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Cyclic loading tests of RC columns strengthened with high ductile fiber reinforced concrete jacket

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HIGHLIGHTS

- The HDC jacket effectively changed the brittle failure mode of RC columns.
- No diagonal cracks occurred on the bar mesh reinforced HDC jacket.
- The seismic response of the RC columns was remarkably improved by HDC jacket.
- Bar mesh reinforced HDC jacket can be used to strengthen the high axial load columns.

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ABSTRACT

High ductile fiber reinforced concrete (HDC) is characterized by its tensile strain-hardening behavior and high compressive strain ability. This paper investigates the seismic performance of reinforced concrete (RC) columns strengthened with HDC jacket, eight RC columns were designed and six of them were strengthened with HDC jacket or bar mesh reinforced mortar (BMRM) jacket. The influence of jacketing schemes and axial load ratio on the failure modes, hysteresis loops, skeleton curves, deformation capacity and energy dissipation capacity is analyzed respectively. The experimental results from lateral cyclic loading tests on the specimens show that the failure mode of the columns could be changed from brittle to ductile under the confinement effect of the HDC jackets. The HDC jacket without bar mesh was certified to be more effective than the BMRM jacket in improving the plastic deformation capacity of the original columns. The HDC jacket with bar mesh is the best strengthening scheme, the columns jacketed by which exhibited tremendously enhancement in drift capacity and energy dissipation capacity by developing plastic hinges in the column foot even when the column was under high axial load ratio.

1. Introduction

The earthquake damage of reinforced concrete frame structure in previous earthquakes is mainly the failure of columns. Most of these frame structures were built before the enforcement of the modern seismic design codes, thus the earthquake loads were not taken into account or not sufficiently considered. As a result, the shear resistance capacity of the columns is usually insufficient. The occurrence of shear failure or non-ductile bending-shear failure in frame columns due to insufficient shear strength is likely to cause serious damage to the structure or even collapse. Therefore, the pre-earthquake strengthening of the vulnerable concrete columns is necessary.

Ferrocement jacket is a thin laminated cement based composite, which can be used to strengthen or repair the reinforced concrete columns. Takiguchi and Abdullah [1] strengthened four square reinforced concrete columns using circular ferrocement jacket. The influence of the numbers of layers of wire mesh on the ductility of the columns was tested. Then, Abdullah and Takiguchi [2] investigated the effect of axial load ratio, jacket schemes (circular section or square section) and the numbers of layers of wire mesh on behavior of six columns, finding that the jacketed columns exhibited tremendous improvement in ductility. Kazemi and Morshed [3] retrofitted shear deficient short columns by ferrocement jacket. The main variables were the spacing of ties in original specimens and the volume fraction of expanded metal in jackets. Research work by Takiguchi and Abdullah [4] confirmed that ferrocement jacket is an effective method for repairing the damaged columns. Overall, the ferrocement jackets can effectively

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improve the ductility of the concrete columns, however, the application of ferrocement jacketing mentioned above are mainly for small-scale columns. It is difficult to determine whether it is suitable for large-scale components. In addition, the matrix of the ferrocement jacket is a material with brittle, which is easy to crush under high compressive stress.

High ductile fiber reinforced concrete (HDC) [5–7] is a class of fiber reinforced cementitious composite like engineered cementitious composites (ECC) [8–10] and high performance fiber reinforced cementitious composites (HPFRCC) [11–13], which exhibits strain-hardening behavior in tension and high toughness in compression. Research work and application of fiber reinforced cementitious composite materials used in strengthening and repairing are increasing been presented recently. Wang [14] used high toughness cementitious composite (UHTCC) layer for enhancing the crack controlling and ultimate load-carrying capacity of the concrete beams. Hung and Chen [15] investigated the cyclic behavior of U-shaped ECC jacketing for retrofitting shear-deficient concrete beams. Li et al. [16] investigated the cyclic behavior of damaged concrete columns repaired with HPFRCC. However, there are few reports about the application of fiber reinforced cementitious composite in pre-earthquake strengthening of concrete columns.

Eight identical RC columns were fabricated to study the seismic performance of concrete columns strengthened with HDC jacket. Two of them are employed as the control specimens. The six other specimens are strengthened with HDC jacket or bar mesh reinforced mortar (BMRM) jacket. The design variables of the tests include: (1) presence or absence of bar mesh in HDC jacket, (2) mortar or HDC as the matrix of bar mesh reinforced jacket, (3) axial load ratio. The failure modes, hysteresis loops, skeleton curves, deformation capacity and energy dissipation capacity of the specimens are studied and analyzed by the lateral cyclic loading tests.

2. HDC materials

The mixed proportions for the cement-based matrix of the HDC used in this study are summarized in Table1. The components of HDC include cement, fly ash, river sand, water reducers, water and Polyvinyl alcohol (PVA) fibers. A 2% volume incorporation of PVA fibers is used in the HDC and the mechanical properties of the PVA fibers are shown in Table 2.

The tensile and compressive stress-strain curves of HDC are shown in Fig. 1. The fiber type is a controlling factor of the tensile properties of HDC. As shown in Fig. 1, the tensile strength and the ultimate tensile strain of HDC using Japanese fiber are 26.4% and about 150% higher than those of Chinese fiber respectively because the tensile strength and the elastic modulus of the Japanese fiber are much higher than those of the Chinese fibers (shown in Table 2), while the compressive strength and the peak compressive strain (about 0.6%) of them were almost equal.

Table 1
Mixed proportion of HDC (kg/m^3).

Cement	Fly ash	Sand	Water	PVA fiber	HRWR[a]
593	593	427	344	26	8

[a] High-range water reducers.

Table 2
Performance Indicators of PVA.

Fiber type	Length/ mm	Diameter/ mm	Tensile strength/ MPa	Elastic modulus/ GPa	Elongation/ %	Specific gravity
Japanese	12	39	1600	40	7	1.3
Chinese	12	39	1200	32	8	1.3

3. Experimental program

3.1. Specimen designs

Eight identical inverted T-shaped RC columns with a cross section of 250 mm × 250 mm and a height of 850 mm were fabricated. The effective height *H*, defined as the distance from the top surface of the foundation beams to the lateral loading point of columns, was 750 mm. The longitudinal reinforcements of the columns consisted of 6 steel bars with a diameter of 16 mm and the transverse reinforcements consisted of 8 mm-diameter hoops spaced at 100 mm. The foundation beams had a cross section of 400 mm × 400 mm with a length of 1200 mm. Table 3 lists the main parameters of the specimens. The target 28-day cube compressive strength of concrete of the specimens was about 40 MPa (C40). The specimens were divided into four groups. Group1 included specimens C-1 and C-6, which were employed as control specimens. Group2 included specimens C-5 and C-8 strengthened with bar mesh reinforced mortar (BMRM) jacket. Specimens C-2 and C-3 in Group 3 were strengthened with HDC (HDC-0) jacket without bar mesh. Group4 included specimens C-4 and C-7 strengthened with HDC (HDC-B) jacket with a layer of bar mesh. The strengthening jacket was four-sided layer with a thickness of 30 mm and the bar mesh spacing (Group 2 and Group 4) was 80 mm. The PVA fibers used in the jacket of specimen C-3 were produced in China (HDC-2) and the fibers in other HDC jackets were made in Japan. Fig. 2 shows the geometric sizes and reinforcement details of the specimens.

The construction steps of columns to be strengthened were gouging of concrete cover, cleaning of the concrete debris, inserting the vertical bar mesh (Group2 and Group4) into the foundation beams (with an anchoring length of 150 mm), spraying appropriate water on the surface of the gouged concrete, erecting the templates and casting the strengthening jackets. Fig. 3 shows the strengthening procedure before jackets casting.

3.2. Mechanical properties of materials

Table4 shows the mechanical properties of reinforcement bars used in the tests. The compressive strength of concrete, HDC and mortar were tested by three cubes (100 mm × 100 mm × 100 mm) respectively and the average values of them are listed in Table 5.

3.3. Test devices and loading procedure

All specimens were tested under combined constant vertical load and lateral cyclic load. The cyclic loading test set-up is shown in Fig. 4. The vertical load was applied on the top surface of the column by a hydraulic jacks and the lateral load imposed on the specimens was applied through a hydraulic actuator. The foundation beams were fixed on the ground with four anchor bolts.

As shown in Fig. 5, the loading procedure involved a force-controlled stage and a displacement- controlled stage. In the force-controlled stage, the increment of lateral cyclic load was 20kN until the columns yielded. Subsequently, the loading procedure was changed into the displacement-controlled stage. The yield point in Fig. 5 was defined as the lateral displacement corresponding to the first yielding of the longitudinal steel bars during the tests. The increment of the displacement was 4 mm, n is the step number of displacement load. Each displacement load step was repeated three times until the specimen failed or the lateral load of the specimens dropped below 85% of the peak value.

3.4. Measurement and data acquisition devices

As shown in Fig. 6, the lateral displacement of the load point of all specimens was measured by a linear variable differential trans-