

IMPLEMENTATION OF EXPERIMENTAL DATA IN ANALYSES OF TEXTILE REINFORCED CONCRETE STRUCTURES

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Abstract

Textile reinforced concrete (TRC) is an innovative high performance composite material which has revealed many promising attributes in various applications but has not yet reached its recognition due to a lack of available design tools. To be able to reach this stage, standardized test methods and reliable numerical models need to be established to reduce uncertainty and the need for extensive experimental studies.

The aim of this paper is to present an approach which links experimental methods to simplified numerical analyses. The applied experimental methods are categorized according to the mechanical behaviour features they encompass: *material*, *interaction* and *global* levels. A 2D-macro-scale FE-model was developed, as a case study, using experimental data from material and interaction levels as input. The outcome of this analysis was compared to the *global* level data to identify the effects of key parameters in FE-modelling of TRC.

Comparison of the FE-analysis results and the experiments indicated that the developed modelling method describes certain mechanisms adequately while posing certain limitations. It was shown that the bond between the textile and the concrete is a very critical input parameter which affects crack development, deflections, and failure mechanisms.

Key words: Textile Reinforced Concrete (TRC), experimental methods, mechanical properties, macro-mechanical modelling

1. INTRODUCTION

In fibre composite materials, such as textile reinforced concrete (TRC), the existing complex heterogeneous structure poses challenges concerning modelling and design. The underlying complexity is related to the bond between reinforcement and the fine-grained concrete matrix but also to the bond between the individual filaments found within a yarn. Various types of numerical methods have been developed for the purpose of deepening the understanding of the bond behaviour and interaction between the filaments [1-4], yet these can be computationally expensive when linked to other levels of simulation, i.e. multi-scale, and the required input parameters are also difficult to come by. Simplified numerical models could however be developed using detailed experimental input parameters which describe the complex bond behaviour along with important material and mechanical behaviours.

An approach which links experimental methods to simplified numerical models is presented in this work, similar concepts have also been applied by others [5-7]. Macro-scale modelling is investigated using experimental inputs obtained at various levels of detail (see Figure 1). These experimental inputs capture different features of the mechanical behaviour of TRC, which are defined in this work as *material*, *interaction* and *global*. The material level consists of the quantification of the material characteristics of the concrete and reinforcement, e.g. tensile and compressive behaviour. The composite behaviour of these two materials is thereafter taken into account through experimental testing at the interaction level, i.e. pull-out tests. As for the global level, TRC is tested in the form of a composite structure under prescribed loading conditions, i.e. tensile or flexural loading. Thereafter, the outcome of the macro-scale level is applied to validate and gain insight on the sensitivity of input parameters related to the associated numerical model.

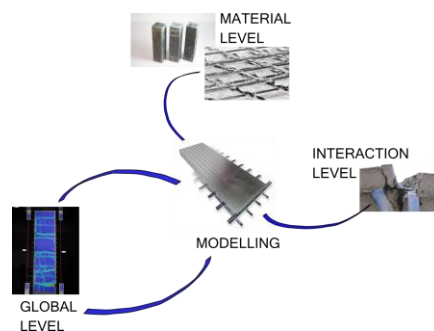


Figure 1: Conceptual figure of the implementation of experimental data in a macro-scale mechanical model

A comprehensive experimental test program based on the defined experimental levels, shown in Figure 1, is presented in this paper. The resulting outputs of the experiments at the material and interaction level were included as input parameters in a case study of a 2D macro-scale model of a TRC panel undergoing four-point bending. By doing so, one can gain a better understanding of the complex heterogeneous behaviour and the effects of different key parameters used in the macro-modelling of TRC.

2. EXPERIMENTAL WORK

2.1. Material level

The material level includes the measurement of the material characteristics pertaining to both hardened concrete and the selected textile reinforcement. Concerning the concrete, for simplicity, the properties of interest here are categorized as compressive and tensile nature at an age of 28 days.

The mechanical behaviour of concrete in compression was evaluated based on EN 12390-3 [8] and EN 12390-13 [9] to obtain the stress-strain relation, $\sigma(\epsilon)$, compressive strength, f_c , ultimate strain, ϵ_{cu} , modulus of elasticity, E_c , and Poisson's ratio, ν_c . The tests were carried out in a GCTS servo-hydraulic machine with a stiff load frame and load measurement accuracy of 1 %. The axial deformation of the specimen was obtained by two inductive displacement transducers measuring the distance change between two aluminium rings attached to the specimen. The transducers had a measuring range of ± 2.50 mm and a relative error less than 1 %. The circumferential deformation was obtained by using a chain mounted around the specimen at half height. The change in chain-opening gap was measured by an inductive displacement transducer. The instrumentation for axial and circumferential deformation measurements is illustrated in Figure 2 (left).

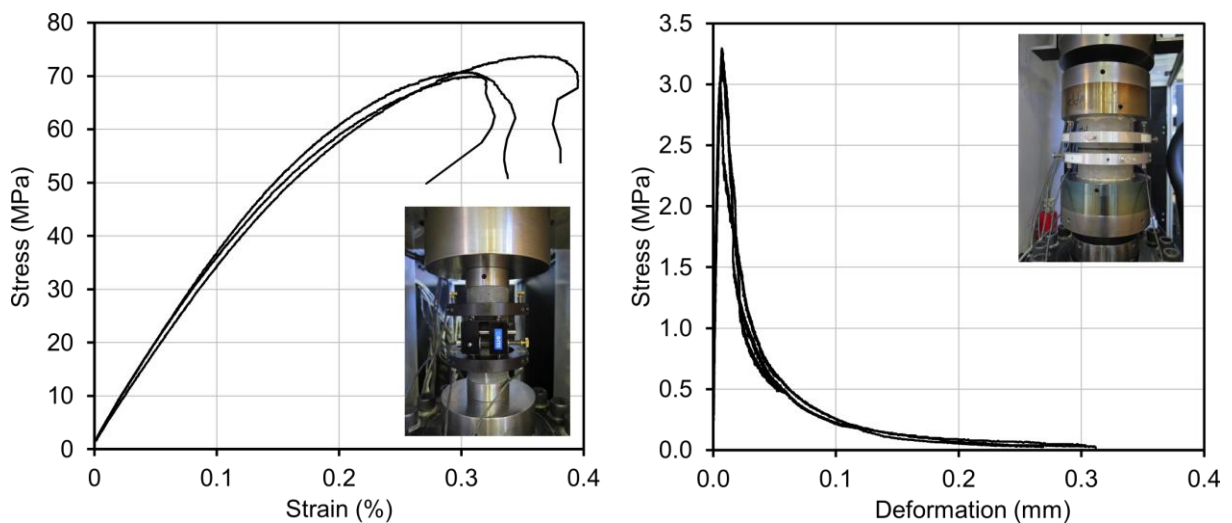


Figure 2: Example of compressive stress-strain results (left) and tensile stress-deformation results (right)

The material characteristics in tension, including tensile strength, f_t , stress-crack opening relation, $\sigma(w)$, and fracture energy, G_F , were evaluated using uniaxial tensile tests on notched cylinders (see Figure 2 (right)) based on RILEM TC 187-SOC [10] and RILEM TC 162-TDF [11]. The tests were conducted using the same test apparatus used for the compressive tests. The deformation was measured locally over the notch with three inductive displacement transducers, whereas the deformation, δ , was calculated as the mean value of the three displacement gauges.

The accuracy of the load measurement as well as measuring range and relative error of the transducers were the same as for the compressive tests.

As a part of the evaluation, the stress-deformation curve shown in Figure 2 (right) was used for deriving the softening behaviour of the concrete material. The tensile stress, σ , was derived by dividing the load by the effective cross-section, A_{eff} , at the notch. The tensile strength, f_t , is defined as the peak stress and deformation at peak stress, δ_{tu} , which takes place at the onset of macro cracking.

General material and mechanical properties are commonly provided by the textile reinforcement producers, which include geometric parameters of the mesh/grid, weight, applied coating, tensile strength, modulus of elasticity and elongation, but are not limited to these parameters. However, the methods used to obtain the mechanical properties vary based on the source and are most often not documented, thus the soundness of the available data could be questioned. The quantification of the general material properties of the textile reinforcement was conducted using tensile testing according to the standard method stated in ISO 10406-1 [12]. The ultimate tensile capacity, F_u , tensile rigidity EA , and ultimate strain, ϵ_u , of the textile reinforcement are the general outputs of this test method, yet these can also be converted to tensile strength and Young's modulus of the material. The tests were carried out using a universal testing machine (Sintech 20D) illustrated in Figure 3 and the force was recorded by a load cell with an accuracy of 1 %. The deformation was measured by a Messphysik Videoextensometer ME46 with backlight technique in the background and digital camera in the foreground as per Figure 3. Further details pertaining to this experiment are documented in Williams Portal, Flansbjerg, et al. [13].

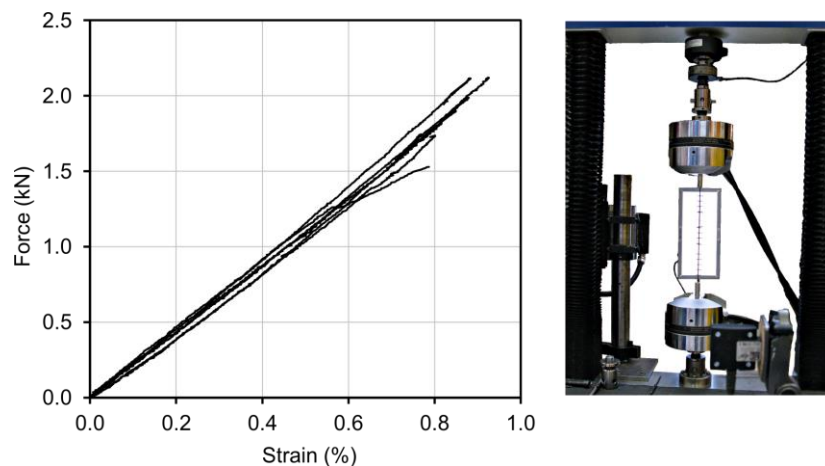


Figure 3: Example of tensile test results (left) and tensile test setup with video extensometer (right).

2.2. Interaction level

The interaction level comprises the quantification of the complex heterogeneous behaviour between the cementitious matrix and the textile reinforcement. This behaviour was measured by means of pull-out tests and was characterized as a calibrated bond stress-slip relationship of TRC with carbon textile reinforcement. The pull-out tests consisted of a double-sided unsymmetrical configuration, whereby the

specimen was divided into a shorter embedment length zone and a longer anchorage length zone. The specimens had dimensions of 400 x 100 x 15 mm and were reinforced by a centrally cast layer of reinforcement mesh. The varying of embedment lengths was studied in order to characterize both pull-out and rupture of the textile. The experimental setup developed to conduct the pull-out tests is shown in Figure 4. A detailed account of the experimental program, and the evaluation of a bond stress-slip behaviour, is reported in Williams Portal, Perez Fernandez, et al. [5] and Williams Portal, Lundgren and Malaga [14]. It should be noted that the concrete and textile reinforcement applied in these particular tests slightly differ from the other presented tests. This bond stress-slip behaviour is however applied in the case study as an expected behaviour.

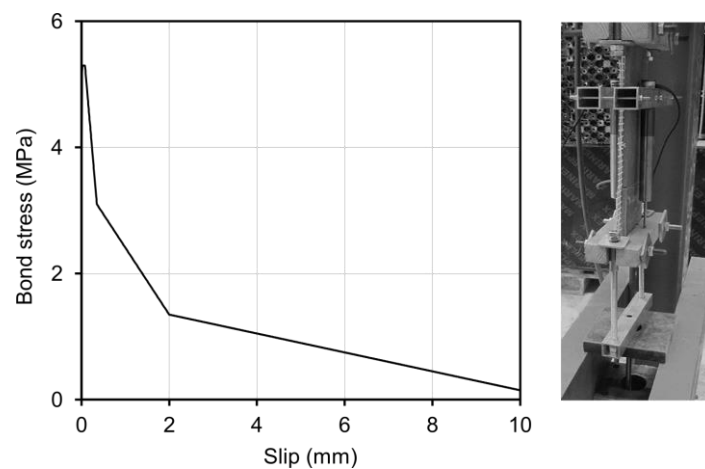


Figure 4: Bond stress-slip curve (left) derived from the pull-out tests (right)

2.3. Global level

The global level includes experiments that describe the global behaviour of TRC structures. These obtained data can be used in a further step to verify the composite behaviour of the given developed macro-mechanical model. For instance, from the tensile tests of TRC, it is possible to evaluate the stress-deformation relation, first crack stress and maximum load resistance, type of failure, crack spacing and crack widths. Similar outputs can be retrieved from flexural tests, with the addition of load-midspan deflection relation and flexural resistance.

To determine the tensile load bearing behaviour of TRC, uniaxial tensile tests were performed according to the draft recommendations given in RILEM TC 232-TDT [15] (see Figure 5 (right)). In this study, the specimens were 700 x 100 x 20 mm with two layers of carbon textile reinforcement (see Figure 6). These tests were carried out in an electro-mechanical universal testing machine (Sintech 20D) and were displacement controlled. The load and machine displacement were recorded in a data acquisition system (sampling rate of 10 Hz).

In order to investigate the flexural properties of TRC, four-point bending tests were performed based on EN 12390-5 [16], yet other comparable provisions could also be applied. The tests were performed using a servo-mechanical testing machine (Instron 1195). The sample panels with the same geometry as those used in the tensile tests

were placed on roller supports with a span of 600 mm as depicted in Figure 5 (left). The samples were loaded by two upper point loads each applying a load of $P/2$ with a distance 200 mm apart from each other. The loading was applied using displacement control. On opposite sides of the panels, two linear displacement transducers (LVDT) were placed at midspan.

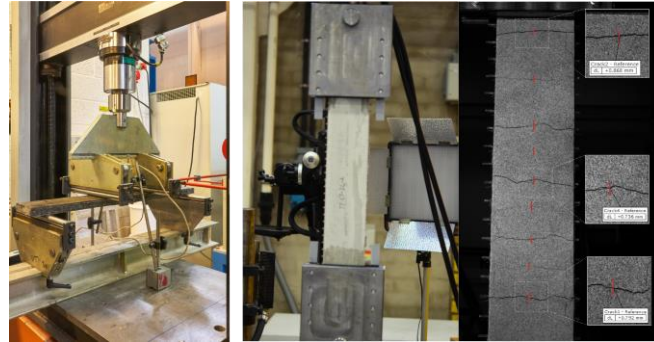


Figure 5: Flexural test (left) and uniaxial tensile test setup with crack measurements from DIC measuring system (right)

To obtain precise measurements of the resulting deformations and crack developments, an optical full-field deformation measurement system ARAMIS™ 12M by GOM was used for tensile tests, but could also be applied to flexural tests. The system uses a measurement technique based on Digital Image Correlation (DIC) with a stereoscopic camera setup, consisting of two CCD-cameras. Over the course of the uniaxial tensile testing in this study, this system was used to record the displacement of the specimen during testing by tracking the deformation of a speckle pattern in a series of digital images acquired during the loading. The displacement of the pattern within discretized facets of the image was thereafter analysed. It is possible to capture the initiation of the first crack as well as close up images of the local crack measurements by means of virtual extensometers as shown in Figure 5 (right).

3. NUMERICAL MODEL

A case study is presented here consisting of a non-linear 2D macro-scale model which was developed based on the presented four-point bending tests of a TRC specimen reinforced by two layers of carbon textile reinforcement grid (see Figure 6). The commercial software DIANA (Displacement ANAlyser) with pre- and post-processor Midas FX+ was used to perform the analyses. The main purpose of this model was to verify the experimentally observed flexural behaviour and failure mode, as well as to identify difficulties and uncertainties in the modelling of TRC.

A mesh size of 2 x 2 mm was chosen to fit element rows below or above the reinforcement while ensuring that the textile reinforcement was located at a row of nodes. Interface elements are included here because the bond between the textile reinforcement and matrix cannot be assumed to be perfect due to the heterogeneous structure of the yarns. The element types used for the various model components are provided in Table 1 along with a description of the associated data inputs.

In the model, the point loads were applied as fixed deformations. In each step, equilibrium was calculated using secant iterations, which was found to yield the most suitable solution. This deformation controlled loading means that the behaviour, especially during the cracking state, can be followed more accurately which can also lead to improved comparison with the experimental results.

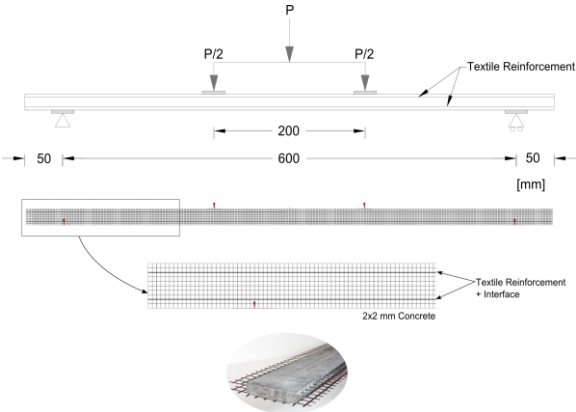


Figure 6: Overview of developed macro-scale model

Table 1: Model inputs from material and interaction levels.

Component	Element type	Material Level input	Interaction Level input
Concrete	2D quadrilateral isoparametric plane stress; 4 nodes (<i>Q8MEM</i>)	<ul style="list-style-type: none"> - Compressive behaviour (72 MPa , Figure 2) - E-modulus (36 GPa) - Tensile behaviour (3.2 MPa, Figure 2) - Fracture energy (96 N/mm) - Poisson's ratio (0.2) 	—
Textile reinforcement grid	1D truss bar; 2 nodes (<i>L2TRU</i>)	<ul style="list-style-type: none"> - Tensile behaviour (Figure 3) - E-modulus (250 GPa) 	—
Interface	2D line-interface; 4 nodes (<i>L8IF</i>)	—	- Bond stress-slip curve (Figure 4)

4. RESULTS AND DISCUSSION

The numerical simulation results were compared to the *Global* experimental results related to the abovementioned TRC specimen undergoing four-point bending. The load versus midspan deflection relationship of two simulations, denoted as 1 and 2 are compared to the experimental data in Figure 7. It should be noted that the main difference between Simulations 1 and 2 is the defined contact perimeter of the reinforcement which has been adjusted to visualize the need for matching *Interaction* level input parameters, which was similarly implemented in Williams Portal,

Lundgren, et al. [6]. As can be observed, first cracking of Simulation 1 takes place at a comparable load level to that of the experiments, yet it is delayed presumably due to the dissimilar *Interaction* level input. An attempt to yield an improved correlation was made with Simulation 2, wherein first cracking takes place nearer to the actual deflection value and slightly lower load. Also, the load drop after the first crack is smaller while the post-crack stiffness is comparable to the experimental curves. The state of stress and strain at first cracking for Simulation 2 is depicted in Figure 7.

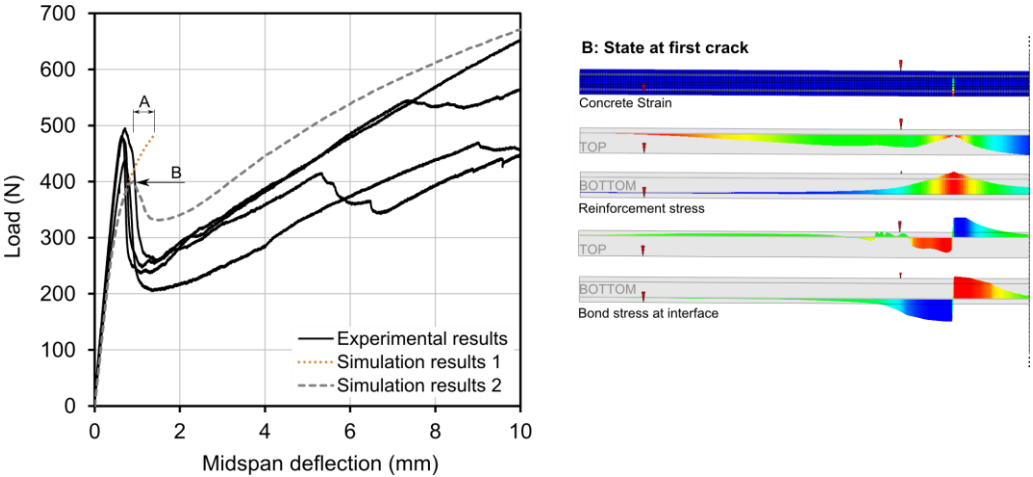


Figure 7: Load versus mid-span deflection relationship. A: shift between first cracking for Simulations 1 and 2.

Furthermore, in previous work by Pettersson and Thorsson [17], it has been shown that an adequate comparison between experimental and numerical results can be achieved by using a bond stress-slip curve corresponding to the given *Global* experimental material combination. Accordingly, it is important to note that these presented analyses can be further enhanced by incorporating corresponding *Interaction* level input, reduction of concrete tensile strength at yarn cross-thread locations, as well as more refined computation using more adept solvers able to capture the vertical load drops at crack occurrences.

5. CONCLUSIONS AND OUTLOOK

An approach linking experimental methods to simplified numerical models has been presented in this paper. The implementation of experimental input data obtained from various levels of detail (*Material* and *Interaction*) in macro-scale modelling was shown to be a promising approach to compare simulation results to those from the experimental *Global* level. One main observation which can be drawn is such that the bond stress-slip relationship from the *Interaction Level* is a critical input parameter in macro-scale analyses. Accordingly, it is paramount to have detailed experimental methods which can characterize input data at the various stated levels for the sake of yielding accurate numerical analyses. Lastly, it should be highlighted that the geometries applied in this work are based on a given application, testing apparatuses and test requirements, but can be varied according to the intended design scenario.

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