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Shear strength of beam–column joint with enlarged joint area

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ABSTRACT

This paper presents planar joint enlargement for increasing the shear strength of sub-standard beam–column joint. Five beam–column specimens were tested under quasi-static cyclic loads. Two control specimens were tested. One was the beam–column joint without joint enlargement and the other was the beam–column joint strengthened by monolithically cast square enlargement. The other three specimens were strengthened by joint enlargements with various sizes. Test results indicated a brittle joint shear failure in the first control specimen and a beam flexural failure in the second control specimen. Depending on the size of enlargement, the failure types of strengthened specimens ranged from flexural failure in the beam to crushing failure in joint panel and enlarged areas. The joint enlargement can increase the strength, stiffness and energy dissipation. The experimental results indicated the decrease in joint shear stress in strengthened specimens. However, the distribution of horizontal shear stress is not uniform, with larger value in the joint panel than in the beam sections within the enlarged areas. Finite element analysis has been conducted to examine the flow of stresses in the joint and enlarged areas. The finite element analysis illustrates the principal diagonal strut in the joint panel and additional struts along the edge of enlargements and in beam sections within the enlargement zone. Based on principal stress pattern obtained from finite element analysis, strut-and-tie model is constructed to analyze the strengthened specimens. The proposed strut-and-tie model can predict the failure mode, column shear force and tension forces in longitudinal steel bars and dowels. It can also predict the distribution of horizontal shear stress in the joint panel and beam sections within the enlarged areas.

1. Introduction

Several earthquakes have demonstrated many collapses of buildings due to the brittle failure of sub-standard beam–column joint. There are plenty of researches on experimental investigation of RC beam–column joints [1–3]. The failure of beam–column joint can be very disastrous and the need to retrofit existing beam–column joints to resist earthquake excitation is therefore a critical consideration.

Several methods for retrofitting beam–column joints have been proposed in the past [4–6]. Concrete jacketing is one of the common techniques [7]. However, this method produces protruding parts of the concrete jacketing, which reduces usable floor space and may make it architecturally unacceptable in many cases. Other researchers [8,9] have attempted to strengthen beam–column joints by steel plates, angles and rods. However, there is a problem of corrosion and the need to fireproof the added steel elements.

The use of fiber-reinforced polymer (FRP) materials has been investigated by several researchers [10–14]. FRP composites have the advantages of fast and easy application, high strength to weight ratio and corrosion resistance. Externally bonded glass or carbon composite materials (GFRP or CFRP) have been attached onto the faces of the joint with epoxy resin. Significant improvements in joint strength and ductility have been achieved.

The authors presented the joint strengthening method using joint enlargement technique [15]. The existing joint in the frame is enlarged by cast in situ concrete to increase the joint size. The enlargement is performed two-dimensionally so that it can be hidden in partitions in either transverse or longitudinal directions or both (Fig. 1). This method is cost-effective because it uses conventional materials such as concrete and steel bars. Furthermore, unlike concrete jacketing, the perforation in slab is not required in this method. Experimental works [15] confirmed the feasibility of this method to upgrade the joint shear strength. However, it should be cautioned that the joint enlargement may shorten the length of beams and columns, making them prone to shear failure. It is therefore recommended to check the adequacy of shear capacity of shortened members after strengthening.

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Nomenclature

V_j	horizontal joint shear force
T_1, T_2	tension force and tension force on opposite face
V_c	column shear force
V_n	joint shear capacity
k	1.7, 1.25 and 1.0 for joints confined on all four faces, three faces or two opposite faces and others, respectively
f'_c	cylindrical compressive strength of concrete
A_j	effective joint area
V_{jT}	total horizontal shear force
C_2	compression force in concrete and compression steel
V_{jp}	horizontal shear force carried by the joint panel
V_{js}	horizontal shear force carried by the beam sections within the enlargements
V_{js1}, V_{js2}	horizontal shear force carried by the beam sections in the left and right parts of the enlargements, respectively
T'_1, T'_2	forces in tensile reinforcements at column faces
T_{p1}, T_{p2}	forces in dowel bars of joint enlargement
D_1	compression strut in the joint panel
D_2, D_3	compression strut in beam sections within the joint enlargement
D_4, D_5	compression strut in planar joint enlargement
a_b	depth of longitudinal compressive strut in beam
a_c	depth of longitudinal compressive strut in column
d_{bs}	depth of diagonal strut in beam
d_{cs}	depth of diagonal strut in column
d_j	depth of diagonal strut in joint panel
d_p	depth of diagonal strut in joint enlargement
f_{cu}	compressive stress limitation in strut
$V_{jp,stm}$	horizontal shear force carried by joint panel predicted by strut-and-tie model
α_1	the angle between joint panel strut and horizontal axis
α_2, α_3	the angle between struts in beams and horizontal axis
b_b	beam width
b_c	column width
b_j	width of effective joint area
b_p	width of joint enlargement
f_y	yield strength of steel
h_c	column depth
h_h	dimension of joint enlargement along beam
h_v	dimension of joint enlargement along column

In this paper, the study of shear resistant mechanism in the joint panel and joint enlargement is presented. Two additional specimens have been included for this purpose. The function of the enlargement to resist the load has been identified. Strut-and-tie model is also introduced to simulate the load bearing mechanism. The adoption of strut-and-tie model can serve as a tool to investigate the shear resisting behavior and can possibly serve as a design tool.

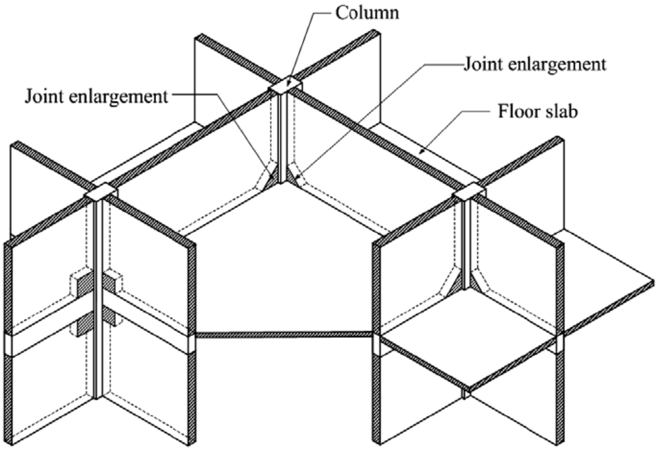

Fig. 1. Beam–column joint strengthened by planar joint enlargement.

2. Concept of horizontal joint shear force

Joint shear failure has been widely reported as one of the common failure types of beam–column joint [16–18]. Regarding the joint shear design, the ACI code [19] adopts the horizontal joint shear concept in which the joint is assumed to be subject to horizontal shear force (V_j) at the mid-plane (Fig. 2(a)) which can be calculated by

$$V_j = T_1 + T_2 - V_c \tag{1}$$

where T_1 is tension force; T_2 is tension force at the opposite column face; and V_c is the column shear force. The horizontal shear force is largest when beam sections develop moment capacity at column faces, i.e., when tension forces in steel (T_1 and T_2) reach yield strength. If the joint shear force is greater than the joint shear capacity (V_n), joint shear failure occurs. The ACI code [19] provides the following empirical formula for joint shear capacity,

$$V_n = k\sqrt{f'_c}A_j \text{ (N)} \tag{2}$$

where k is 1.7, 1.25 and 1.0 for joints confined on all four faces, three faces or two opposite faces and others, respectively; f'_c is cylindrical compressive strength of concrete (MPa); and A_j is the effective joint area (mm^2). Additionally, in New Zealand code [20], the joint shear stress (calculated as the joint shear force divided by the joint area) is limited to $0.2f'_c$ to avoid crushing of concrete in the joint.

Figs. 3 and 4 show that the joint enlargement can increase the effective joint area. Based on the equilibrium of the upper half of the joint (Fig. 2(b)), the horizontal joint shear force may be calculated by Eq. (1). However, the horizontal shear stress may not be distributed uniformly along the horizontal plane passing the beam sections and joint panel. Thus, the conventional ACI [19] design concept using effective joint area may not be applicable to design the joint enlargement. The distribution of shear stresses depends on the mechanisms by which the joint enlargement and the joint panel resist the force. In this paper, horizontal shear stress is analyzed based on the equilibrium of force transfer in the joint. Finite element analysis is conducted to identify the load resistant mechanism of strengthened specimens. Strut-and-tie model is also developed to serve as a mechanical model to simulate the shear resistant behavior. The next section will briefly introduce an experimental program to report the performance of specimens observed in the test.

3. Experimental program

3.1. Specimens, construction method and materials properties

3.1.1. Control specimen

The experimental program consisted of five interior beam–column specimens, namely, J0, PJE1, PJE2, PJE3 and PJE4. Specimen J0 was an un-strengthened control specimen. Specimen PJE1