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Using digital image correlation to evaluate fatigue behavior of strengthened reinforced concrete beams

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ABSTRACT

The fatigue behavior of reinforced concrete beams strengthened with externally bonded carbon fiber reinforced polymer (EBR) plates and near-surface mounted (NSM) bars has been investigated using a digital image correlation (DIC) technique. Displacement fields obtained from digital images recorded during specific load cycles in fatigue tests are analyzed to provide information on crack width, beam deflection and curvature, and major principal strains to enable crack detection. The results obtained in this way were compared to data gathered using conventional sensors, revealing that the DIC technique provided very accurate and detailed information, which is not possible to obtain using conventional techniques. The experimental results for plate-strengthened, bar-strengthened and unstrengthened beams are discussed.

1. Introduction

In recent years, the use of Fiber Reinforced Polymer (FRP) elements to strengthen reinforced concrete members has become a widely accepted method for stabilizing existing deteriorating or deficient structures. Two types of FRP element are used, both of which are bonded to the concrete surface with epoxy: plates or sheets that are externally bonded to the tension surface of the member – externally bonded reinforcement (EBR), or solid square rods that are positioned inside the member at a near-surface mounted (NSM) location.

Several studies on reinforced concrete beams strengthened with CFRP under fatigue loads have been reported [1–8]. The most common fatigue failure modes observed in these works involved the rupture of the tensile reinforcing steel followed by FRP debonding. Most of these studies did not consider the effect of crack distribution on the fatigue behavior of strengthened beams nor did they seek to determine which strengthening techniques are most effective at limiting crack spacing and width so as to prevent or reduce the corrosion of the steel reinforcement bars during the expected fatigue life of reinforced concrete members. In addition, there have been few investigations into the mechanical responses of cracks bridged by a bonded composite laminate under fatigue load.

Digital Image Correlation (DIC) is a very accurate method for studying the cracking of concrete. It can be used to monitor concrete members of various sizes under a wide range of loading conditions, and has a number of important advantages over conventional sensor-based methods. In particular, it permits measurements over the entire visible surface of the studied member rather than only at a limited number of discrete points. In addition, DIC is capable of detecting early cracks, and does not require tests to be paused so that new cracks can be marked and measured as they form; the latter quality is particularly useful in dynamic tests.

Destrebecq et al. [9] used DIC to detect and measure the widths of cracks in reinforced concrete beams, and to measure the mid-span deflection profiles of beams. The deflection profiles were then used to calculate the curvature evolution of beams over five load cycles. DIC has also been used to examine the bonding between CFRP elements and concrete in single lap tests [10,11], reinforced concrete specimens strengthened with composite plates [12], crack behavior in a RC beam [13], and for crack detection in a concrete beam [14,15], full-scale of prestressed concrete structures [16]. However, to the authors knowledge, DIC has not previously been used to study reinforced concrete members strengthened with CFRP under fatigue loads.

The DIC approach involves painting the area to be studied with a stochastic pattern and then imaging the painted surface with a

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digital camera of known resolution to monitor the deformation of the pattern over time. The captured digital images are divided into grids of square pixels known as facets. The greyscale values of each pixel in a facet are recorded, enabling its deformation and displacement to be tracked over time in order to determine the full field displacement of the imaged area.

This work presents fatigue test results for unstrengthened reinforced concrete beams and beams strengthened with either EBR plates or NSM bars. The main objectives of the experimental work were to analyze the displacement fields determined by DIC to determine the evolution of the deflection and flexural curvature of the beams during fatigue loading, to investigate crack initiation and propagation during fatigue loading, and to compare the results obtained for the different types of beams. The DIC software used for these purposes was the ARAMIS v6.3.0 (GOM GmbH, Braunschweig, Germany) non-contact optical strain measurement system. The results obtained confirm that DIC is an accurate method for measuring full field displacement and locating cracks, and provides a very easy way of measuring displacement at multiple points on the surface of a beam.

2. Specimen details and material properties

The beams used in this study were 4000 mm long with rectangular cross sections of 200 × 300 mm as shown in Fig. 1. Their longitudinal steel reinforcements in tension and compression were two rods with nominal diameters of 16 mm. The shear reinforcement, which was designed to ensure flexural failure in the strengthened beams, consisted of 10 mm stirrups at a spacing of 75 mm. Three beam types were tested – one strengthened with NSM bars, one with traditional EBR plates, and one without FRP strengthening. The unstrengthened beams were used as controls in the fatigue load tests. The same mass of FRP material was used in each of the strengthened beams so as to compare systems with similar specifications. The length of the strengthening plates and rods (3200 mm) was chosen to match the critical anchorage length of the beams [17].

Plate strengthening was performed with two strips of 1.4 mm thick CFRP, one with a width of 100 mm (StoFRP Plate IM 100C) and another with a width of 43 mm that was cut from a strip of material with a width of 60 mm (StoFRP Plate IM 60C). The plate strips were bonded to the surface of the beam soffit using StoPox SK41 epoxy after surface grinding to expose the gravel and primer application; the thickness of the adhesive epoxy layer after plate bonding was 2 mm. After the strengthening plates had been applied, two layers of CFRP sheeting were wrapped around the plate-strengthened beam to form a 300 mm wide U-jacket with the fiber direction being perpendicular to the longitudinal axis of the beam. The jacket was formed using the wet lay-up technique and placed toward one of the far ends of the beam, well away from the mid span. It was bonded to the beam using StoPox LH epoxy.

NSM strengthening was performed using two 10 × 10 mm quadratic rods (StoFRP BAR IM 10C), Fig. 1. The rods were fitted to the beam by cutting two parallel grooves along length of the beam using a concrete saw with two parallel saw blades. After chipping away the cut concrete, two grooves with widths of 15 mm and depths of 17 mm were obtained, with smooth sides and rough lower surfaces. The surfaces of the grooves were coated with primer and epoxy (StoPox SK41) before placing the NSM bars into the groove. The thickness of the adhesive layer surrounding the bonded NSM bars was 2.5 mm on the three bonded sides.

The compressive and tensile strengths of the concrete used can be seen in Table 1. For each beam, three tests were made for both the compressive and tensile strength of the concrete at time of test companion beam. The compressive and tensile strength of the concrete were determined according to Swedish standards SS

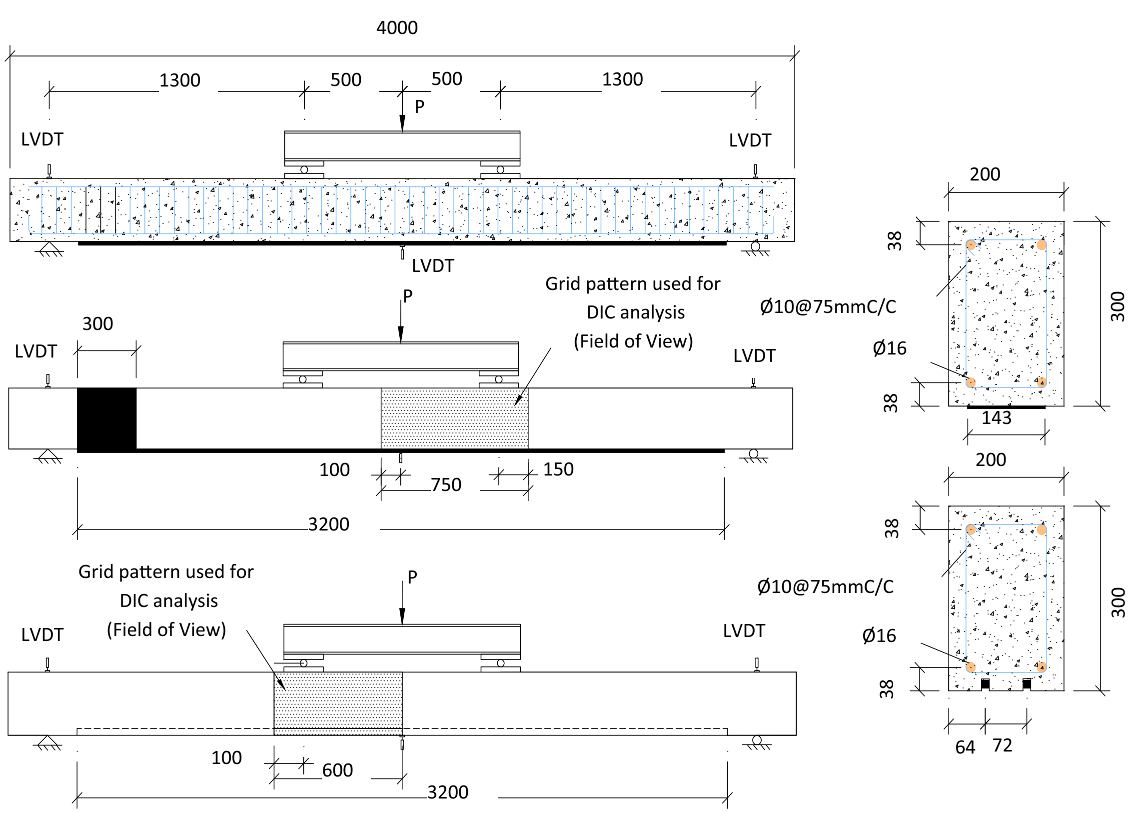

Fig. 1. Beam details and setup. All dimensions are in millimeters.