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Exploratory study of adopting longitudinal column reinforcement details as a design-controllable tool to seismic behavior of exterior RC beam-column joints

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ABSTRACT

This study presents the test results of seven exterior beam-column joints with different longitudinal reinforcement details for the columns. The test program included a beam-column joint designed to serve as a control specimen, in which column reinforcement was continuous ribbed steel bars. The other six specimens were divided into two groups, three specimens for each group. In the first group, the longitudinal column reinforcement was detailed with well-confined lap-splice longitudinal bars: two specimens were reinforced with lap-splice deformed steel bars and the later was with lap-splice plain steel bars. The same reinforcement details were used for the second group but additional longitudinal basalt fiber reinforced polymer (BFRP) rebars were placed at the joint and extended to the upper and lower columns. The test results showed that splicing the longitudinal column reinforcement successfully reduced the contribution of the joint to the deformability of the beam-column joint. Furthermore, adding BFRP rebars to the beam-column joint could be applied as damage controllable bars reducing both the damage level at the serviceability state and the shear deformability of the joint up to failure. A sole strut resistant mechanism was realized by the joints of all test specimens detailed with lap-spliced longitudinal column reinforcement. Ultimately, the test results point to a probability to the renunciation of the ACI 318-11 requirements for splicing longitudinal column reinforcement at column mid-height.

1. Introduction

Several examinations have been carried out on reinforced concrete (RC) structures constructed before 1970s and experienced different damage levels due to moderate-to-massive earthquakes. Generally, the main conclusion is that beam-column joints are considered to be the most vulnerable zones. Hence, a lot of static tests and some pseudo-dynamic tests have been conducted on RC beam-column sub-assemblages designed for gravity loads [1–9, among others], which finally produced design codes for earthquake-resistant structures.

On joints designed according to the current seismic-design codes, the interest of several investigations has been to confirm the role of different reinforcement details and to evaluate the impact of influential design parameters on the behavior and failure mechanism. Kitayama and Aoyama [10] tested varying reinforcement detailing and amount in the joints of three specimens. Joint lateral reinforcement ratios were 0.35% in two specimens and 0.88% in the third one. In the three specimens, they observed that the joint shear deformation represented approximately 40% of the total story drift. At a high imposed drift of 1/25 rad, damage of the sub-assemblages concentrated in the joint panel due to high shear. Tsonos [11] examined the cyclic response of four sub-assemblages incorporating full seismic details according to different seismic-design codes. It is demonstrated that some of the available seismic-design codes [12–16] should be revised to avoid premature joint shear failures. That is, the behavior of seismically designed sub-assemblages point to that it is still essential to limit the joint shear deformation and prevent its failure to ensure a much better performance for modern constructions. Experimental test results of RC beam-column joints designed according to modern codes by [17,18] confirmed also this conclusion, where a considerable increase in the contribution of the joint shear deformation to the deformability of beam-column sub-assemblages with the increase in the applied loads was measured. Furthermore, Masi et al. [8,9] studied the effects of several structural parameters including the axial load ratio on the performance of seismically designed exterior beam-column joints, and they observed a mixed beam failure and joint failure with a significant reduction in the global deformability capacity of the sub-assemblage with low axial load ratio.

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In order to prevent this failure mode, it is recommended to use heavy joint shear reinforcement, which could be associated with congestion of the joint reinforcement. Otherwise, the joint shear stresses have to be more conservative than the limits of the code recommendations to avoid the usage of a large amount of joint transverse reinforcement. Here, the authors scrutinized the available experimental results of different sub-assemblages that did not experience joint failure, which could be a reasonable guide to find out a sensible way to control the joint deformability. For example, it was realized from the study of Fernandes et al. [1] that using plain bars caused a considerable reduction in the contribution of the joint shear deformation to the sub-assemblage deformability. This was also observed from the cracking pattern for the specimen with plain bars, in which the developed cracks were concentrated at the interfaces of the joint to the adjoining elements without a considerable damage in the joint zone. Melo et al. [2] conducted an experimental study on five exterior full-scale beam-column joints with different reinforcement details using plain bars, and they stated that that no shear cracks was seen on the core of the joint of the specimens with lap-splice reinforcement. Hence, it seems that texture and lap-splice details of the reinforcement of a beam-column assemblage could play a rule in controlling the joint deformability.

Lap-splicing of the longitudinal column reinforcement is a practical requirement, and it is commonly preferable to be located just above the floor level. Although the current design codes adopt the design philosophy of strong column-weak beams, splicing of the longitudinal column reinforcement is only acceptable at the column mid-height. In fact, splicing of the longitudinal column reinforcement would be associated with a slippage, which could cause a significant impact on both the induced tensile stresses in the spliced bars in a high stress region and the deformability components of the beam-column joint. That is, lap-splicing of the column steel bars could affect the underlying mechanism of the joint resistance to the action of the forces transferred to it by the adjacent elements. Therefore, this study aims to explore the feasibility of employing column reinforcement details as a mean to control the seismic behavior of exterior beam-column joints, which in turn could be applied to control the global seismic performance of RC structures. An experimental program studying the effect of well-confined lap-splice columns on the behavior of exterior beam–column joints under seismic actions was conducted. The program included seven 2/3 scale exterior reinforced beam-column joints tested under the effect of low fatigue cycle loading. One specimen served as a reference, in which the column main reinforcement was continuous deformed steel bars. The columns of the other six specimens were reinforced with lap-spliced steel bars just above the joint. The examined parameters were the texture of the steel bars (plain and deformed bars), lap-splice lengths (15*d* and 20*d*, where *d* is the diameter of a steel bar), and the existence of additional fiber reinforced polymer (FRP) rebars passed through the joint and extended to the upper and lower columns.

2. Experimental program

2.1. Material properties

Table 1 summarizes the concrete compressive strengths of the examined specimens as the average results of three cubes at the testing day. High tensile steel-deformed bars of 10 and 12 mm diameter and mild steel plain bars of 12 mm diameter were used as main longitudinal reinforcement for the test specimens. In addition, 6 mm diameter plain steel bars were used as a transverse reinforcement for all components of the beam-column sub-assemblage. Table 1 summarizes test results of steel bars used. In addition, the tensile strength and the elastic modulus of basalt FRP rebars according to the manufacturer are listed in Table 1.

2.2. Test specimens

The specimens considered in the experimental program represent 2/3 scale models of an exterior beam-column joint extending between the inflection points of a ductile intermediate moment resisting frame subjected to seismic action. The specimen size was selected to represent fully the complexities and behavior of the real materials and of the load transfer mechanisms. All beam-column joints had identical concrete dimensions and beam reinforcement details. Beam dimensions were 200 mm width, 400 mm depth, and 1500 mm length from the loading point to the column centerline, and it was reinforced with six longitudinal steel bars of 10 mm diameter, which was over the minimum reinforcement ratio required by (ACI 318-11) [19], and with stirrups of 6 mm diameter spaced at 80 mm. Column cross-section was 200 mm width and 300 mm depth, and it was reinforced with six longitudinal steel bars of 12 mm diameter (reinforcement ratio 1.1%) and with transverse reinforcement of 6 mm diameter spaced at 80 mm. According to the concrete dimensions, the reinforcement details shown in Fig. 1, and the material properties listed in Table 1, the nominal beam flexural strength is 49.3 kN m, which corresponds to a beam shear of 32.8 kN over the 1500-mm length. The shear strength of the beams of the tested specimens is 87.37 kN. In other words, the hinging region was designed to maintain the shear capacity while the plastic hinge undergoes flexural yielding in both the positive and negative bending. On the other hand, the column nominal shear strength is 102.7 kN and the flexural strength is dependent on the column reinforcement details and it is calculated to be 62.8 kN m up to 77.7 kN m for the different studied cases. That is, the column to beam flexural strength ratio satisfied the design philosophy of strong column-weak beam $((\Sigma M_c/\Sigma M_b) \geq 1.2)$. Steel stirrup of 6 mm diameter was used as a joint transverse reinforcement and spaced at 50 mm. It is worth mentioning that this amount represents 49% of that required by ACI 318-11 [19] for special resisting moment frame. The reduction is based on the recommendation of [20] to avoid congestion steel reinforcement within the joint region because additional transverse reinforcements may have less effect on the enhancement of the joint shear strength.

According to the current seismic-design codes, lap splices for the column main reinforcement shall be permitted only within the center half of the column height. On the practical side, this type of reinforcement details is directly applied above the floor to ease the construction process. In a recent study by Elsouri and Harajli [21] on the behavior of interior RC wide beam-narrow column joints, they pointed to a probable renunciation of the ACI requirements for splicing column reinforcement at column mid-height because the recorded strain measurements of the lap-spliced steel bars were less than the steel yielding strain and they did not observe bond failure between the spliced bars

Table 1
Mechanical properties of the materials used.

Material		Characteristics	Characteristic values
Steel bar	6 mm diameter (smooth)	Yield strength (MPa)	335.1
		Ultimate strength (MPa)	531.1
	10 mm diameter	Yield strength (MPa)	578.1
		Ultimate strength (MPa)	678.3
	12 mm diameter	Yield strength (MPa)	509.0
		Ultimate strength (MPa)	644.9
	12 mm diameter (smooth)	Yield strength (MPa)	354.1
		Ultimate strength (MPa)	502.7
Concrete	R-CO	Cube compressive strength (MPa)	39.6
	R-SP15		39.6
	R-SP20		39.2
	S-SP15		39.6
	R-SP15-FRP		32.5
	R-SP20-FRP		32.5
	S-SP15-FRP		32.5
BFRP rebars of 6 mm nominal diameter		Tensile strength (MPa)	2068
		Modulus of elasticity (GPa)	124