CORRELATION BETWEEN THE MATERIAL TENSILE PROPERTIES AND THE FLEXURAL RESPONSE OF UHPFRC PANELS

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Abstract

This paper describes the results of an experimental test program carried out to study the correlation between the tensile properties of a UHPFRC material and the flexural response of structural panels. The material tensile response was characterized through a direct tension test method using both mould cast and extracted specimens and validated through an image analysis technique. A significant effect of the casting process on the fiber orientation distribution and thus on the material tensile properties was observed and quantified at different specimen orientations. In order to correlate the material tensile properties and the flexural response of structural components, one-way and two-way flexural tests on UHPFRC panels were also completed and analyzed in light of the previous material characterization results. The fiber orientation distribution derived from the casting process and the element configuration were key factors in the structural response of the UHPFRC panels, particularly for elements tested in the one-way configuration with no structural redundancy. A good agreement was observed between the experimental results and the response estimated through a sectional analysis.

Résumé

Cet article décrit le résultat d'un programme d'essais effectués pour étudier la relation entre les propriétés en traction du BFUP et la réponse en flexion de panneaux structuraux. La réponse à la traction du matériau a été caractérisée en traction directe sur des échantillons moulés et prélevés par sciage, et validée par une technique d'analyse d'image. Un effet significatif du processus de coulage sur la répartition et l'orientation des fibres et donc sur les propriétés de traction des matériaux a été observé et quantifié pour différentes orientations d'échantillons. Afin de corréler les propriétés de traction du matériau et la réponse en flexion des éléments structuraux, des tests en flexion unidirectionnelle et bidirectionnelle ont été effectués sur des panneaux en BFUP et analysés à la lumière des résultats de caractérisation susvisés. La distribution de l'orientation des fibres découlant du processus de coulage et la configuration des éléments sont apparus déterminants dans la réponse structurelle des panneaux de BFUP, particulièrement pour les éléments testés en configuration unidirectionnelle isostatique. Une bonne concordance a été observée entre les résultats expérimentaux et les estimations issues d'un calcul de section.

1. INTRODUCTION

The need for more durable, sustainable and resilient infrastructure requires the engagement of high performance materials and new design approaches. Ultra-high performance fiber reinforced concrete (UHPFRC), a class of cementitious composite material that exhibits exceptional mechanical and durability properties, offers a range of opportunities for architects and structural engineers. The mechanical properties are characterized by compressive strength over 150 MPa and outstanding tensile ductility and toughness derived from the use of fibers as reinforcement [1-2]. However, the growing interest within the engineering community and the steady increase in UHPFRC related projects have illuminated the need of developing a better understanding of the mechanical properties, in particular, the tensile properties, to fully exploit the material and structural opportunities.

This study aims to provide useful experimental evidence for a better understanding of the tensile properties at the material and structural levels. The experimental study comprises tests at both material and semi-structural levels, thus allowing for consideration of correlation between the material tensile properties and the performance of structural components.

2. EXPERIMENTAL PROGRAM

A large experimental research project on the structural efficiency of fiber reinforcement was completed at the Turner-Fairbank Highway Research Center of the U.S. Federal Highway Administration (FHWA) in Virginia, US. The UHPC used in this study is a proprietary material, whose basic formulation has been detailed elsewhere [3,4]. The steel fibers were nondeformed, cylindrical, high tensile strength steel with a diameter of 0.2 mm, a length of 12.7 mm, and a minimum tensile strength of 2.4 GPa. A fiber reinforcement volume fraction of 2.0 % was used for this study.

A total of five slabs 3.0-m long, 0.9-m wide and 50-mm thick were cast using UHPFRC material. The slabs were cast pouring the material at one end of the elements at letting it flow to the other end of the wood formwork. A plexiglass plate was placed and clamped at the top of the formwork to have a confined flow regime representative of the usual casting conditions of thin slab elements, see Figure 1.

Figure 1. Formwork for casting of thin slab elements

2.1 Characterization of the uniaxial tensile response

The direct tension test method developed by Graybeal and Baby [5] was used to characterize the material tensile response. The test method allows for testing prismatic specimens either cast in molds or extracted from structural elements, which is relevant for UHPFRC materials where the tensile response is not precisely an intrinsic property.

Prismatic specimens were saw cut from one of the thin slabs cast using UHPFRC. The prismatic elements were cut at three different inclinations: 0 (F0), 45 (F45) and 90 (F90). Further details of the experimental setup can be found in Maya and Graybeal [6]

2.2 Flexural response of thin plates

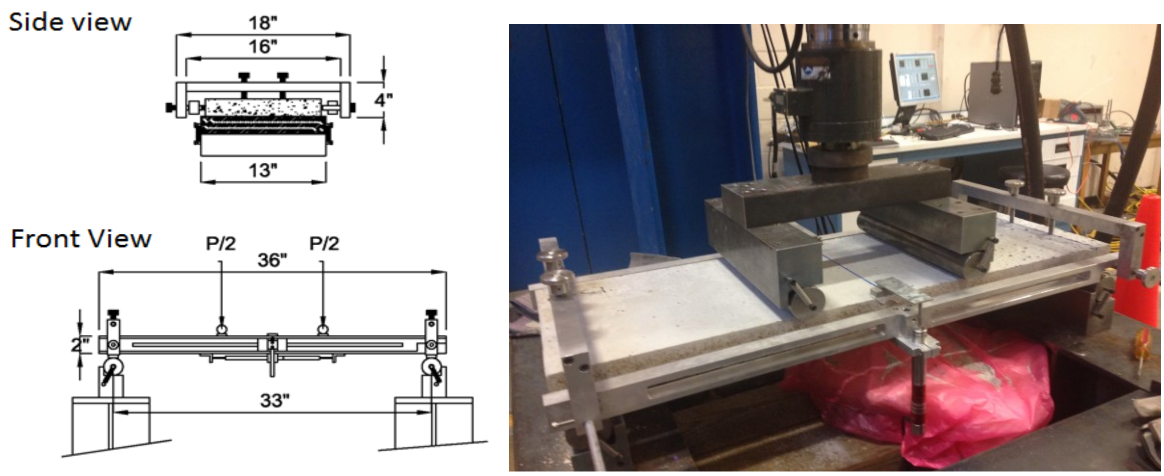

Figure 2. Four-point bending test configuration

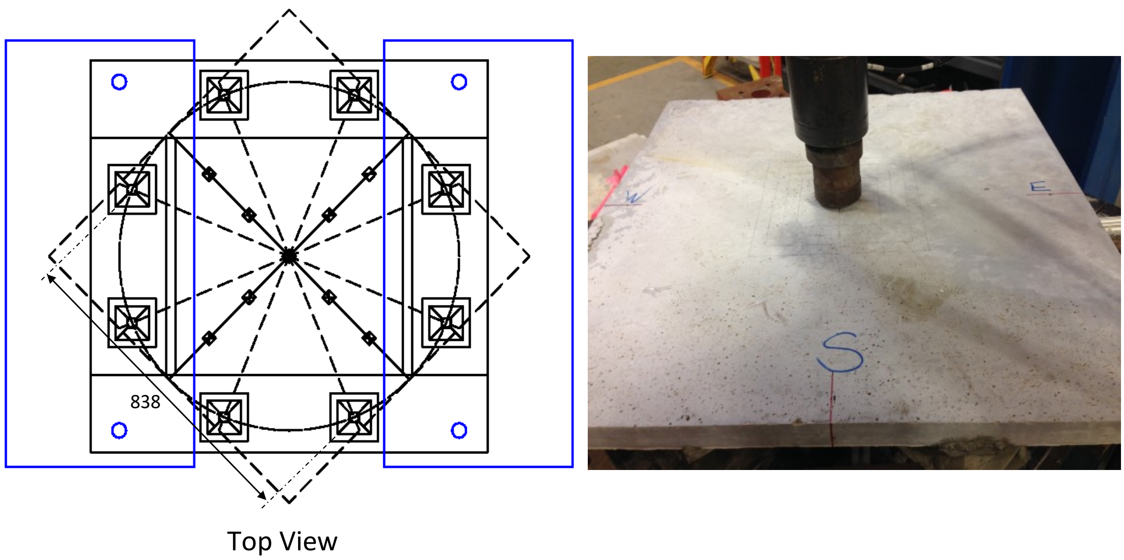

Figure 3. Test setup for square slabs

The flexural performance of thin slab elements was studied through one-way and two-way flexural test configuration. Slab strips 300 mm wide and 914 long were tested under a four point bending test configuration as shown in Figure 2. Low-friction supports were used as suggested in Wille and Parra-Montesinos [7] to avoid bending strength overestimation. The slab strips were saw cut at two different directions from the larger UHPFRC slab elements; parallel and perpendicular to the UHPFRC flow direction during the slab casting. Finally, three 914-mm side square slabs were tested. The slabs were supported at eight concentric points and an incremental load was applied at the center of the slab on a steel square pad of 38 mm side glued to the slabs. Figure 3 shows the testing set up and a schematic of the tested elements.

3. EXERIMENTAL RESULTS

3.1 Uniaxial tensile response

The quantified tensile response of both cast and extracted specimens is shown in Figure 4. The stress versus average axial strain results are presented for the four sets of specimens; specimen sets F0, F45, and F90 which correspond to specimens extracted from the slab and specimen set FEC, which corresponds to the companion prismatic specimens cast in molds. The thin lines correspond to individual specimens, while the thick lines are the averages for each specimen set. Table 1 summarizes the main average results for each specimen set, i.e., compressive strength, elastic modulus, first cracking stress, average multi-cracking strength, and strain at localization. A detailed description of the tests results was can be found in Maya and Graybeal [6]

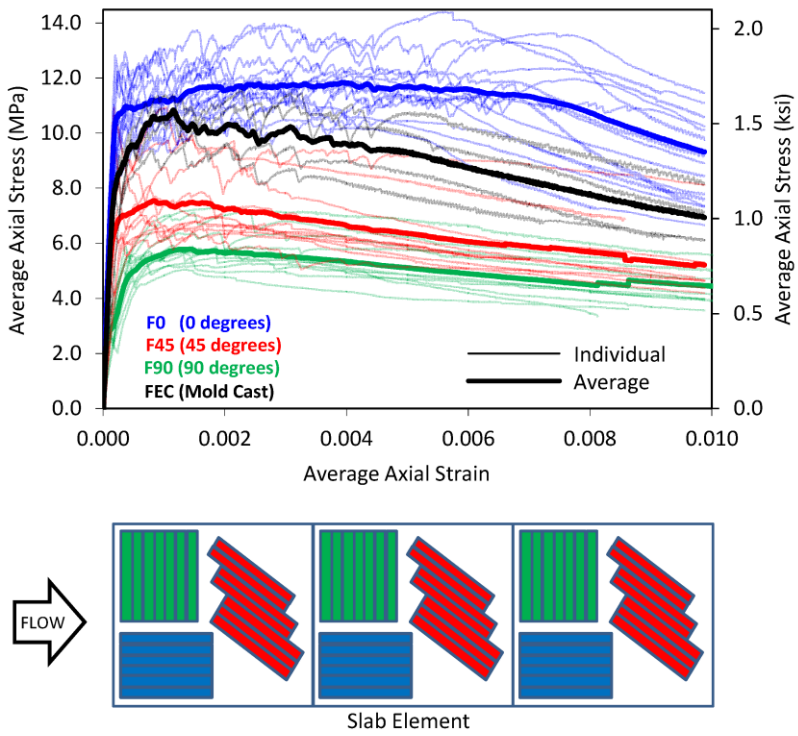

Figure 4. Tensile response of prismatic elements

The specimens extracted parallel to the material flow direction overperformed the rest of the specimen sets in terms of average cracking stress, average multi-cracking stress, strain at localization and elastic modulus. A significant reduction in the average cracking stress was observed for specimen sets F45 and F90 which might suggest that the relevant influence of the fiber orientation distribution not only on the post-cracking response, usually determined by the fiber bridging mechanisms, but also on the first cracking stress, which is sometimes related to the tensile strength of the unreinforced matrix.

Table 1. Tensile response of prismatic specimens

Set	Compressive strength (MPa)	Elastic Modulus (GPa)	First cracking strength (MPa)	Average multi-cracking stress (MPa)	Strain at localization ε_μ (m/m)
F0		63.5	9.9	11.4	0.0060
F45	176.5	60.3	7.0	7.1	0.0027
F90		571	5.1	5.6	0.0029
FEC		59.3	8.5	10.1	0.0035

3.2 Flexural response of thin plates

Figure 5 presents the load-deflection curves for the slab strips tested under the four-point bending tests configuration. The load was normalized by the strip width as well as by the estimated nominal plastic load, which is the estimated load at the critical section at which the characteristic multi-microcracking regime of the UHPFRC ends. A simplified elastoplastic approach [8] was adopted to estimate the plastic load $P_{pl,max}$, as shown in Equation (1).

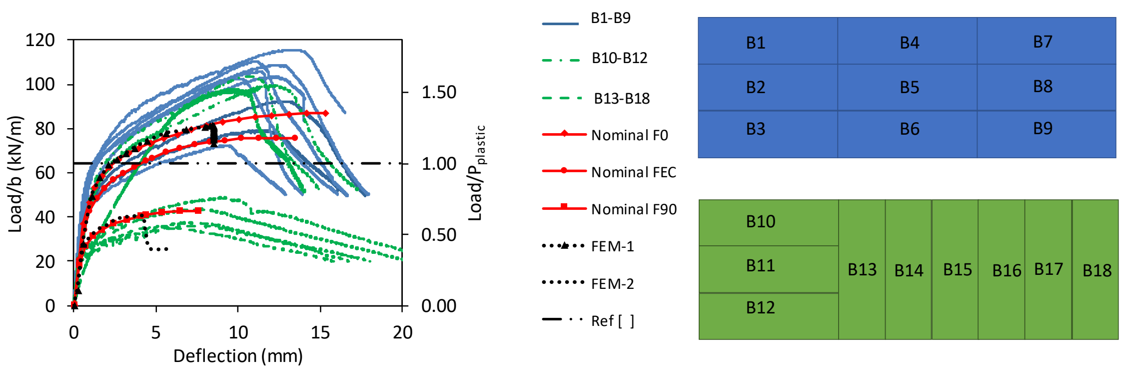

Figure 5. UHPFRC slabs, four point bending test results

$$P_{pl,max} = f_{ct} n_{f_{ct}} \frac{b h^2}{6 L_{shear}} \qquad (1)$$

$$n_{f_{ct}} = \left(3 - \frac{2\sqrt{2} f_{ct}}{\sqrt{f_{ct}\left(E_c \varepsilon_\mu + \sqrt{f_{ct}(2E_c\varepsilon_\mu - f_{ct})} \right)}} \right) \qquad (2)$$

where f_{ct} is the elastic tensile strength, E_c is the elastic modulus of the UHPFRC, and ε_μ is the tensile strain at crack localization; L_{shear} is the shear span and b and h are the slab width and thickness, respectively.

A significant reduction in the bending strength was observed for the thin elements cut perpendicular to the direction of the material flow during the casting; specimens B13 to B18. The thickness of the elements, the casting procedure, and the confined flow regime are the main factors affecting the fiber orientation distribution and thus leading to the anisotropic flexural properties.

A sectional analysis was used to estimate the load-deflection response of the tested elements. The sectional analysis method enables the estimation of the flexural response based on the material tensile characterization tests results. An explicit back analysis method was also implemented to obtain the tensile stress-satin constitutive relationship directly from the flexural tests [9]. The load-deflection responses estimated using the former sectional analysis method and the material characterization tests are also shown in Figure 6. Moreover, the load-deflection response was also estimated through a finite element analysis. ABAQUS finite element software was used and the concrete damage plasticity model was implemented for the UHPFRC material [10]. Although there is an inherent variability in the flexural response, both the sectional analysis and the FE model provide a good estimation of the general response of the thin slabs.

Figure 6 presents the flexural response of the square slab elements concentrically supported and loaded at the central point. The load is presented normalized by the estimated failure load calculated using Equation 3 as proposed by Spasojevic [8], which offers practically the same load estimated through the yield line method [11].

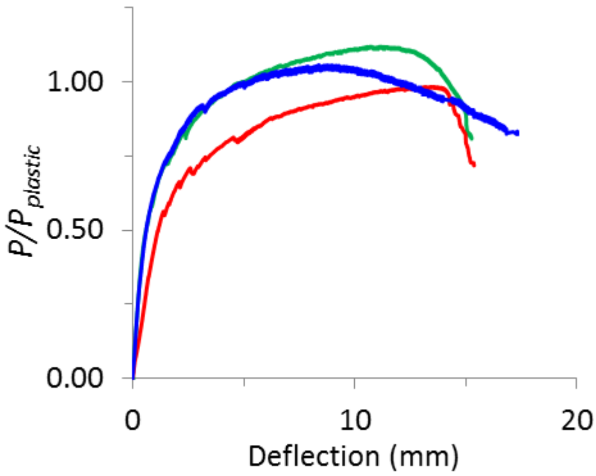

Figure 6. UHPFRC square slabs, two-way flexural tests

$$P_{max} = 6.123 n_{fct} f_{ct} \frac{h^2}{6} \tag{3}$$

All elements exhibited a similar response characterized by an initial linear response up to around 60% of the peak load, which was the followed by an inelastic phase where the deflection increased with the load. The occurrence of multiple microcracking was verified during the post-test inspections, the final failure mode was, however, characterized by the propagation of a main crack running perpendicular to the direction of the material flow during the casting, Figure 7.

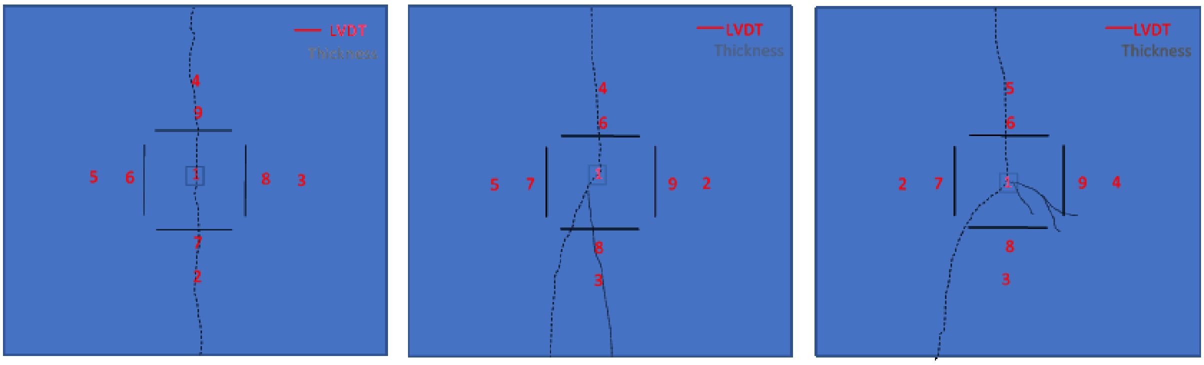

Figure 7. Final cracking pattern of UHPFRC square slabs

4. CONCLUSION

This paper summarizes the results of an experimental study carried out to investigate the correlation between the material tensile properties and the flexural response of thin UHPFRC panels. The material tensile response was characterized through a direct tension test (DTT) method, which allows testing both mould cast specimens and specimens extracted from structural elements. The DTT results corroborate that the tensile response of UHPFRC is not an intrinsic property and it depends on a number of factors, such as the element dimensions, the casting procedure, the flow regime of the material during the casting, among others. A reduction in the average cracking, the average multi-cracking stress, and the strain at localization was observed for specimens extracted at orientations not parallel to the direction of the material flow during the casting. Therefore, the final fibre orientation can lead to clear anisotropy in the tensile material properties.

The anisotropy in the tensile material properties was also corroborated in the flexural tests. A significant reduction in the bending strength was observed for elements saw-cut perpendicular to the direction of the material flow during the casting and tested under a four-point bending configuration. Both sectional analysis methods and FE analysis can provide good estimations of the flexural response of UHPFRC components, however, the potential anisotropy in the material properties need to be properly addressed.

Moreover, the anisotropic material tensile properties can be more relevant for elements without structural redundancy, as observed for the slabs strip saw-cut perpendicular to the direction of the material flow during the casting and tested under the four-point bending test configuration. The UHPFRC square slabs were tested under supporting conditions that provided structural redundancy and, thus, exhibited some level of load redistribution.

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