EXPERIMENTAL INVESTIGATION OF INNOVATIVE BRIDGE COLUMNS FOR A RESILIENT BRIDGE INFRASTRUCTURE

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Abstract

The ductile behavior of engineered cementitious composites (ECC), which is a special class of high-performance fiber-reinforced concrete (HPFRC), in tension and its superior shear resistance, energy absorption and bond characteristics compared with conventional concrete, provide a unique opportunity to improve the seismic performance of structural components. In this study, an innovative bridge column design is developed using a reinforced ECC (R/ECC) tube filled with conventional concrete. Both the innovative and conventional reinforced concrete (RC) columns are tested under simulated seismic loading. A comparison of results indicates that the proposed concept provides a higher lateral strength and reduces damage, while minimizing the use of more expensive material ECC.

Introduction

Functionality following a major disaster to support quick response and recovery, to reduce direct and indirect losses, and to secure the lives of civilians are the major concerns in designing infrastructure located in hazard prone regions. The current seismic design practice allows yielding of plastic hinge reinforcing bars (rebar) in bridge columns as a mechanism to dissipate energy from strong earthquakes. This practice might cause severe damage in columns resulting in large permanent displacements rendering the entire structure unfunctional in the aftermath of an earthquake. Since the response and recovery efforts largely depend on a functional transportation network, the resiliency of an entire community could be effected from the failure of a small number of bridges.

The use of novel materials, which have high ductility and energy absorption capacity, can partially alleviate this problem. In late 90s, Li and coworkers introduced engineered cementitious composites (ECC) as an alternative for concrete (Li, 1992b, a; Li and Leung, 1992; Li and Wu, 1992). ECC exhibits high ductility with tensile strain

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capacity reaching as high as 5%, and low crack widths, generally limited to below 100 μm (Li et al., 2001; Kesner and Billington, 2004; Boshoff, 2014). These features improve not only the mechanical performance of structural elements in terms of drift and energy absorption capacity, but also they improve the long-term performance by reducing the rate of ingress of corrosive agents. Figure 1 presents tensile behavior of ECC compared with conventional concrete.

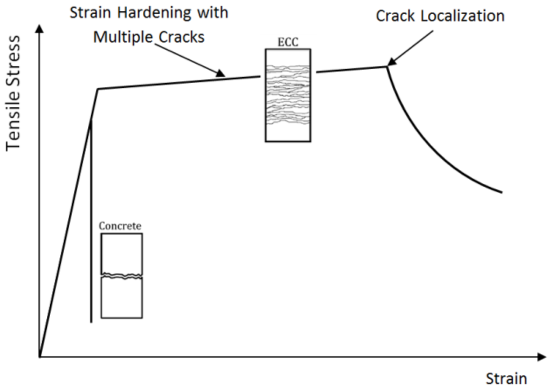


FIGURE 1: BEHAVIOR OF ECC AND CONCRETE IN TENSION

Over the years, several studies were conducted to investigate the performance of structural elements made of ECC with a specific focus on seismic performance. Cyclic response of rectangular reinforced concrete (RC) columns with reinforced ECC (R/ECC) applied in the plastic hinge region was investigated by Cho et al. (2012). It was shown that improvement in the performance of columns subjected to horizontal cyclic loading could be achieved by delaying or eliminating local damage, concrete crushing, and spalling. Fischer and Li (2002) showed that a reduction in transverse reinforcement requirement as well as structural damage under large deformation reversals could be achieved with R/ECC members. Compatible deformation between ECC matrix and the longitudinal reinforcement in both elastic and inelastic regimes resulted in a ductile response of these members. It was also demonstrated that the high shear resistance of ECC reduces the risk of brittle failure modes and leads to a more ductile flexural failure even for squad elements (Suwada and Fukuyama, 2010). Researchers also investigated the use of ECC alongside with other materials such as shape memory alloys or fiber reinforced polymers (Saiidi and Hillis, 2009; Zohrevand and Mirmiran, 2011). Substituting concrete with HPFRC in circular bridge columns resulted in an improvement in energy absorption and reduced damage at similar drift levels when subjected to bidirectional cyclic loading (Aviram et al., 2014). Billington and Yoon (2004) investigated embedment length effect on the performance of precast segmental bridge columns with HPFRC segments at the plastic hinges. Delay in localization of cracks at the base and a higher energy absorption were observed in columns with longer embedded length. Performance of circular concrete bridge columns with R/ECC plastic hinges subjected to dynamic earthquake loads was studied by Saiidi et al. (2011). It was observed that damage could be reduced and considerable enhancement in cumulative energy absorption compared with conventional RC bridge columns could be achieved.

Despite a large body of literature on improved mechanical performance of ECC elements, its application in bridge columns has been limited (Saiidi, 2013). In this paper, an innovative design of bridge columns using ECC is introduced. A precast R/ECC tube, which is filled with conventional concrete in-situ, is proposed to improve the mechanical, and durability performance of bridges. It is expected that the reduced use of ECC and the tube serving as a formwork will lower the cost of construction, the precast elements will ensure the material quality control, and the use of ECC throughout the entire length of the columns will protect the rebar from external agents. This paper discusses the mechanical performance of the proposed approach under simulated seismic loading. The durability aspects will be the topic of future publications.

Research Significance

Previous strong earthquakes have shown that conventional RC bridge columns are susceptible to substantial structural damage, which might render the entire structure unfunctional. Additionally, according to American Society of Civil Engineers (ASCE), more than 150,000 bridges in the United States are either functionally obsolete or structurally deficient (ASCE, 2013). A significant number of these bridges suffer from corrosion damage. In this research, a new column design is proposed using ECC to address the resiliency and durability objectives for bridge infrastructure. A precast, reinforced ECC tube that is filled with conventional concrete in-situ is proposed. The mechanical performance of the proposed concept is experimentally evaluated under simulated seismic loading. The research findings indicate that the proposed concept can improve the lateral resistance of columns, reduce damage, and minimize the extra cost of materials and construction.

Innovative Column Design and Description of Test Specimens

The proposed design concept is shown schematically in Figure 2. An R/ECC tube that comprises the longitudinal and transverse reinforcement is proposed. The tube is embedded inside the footing up to a certain depth and filled with conventional concrete at the same time with the casting of the footing and the column bent. It is expected that the proposed approach will improve the performance of bridge columns in terms of lateral strength and ductility (due to improved tensile stress-strain behavior of ECC), minimize the extra cost of construction by minimizing the use of more expensive ECC material, and improve the durability as a result of significantly lower permeability of R/ECC tube compared to conventional concrete servings as a protective layer for rebar. Additionally, material quality control could be easily achieved with a precast tube, and the total cost of construction could even be reduced by reducing the amount transverse reinforcement (due to higher shear resistance of ECC) and workmanship (due to R/ECC tube serving as a formwork).

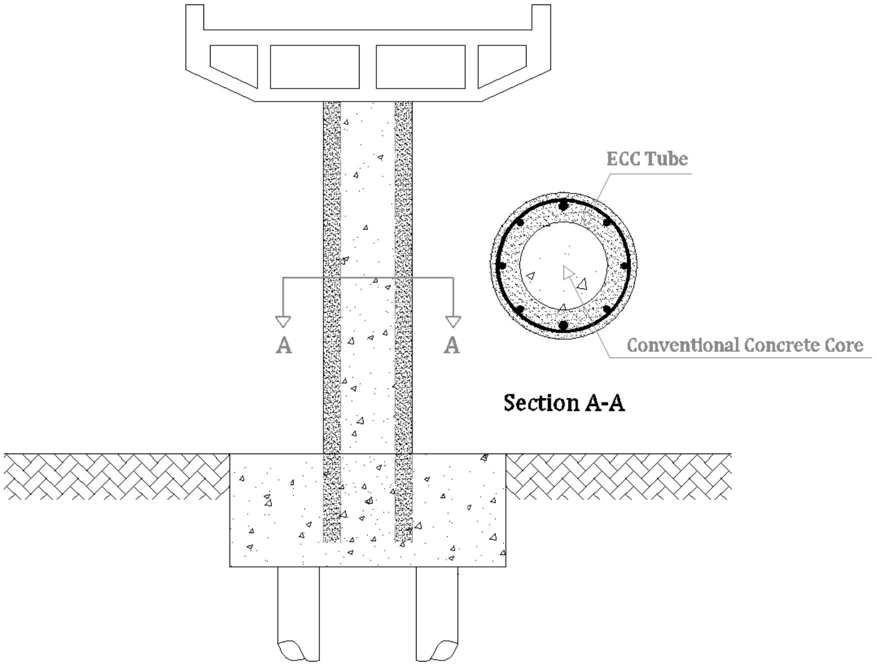
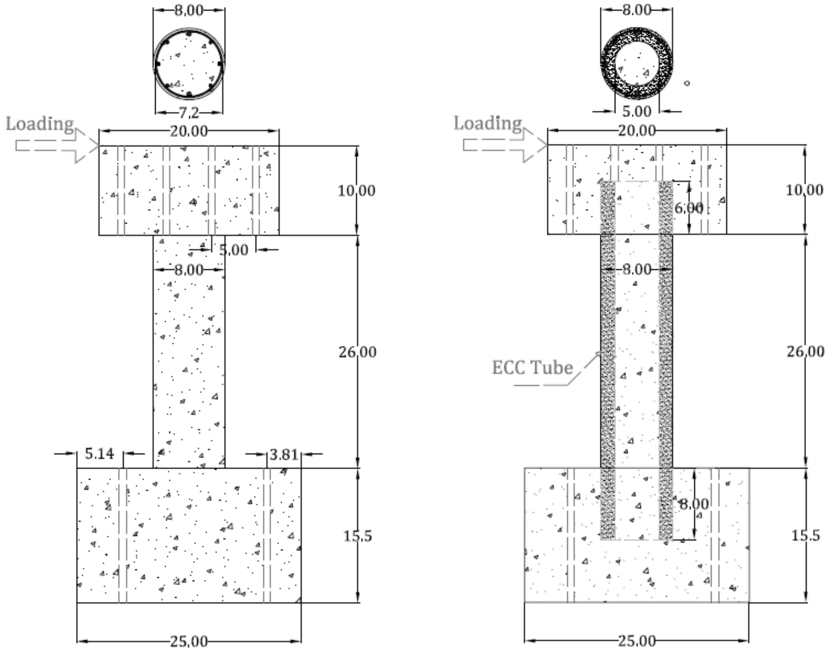


FIGURE 2: PROPOSED BRIDGE COLUMN DESIGN

The flexural behavior of three reduced-scale (approximately 1/4-scale factor) bridge columns constructed according to the proposed concept were investigated and compared with that of a conventional RC column. Four specimens having the same geometry with 8 inch (203.2 mm) diameter circular cross section and 36 inch (914.4 mm) height, as shown in Figure 2, were tested. The scale factor was chosen based on the force and displacement capacities of the testing equipment used. One of the columns was constructed entirely from R/ECC. An ECC mixture with a high fly ash (HFA) content was used, and therefore, the specimen was labeled "HFA-Column". Two other specimens were constructed using the proposed concept with an R/ECC tube on the outside that is filled with conventional concrete. Two different ECC mixes were used: the HFA mix mentioned above, and a high cement content mix called M-45 (the material properties for these mixtures are discussed in more detail in the following section). These two columns were labeled "HFA-Tube" and "M45-Tube", respectively. Finally, a conventional RC column was constructed as a control specimen and it was labeled "RC-Column".

On top of each column, a 20 x 20 inch (508 x 508 mm) square end cap with 10 inch thickness was poured to transfer loads from the testing equipment. The footings had plan dimensions of 25 x 25 inch (635 x 635 mm) with a depth of 15.5 inch (394 mm). Both the end cap and the footing were constructed from conventional concrete and they were heavily reinforced to prevent damage in these regions. In construction of HFA-Tube and M45-Tube, the precast R/ECC tube was filled with concrete simultaneously with the footing and the end cap. To prevent the formation of cold joints, the precast R/ECC tube was inserted 6 and 8 inch (152 and 203 mm) in the top end cap and footing, respectively.



(A) (B)

FIGURE 3: SPECIMEN GEOMETRY, (A) RC- AND HFA-COLUMNS, (B) HFA-TUBE AND M45-TUBE COLUMNS (ALL DIMENSIONS ARE IN INCH)

The longitudinal reinforcement in each specimen consisted of eight Grade 60 rebar distributed evenly in a circular pattern. To achieve a 2% longitudinal reinforcement ratio, two #4 [0.5 inch (12.7 mm) diameter] rebar were placed at the section's neutral axis and three #3 [0.375 inch (9.5 mm)] rebar were placed on each side as shown in Figure 3. As for the transverse reinforcement, a #9 gauge galvanized smooth steel bar with 0.153 inch diameter (3.9 mm) was used to form a spiral with a pitch of 1.25 inch (32 mm). This configuration meets the requirements of current provisions for seismic design of highway bridges (NCHRP, 2002).

Material Properties

The same mixture with a maximum aggregate size of 3/8 inch (9.5 mm) was used as the conventional concrete for all the specimens. The average compressive strength of 4 x 8 inch (102 x 203 mm) cylinders at testing dates were 7.13, 5.31, and 5.17 ksi (49.2, 36.61 and 35.65 MPa), respectively for the RC-Column, HFA-Tube, and M45-Tube specimens. Note that the reported values for the latter two specimens are for concrete poured inside the R/ECC tube. Both ECC mixtures (HFA and M45) contained 2% by volume of 0.315 in (8 mm) long polyvinyl alcohol (PVA) fibers. Average compressive strength of ECC mixtures at testing dates for HFA-Column, HFA-Tube, and M45-Tube were 7.4, 6.92 and 9.36 ksi (51.02, 47.71 and 64.53 MPa), respectively. Tensile tests of dog bone shaped specimens from HFA ECC-mixture exhibited considerable ductility with hardening after yielding as shown in Figure 4. M45 ECC-mixture showed lower tensile strength and softening after a short hardening plateau under direct tensile test.

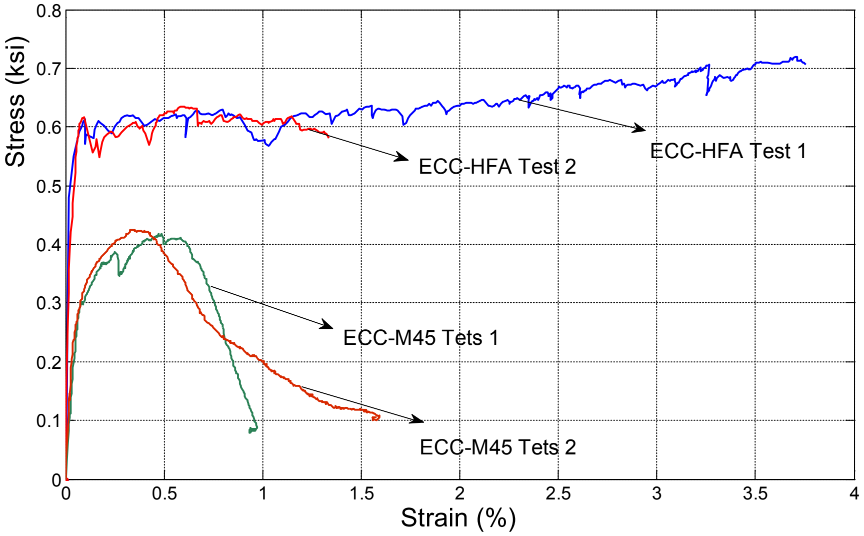


FIGURE 4: TENSILE STRESS-STRAIN BEHAVIOR OF ECC MIXTURES

Test Setup and Loading Protocol

The specimens were tested under combined horizontal and axial loading using state-of-the-art multi-axial testing units capable of imposing any combination of displacements and forces in all 6 degrees-of-freedom (DOF) [see Figure 5]. The loads were transferred from the platen of the multi-axial testing units to the specimens through 12 post-tensioned high strength bolts. For ease of placing the specimens, steel adapter plates were designed and post-tensioned to strong floor and the specimens' footings. Although the loading units are capable of measuring deformations in all six DOF, six external linear potentiometers were installed to eliminate the measurement error due to elastic deformations of the multi-axial loading units and/or the load frame. The damage evolution was recorded by three high resolution digital cameras during the test. The cameras were synchronized with the loading protocol to capture crack propagation at each loading step. The test setup is presented in Figure 5.

A horizontal incremental cyclic displacement (see Figure 6) was applied to top of the specimens at a quasi-static rate. The lateral loading pattern was based on drift ratio by taking the distance between top of the footing and the top of the end caps as the total height of the column. In addition to the horizontal displacement cycles, a constant vertical load of 22.5 kips (100 kN) was applied on the columns resulting in an axial load approximately equal to 7.5% of squash capacity of the columns. To simulate the boundary conditions of a cantilever column, the multi-axial testing unit was programmed to keep the in-plane moment equal to zero.

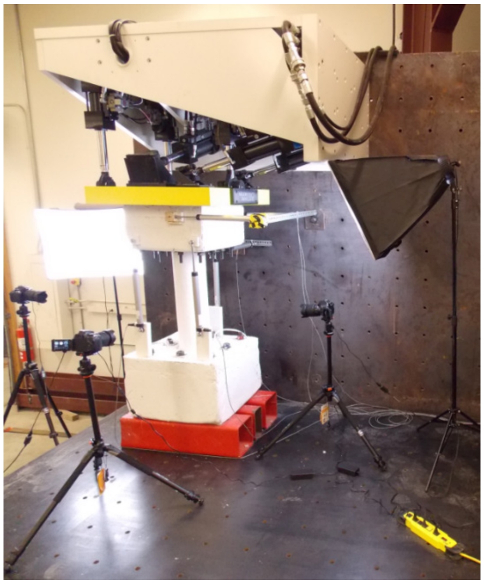


FIGURE 5: TEST SETUP

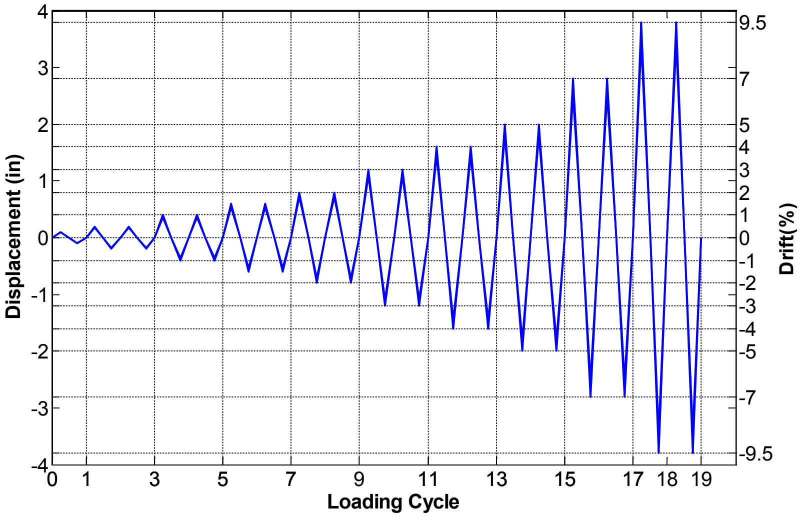


FIGURE 6: LOADING PROTOCOL

Experimental Results

The observed damage at 2, 5, 7 and 9.5% drift ratios is shown in Figure 6. A comparison of the observed damage at different drift ratios reveals finer and more distributed cracks in concrete filled R/ECC tubes than in RC or R/ECC columns. Although the specimens showed distributed cracking along the height of the columns at low drift ratios, finally the damage was localized in the plastic hinge regions of the columns. Damage localization was delayed in columns using ECC mixture and concrete spalling was observed only in the conventional RC-Column.

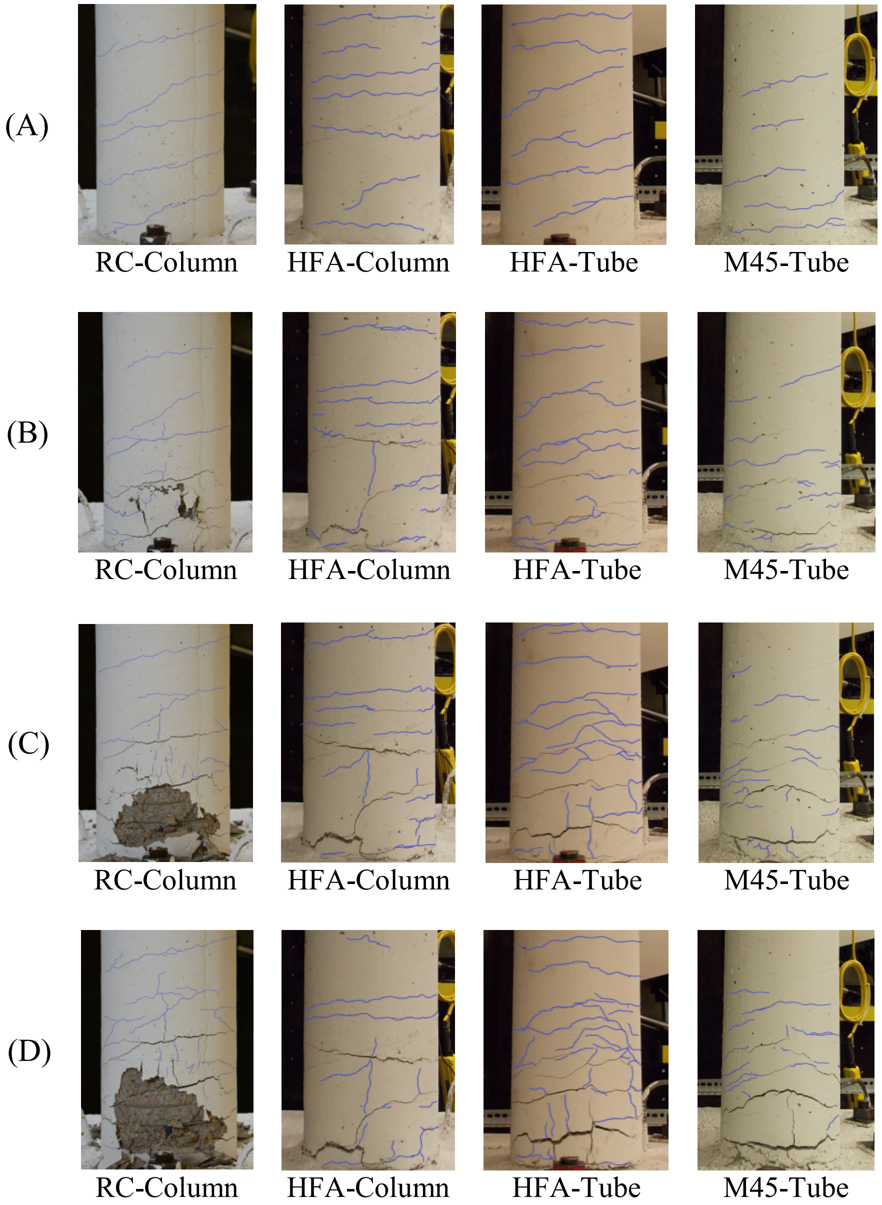
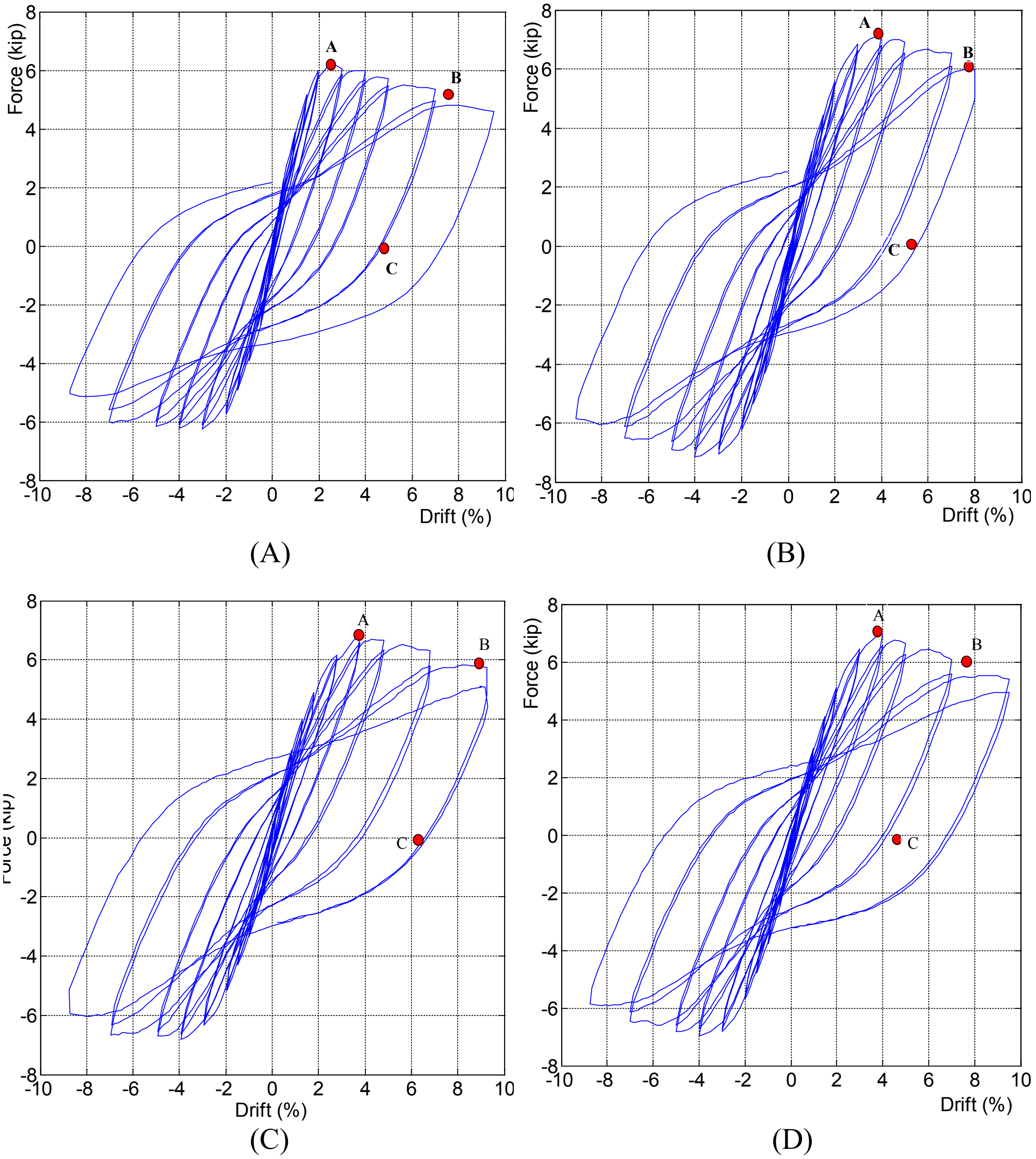


FIGURE 7: OBSERVED DAMAGE AT: (A) 2%; (B) 5%; (C) 7%; (D) 9.5% DRIFT RATIO

The hysteretic load-drift curves are presented in Figure 8. In these diagrams points A, B and C present lateral strength, failure point (defined as 15% drop in lateral resistance), and the permanent deformation (defined as the displacement after the removal of the lateral load following the failure point). The points B and C were defined by interpolation whenever needed. The data corresponding to mentioned points is summarized in Table 1. The energy absorption shown in Table 1 is calculated as the total area under the load deformation diagram up to end of the first complete 9.5% drift cycle.

An increase of approximately 10% was observed in the peak lateral force (at point A) and energy absorption capacity of R/ECC columns compared with the control RC-Column. The drift ratio corresponding to the lateral strength (at point A) was substantially higher for R/ECC specimens. This is attributed to improved bond and tensile strain hardening behavior of ECC. The strength and drift ratios corresponding to the ultimate point (B) were also improved. HFA-Tube experienced slightly lower strength gain and energy absorption compared to other two specimens using ECC.



(A)

(B)

(C)

(D)

FIGURE 8: LOAD-DEFORMATION HYSTERESIS CURVES: (A) RC-COLUMN; (B) HFA-COLUMN; (C) HFA-TUBE; (D) M45-TUBE.

TABLE 1: SUMMARY OF EXPERIMENTAL RESULTS

	RC-Column	HFA-Column	HFA-Tube	M45-Tube
Strength at Point A, kips (kN)	6.246 (27.78)	7.142 (31.769)	6.803 (30.261)	6.967 (30.991)
Strength Gain, %	-	14.35	8.9	11.54
Drift Corresponding to Point A, %	2.03	3.61	4.00	3.80
Strength at Point B, kips (kN)	5.301 (23.58)	6.07 (27.00)	5.783 (25.724)	5.922 (26.342)
Drift corresponding to point B, %	7.22	7.85	9.17	7.65
Drift at Point C, %	4.871	5.259	6.389	4.721
Energy Absorption, kips.in (kN.m)	214.023 (24.18)	236.154 (26.68)	233.943 (26.43)	237.503 (26.83)
Energy Absorption Difference, %	100	110.34	109.31	110.97

Conclusions

Performance of an innovative bridge column design was investigated experimentally with reduced-scale specimens subjected to simulated seismic loading. The main findings are summarized as follows:

1. The reinforced engineering cementitious composite (R/ECC) columns showed an increase of approximately 10% in lateral strength and energy absorption compared to a conventional reinforced concrete (RC) column.
2. The R/ECC columns experienced significantly less damage at the same drift ratios in comparison to the conventional RC column: damage localization was delayed and no cover spalling was observed.
3. Although the specimens experienced distributed cracking at low drift ratios, damage was localized in the plastic hinge region as the drift ratio increased. Among all the specimens, the HFA-Tube showed the least damage localization.
4. Overall, HFA-Column and HFA-Tube specimens showed similar performance. The proposed approach can lead to more economical bridge columns with the similar structural performance of a column constructed completely from R/ECC by accelerating the construction process by eliminating the need for formwork. Additionally, better quality control could be achieved for the precast R/ECC tube. The proposed approach is also expected to improve the durability of the bridge columns by reducing the rate of ingress of external agents with less permeable ECC layer on the outside.

Unit Conversion

U.S. Customary Units	**SI**
1 in	25.4 mm
1 kips	4.448 kN
1 ksi	6.895 MPa
1 kips.in	0.1129792 kN.m

Acknowledgments

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