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Seismic behavior of 3-D ECC beam-column connections subjected to bidirectional bending and torsion

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ABSTRACT

Special moment resisting frames (SMF) are commonly used in low- and medium-rise buildings located in regions of high seismicity. Although adequate performance of this seismic force resisting system was observed in prior earthquakes in terms of protecting buildings from collapse, the formation of plastic hinges in the beams and columns causes irreparable damage to the beam-column connections. Recently, interest in using fiber-reinforced concrete (FRC) has been growing to enhance energy absorption capacity and damage tolerance of beam-column connections and other components in reinforced concrete (RC) buildings. Prior research has mostly focused on the application of steel FRC (SFRC) in 2-D beam-column connections. However, little is known about the performance of exterior beam-column connections that 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 more involved test setup (i.e., with an out-of-plane beam and proper boundary conditions). In this research, the use of engineered cementitious composites (ECC) in 3-D exterior beam-column connections is investigated experimentally to improve building seismic performance. ECC is a special class of high-performance fiber-reinforced cementitious composites (HPFRCC) that, compared to conventional concrete, exhibits higher tensile ductility, energy absorption and shear resistance, in addition to improved bond performance with reinforcing steel (rebar). To understand the performance of exterior beam-column connections under complex loading conditions, scaled 3-D specimens were constructed and tested under simulated seismic loads. To improve the performance of the connections, conventional RC was replaced with reinforced ECC (RECC) that extends from the panel zone to the adjoining beams and columns to cover the potential plastic hinge regions. This paper discusses the loading protocols, the test setup for 3-D exterior beam-column connections, and the improvement in the joint behavior with the application of RECC as compared to conventional RC. The results suggest that the efficient use of ECC in the potential plastic hinge regions can improve the capacity and damage tolerance of beam-column connections under realistic seismic loading conditions.

1. Introduction

Reinforced concrete (RC) special moment resisting frames (SMF) is a common structural system for residential and commercial buildings as well as for important social service facilities such as hospitals, police and fire stations, and schools. Recent strong earthquakes showed that RC beam-column connections are susceptible to extensive damage, in some cases, resulting in the collapse of the buildings. Beam-column connections in RC frames generally experience large shear stresses during earthquake induced lateral displacements [1]. The focus in current design codes and recommendations for RC beam-column connections is to prevent the collapse of the structure and loss of lives. These codes and recommendations include ensuring strong column-weak beam behavior, providing enough confinement and sufficient strength for the joint and critical regions of the adjoining members, and proper anchorage of the longitudinal rebar [2,3]. However, satisfying these requirements does not necessarily prevent bond deterioration under cyclic loading or the formation of large diagonal cracks during strong earthquakes. Furthermore, reinforcement congestion in the joint region might be inevitable in certain cases to meet these requirements.

Using fiber reinforced concrete (FRC) in the beam-column connections is one of the options that has been recently investigated by researchers to improve their rotational capacity while minimizing the post-earthquake repair needs. Shakya et al. [4] demonstrated that using

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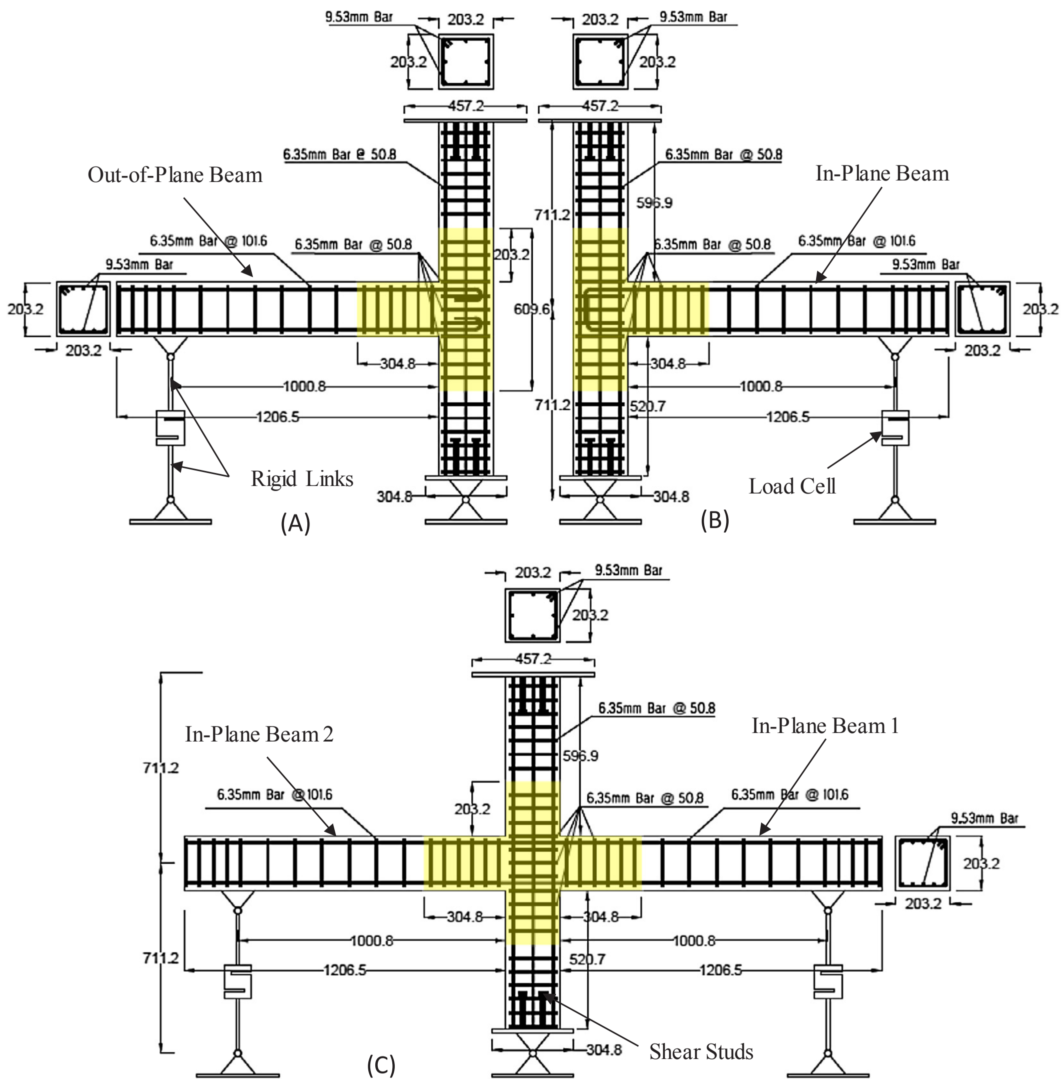

Fig. 1. Beam-column subassemblies (shaded areas show the locations of ECC, dimensions are in mm): (A) out-of-plane view of corner and exterior subassemblies; (B) in-plane view of corner subassembly; (C) in-plane view of exterior subassembly.

1.5% of steel fibers in concrete improves flexural and shear capacity of beam-column connections and reduces the beam longitudinal and joint transverse steel rebar requirements. No comparison of the performance of the connections with and without fibers was performed. However, a similar energy absorption was observed when the longitudinal and transverse reinforcement was reduced by 27% and 29.2%, respectively, compared to the control specimens with 1.5% steel fibers in the concrete. In addition to the steel fiber-reinforced concrete (SFRC), implementation of high-performance fiber-reinforced cement composites (HPFRCC) has been considered to improve the seismic performance of beam-column connections. High shear strength and flowability characteristics of engineered cementitious composite (ECC), as a special type of HPFRCC, makes it an ideal choice for seismic applications [5–11]. Several studies have been conducted to investigate the performance of beam-column connections constructed with HPFRCC and subjected to reversed cyclic loading. Generally, ECC is only used in the joint panel zone and the potential plastic hinge regions of the adjoining elements because of its relatively high cost compared to conventional concrete. Qudah and Maalej [12] reported that using ECC can increase the energy absorption capacity of interior beam-column connections up to 20%. The specimens preserved their structural integrity and no major crack or spalling was observed under high inelastic deformations caused by an 8% lateral drift. Zhang et al. [13] demonstrated that replacing the panel zone transverse reinforcement with polypropylene based ECC maintains flexural failure mode of the connection, indicating that ECC can be a potential alternative for stirrups in the joint panel zone. Removal of 0.67% and 0.26% of the transverse reinforcement of the beams and columns, respectively, in one-sixth scale specimen resulted in 19.3 kN lateral strength, compared to 23.4 kN for the same in the control RC specimen, when ECC is implemented in the entire geometry of the beam-column connection. Parra-Montesinos et al. [1] developed a damage tolerant interior beam-column connection by applying HPFRCC to the joint panel zone and the potential plastic hinge regions of the adjacent beams. The specimens showed a high deformation capacity and no bond deterioration of the longitudinal reinforcement was observed.

As mentioned above, the beam-column connections have been studied extensively in the past because of their importance in the overall building response. However, the experimental studies were limited to testing T- or cruciform connections under in-plane loading. In these tests, the column is usually pinned at the base and the vertical and horizontal displacements are applied to the beam and column ends, respectively. These tests do not necessarily represent the actual 3-D geometry of the connections and the deformations to which they are subjected in real structures, especially when connections at the perimeter frames of a building are considered. In reality, earthquakes