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Experimental and Numerical Analysis of Fracture in Prestressed Concrete

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Abstract

This work examines the crack initiation and propagation in Prestressed Concrete (PC) beams by a combined experimental and numerical approach. Four-point bending tests performed on PC sleepers lead to the formation of multiple cracks, in a number that depends on the specimen. The location of each fracture and its growth with time is monitored by Digital Image Correlation (DIC). The experiments are simulated by a finite element approach, reproducing the concrete response by a smeared crack model. The model parameters are calibrated to match the experimental moment deflection curve. In this study, only the beam segment enclosing one crack is discretized. The effect of the external load is simulated by applying the horizontal displacements returned by DIC at the vertical boundaries of the analyzed region. Thus, uncertainties are reduced since there is no need to discretize the PC element in its whole length, to include the supports and the loading plates, and to simulate the interactions between the different components.

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Keywords: Fracture, Prestressed Concrete, Four-point bending test, Digital Image Correlation, Finite Element modeling

1. Introduction

Crack initiation and propagation in concrete is frequently a concern, even in prestressed elements. De Wilder et al. (2015) tested nine Prestressed Concrete (PC) beams under 4-Point Bending Tests (4PBT). The results showed that flexural cracks are formed in all beams except one, and that the number of cracks was unique for each specimen. In

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another study, Rezaie and Farnam (2015) performed three-point bending tests on PC sleepers with an initial crack length varying from 0 to 45 mm. The results showed complex fracture patterns, with initial vertical crack growth followed by bifurcation, horizontal propagation and the formation of further cracks around the main one. Silva et al. (2020) also tested some PC sleepers in three-point bending. In this case, the final failure occurred by concrete crushing after the extension of bending and shear cracks accompanied by the fracture of the lower prestressing tendons. Rezaie and Farnam (2015) and Silva et al. (2020) performed numerical studies on PC elements to simulate the experiments they carried out. In both studies the so-called Concrete Damaged Plasticity constitutive law implemented in the commercial code Abaqus (2022) was used.

Recently, Digital Image Correlation (DIC) has been adopted as a tool to monitor the outcome of tests performed on concrete elements where cracks are hardly visible, especially at the early loading stages. Cholostiakow et al. (2020) used DIC to analyze the shear failure crack patterns in concrete beams reinforced with fiber reinforced polymers. Also Liu et al. (2020) used DIC to measure the crack evolution at the rail seat section in PC sleepers tested under three-point bending.

In this study, 4PBTs conducted on three PC sleepers were also monitored by DIC. The collected measurements are exploited to analyse the experimental output with the aid of a reduced Finite Element (FE) model, which considers a limited portion of the tested samples, around one of the formed cracks. This approach has the advantage that there is no need to model the loading plates and the supports, and to define their interactions with concrete.

2. Experimental work

2.1. Experiment setup

Three nominally identical PC sleepers were subjected to 4PBT. The center-to-center distance between the supports is 2000 mm, and the distance between the two loading plates is 700 mm. The beam height in this segment is 208 mm. The elements contain six tendons of 9.4 mm diameter, while no reinforcement bars are present.

The test setup is shown in Fig. 1. The loading is applied at a constant rate of 120 kN/min. by means of a 300 kN servo-hydraulic actuator. A steel loading beam is used to evenly distribute the force over the two loading plates, which is equipped with hinges to avoid torque transmission. The same provision is adopted for the supports.

Three triangulation laser sensors (OPTO NCDT 1302-50) measure the vertical displacements of the two supports and of the midspan. In this way the net deflection of the specimen can be calculated, compensating for the deformations of the rubber pads at the supports. Compensated data are presented in the following.

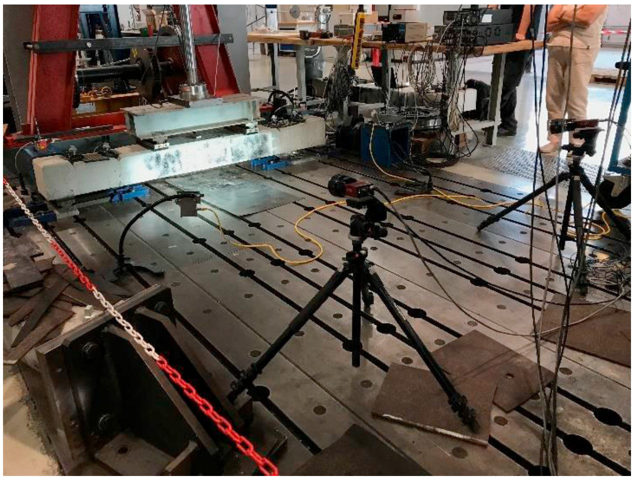

Fig. 1: Experimental setup

2.2 Digital Image Correlation

3D DIC monitors the element deformation and the crack propagation during the test. The vision-based measurement system is composed of two GX3300 digital cameras equipped with Zeiss lenses of 50 mm optical length. The cameras are mounted on tripods placed in the front of the sleeper, to face the area where cracks are most likely to appear, and are connected to an external PC controlling them by means of a custom software developed in National Instruments LabVIEW environment. The cameras are synchronized through a trigger line, connected to a waveform generator. They are programmed to trigger on the rising edge of the square wave signal produced by the function generator, obtaining a sampling frequency of 1 Hz.

The main components of the DIC system, the lighting source and two calibrated cameras, are shown in Fig. 1. The speckle pattern painted on the sleeper is also visible. The area between the two loading plates, which is the segment of maximum constant bending moment, is selected as the region of interest in the DIC analysis, and the displacement and strain maps in this portion are reconstructed. The calibration process is based on target images, and the correlation analysis is carried out using VIC 3D software.

The out-of-plane deformation is found negligible in this application. Therefore, only the in-plane results are presented in the following. Strains are calculated as the numerical derivative of the displacement distribution. Thus, large immaterial values are obtained in correspondence with the discontinuities induced by fracture. Nonetheless, the strain maps provide a clear visualization of the crack locations.

3. Experimental results

Three PC elements (labelled as S1, S2, and S3) were tested at the maximum applied load 120 kN. The DIC data were compared to the laser sensor readings and to the recordings of the loading cell. The graphs in Fig. 2 compare the load vs displacement curves obtained from DIC and from the laser sensor for specimen S3. The results match, thus confirming the accuracy of the measurements.

The load-deflection curve of the three samples is displayed in Fig. 3. The response is different for the three cases, although the sleepers are nominally identical and controlled industrial products. The discrepancy is likely due to small local imperfections that induce a unique crack pattern in each specimen.

The strain map generated by DIC at the maximum load of sample S3 is shown in Fig. 4a. It evidences the presence of the four major cracks that are hardly visible in the pictures taken by the cameras at the same testing time (Fig. 4b).

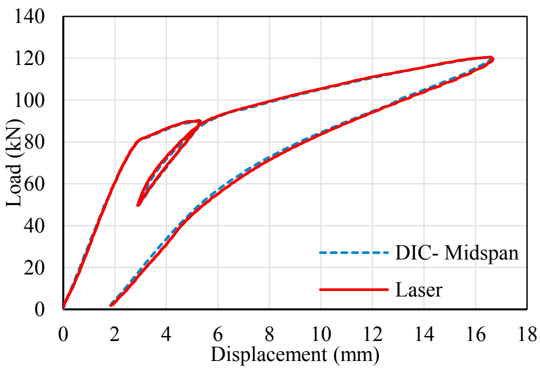

Fig. 2: Comparison of the load displacement curves reconstructed from DIC and laser sensor measurements for specimen S3

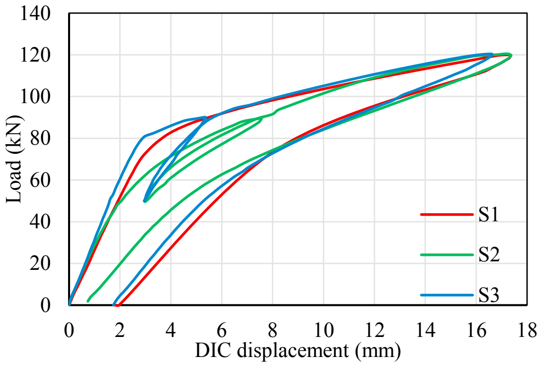

Fig. 3: Load-deflection curves

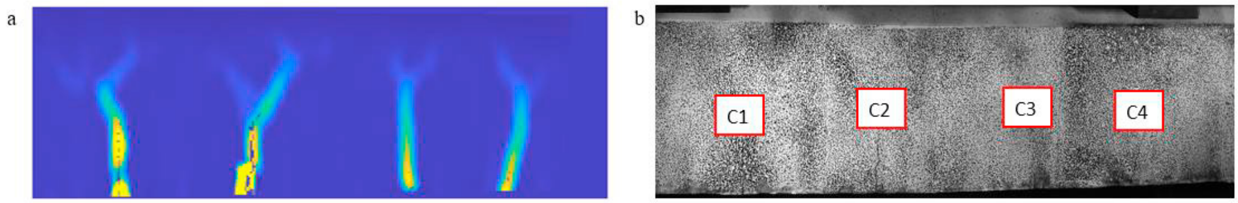

Fig. 4: (a) Strain map reconstructed by DIC and (b) the image of the surface of specimen S3 at peak load

4. Numerical simulation

The experimental results can be interpreted with the aid of a simulation model of the test. A preliminary plane stress FE analysis is developed using Abaqus (2022). The effect of the pre-tensioning cables is accounted for by introducing a predefined uniform stress field in the discretized domain. A smeared crack model is assumed to represent the mechanical response of concrete, with parameters calibrated on the experimental output.

DIC results are exploited to reduce the computing burden, by limiting the numerical analysis to the region enclosing one single crack only, as schematized in Fig. 5. The horizontal displacements extracted from the full-field DIC measurements are introduced as boundary conditions on the vertical sides of the investigated domain. Thus, there is no need to model the loading plates, the supports, and their interaction with concrete. Uncertainties are also reduced.

The external action (bending moment) is evaluated from the reaction forces. Fig. 6 displays the results corresponding to the initial phase of S3 testing. The segment modeled in this case is centered on the first crack (C1) shown on the left of Fig. 4. The size of the discretized domain is 170×208 mm.

Fig. 7 visualizes the numerical distributions of the horizontal stresses and strains corresponding to the last simulation point reported in Fig. 6, at an early stage of the fracture process.

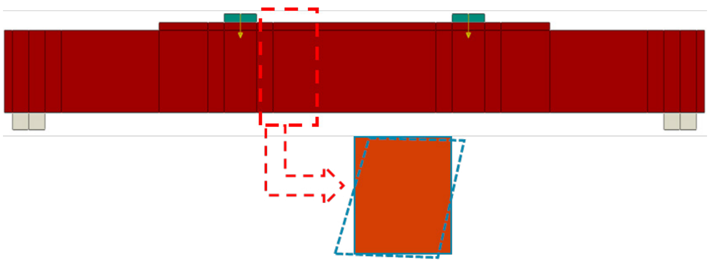

Fig. 5: Schematization of the region subjected to FE simulation

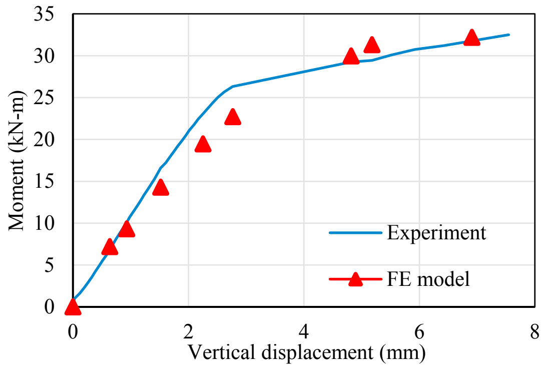

Fig. 6: The experimental moment-deflection curve and the corresponding numerical output

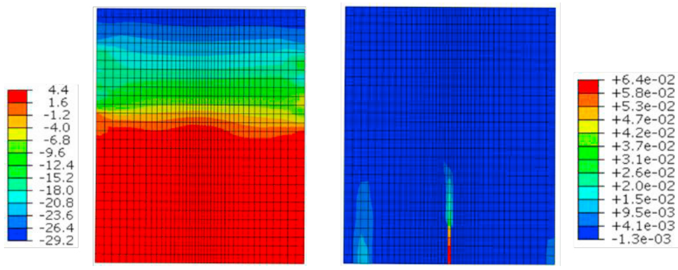

Fig. 7: Horizontal stress (MPa, on the left) and strain (right) distribution in the discretized FE region

Small deviations from the expected stress distribution reflect the measurement noise. The disturbances do not affect the central part of the analyzed region, though, where the main crack develops. However, strain concentration is also observed in a lateral location, and suggests the development of a second minor crack.

5. Conclusion

Four-point bending tests were carried out on nominally identical prestressed concrete members, while monitoring the deformation and fracture processes by 3D DIC. Different patterns of multiple cracks were observed. The experiments were simulated by a reduced FE model, based on the discretization of the area enclosing one single fracture. The full-field displacement distribution recovered by DIC defined the relevant boundary conditions. The preliminary results obtained so far and presented in this contribution show the potentialities of this approach. Future work is however required to overcome the limitations of the smeared crack approach considered so far, exploiting the information about the fracture profiles that is also returned by DIC.

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