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Ductile behavior of high performance fiber reinforced cementitious composite (HPFRCC) frames

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HIGHLIGHTS

- The addition of fibers in concrete frames results in the increase of energy absorption.
- The ductility ratio of a RH frame is higher than that of RCH and RC frames due to the presence of fibers.
- Increasing the magnitude of the vertical load changed the development of plastic hinges in analytical frames.

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ABSTRACT

High performance fiber-reinforced cementitious composite (HPFRCC) materials exhibit strain-hardening behavior under tensile loading. Therefore, experimental studies were conducted to assess their structural performance and to compare them with normal concrete in reinforced concrete frames. The experimental results for reinforced concrete, reinforced composite, and reinforced HPFRCC frames with fixed foundation are presented herein. They indicate that using HPFRCC materials, instead of normal concrete in RC frames, increased the ultimate load, ultimate deflection, ductility ratio, and plastic hinge characteristics of frames. A 3D nonlinear numerical model was developed also, using the finite element (FE) method, and analytical models calibrated with experimental results and new data were generated. A good agreement between experimental and numerical results was observed.

1. Introduction

High Performance Fiber-Reinforced Cementitious Composites (HPFRCC) are defined as materials with a strain-hardening response under uni-axial loading (Fig. 1). Li and Wu [15] introduced a pseudo-strain hardening material that used only fine aggregates with reinforcing polyethylene fibers. Later, Naaman and Reinhardt [18] proposed a characterization framework for the many materials developed over the preceding years. High tensile ductility and strain hardening behaviors are the most important characteristics of this material, which is called HPFRCC. In recent years, a new class of HPFRCC has emerged, entitled Engineered Cementitious Composite (ECC). It was originally developed at the University of Michigan, with a typical tensile strength of 4–6 MPa and ductility of 3–5% [4]. Some of the researchers conducted nonlinear finite element analyses in the case of concrete and HPFRCC sections [5,19]. Results showed that there is an appropriate compatibility between experimental tests and analytical investigations in concrete and HPFRCC members [17,6].Moreover, some experimental and analytical research has been performed by different researchers on layered RC beams and using HPFRCC material in RC beam-column joints in connections and plastic regions [2,16,3,11,10]. These investigations have concentrated on reducing the amount of transverse reinforcements and forming the patterns of cracking in joints. Wilson and Abolmaali [21] compared the material behavior of steel and synthetic fibers in dry cast applications, and Abolmaali et al. [1] investigated the performance of steel fiber-reinforced concrete pipes.

In this paper, an experimental work, together with a finite element analytical study, was carried out on three moment resisting frames for assessing the step-by-step cracking patterns, plastic hinge formations, yielding length of tensile reinforcements,

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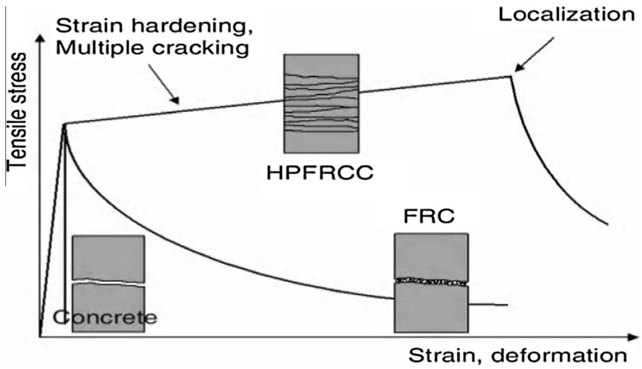

Fig. 1. Tensile stress-strain curves of concrete, FRC, and HPFRCC.

ultimate lateral load, and deformation characteristics of reinforced RC, composite and full HPFRCC frames.

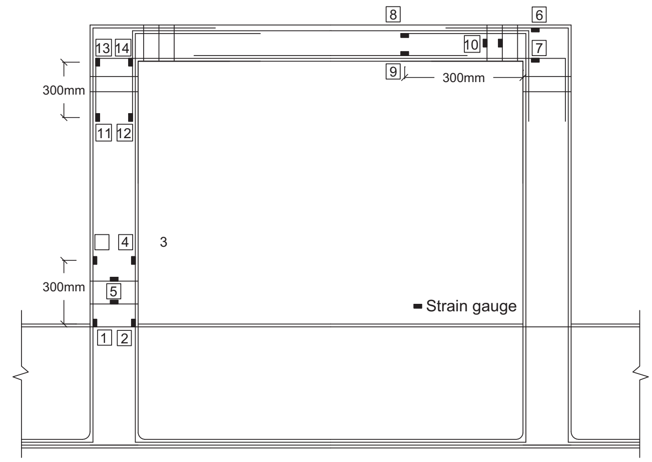

Fig. 3. Locations of installed strain gauges.

2. Experimental program

The test specimens which were chosen for experimental study in this paper were three moment-resisting frames with fixed supports including reinforced concrete (RC), reinforced composite (RCH), and reinforced HPFRCC (RH) frames. The clear span of the whole frames was 1200 mm, with a total span of 1600 mm. The cross section of the beams was 150 mm deep by 200 mm wide. The total height of the frames was 1400 mm, and the cross section of all the columns was 200 mm deep by 200 mm wide, as is shown in Fig. 2-a. Details of the reinforcement layout of the frames are shown in Fig. 2-b. In the RC and RH specimens, the whole frames were cast with concrete and HPFRCC materials, respectively. But in the RCH specimen, the HPFRCC material was used only in beam-column connection zones (300 mm in beams and 400 mm in columns) and the other parts of the frame were cast by normal concrete, according to Fig. 2-a. The frames were formed and casted in reclined position. After the required curing period and removing the form works, the frames were lifted to their upright position. The mat base of the each frame was bolted to the laboratory strong floor, thus giving an essentially fully-fixed condition at the column bases. Strain gauges were installed according to Fig. 3 at different critical positions.

Mix proportions of the concrete and HPFRCC materials are presented in Table 1. The mixture ratios were based on the weight of cement. Coarse aggregate was not used in the HPFRCC material, but polypropylene (PP) fibers, with a length of 12 mm and diameter of 18 µm, were used for achieving the HPFRCC. Coarse aggregate gradations of 4.75–12.5 mm particles and fine aggregate gradations of particles less than 4.75 mm were also used. During the mixing, care was taken to prevent clumping of the fibers. The dry components of the mortar mix were first combined with approximately 25% of the total water required, and then the fibers, along with the remaining 75% of the water, were intermittently added as the mixing process progressed. The fibers were added slowly, while mixing continued, in order to distribute the fibers thoroughly throughout the mix.

To determine the compressive properties of the concrete and HPFRCC material, compression tests on 100 × 100 mm cubes were performed, as shown in Fig. 4-a, and compressive failures of these specimens are presented in Fig. 4-b. As shown in this figure, due to the presence of PP fibers, the HPFRCC maintained its unity under severe loading and consequently showed ductile behavior. Material properties are summarized in Table 2.

Two loads, including constant vertical and monotonic lateral loadings, were applied on these frames. A vertical load was applied as a concentrated load placed on centerline of the frame, and the lateral load was applied on the exterior side of the column with rate of 0.02 mm/s, as shown in Fig. 5.

3. Experimental observations and results

3.1. Crack observations

In the first step, the constant vertical load of 30 kN was applied on the mid-span of the beam of the RC frame specimen, resulting in cracking in the mid-span of the beam and beam-to-column connections, as presented in Fig. 6-a. In the second step, the monotonic lateral load was applied to the frame. The first cracking was observed at the lateral load and displacement of 26 kN and 2.5 mm, respectively, at the beam top near the left beam-column junction, and at the column top near the right column-foundation connection. Further loading caused the cracking to spread at the beam-column junctions and column-foundation connections of the RC frame, as shown in Figs. 6-b and 7. The initial

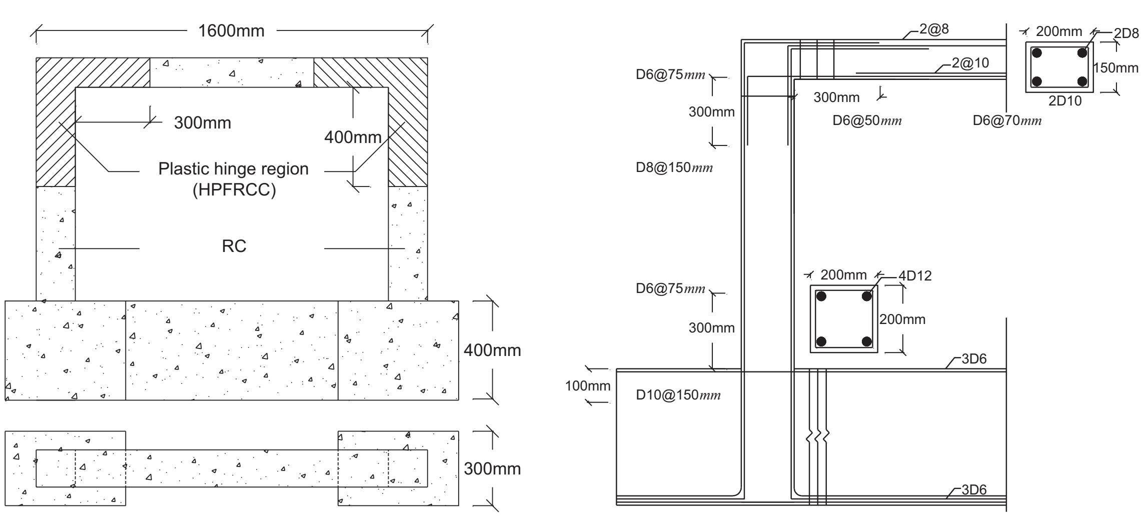

Fig. 2. (a) Dimensions of RCH specimen and (b) Reinforcement details of the all experimental specimens.