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Analytical model for shear strength estimation of reinforced concrete beam-column joints

Leonardo M. Massone*, Gonzalo N. Orrego

Department of Civil Engineering, University of Chile, Blanco Encalada 2002, Santiago, Chile

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ABSTRACT

A model capable of predicting the shear response of beam-column joints subjected to seismic actions is presented. The analytical model, originally developed for walls and based on a simple physical formulation, is adapted. It considers mean stress and strain fields based on a reinforced concrete panel representing the joint, under the assumption that the principal concrete stress and principal strain directions coincide. Simple constitutive material laws are considered for concrete and steel. To estimate the shear capacity, the model satisfies the equilibrium in the longitudinal (vertical) direction. In order to analyze the accuracy of the model, a database integrated by 92 tests of exterior and interior beam-column joints is collected from the literature. Noting that the original model does not consider the effect of confinement product of adjacent elements to the connection, this effect is introduced through factors that reduce the values of the longitudinal and transverse strain used to calibrate the angle of the strut. In addition, the contribution of the transverse reinforcement in the capacity of the element is included. These modifications together with the influence of the boundary reinforcement, yields a good strength estimate for exterior and interior joints that fail in shear. When comparing with other models from the literature, it is observed that the proposed model provides one of the best correlations.

1. Introduction

Beam-column joints are used in frame structures and fulfill the function of delivering continuity to the structure, in addition to transferring shear and moment forces from one structural element to another. For these reasons it is required a correct design of these connections in order to maintain stable structures. Structure collapse can occur when a beam-column joint (reference as joints in the text) fails in shear, which is a brittle failure response (Fig. 1a). Other type of potential failure occurs when one of the elements adjacent to the joint fails before the joint (Fig. 1b).

In frame analysis, most models assume a rigid behavior for beam-column joints, giving only flexibility to column and beam elements. Some previous works have modified the properties of the elements framing into the joint in order to account for the additional joint flexibility (e.g., Hoffmann et al. [1]). Many models have evolved from there incorporating, among others, bond slip observed in the longitudinal reinforcement of beams, confining effect of surrounding elements, and shear response of the joint (e.g., Youssef and Ghobarah [2]); however, for the shear response in some cases only simple models have been included. In order to correctly predict the shear response of the joint, more complete and complex formulations have been included, based on panel response (e.g., modified compression field theory in models such as in Lowes and Altoontash [3] and Pan et al. [4]). Such formulations allow representing the observed failure modes and are intended for nonlinear analysis of elements or entire structures in finite element formulation, rather than shear strength predictions for design.

The current work focuses in the shear strength estimation of beam-column joints for different failure modes. In the literature there are different models to estimate shear response in beam-column joints. Some of them are based on a strut-and-tie model that incorporates forces equilibrium, strain compatibility and the material constitutive laws (e.g., [5,6]). There are also closed-form expressions, some as simple as the one in ACI318-14 [7], semi-empirical expressions such as the model by Kassem [8], and Kim and LaFave [9] that require calibration of parameters and others more elaborated such as the model developed by Wang et al. [10].

Hwang and Lee [5,6] present a strut-and-tie model to predict the shear strength of interior and exterior reinforced concrete joints, which satisfies conditions of equilibrium forces, strain compatibility and constitutive law of cracked concrete. In those works, they propose to model the distribution of stresses of the joint as a statically indeterminate lattice, through three mechanisms: one diagonal, one horizontal and one vertical (Fig. 2). The diagonal mechanism (Fig. 2a)

* Corresponding author.
E-mail address: lmassone@ing.uchile.cl (L.M. Massone).

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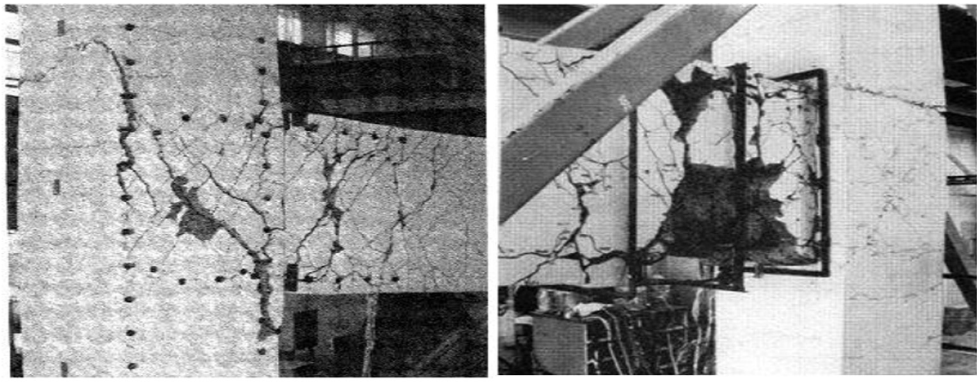

(a) (b)

Fig. 1. Type of failure in a joint – (a) Shear failure at the joint [38] and (b) failure of the beam adjacent to the joint in flexure [24].

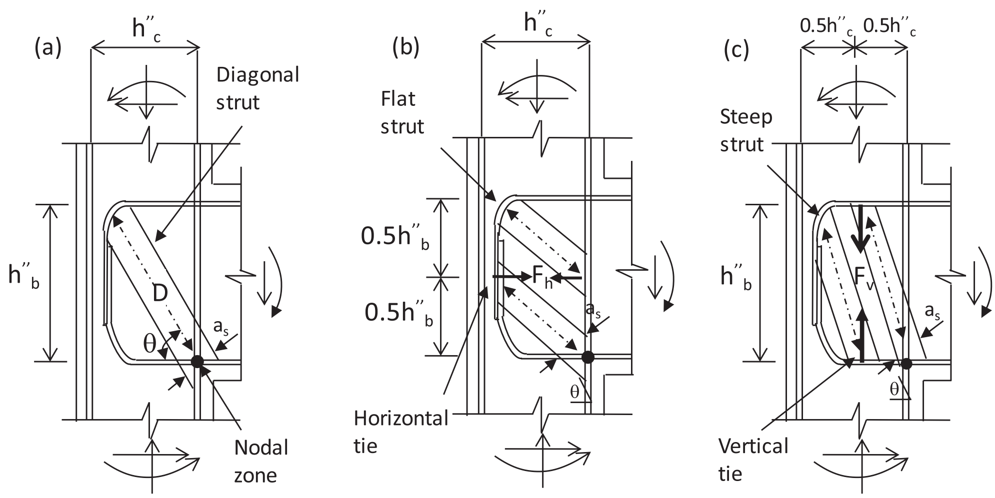

Fig. 2. Shear resistant mechanisms – (a) diagonal mechanism, (b) horizontal mechanism, and (c) vertical mechanism (after [5]).

consists of a diagonal compression strut with an angle of inclination $\theta = \tan^{-1}(h_b''/h_c'')$, where h_b'' and h_c'' (Fig. 2) are the distances between the end longitudinal reinforcements of the beam and the column, respectively. In addition, it is assumed that the direction of the diagonal strut coincides with the main direction of compression of the concrete. The horizontal mechanism (Fig. 2b) consists of a horizontal tie and two flat struts, in which the stirrups of the column constitute the tie. It is also assumed that the stirrups in the core of the joint are considered 100% effective when calculating the area of horizontal reinforcement, while those located at the ends of the joint are considered providing only 50% of their force as effective. The vertical mechanism (Fig. 2c) includes a vertical tie and two steep struts. The vertical tie is considered as the vertical intermediate reinforcement of the column. The combination of the 3 lattices determines the complete system, so that by equilibrium the resulting shear force is defined as,

$$V_{jh} = -D\cos\theta + F_h + F_v\cot\theta \qquad (1)$$

where D is the compression force at the diagonal strut; and F_h and F_v are the forces in the horizontal and vertical struts, respectively. As the system is hyperstatic, a load distribution pattern is assumed between the 3 mechanisms.

Failure of the compression strut is defined when the concrete at the end of the diagonal in compression, that is, in the nodal zone (Fig. 2a) reaches its maximum compressive capacity. To determine the capacity, it is necessary to define the constitutive laws of the materials. For concrete, as same as in this work, the ascending branch for the compression curve in the cracked concrete of the model by Zhang and Hsu [11] is considered to characterize the biaxial action present in this material. As for reinforcing steel, its behavior is considered elastoplastic. When incorporating compatibility, forcing average deformations for the entire element, the nonlinear system requires an iterative process to validate compatibility, which allows determining the shear capacity.

In the ACI 318-14 [7], on the other hand, the shear strength is obtained as a function of the compressive strength of concrete, defined as,

$$V_{jh} = \gamma\sqrt{f_c'}A_j \qquad (2)$$

where γ is a function of the confinement delivered by the surroundings beams. For the purpose of this work, where joints with confluent beams on only 1 or 2 sides are considered, for interior joints (beams in 2 faces) $\gamma = 1.2$ if the width of these beams is at least 75% of the width of the joint. In other cases, $\gamma = 1.0$. A_j represents the effective area of the joint, which for beams centered on the joint includes the entire cross-sectional area of the joint.

Another closed-form expression is the model proposed by Wang et al. [10], where it is assumed that the shear capacity of the joint is obtained when the stresses in the concrete, located at point C (Fig. 3) have reached their material failure envelope. The point C is considered only subjected to an axial stress σ_y and a shear stress τ_{xy}. Also, it is assumed that the principal stresses at the joint at the moment of failure, coincide with the two normal stresses acting along and perpendicular to the diagonal strut AB.

On the other hand, the angle α is defined as $\alpha = \tan^{-1}(h_c/h_b)$, where h_c is the width of the column; h_b corresponds to the height of the beam;