SEISMIC BEHAVIOR OF 3D ECC BEAM-COLUMN JOINTS IN SPECIAL MOMENT RESISTING FRAMES

F. Hosseini¹, B. Gencturk² and S. Lahour Pour³

ABSTRACT

Special moment frames (SMF) are commonly used in buildings located in high seismicity regions. It is known that the formation of plastic hinges in the beams and columns causes considerable damage to the beam-column joints and in most cases irreparable damage to the building. In this research, the application of a special type of high-performance fiber-reinforced cementitious composite (HPFRCC) in the plastic hinge regions of exterior beam-column joints in SMF is investigated. Prior research focused on the use of steel fiber-reinforced concrete in planar (2D) beam-column connections. However, exterior beam-column joints are usually subjected to more complex loading during an earthquake, involving bi-directional bending and torsion of the column. In addition to the loading, the geometry of the connection requires a 3D test setup (i.e., with an out-of-plane beam). In this research, the use of engineered cementitious composites (ECC) in a 3D exterior beam-column joint is investigated experimentally. The specimen was subjected to bi-directional lateral cyclic displacements and an axial compressive load while both in- and out-of-plane beams were pin supported at their ends. This paper compares the behavior of the beam-column joint with ECC in the plastic hinge region with that of the conventional reinforced concrete (RC) joint.

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Special moment frames (SMF) are commonly used in buildings located in high seismicity regions. It is known that the formation of plastic hinges in the beams and columns causes considerable damage to the beam-column joints and in most cases irreparable damage to the building. In this research, the application of a special type of high-performance fiber-reinforced cementitious composite (HPFRCC) in the plastic hinge regions of exterior beam-column joints in SMF is investigated. Prior research focused on the use of steel fiber-reinforced concrete in planar (2D) beam-column connections. However, exterior beam-column joints are usually subjected to more complex loading during an earthquake, involving bi-directional bending and torsion of the column. In addition to the loading, the geometry of the connection requires a 3D test setup (i.e., with an out-of-plane beam). In this research, the use of engineered cementitious composites (ECC) in a 3D exterior beam-column joints is investigated experimentally. The specimen was subjected to bi-directional lateral cyclic displacements and an axial compressive load while both in- and out-of-plane beams were pin supported at their ends. This paper compares the behavior of the beam-column joint with ECC in the plastic hinge region with that of the conventional reinforced concrete (RC) joint.

Introduction

Special moment frame (SMF) is a common structural system for low and mid-rise buildings in regions with high seismic activities. Extensive damage to the beam-column joints, as important components of SMFs, can lead to collapse of the building or endanger its serviceability. Recent strong earthquakes have shown that reinforced concrete (RC) beam-column joints are susceptible to extensive damage due to large shear demands [1]. It should be noted that the existing design recommendations [2], which follows a strength-based methodology, mainly focus on addressing the minimum requirements in beam-column joints to prevent collapse of the structure. This design...
approach allows formation of large shear cracks during a strong earthquake. Even though, significant effort has been devoted to study seismic behavior of beam-column joints, most of the past research concentrated on T-joints wherein the beams and columns have been subjected to in-plane (uniaxial) bending moments. This configuration suffers from neglecting the effect of biaxial bending imposed to the exterior beam-column joints, particularly, during an earthquake [3]. The biaxial bending causes rapid stiffness degradation in the beam-column joints by reducing the favorable confinement effect of the stirrups [4].

Using newly developed materials, such as high-performance fiber reinforced concrete (HPFRC), is a growing approach to enhance the damage tolerance of beam-column joints and improve their deformation capacity [5-7]. Superior characteristics of engineered cementitious composites (ECC) as a special type of HPFRC make it an interesting choice for seismic applications. Strain-hardening behavior in tension up to 5% tensile strain, developing multiple fine cracks in tension with crack width limited to 100 µm, and higher shear and bond strength compared to the conventional concrete are some of these unique properties [8-10]. Application of ECC in structural elements such as bridge columns and beams have been extensively studied [11-15]. However, there are limited studies considering utilization of ECC in beam-column joints [5,6]. The objective of this research is to assess the performance of 3D exterior beam-column joints constructed with ECC and subjected to bidirectional bending through an experimental work. In the experimental program, the conventional concrete was replaced with ECC in the panel zone of a 1/4-scaled corner beam-column subassembly which extended to the potential plastic hinge regions of the adjoining beams and columns. Upon testing the specimen, the results were compared with those obtained from the control specimen constructed completely with the conventional concrete to examine efficiency of ECC in improving the damage tolerance of the exterior beam-column joints.

Experimental Program

To conduct the experimental work, a 1/4-scaled corner beam-column subassembly from first story of a four story-three bay archetype RC SMF designed for high seismicity regions [16] was considered. The subassembly consisted of the panel zone extended to the midpoint of the adjoining beam and columns where zero moment condition occurs due to lateral forces. Figure 1(A) demonstrates the geometry of the beam-column subassembly. To maintain symmetry in the subassembly and create a 3D configuration, the out-of-plane beam was considered the same as the in-plane beam of the SMF. 9.5 mm (#3 U.S. designation rebar) grade 60 reinforcing steel and 6.4 mm grade 60 deformed bars were used for longitudinal and transverse reinforcement, respectively. The columns had 1.3% longitudinal reinforcement in a square pattern while 1.7% longitudinal reinforcement was distributed equally on top and bottom of the beams. The spacing between the stirrups was calculated based on the requirements for SMFs in ACI-318 [2]. To investigate application of ECC in corner beam-column joints, the conventional concrete in the panel zone was replaced with ECC and extended 304.8 mm and 203.2 mm to the adjoining beams and columns, respectively, to cover the corresponding potential plastic hinges. To construct the RC sections, ready mix concrete with target compressive strength of 31 MPa at 28 days was used while M21 composition from studies of Pan et al. [17] was used for the ECC mix design. Additionally, two steel plates with four 19 mm high strength bolts, as shear studs, were installed at the ends of the
top and bottom columns to transfer the loads from the loading unit and connect the specimen to a universal joint attached to the strong floor. Figure 1(B) illustrates the boundary condition where zero moment condition was satisfied at the end of the beams and columns. Additionally, the twist around Z-axis was restrained to prevent any global instability in the system through torsion.

Figure 1. (A) Geometry of beam-column subassembly (dimensions are in mm and the highlighted area is ECC), (B) boundary conditions.

Figure 2(A) shows the test setup. A universal joint was considered underneath of the bottom column to provide zero moment condition and transfer the loads to the strong floor. The specimen was connected to the loading unit and the strong floor using 12 and eight high strength post tensioned bolts, respectively. To prevent concrete cracking under stress concentration, two ends of the column was confined externally by steel plates connected to each other through four post tensioned bolts. Truss elements, consisted of two universal joints connected with rigid links to each other, were used to simulate zero moment condition at the end of the beams in addition to fixed supports implemented to prevent the torsional instability in the system. Additionally, three high resolution cameras were synchronized with the loading unit to take pictures in each loading step in order to capture the damage evolution. A state of the art testing unit capable of applying loads or deformations simultaneously in all six degrees of freedom was used to apply a biaxial lateral loading and constant axial load of 89 kN at the top of the column. Figure 2(B) presents the lateral loading pattern. The biaxial lateral loading was imposed in displacement control to the top of the top column, where the zero-moment condition was satisfied by the loading unit, up to 6.53% lateral drift. The drift was calculated by dividing the maximum distance of the cloverleaf pass from the origin, \( R \), to the height of the specimen, which was taken as the distance from the center of the universal joint to the upper surface of the top steel plate, 1422.4 mm. The biaxial bending loading protocol consisted of one complete cycle of 0.45%, 1.4%, 2.8%, 3.73%, 4.70%, and 6.53% drift ratios.
The applied deformations and the corresponding forces were measured using LVDTs and load cells utilized in the testing unit. Furthermore, four linear pots were used in a square formation to measure the shear deformations of the panel zone, see Figure 3(A). A tension-compression S-shaped load cell along with a compression only donut-shaped load cell were used to measure the corresponding reactions from the truss element and the fixed support, respectively, see Figure 3(B).

Results and Discussions

Figure 4 shows the resulted load-deformation diagrams of the tested specimens. RC in Figure 4(A) refers to the control specimen constructed completely with conventional concrete while RECC in Figure 4(B) refers to the specimen with ECC in the panel zone and the plastic hinge regions of the adjoining beams and columns. The numbers in Figure 4(B) presents enhancement of the lateral
strength compared to the control RC specimen. As evident, incorporating ECC in the beam-column joint increased the lateral strength by 15.7% while kept the general response of the beam-column subassembly similar to the control RC case. Figure 5 illustrates the crack pattern at the final stage of loading. A comparison between the damage level at the final stage of the testing program revealed that incorporating ECC significantly enhances the damage tolerance of the beam-column joint studied here. Large diagonal cracks and concrete spalling were observed in the RC specimen while damage was limited to fine diagonal cracks in the RECC specimen. Additionally, considerably higher number of cracks developed in the panel zone of the RECC specimen compared to the RC specimen. This behavior can be attributed to the tensile strain-hardening property of ECC and its ability to develop multiple cracks in tension.

Figure 4. Load-deformation diagrams: (A) RC specimen, (B) RECC specimen.

Figure 5. Crack pattern at the final stage: (A) RC specimen, (B) RECC specimen.

Figure 6 represents the measured shear deformations in the panel zones of the tested specimens. It is seen that both of the specimens experienced similar shear deformations up to 3.7% lateral drift where the linear pots started detaching from the RC specimen due to extensive damage to the panel zone and spalling of the cover concrete. On the other hand, the RECC specimen could tolerate a 0.57-degree (0.01 rad) shear deformation with considerably lower damage, see Figure 5(B), which is the threshold for designing joints with moderate shear distortions required for performance-based design of SMFs [1]. The enhanced shear deformation capacity can be related
to superior shear properties of ECC compared to the conventional concrete. Figure 7 shows the measured reactions at the boundaries. Higher reactions were measured at the boundaries of the RECC specimen, in general, because of the higher lateral strength of the RECC specimen, see Figure 4(B).

Figure 6. Shear deformations in the panel zone: (A) RC specimen, (B) RECC specimen.

Figure 7. Measured loads at the boundaries: (A) S-load cells of RC specimen, (B) S-load cells of RECC specimen, (C) donut load cells of RC specimen, (D) donut load cells of RECC specimen.
Conclusion

The main findings of this study are listed below:

- Incorporating ECC in the 3D corner beam-column joint increased the lateral strength in both in-plane and out-of-plane directions by 15.7% compared to the control RC specimen.
- Incorporating ECC in the 3D corner beam-column joint significantly enhanced its damage tolerance. No concrete spalling or major cracks were observed in the panel zone unlike the control RC specimen.
- The RECC joint could tolerate extensive shear distortions with limited damage to the panel zone. Therefore, it can be considered as an option for moving toward performance-based seismic design of SMFs.

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