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Cyclic behavior of damaged reinforced concrete columns repaired with high-performance fiber-reinforced cementitious composite

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ABSTRACT

A high-performance fiber-reinforced cementitious composite (HPFRCC) prepared with high-volume fly ash is proposed to repair damaged reinforced concrete (RC) columns. This study aims at developing an effective and easy-to-apply repairing technique for RC columns damaged in earthquake. Four columns with 200 mm × 200 mm cross section and 900 mm height were prepared and tested to 85% of the load-carrying capacity under amplitude-increasing lateral loads and a constant axial load. The damaged columns were repaired using the HPFRCC: two repair heights (300 and 500 mm) and two repairing processes (with and without axial loads). The effectiveness of the repairing schemes was evaluated by comparing load-carrying capacities, displacement ductility, stiffness, and energy dissipation of the columns. The results indicated that the load-carrying capacity and ductility of the repaired columns could be respectively 14% and 29% higher than those of the original columns. With axial loads during repairing, the repaired columns displayed better cyclic performance. Increasing the repair height beyond the plastic hinge zone slightly improved the load-carrying capacity and ductility. Considering the performance-to-cost ratio, it is recommended that the repair height of HPFRCC be 1.5 times the depth or width of the damaged column.

1. Introduction

Civil infrastructure is mostly designed for structural safety under normal and extreme loads. In the event of earthquakes or fires, it is allowed to experience limited damage due to economic consideration. Once damaged, however, the mechanical performance and service life of reinforced concrete (RC) structures can be compromised significantly. For example, the load-carrying capacity of structural elements and components can be reduced, and the durability of structural systems can be weakened due to accelerated corrosion of steel rebar as chloride and moisture reaches to the surface of steel rebar through cracks. The degradation in structural performance greatly increases the risk of catastrophic consequences in post-earthquake events. For this reason, more attention has recently been paid to effective repairing or strengthening techniques for columns, beams, and walls in buildings and bridges [1–6]. In particular, RC columns have been extensively investigated since their integrity largely determines the seismic performance of building and bridge systems under lateral loads. In most modern seismic design codes, columns are expected to sustain relatively large inelastic deformation in plastic hinge zones without significantly reducing the load-carrying capacity and energy absorption capability of structural systems [3–5]. In this case, damaged columns experience concrete cracking and spalling and rebar yielding within the "plastic hinge" zone [6].

Various strengthening materials such as carbon fiber reinforced polymer [5], glass fiber reinforced polymer [7], and steel [8] have been applied to wrap or confine damaged columns for improved performance. In these cases, epoxy- and cement-based adhesives [9,10] were used to bond the repairing or strengthening materials to existing concrete. The repairing techniques were demonstrated to successfully recover or even enhance the performance of original columns [5,7–10].

High-performance fiber-reinforced cementitious composite (HPFRCC) is another group of strengthening materials that have desirable tensile properties. A HPFRCC is a mixture of cementitious materials, sand, fiber reinforcement, and admixtures. They have low water-to-cementitious materials ratio, high mechanical strengths and ductility, and extended service life due to their refined microstructures [11]. Engineered cementitious composite [12–14] and ultra-high-performance concrete [15–17] are two

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typical forms of HPFRCC. Due to the "bridging effect" of fiber reinforcement, HPFRCCs exhibit enhanced tensile performance. Once initiated in the cementitious matrix, cracks can be restrained from widening by the fiber reinforcement and the stress field at the crack surfaces can be distributed to surrounding areas, resulting in multiple fine cracks with reduced crack widths. For this reason, HPFRCCs can carry higher or sustained loads even with the presence of cracks.

HPFRCCs have been applied to effectively retrofit existing beams, beam-column joints, panels, masonry frames, and walls [18–26]. They have also been used in column construction [14,27] or column retrofitting [28] for load-bearing capacity and ductility under cyclic loads. However, the use of HPFRCCs for column repairing is limited. Even with other strengthening materials, damaged columns were repaired when the axial loads applied on the columns were removed in most, if not all, existing studies. Completely unloading the axial loads during column repairing is not only impractical in applications, but would also affect the seismic performance of repaired columns. In addition, HPFRCCs with high-volume cement content led to high embodied energy and carbon footprint [29], resulting in significant environmental impacts [30].

The main objectives of this study are to understand the cyclic behavior of damaged RC columns repaired with an environment-friendly HPFRCC prepared with high-volume fly ash [31,32] under lateral loads and to evaluate the effects of axial load and repair height on the performance of repaired columns. Four columns with 200 mm × 200 mm cross section and 900 mm height were prepared and tested to 85% of the load-carrying capacity under a constant axial load and amplitude-increasing lateral loads. The damaged columns were repaired using the HPFRCC: two repair heights and two repairing processes (with and without axial loads). The effectiveness of the repairing schemes was evaluated by comparing load-carrying capacities, ductility, and energy dissipations of the columns before and after repairing.

2. Materials

2.1. Normal concrete

Normal concrete with a water-to-cement ratio of 0.46 by weight was used to fabricate original RC columns. The maximum size of coarse aggregates used was 16 mm. Following standard tests, the compressive and splitting tensile strengths of the concrete were found to be 32 and 1.8 MPa, respectively.

2.2. Steel reinforcement

Three sizes of deformed bars (∅6, ∅16, and ∅18) were used as specified in GB1499.2-2007 [33]. Their nominal diameters are 6, 16, and 18 mm, respectively. The ∅6 bars had yield and ultimate strengths of 400 MPa and 570 MPa, respectively. Both ∅16 and ∅18 bars had a yield strength of 500 MPa and an ultimate strength of 600 MPa.

2.3. HPFRCC mixture

A HPFRCC mixture proportioned with high-volume fly ash was applied as the repairing material. The binder material was composed of 40% ordinary Portland cement and 60% Class F fly ash. The water-to-binder ratio was set to 0.24. Finely ground quartz sand was used at a sand-to-binder ratio of 0.46. Polyvinyl Alcohol (PVA) fibers were used at a content of 1.7% by volume of the binder. The PVA fibers were 12 mm in length, 0.04 mm in diameter, and 1300 kg/m^3 in density. The tensile strength and Young's modulus of the PVA fibers were 1.6 GPa and 43 GPa, respectively. A superplasticizer was used at a dosage of 0.1% by volume of the binder, ensuring that the HPFRCC mixture was self-consolidating.

The HPFRCC mixture was prepared using a 20-L Hobart mixer. The cement, fly ash, and quartz sand were first mixed in dry condition for 2 min. The superplasticizer was dissolved in water, and then added into the mixer and mixed for 8 min. Finally, the PVA fibers were slowly added within 2 min and mixed for another 3 min. All test specimens were cast in one lift without mechanical consolidation. They were kept in mold for 24 h, then cured in lime-saturated water for 7 days, and finally cured in air till 28 days.

Three prism specimens (71 mm × 71 mm × 214 mm), as depicted in Fig. 1a, were prepared in accordance with JGJ/T70-2009 [34]. Each specimen was tested in compression, as shown in Fig. 1a, at a displacement rate of 0.1 mm/min. The stress-strain curves of the three specimens are plotted in Fig. 1b. Their compressive strengths were consistent with an average of 42 MPa.

Five dog-bone specimens, as shown in Fig. 2a, were prepared. Each specimen was tested in tension at a displacement rate of 0.1 mm/min. The applied load and the specimen elongation were measured using a load cell of the load frame and a clip-on extensometer, respectively. During the test, each crack occurred in the cementitious matrix did not propagate and was not widened due to the "bridging effect" of PVA fibers, resulting in multiple cracks as indicated in Fig. 2a. Fig. 2b shows the stress-strain curves of the five specimens. The test results indicated that each specimen can sustain the applied load for extensive deformation during the development of multiple cracks as identified from the stress-strain curve.

3. Experimental program

Four RC columns were cast and tested to a predetermined damage state under cyclic loads, repaired with HPFRCCs, and tested again following the same load protocol in the Structural Engineering Research Laboratory at Shandong Jianzhu University. This process allows the simulation and testing of applicability, constructability, and performance of the proposed easy-to-apply repairing technique following an earthquake event.

3.1. Original column specimens

The original columns were designed to represent typical building columns constructed with normal concrete and steel reinforcing bars in accordance with GB50010-2010 [35]. Fig. 3 depicts the dimensions and reinforcement details of a test specimen, including a load stud, column, and footing. The specimen was 1380 mm tall with an effective column height of 900 mm measured from the top surface of the footing to the center of the load stud. Each column with a 200 mm × 200 mm square cross section was reinforced with four ∅16 bars in the longitudinal direction and ∅6 stirrups spaced at 80 mm in the transverse direction. The longitudinal reinforcement ratio was 1% of the effective cross section of the column. The footing with a rectangular cross section of 300 mm × 400 mm was reinforced with eight ∅18 bars in the longitudinal direction and ∅6 stirrups spaced at 100 mm in the transverse direction. The cross section of the footing was designed to have load-carrying capacity and flexural stiffness that were much larger than those of the column. Thus, the footing can be considered as a rigid component compared with the column.

3.2. Test Setup, Instrumentation, and loading protocol

Each test specimen was setup as shown in Fig. 4 with its footing anchored to the strong floor of the laboratory with steel bolts that