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SEISMIC PERFORMANCE OF A HIGHLY DAMAGE-TOLERANT ULTRA-HIGH PERFORMANCE FIBER-REINFORCED CONCRETE COLUMN

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Abstract

Reinforced concrete (RC) columns in the lower stories of high-rise buildings are usually subjected to high axial loads and large lateral earthquake forces in seismic regions. In addition, to satisfy the strength limit state, these RC columns have to exhibit adequate ductile behavior without dramatic strength loss. The application of high-strength concrete (HSC) for the design of such columns could be attractive by potentially reducing the stress demands. However, the increased brittleness of HSC makes it less favorable for the seismic design of structures. In this study, the potential application of ultra-high-performance fiber-reinforced concrete (UHP-FRC) to improve the seismic performance of RC columns was evaluated based on its capability to enhance both the strength and ductility of conventional concrete materials. As an innovative material, UHP-FRC provides high compressive strength (150~207 MPa), excellent tensile cracking behavior, and improved compressive ductility with excellent confinement characteristics. The addition of high strength steel microfibers into the concrete mix can alleviate the need for excessive transverse reinforcement. In this study, full-scale moment-frame columns, constructed with both normal strength concrete and UHP-FRC, were tested under cyclic displacement reversals up to collapse. The performance of the UHP-FRC column is evaluated by comparing it with the conventional RC column. Test results show that the UHP-FRC column exhibited a completely different failure mode from the conventional RC column by improving the confinement effect and avoiding concrete crushing. Experimental results show that the UHP-FRC column exhibited a higher peak strength and greater drift capacity. The lateral displacement of the ACI compliant RC column primarily resulted from the flexural rotation of the plastic hinge region above the column base; on the other hand, the lateral displacement of the UHP-FRC column came from the plastic rotation at the column base due to a strain penetration effect into the footing.

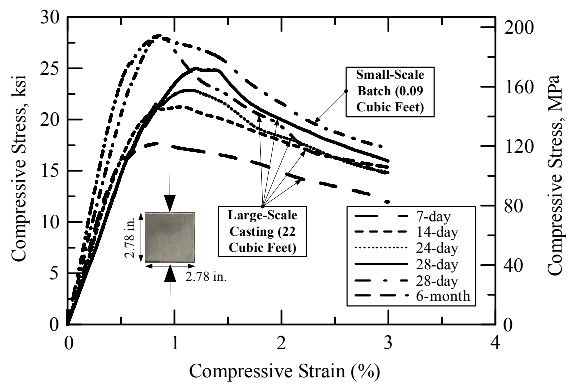
Keywords: Column; fiber; reinforced concrete; UHP-FRC; plastic hinge; high strength

1. Introduction

High-strength concrete (HSC) is often utilized as a cost-effective design solution in the lower stories of high-rise buildings. There are many advantages for the use of HSC in high-rise buildings, particularly in the column members. HSC has the potential of reducing the stress demands on the column section. It can also be used to reduce section sizes; hence, reducing some construction costs due to less labor and formwork, while maximizing the rentable floor space [1]. However, the brittleness of HSC makes it a less attractive material for structures in high seismic areas. This is due to the fact that excessive transverse reinforcement is needed in the column cages in order to provide confinement and increase the ductility of the columns. The addition of transverse reinforcement can lead to severe congestion in the plastic hinge regions, which can create great difficulties during construction and concrete placement. Another negative effect of using HSC on the seismic performance of columns is that HSC causes early cover spalling, which leads to a decrease in strength [2]. Researchers have improved the confinement and seismic performance of concrete columns through the use of fiber-reinforced concrete (normal strength 35~55 MPa with moderate compressive ductility). Additional dowel reinforcement combined with debonding techniques to prevent damage concentration [3] have also been used. However, these techniques could complicate the design, and they have been known to fail in the prevention of concrete deterioration, crushing, and bar buckling. In recent years, the development of ultra-high-performance fiber-reinforced concrete (UHP-FRC) has provided an innovative method that can resolve the brittleness issue of HSC while maintaining constructability. The superior mechanical properties of UHP-FRC offer a new way to design earthquake-resistant moment frame members. With limited UHP-FRC full-scale data available, this study offers a valuable comparison between the seismic performance of a full-scale column with its plastic hinge region cast with UHP-FRC and a column fully cast with conventional normal-strength reinforced concrete.

2. Mechanical Properties of UHP-FRC Used in the Column

An independent material study was done by Aghdasi et al. [4] to develop a suitable UHP-FRC mix for large-scale column casting with characteristics such as high compressive strength and ductility, tensile ductility, and flowability, which are all critical properties for concrete columns subjected to seismic loading. UHP-FRC is an innovative material, which is made based on the dense particle packing concept. It allows for a high compressive strength and improved ductility while maintaining a nearly self-consolidating consistency. UHP-FRC shares the advantages of HSC with a uniaxial compressive strength of approximately 190 MPa. The integration of high strength straight steel microfibers resulted in higher shear and tensile capacities, which can alleviate the need for excessive transverse reinforcement in concrete columns. The complete stress-strain curves at 7, 14, 24, 28, and 180 days of age are shown in Fig. 1 where the 24th day is the day of full-scale column testing.



- 1 in. = 25.4 mm
- 1 Cubic Feet = 0.0283 Cubic Meter
- Each curve is based on average of two 2.78-in.-cubes
- 24-day was when the full-scale column was tested

Fig. 1 – The compressive stress-strain curves of the UHP-FRC

3. Experimental Program

While the capabilities of UHP-FRC suggest it to be a valuable alternative in earthquake resistant structures, it has yet to be tested in large scale structural applications. This study primarily focuses on the characteristics and behavior of two full-scale space frame column specimens consisting of a normal strength concrete specimen and a specimen with its plastic hinge region cast with UHP-FRC. Both tested under large displacement reversals.

3.1 Specimen geometry and design

Each column specimen consists of a footing block, a column section, and a loading block. The space frame column is a 2.69 m tall square column and represents half the total height of an actual column with cross-sectional dimensions of 711 × 711 mm and is reinforced with 12 No. 8 bars (ASTM A706 Grade 60) distributed evenly around the perimeter of the cross section. Although using ultra-high strength concrete for high-rise building members such as columns is beneficial, the increasing brittleness of concrete with high compressive strength has become a major concern, especially for seismic applications. For this reason, proper confinement (that is, transverse reinforcement) of concrete is essential for the safe use of high strength concrete. Fig. 2 shows typical construction for seismic resistant reinforced concrete moment frame columns with normal strength concrete (35 MPa). The congestion of steel reinforcement is mainly due to transverse reinforcement requirements [5]. The amount of transverse reinforcement largely depends on compressive strength. ACI ITG–4.3R [6] indicates that when the concrete compressive strength is increased from normal strength to ultra-high strength, significant amounts of transverse reinforcement are needed to confine the concrete in order to prevent premature brittle failure even though this is practically impossible due to the already congested reinforcing cage for normal strength concrete (Fig. 2). However, the amount of transverse reinforcement can be considerably less when UHP-FRC is used due to the much enhanced ductility caused by the addition of fibers. This allows the transverse reinforcement amount used in UHP-FRC to be the same as that used in the plastic hinge region of a normal strength RC column. The transverse reinforcement consists of groups of three overlapping ties bent from No. 5 bars (ASTM A615 Grade 60) spaced at 12.7 cm for the first 1.07 m near the plastic hinge region, and 15.2 cm for the remainder of the height of the specimen above the plastic hinge region (Fig. 3).

Note that in this research, when designing the column with UHP-FRC, the dimension was kept the same as that of the conventional RC column because: 1) in an actual design of RC moment frames, usually the stiffness requirements control the member dimensions; 2) it is easier to compare two specimens when variables are minimized. This leads to a significantly lower axial load ratio for UHP-RFC column, which reduces the stress and ductility demand imposed on the UHP-FRC column.

Fig. 2 – Typical Confinement Reinforcement Used in Normal Strength Columns for RC Moment Frames (photo by Shih-Ho Chao)

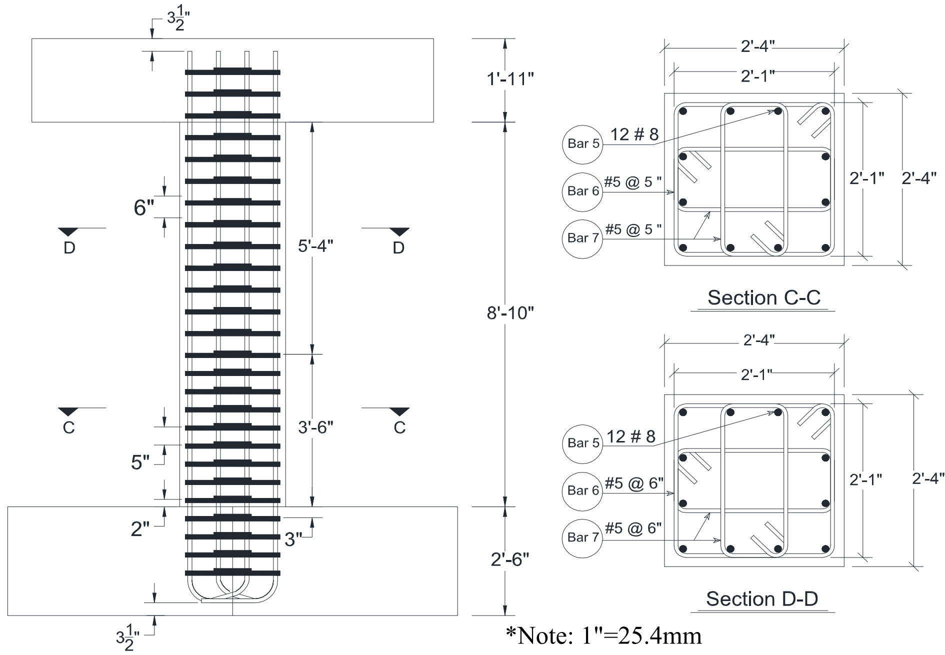
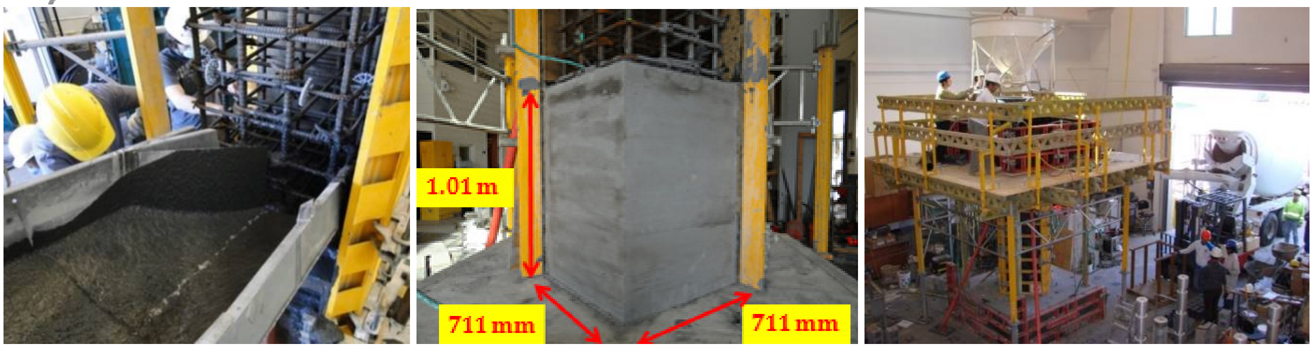


Fig. 3 – Space Frame Column Reinforcement Details

3.2 Specimen construction

The column specimens were constructed at the University of Texas at Arlington Civil Engineering Laboratory Building (UTA CELB). Each specimen was built in three major parts and cast vertically to simulate real-world construction. Once the footing block cage was completed, it was placed inside the formwork and a truss frame was erected. After completion of the column cage, it was placed vertically inside the footing cage, centered and secured with straps to the truss frame to prevent it from moving during casting. The footing block was cast first using 35 MPa concrete. After the footing block concrete had gained sufficient strength, the formwork for the column and platform was erected. The remainder of the specimen was then cast using a nearly self-consolidating concrete with 9.5 mm. aggregates and a specified compressive strength of 35 MPa provided by a ready-mix truck. A crane was used to lift the large bucket of fresh concrete poured into the column section. After two days of curing, the formwork was removed and the column was prepared for shipping. Column specimens were post-tensioned axially using four post-tensioning rods to protect them from cracking during lifting and transportation. The columns were removed from UTA CELB by heavy duty forklifts and placed on a flatbed truck for delivery to NEES (Network for Earthquake Engineering Simulation) Multi-Axial Subassemblage Testing (MAST) facility at the University of Minnesota for testing.

Construction of both columns followed the same protocol. However, the first 1.01 m above the footing of the second column specimen was cast with UHP-FRC. Using a custom-made high shear concrete mixer, dry mix was added first, followed by water, superplasticizer, and fibers. The UHP-FRC concrete was then poured into the formwork until completely filled (Fig. 4a). The UHP-FRC mix was nearly self-consolidating requiring no vibration resulting in a very smooth finish with no visible voids (Fig. 4b). After casting the UHP-FRC section, the remainder of the column was cast identically to that of an RC column specimen (Fig. 4c) using normal strength 35 MPa concrete.



(a) (b) (c)

Fig. 4 – UHP-FRC (a) pouring and (b) completed Section (c) Final Casting

3.3 Instrumentation

A comprehensive set of instrumentation was installed to closely monitor the behavior of specimens in terms of global deflections and rotations, segmental flexural rotation, shear deformation, and strains of the longitudinal and transverse reinforcement and concrete. The layout of the external instrumentation is shown in Fig. 5 where rotation and flexural deformation were derived from pairs of linear variable differential transformers (LVDTs) at the same levels in SE and NW directions, and shear deformation was calculated with the crossed string pots and LVDTs. Fig. 6 shows the strain gauges installed on the longitudinal reinforcing bars. To measure the internal strains of the concrete during testing, each specimen was instrumented with embedded concrete strain gauges. It should be noted both specimens were instrumented in exactly the same way for comparison purposes.

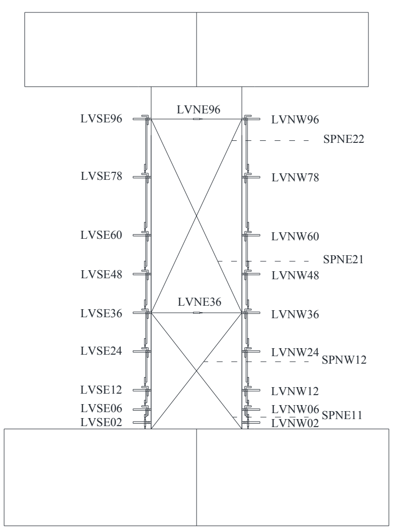


Fig. 5 – LVDT layout for both RC and UHP-FRC specimens

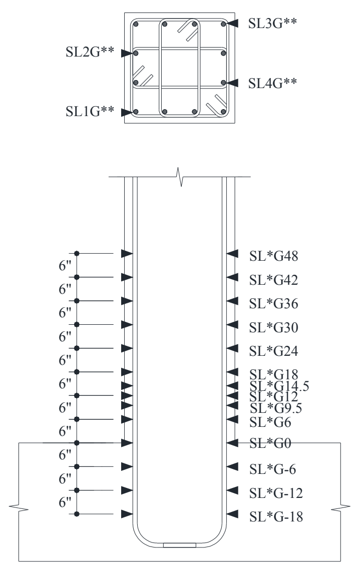


Fig. 6 – Strain gauges installed on longitudinal reinforcement of both RC and UHP-FRC specimens

3.4 Loading protocol

The same cyclic loading protocol was used for both specimens. The loading protocol used in this study was in accordance with ACI 374-05 [7]. An axial load of 5,231 kN was applied at the beginning of each test and kept vertical and constant throughout the entirety of the test. This gave an axial load ratio (Pu/Agf'c) of 0.28 for the conventional RC column (the actual compressive strength was 36.4 MPa), and 0.06 for the UHP-FRC column. After the application of the axial load, the specimens were subjected to the reverse cyclic loading protocol. Fig. 7

shows three fully reversed cycles applied at each drift level gradually increasing in magnitude. In between each increasing drift level, intermediate cycles were applied at a magnitude, which was one-third of the preceding drift level. The criteria for stopping the test was based on the displacement limitations of the crosshead actuators or until the specimen's strength degraded to 20 percent or less of their peak resistance exhibited during the test in both directions.

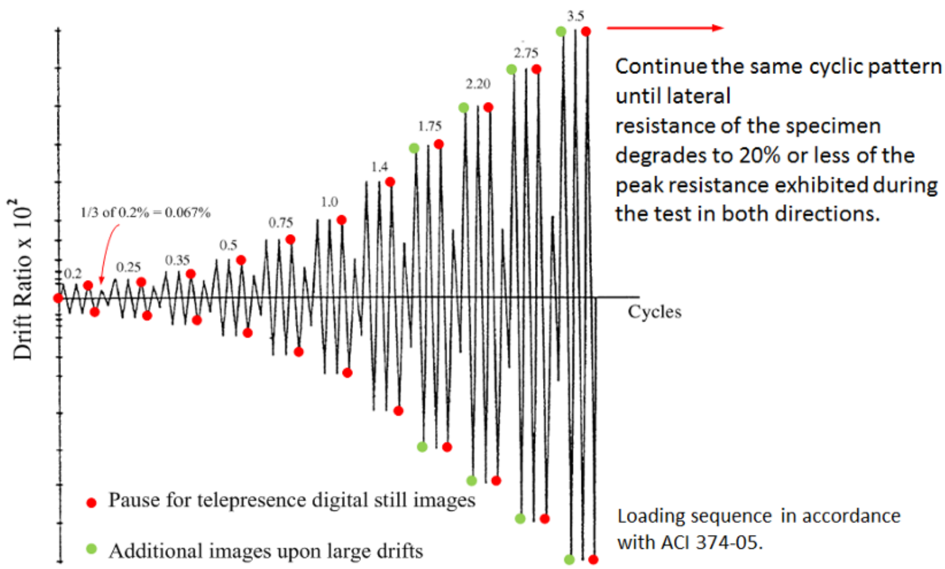


Fig. 7 – Reversed cyclic loading protocol for column specimens

4. Experimental Results

The two column specimens were tested at the MAST facility at the University of Minnesota. The UHP-FRC column specimen can be seen in Fig. 8a prior to the beginning of the test. The hysteresis curves for both specimens are shown in Fig. 8b. The typical failure mode was observed in the RC column for normal strength concrete columns subjected to seismic loading. The first observable flexural cracks were seen at 0.5% drift ratio at 20 cm and 40 cm above the footing. The first longitudinal bar yielded at approximately 0.75% drift ratio. The failure of the RC column initiated with concrete crushing at the corners of the columns at 1.0% drift ratio. Soon after the crushing, a decrease in strength was observed at 1.38% drift ratio. As the cyclic reversals continued, the concrete cover was eventually lost, followed by the bulging and opening of the transverse reinforcement, and then the buckling and fracture of the longitudinal reinforcement. This deterioration resulted in a significant decrease in strength and eventual failure of the RC column. The force versus drift response shown in Fig. 8b indicates that the UHP-FRC column could maintain strength up to nearly 4% drift ratio while the conventional reinforced concrete column deteriorated very fast after 2% drift ratio. The smaller axial load ratio at the UHP-FRC column minimized the ductility demand and the influence of the axial load effect at the post-elastic stage.

ACI 374-13 [8] requires that for frame buildings the maximum story drift ratio should be kept within 4% to meet the "Collapse Prevention" performance level requirement. To meet "Life Safety" performance level requirement, a structure should not have strength degradation up to 2% story drift ratio. Fig. 8b shows that UHP-FRC column was able to maintain nearly the full peak strength up to 4% story drift ratio, and it had no strength degradation up to approximately 2.5% story drift ratio.

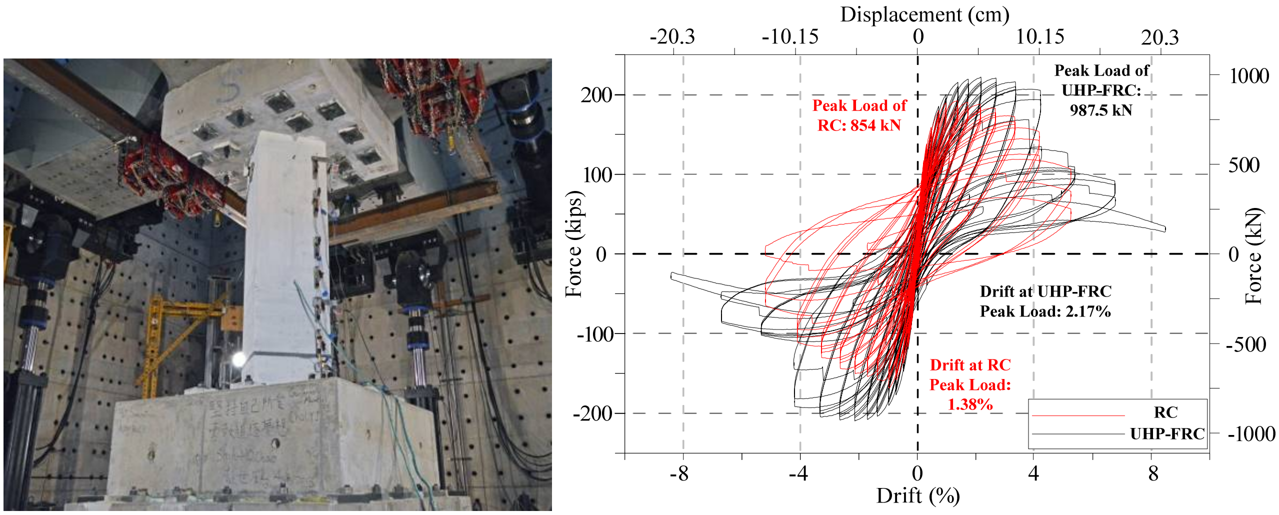


Fig. 8 – (a) UHP-FRC specimen prior to testing and (b) force versus drift curves for RC (red) and UHP-FRC (black) specimens

The use of UHP-FRC completely changes the typical failure mechanism observed in conventional reinforced concrete columns due to its high strength and high compressive ductility. There was no visible concrete damage observed in the plastic hinge region of the UHP-FRC column throughout the test. This allowed the longitudinal reinforcement to be utilized to its ultimate capacity without buckling. Furthermore, transverse reinforcement in the UHP-FRC region recorded only minor strains of less than 50% yielding strain, suggesting that the transverse reinforcement may be significantly reduced in UHP-FRC columns allowing for less congestion and greater ease of construction. Fig. 9 compares both columns at 5.25% drift ratio showing significant concrete crushing and bar buckling in the RC column while no visible damage is detected in the UHP-FRC column. The UHP-FRC column failure was due to low cycle fatigue fracture of the longitudinal reinforcement at the interface between the footing and the column section. The RC column reached a maximum lateral peak force of 854 kN at 1.38% drift ratio, while the UHP-FRC specimen reached a lateral peak force of 987.5 kN at 2.17% drift ratio. Fig. 10 compares both specimens, at the same load of 845 kN, with embedded concrete gauges at a cross-section of 254 mm above the footing This shows the measured concrete tensile strains in the UHP-FRC column to be significantly lower than those in the RC column. The results indicated the great inherent confinement characteristic of UHP-FRC material. Fig. 11 shows the strain distribution of the longitudinal reinforcement along the height of the specimens with increased drift levels. The strain gauge data of the UHP-FRC specimen from the column base up to 380 mm high was missing for large drift ratios of 2.75% and 3.5% since the strain exceeded the range of the strain gauge measurement, while the RC specimen recorded a maximum strain of 0.02 at drift ratio 3.5%. Up to the drift ratio of 2.2%, the strain of the longitudinal steel of the RC specimen was more than that of the UHP-FRC specimen due to debonding in the RC column and the better bond provided by UHP-FRC than RC. After 2.2% drift ratio, the bond between UHP-FRC and steel started degrading and the steel was more strained in order to accommodate the large rotation demand at the column base. The UHP-FRC specimen also experienced more strain penetration into the footing which mainly occur in an area 305 mm deep below the column base. Fig. 12 shows the segmental rotation profile along the height of the specimens, which was calculated using pairs of LVDTs at the same levels. The rotation was assumed to happen at the center of each gauge length in a vertical direction. Fig. 12 shows that rotation of both columns mainly resulted from the lowest segment from the bottom up to 305 mm high. Despite the less moment demand, the RC specimen experienced a larger rotation than the UHP-FRC specimen from 305 mm up to 1220 mm high due to the propagation of the damage while no damage occurred in the UHP-FRC column in the same region. It should be noted that the accumulated rotation from LVDTs for both specimens matched the rotation at the inflection point measured by the installed tiltmeter, which validated the LVDT measurements.

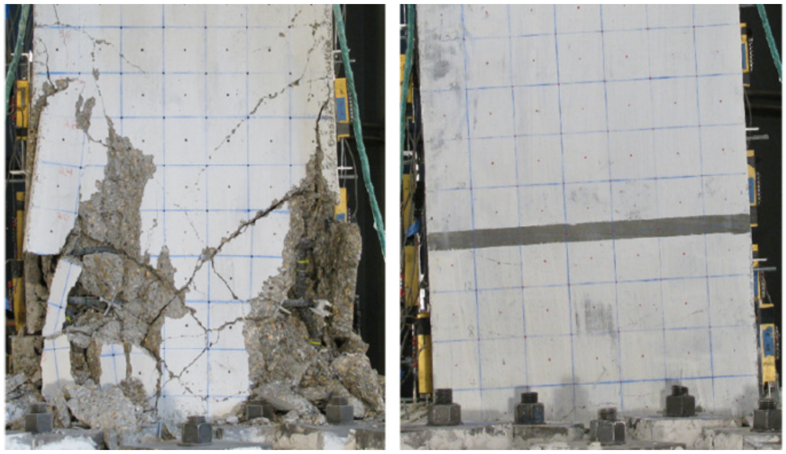


Fig. 9 – Comparison of RC (left) and UHP-FRC (right) specimens at 5.25% drift

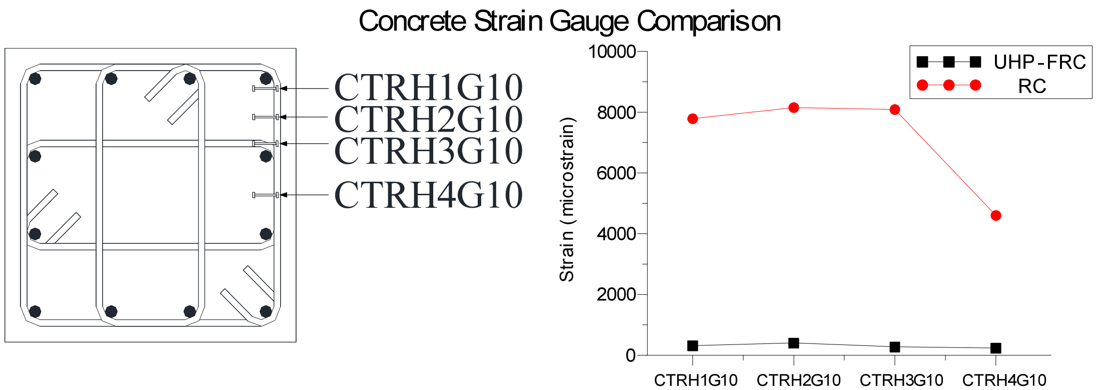


Fig. 10 – Comparison of RC (left) and UHP-FRC (right) specimens at 5.25% drift

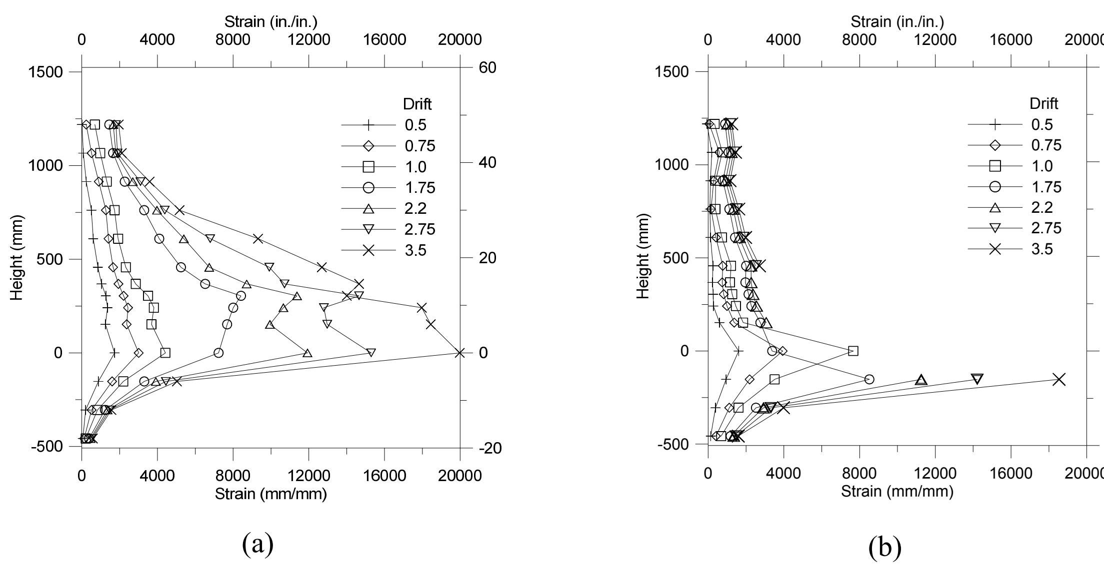
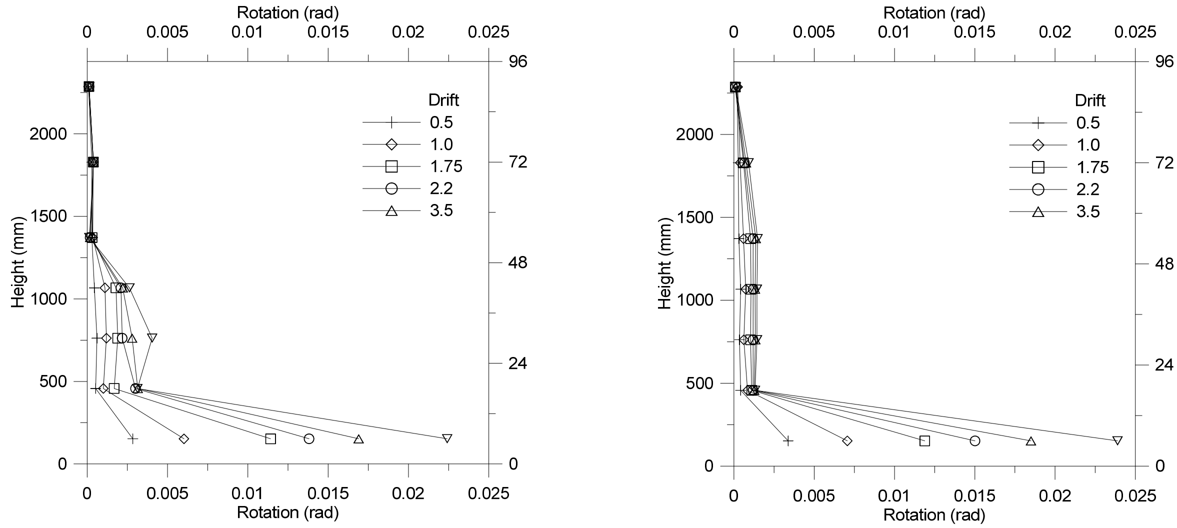


Fig. 11 –The strain distribution of the longitudinal reinforcement along the height of the specimens (a) RC and (b) UHP-FRC



(a) RC (b) UHP-FRC

Fig. 12 – The segmental rotations along the height of the specimens (a) RC and (b) UHP-FRC

5. Conclusions

1. At moderate drift ratios (1.0~2.0%), damage in the UHP-FRC column was very minor compared to that of the RC column. This can result in considerable cost-savings in post-earthquake repairs in buildings constructed with UHP-FRC columns.
2. The measured concrete strains as well as strains in the transverse reinforcement were essential in the elastic range for the UHP-FRC column; this suggests that the transverse reinforcement in UHP-FRC columns can be considerably reduced.
3. The UHP-FRC column exhibited higher strength and greater drift capacity before significant strength degradation compared to the RC column.
4. The seismic performance of the UHP-FRC column such as strength or ductility was solely dependent on the tension/low-cycle fatigue behavior of the longitudinal reinforcing bars. Other factors such as bar buckling, concrete spalling, concrete crushing, and failure of hoops were eliminated in the UHP-FRC column.
5. While further research is still needed on the full-scale applications of UHP-FRC, this study indicates that UHP-FRC columns have advantageous characteristics compared to that of RC and HSC columns and can be a viable design solution for seismic regions in the near future.

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7. References

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