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A testing method for studying the serviceability behavior of reinforced UHPFRC tensile ties

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Abstract. Structural control under the serviceability limit state is a requirement of design codes to ensure the durability of structural elements. As it is possible to consider fibers to be reinforcement in concrete, UHPFRC can be used to guarantee properly distributing cracks and limiting crack width in the serviceability limit state. This research presents an experimental testing method for direct tensile tests on UHPFRC specimens. The results obtained from the proposed method, such as the specimen's average tensile stress-strain curve, tensile stress in concrete, number and width of cracks, can be used to consider the behavior and design requirements of UHPFRC under serviceability conditions.

1. Introduction

Ultra high-performance fiber-reinforced concrete (UHPFRC) is a material with high compression stress, and great ductility and toughness due to the inclusion of steel fibers. The addition of fibers to the concrete matrix leads to significant energy being absorbed and helps control crack opening [1,2]. The presence of fibers in cracks limits the width of cracks, and results in their proper distribution and increases their serviceability [3,4]. In all concrete structure design codes, controls related to the serviceability state and cracking control are important. Many research works have been conducted to study only the tensile behavior of UHPFRC [5–9]. They have focused on the mechanical properties of UHPFRC without reinforcements. However in real structural elements, concrete is usually accompanied by reinforcement. One method for recognizing this behavior is to test the direct tensile tie (a prismatic concrete member with a high length-to-width ratio and a reinforcing steel bar in the center of the cross-section). In order to understand the tensile behavior of concrete as a simple material, and of concrete combined with conventional reinforcement, parameters like crack width, distance between cracks and tension stiffening have been studied for many years [10–13]. As adding fibers to concrete limits the cracking phenomenon by narrowing cracks with short distances among them, it is important to analyze how the aforementioned parameters could be affected when UHPFRC is combined with a steel bar. In recent years, very few studies have analyzed the tensile behavior of UHPFRC by including steel bar reinforcement [14–16].

The present paper focuses on providing an appropriate testing method to investigate the UHPFRC cracking behavior under the serviceability limit state (SLS). For this purpose, tensile tie experiments were proposed and developed. A new method is provided to measure the ability to transfer tensile force to a concrete member. Some parameters were evaluated by this testing method, such as the element's average tensile stress-strain diagram, the element's strain behavior in small segments and the development of cracks and their frequency.

2. Research Significance

Performing a direct tensile test on reinforced concrete specimens and applying tensile force to concrete specimens are not easy tasks. This present work provides a simple testing method for studying the behavior of reinforced UHPFRC under uniaxial tension load. This method is able to analyze the multicracking behavior of a UHPFRC tensile tie using different types of measurements equipment. It also helps us to analyze the interaction between concrete and steel reinforcement and the possible synergy between them under SLS.

3. Experimental Program

The experimental program was considered for one type mixture to evaluate the behavior of the UHPFRC tensile tie. Due to the capacity limitation of the laboratory mixer and the number of molds, five batches with the same dose were prepared (C1 to C5). The mixture design of UHPFRC is reported in Table 1. The achieved average 28-day compressive strength test of concrete cubs of 10 cm x 10 cm was 158.41 MPa and the average Young's Modulus was 48.88 GPa. The length and diameter of applied steel fibers in this study were 13mm and 0.2mm respectively and their tensile strength was more than 2000MPa.

Table 1. The UHPFRC Mixture Design.

Component	**Content (kg/m^3)**
Cement I 42.5 R/RS	800
Silica Fume 940 D Elkem UD	175
Silica Flour U-S500	225
Fine Sand 0.5 mm	302
Medium Sand 0.6-1.2 mm	565
Water	160
Superplasticizer, Viscocrete 20 HE	30
Fiber	160

All the specimens were made as follows: the considered specimen length was 1000 mm and a central bar was located over the entire element with a length of 1450 mm. Two complementary rebars were located at both ends with a length of 450 mm. These reinforcement bars were welded to the main bar. This experimental research was conducted for one cross-section type (i.e. 80 × 80 mm) and three tie series with rebars ratios of 1.23 %, 1.77% and 3.14% (rebars were 10 mm, 12 mm and 16 mm). The nominal yield stress of the rebars was 500 MPa. To identify specimens, the first number represents the reinforcement diameter, whereas the second number refers to the number of series per specimen; e.g., for the tensile tie with a 10-mm reinforcing bar, the ID specimens were named (T-10-1), (T-10-2) and (T-10-3). Figure 1. illustrates specimen details.

During the manufacturing procedure, an attempt was made to locate the rebar exactly on the center section to avoid eccentricity and bending effects. Specimens were stored in a curing chamber at 95% relative humidity and a temperature of T = 20±2°C until 2 or 3 days before testing. UHPFRC was cast horizontally so that the casting process would start from one extreme to the other extreme by applying a uniform velocity to ensure a good alignment of the steel fibers in the concrete mixture.

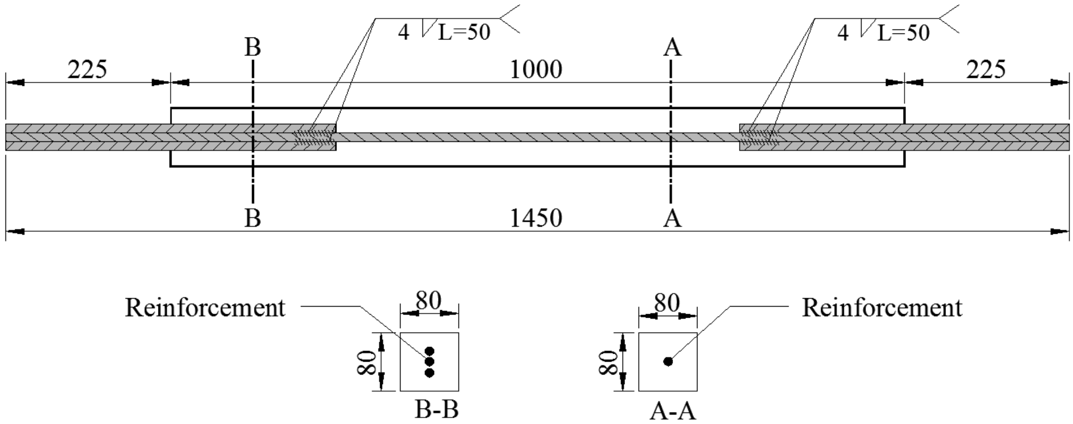

Figure 1. Specimen reinforcement details (units in mm).

4. Experimental setup and method

4.1. Description of the test system

In order to perform this test, a 2-meter steel structural frame was used, as outlined in [17] 'Figure 2.a'. This structure was made using two plates whose thicknesses were 5 cm on both extremes, along with four 60 × 60-mm rectangular tube sections of 8 mm thickness. As tensile force had to be transferred to the specimen, two two-piece steel jaws (2 mm high) with indented corrugations were used as shown in Figure 2.b.

In order to prevent the main bar from yielding and failing on both ends without concrete, two 45-cm long rebars were used in the external region of the specimen, and penetrated 22.5 cm into the concrete specimen (Figure 1). The test zone lay in the center part of the member where only one rebar existed. As previously mentioned, two st52 steel jaws were used to transfer tensile force from the system to both the concrete specimen and the ending reinforcing bars. Each jaw consisted of two segments with six high-strength bolts whose diameters were 13 mm. By tightening these bolts, tensile force was transferred by the hydraulic jack to the bar embedded in the concrete specimen because of the frictional force between the rebar and the interior side of the jaw. In order to distribute the force caused by tightening the bolts uniformly, this process was done in a zigzag manner. Figure 2. b. provides details of the jaw and the assembled connection.

Hydraulic jacks are designed as cylinders and a bar can be passed to their centers. A Ø20-mm high-strength steel bar (fy=1000MPa) was used to transfer the tensile force caused by the movement of the hydraulic jack. At the end of these bars, a circular steel rod end bearing was embedded (Figure 2.c). At both ends of the jaws, there was a Ø25-mm bolt that allowed the steel jaw to be connected to the bars through the steel rod end bearing. This connecting system displayed a hinge behavior and allowed bending or twisting at both specimen ends (Figure 2.d).

4.2. Instrumentation and experimental procedure

As previously mentioned, this experiment aimed to study the tensile behavior of the UHPFRC reinforced tie. To conduct this study, the behavior of the member was studied at both the general and local levels. To investigate the general behavior, displacement transducers were employed, while local behavior was evaluated using demountable mechanical gauges (DEMEC points). The position of the measurement equipment is illustrated in Figure 3.

For this purpose, specimens were tested under the displacement control. On both sides of the concrete specimen and on four surfaces, four 35-cm long displacement transducers were installed (Figure 3). In this method, it was assumed that the strain of the rebar located in the center of the section would equal the average value of the strains recorded for four external surfaces. For the local level measurement, #16 DEMEC steel discs were installed at a 1-cm distance from the upper and lower edges on each specimen edge (see Figure 3). The reason for using four displacement transducers on the four specimen surfaces was to study the possible bending and rotations due to asymmetric cracks occurring.

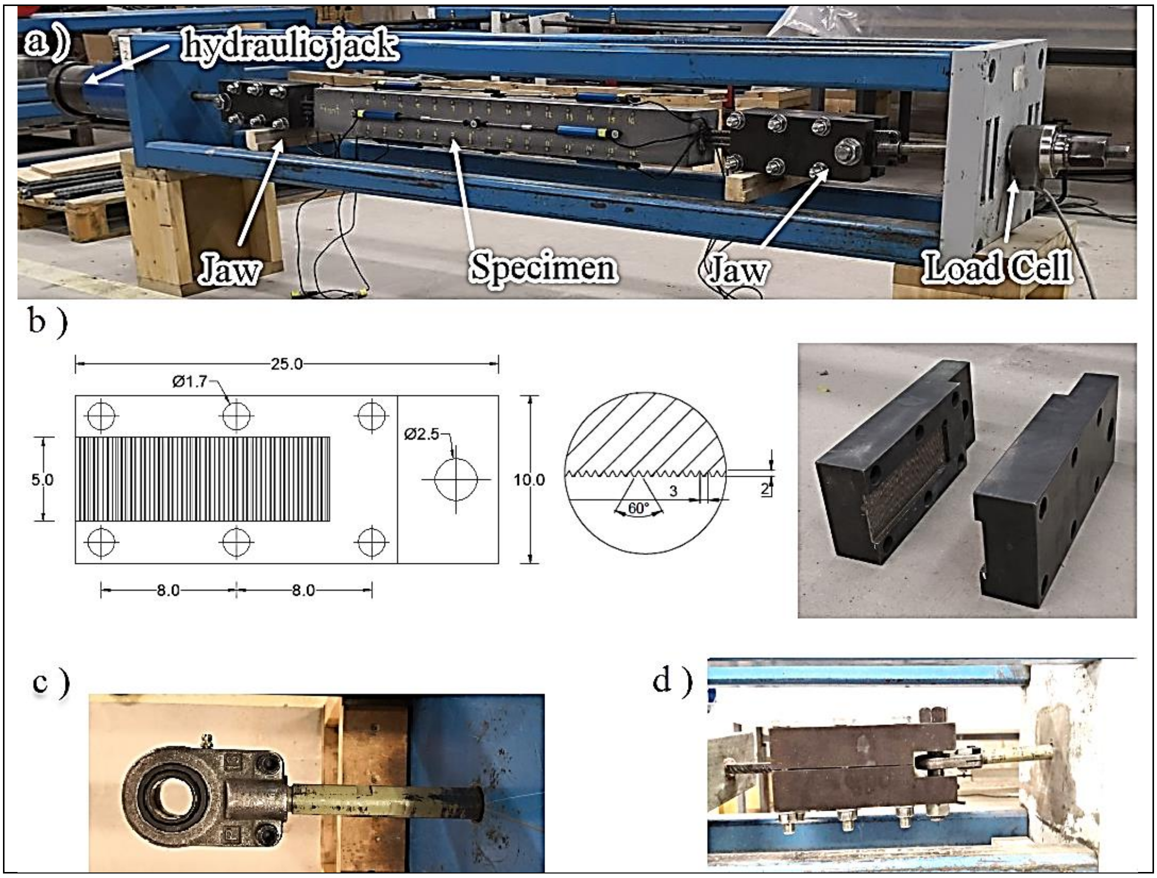

Figure 2. a) Tensile test equipment. **b)** Jaw details. **c)** rod end bearing. **d)** assembled Jaw connection.

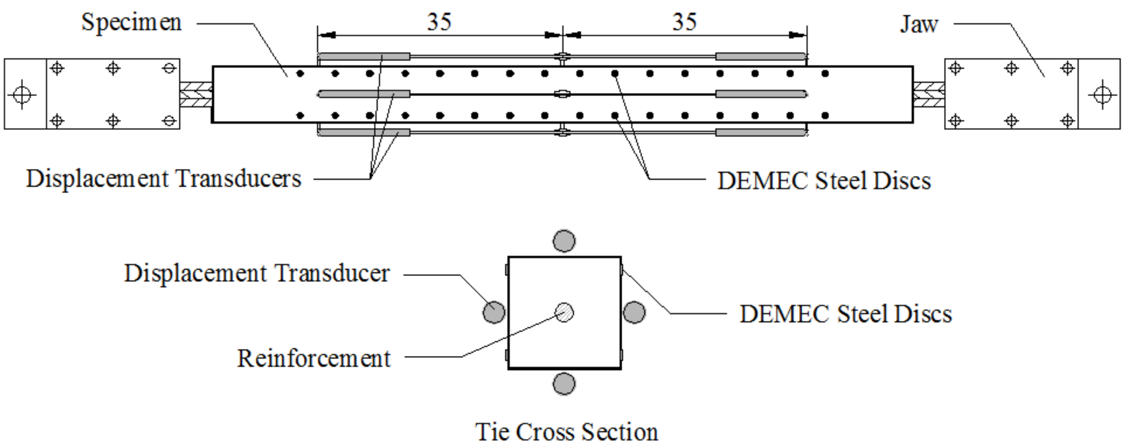

Figure 3. Measurement equipment: positions of the displacement transducers and the DEMEC points along the element.

After installing the concrete specimen within the test equipment, force was applied by the hydraulic jack and the increase in force was stopped in strains of 0.03‰, 0.05‰, 0.10‰, 0.15‰, 0.5‰, 1‰, 1.5‰ and 2‰. Then the changes in length between the DEMEC disks were measured. While testing, an attempt was made to maintain force at constant levels.

As the average displacement recorded by the displacement transducers reached an equivalent strain of 2‰, the experiment was stopped, and the number of cracks on the upper and lower edges between the DEMEC points was recorded by plotting the crack pattern on the specimen surfaces. For the specimens containing the ∅16 bars, it was difficult to reach the tension strain of 2‰ because the bars slipped at a high load value. Therefore, the experiment continued for these specimens until a displacement corresponding to a strain of 1.5‰ took place.

5. Results and Discussion

A tensile stress-strain diagram of specimens was obtained from the average of the four displacement transducers located on the left and right specimen sides. Figure 4. illustrates the displacement-force curves due to the tensile force on both the left and right sides of specimen T-12-2, respectively.

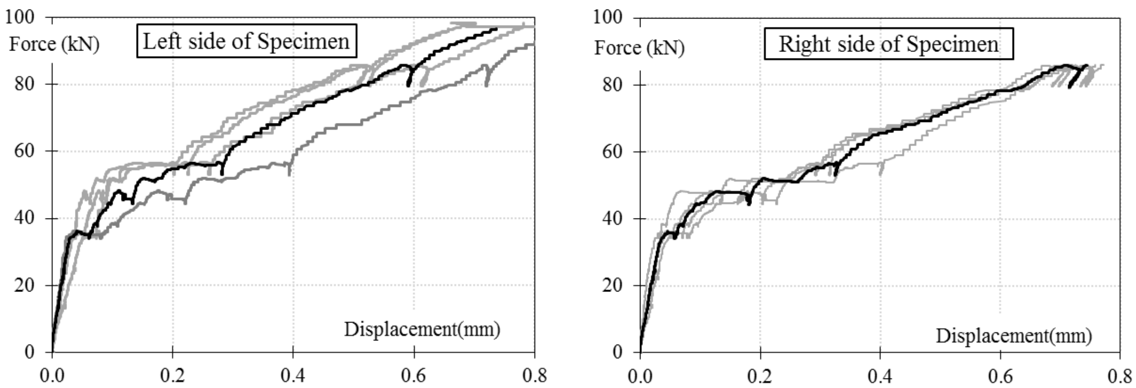

Figure 4. Displacement-force relationship for specimen #T-12-2.

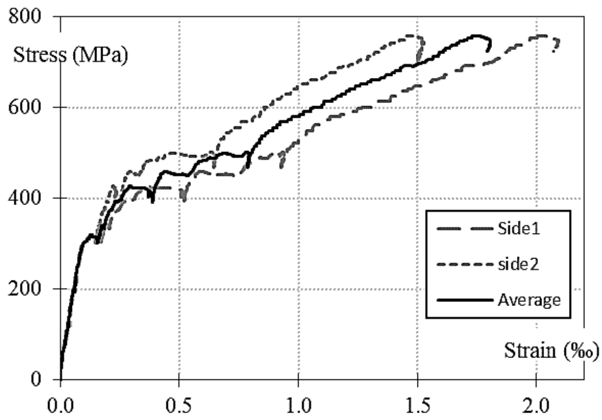

Figure 5. Tensile stress-strain diagram for specimen #T-12-2 and the average values.

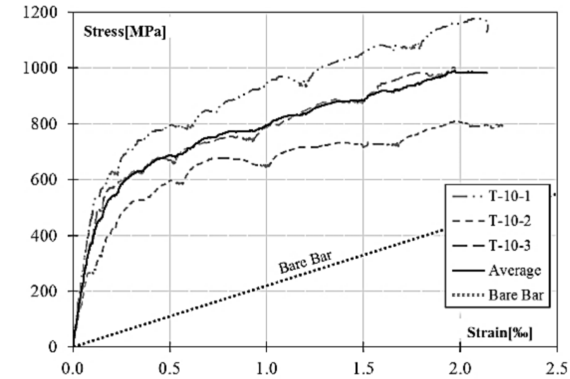

Figure 6. Stress-strain diagram based on the rebar area for tie 8x8cm with the Ø10-mm bar.

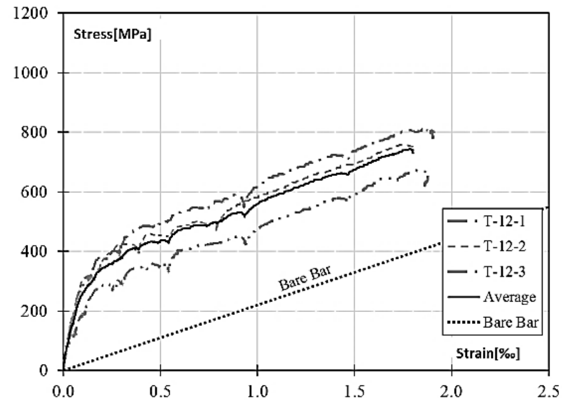

Figure 7. Stress-strain diagram based on the rebar area for tie 8x8cm with the Ø12-mm bar.

As previously stated, a slight difference in the diagrams was due to asymmetric cracks appearing on the specimen's cross-section, as well as very small localized bending because of the difference in the cracking inertia along the member. Figure 5. presents the average tensile stress-strain curve for both the specimen's left and right sides. These two diagrams are similar to one another, and the average behavior diagrams for the specimen's left and right sides can be described as the tensile behavior of the tensile tie. The stress expressed in this diagram is shown as the equitant steel stress, which was obtained by dividing the total tensile force by the area of the reinforcing steel. The results obtained for each series of specimens are shown in Figures 6, 7 and 8.

As the equivalent stresses shown in the above diagrams are based on the area of the reinforcing steel, the numerical value of this stress is higher for the bars with smaller areas. As observed in the diagrams, the tie's stress-strain behavior is relatively in parallel to that of the steel bar after the member cracked under tensile force, and reducing of the stiffness and change in slope of the stress-strain diagram.

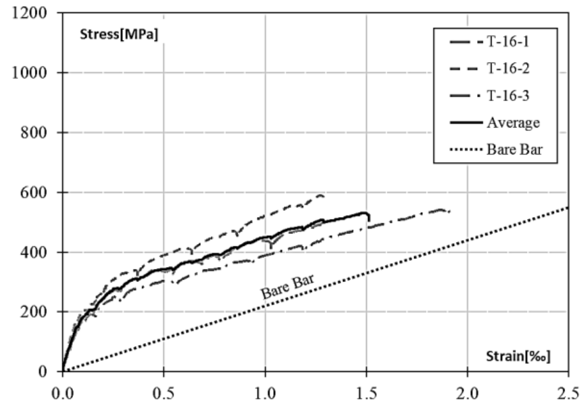

Figure 8. Stress-strain diagram based on the stress on rebar area for tie 8x8cm with the Ø16-mm bar.

Regarding the above diagrams, the elastic stiffness in the linear region varied from 39 to 42 GPa for the ties with the Ø10-mm bar, from 19 to 25 GPa for the ties with the Ø12-mm bar, and from 15 to 18 GPa for the ties with the Ø16-mm bar. By assuming the simultaneous participation of concrete and steel in tension and with the same strain, it was possible to obtain tensile stresses in concrete by subtracting the strain-stress curve of the bare rebar from the total stress-strain curve; e.g., the tensile stress of concrete is calculated in Figure 9. The average tensile stresses for all three tie series are shown in Figure 10. It should be noted that no significant strain-hardening behavior was observed for UHPFRC. With this diagram, it is possible to compute the tensile stresses that correspond to the desired strains and to compare them with the allowable SLS values.

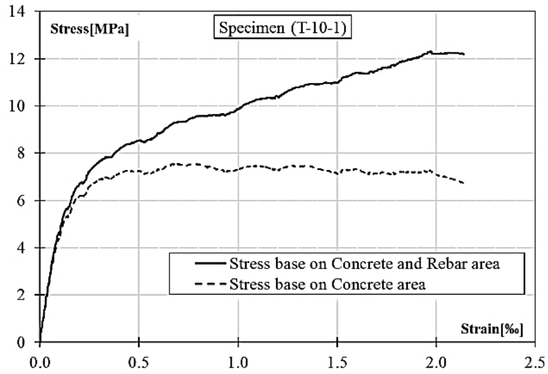

Figure 9. Tensile stress-strain curve for specimen T-10-1 (stress based on concrete area).

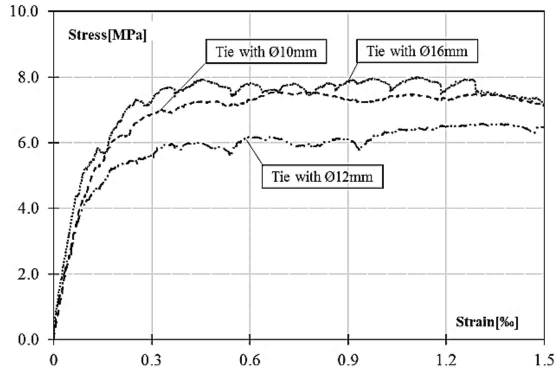

Figure 10. Average tensile stress-strain curve calculated according to the concrete area for all three specimens per series.

It should be noted that due to the asymmetry and uniformity of cracking in concrete, strains would not be identical on the element's four edges.

By way of example, for specimen T-12-2 at the force level of 2.31 kN, the average value of the strains of all the elements obtained by DEMEC was $\varepsilon = 0.066$ ‰ and the average value obtained by the displacement transducer was $\varepsilon = 0.059$ ‰, with a difference of 10.5%.

It is worth noting that in some specimens, it was not possible to record the increased length using DEMEC within the required strain intervals because cracks and a sudden increase in the longitudinal strain occurred.

At the end of the test and after accessing the tensile strain of 2 ‰ (1.5 ‰ for the specimen with the Ø16-mm bars), the number of cracks between the disks installed on the specimen's six edges was recorded by wetting the surface with water. Due to the rough surface created on the specimen surface that did not come into contact with the steel mold, no cracks were seen (see Table 2).

Table 2. The average number of cracks recorded between DEMEC disks and the average width of cracks for specimen T-12-2 (force value 2.31kN, strain obtained= 2 ‰).

Point Number		Total Number of Cracks	Achieved Elongation (mm)	Mean Crack Width (μm)
Up side	Edge1	70	0.632	9
	Edge2	91	0.632	7
Front Side	Edge1	69	0.632	9
	Edge2	86	0.632	7
Back Side	Edge1	92	0.632	7
	Edge2	56	0.632	11
			Mean	8

The number of cracks and the average crack widths are shown for specimen T-12-2. A large number of cracks and the short distance among them are some of the important characteristics of UHPFRC, as evidenced by the crack pattern shown in Figure 11.

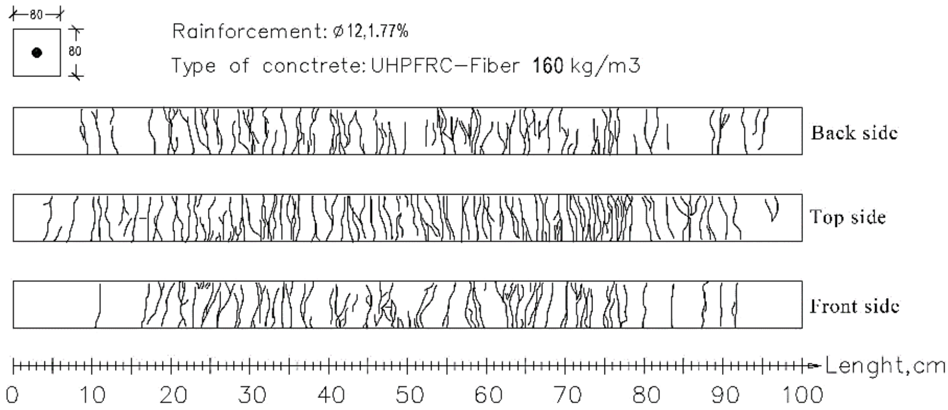

Figure 11. Cracks pattern for specimen T-12-2.

6. Conclusion

In order to study the necessary UHPFRC design requirements under SLS, a new testing method was developed to perform direct tensile tests. This method is able to examine the behavior of these elements under serviceability conditions and can determine tensile strains from the multicracking phase to the localized crack development stage.

In this method, the average tensile stress-strain curve of tensile ties was obtained by installing four displacement transducers on the specimen's four surfaces on both sides. Some parameters were obtained, such as the stiffness of elastic region, the tensile stress-strain diagram of concrete, and the width and number of cracks. The tensile strain on the 5-cm elements was acquired by installing DEMEC equipment on the four edges of the cross-section. Using the data obtained by this method, the tensile strain variations along the member were studied. In the final loading stage, after reaching the strain of 2 ‰ recorded by the displacement transducers, the cracking pattern along the specimen, the number of cracks on each 5-cm element on four edges and the average crack widths of the specimens were obtained. The proposed testing method and the obtained results will enable the study of UHPFRC behavior under direct tension under serviceability conditions.

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References

[1] Wille K, El-Tawil S and Naaman A E 2014 Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading *Cem. Concr. Compos.* **48** 53–66

[2] Japan Society of Civil Engineers 2008 Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fine Cracks (HPFRCC) *Concr. Eng. Ser.* **82** Testing Method 6-10

[3] di Prisco M, Plizzari G and Vandewalle L 2009 Fibre reinforced concrete: new design perspectives *Mater. Struct.* **42** 1261–81

[4] R. Yu et al. 2015 Development of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) : towards an efficient utilization of binders and fibres *Constr. Build. Mater.* 273–82

[5] Naaman A E 2006 Proposed classification of HPFRC composites based on their tensile response *Mater. Struct.* **39** 547–55

[6] Kusumawardaningsih Y 2015 Tensile strength behavior of UHPC and UHPFRC *Procedia Eng.* **125** 1081–6

[7] Hun S, Joo D, Sung G and Taek K 2012 Tensile behavior of Ultra High Performance Hybrid Fiber Reinforced Concrete *Cem. Concr. Compos.* **34** 172–84

[8] Eduardo J. Mezquida-Alcaraz, Juan Navarro-Gregori, Juan Ángel López and Pedro Serna-Ros 2019 Validation of a non-linear hinge model for tensile behavior of UHPFRC using a Finite Element Model *Comput. Concr.* **23** 11–23

[9] López J Á, Serna P, Navarro-Gregori J and Coll H 2016 A simplified five-point inverse analysis method to determine the tensile properties of UHPFRC from unnotched four-point bending tests *Compos. Part B Eng.* **91** 189–204

[10] Bernardi P, Michelini E, Minelli F and Tiberti G 2016 Experimental and numerical study on cracking process in RC and R/FRC ties *Mater. Struct. Constr.* **49** 261–77

[11] Rimkus A, Jakstaite R and Kupliauskas R 2017 Experimental identification of cracking parameters of concrete ties with different reinforcement and testing layouts *Procedia Eng.* **172** 930–6

[12] Bernardi P, Cerioni R, Ferretti D and Michelini E 2014 Role of multiaxial state of stress on cracking of RC ties *Eng. Fract. Mech.* **123** 21–33

[13] Tan R, Eileraas K, Opkvitne O, Giedrius Ž, Hendriks M A N, Geiker M and Terje D B 2018 Experimental and theoretical investigation of crack width calculation methods for RC ties 1–12

[14] Redaelli D and Muttoni A 2007 Tensile Behaviour of Reinforced Ultra-High Performance Fiber Reinforced Concrete Elements Symp. Dubrovnik. *Concr. Struct.* 267–74

[15] Sigrist V and Rauch M 2010 Deformation behavior of reinforced UHPFRC elements in tension *Tailor Made Concr. Struct.* 106–106

[16] Redaelli D 2006 Testing of reinforced high performance fibre concrete members in tension Proc. 6th Int. Ph.D. Symp. Civ. Eng. 9

[17] Caro L A, Serna P and Marti J R 2013 Experimental Technique for Measuring the Long-term Transfer Length in Prestressed Concrete 125–34