FLEXURAL TENSION TEST METHODS FOR DETERMINATION OF THE TENSILE STRESS-STRAIN RESPONSE OF ULTRA-HIGH PERFORMANCE FIBRE REINFORCED CONCRETE

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Abstract: The tensile stress-strain response of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is a basic constitutive property, and reliable knowledge of this response is necessary for appropriate application of the tensile-carrying capacity of such advanced cement materials. Reference tests methods like direct tensile tests which aim at assessing this property, have found limited application due to their complexity and their impracticality when considered in terms of a commercial testing environment. Thus, flexural tests, whose implementation is easier, represent an interesting alternative. Nevertheless these methods provide indirect information and need to be complemented by inverse analysis in order to obtain the tensile behaviour of tested materials. A joint research effort recently completed by the U.S. Federal Highway Administration and the French IFSTTAR (formerly LCPC) has succeeded in further investigating the field of flexure testing and subsequent analysis. Bending tests have been carried out on multiple UHPC-class materials with different instrumentations. New proposed analytical inverse analysis have been tested and discussed. This paper will detail these recent advances.

1 INTRODUCTION

Ultra-high-performance-fibre-reinforced concrete (UHPFRC) is a class of cementitious composite materials designed to exhibit outstanding mechanical properties including sustained postcracking tensile strength ([1-8]). Due to the multiple-fine-cracking capacity of UHPFRC elements, a stress-strain approach can be appropriate to grasp the UHPFRC behaviour under tension.

When using four-point flexural tests for identifying a stress-strain constitutive law, an inverse analysis is necessary to determine the uniaxial tensile behaviour. Analytical inverse analyses for four-point flexural tests on UHPFRC or high-performance fibre-reinforced cementitious composites (HPFRCCs) have been developed by many researchers ([4], [9-12]) with some success. Nevertheless, these methods require some assumptions which induce eventual bias. Thus a joint research effort has recently been completed by the U.S. Federal Highway Administration and the French IFSTTAR (formerly LCPC) in order to optimize analysis methods for deriving the tensile stress-strain response of UHPFRC from four-point flexural tests.

2 PROPOSED METHODS

Two methods have been developed ([13]). The first one is based on midspan strain measurement on the specimen tensile face ([14]). Conversely the second one requires only midspan deflection measurement ([13]).

2.1 Method based on strain measurement

Concerning the tensile stress-strain response of UHPFRC, the easiest way to determine the strain value without making any assumptions is to use a direct measurement. In this test program, two linear variable differential transducers (LVDTs) used as extensometers are applied to the tensile face of each specimen to measure the midspan strain on the tensile face (see Figure 1) and determine the crack localization. Then, the tensile stress-strain relationship of the tested material is derived from the experimental bending-moment versus midspan strain on the tensile face response without assuming the profile of the tensile stress-strain curve ([14]).

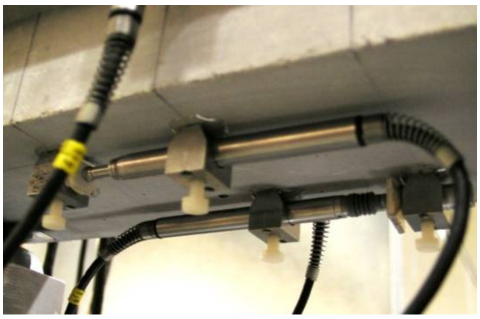

Figure 1: Midspan strain measurement including staggered extensometers on the tensile face

Determination of crack localization

The use of a pair of staggered LVDTs allows for simplified identification of crack localization. It helps distinguish the onset of bifurcation of the cracking process, with crack localization over one of the gauge lengths while cracking remains diffuse over the other gauge length (Figure 2). In some cases, two localized cracks can occur before reaching the main failure crack, or the localized crack can be detected by both LVDTs (case (c) in Figure 2). For these latter cases, the crack localization is assumed to correspond to the maximum bending stress. In case (a) three steps can be observed: (1) elongations measured by both LVDTs increase, (2) one elongation stops increasing, and (3) an unloading branch occurs with a decreasing value for one elongation. In this case, the “Bending Moment – Midspan Strain on Tensile Face” curve can exhibit a long plateau with little increase of the load before reaching the maximum load. During this step, the elongation rate reported by one elongation stops increasing. This step could be explained by a very low stress decrease in the “localized crack” phase combined with the bending configuration which allows stabilization of or a small increase in the load.

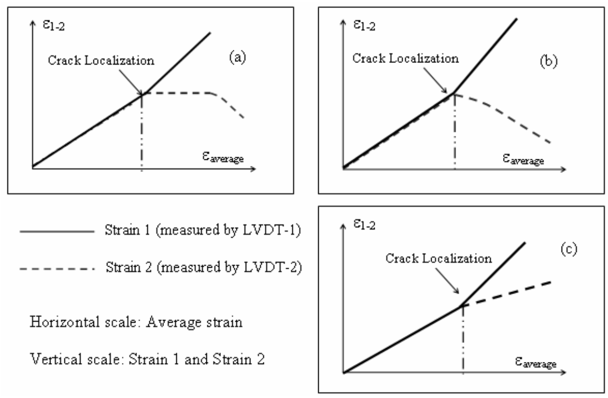

Figure 2: Proposed method to detect the crack localization with identification of the elastic unloading

Point-by-point inverse analysis

The experimentally captured bending-moment versus midspan strain on the tensile face response is converted into a tensile stress-strain curve through an inverse method applicable from elastic loading through crack localization. The stress-strain curve is based on the equilibrium of moments and forces in a sectional analysis for each value of midspan strain on the tension face and the corresponding bending moment. Assumption of the profile of the tensile stress-strain relationship is not required. The strain distribution is considered as linear (see Figure 3). This assumption is acceptable if the UHPFRC has a pseudo-strain-hardening behaviour in tension. The compressive behaviour of UHPFRC is assumed to be linear elastic, which is realistic for this kind of material ([3]). More details on this point-by-point inverse analysis are given in ([14]).

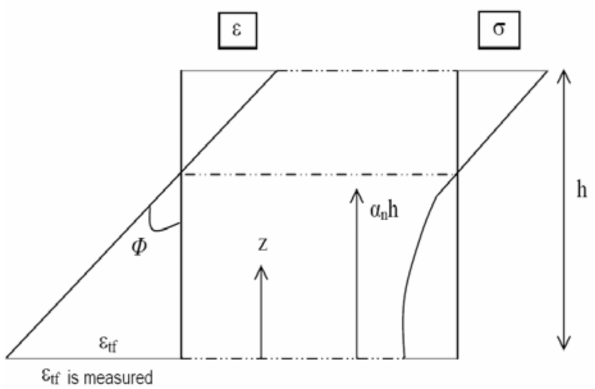

Figure 3: Strain and stress distribution for the studied section

2.2 Method based on deflection measurement

The curvature in the constant bending moment zone is derived thanks to a first inverse analysis from the "bending moment versus midspan deflection experimental response". Then a second point-by-point inverse analysis is used to derive the tensile stress-strain relationships from the curve "Bending moment – Curvature" without assuming the profile of the tensile stress-strain curve. Thus, from the "bending moment versus midspan deflection experimental response", the UHPFRC tensile stress-strain relationship is derived through a method which reduces the reliance on assumed behaviours.

Preliminary inverse analysis: conversion of the curve "Bending Moment – Midspan Deflection" into a curve "Bending Moment –Curvature"

The methods proposed by ([11], [12]) use a similar equation to relate the deflection of the prism to the curvature at the load points or at midspan. This equation is based on elastic structural mechanics and is considered reasonably valid for approximating nonlinear behaviour. Nevertheless the use of this relationship for non-linear behaviour induces an overestimation of the deflection for a given curvature along the middle third of the span, or an underestimation of the curvature for a given value of deflection (see Figure 4). As a consequence, the methods based on this mechanical assumption underestimate the real strain during the hardening phase and overestimate the post-cracking stress. In order to obtain more realistic results, it is necessary to take into account the real calculation of the deflection. Two integrations of the curvature over the length of the prism have to be performed. A numerical integration is used. More details are given in ([13]).

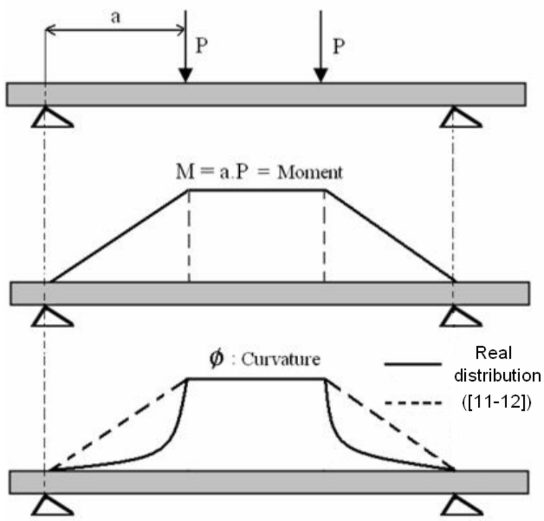

Figure 4: Distribution of the curvature along the specimen tested in four point bending: real distribution and assumptions adopted by ([11-12]).

Second inverse analysis: derivation of the tensile stress-strain relationship from the curve "Bending Moment – Curvature"

The experimental curve "Bending Moment – Curvature" is converted into a tensile stress–strain curve through an inverse analysis method applicable from elastic loading through crack localization considered concomitant with the maximum bending moment. The stress-strain curve is based on the equilibrium of moments and forces in a sectional analysis for each value of midspan strain on the tension face and the corresponding bending moment. It is not needed to assume the profile of the tensile stress-strain relationship. The process used in this study is similar to the point-by-point inverse analysis of ([12]).

Global Procedure
The whole outline of the inverse analysis procedure is described in Figure 5.

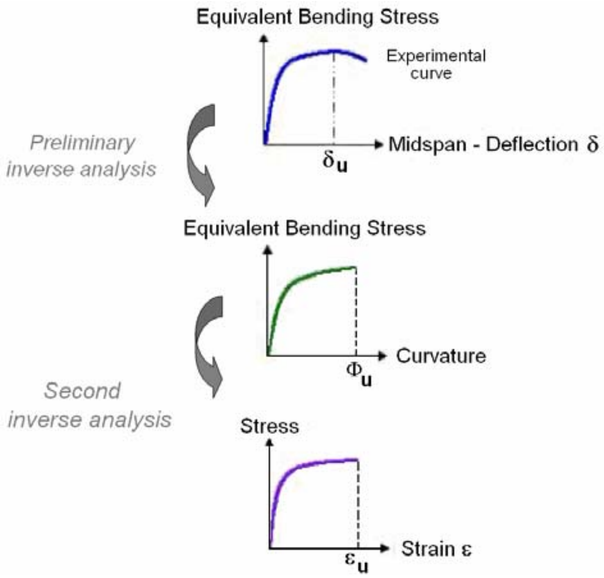

Figure 5: Global process used for the inverse analysis method based on deflection measurement

3 EXPERIMENTAL PROGRAM

The experimental program included the completion of four-point flexural tests on four sets of UHPFRC specimens and other associated tests, such as direct tension tests, as well as compressive tests aimed at determining the UHPFRC constitutive law in compression (see Table 1). In order to assess the applicability of the test methods, two different commercially available UHPFRCs were engaged along with two different steel fibre reinforcement contents. The curing regime applied to the UHPFRC was also a variable, with one of the UHPFRCs being used to create both steam treated and ambient laboratory cured specimen sets. The prism flexure specimens, direct tension test (DTT) specimens and associated compression test specimens in each set were all fabricated simultaneously from a single UHPFRC mix.

The UHPFRCs considered in this test program all had compressive strengths ranging from 190 to 237 MPa, modulus of elasticity ranging from 59 to 65 GPa, and density ranging from 2560 to 2690 kg/m^3 (see Table 2). The fibre reinforcement for UHPFRC-F was 13 mm long, 0.2 mm diameter, straight steel fibres. These fibres were included at either 2 percent or 2.5 percent by volume. The other UHPFRC (UHPFRC-B) contained 20 mm long, 0.3 mm diameter, straight steel fibres included at 2.5 percent by volume. Sets of test specimens nominally included at least 10 identical prisms, with five allocated for the direct tension test and five for the prism flexure test. All prisms had a 51 mm by 51 mm cross section. Two different specimen lengths with corresponding changes in four-point flexural test and DTT configuration were tested within the program. "Long" refers to a 432 mm long prism with a span of 355.6 mm and a distance between the upper rollers equal to 102 mm (see Figure 6). "Short" refers to a 304.8 mm long prism with a span of 228.6 mm, and a distance between the upper rollers equal to 76.2 mm.

Prisms were cast in open-top steel forms by pouring the UHPFRC into the form at one end then allowing it to flow toward the other end. Tests were completed after the UHPFRC has been allowed to cure for at least 3 months.

Figure 6 Prism flexural test setup

Table 1: Sets of Test Specimens

Specimen Set	UHPFRC	Steel Fibre Vol. (%)	Curing Regime	4-Point Flexure Short	4-Point Flexure Long	DTT – Short	DTT – Long
F1A	F	2	Steam		X	X	X
F2A	F	2	Lab		X	X	X
F1C	F	2.5	Steam	X	X	X	X
B2A	B	2.5	Lab	X		X	

Table 2: UHPFRC Material Properties

Specimen Set	UHPFRC	Density, (kg/m^3)	Compressive Strength, (MPa)	Modulus of Elasticity, (GPa)
F1A	F	2570	220	61.0
F2A	F	2545	192	62.8
F1C	F	2569	212	60.3
B2A	B	2690	213	63.9

4 COMPARISON WITH EXPERIMENTAL RESULTS

A joint research program was recently completed by the U.S. Federal Highway Administration and the French IFSTTAR (formerly LCPC) to develop a Direct Tension Test (DTT) applicable to UHPFRC that covers the full range of uniaxial tensile behaviour through strain localization and can be completed on cast or extracted specimens ([15]): see Figure 7. In the context of this study, this DTT method was applied for all specimen groups. Thus the comparison is realized in reference to DTT results.

From Figure 8 to Figure 12, the average tensile stress-strain relationships obtained from the proposed inverse methods, and the average experimental curves obtained from the DTT are presented for each specimen group.

In terms of strength, the proposed inverse analysis methods slightly overestimate the strength when considering average curves. In considering the average stress of the post-cracking part, the average deviation with the DTT results is equal to 3 % (with a maximum close to 8 %) for the method based on strain measurement ([14]) and 4 % (with a maximum close to 8 %) for the method based on deflection measurement ([13]).

In terms of strains, the average overestimation of the strain at crack localization is equal to 30 % (with a maximum close to 50 %) for the method based on strain measurement ([14]) and 36 % (with a maximum close to 50 %) for the method based on deflection measurement ([13]). Indeed, the flexural tests involve an overestimation of the strain capacity due to the fact that the side under higher tension corresponds to the zone where the preferential orientation of fibres is optimal. This phenomenon has already been observed by ([16]) on a multi-scale cement-based composite (MSCC). Completing the tests on larger prisms would minimize the strain gradient effect and thus would allow the results to be closer to the DTT results.

Investigating this size effect was outside of the scope of this experimental program.

Figure 7 Direct tension test: testing of a 432 mm long specimen

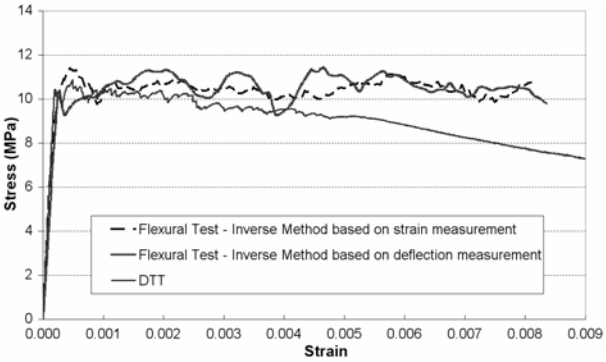

Figure 8 Average tensile stress-strain curves for F1A-L specimen group (51mm*51mm*432mm): Proposed inverse methods and DTT

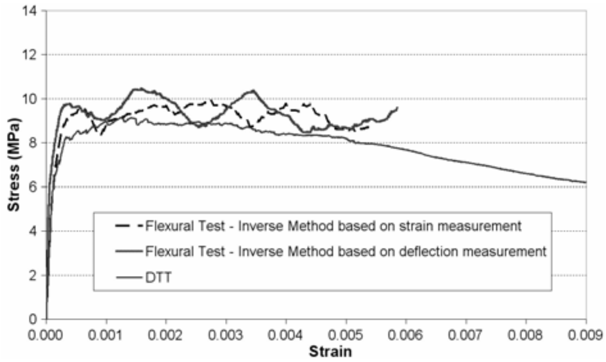

Figure 9 Average tensile stress-strain curves for F2A-L specimen group (51mm*51mm*432mm): Proposed inverse methods and DTT

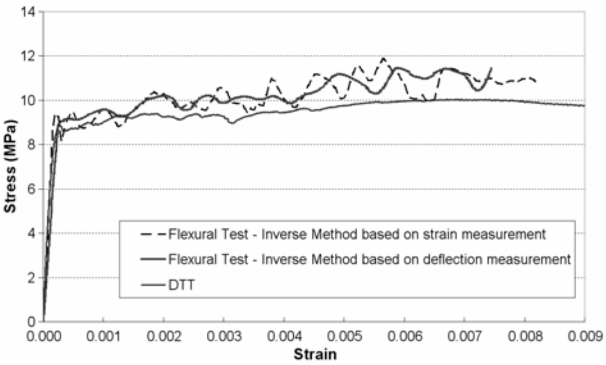

Figure 10 Average tensile stress-strain curves for B2A-S specimen group (51mm*51mm*305mm): Proposed inverse methods and DTT

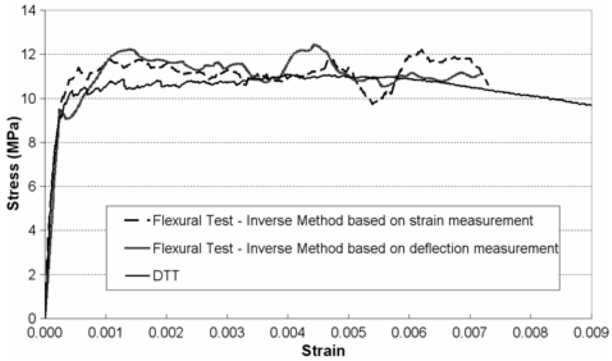

Figure 11 Average tensile stress-strain curves for F1C-S specimen group (51mm*51mm*305mm): Proposed inverse methods and DTT

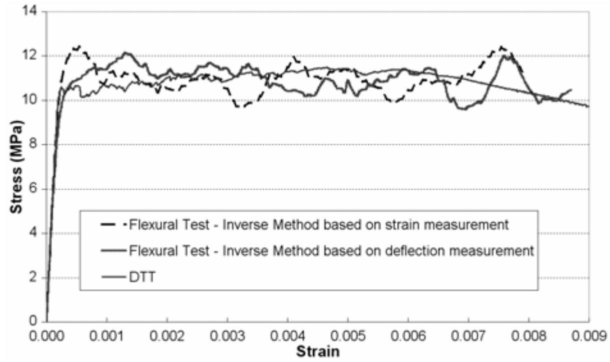

Figure 12 Average tensile stress-strain curves for F1C-L specimen group (51mm*51mm*432mm): Proposed inverse methods and DTT

5 CONCLUSIONS

The research described herein has presented new methods based on flexural tests to determine the tensile stress-strain response of UHPFRC with pseudo-strain hardening behaviour in tension. These methods reduce the number of required assumptions to obtain the stress-strain relationship from the curves “Bending Moment – Midspan strain on the tensile face” or “Bending Moment – Midspan Deflection”. Thus, the UHPFRC tensile stress-strain relationship is derived while minimizing the assumptions which can introduce deviations or artifacts on the results.

A comparison of these methods was completed on diverse UHPFRC specimens with different steel-fibre ratios or different curing regimes. The results show that it seems possible to evaluate the tensile stress-strain relationship of UHPFRC in a four point bending configuration in using an inverse analysis based on the direct calculation of deflection because it is equivalent to the curve obtained with direct strain measurement.

From the comparison with the companion DTT results, it has been shown that the average tensile stress-strain response of UHPFRC derived from flexural tests is slightly higher in terms of strength and strain capacity when compared with curves obtained from DTTs. This response results from a smaller tested tensile zone for flexure tests.

Using larger cross-section prisms would minimize the strain gradient effect and thus would likely facilitate greater coincidence in the accuracy of the flexure test results as compared to the DTT results to provide reliable design figures. In the case of thin elements made of UHPFRC under predominant direct tension and whose characterization of tensile post-cracking behaviour is realized from four-point flexural tests, the strain capacity has to be reduced to take into account the strain overestimation (before reaching crack localization) due to the flexural test configuration.

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