratio identified by the ratio of volume or cross-section between the reinforcement textile and the cementitious matrix. To identify ultimate values for all cases, it needs more experimental studies that have more cost and time. So, the numerical approach could be an alternative solution to solve this problem.

This article aims to elucidate the ultimate properties of TRC composite for strengthening design purposes. It presents both experimental and numerical findings regarding the mechanical behaviour of carbon TRC composite, spanning

reinforcement ratios from 0.5 to 1.5%. In experimental work, the carbon TRC specimens with different numbers (0, 1, and 2 layers) of carbon textile layers were tested to identify the mechanical behaviour and tensile properties. For the numerical approach, a numerical model would be developed to predict the tensile behaviour of carbon TRC with different reinforcement ratios. From that, the effect of the reinforcement ratio on the carbon TRC's mechanical behaviour and properties could be found and analysed.

2 Experimental works

2.1 Material used

2.1.1 Cementitious matrix

The cementitious matrix was formulated based on findings from previous studies [24,25] and subsequently tailored to suit laboratory conditions for fabricating TRC composite specimens. This matrix comprised synthetic silico-aluminous-calcium aggregate and calcium aluminate cement, designed for specialized applications. To ensure a low application thickness, superplasticizer and viscosity modifier were incorporated into the matrix composition. The mechanical properties of the matrix in its hardened state were evaluated through laboratory tests, including three-point bending and compressive strength assessments (Figure 1). Table 1 provides details of the mixture composition as well as the physical and mechanical properties of the cementitious matrix in this experimental investigation.

2.1.2 Carbon textile

The carbon textile, depicted in Figure 2, comprises a bidirectional carbon grid with longitudinal and transverse dimensions of 17 mm × 17 mm. It boasts several advantages, including remarkable high tensile capacity (with an ultimate strength of 1,312 MPa and Young's modulus of 144 GPa), high heat and corrosion resistance, low surface mass (density of 1.79 g/cm³), and a simple and flexible application for structural reinforcements, even with low thickness (such as underneath slabs). To enhance bonding strength with the cementitious matrix, the carbon fibre underwent treatment with amorphous silica. Each cross-section of the textile yarn (both weft and warp) measures 1.795 mm². They consist of approximately 3,200 monofilaments, with 2 × 1,600 tex/strand for the weft and 1 × 3,200 tex/strand for the warp.

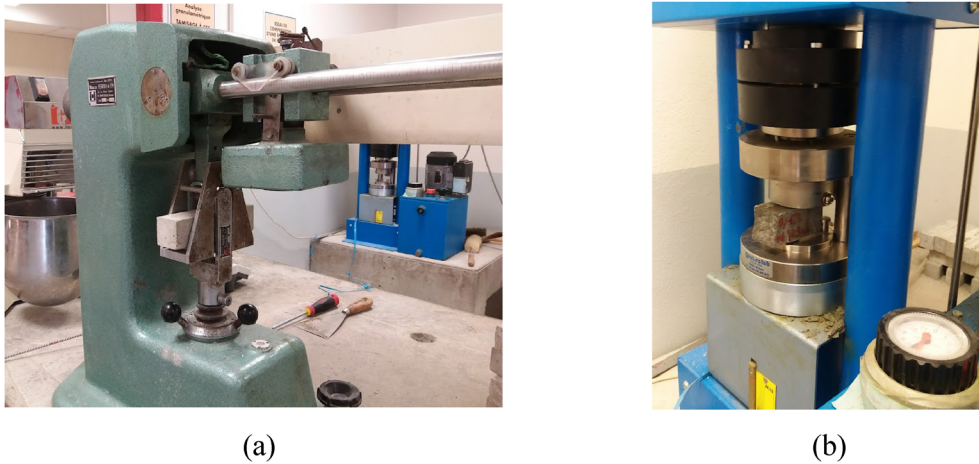


Figure 1: Images of tests for mechanical properties of the cementitious matrix. (a) Three-point bending test. (b) Compressive test.

2.2 Specimen preparation

2.2.1 Non-reinforced cementitious matrix specimens

The non-reinforced cementitious matrix specimens were manufactured in laboratory conditions for direct tensile tests. The rectangular specimens with dimensions of 600 mm × 51 mm × 20 mm in length × width × thickness were moulded by hand lay-up moulding technique. They were embraced in 28 days for curing. As a result, the direct tensile strength of non-reinforced cementitious matrix specimens was 5.29 MPa on average, while Young's modulus was 8.41 GPa. These results would be used to compare and identify the reinforcement efficiency of carbon textiles.

2.2.2 Carbon TRC specimens

The carbon TRC composite, consisting of the cementitious matrix and carbon textile reinforcement (referred to as C-TRC), was fabricated under laboratory conditions using a hand lay-up technique, as illustrated in Figure 3. First, a

rectangular concrete mould was prepared for C-TRC specimens. Next, a layer of the cementitious matrix was applied to the mould, ensuring its thickness matched the calculated layer thickness. A layer of carbon textile was then placed and secured at both ends using specialized clamping devices. This was followed by another layer of the matrix, matching the thickness of the initial layer. The process continues or halts based on the design specifications for the number of textile layers and matrix layers required for the sample.

To investigate the effect of the reinforcement ratio on the mechanical behaviour of the TRC composite, one layer and two layers of carbon textile were used as reinforcement. The dimensions of the one-layer C-TRC specimen measured 740 mm × 51 mm × 11.5 mm (length × width × thickness), while those of the two-layer C-TRC specimens were 740 mm × 51 mm × 16 mm. The reinforcement ratio corresponding with one and two carbon textile layers, calculated by the fraction of cross-section between the carbon textile and the TRC composite (S_f/S_{total}), was 0.92 and 1.32%, respectively. Aluminium plates were bonded to both ends of the C-TRC specimens to ensure proper transmission of tensile force. The specimen cross-section was determined by

Table 1: Scientist information on the cementitious matrix

Composition	Density (g/cm ³)	Compressive strength after 28 days (MPa)	Flexural tensile strength after 28 days (MPa)
Aggregate (kg/m ³)	1,676	2.53	58.1
Cement (kg/m ³)	669		12.5
Superplasticizer (kg/m ³)	4.34		
Viscosity modifier agent (VMA) (kg/m ³)	0.51		
Water (kg/m ³)	234.2		
Water/cement ratio	0.35		

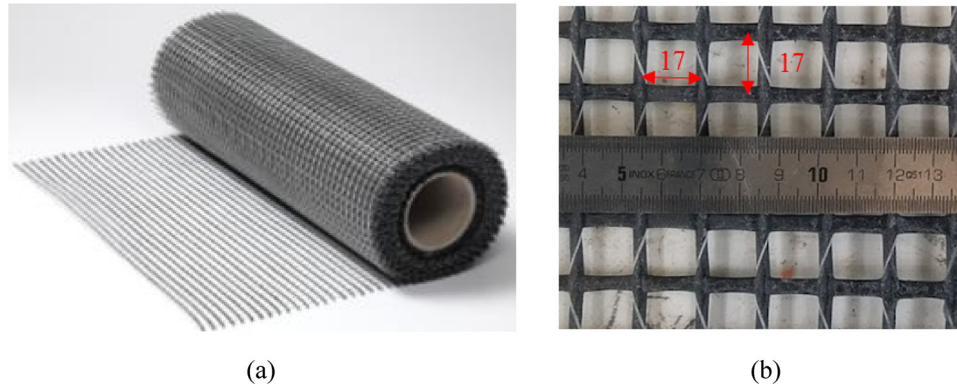


Figure 2: Carbon textile for the experiment. (a) Roll of carbon textile (1.95 m × 50 m). (b) Geometry of carbon textile.

averaging three measurements (width and thickness) taken at three different cross-sections along each specimen.

2.3 Test setup

As in the authors' previous research [26,27], the equipment used for the experimental works was the universal traction machine (mechanical capacity of 20 kN), which was additionally equipped with a laser sensor placed outside the machine to measure specimen deformation. This measured equipment is based on the non-contact measurement method that provided reasonable and precise measurement results in previous studies [28,29]. Figure 4 shows

the test setup with the equipment used for the non-reinforced cementitious matrix and C-TRC specimens. The experimental techniques and methods for verifying the results were detailed in the authors' previous publications [26–29].

3 Experimental results

3.1 Mechanical behaviour of carbon TRC

Figure 5 shows the stress–strain curves depicting the tensile mechanical behaviour of carbon TRC with the reinforcement of one and two carbon textile layers. As a result,

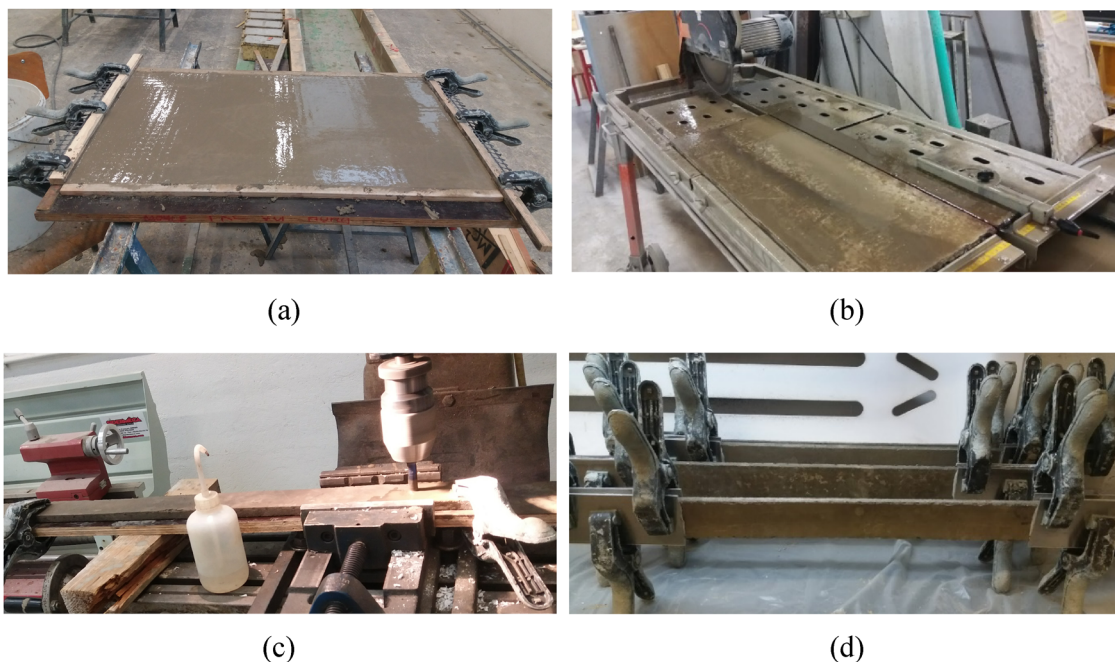


Figure 3: Procedure for preparing the C-TRC composite specimens. (a) Hand lay-up moulding technique. (b) Cutting to C-TRC specimens. (c) Making hole in the C-TRC specimens. (d) Bonding two ends with aluminum plates.

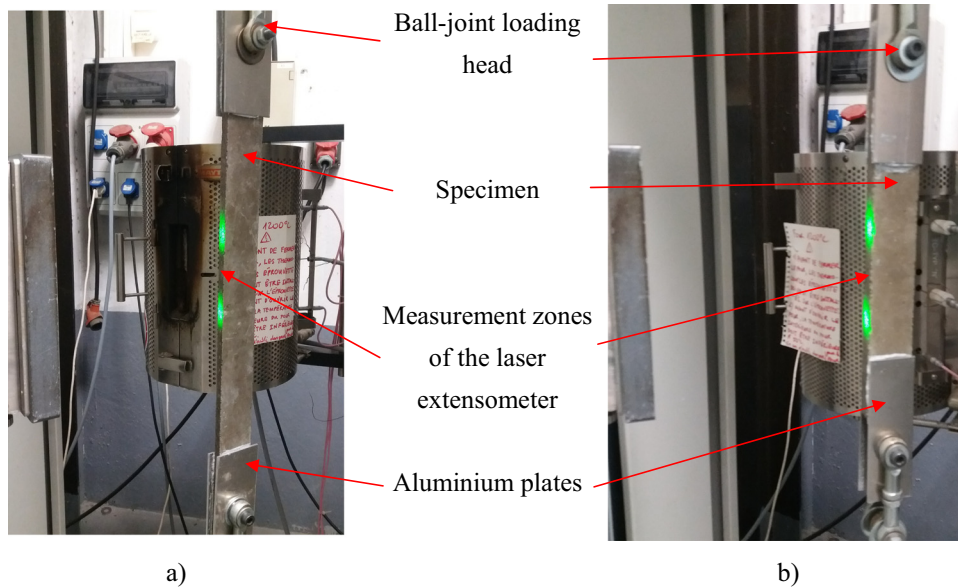


Figure 4: Test setup in the experimental works. (a) For carbon TRC specimens. (b) For non-reinforced cementitious matrix specimens.

C-TRC specimens exhibited a strain-hardening behaviour characterized by three distinct phases: linear phase, cracking phase, and hardening phase. During the initial linear phase, the C-TRC specimen provided a quasi-linear behaviour from the onset of the curve to the beginning of cracking. Subsequently, in the cracking phase, cracks occurred progressively on the surface of the cementitious matrix, leading to a drop in stress on the stress-strain curves. In the final phase, after being already cracked, the cementitious matrix had no contribution to the tensile performance of the C-TRC specimen, the carbon textile almost supported all applied tensile force. So, C-TRC specimens exhibited a quasi-linear behaviour in their failure.

3.2 Mechanical properties of carbon TRC specimens

An idealized representation of the strain-hardening curves was employed to characterize the mechanical properties of the C-TRC composite. Three points corresponding with the beginning of cracking (point I), the end of cracking (point II), and ultimate stress (UTS point) are characterized and divided into three phases of the mechanical behaviour of the C-TRC composite. The stress and strain at these points, along with the tangent of the three phases, were utilized to determine the mechanical properties of C-TRC. As a result, for C-TRC with one textile layer, the cracking stress (σ_I) was

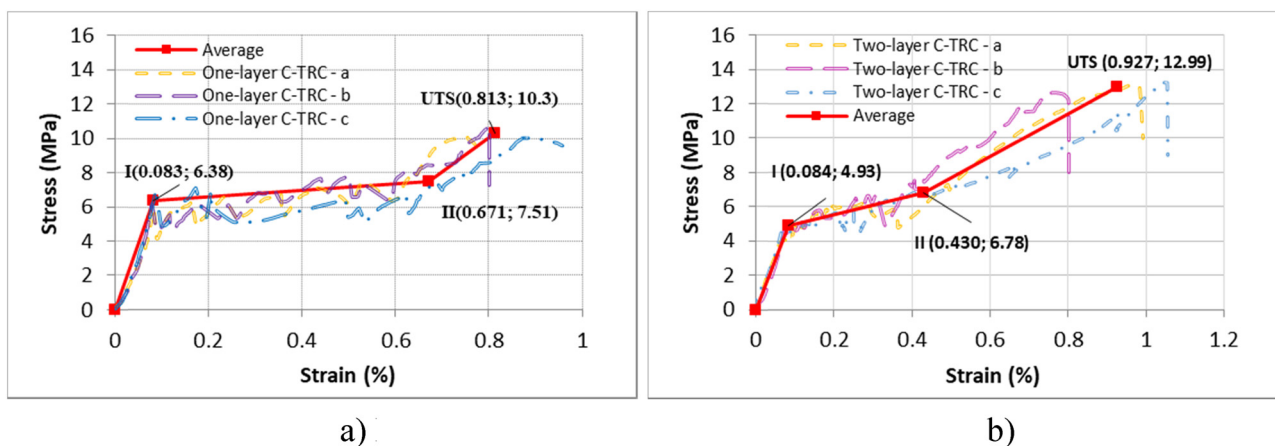


Figure 5: Mechanical behaviour of carbon TRC composites. (a) For one-layer C-TRC specimens. (b) For two-layer C-TRC specimens.

Table 2: Experimental results of tensile tests performed on C-TRC specimens

Specimen	First crack values			Post crack values					
	σ_I (MPa)	ε_I (%)	E_I (GPa)	σ_{II} (MPa)	ε_{II} (%)	E_{II} (GPa)	σ_{UTS} (MPa)	ε_{UTS} (%)	E_{III} (GPa)
C-TRC-a	5.96	0.083	11.27	7.00	0.614	0.36	10.11	0.750	2.94
C-TRC-b	6.19	0.079	11.99	7.89	0.644	0.45	10.78	0.801	2.48
C-TRC-c	6.99	0.087	10.74	7.64	0.754	0.18	10.02	0.889	2.08
Average	6.38	0.083	11.33	7.51	0.671	0.33	10.30	0.813	2.50
2-Layer C-TRC-a	4.86	0.094	9.00	6.55	0.450	0.23	13.11	0.963	1.53
2-Layer C-TRC-b	4.83	0.075	7.98	7.02	0.385	0.49	12.64	0.764	1.52
2-Layer C-TRC-c	5.10	0.095	7.93	6.76	0.456	0.66	13.22	1.053	1.43
Average	4.93	0.084	8.30	6.78	0.430	0.46	12.99	0.927	1.49

6.38 MPa, corresponding with the first phase deformation (ε_I) of 0.083% (average value), while the stiffness in the first phase was 11.33 GPa (value average). The mechanical capacity of the one-layer C-TRC specimen was identified by the ultimate strength (σ_{UTS}) of 10.3 MPa and the ultimate strain (ε_{UTS}) of 0.813. Concerning the mechanical properties of the two-layer C-TRC specimen, they were similar to the value for the one-layer C-TRC specimen at the linear and cracking phases. However, this composite reached the ultimate strength of 12.99 MPa and the ultimate strain of 0.927 for ultimate mechanical properties. Table 2 presents all the mechanical properties of C-TRC specimens with one and two layers of carbon textile.

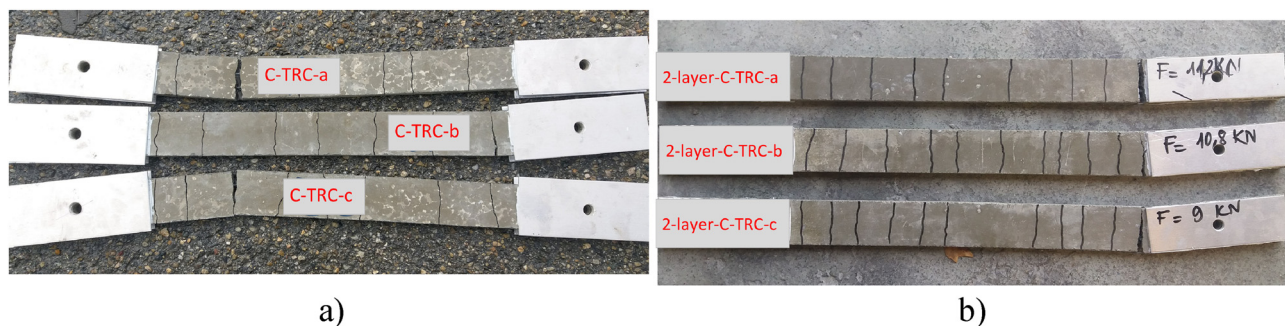
cementitious matrix, which occurred more rapidly and intensely after each crack. As a result, the matrix reached its critical state for subsequent cracks sooner, leading to a reduction in the distance between successive cracks. However, both C-TRC specimens presented a fragile failure mode in the end, which was remarkable by a significant drop in stress on the stress–strain curves. Furthermore, the failure mode was also observed by the opening of main cracks that showed the damage of carbon textile or the pull-out slip of the carbon textile/cementitious matrix interface.

3.3 Failure mode

The C-TRC specimens after being damaged were observed to analyse their failure modes, as presented in Figure 6. On the surface of the cementitious matrix, there were transversal cracks that occurred during the cracking phase. The number of these cracks increased when two layers of carbon textile were used. This increase was due to the enhanced transfer of shear stress from the textiles to the

4 Numerical modelling

To investigate the effect of the reinforcement ratio on the mechanical behaviour and properties of the C-TRC composite, numerical modelling was performed on Ansys Mechanical. In this study, the reinforcement ratio ranged from 0.5 to 1.5% by changing the thickness of the cementitious matrix layer in the model. This section comprehensively outlines all numerical procedures, encompassing the construction of the numerical model, integration of experimental data, and analysis of the results.

**Figure 6:** Failure mode of the C-TRC specimens. (a) For one-layer C-TRC specimens. (b) For two-layer C-TRC specimens.

4.1 Finite-element (FE) model

The FE model was meticulously constructed in Ansys mechanical corresponding to half of the C-TRC specimen as in the experiment. Two types of elements were employed for the constituent materials: LINK180 (3D spar or truss) for carbon textile yarns and SOLID65 (3D reinforced concrete solid) for the cementitious matrix, as depicted in Figure 7a. The properties of both used elements have been presented in the author's previous studies [30,31]. Boundary conditions and loads were applied in accordance with the experimental setup: Fixed supports were assigned to all nodes in the end zone, while imposed displacement was applied to all nodes at the right end, as illustrated in Figure 7c. This configuration ensured consistency between the numerical model and experimental conditions.

4.2 Material model and input data

In this study, the material models utilized for the components of the C-TRC composite were selected based on their mechanical behaviour. For the carbon textile yarns, a linear elastic model was employed, with the ultimate strength and Young's modulus serving as the principal input parameters.

For the cementitious matrix, the concrete model (CONCR – nonlinear behaviour concrete) that takes into account the cracking behaviour by a material failure criterion was chosen [33]. The stress–strain relationship of this model, in the case of cracking occurring in one direction only as observed in the C-TRC specimens, is illustrated in Figure 7b, where f_t is the uniaxial tensile cracking stress, T_c is a multiplier for the amount of tensile stress relaxation, ϵ_{ck} is the uniaxial tensile cracking strain, and R_t is the slope (secant modulus), as defined in Figure 7b. Table 3 presents all the input data of the numerical model and parametric study of the effect of reinforcement ratio.

4.3 Numerical result

The numerical model provided the strain-hardening curves of the mechanical behaviour of the C-TRC specimen, as depicted in Figure 8a. However, depending on the reinforcement ratio, the C-TRC specimen exhibited different shapes of stress–strain curves. When the reinforcement ratio decreases, the cracking phase is extended at a lower stress level. For instance, with a reinforcement ratio of 0.5%, the C-TRC specimen was damaged in the cracking phase, leading to the shortening of the stress–strain curve. Similarly, at a

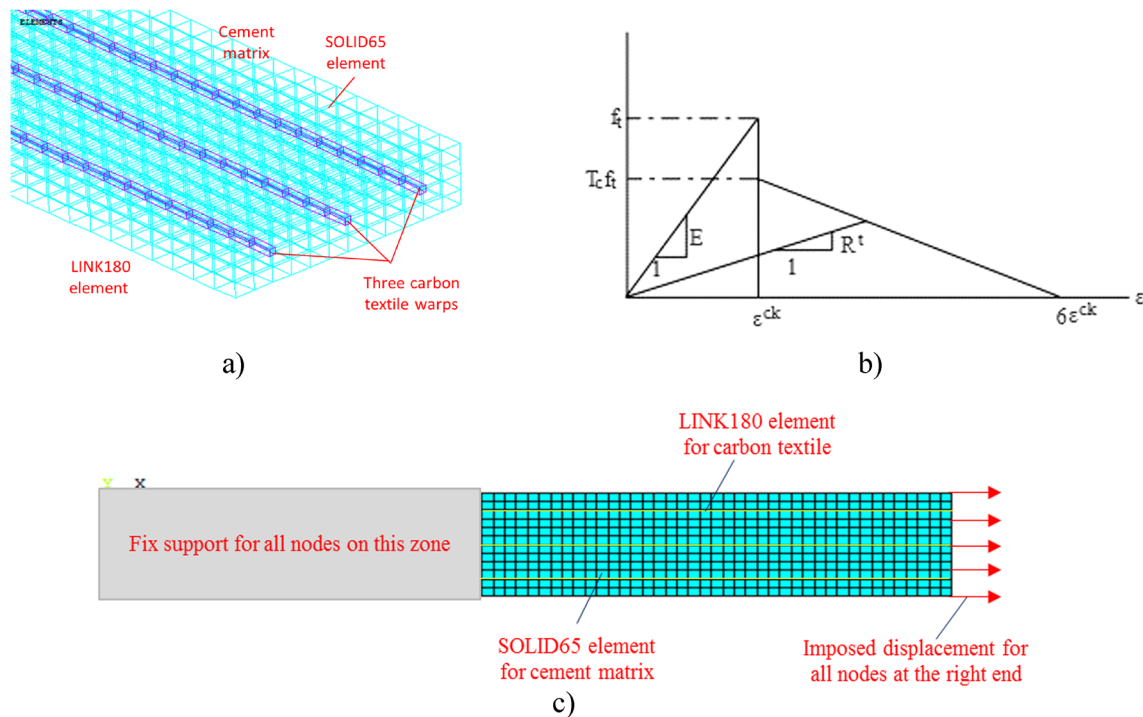


Figure 7: Configuration of meshing, boundary conditions, and loads for the C-TRC specimen model. (a) Elements for textile warps and cementitious matrix. (b) Material model for concrete model (CONCR – Nonlinear Behavior – Concrete) [32]. (c) Boundary conditions and loads.

Table 3: Input data for numerical model

Materials	Carbon textile		Cementitious matrix			
	E_f (GPa)	σ_f (MPa)	E_m (GPa)	f_t (MPa)	ε_{ck} (10^{-4})	T_c
C-TRC	144	1312	8.41	5.29	6.29	0.8
Effect of the reinforcement ratio						
Reinforcement ratio (%)	0.5	0.70	0.90	1.10	1.30	1.50
Thickness of matrix layer (mm)	21.12	15.08	11.73	9.60	8.12	7.04

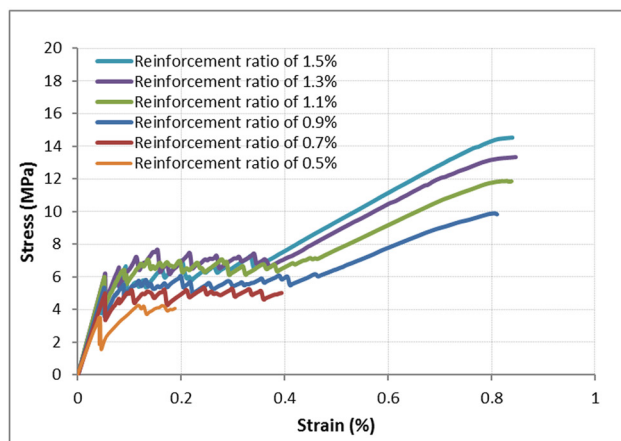
reinforcement ratio of 0.7%, the stress–strain curve fully reached the cracking phase, but not enough for the third phase. However, with a reinforcement ratio exceeding 0.7%, the model demonstrated strain-hardening curves characterized by three distinct phases. Hence, it is reasonable to consider the reinforcement ratio of 0.7% as the critical value, as discussed in the study by Contamine [9]. This outcome is attributed to the model's assumption of perfect bonding between the textiles and the cementitious matrix, ensuring that the results align with previous theoretical analyses.

Figure 8b shows a comparison between experimental results and those predicted by the numerical model. The experimental study reports the strength of C-TRC with reinforcement levels of 0.92 and 1.32%, corresponding to one and two reinforcement layers, respectively. Comparing these results with the numerical model, the experimental data (in red) closely align with the predicted values (in blue). This agreement indicates that the experimental results and the numerical model are well-matched. Consequently, the numerical model can effectively be used to assess the impact of reinforcement content on the mechanical properties of C-TRC composites.

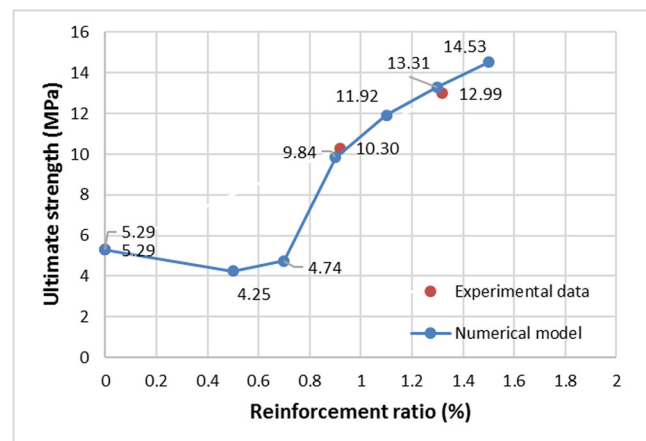
4.4 Effect of the reinforcement ratio

In the experiment, the results obtained on the one and two-layer C-TRC specimens were compared with those of non-reinforced cementitious matrix specimens to find the effect of the reinforcement ratio. As a result, the ultimate strength (σ_{UTS}) of C-TRC was improved by 95 and 146% compared to that of non-reinforced specimens, respectively, with the reinforcement of one and two carbon textile layers. However, the cracking stress (σ_f) exhibited a different trend: it increased by approximately 21% with one layer of reinforcement but decreased slightly by 7% with two layers. This reduction in cracking stress with additional layers can be explained similarly to the case of the number of cracks observed on the specimen surface. The increased number of layers made the cementitious matrix more prone to cracking, causing the first crack to appear earlier and thereby reducing the stress intensity at cracking. This finding is consistent with the results reported by Rambo *et al.* [20] in their study of basalt TRC specimens.

In the numerical modelling of the C-TRC composite, the ultimate strength increased from 4.25 to 14.53 MPa with the



a)



b)

Figure 8: Numerical results on C-TRC composite. (a) Stress–strain curves depending on the reinforcement ratio. (b) Evolution of ultimate strength depending on the reinforcement ratio.

rise of the reinforcement ratio. The effect of the reinforcement ratio on the tensile capacity of the C-TRC specimen could be divided into two intervals: a slightly negative impact when the reinforcement ratio is lower than 0.7% and a positive effect when the reinforcement ratio is higher than 0.7%. In the first interval, one carbon textile layer was not strong enough to reinforce the cementitious matrix because of the thickness of this layer. In the second, the ultimate tensile strength was improved with the non-linear curve, depending on the reinforcement ratio (Figure 8b). The curve trends towards a horizontal asymptote, indicating that at a certain critical value, further increases in reinforcement content lead to only marginal gains in TRC strength. This behaviour is attributed to the decreased efficiency of the textile layers working together at high reinforcement ratios, resulting in only modest improvements in reinforcement effectiveness. Consequently, selecting the optimal number of reinforcement layers (or reinforcement ratio) is crucial to meet technical requirements while minimizing waste.

5 Conclusion

This article presents the experimental and numerical results on the effect of reinforcement ratio on the mechanical behaviour and properties of carbon TRC composite. As a result, the following conclusions can be drawn from this work:

Experimental work showed the strain-hardening behaviour of both C-TRC specimens with reinforcement ratios of 0.92 and 1.32%. The ultimate strength of C-TRC specimens was improved by 95 and 146% compared to that of non-reinforced specimens, respectively, with a reinforcement ratio of 0.92 and 1.32%. However, the cracking stress (σ_f) increased by approximately 21% with one layer of reinforcement but decreased slightly by 7% with two layers. The failure mode of C-TRC specimens showed transversal cracks along the specimen length, and the number of cracks increased with the rise of the reinforcement ratio.

The numerical model could predict the mechanical behaviour of the C-TRC composite with different shapes depending on the reinforcement ratio. The model reached the strain-hardening curve with three distinct phases when the reinforcement ratio was higher than a critical value (0.7%). The impact of the reinforcement ratio on the tensile capacity of the C-TRC specimens can be categorized into two intervals: a slightly negative effect for ratios below 0.7% and a positive effect for ratios above 0.7%. As the reinforcement ratio increased from 0.5 to 1.5%, the ultimate strength of the C-TRC composite improved significantly, rising from 4.25 to 14.53 MPa.

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Conflict of interest: Authors state no conflict of interest.

Data availability statement: Most datasets generated and analysed in this study are comprised in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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