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Seismic retrofit of external concrete beam-column joints reinforced by plain bars using steel angles prestressed by cross ties

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ABSTRACT

A method for seismic retrofit of beam-column joints, designed without seismic considerations and reinforced by plain bars, is examined. The method, already applied to connections reinforced by deformed bars, has been modified for joints with plain bars. Retrofit of these relatively old connections needs special attention due to the weak steel–concrete bond, let alone the lack of seismic consideration in design. In this method, steel angles are placed on the faces of beam-column intersections and are externally fixed by prestressed cross-ties. Five half-scale specimens were tested under cyclic load: two control specimens under two levels of axial load, and three retrofitted specimens with varying dimensions of angles, different number and prestressing rate of cross ties, with and without stiffener plates in the angles. The tests show significant improvement of the retrofitted specimens in terms of protecting the joint region against large deformation, showing more ductile response and higher hysteresis energy capacity, as well as moderate strength improvement. The tests show that the specimen with the minimum level of retrofit, which had the smallest angle, minimum number of cross ties, and lowest rate of prestressing, with no stiffeners, has performed well. Accordingly, the corresponding retrofit measures may be recommended for similar cases.

1. Introduction

Most of Reinforced Concrete (RC) structures, including bridges in late 60s and early 70s were constructed without any seismic consideration, and reinforced with plain bars. It is widely known that seismic capacity and retrofit measures of non-seismically detailed RC buildings constitute major concerns in earthquake prone regions. The structural systems and sub-systems of old buildings have suffered severe damages under moderate to great earthquakes in different countries [1–6]. Among different elements, the beam-column joints have been highly susceptible to seismic excitations and the failure of joint panel has been frequently observed [1–7]. Performance of these connections are also negatively affected by the quality of the bond between concrete and plain bars. Mo and Chan have shown experimentally that the bond strength of plain rebars was only 28.6% that of deformed rebars; the slip at failure was greater for the plain rebars than for the deformed rebars [8]; and increasing the concrete compressive strength was able to improve the bond properties [8,9]. In another experimental study on bond behavior between plain reinforcing bars and concrete, Xing et al. concluded that the bond stress experienced by plain bars is quite lower than that of the deformed bars given equal structural characteristics and details. In average, plain bars appeared to develop only 18.3% of the bond stress of deformed bars [10].

In this study, the behavior of non-seismically detailed external beam–column joints of existing concrete structures reinforced by plain bars is examined. In addition, a retrofit method of the joint using steel angles pre-stressed by cross-ties is tested. The method has several advantages such as lack of damage to the structural elements, effective improvement of both strength and displacement capacities of the joint, and protection of the joint panel against large deformation by relocating the damaged zone of the beam far away from the face of the joint.

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2. Literature review

Experimental studies of concrete structures reinforced by deformed bars have shown that the failure of the joint panels is governed either by shear or by deterioration of bond between steel and concrete. The stress distribution due to flexural and shear forces produce diagonal crack pattern in the panel which leads to crush of the compressive strut, and consequently, to deterioration of strength and stiffness of the joint. [11–13] The bond between concrete and steel also diminishes under cyclic action of the joint, and this in turn, yields to reduce flexural strength and ductility of the framing elements [11,12], and an increase in the story drift [13].

In concrete structures reinforced by plain bars the behavior of joints is different from those reinforced by deformed bars. That is, the mode of sliding of steel bars commonly governs failure of the joint and diagonal shear failure is less influential [e.g., 14]. Different experimental studies [e.g., 15–17] on joints reinforced by plain bars have shown that low shear capacity of panel zone prevents formation of flexural plastic hinge in beams. In addition, early sliding of plain bars, especially in beams, prevents a beam to reach its ideal flexural capacity, and this prevents shear cracking to form in the joint. Also it can be found similarities between lateral behavior of substructures reinforced by plain bars and precast, prestressed substructures [18,19].

Different methods to retrofit structural elements including beam-column joints have been proposed in the literature such as using the near surface mounted (NSM) technique, wrapping the joint by fiber reinforced polymer (FRP) sheets, enlargement of the beam-column joint, and strengthening the joint by steel sheets [20–45] A number of recent investigations in this area is reviewed subsequently.

Park and Liu [21–23] tested four exterior beam-column joints reinforced by plain round bars subjected to simulated seismic loading. The column regions adjacent to the joint core were jacketed with fiber glass. The study shows that the retrofit technique much improves stiffness and strength of the units. In a research by Idris Bedirhanoglu et al. [24], two series of exterior beam-column joints were load tested. In this study, the hooks of top longitudinal bars of the beams were welded to the hooks of bottom bars in the joint region. The welded specimens show more brittle behavior and rapid decrease of load carrying capacity. In a study by Rusu and Pauleta [25], the longitudinal bars of the beam were anchored to steel plates placed on the exterior column surface. As a result, the strength of the beam-column joint increased and yielding of the beam bars produced more dissipation of energy.

In another retrofit scheme presented by Pampanin and Chiristopolos [26,27], panel zone of the joints was protected by migrating the plastic hinge some distance away from the face of the column and by redirecting the beam shear forces to the column through axial straining of the haunch. The method causes a decrease of the maximum drift in the structure. This idea had already been used for steel structures, after 1994 Northridge earthquake by Yu, Uang [46,47].

Shafaei et al. [30,31] suggested a retrofit method for concrete joint reinforced by deformed bars. In this method, the connection area was strengthened by steel angles prestressed by cross ties where stiffeners were welded to the angles (Fig. 1). The proposed method shows significant enhancement of the seismic capacity of the joints, in terms of strength, stiffness, energy dissipation and ductility. Also the technique improved the bond between longitudinal reinforcement and concrete in the joint.

In the study reported in this paper, the technique proposed by Shafaei et al. [30,31] is extended for joints reinforced by plain bars. The technique has some important advantages such as efficient enhancement of seismic capacity, relatively low cost, and lack of damage to the joint. The technique is based on prevention or delay of sliding of the smooth bars, as the governing mode of failure, and relocation of the large deformation zone to a distance away from the joint region. In terms of load transfer, the use of angles prestressed by cross-ties leads to two-dimensional enlargement of the external beam–column joints (Fig. 1). The steel angles are placed both above and below the corners of the joint and linked to a steel plate at the back of the joint.

3. Experimental program

The external beam–column joints are considered to be isolated from an existing three-story residential RC building built prior to the 1970s [48–53] and having an inter-story height of 2.8 m and a beam effective span of 5.5 m. External beam–column joints are selected because they are more vulnerable than internal joints, and also the proposed retrofit method can be easily adapted to internal joints.

The experimental program consists of reverse-cyclic quasi-static unidirectional loading of five half scale external RC beam–column joints. Two units are tested as-built to serve as control beam–column joints, and three units are retrofitted prior to testing using the proposed method. The nomenclature used for various specimens is presented in Table 1.

3.1. Material properties

All test specimens were constructed using normal weight and ready mixed concrete. Table 2 shows the concrete strength on the day of testing for the five specimens. Mechanical properties of the steel reinforcement used in the specimens are shown in Table 3.

3.2. Test specimens

A total of five specimens were tested. SC1 and SC2 were control specimens, and SR1, SR2, and SR3 were retrofitted specimens. Specimens SC1 and SC2 underwent axial loads to the respected columns as much as 7% and 15% of the section capacity ($A_g f'_c$) respectively (Fig. 2). The main defects of the non-seismic beam–column joints include use of plain bar, absence of transverse steel hoops, and the anchorage condition of longitudinal reinforcements. The anchorage length of the beam bars is almost equal to the joint effective width with 180-degree hooks at the ends of the bars. The cross section dimensions of column and beam are 250 × 250 mm and 200 × 300 mm, respectively. The column is reinforced by 4Φ14 plain bars, 1% reinforcement ratio, and the transverse reinforcement is Φ6.5 plain bars with 135° end hooks that are spaced at 160 mm outside the joint panel zone only. The details of the control specimens are shown in Fig. 2.

3.3. Retrofitted specimens

Both of specimens SR1 and SR2 were retrofitted by a steel angle of 150 mm × 150 mm × 10 mm and a steel plate of 610 mm × 330 mm × 10 mm. Specimen SR1 was strengthened by five stiffener plates welded to the angles as shown in Fig. 3. The crossing bolts in this specimens were prestressed by approximately 70% of f_y. Specimen SR2 was not strengthened by stiffeners and the crossing bolts were prestressed by approximately 50% of f_y. (Fig. 3) The cross bolts were high tensile strength M16 bars, used by washers and nuts. The length and specified ultimate tensile strength of the prestressed bars were 400 mm and 1000 MPa respectively. Tightening was achieved using a calibrated wrench