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Exterior beam column joints – Shear strength model and design formula

Margherita Pauletta [a,*], Daniele Di Luca [b], Gaetano Russo [b]

[a] Department of Civil Engineering and Architecture, University of Udine, Viale delle Scienze, 206, 33100 Udine, Italy
[b] Department of Civil Engineering and Architecture, University of Udine, Viale delle Scienze, 208, 33100 Udine, Italy

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ABSTRACT

A new model to determine the shear strength of exterior reinforced concrete (RC) beam–column joints under seismic actions is proposed in this paper. An explicit formula that considers the shear strength contributions provided by the strut-and-tie mechanism due to two diagonal concrete struts, as well as the horizontal hoops and the intermediate vertical bars of the column, is derived. The coefficients of each contribution are calibrated using 61 test data sets available in the literature, most of them from cyclic tests. This paper compares the shear strength predictions using the proposed expression, the model of Hwang and Lee, and the model of Park and Mosalam, the last of which is valid for unreinforced joints only. A design formula is also proposed and its predictions are compared to those of Eurocode 8 and ACI Code.

1. Introduction

The key point of the aseismic performance for beam–column joints is to ensure and maintain the energy absorption capacity of plastic hinges of adjoining members, usually the beams, avoiding any shear or anchorage failure in the joint core. By contrast, due to the small value of shear span to depth ratio, the strength of external beam–column joints can be governed by shear rather than flexural strength.

Various codes and authors try to predict the real shear strength of exterior beam–column joints under seismic loads [1–7] following different approaches. However, the obtained predictions are often not accurate, mainly because of the several mechanisms involved in the actual behavior.

This paper proposes a strut-and-tie model for determining shear strength of exterior RC beam–column joints that represents an evolution of the model proposed by Hwang and Lee [1]. A plane frame joint is considered in the following for the sake of simplicity. The proposed model is based on a softening approximate constitutive law for plain concrete and it considers diagonal compressed concrete strut, diagonal compression due to bond resistance of beam longitudinal reinforcement, and resisting contributions of horizontal hoops and intermediate column bars within the joint core. A single analytical expression is proposed to evaluate the tensile stress trend in the longitudinal reinforcing bars of the beam when joint shear failure occurs. This allows one to avoid a solution iterative procedure up to the ultimate load. The coefficients of each contribution are calibrated on the basis of 61 test data sets and results, which have been selected from reports on exterior RC beam–column joints that failed due to shear only mainly under reversed cyclic loads. The data also include 17 beam–column joints without transverse reinforcement.

Uniformity and accuracy of the model predictions are assessed by comparing these predictions with those of the iterative procedure of Hwang and Lee [1] with the 61 experimental results.

The predictions regarding joints without transverse reinforcement are compared with predictions from the simplified strength model proposed by Park and Mosalam [2]. A design formula is also proposed, and its predictions are compared with those obtained through the shear strength design formulas provided by Eurocode 8 [3] and ACI Code 318-11 [4].

2. Research significance

The aim of the present study is to solve the problem of the external RC beam–column joint shear strength prediction by means of a single expression more accurate and consistent (uniform in the prediction) than existing formulas or time-consuming computing procedures. The proposed expression highlights four principal resistant contributions: the first two are based on a mechanism consisting of two inclined concrete struts in the joint, whose contributions are affected by the type of anchorage of the beam longitudinal reinforcing bars into the joint region; the third contribution is due to horizontal stirrups reinforcement; and the

* Corresponding author. Tel.: +39 0432 558065; fax: +39 0432 558052.
E-mail addresses: margherita.pauletta@uniud.it (M. Pauletta), diluca.daniele@spes.uniud.it (D. Di Luca), gaetano.russo@uniud.it (G. Russo).

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last one is provided by the vertical intermediate column bars. A design formula, whose predictions incorporate an adequate margin of safety, is also proposed.

3. Model bases

For the case of a typical exterior RC beam–column joint subjected to seismic load, the shear and compression acting forces are shown in Fig. 1. The horizontal joint shear force in the joint core V_{jh} can be calculated as

$$V_{jh} = T_b - V_{c1} \tag{1}$$

where

$$T_b = A_{sb} \cdot f_b \tag{2}$$

with T_b the tensile force in the beam longitudinal reinforcement, A_{sb} and f_b the area and stress of this reinforcement, respectively, and V_{c1} the column horizontal shear above the joint.

The shear on the beam V_b, the beam flexural moment M_b, and the column shear above the joint (Fig. 2) are calculated as follows

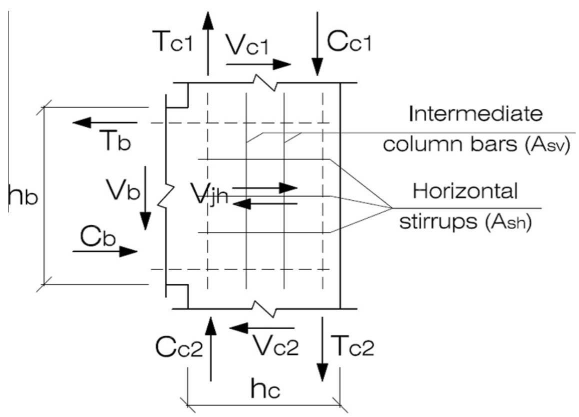

Fig. 1. External actions on the exterior beam–column joint core.

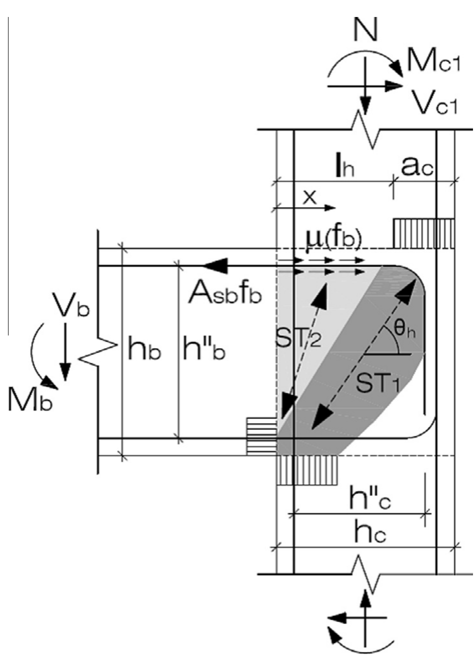

Fig. 2. The two inclined struts in unreinforced exterior joints.

$$V_b = \frac{A_{sb} f_b j_{bd}}{L} \tag{3}$$

$$M_b = V_b \cdot L \tag{4}$$

$$V_{c1} = \frac{L + h_c/2}{H} V_b \tag{5}$$

where L is the length from beam inflection point to column face; h_c is the total height of column cross section; H is the height of the column, equal to the height between upper and lower column inflection points (Fig. 3); and j_{bd} is the internal moment arm of the beam cross section that can be calculated as follows

$$j_{db} = h_b - \frac{x_b}{3} - \delta_{sb} \tag{6}$$

In Eq. (6) h_b is the beam depth, δ_{sb} is the distance from the centroid of the tensile beam reinforcement to the closest edge of the beam cross section, and x_b is the depth of the compression zone in the beam cross section (Fig. 3). After having verified that concrete in compression remains within the elastic range [6], the value of x_b can be obtained by imposing the equilibrium of beam internal forces, which leads to

$$\frac{b_b x_b^2}{2} + (A_{sb} + A'_{sb}) n_{h,b} x_b - (A_{sb} d_b + A'_{sb} \delta'_{sb}) n_{h,b} - A'_{sb} \delta'_{sb} = 0 \tag{7}$$

where b_b is the width of the beam cross section at the face of the column, A'_{sb} is the area of the beam longitudinal compressive reinforcement, d_b is the effective depth of the beam cross section, δ'_{sb} is the distance from the centroid of compressive beam reinforcement to the closest edge of the beam cross section, and $n_{h,b}$ is the modular ratio given by

$$n_{h,b} = \frac{E_{sb}}{E_c} \tag{8}$$

with E_{sb} the steel elastic modulus of the beam reinforcement, whose value, if not provided by the experimental papers, can be assumed equal to 200,000 [MPa] [4]; and E_c the concrete elastic modulus whose value, if not provided, can be assumed equal to $4700(f'_c)^{0,5}$ [MPa] [4].

Substituting Eqs. (3) and (5) into Eq. (1), the horizontal shear force in the joint core can be expressed by

$$V_{jh} = A_{sb} f_b \left[1 - \frac{(L + h_c/2) j_{db}}{H \cdot L}\right] \tag{9}$$

The shear nominal strength of exterior RC beam–column joints V_n is assumed equal to the sum of two independent resisting contributions

$$V_n = V_{hc} + V_{hs} \tag{10}$$

where V_{hc} is the shear strength contribution provided by two diagonal struts, ST1 and ST2 in Fig. 2, and V_{hs} is the shear contribution given by steel horizontal and vertical reinforcements.

It is assumed that failure is governed by the crushing of the diagonal compressive strut ST1 in Fig. 2 stiffened by the steel horizontal and vertical reinforcement (Fig. 1). The formation of the strut is highlighted by the appearance of inclined cracks in the joint.

4. Strut and tie mechanism

Similar to what is reported by Hwang and Lee [1], the proposed strut and tie model is composed of diagonal (V_{hc}), horizontal and vertical mechanisms (V_{hs}).

For joints without horizontal stirrups and intermediate vertical bars in the joint region, the horizontal joint shear force can be assumed to be resisted by the horizontal components of the forces acting in the two inclined struts (Park and Mosalam [1]), which are