Seismic-improved reinforced-concrete composite column using a high-ductile fiber cementitious composite precast box

Chang-Geun Cho*, Hyung-Ju Moon*, Ho- Yeon Kim* and Kang-Seok Lee
*Architectural Engineering, Chosun University, Gwangju, South Korea; †Department of Architectural Engineering, Hanyang University, Ansan, South Korea

ABSTRACT

The purpose of this study is to investigate the applicability of the high-ductile fibre cementitious composite to develop seismically improved reinforced concrete columns. The high-ductile fibre cementitious composites were fabricated to exhibit high-ductile tensile strains as above 2.0% with sustaining the tensile stress after cracks and to develop multiple micro-cracks while avoiding crack localisation. In order to seismically improve the reinforced concrete column, the precast box made of the high-ductile fibre cementitious composite was locally used at the flexurally critical region in the column plastic hinge zone, and the construction process was also proposed. In seismic capacity evaluation of the developed column, cyclical loading tests were carried out by using four column specimens fabricated. It was revealed, from experiments, that the developed reinforced concrete and the high-ductile fibre cementitious composite columns showed an improvement of the seismic capacity of the column as well as a minimisation of flexural and shear cracks in the bending critical region of the column.

1. Introduction

Since attention on high-performance characteristics in many building structural systems including high-rise buildings and long-span bridges has increased, researches on concrete and cementitious composites have been vigorously developed in the design and applications of building structures. The tensile strength of concrete is much lower than its compressive strength, and concrete can be brittle and cracks are easily developed under lower tensile stress.

On the other hand, in seismic improvements in the design of building structures, columns as the main structural members are demanded to have high load-carrying capacities as well as ductile deformation capacities for overall structural safety. Many studies in conventional reinforced concrete columns, however, including Japan Building Disaster Prevention Association (JBDPA) (2001), Cho et al. (2005), Paulay and Priestley (1992), Priestley, Seible, and Calvi (1996) investigated that the damages of concrete and deformations of steel re-bars in the column plastic hinge zone leads to failure caused by flexural cracks of the concrete, yielding and buckling of the longitudinal re-bars as well as crushing of the concrete in the flexural critical zone, as shown in Figure 1.

The use of fibre-reinforced cementitious mortar on reinforced concrete members is one of economic and practical attempts to develop seismic strengthening technologies (Li 1993; Li and Hashida 1993; Cho, Ha, and Kim 2008). To compare with normal concrete, fibre-reinforced concrete or high-performance fibre cementitious composites can improve not only tensile and flexural strength, but also crack controlled performances, ductility, and shear strength (Kanda and Li 1998; Lee et al. 2012; Lin and Li 1997). The shortcoming of brittleness in concrete could be improved to achieve better ductile characteristics by applying fibres mixed into cementitious mortar, the so-called high-ductile fibre cementitious composite.

In this research, a scheme with a half precast construction method to develop seismically improved reinforced concrete columns was newly attempted by applying the high-ductile fibre cementitious composite. In this method, the high-ductile fibre cementitious composite precast box was located in the flexurally critical region of the column in order to have relatively enhanced lateral deformation and load-carrying capacities of the column. The practical construction process of the developed column was also presented by a half precast column method. In order to evaluate the seismic performances, three column specimens were fabricated and examined under cyclical lateral loads with a constant axial load.

2. Mixing and characteristics of high-ductile fiber cementitious composites

In tension, the high-ductile fibre cementitious composite had the advantage that the localised cracks could be minimised, but multiple micro cracks were...
distributed widely so that overall flexural and shear strength could be improved with increase of ductile deformation capacities. The high-ductile fibre cementitious composite was manufactured by mixing polyvinyl alcohol (PVA) fibres, ordinary Portland cement (OPC), fine aggregates (maximum grain size 0.25 mm), water, a high-range water-reducing admixture, and admixtures to enhance the fresh properties of the mortar (Cho, Ha, and Kim 2008).

In order to achieve fluidity of the cement and dispersibility of the fibres, a polycarboxylate superplasticiser (PCSP) was applied, while hydroxypropyl methylcellulose (HPMC) was added to avoid the segregation of materials such as silica, fly ash (FA), blast-furnace slag (BFS), fine powder and fibres, and antifoaming agent was added to finish the surface and control the air content (Cho, Ha, and Kim 2008). PVA fibres had a length of 12 mm and the tensile strength of 1,600 MPa; with the surface treated by an oiling agent, as shown in Table 1, were reinforcing materials mixed in the high-ductile fibre cementitious composite in order to improve the brittle nature of the binder and have high-ductile tensile strain above 2.0%. The high-ductile fibre cementitious composite was mixed with a water/binder ratio (W/B) of 45%, a sand/cement ratio (S/C) of 71%, and a PVA fibre volume fraction of 1.5% (Cho, Ha, and Kim 2008).

A direct uniaxial tensile test was carried out to investigate the tensile strain of the hardened high-ductile fibre cementitious composite, as shown in Figure 2. The tensile test was set to a 10 kN capacity universal testing machine by control of the displacement with 0.2 m/min. Two LVDTs were attached to two sides of the specimens in order to obtain the tensile strains from the measured displacements. The specimen for the tensile test was made with a dog-bone shape (Lee et al. 2012), and the hardened high-ductile fibre cementitious composite specimen was removed from the mould one day after placement and cured in water for 28 days. The specimen had a dimension of a 36 × 20 mm cross-section and length of 350 mm.

As shown in Figure 3, the direct tensile behaviour of the high-ductile fibre cementitious composite had been measured from the tensile test that showed a high-ductile performance after reaching tensile cracking, with a measured tensile strain of about 3.0%. The high-ductile tensile characteristic was caused by multiple micro cracks as shown in Figure 2.

After the cracks, the specimen showed strain hardening behaviour and clear ductility with multiple cracking. The premature cracking strength was ~4.0 MPa, while the maximum tensile strength measured in the interval of the curing behaviour was 5.0 MPa. The experimental result explained that the high-ductile fibre cementitious composite had a high-ductile tensile strain with multiple micro cracks, thus avoiding crack localisation and enhancing the brittleness of the concrete.

### 3. Application of high-ductile fibre cementitious composite precast box in reinforced concrete composite columns

#### 3.1 Details and development of high-ductile fibre cementitious composite precast box

In order to enhance the seismic performance of conventional reinforced concrete columns, a new strengthening method was proposed such that the reinforced concrete column section in the length of the plastic hinge zone was designed and manufactured by a high-ductile fibre cementitious composite precast box instead of concrete. The mixing and mechanical properties of the precast box were the same as explained in the previous chapter. Since mixing and placing of the composite in sites of concrete building construction was not conducive to give sufficiently good outcomes of fibre dispersion, high-ductility, and durability, the high-ductile fibre cementitious composite box was made by precast with wet curing.

The manufacture process and descriptions of the high-ductile fibre cementitious composite precast box are presented in Figure 4. The precast box is designed to have transverse reinforcements and lead holes. The lead holes which will be transperierced by the main reinforcing bars are made using vinyl tube in the process of formwork. At seven days of curing of the box, formwork and vinyl tube are removed. At the placing stage of the topping concrete, the lead holes are filled with non-shrink mortar after the main reinforcing bars have transperierced, and the inside of the box is filled with concrete.

| Table 1. Characteristics of dimension of the PVA fibre. |
|------------------------------------------------------|
| Density (g/mm³) | Length (mm) | Diameter (µm) | Tensile Strength (MPa) |
|-----------------|-------------|--------------|------------------------|
| 1.3             | 12          | 39           | 1600                   |
3.2 Application of high-ductile fiber cementitious composite precast box in column plastic hinge zone

By using the high-ductile fibre cementitious composite precast box, a half precast composite column method has been proposed as shown in Figure 5. It is considered that this column method can apply in the first storey or in the basement directly connected with reinforced concrete footing.

There are seven stages of the manufacturing process for the proposed column in construction. At first, the reinforced concrete footing is cast with assembling of reinforcing bars and placing of concrete in which the footing surface on the location of the column is cast to a rectangular column seat with lower height of 120 mm in order to inset a precast box and the main reinforcing bars are lengthened from the inside of the footing.

A precast box is put down along the main reinforcing bars which will transpire the lead holes in the box, and the precast box is inset about 120 mm into the column seat on the footing surface.

After locating the precast box on the footing, the gaps of the footing surface and the box as well as the gaps of the lead hole and the main reinforcing bar are injected by non-shrink mortar in order to obtain sufficient integrity between the box and the footing.

Finally, in order to place the topping concrete, the main reinforcing bars are extended by bar couplers, hoop reinforcing bars are assembled, and the formworks for topping concrete are installed and the concrete is placed. Finally, the half precast high-ductile fibre cementitious composite and reinforced concrete composite column is completely constructed after curing of the topping concrete and removal of the formwork.

4. Experiments on cyclic loadings of proposed column specimens

4.1 Design and details of column specimens

In order to evaluate seismic responses of the proposed column, three column specimens were manufactured, representing the first-storey column between the footing and the inflection point, with the column being fixed to the column base as a cantilever column. Two specimens were strengthened by the precast box in the column plastic hinge zone and one specimen as the conventional reinforced concrete column. Table 2 summarises four specimens with experimental variables and Figure 6 illustrates the geometry and reinforcement details of PCHD-N and -S specimens.
The main variables in the experiments were the numbers of hoop reinforcing bars with the strengthening by the precast box. Each column had a 300 × 300 mm cross-section, height of 1,400 mm from the base to the top of the column, a 400 × 400 mm cross-section of the head part of the column and the column base which was connected to a reinforced concrete footing, measuring 900 × 900 × 700 mm. All specimens had main longitudinal reinforcements as eight units of D13 bars. For specimen PCHD-N, the transverse reinforcements were not placed at the precast box in order to evaluate the control of shear cracks by the high-ductile fibre cementitious composite, while for all the other cases, the transverse reinforcements were assembled with D10 bars with a space of 100 mm or 200 mm.

Figure 4. Precast process of the developed high-ductile fiber cementitious composite precast box.
Figure 5. Manufacturing stages of the proposed column specimen.
Two types of steel reinforcements produced in Korea were used in column specimens. The yielding stresses of the reinforcing bars for the main longitudinal bars, D13, and the transverse bars, D10, measured 385 MPa and 383 MPa, respectively. The concrete was mixed with OPC, crushed stone with a maximum aggregate size of 20 mm, sand and admixtures. Cylindrical specimens were cast to test the compressive strength of the concrete and the uniaxial compressive strength of the concrete was measured as the average of 27.6 MPa.

The actual manufacturing process of the column specimen of a high-ductile fibre cementitious composite and reinforced concrete composite columns are shown in Figure 7.

4.2 Loading test of column specimens under cyclic load

The installation of the test frame for column specimens was set up to provide cantilever-type loading conditions; the bottom stub of each specimen was fixed to the base in order to achieve full fixity at the base (Cho et al. 2012). Lateral loading was applied through a reaction wall equipped with a 100 kN capacity actuator according to a predetermined displacement-controlled loading sequence.

The cyclical lateral load was controlled by the top-displacement of the column. To apply axial loading, external steel tendons were attached between the pin and the loading frame and tensioned by hydraulic actuators. The axial load of the column was set to 196.2 kN during the loading operation. The specimens were equipped with a displacement transducer at the top of the column to measure and control the lateral displacement of the column (Cho et al. 2012).

5. Summaries and discussions on cyclic load test

Each specimen of the column was tested by the loading frame under the laterally reversed cyclical load combined with the constant axial load, and cracks and failure patterns at ductility levels are shown in Figure 8 through 10, respectively. Cyclical lateral load and top-displacement responses of specimens are also shown, respectively, in Figure 11.

For the specimen of a conventional reinforced concrete column, RC-C0, the initial flexural crack occurred at a displacement of 6.1 mm and yielding of the initial main reinforcement was reached at a displacement of 16.5 mm. The displacement of the initial yield point of the main reinforcement increased with the load, up to 58.3 mm at a maximum load of 78.6 kN. In cyclical responses of the column specimen RC-C0, tremendous tendencies to rapid strength deterioration and stiffness degradation during cyclical responses were observed due to the lack of transverse reinforcements.

The load carrying capacity was limited by internal degradation in the plastic hinge regions caused by yielding and buckling of the main reinforcements accompanied by insufficiencies of the hoop bars. The plastic hinge regions were more extended from the bottom to the top of the column, with severe damage to the concrete and steel bars, and the

---

**Table 2. Experimental variable of column specimens.**

| Specimen name | PVA Volume (Vf) | Height of HDFC box (d) | Reinforcement (Main/Hoop) |
|---------------|-----------------|------------------------|--------------------------|
| RC-C0         | -               | -                      | 8-D13 / D10@100          |
| PCHD-N        | 1.5 %           | 2.0d                   | 8-D13 / Not tied         |
| PCHD-S        | 1.5 %           | 2.0d                   | 8-D13 / D10@200          |

---

**Figure 6.** Detail of reinforced high-ductile fiber cementitious composite box and concrete column specimens.
maximum lateral top displacement was measured as 68.7 mm (see Figures 8 and 11).

For the specimen PCHD-N, as shown in Figure 9 and Figure 11(b) without transverse reinforcements in the high-ductile fibre cementitious composite precast box, the initial flexural crack was identified at a horizontal displacement of 4.8 mm and the load carrying capacity increased after the first crack; however, the yielding of the initial main reinforcement occurred at a horizontal displacement of 17.4 mm. The maximum load carrying capacity of 92.5 kN was reached at a horizontal displacement of 65.6 mm; maximum displacement was reached at 112.3 mm.

Unlike the specimen RC-C0, shear cracks were not observed during the loading sequence; spalling and damage in the high-ductile fibre cementitious composite precast surface were not as serious, and finally the specimen reached failure with bending cracks near the column base.

For specimen PCHD-S, as shown in Figure 10 and Figure 11(c) strengthened with the high-ductile fibre cementitious composite precast box with hoop

Figure 7. Manufacture process of column specimens.
reinforcements in the plastic hinge region, an initial flexural crack occurred at a displacement of 5.2 mm. Yielding of the main reinforcement occurred for the first time at a horizontal displacement of 15.4 mm after showing an increase in load-carrying capacity according to the increase in displacement with definitive stiffness. The maximum load carrying capacity of 97.7 kN was reached at a horizontal displacement of 31.5 mm. The horizontal displacement was up to 77.9 mm with increasing horizontal displacement and decreasing strength. The test results for the specimen PCHD-S showed that no more load carrying capacity could be maintained due to internal degradation in the plastic hinge region caused by yielding of the main reinforcement at a maximum displacement of 101.9 mm. Shear cracks on the surface of the high-ductile fibre cementitious composite box were not observed until the column reached failure by bending, and in the column plastic hinge zone, spalling and damage to the composite surface as well as
buckling of the main bars were not observed, in comparison with the specimen of a conventional reinforced concrete column.

For each column, the estimated overall responses of the initial lateral yield load, the maximum lateral load, the maximum lateral displacement, and the lateral displacement ductility ratio are compared respectively in Figure 12. The damages in the column plastic hinge region were minimised by replacing the region of concrete as high-ductile fibre cementitious composite precast box and the overall responses of the column were also enhanced in lateral load and deformation capacities.

6. Conclusions

The following conclusions were obtained after evaluating through cyclical loading tests on a newly developed seismic strengthened reinforced concrete column
method by applying the high-ductile fibre cementitious composite precast box in flexurally critical regions.

By intensively placing the precast box near the flexurally critical region of the reinforced concrete column, it had been shown that the box could control the flexural and shear cracks, spalling and damages, buckling of main reinforcing bars, and cover debonding in the plastic hinge regions of the column, thus improving the flexural capacity of the column while ensuring the safety of axial loads.

In comparison with a specimen of a conventional reinforced concrete column, the column specimens improved by a high-ductile fibre cementitious composite precast box showed improved responses to minimise shear cracks and shear failures in spite of minimum use of transverse reinforcements as well as the concentrated local damage of the column in the plastic hinge zone induced by bending cracks, spalling of cover, and buckling of main reinforcing bars.

Therefore, specimens of improved columns by a high-ductile fibre cementitious composite precast box were sufficient to improve the overall lateral load-carrying and deformation capacities under cyclical lateral loads when compared to the conventional reinforced concrete column specimen.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

This research was supported by research funds from Chosun University (2018).

**Notes on contributors**

Chang-Geun Cho is a professor at the department of architectural engineering, Chosun University, Gwangju, South Korea. He received his PhD degree from the Tokyo Institute of Technology, Japan. His research interests include seismic capacity evaluation of concrete structures, especially columns as well as the finite element analysis.

Hyung-Ju Moon is a PhD candidate at the graduate school of architectural engineering, Chosun University, Gwangju, South Korea. His main research area is seismic capacity evaluation of concrete columns.

Ho-Yeon Kim is a PhD candidate at the graduate school of architectural engineering, Chosun University, Gwangju, South Korea. Her main research area is seismic capacity evaluation of concrete structural system.

Kang-Seok Lee is a professor at the department of architectural engineering, Hanynag University, Ansan, South Korea. He received his MS and PhD degrees from the University of Tokyo, Japan. His research interests include seismic capacity evaluation and rehabilitation of concrete structures, seismic risk assessment of urban cities, and optimal structural design.

**References**

Cho, C. G., G. J. Ha, and Y. Y. Kim. 2008. “Nonlinear Model of Reinforced Concrete Frames Retrofitting by In-Filled HPRCC Walls.” *Structural Engineering and Mechanics* 30 (2): 211–223.
Cho, C. G., Y. Y. Kim, L. Feo, and D. Hui. 2012. “Cyclic Responses of Reinforced Concrete Composite Columns Strengthened in the Plastic Hinge Region by HPFRC Mortar.” Composite Structures 94: 2246–2253. doi:10.1016/j.compstruct.2012.01.025.

Cho, C. G., M. Kwon, and E. Spacone. 2005. “Analytical Model of Concrete-Filled Fiber-Reinforced Polymer Tubes Based on Multiaxial Constitutive Laws.” Journal of Structural Engineering, ASCE 131 (9): 1426–1433.

JBDPA (Japan Building Disaster Prevention Association). 2001. Standard for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings, 450. Tokyo, Japan.

Kanda, T., and V. C. Li. 1998. “Interface Property and Apparent Strength of a High Strength Hydrophilic Fiber in Cement Matrix.” ASCE Journal of Materials in Civil Engineering 10 (1): 5–13.

Lee, B. Y., C. G. Cho, H. J. Lim, J. K. Song, K. H. Yang, and V. Li. 2012. “Strain Hardening Fiber Reinforced Alkali-Activated Mortar - A Feasibility Study.” Construction and Building Materials 37: 15–20.

Li, V. C. 1993. “From Micromechanics to Structural Engineering - the Design of Cementitious Composites for Civil Engineering Applications.” Journal of Structural Mechanics & Earth Engineering 10 (2): 37–48.

Li, V. C., and T. Hashida. 1993. “Engineering Ductile Fracture in Brittle Matrix Composites.” Journal of Materials Science Letters 12: 898–901. doi:10.1007/BF00455611.

Lin, Z., and V. C. Li. 1997. “Crack Bridging in Fiber Reinforced Cementitious Composites with Slip-Hardening Interfaces.” Journal of the Mechanics and Physics of Solids 45 (5): 763–787.

Paulay, T., and M. J. N. Priestley. 1992. Seismic Design of Reinforced Concrete and Masonry Buildings, 744. New York: Wiley & Sons.

Priestley, M. J. N., F. Seible, and G. M. Calvi. 1996. Seismic Design and Retrofit of Bridges, 686. New York: John Wiley & Sons.