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A SEISMIC RESILIENT CONCRETE COLUMN USING ULTRA-HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE

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Abstract

Columns are critical structural members providing collapse prevention and assuring post-earthquake functionality and limited repair costs of buildings and bridges in earthquake-prone areas. Their resilience and damage resistance against multiple strong excitations are critical to the resilience of earthquake-prone structures and society. This paper describes research which develops highly sustainable and resilient reinforced concrete (RC) columns by utilizing emerging high-performance materials. These materials include ultra-high-performance fiber-reinforced concrete (UHP-FRC) and corrosion resistant, high-strength fiber-reinforced polymer (FRP) bars. The new type of UHP-FRC columns were designed based on a newly developed design concept, ductile-concrete strong-reinforcement (DCSR), in which the ductile component is the concrete and the elastic component is the reinforcement. The advantages of using such a design is to fully utilize the ultra-high compressive strength and ductility of UHP-FRC and to minimize cracking by reducing the elongation of reinforcement, thereby maintaining stiffness, bond strength, and shear strength of the members. The proposed UHP-FRC columns can sustain very large drift ratios under reversed cyclic loadings without major damage in the material. Because of the DCSR design concept, the reinforcement remains elastic, thus providing a self-centering capability. This allows very sustainable and resilient structures subjected to major earthquake loadings. Two pilot scaled column specimens were tested under large displacement reversals. Specimens were reinforced with non-corrosive high-strength (1014 MPa) basalt fiber reinforced polymer (BFRP) rebars. Both column specimens had a reinforcement ratio of 14.8%. The first specimen used ultra-high-molecular-weight-polyethylene (UHMW PE) fibers (13 mm in length and 0.0015 mm in diameter with a tensile strength of 2585 MPa). The second specimen used micro steel fibers (13 mm in length and 0.2 mm in diameter with a tensile strength of 2750 MPa). Experimental results show that both columns sustained very large cyclic displacements without major damage to the UHP-FRC material, which provided ample shear strength and confinement to the reinforcement throughout the testing. Even with the high amount of reinforcement, UHP-FRC's superior ductility provided a very stable cyclic behavior up to exceptionally large drift ratios. All specimens also exhibited very high damage-resistance and a self-centering ability, which considerably reduced the residual displacement after experiencing large displacements. This pilot testing also verified that characteristics of the proposed columns made of high-performance materials and designed by the DCSR concept can provide excellent seismic resilience (which requires no repair work after major earthquakes). Incremental dynamic analyses (IDA) carried out on four-story and 20-story prototype buildings indicate that buildings with the new DSCR-designed columns have an improved collapse resistance compared to conventional RC buildings.
Keywords: Ultra-high-performance fiber-reinforced concrete (UHP-FRC), Column, Self-centering, Resilience

1. Literature review

1.1 Ultra-High-Performance Fiber-Reinforced Concrete (UHP-FRC)

Ultra-high-performance fiber-reinforced concrete (UHP-FRC) is a new generation of fiber-reinforced concrete, which has ultra-high compressive ductility and strength (124 to 207 MPa for ultimate compressive strength and 69 to 83 MPa after 24 hours).Concrete with only ultra-high compressive strength is not suitable for earthquake resistant applications, even when reinforced with mild reinforcing steel, as the very brittle nature can cause potential issues such as abrupt, unpredictable failures and a minimum capability of stress redistribution. UHP-FRC was developed by changing the porous nature of conventional concrete through reducing dimensions of microcracking (or defects) in the concrete. This is achieved in UHP-FRC through a very low water to cementitious materials ratio (0.18 to 0.25) and a dense particle packing. The consequences of a very dense microstructure and low-water ratio result in enhanced compressive strength [1] and delayed liquid ingress [2]. Furthermore, the addition of high-strength steel or synthetic fibers improves the brittle nature of concrete by increasing the tensile cracking resistance, post-cracking strength, ductility, and energy absorption capacity. In terms of corrosion resistance, research has indicated that UHP-FRC has a much greater durability than conventional concrete due to its very dense microstructure [3]. This dense microstructure impedes the conductive chloride ions from coming into direct contact with the steel reinforcing bars, which protects the reinforcing bars from corrosion. Table 1 provides a comparison between typical conventional concrete and UHP-FRC.

Table 1 – Comparison of typical conventional concrete and UHP-FRC
(all data from UT Arlington research except rapid chloride penetration test)

Properties of Concrete	Conventional Concrete	UHP-FRC
Ultimate Compressive Strength	< 55 MPa	124 to 207 MPa
24-hour compressive strength	< 21 MPa	69 to 83 MPa
Flexural Strength	< 4.6 MPa	17 to 41 MPa
Shear strength	< 1.2 MPa	> 4.1 MPa
Direct Tension	< 3 MPa	up to 10 MPa
Rapid Chloride Penetration Test [3]	2000-4000 Coulombs passed	Negligible (< 100 Coulombs passed)
Ductility	Negligible	High ductility
Ultimate Compressive Strain, ε_{cu}	0.003	0.015 to 0.03
Confining	Negligible	High confining capability

Fiber-reinforced concrete (FRC) has been used for many decades; however, conventional FRC only enhances post-cracking ductility, and its compressive strength is close to that of plain concrete (35 to 55 MPa). In other words, conventional FRC does not fundamentally change the micro-structure of concrete, but it has a greater residual tensile capacity and ductility after cracking. Research shows that even a high-performance FRC column (an FRC with tensile strain-hardening behavior) has essentially the same failure mode as that of an RC column after FRC is crushed, which leads to rebar buckling and fracture [4]. Typically, UHPC mix without fibers has a characteristic compressive strength of higher than 150 MPa, with a high modulus of elasticity in the range of 45 GPa to 55 GPa, and a tendency to exhibit extreme brittle failure after peak strength. Similar to conventional and high strength concretes, an increase in compressive strength leads to an increase in brittleness in UHPC. The increased density of the hardened paste results in a higher modulus of the elasticity. The explosive nature of UHPC prevents the recording of the post-peak curve. However, the addition of fibers to the UHP-FRC matrix decreases the brittleness and increases the maximum usable compressive strain. Also, the presence of fibers slightly increases the compressive strength. The UHP-FRC shows more distinct nonlinear behavior before the peak compressive strength as compared to regular concrete and UHPC without fibers. The UHP-FRC mix [5] used in this study shows a maximum useable strain of approximately 1.2-1.4% as shown in Fig. 1.

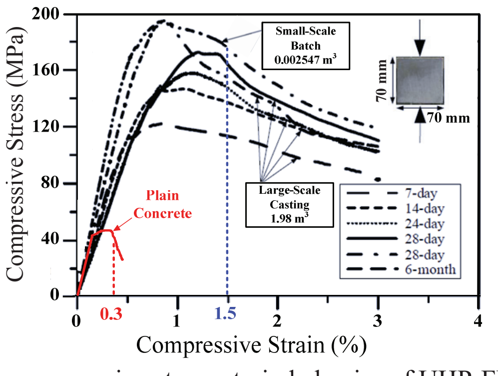


Fig. 1 – Comparison between compressive stress-strain behavior of UHP-FRC [5] and regular concrete

1.2 Fiber-Reinforced Polymer (FRP) reinforcement

Corrosion is an issue of concern when steel reinforcement is used for concrete structures exposed to aggressive environments. Composite materials such as fiber-reinforced polymer (FRP) are a suitable alternative to steel reinforcing bars when RC structures are exposed to deicing salts, seawater, or other corrosive environments. Fiber-reinforced polymers use a polymeric resin system reinforced with fibers. Fibers are typically aramid, basalt, carbon, or glass, and the polymer is usually an epoxy, phenol formaldehyde resin, polyester thermosetting plastic or vinyl ester. In this study, basalt fiber-reinforced polymer (BFRP) reinforcement was used. Basalt fibers are a mineral-based inorganic product and were recently introduced to the structural engineering community [6].

The tensile behavior of FRP bars is controlled by fiber and resin properties, fiber volume fraction, as well as fiber geometry and orientation within the matrix [7]. FRP materials are anisotropic in nature and show purly elastic behavior until failure. This lack of ductility should be taken into considerations while designing concrete structures reinforced with FRP bars. FRP bars have much higher tensile strength than steel bars but the tensile modulus of FRP bars is significantly lower than their steel counterparts, as small as 20% [8]. BFRP bars used in this study have an ultimate tensile strength of approximately 1014 MPa and an ultimate tensile strain of 0.017 to 0.025.

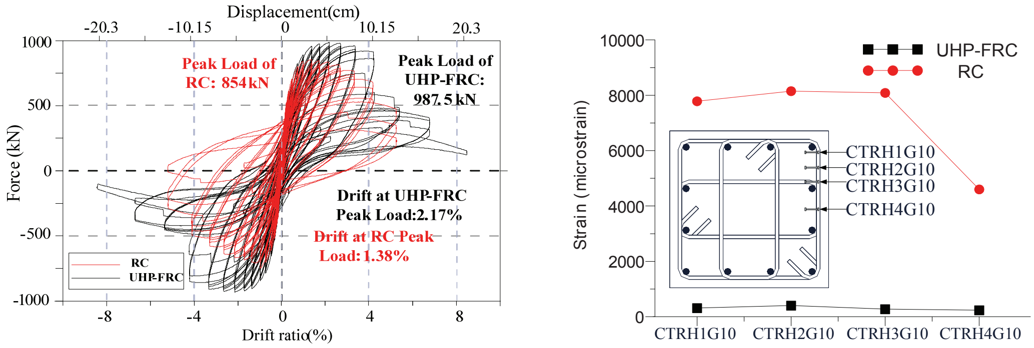
1.3 Brittle flexural failure of conventional concrete reinforced with FRP bars

Design of reinforced concrete members with FRP reinforcement is similar to the design of steel-reinforced concrete members. However, unlike steel, the FRP bars do not exhibit ductility. Hence, the failure of reinforced concrete due to rupture of FRP bars before concrete crushes is sudden, destructive and not desirable. In addition, the low axial stiffness of FRP bars typically causes large crack width and significantly smaller shear capacity due to the loss of aggregate interlock for widened crack widths. Consequently, it is preferable for FRP-reinforced concrete members to fail in compression rather than by the rupture of FRP bars [9]. However, for FRP-reinforced structural members, neither tension-controlled nor compression-controlled failure mode can provide sufficient ductility to the structure. Therefore, ACI 440.1R [8] suggests a more conservative design for FRP-reinforced members than for the steel-reinforced members. If high-strength concrete is used with the FRP reinforcement bars, stiffness of the cracked section is increased but it reduces the deformability of the flexural member compared to normal strength concrete [8].

1.4 Previous full-scale UHP-FRC column experiment

The potential of using the superior mechanical properties of UHP-FRC to improve the low damage resistant ability of conventional concrete was demonstrated in a pilot study where a full-scale ACI 318-compliant RC column [10] and a UHP-FRC column were tested under a large axial load and displacement reversals up to failure [11, 12]. Both columns had the same reinforcement details with Gr. 420M steel rebars. Both column specimens used the same dimensions. The specimens were fabricated at UT Arlington's Civil Engineering Laboratory Building (CELB) and tested at the Multi-Axial Subassemblage Testing (MAST) laboratory at the University of Minnesota. The UHP-FRC material used in the experiment was developed at the UT Arlington, based on a dense particle-packing concept [5], and its compressive stress-strain curve is shown in Fig. 1.

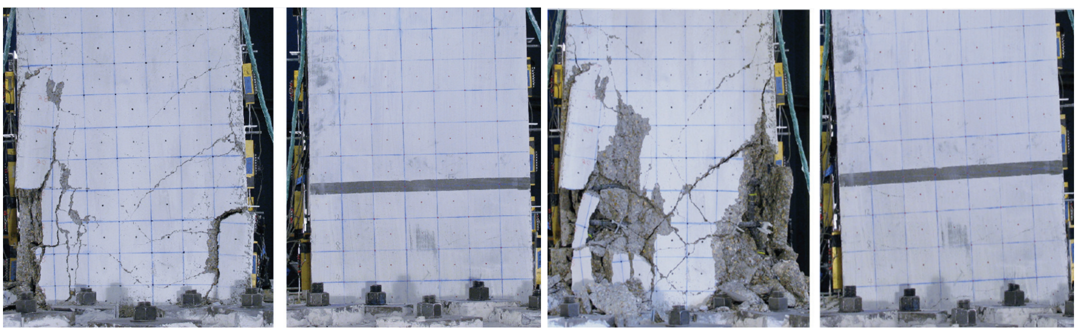
The hysteresis responses for both column specimens are shown in Fig. 2. For the RC column with normal strength concrete (35 MPa), the first observable flexural cracks were seen at 0.5% drift ratio, and the first longitudinal bar yielded at 0.75% drift ratio. The failure of the RC column started with 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. On the other hand, the UHP-FRC column maintained its strength up to nearly 4% drift ratio. Note that ACI 374-13 [13] 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 the "Life Safety" performance level requirement, a structure should not have a strength degradation up to 2% story drift ratio. Fig. 2a shows that the UHP-FRC column was able to maintain nearly full peak strength up to 4% story drift ratio, and it had no strength degradation up to approximately 2.5% story drift ratio. Note that while the axial load ratio ($P_u/A_g f'c$) for the RC column was 0.3, it dropped to 0.06 for the UHP-FRC column due to the high compressive strength of UHP-FRC. This smaller axial load ratio in the UHP-FRC column minimized the influence of the axial load effect at the post-elastic stage, which is very beneficial for columns.



(a) (b)

Fig. 2 – Comparison of UHP-FRC and RC columns: (a) hysteresis loops and (b) confinement characteristics.

The use of UHP-FRC significantly changes the failure mechanism observed in conventional RC columns due to its high strength and high compressive ductility. No visible concrete damage was observed in the plastic hinge region of the UHP-FRC column throughout the test (Fig. 3). This allowed longitudinal reinforcement to be fully utilized to its ultimate tensile capacity without buckling. Furthermore, the strain data of transverse reinforcement in the UHP-FRC region only indicated minor strains of less than 50% yielding strain, suggesting that transverse reinforcement may be significantly reduced in UHP-FRC columns allowing for less congestion and greater ease of construction. Fig. 2b compares both specimens, at the same lateral load of 845 kN, with embedded concrete gauges at a cross-section 250 mm above the footing. It shows that the measured concrete tensile strains in the UHP-FRC column is significantly lower than those in the RC column, which illustrates the great confinement provided by UHP-FRC material. Fig. 3 compares both columns at 2.75% and 5.25% drift ratios showing significant concrete crushing and bar buckling in the RC column with no visible damage detected in the UHP-FRC column. The ultimate failure of the UHP-FRC column was due to the low-cycle fatigue of the longitudinal reinforcement at the interface between the footing and the column section. These pilot test results show the great resilience capability of columns made of UHP-FRC materials.



(a) (b)

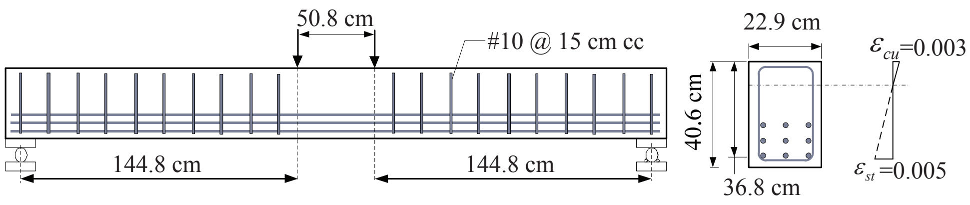
Fig. 3 – Experimental test results: (a) conventional reinforced concrete column (left) and UHP-FRC column (right) at 2.75% drift ratio and (b) conventional reinforced concrete column (left) and UHP-FRC column (right) at 5.25% drift ratio [11]

2. Ductile-Concrete Strong-Reinforcement (DCSR) Design Concept

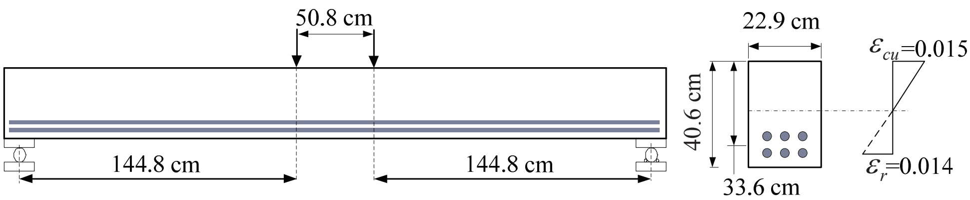
In this research, a new design concept is developed to obtain highly sustainable and efficient reinforced concrete structural members. UHP-FRC offers a new way to design reinforced concrete flexural members due to its superior mechanical properties as compared to conventional concrete. For plain concrete, AASHTO LRFD [14] and ACI 318 [10] use 0.003 as the maximum usable strain, also referred to as the crushing strain of plain concrete (Fig. 1). However, the maximum usable compressive strain of UHP-FRC (at a post-peak stress of approximately 80% of the peak stress), ε_{cu}, is approximately 0.015 (Fig. 1). Since the UHP-FRC's compressive strain is five times greater, a flexural member made of UHP-FRC can be more efficiently utilized by placing a considerably higher amount of longitudinal reinforcement. A new ductile-concrete strong-reinforcement (DCSR) design concept is proposed in which UHP-FRC is used as the ductile element and fiber-reinforced polymer (FRP) bars serve as the elastic element. DCSR is opposite to the conventional RC design approach where the steel bars are the ductile element, and the concrete is the brittle element. The advantages of using the DCSR design is being able to fully utilize the ultra-high compressive strength and ductility of UHP-FRC and to minimize cracking by reducing the elongation of reinforcement, thereby maintaining the stiffness, bond strength, and shear strength of the members.

2.1 Proof-of-concept testing using UHP-FRC and DCSR

ACI 440 [8] suggests a very conservative design for concrete members reinforced with FRP bars because both concrete and FRP bars are brittle materials. However, combining UHP-FRC (very ductile) and FRP bars can provide an excellent solution for concrete structures. In a previous test conducted at the University of Texas at Arlington [15] two beams were tested monotonically up to failure to verify the new DCSR design concept. One UHP-FRC beam reinforced with BFRP (basalt) bars was tested along with an RC specimen with conventional Gr. 420M steel bars. The BFRP bars have an ultimate tensile strength of approximately 1014 MPa and an ultimate tensile strain of 0.017 to 0.025. The RC beam was designed to have the highest amount of longitudinal reinforcement while still maintaining a tension-controlled behavior according to ACI 318 [10]. Thus, the bottom tensile reinforcement reaches a strain of 0.005 when the maximum concrete compressive strain is 0.003 (Fig. 4a). This led to the use of nine Gr. 420M #16 rebars with a reinforcement ratio of 2.58%. The design concrete compressive strength of the RC beams was 35 MPa. For the UHP-FRC beam, the design concrete compressive strength of UHP-FRC was 152 MPa, and the maximum usable compressive strain, ε_{cu}, was taken as 0.015. A lower bound BFRP rupture strain of 0.014 was used in this design (Fig. 4b), which led to a reinforcement ratio of 3.02% provided by six #25 BFRP rebars. Due to high shear strength of UHP-FRC (Table 1), no shear reinforcement was used in the UHP-FRC beam.



(a)



(b)

Fig. 4– Strain profile of (a) RC (Gr. 420M steel rebars) and (b) UHP-FRC (BFRP bars).

Fig. 5 shows the test results, which indicate that the UHP-FRC beam has a higher stiffness and a strength three times that of a conventional RC beam. The UHP-FRC beam also have an excellent ductility, allowing a large deformation or warning sign to occur before failure.

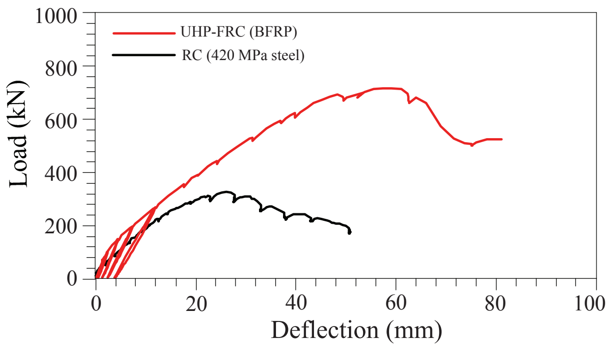


Fig. 5 – Responses of RC beam and UHP-FRC beam with FRP bars.

3. Experimental Test: columns designed with DCSR concept

Two small scale columns were designed and tested under large displacement reversals to investigate the new UHP-FRC/FRP column and the proposed new DCSR design concept. The first specimen was designed with a fiber dosage of 0.75% by volume of ultra-high molecular weight polyethylene (UHMW PE) fibers (13 mm in length and 0.0015 mm in diameter with a tensile strength of 2585 MPa). The second specimen used 3% by volume of micro high-strength steel fibers (13 mm in length and 0.2 mm in diameter with a tensile strength of 2750 MPa). Both specimens were reinforced with BFRP bars of 25 mm diameter with a tensile strength of 1014 MPa. The total reinforcement ratio was 14.8% for both specimens. Fig. 6 shows the details of the cross-section and dimensions as well as the loading protocol. Loading was applied at a distance of 864 mm from the base. Note that, as discussed earlier, the axial load ratio ($P_u/A_g f'c$) is smaller for UHP-FRC columns due to its high compressive strength; thus, no axial load was applied in the test specimens.

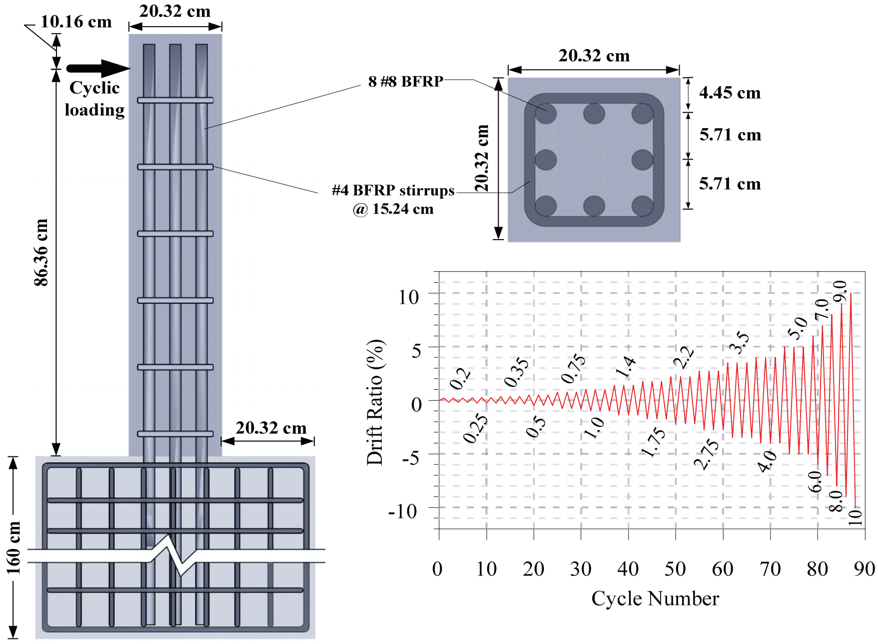
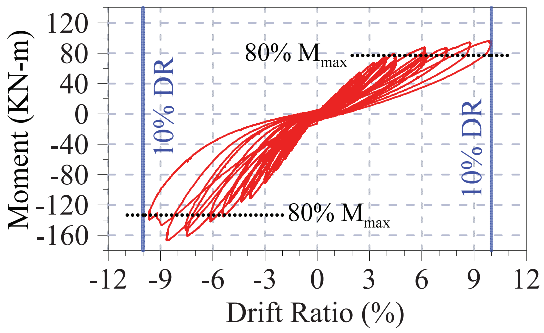


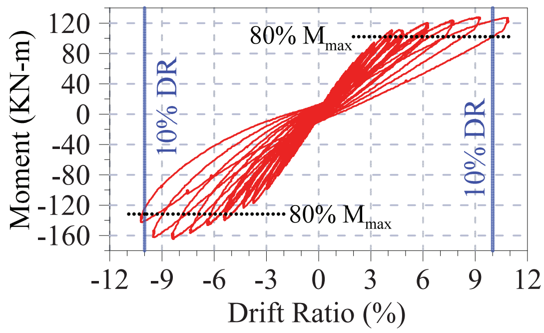
Fig. 6 – Cross-section and dimensions details of the UHP-FRC column specimens and loading protocol

4. Experimental test results

In this research, 70.7 mm cubes were used to determine compressive strength. The obtained comprehensive strengths on the testing day for first and second specimens were 105 MPa and 137 MPa, respectively. For the first specimen, a maximum moment of 166 kN-m was recorded at a drift ratio of 10%. The testing was terminated at 10% drift ratio due to the actuator's limited stroke distance. Moment versus drift ratio relationship showed large cyclic displacements without significant damage in the UHP-FRC material. As shown in Fig. c, UHP-FRC reinforced with UHMW PE fibers exhibits multiple cracks but has no severe concrete spalling and crushing like that which appears in conventional concrete or fiber-reinforced concrete at large drift ratios. A stable cyclic behavior was observed up to 9% drift ratio after which the moment started to decrease in the negative direction (Fig. a). The maximum moment recorded for the second specimen was 162 kN-m at the drift ratio of 8%. Fig. b shows the second column specimen with a stable behavior and no strength degradation up to approximately 9% drift ratio. Similar to the first specimen, no significant damage was observed under large cyclic loading in the UHP-FRC material. Fig. 9c shows that UHP-FRC reinforced with micro high-strength steel fibers with much less cracking than UHP-FRC with UHMW PE fibers. Both cases indicate a significant reduction in repair costs after a moderate or design basis earthquake.



(a)



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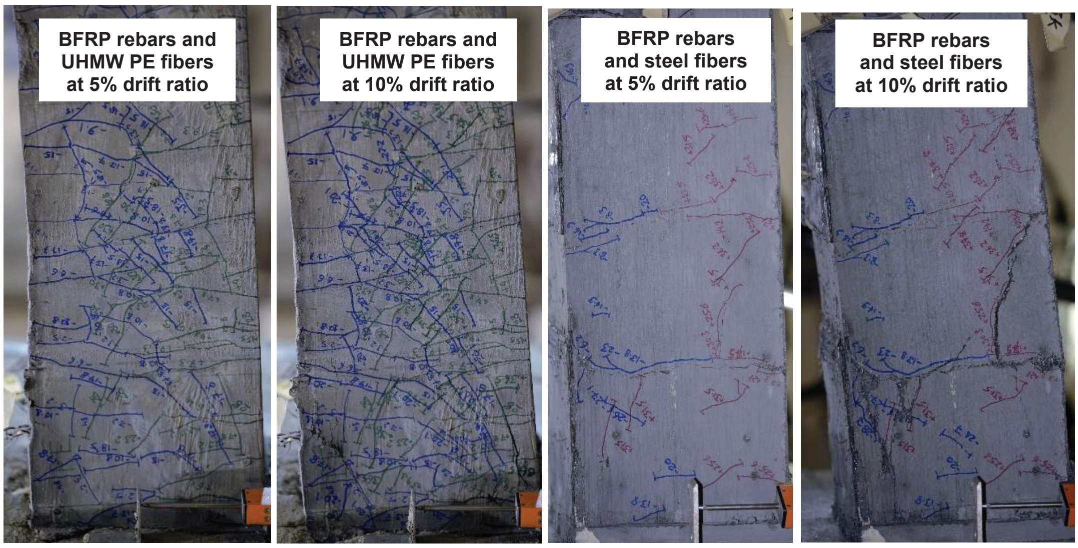


(c)

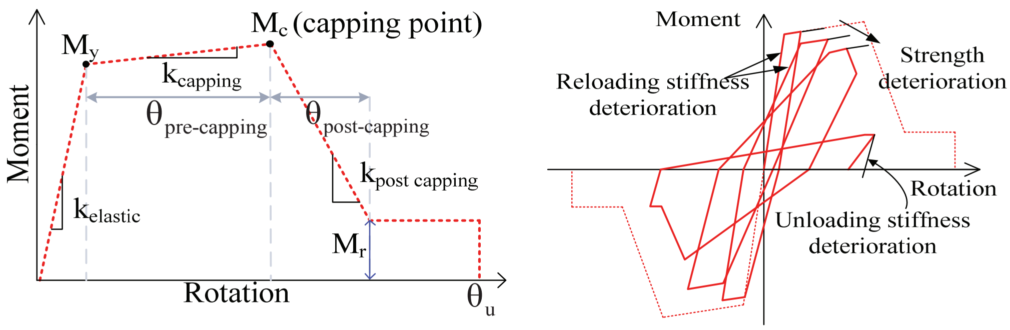
Fig. 7 – Moment vs DR for specimen with UHP-FRC compressive strength of (a) 105 MPa and (b) 137 MPa, and (c) cracking patterns in UHP-FRC columns with different types of high-performance rebars and fibers

During the experiments, minor residual deformation was recorded for both specimens. Since the FRP bars remain elastic up to large drifts, they serve as the restoring force to pull back the columns to the initial position and enhance the resilience of the columns. The results show that even after experiencing large drift ratios (DR=10%), the columns could still maintain 80% of their maximum peak strengths.

5. Collapse resistance of UHP-FRC columns designed by DCSR design concept

5.1 Plastic hinge model for collapse simulation

A plastic hinge in a member is usually simulated by a lumped spring model that has a zero length. Although the nonlinearity of the member occurs along a certain length, the zero-length plastic hinge model can typically be formulated to well simulate the overall behavior of entire plastic hinging region including flexural, shear, and slip deformation. The model used to simulate the plastic hinge of the conventional RC column is a peak-oriented model proposed by Ibarra [16]. Fig. a shows the monotonic backbone and hysteretic behavior of this model. The first slope in the monotonic backbone represents the elastic behavior of the section. After reaching the yielding moment, the section enters the strength hardening branch and continues up to the capping (peak) point. The post-peak stiffness becomes negative to indirectly simulate the in-cycle degradation of the section. In each cycle, the monotonic backbone shrinks to capture the cyclic degradation. Also, the reloading and unloading stiffness can be reduced to match the model with the experimental results. The monotonic backbone curve of this model can be defined through yield strength (M_y), elastic stiffness ($k_{elastic}$), strain hardening ratio (M_c/M_y), pre-capping rotation ($\theta_{pre\text{-}capping}$), post-capping rotation ($\theta_{post\text{-}capping}$), and residual strength (M_r) (Fig. a). With its energy-based deterioration parameters, this model captures the loading stiffness and strength deterioration, as well as the accelerated reloading and unloading stiffness deterioration. The hysteretic rules of Ibarra's model are used for the RC column as shown in Fig. b. This model has been implemented in OpenSees [17], which was used to carry out the nonlinear time-history analyses in this study.



(a) (b)

Fig. 8 – (a) Monotonic backbone and (b) cyclic model recommended by Ibarra [16]

The model was also calibrated based on the test results of the two small-scale UHP-FRC/FRP columns, such that it can simulate the overall behavior of the member including all sources of deformation, as well as the self-centering behavior observed in the experimental tests. Although the strengths of the tested UHP-FRC columns maintained more than 80% the peak strengths up to 10% drift ratio (Fig. 7), a maximum deformation limit of 9% drift ratio was conservatively assigned in the model. To simultaneously achieve the appropriate self-centering nonlinear cyclic behavior of a UHP-FRC column reinforced with FRP bars, three models were combined parallel to each other: 1) the Ibarra's model was used to simulate the degradation behavior, 2) a self-centering model [18] was used to simulate the self-centering behavior, and 3) a MinMax model was defined to conservatively limit the deformation capacity of the model (Fig. 8). When the MinMax material is applied to a model, it is assumed that the strength (or moment) of the model failed from that point on if the strain (or rotation) exceeds the minimum and maximum thresholds.

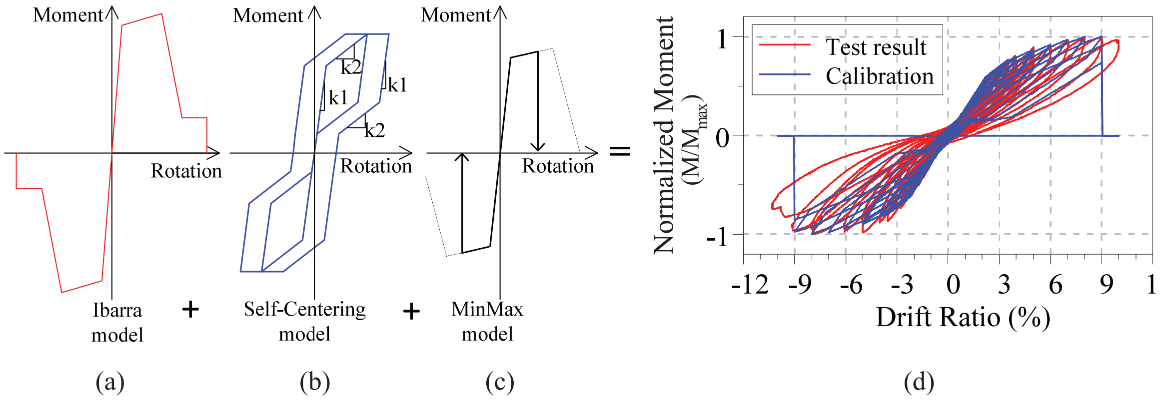


Fig. 8 – Ibarra, self-centering, and MinMax models were used parallel to each other to simulate column behavior

5.2 Incremental dynamic analysis (IDA) for special moment frame: RC and UHP-FRC

To investigate the collapse resistance of the UHP-FRC columns reinforced with FRP rebars, which are designed by the ductile-concrete strong-reinforcement (DCSR) design concept, two pairs of two-dimensional four-story and 20-story special moment frame (SMF) building were designed and analyzed. One of each pair was designed using conventional RC columns, and the other was designed using new UHP-FRC columns with FRP bars. The OpenSees software platform [19] was used for the numerical simulations through incremental dynamic analysis (IDA) [20]. To perform the IDA, a suit of 22 far-field records were selected. Since the structures were designed for stiff soil, the related records (site class C and D) were adopted from FEMA-P695 [21], which were collected from the PEER-NGA database [22].

Conventional plastic hinge models were used for the beams in both structures. Lumped plastic hinges (PHs) were placed at both ends of the elements. To connect the PHs at the joints, beams and columns were connected through a two-dimensional beam-column-joint element object [17]. Since the joints were designed by a strong-joint weak-column approach, the joints were modeled as an elastic element and their contribution to the drift ratio was negligible. A leaning column was modeled to account for the P-Delta effects of the gravity loads. This leaning column is pin-connected to the SMF and the base; hence, it does not contribute to the strength and stiffness of the frame. The built model is schematically shown in Fig. 9.

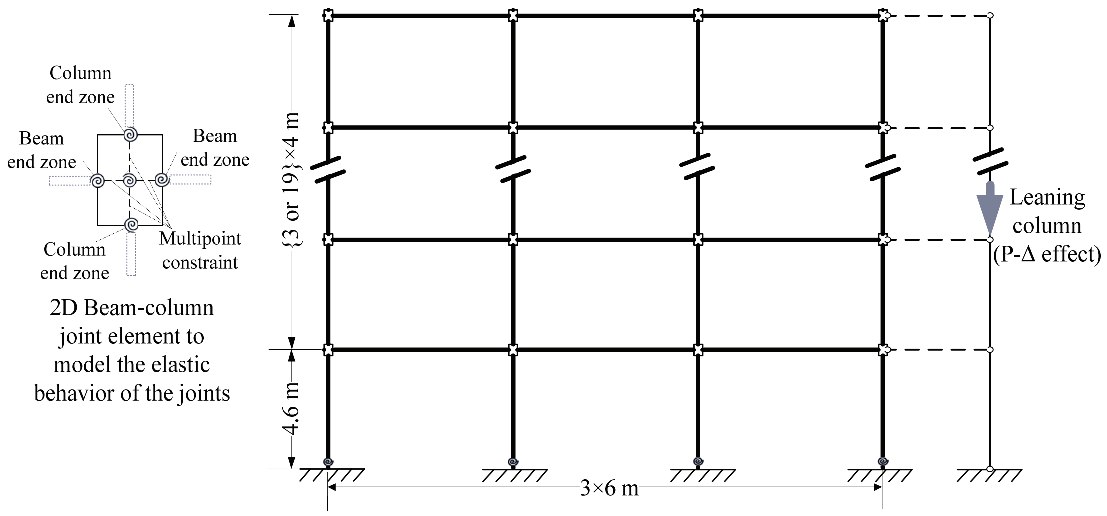


Fig. 9 – Schematic of the numerically modeled special moment frame (SMF)

5.3 Collapse resistance for the RC and UHP-FRC frames

The intensity measure (IM) is the spectral acceleration at the fundamental mode period of the building, while the damage measure (DM) is the maximum interstory drift ratio. A collapse IM is the point where a minor increment in the IM results in a significant increase in the DM. Fig. 10a and Fig. 10b illustrate the incremental dynamic analysis (IDA) results for four-story and 20-story buildings, respectively.

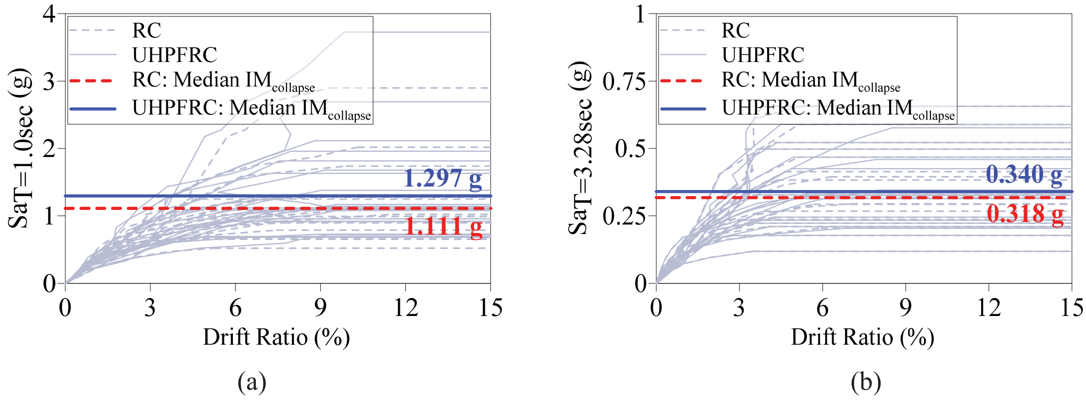


Fig. 10 – IDA results for RC and UHP-FRC (a) a 4-story SMF and (b) a 20-story SMF

The gray lines represent a single IDA curve for each record. The solid line in each figure represents the IDA response of a UHP-FRC frame and each dashed line represents the IDA response for an RC frame. For the four-story building, the median IM for the frame with UHP-FRC columns that causes collapse is 17% (1.297g/1.111g) greater than the corresponding value for the RC frame. This shows the building that uses the new UHP-FRC/FRP columns and is designed by the DCSR concept has a larger collapse resistance than the conventional RC one. The median collapse IM for the 20-story building with UHP-FRC/FRP columns is 7% (0.340g/0.318g) higher than the RC frame. The smaller difference in the collapse resistance for taller buildings is primarily because high-rise buildings experience less inelastic deformations. Studies on single-degree-of-freedom (SDOF) systems have shown that, the peak deformation ratios between inelastic and elastic analyses increases as the fundamental period of the system decreases [23, 24]. This implies that the nonlinear behavior has a less dominating effect in long-period structures. Also, due to self-centering behavior of the UHP-FRC/FRP columns the residual deformations were very small, which indicates a fast recovery of the structures after a major earthquake. Fig. 11a and Fig. 11b compare the first story residual drift ratios for the four-story and 20-story buildings with RC or UHP-FRC/FRP columns subjected to a design-basis earthquake (DBE) using Hector Mine earthquake ground motion.

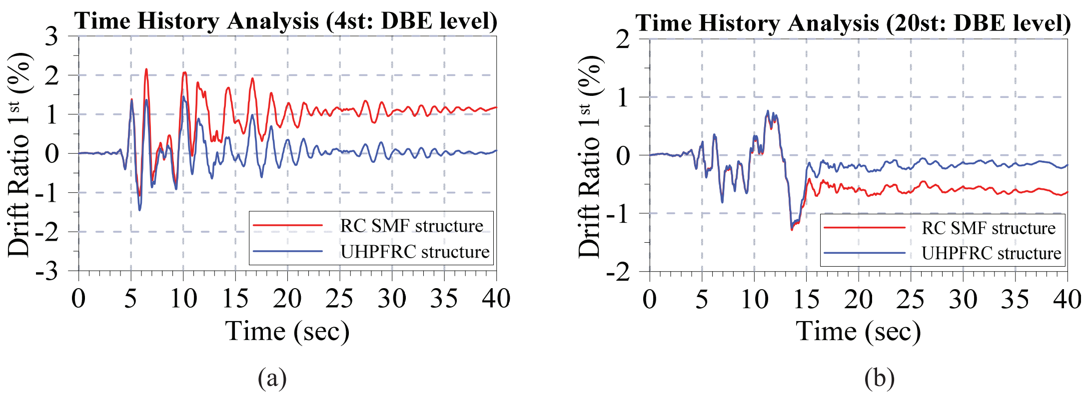


Fig. 11 – Drift Ratio for the first story during time-history analysis results
for RC and UHP-FRC/FRP columns (a) 4-story SMF and (b) 20-story SMF

When comparing both the four-story and 20-story building pairs, the self-centering behavior led to a much smaller residual drift ratios in the building with UHP-FRC/FRP columns, which contributes to the superior benefits of using UHP-FRC/FRP columns designed with the DCSR design concept.

6. Summary and Conclusions

This research investigated a new highly sustainable and resilient reinforced concrete column. This new column is made of ultra-high-performance fiber-reinforced concrete (UHP-FRC) and corrosion resistant high-strength fiber-reinforced polymer (FRP) bars. The new type of UHP-FRC columns are designed based on a newly developed design concept, ductile-concrete strong-reinforcement (DCSR), in which the ductile component is the concrete and the elastic component is the reinforcement. The advantages of using such a design is to fully utilize the ultra-high compressive strength and ductility of UHP-FRC and minimize the cracking by reducing the elongation of reinforcement, thereby maintaining stiffness, bond strength, and shear strength of the members. The proposed UHP-FRC/FRP columns can sustain very large drift ratios under reversed cyclic loading without major damage to the material. Because of the DCSR design concept, the reinforcement remains elastic thus providing a self-centering capability which allow a fast recovery of the building after a major earthquake.

Experimental testing on two small-scale columns showed that the ductility of both columns under cyclic loading was maintained up to a drift ratio of approximately 9% without strength degradation. Also, the post-peak strength was more than 80% of the peak strength at 10% drift ratio. Collapse simulations were carried out to investigate the collapse resistance of SMFs using the new UHP-FRC/FRP columns designed by the DCSR concept. Two four-story and two 20-story SMF buildings were designed and analyzed by incremental dynamic analyses (IDA). One building in each pair of four-story buildings and one building in each pair of 20-story buildings was a made of conventional reinforced concrete frames based on ACI 318 and the other building in each pair used the UHP-FRC/FRP columns. The analysis indicates that both special moment frames with UHP-FRC/FRP columns showed greater collapse resistance compared to the conventional RC SMFs. Notably, the enhanced collapse resistance tends to be higher for short period structures. In addition, the time-history analyses indicate that SMFs with the new columns have much smaller residual drifts after sustaining a major earthquake.

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