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A new ductile moment-resisting connection for precast concrete frames in seismic regions: An experimental investigation

Hossein Parastesh [a], Iman Hajirasouliha [b,*], Reza Ramezani [c]

[a] Department of Civil Engineering, University of Science and Culture, Tehran, Iran
[b] Department of Civil & Structural Engineering, The University of Sheffield, Sheffield, UK
[c] Department of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran

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ABSTRACT

A new ductile moment-resisting beam–column connection is developed for precast reinforced concrete (RC) frames in high seismic zones. The proposed connection provides good structural integrity in the connections and can reduce construction time by eliminating the need for formworks and welding, and minimizing cast-in-place concrete volume. A series of cyclic loading tests were carried out on six full-scale interior and exterior precast connections and two monolithic connections, all designed for use in high seismic zones. Test variables included the type of stirrups (open and closed) and the stirrup spacing in the beam connection zone. Test specimens were subjected to a constant axial load and a reverse cyclic loading based on a given displacement history. Flexural strength, ductility, strength degradation and energy dissipation capacity of the precast and monolithic connections are compared. The proposed interior and exterior moment-resisting connections proved to be efficient at improving the seismic performance of precast concrete frames in high seismic zones. While the precast connections provided adequate flexural strength, strength degradation and drift capacity, they exhibited considerably higher ductility and energy dissipation compared to similar monolithic specimens.

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1. Introduction

With population growth and increasing demand from higher standards, construction industry is facing new major challenges. Societal and legal pressures mean that the structural systems need to comply with modern requirements such as cost efficiency, fast construction, resilience and mass production. Prefabricated building systems have advantages such as high quality control, fast construction and cost efficiency by reducing the amount of waste material [1]. Therefore, precast buildings are replacing conventional cast-in-place systems, especially by dominance of mass construction in developing countries. However, these structural systems may be vulnerable to strong earthquakes. Extensive damage and catastrophic failure of precast RC structures in major earthquakes was mainly due to failure of joints and inadequate ductility, which highlighted the importance of ductile connections in precast structures [2–5].

Moment-resisting beam–column connections are, in general, suitable systems to maintain lateral stability and structural integrity of the multi-storey precast concrete structures in high seismic zones. Park and Bull [6] conducted full-scale tests on three exterior precast concrete beam–column connections, and showed that the specimens detailed for seismic loads have adequate strength, ductility, and energy dissipation for ductile moment-resisting frames. Similar results were reported by French et al. [7,8] on three different types of precast concrete connections. The results of their study indicated that the precast connections can provide adequate strength and energy dissipation with respect to monolithic concrete specimens.

Cheok and Lew [9] experimentally investigated the performance of precast concrete beam–column connections subjected to cyclic inelastic loading. The objective of their study was to develop a moment resistant precast connection that is economical and can be easily assembled at site. Similarly, Castro et al. [10] studied the seismic performance of eight two-thirds scale precast beam–column joints and a monolithic specimen with the same beam size. Their results showed that precast connections can sustain large inelastic deformations under cyclic loads, if they are designed properly. Stone et al. [11] developed a new hybrid moment-resisting beam–column connection for precast frames in regions with high seismicity. Their proposed system utilised mild steel bars to improve energy dissipation and post-tensioning clamps to provide adequate shear resistance. The precast

* Corresponding author. Tel.: +44 1142225710; fax: +44 1142225700.
E-mail address: i.hajirasouliha@sheffield.ac.uk (I. Hajirasouliha).

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connections were designed to have the same flexural strength, energy dissipation and drift capacity of typical monolithic connections. In another study, Priestley et al. [12] reported the satisfactory seismic performance of two un-grouted post-tensioned precast concrete beam–column joint subassemblies under cyclic loading.

SCOPE systems are framed structures consisted of precast prestressed concrete components. Cai et al. [13] showed that these structural systems can provide full hysteretic loops and good energy dissipation capacity under low cyclic and reciprocal loading. Khaloo and Parastesh [14,15] developed a moment-resisting precast concrete connection for high seismic zones. Experimental tests on eight beam–column interior connections under inelastic cyclic loading demonstrated the good seismic performance of their proposed moment-resisting connections compared to conventional monolithic connections. In a similar research, Ertas et al. [16] presented the test results of four types of ductile moment-resisting precast concrete frame connections and one monolithic concrete connection, all designed for use in high seismic zones. Based on their results, the hysteresis behaviour of the precast specimens was similar to the monolithic connection, and most of the precast concrete connections reached their designed ultimate moment strength capacity.

Kulkarni et al. [17] proposed a new precast hybrid-steel concrete connection, which showed satisfactory flexural performance under inelastic cyclic loading. Based on the results of their study, the thickness of the connecting plate plays an important role in the energy dissipation and deflection capacity of the connection. Xue and Yang [18] reported the results of their experimental investigations on four full-scale precast concrete beam–column connections including an exterior connection, an interior connection, a T connection, and a knee connection. In a recent study, Vidjeapriya and Jaya [19] experimentally investigated the hysteresis behaviour, load carrying capacity, energy dissipation capacity and ductility of two types of precast beam–column connections using J-Bolts and cleat angles. It was concluded that beam–column connection using J-Bolt can provide higher ductility (and energy dissipation) compared to similar monolithic specimens, whereas cleat angle connections are less ductile.

Different types of open and closed stirrups (such as multi-leg, U-shape and spliced) can be used as shear reinforcement in RC beams [20]. Varney et al. [21] investigated the effects of stirrup anchorage on the shear strength of RC beams. The results of their study indicate that the reinforcement anchorage does not have a significant effect on the shear capacity of RC beams. However, several studies showed that the shear behaviour and cracking strength of RC beams can be considerably improved by using closed-stirrups and/or decreasing the stirrup spacing [22,23]. Most of the previous studies concluded that the precast beam–column connections can be detailed as strong as conventional monolithic connections. However, the need for welding, bolting or extensive cast-in-place concrete work for installation of most of the existing prefabricated concrete connections can considerably increase the construction costs and installation time. Moreover, moment-resisting connections in the seismic regions should have adequate ductility to dissipate large amounts of energy and prevent failure under strong earthquakes. In this study, a new ductile moment-resisting connection is developed for precast concrete frames in seismically active regions. The main advantages of the proposed connections compared to the conventional precast connections are speed of construction, lower cost, and reduced need for skilled labour, which are achieved by minimizing cast-in-place concrete volume and eliminating the need for formworks, welding, bolting and prestressing. The proposed detailing can also enhance the flexural strength, ductility and energy dissipation capacity of the connections and provide better structural integrity between beam, column and slab elements. The efficiency of the proposed system is investigated by comparison between the performance of eight full-scale precast and monolithic connections (interior and exterior) under inelastic cyclic loading.

2. Developed moment-resisting connection

Fig. 1 illustrates details of the developed interior and exterior moment-resisting connections for precast concrete frames. In the proposed system, prefabricated concrete columns are cast continuously in the elevation with a free space in the connection zone to connect beam elements. Four diagonal bars are used in the empty zone of the precast columns (i.e. beam–column joint core) to provide adequate strength and stability during the installation process (see Fig. 1). The diagonal bars behave like truss elements and can considerably increase the axial strength of the columns under construction/transportation loads. The shear links used in the connection core (shown in Fig. 2) can prevent the buckling of the longitudinal and diagonal bars under the self-weight of the precast columns. However, for the safe transportation and handling of full scale 12 m columns, temporary supports (e.g. by using steel profiles) may be required.

In the connection zone, the precast concrete beams have a hollow U shape cross section. A longitudinal bar is used in the precast concrete U section to support diagonal stirrup bars (see Fig. 1), which can also provide adequate tensile strength to resist installation loads. The surface of precast members at the U section zone was smooth, and no slippage was observed between the precast members and the grout during the experimental tests. The length of the connection zone (i.e. plastic hinge zone) of the precast beams was calculated to be 600 mm (hollow U shape section in Fig. 1).

After fixing the longitudinal reinforcement bars, the connection zone is filled with cast-in-place concrete to provide a good structural integrity between beam, column and slab elements. The bottom longitudinal reinforcement bars are spliced in the cast-in-place area of the beam. The top reinforcement bars are continuous through the beam–column joint (as shown in Fig. 2) and are fixed to the precast beams outside the connection zone with a layer of grout. Diagonal stirrup bars and U-shaped anchorages are used to provide enough shear strength before using cast-in-place concrete. The connection region is then grouted to form a moment-resisting beam–column connection. No diagonal bracing bar is used in the joint core of the monolithic specimens.

The proposed precast connection can be easily assembled as it eliminates the need for welding or using mechanical splices for beam longitudinal reinforcement at joints. Temporary supports for beams are provided by means of steel angles on each side of the columns (see Fig. 1). The steel angles provide enough bearing area for sitting the RC beams and transferring the construction loads before in situ concrete becomes structural. Therefore, in the proposed system, there is no need for using formwork and temporary vertical supports for beam and slab elements. This can lead to a low-cost fast-construction system for multi-storey buildings, where multiple stories can be constructed at once.

3. Experimental program

3.1. Design basis

All tested specimens were designed to accommodate loads of a four storey building shown in Fig. 3. Connections were designed for lateral loads in both transverse and longitudinal directions. The prototype building has plan dimensions of 37.2 × 18.6 m, column spacing of 4.65 m, and storey height of 3.2 m as shown in Fig. 3.

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