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IDENTIFICATION OF UHPFRC TENSILE BEHAVIOUR: METHODOLOGY BASED ON BENDING TESTS

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Abstract

Characterization methods of UHPFRC tensile behaviour have been developed to determine material response considering a given UHPFRC in a given structure. These methods are based on the four point bending test on unnotched specimens. An inverse analysis of the experimental results permits to deduce the "stress – strain" relationship (in the case of hardening UHPFRC) or "stress – crack opening" relationship (in the case of softening UHPFRC). The results depend on the assumptions taken into account for the inverse analysis. Thus, analysis methods have been developed which minimize the number of hypotheses to predict the most realistic design constitutive law. Considering different specimen sizes and two UHPFRC mixes, the results obtained from four point bending tests associated with the inverse analysis have been compared to those obtained with direct tensile tests. The effectiveness of the proposed method and particularly, its capability to derive a strain-hardening or strain-softening constitutive law of the material from observed crack patterns has been shown.

Résumé

Des méthodes de caractérisation du comportement en traction des BFUP ont été mises au point de manière à déterminer quel comportement est à prendre en compte pour un BFUP et un élément structurel donné. Ces méthodes se fondent sur l'essai de flexion quatre points réalisé sur éprouvette non-entaillée. Cet essai nécessite l'utilisation d'une analyse inverse afin d'obtenir la loi de comportement « contrainte-déformation » (dans le cas d'un BFUP écrouissant en traction directe) ou « contrainte-ouverture de fissure » (dans le cas d'un BFUP adoucissant en traction directe). Les résultats obtenus dépendant des hypothèses prises en compte dans l'analyse inverse, on s'est donc attaché à développer des méthodes d'analyse limitant le nombre d'hypothèses. Dans le cadre d'une campagne expérimentale portant sur différentes tailles de prisme et mettant en oeuvre deux BFUP différents, les résultats de l'analyse inverse des essais de flexion ont été comparés à ceux des essais de traction directe. La robustesse des méthodes d'analyse proposées en particulier vis-à-vis de la cohérence de la discrimination écrouissant/adoucissant à partir du relevé de fissures sur chaque éprouvette a été démontrée.

1. INTRODUCTION

Ultra-high-performance-fibre-reinforced concrete (UHPFRC) is a class of cementitious composite materials designed to exhibit outstanding mechanical properties including sustained post-cracking tensile strength [1-8]. The different existing methods used to identify the FRC (hardening or softening) post-cracking behaviour under tension can be classified as follows: direct tensile tests on notched specimens or unnotched specimens and indirect tensile tests on notched specimens or unnotched specimens. A joint research program was completed by the U.S. Federal Highway Administration and the French IFFSTAR (formerly LCPC, the Public Works Research Institute) to develop characterization tests applicable to UHPFRC with the following specifications:

- Identification of the UHPFRC softening or hardening behaviour under tension. Thus the specimens should not be notched.
- Acquisition/Derivation of a “stress-strain” relationship in the case of hardening UHPFRC and “stress-crack opening” relationship in the case of softening UHPFRC.
- Adaptability of the test procedure to specimens extracted from a real structure (thus often with a constant cross section).
- Quick execution to be adapted to an operational context.

Two kinds of test configurations have been chosen. The first one consists to characterize the UHPFRC behaviour under tension from a direct tensile test on unnotched prisms [9]. The second one is based on four point bending tests on unnotched specimens. For this latter, it has to be associated to an inverse analysis to obtain the constitutive relationship: “stress-strain” when UHPFRC is hardening under direct tension and “stress - crack opening” for UHPFRC exhibiting a softening behaviour under direct tension. For these inverse analyses, the result depends on assumptions taken into account. As a consequence, inverse analyses using a minimum of hypotheses have been developed, thereby increasing the well-foundness of the analytically produced results. The global approach adopted and detailed in the present paper is summarized in Fig. 1. The results obtained from bending tests and associated inverse analyses are compared to results from direct tensile tests. This comparison has been carried out using results of an experimental campaign considering different specimens dimensions and two UHPFRC mixes.

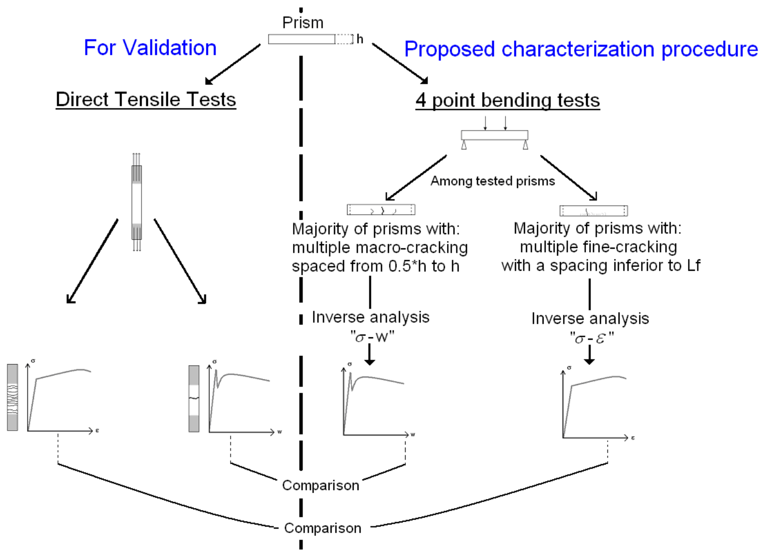


Figure 1: Proposed bending tests methodology to characterize the UHPFRC tensile behaviour

2. METHODOLOGY FOR BENDING TESTS AND PROCESSING

2.1 Principle

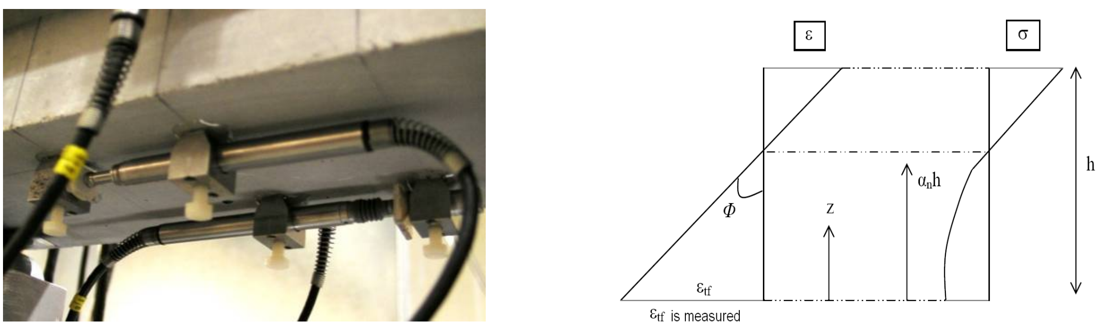
During the bending test on an unnotched specimen, the responses of a pseudo-strain hardening and of a softening UHPFRC prism under tension are significantly different in spite of the deflection hardening property of both materials. For a pseudo-strain hardening UHPFRC, a fine multiple cracking pattern (with a low spacing value around ¾*Fibre length) develops and one or many cracks localize only when reaching the maximum load. For a softening UHPFRC under tension, before reaching the maximum flexural strength, many macro-cracks have developed with a spacing value ranging from mid-height to one height of the tested specimen. These macro-cracks which can be qualified as structural and may be surrounded by fine cracks at a distance inferior to the fibres length due to the local capacity of fibres to bridge cracks [3]. From this experimental observation, a global methodology has been developed (see Figure 1). From the cracking scheme identification realized on each tested specimen, it is possible to associate a presumption of hardening or softening behaviour under direct tension of the tested UHPFRC. To each situation, an analysis method is associated to determine a tensile "stress-strain" relationship (presumed pseudo-strain hardening behaviour) or "stress-crack opening" relationship (presumed softening behaviour). These methods are detailed in the following sections.

2.2 Analysis methods for UHPFRC characterized by a multiple-fine cracking

A first method has been developed based on midspan strain measurement on the specimen tensile face [10]. An alternative one requires only midspan deflection measurement [11].

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 2a) 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 necessity to pre-determine the profile of the tensile stress-strain curve [10].



(a) (b)

Figure 2: Method based on strain measurement:
(a) Midspan strain measurement with staggered extensometers on the tensile face;
(b) Strain and stress distribution for the studied section

The use of a pair of staggered LVDTs (see Figure 2a) 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. 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 2b). 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 [10].

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. 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 [11].

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. This second inverse analysis is similar to that used for the method based on strain measurement. 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.

2.3 Analysis methods for UHPFRC characterized by a multiple-macro cracking

For UHPFRC characterized by a multiple-macro cracking, two methods have also been developed [12]. The first one is based on crack opening measurements on the specimen tensile face. Conversely the second one requires only midspan deflection measurements.

Method based on cracks opening measurement

This method uses the same sensors equipment as previously described (see Figure 1) to avoid a change of the experimental process depending on the tested material response which can not be presumed before performing tests. Thanks to this instrumentation, an experimental “Bending moment – Crack opening” curve is obtained. An inverse analysis has to be applied to derive the “stress – crack opening” relationship. A model based on non-linear hinge similar to that adopted by the French Recommendations on UHPFRC [4] has been chosen. Nevertheless, in order to take into account the multiple macro-cracking, an adaptation derived from [13] for slabs made of FRC with conventional reinforcement is applied. The width of the disturbed zone is taken equal to the average spacing of cracks $s_{average\text{-}failure\text{-}crack}$ around the failure crack. Thus the kinematic equation linking the crack opening and the curvature of the undamaged part becomes:

$$w_0 = \frac{\alpha \cdot h}{3} \times s_{average-failure-crack} \times \left(\phi_m + 2 \cdot \phi_e\right) \quad (1)$$

The average spacing of cracks around the failure crack $s_{average\text{-}failure\text{-}crack}$ is determined from the cracking scheme identified for each specimen.

Method based on deflection measurement

The inverse method based on the experimental curve "Bending moment – Midspan deflection" needs to distinguish following two steps in the UHPFRC post-cracking response:

- Between the limit of linearity and the maximum load: multiple macro-cracking phase.
- After maximum load: failure crack localization and crack opening increase with unloading of the rest of the specimen.

During the first step, all macro-cracks are assumed to be characterized by the same opening. Thus for this step, a continuous approach similar to [14] and [3] is chosen. For this kind of approach, the crack opening has to be normalized with a characteristic length L_c. This length is taken equal to the average spacing of cracks $s_{average}$. This average spacing is determined from the cracking scheme identified for each specimen. The "Bending moment – Midspan deflection" curve is thus converted into a "stress-strain" relationship from the inverse method used for hardening UHPFRC and previously described. Then the "stress-crack opening" law is derived from the following equation: $w = \varepsilon \bullet s_{average}$.

During the second step, only one crack opens. Thus a discrete approach is adopted. The model based on non-linear hinge described in the previous section is adopted. The length of the disturbed zone is considered to be equal to the average spacing of cracks $s_{average\text{-}failure\text{-}crack}$ around the failure crack. However, in order to solve the inverse problem, it is necessary to obtain an additional equation which converts the midspan deflection into localized crack opening. Simplifications have been adopted to obtain a direct relationship between failure crack opening and midspan deflection ([12]):

- Elastic deformations are neglected.
- The failure crack height is assumed to be equal to the specimen height.
- The failure crack is considered as a hinge between two perfectly rigid blocks (see Fig. 3).

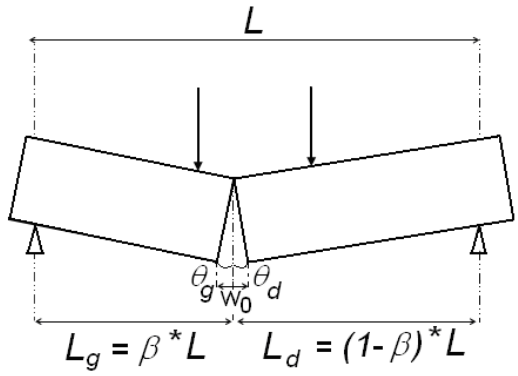


Figure 3: Simplified scheme of failure crack

In considering these assumptions the relationship between midspan deflection δ_{center} and failure crack opening w_0 reads:

$$w_0 = \left(\theta_g + \theta_d\right) \cdot h = \delta_{crack} \cdot \left(\frac{1}{\beta \cdot L} + \frac{1}{(1-\beta) \cdot L}\right) \cdot h = \frac{2}{\beta \cdot L} \cdot \delta_{center} \cdot h \qquad (2)$$

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 and processing 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 produce both steam treated and ambient laboratory cured specimen sets. The prismatic 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 1). The fibre reinforcement for UHPFRC-F consisted in 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 at a 2.5 percent content per 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 bending 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 Direct Tensile Test (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. "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 had been allowed to set and harden for at least 3 months.

Table 1: Sets of Test Specimens and UHPFRC Material Properties

Specimen Set	UHPFRC	Steel Fibre Vol. (%)	Curing Regime	4-Pt Flexure Short	4-Point Flexure Long	DTT – Short	DTT – Long	Density, (kg/m^3)	Compressive Strength, (MPa)	Modulus of Elasticity, (GPa)
F1A	F	2	Steam	X	X	X	X	2570	220	61.0
F2A	F	2	Lab	X	X	X	X	2568	231	61.9
F1B	F	2	Steam	X		X		2545	192	62.8
F1C	F	2.5	Steam	X	X	X	X	2569	212	60.3
B2A	B	2.5	Lab	X		X		2690	213	63.9

4. COMPARISON OF RESULTS AND VALIDATION OF THE TEST PROCESSING METHODOLOGY

4.1 Types of post-cracking behaviour

Table 2 gives a synthesis of results obtained with DTT and four point bending tests resulting in the identification of the type of post-cracking behaviour under tension for each specimens group. For the four point bending tests, the experimental results (in particular the cracking pattern identified for each specimen) allow distinguishing:

- Prisms groups characterized by a multiple fine-cracking with a low spacing (lower than the fibres length) which presumes a pseudo-strain hardening behaviour under tension: B2A-S, F1A, F2A-L, F1C.
- Prisms groups characterized by a multiple macro-cracking with main cracks spacing ranging from half to one times the specimens height, which presumes a softening behaviour under tension: F1B-S and F2A-S.

Noticeably, all tested specimens have been characterized by a deflection hardening behaviour. For all specimen groups, the adopted approach based on four point bending tests with identification of the cracking pattern for each prism seems to be efficient to characterize the presumed type of UHPFRC post-cracking behaviour under tension. However this statement requires further confirmation, namely due to the relatively small number of specimens for DTT.

Table 2: Types of behaviour under tension for each prisms group deduced from the cracking scheme identification

	Direct Tensile Tests			Four Point Bending Tests					
								Type of adopted approach	
Groups	Number of tested prisms	Hardening / Softening	Number of prisms taken into account	Number of tested prisms	Number of prisms characterized by a multiple fine-cracking	Number of prisms characterized by a multiple macro-cracking	Type of presumed post-cracking behaviour	« σ–ε » / « σ–w »	Number of prisms taken into account
B2A-S	6	Hardening	4	5	5	-	Hardening	« σ - ε »	5
F1A-S	5	Hardening	2	6	3	3	No trend	« σ - ε » / «σ- w »	3 / 3
F1A-L	5	Hardening	3	5	5	-	Hardening	« σ - ε »	5
F1B-S	5	Softening	3	6	1	5	Softening	«σ– w »	4
F2A-S	5	Softening	2	6	-	6	Softening	«σ– w »	5
F2A-L	5	Hardening	3	5	5	-	Hardening	« σ - ε »	5
F1C-S	5	Hardening	4	6	6	-	Hardening	« σ - ε »	6
F1C-L	3	Hardening	3	5	5	-	Hardening	« σ - ε »	5
S = Short / L = Long									

4.2 Method validation for UHPFRC characterized by a multiple-fine cracking

In Figure 4, 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 concerned 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 [10] and 4 % (with a maximum close to 8 %) for the method based on deflection measurement [11]. 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 [10] and 36 % (with a maximum close to 50 %) for the method based on deflection measurement [11]. 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 [15] on a multi-scale cement-based composite (MSCC).

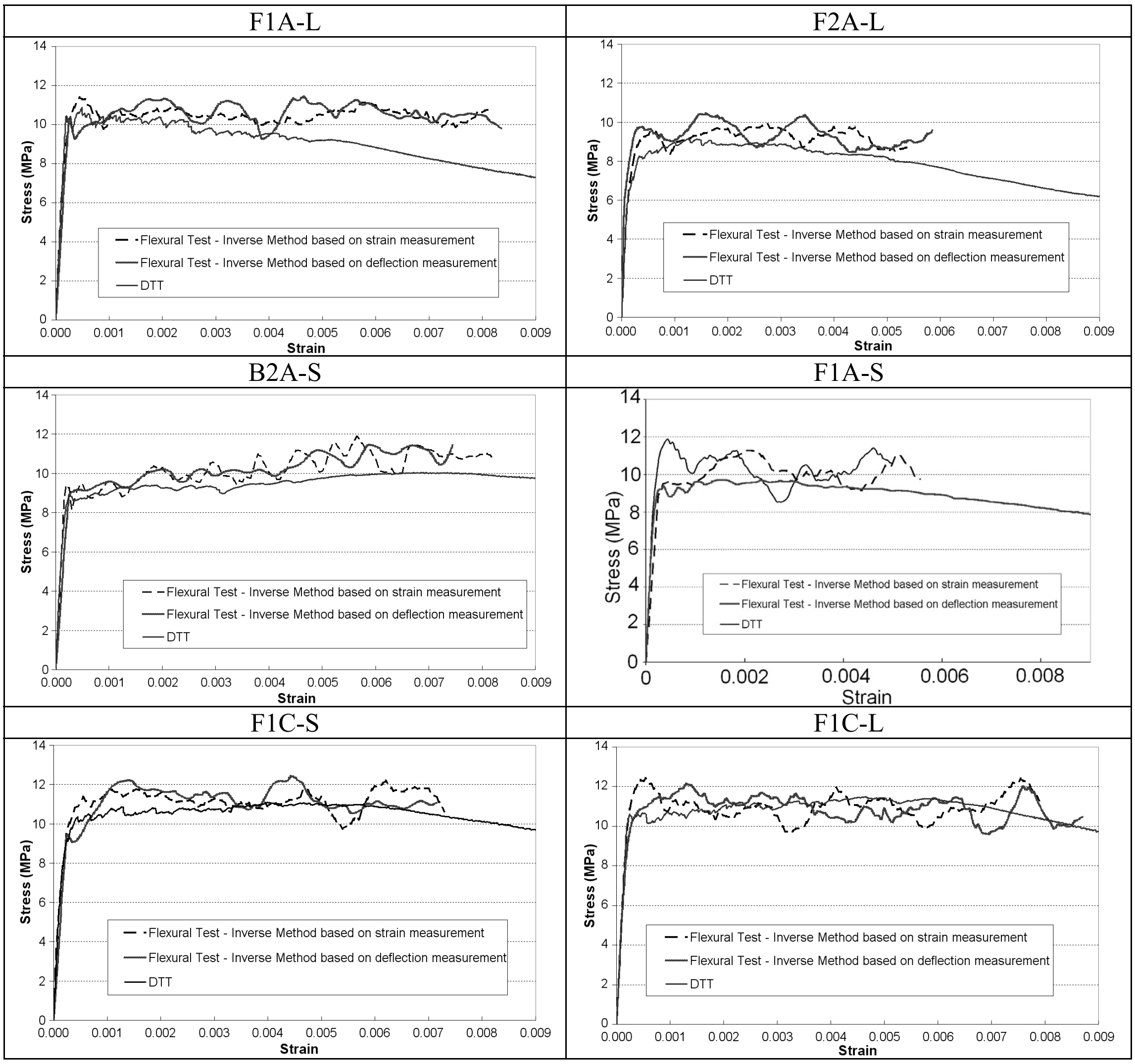


Figure 4: Average tensile stress-strain curves for specimen groups characterized by a hardening behaviour under tension: Proposed inverse methods and DTT

4.3 Method validation for UHPFRC characterized by a multiple-macro cracking in bending

In Figure 5, average "stress-crack opening" curves obtained from DTT and derived from four point bending tests associated with both proposed inverse analyses respectively based on crack opening measurements and midspan deflection measurements are presented for each concerned specimen group.

In order to obtain the « stress – crack opening » relationship from four point bending tests, the approach based on crack opening measurements seems to be efficient. Indeed the absolute value of the deviation with the DTT results is on average equal to 6 % for F1B-S and 7.5 % for F2A-S. For the method based on midspan deflection measurement, the continuous approach used until reaching the maximum load underestimates the crack opening and thus overestimates the tensile strength. The comparison with DTT results confirms this conclusion. Indeed it seems that the development of the crack which will become critical is more important compared to other cracks, even before reaching the maximum load.

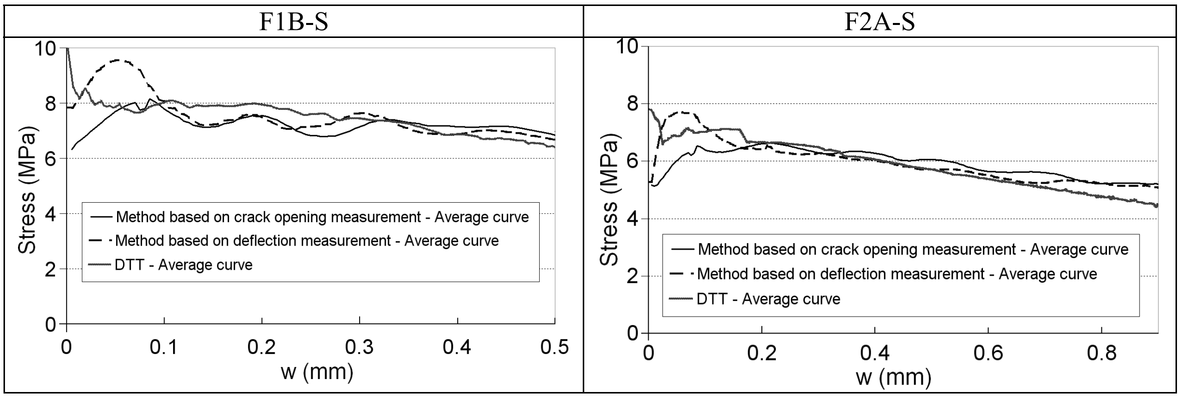


Figure 5: Average tensile stress-crack opening curves for specimen groups characterized by a softening behaviour under tension: Proposed inverse methods and DTT

5. CONCLUSIONS

The research described herein has presented a methodology based on the four point bending test configuration to characterize the UHPFRC behaviour under tension. This methodology consists, first, to identify if the tested UHPFRC has a pseudo-strain hardening or softening behaviour under direct tension based on identification of the cracking pattern of each specimen. Then a "stress – crack opening" relationship (for UHPFRC characterized by a multiple macro-cracking presuming a softening behaviour) or a "stress – strain" relationship (for UHPFRC characterized by a multiple fine cracking presuming a hardening behaviour) is determined from inverse analyses based on strain/crack opening measurement or deflection measurement. A comparison of these methods was completed on diverse UHPFRC specimens with different steel-fibre ratios or different curing regimes. The results have shown the efficiency of the proposed methodology in particular for the distinction of hardening/softening behaviour from the cracking pattern identification in bending tests.

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