

# Seismic Behavior of Ultra-High-Performance Fiber-Reinforced Concrete Moment Frame Members

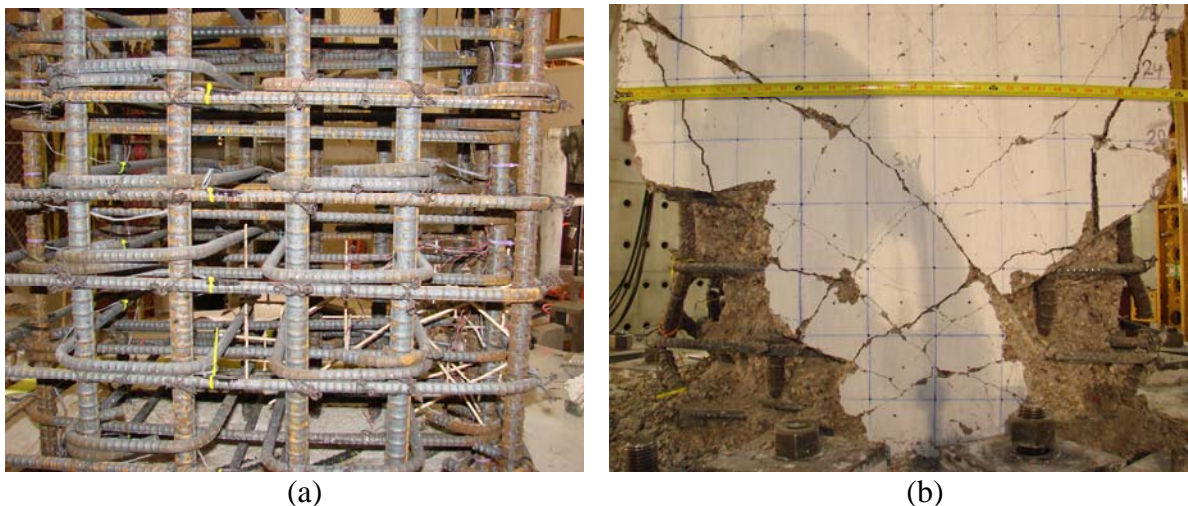
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**Abstract:** Ultra-high-performance fiber-reinforced concrete (UHP-FRC) has superior material properties with high compressive strength ( $> 22$  ksi [150 MPa]) and shear strength, improved tensile and compressive ductility, and excellent bond and confinement characteristics. All of these features provide an improved and innovative way to design earthquake-resistant moment frame members. In order to maintain adequate ductility, high-strength concrete (HSC) requires a large amount of transverse reinforcement, which has traditionally added to the complexity of the process. In UHP-FRC, the addition of high-strength steel microfibers into high-strength concrete can resolve such congestion issues and still allow the concrete to remain self-consolidating. The use of UHP-FRC completely changes the typical failure modes of flexural concrete members of moment frames as it improves confinement and prevents premature concrete distress and bar buckling, which provides increased resistance to strong seismic forces. Current ACI 318 provisions limit the longitudinal reinforcement ratio in beams of special moment frames to prevent undesirable shear damage. On the other hand, using UHP-FRC can also result in reduced cross sections or an increased number of longitudinal bars because of its high shear resistance capacity. Since the compressive and post-cracking tensile behavior of UHP-FRC is different from that of conventional concrete, new design criteria need to be developed for UHP-FRC flexural members of special moment frames. This paper presents the authors' research on the novel design aspects of UHP-FRC and their experimental results after testing full- and large-scale UHP-FRC moment frame columns and beams.

**Keywords:** UHP-FRC, Column, Beam, Moment Frame, Seismic, Confinement, Earthquake

## 1. Introduction

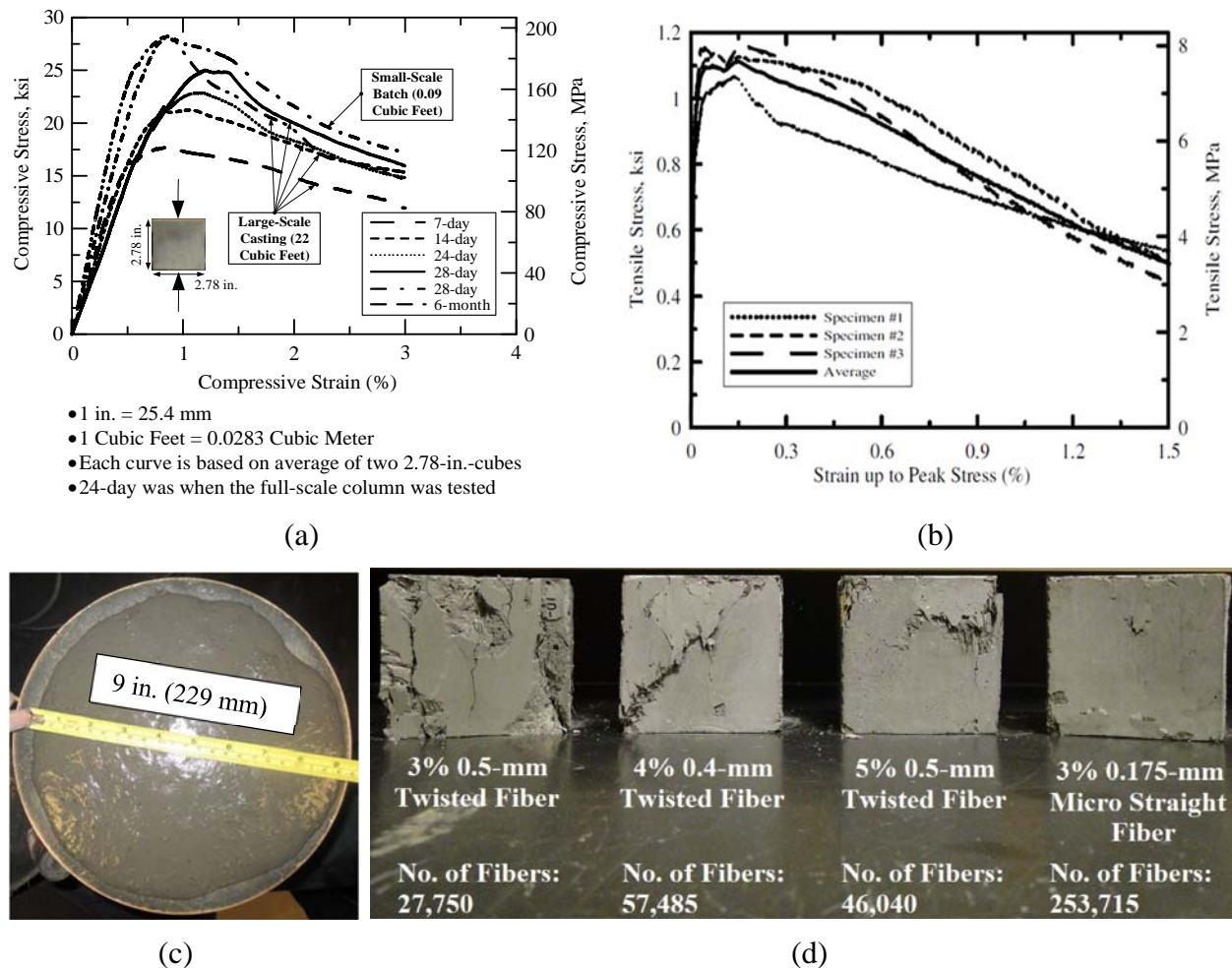
High strength concrete (HSC) is often utilized as a cost-effective design solution in the lower stories of high-rise buildings. HSC has the potential of reducing section sizes hence reducing some construction costs due to less labor and formwork, while maximizing the rentable floor space (Mwafy et al., 2015). However, the brittleness of HSC makes it a less attractive material for structures in high seismic areas. This is due to the fact that extensive transverse reinforcement is needed in the column cages in order to provide confinement and increase the ductility of the columns. Current design practice based on ACI 318 (ACI, 2014) for concrete columns in high seismic zones typically leads to congested reinforcement details due to the large amount of confining transverse reinforcement (**Fig. 1a**). ACI 318 (ACI, 2014) Section 18.7.5.4 requires even more confining reinforcement if  $f'_c$  is beyond 10 ksi (69 MPa). To use a 25 ksi [172 MPa] concrete, for instance, the reinforced concrete (RC) column shown in **Fig. 1a** would need 60% more transverse reinforcement, which would create such great difficulties as to make reinforcement insertion and concrete placement practically infeasible. Typical failure modes of conventional concrete columns subjected to earthquake loading always starts from concrete cracking followed by crushing. After concrete loses its capacity, hoops start yielding and eventually the longitudinal rebars buckle and fracture, leading to column failure. The high compressive ductility and confinement characteristic of ultra-high-performance fiber-reinforced concrete (UHP-FRC) provides a solution to resolve the brittleness issue of HSC while maintaining constructability. In addition, when used in moment frame's beam members, UHP-FRC's confinement characteristic allows complete removal of conventional transverse confining reinforcement and its high shear capacity can maintain the integrity of the plastic hinging zone even with higher amount of longitudinal reinforcement. The superior mechanical properties of UHP-FRC offer a new way to design earthquake-resistant moment frame members. With limited UHP-FRC large-scale testing data available, this study offers a valuable comparison between the seismic performance of moment frame column and beam members made with conventional concrete and UHP-FRC.



**Figure 1. (a) Typical Reinforcing Details in Moment Frame Columns (Concrete Compressive Strength = 5 ksi [34 MPa]) in High Seismic Zone; (b) Typical Failure Mode of RC Columns Subject to Strong Earthquake Forces**

## 2. Background

The UHP-FRC material used in this research was developed based on the dense particle packing concept (Wille et al., 2012) at the University of Texas at Arlington (Aghdasi et al., 2015). The developed UHP-FRC is made of regular Type I cement, silica fume, Sand 1 (500  $\mu\text{m}$ ), Sand 2 (120  $\mu\text{m}$ ), glass powder (1.7  $\mu\text{m}$ ), and 3% by volume straight steel fibers (12.5 mm long and 0.175 mm dia.; tensile strength = 2200 MPa). All materials are available in the U.S. It has the high compressive strength (28 ksi [190 MPa]), high compressive/tensile ductility, and excellent flowability (**Fig. 2**) essential to earthquake-resistant moment frame columns and beams. The integration of high strength straight steel microfibers resulted in higher shear and tensile capacities, alleviates the need for excessive transverse reinforcement in plastic hinging regions of columns and beams.



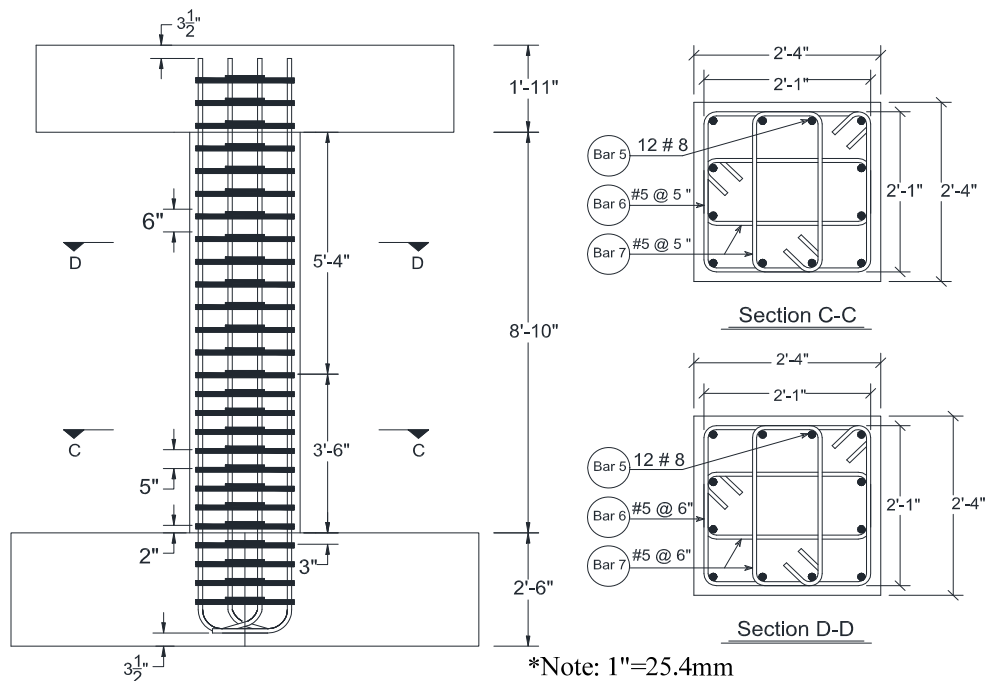
**Figure 2. Features of UHP-FRC used for this study: (a) Compressive Stress-Strength Curves; (b) Tensile Stress-Strain Curves; (c) Flowability; (d) Improved Compressive Ductility with 3% Micro Straight Steel Fibers**

### 3. Experimental Programs

#### 3.1. Columns

This paper reports the behavior of two full-scale moment frame column specimens consisting of a normal strength concrete (5 ksi [35 MPa]) specimen and a specimen with its plastic hinge region cast with UHP-FRC: Both were tested under large cyclic reversals. Each column specimen consists of a footing block, a column section, and a loading block. The space frame column is an 8'-10" (2.69 m) tall square column, which represents half of an actual column with cross-sectional dimensions of 28 × 28 in. (711 × 711 mm) and is reinforced with 12 No. 8 bars (ASTM A706 Grade 60) distributed evenly around the perimeter of the cross section. 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 for comparison between the two specimens when variables are minimized. It is recognized that this leads to a significantly lower axial load ratio for UHP-FRC column, which in a way will reduce the ductility demand imposed on the UHP-FRC column.

As mentioned earlier, using HSC requires a higher amount transverse reinforcement than that used in a normal strength concrete column. However, the amount of transverse reinforcement will be considerably less when UHP-FRC is used due to the much enhanced confinement 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, compliant with ACI 318 (ACI, 2014), consists of groups of three overlapping ties bent from No. 5 bars (ASTM A615 Grade 60) spaced at 5-in. (127 mm) for the first 40 in. (1.01 m) near the plastic hinge region, and 6-in. (152 mm) for the remainder of the height of the specimen above the plastic hinge region (Fig. 3).



**Figure 3. Space Frame Column Reinforcement Details**



Construction of both full-scale columns followed the same protocol. However, the first 40-in. (1.01 m) above the footing of the second column specimen was cast with UHP-FRC (**Fig. 4**). The UHP-FRC mix was nearly self-consolidating requiring no vibration resulting in a very smooth finish with no visible voids. After casting the UHP-FRC section, the remainder of the column was cast identically to that of an RC column specimen using normal strength 5 ksi (35 MPa) concrete. The columns were removed from UT Arlington civil engineering lab building (CELB) by heavy duty forklifts and placed on a flatbed truck for delivery to the Multi-Axial Subassemblage Testing (MAST) facility at the University of Minnesota for testing.



**Figure 4. UHP-FRC (a) Pouring and (b) Completed Section (c) Final Casting**

### **3.2. Beams**

ACI 318-14 Sect. 18.6.3 states that “The longitudinal reinforcement ratio  $\rho$  shall not exceed 2.5% for beams of special moment frames.” This limiting reinforcement ratio is based on considerations of reinforcement congestion and on limiting shear stresses in beams due to the inferior shear capacity of conventional concrete. Due to the high shear capacity and high usable compressive strain ( $\epsilon_{cu}$ ) of UHP-FRC, a higher amount of longitudinal reinforcement can be used even without any transverse reinforcement. In this study, a longitudinal reinforcement ratio of 3.0% was used for both of the RC and UHP-FRC beam specimens. As shown in **Fig. 5**, while the amount and spacing of the transverse reinforcement in the potential plastic hinging region of the RC specimen were designed according to ACI 318 (ACI, 2014), no transverse reinforcement was used in the plastic hinging region of the UHP-FRC specimen.

### **3.3 Loading Protocol**

The same cyclic loading protocol was used for both column and beam specimens. The loading protocol used in this study was in accordance with ACI 374-05 (ACI, 2005). For the columns, an axial load of 1,176 kips (5,231 kN) was applied at the beginning of each test and kept vertical and constant throughout the entirety of the test. After the application of the axial load, the specimens were subjected to the reverse cyclic loading protocol. **Fig. 6** shows three fully reversed cycles were applied at each drift level gradually increasing in magnitude. In between each increasing drift level, intermediate cycles were applied at a magnitude of 1/3 of the preceding drift level.

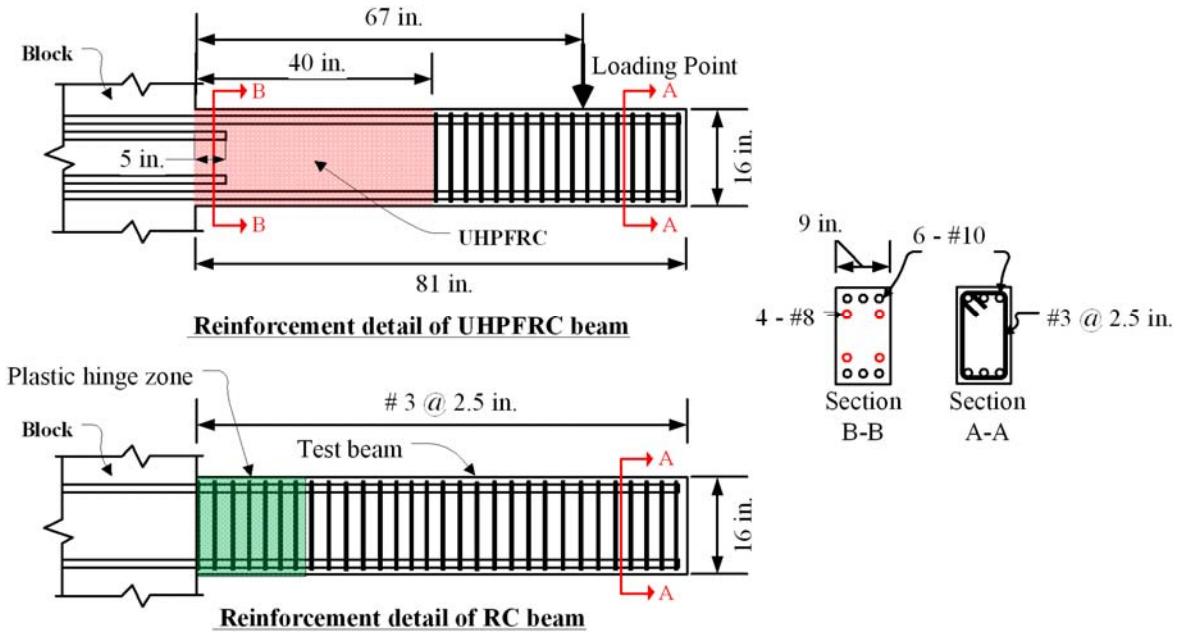


Figure 5. Reinforcement Details of UHP-FRC and Conventional RC Moment Frame Beams

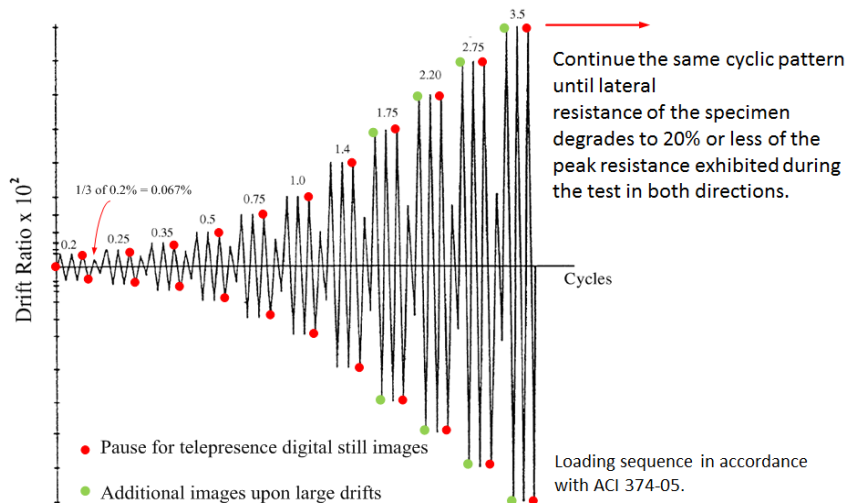


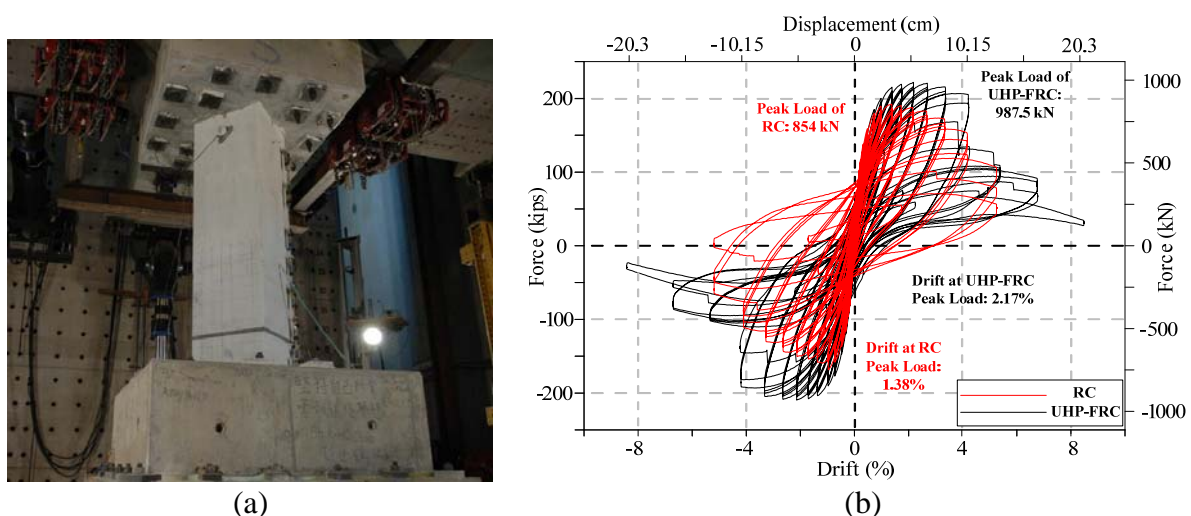
Figure 6. Reversed Cyclic Loading Protocol for Column and Beam Specimens

#### 4. Experimental Results

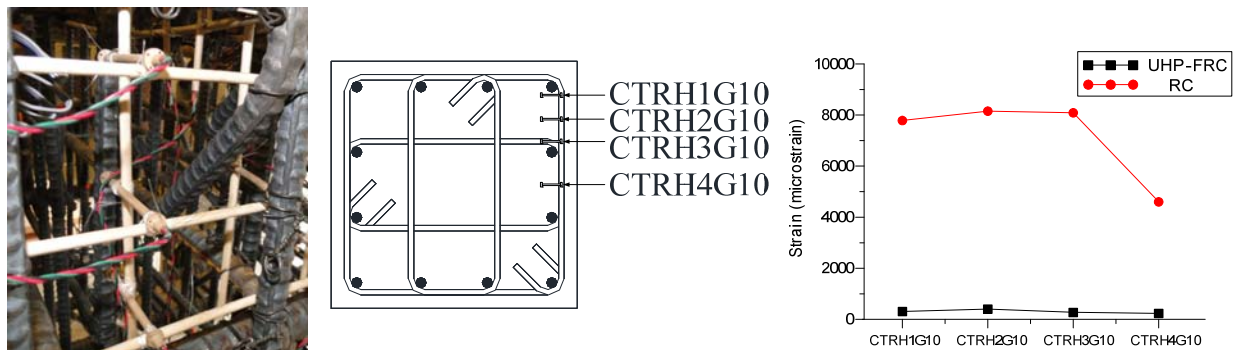
The testing and hysteresis curves for both column specimens are shown in Fig. 7. For the RC column with normal strength concrete, the first observable flexural cracks were seen at 0.5% drift, and the first longitudinal bar yielded at 0.75% drift. The failure of the RC column started with concrete crushing at the corners of the columns at 1.0% drift. Soon after the crushing, a decrease in strength was observed at 1.38% drift. 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. On the other hand, **Fig. 7b** 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 1% drift ratio. Note that while the axial load ratio ( $P_u/A_g f'_c$ ) for the conventional concrete was 0.28, it dropped to 0.06 for the UHP-FRC column due to the high compressive strength of the UHP-FRC. This smaller axial load ratio minimized the ductility demand and the influence of the axial load effect at the post-elastic stage. ACI 374-13 (ACI, 2013) 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. 7b** 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.

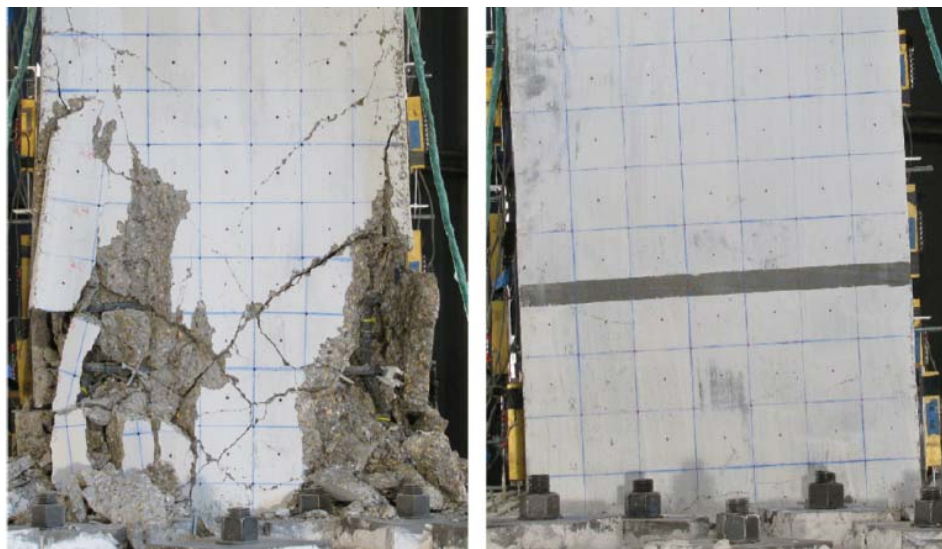
The use of UHP-FRC completely changes the typical failure mechanism observed in concrete columns due to its high strength and high compressive ductility. There was no visible concrete damage observed in the plastic hinge region of the UHP-FRC column throughout the test. This allowed longitudinal reinforcement to be utilized to its ultimate yielding capacity without buckling. Furthermore, strain data of transverse reinforcement in the UHP-FRC region only indicated minor strains of less than 50% yielding, suggesting that transverse reinforcement may be significantly reduced in UHP-FRC columns allowing for less congestion and greater ease of construction. **Fig. 8** compares both specimens, at the same load of 845 kN, with embedded concrete gauges at a cross-section of 10-in. (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, thus indicating the great confinement provided by the UHP-FRC material. **Fig. 9** compares both columns at 5.25% drift showing significant concrete crushing and bar buckling in the RC column with no visible damage detected in the UHP-FRC column. The UHP-FRC column failure was due to low cycle fatigue 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 while the UHP-FRC specimen reached a lateral peak force of 987.5 kN at 2.17% drift.



**Figure 7. (a) UHP-FRC Specimen Prior to Testing (b) Force vs. Drift Curves for RC (Red) and UHP-FRC (Black) Specimens**



**Figure 8. Concrete gauge and strain data comparison between RC and UHP-FRC specimens**



**Figure 9. Comparison of RC (left) and UHP-FRC (right) Specimens at 5.25% Drift**

**Fig. 10** shows the cracking progression of the RC and UHP-FRC beam specimens. Here, severe cracking occurred in the RC specimen due to the high shear demand and weak shear capacity of conventional concrete. After concrete spalled and cracked, the concrete's confinement and shear resistance degraded. However, **Fig. 10b** shows UHP-FRC remaining nearly undamaged up to a very high drift ratio even without any transverse reinforcement. The intact UHP-FRC continued providing confinement to the rebars. **Fig. 11** compares the measured shear deformation in the plastic hinge region of both beams. While the shear deformation in the RC beam kept increasing with the increase of drift ratios, the shear deformation in the UHP-FRC beam remained very small until reaching a 2.2% drift ratio.



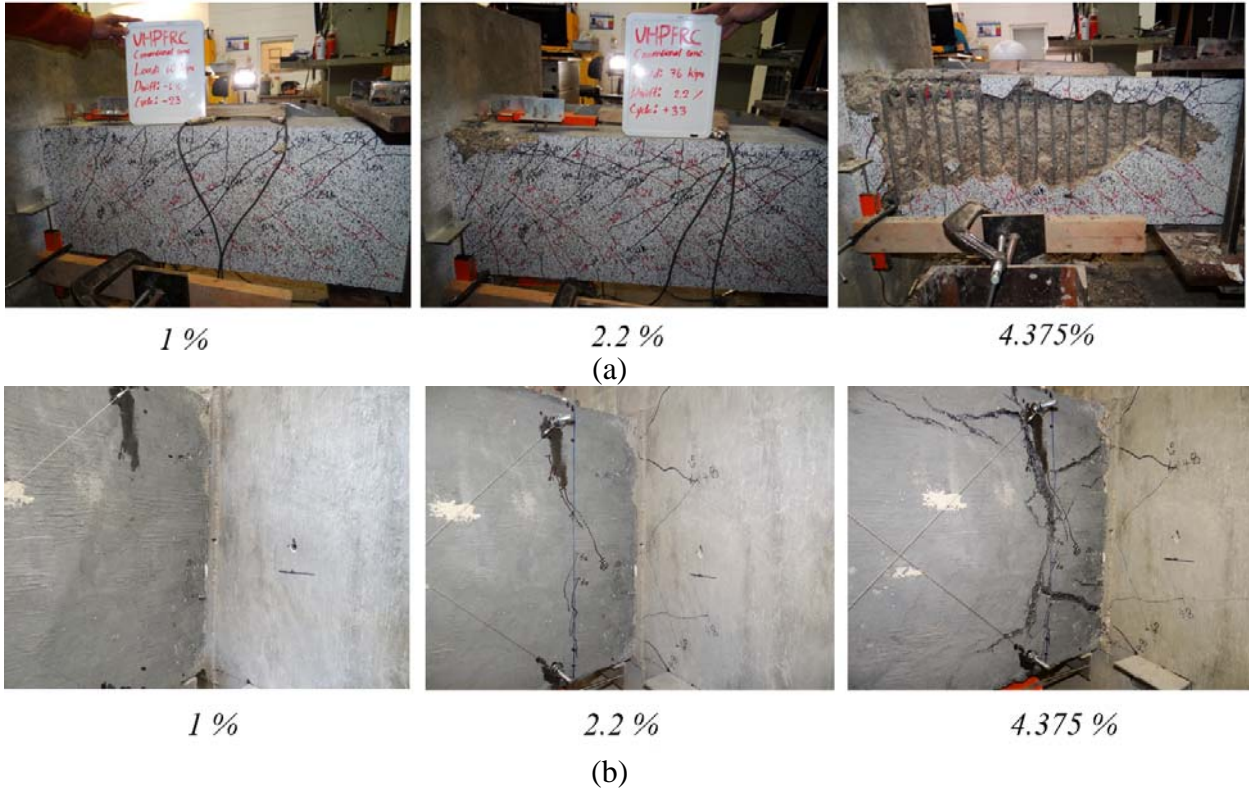


Figure 10. Comparison of Damage Pattern between (a) RC and (b) UHP-FRC Beams

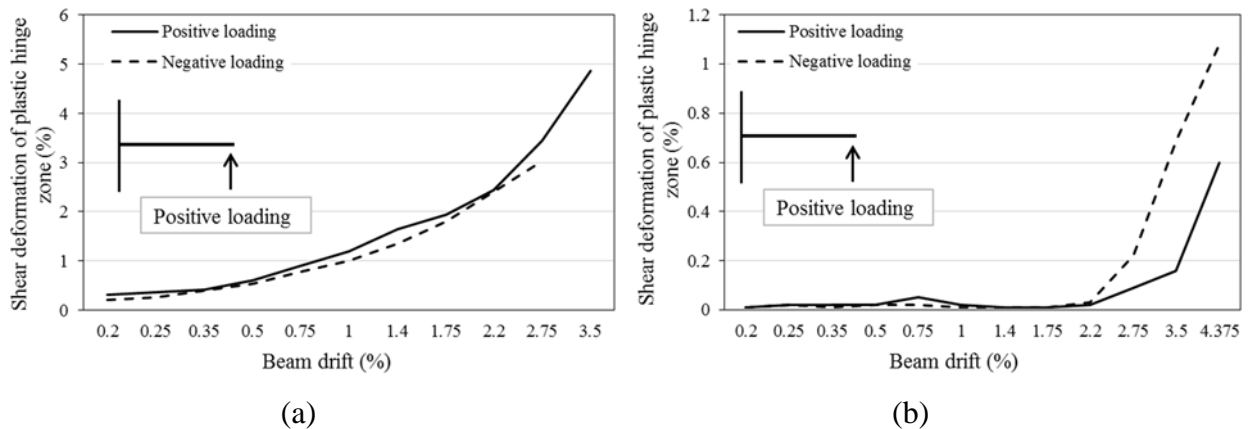


Figure 11. Comparison of Shear Deformation in the Plastic Hinge Region between (a) RC and (b) UHP-FRC Beams

## 5. Conclusions

1. At moderate drifts (1.0 to 2.0%), damage in UHP-FRC column was very minor compared to the RC column, significantly reducing the need for post-earthquake repair.
2. UHP-FRC column exhibited higher strength and greater drift capacity before significant strength degradation compared to the RC column.

3. The seismic performance of UHP-FRC column, such as strength or ductility, is dependent on the tension/low-cycle fatigue behavior of the longitudinal reinforcing bars. Other factors such as concrete spalling, concrete crushing, bar buckling, and failure of hoops are eliminated in the UHP-FRC column.
4. The experimental test results suggest that current seismic design provisions in ACI 318 can be relaxed if UHP-FRC is used. More specifically, the confining requirements and amount of transverse reinforcement necessary can be reduced for columns using concrete with a compressive strength higher than 10,000 psi (70 MPa)
5. Measured concrete strains as well as strains in the hoops were essentially in the elastic range in UHP-FRC column, which indicates that transverse reinforcement could be considerably reduced.
6. UHP-FRC provides high shear and confinement capacity for moment frame beams. A high amount longitudinal reinforcement ( $> 2.5\%$ ) can be used. The reinforcement congestion issue is minimized due to the total removal of transverse reinforcement

## 6. References

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## 7. Acknowledgements

This research was supported by the U.S. National Science Foundation under Awards No. CMMI-1041633 and 1414391. Columns shown in this paper were tested at the Multi-Axial Subassembly Testing (MAST) lab at the University of Minnesota. MAST staff’s assistance is greatly appreciated.