Engineering Structures 107 (2016) 9–22

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Strengthening of substandard reinforced concrete beam-column joints by external post-tension rods

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ARTICLE INFO

Article history:
Received 22 February 2015
Revised 30 October 2015
Accepted 2 November 2015
Available online 17 November 2015

Keywords:
Post-tension
Beam-column joint
Retrofit
Low strength concrete
Plain bar
Shear failure
Cyclic loading

ABSTRACT

The efficiency of the proposed strengthening method using externally applied post-tension rods in reinforced concrete external beam-column joints, which do not comply with any code requirements, is investigated. Five full-scale specimens were tested in the laboratory. They have specific deficiencies resulting from the lack of shear reinforcement in the joint and poor material properties including low strength concrete and the presence of plain round reinforcement bars. While all specimens were built with column and in plane beam, one of the tested specimens consists of a transverse beam to demonstrate the applicability of the presented retrofit technique. All specimens were subjected to a cyclic quasi-static loading up to 8% drift ratio to observe different levels of structural damage. Two post-tension rods, which were mounted diagonally at each side of the joint, are utilized as a local retrofit technique. The reference specimen displayed a brittle behavior with the concentration of shear cracks mostly in the joint while the rest of the RC components were almost in their elastic range. The ultimate lateral load capacity was increased considerably for all retrofitted specimens. However, a brittle type of failure mechanism was observed such as a joint shear failure or beam-joint failure in the three retrofitted specimens. A relatively ductile response was observed in the specimen with transverse beam, although the axial force in the post-tension rods was the same with the specimens without transverse beam. After testing all specimens, it is found that the lateral force capacities of the beam-column assemblies can be improved up to code requirements by the proposed retrofitting method.

1. Introduction

Field reconnaissance after damaging earthquakes in Turkey (Marmara 1999, Bingöl 2003, Van 2011) identified insufficient seismic performance in the reinforced concrete (RC) structures built with low strength concrete, inadequate or no transverse reinforcement in the beam-column joints, plain round bars and improper reinforcement bar detailing [1]. As a result of poor seismic performance of the RC frames, a devastating brittle failure can occur in the members. These local failures can thus actuate the global failure mechanism, which brought the requirement to the seismic upgrading of the deficient structures. The existing retrofit techniques can be classified into two main approaches namely, "Local retrofit techniques" and "Global retrofit techniques". While the global retrofit technique is used to reduce the seismic demand of the buildings by adding extra load resisting elements such as base isolation, addition steel brace and shear wall, the individual elements of the deficient structure are upgraded in the local retrofit technique [2,3]. The global retrofit technique is generally more efficient compared to the local retrofit technique since the overall capacity of the building is enhanced. However, cost efficiency and the feasibility of the retrofit strategy should be taken into account. Therefore, the local retrofit technique can be used for certain cases [3]. The beam-column joint region deserves special interest in the buildings with indicated deficiencies because it can be the critical and possibly the weakest link according to the capacity design principles or hierarchy of strength considerations [4]. Therefore, developing a feasible local retrofit strategy became more of an issue so as to eliminate the brittle type of joint failure.

Most of the existing studies on the behavior of the beam-column joints have mostly focused on well-detailed assemblies [5–10]. There exists limited number of contributions on the joints that were constructed according to pre-1970s construction practice [11–13]. However, the tested specimens in these studies still did not fully represent the deficient RC buildings in Turkey even though they did not comply with former building standards.

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http://dx.doi.org/10.1016/j.engstruct.2015.11.004
0141-0296/

Nomenclature

f_c	cylindrical concrete compressive at experiment date
A_c	gross cross-sectional area of column, beam and joint
P	axial force in the one post-tension rod
V_j	joint shear force corresponds the concrete tensile strength
V_{jmax}	joint shear force corresponds the beam plastic flexure capacity
V_{max}	maximum lateral load that observed during experiment
Δu	ultimate displacement that corresponds 20% reduction of the maximum lateral load
Δu^*	ultimate drift ratio that corresponds 20% reduction of the maximum lateral load
V_y	yield load of specimens
Δy	yield displacement of specimens
Δy^*	yield drift ratio of specimens
μ	ductility
K	initial stiffness
K^p	peak to peak stiffness
E	dissipated energy
ε	joint strain in the horizontal direction
σ_t	experimental value of principal tensile strength in joint
σ_c	experimental value of principal compression strength in joint
τ_j	experimental joint shear stress
σ_1	predicted principal tensile strength in joint which is $0.5\sqrt{f_c}$
σ_x	normal stress in the beam which is 0
σ_y	normal stress in the column which is 0.1 $f_c A_c$
σ_t	experimental value of principal tensile strength in joint
σ_c	experimental value of principal compression strength in joint
τ_{xy}	predicted shear stress in the joint
V_{jh}	estimated joint shear force
V_t	contribution of axial force in the rods to total theoretical shear capacity of the joint

Nevertheless, Bedirhanoglu et al. [14] and Coskun et al. [15] studied on the existing deficient joints in Turkey that were built with smooth bars, low strength concrete and no shear reinforcement in the joint. They emphasized to take necessary precautions for the buildings with the previously indicated deficiencies. Several attempts have been made to retrofit the joints through conventional materials. Karayannis et al. [16] studied on the rehabilitation of joints by using epoxy resin injections. Alcocer and Jirsa [17], Biddah et al. [18] and Tsonos [19] conducted studies on the seismic upgrading by jacketing. Pimanmas and Chaimahawan [20] and Chaimahawan and Pimanmas [21] focused on the joint enlargement by using an additional reinforcement material in the joint. Furthermore, Sharbatdar et al. [22] and Said and Nehdi [23] employed a retrofit strategy by using local steel braces. However, due to emerging technologies on the construction materials, the more recent studies have mostly focused on the strengthening of non-seismically designed joints by using fiber-reinforced polymers (FRP) [24–33]. In addition, some contributions presented retrofit strategies through conventional construction materials. Shafaei et al. [34] studied on the joint enlargement by using pre-stressed steel angles. The presented retrofit method in this study relocated the plastic hinges away from the joint panel by enlarging the joint with pre-stressed steel angles. Kam and Pampanin [35] proposed the local retrofit technique called as selective weakening. In this method, the joint and the beam were retrofitted by post-tension wires. However, the beam flexure capacity can be increased by additional axial force provided by post-tension. Then, other members can fail before plastic hinge takes a place in the beam for certain cases. Hence, the beam flexure capacity is weakened by severing beam longitudinal reinforcements.

In conclusions, issues of cost, difficulties in the application and the development of additional stresses in the rest of the members are still among the limitations of each strengthening technique. Therefore, retrofit of deficient joints still remains one of the most challenging and current task of today.

In this paper, an efficient and practical strengthening solution was conceptually proposed through retrofit of the substandard RC beam-column joints with externally applied post-tension rods. For this purpose, five full-scale test specimens were constructed with low strength concrete, plain round bars and no transverse reinforcement bars in the joint region. Before the application of the retrofit technique, beam hooks were welded to prevent the excessive bar slip deformations as suggested by Ilki et al. [25] for improving the effectiveness of the retrofitting. It should be noted that the proposed method is effective provided that the bond slip failure of the specimens is prevented. Then, effectiveness of the proposed retrofit method in terms of response quantities was investigated in detail.

Various kinds of post-tension applications exist in the literature. Therefore, the application of post-tensioning in new constructions or strengthening of deficient members is considered a conventional method. The application of post-tension rods diagonally for retrofitting substandard beam-column joints can be considered to be a different variation of existing strengthening technique with post-tensioning. The presented method in this study involves implementation of post-tension rods. The rods were mounted diagonally and relied on built-up steel angles in the joint panel. The seismic forces were thus compensated inside the joint panel by the rods. This technique is considered to be effective as no additional force is developed in the rest of the members. In addition, the strength, stiffness and dissipated energy of the beam-column assembly were considerably enhanced. Furthermore, a cost effective and practical solution was presented due to the utilization of the conventional structural materials.

The proposed seismic upgrading technique can be implemented in case of exterior, interior assembles with floor slab and transverse beams. Therefore, it can be a viable solution for on-site construction operations. In order to demonstrate the application of the presented retrofit technique for such structures, one of the tested specimens was constructed with the beam in the transverse direction. The effect of transverse beam to the response was also investigated.

Finally, analytical studies were performed by an algorithm based on truss analogy. The present finding proved that the experiment results and the theoretical calculations matched closely.

2. Experimental program

2.1. Test specimens and materials

Experimental program consists of five full-scale test specimens. T-shaped specimens were taken from the theoretical infection point of the RC frame where the moments are zero under lateral load. The specimens represented most of the deficient RC buildings in Turkey. Any of the specimens did not comply with the design principles of both current and former earthquake codes. The column dimension was 250 × 500 × 3000 mm in all tested