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A new model to simulate joint shear behavior of poorly detailed beam–column connections in RC structures under seismic loads, Part I: Exterior joints

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ABSTRACT

A new model that can simulate the shear behavior of reinforced concrete connections in structures subjected to seismic loads is proposed. The model uses limiting principal tensile stress in the joint as the failure criteria so that due consideration is given to the axial load on the column. The spring characteristics are based on the actual deformations taking place in the sub-assemblage due to joint shear distortion. The model can be easily implemented in any commercial nonlinear analysis package and does not need any special element or subroutine. The model is more rational than the rotational spring models and at the same time being easier to implement in analysis than the multiple spring models. The formulations to obtain the spring characteristics are given in the paper. Currently the model is used to perform nonlinear static analysis for the joints, however, the same can be utilized for the nonlinear dynamic analysis too with an associated hysteretic rule. Highly promising results are obtained using the proposed model for the cases against which the model is validated. This paper focuses on the modeling of exterior joints. An extension to interior joints will be presented later.

1. Introduction

Under the action of seismic forces, beam–column joints are subjected to large shear stresses in the core. These shear stresses in the joint are a result of moments of opposite signs on the member ends on either side of the joint core. Typically, high bond stress requirements are also imposed on reinforcement bars entering into the joint. The axial and joint shear stresses result in principal tension and compression that leads to diagonal cracking and/or crushing of concrete in the joint core. These stresses in the joint core are resisted by the so-called strut and tie mechanism [1–3]. To prevent the shear failure of the joint core by diagonal tension, joint shear reinforcement is needed, which is therefore prescribed by the newer design codes [4–6]. Moreover, these codes prescribe a large anchorage length of the bars terminating in case of exterior joints, so that a bond failure may be avoided. However, a vast majority of the structures world-wide consist of structures designed prior to the advent of seismic design codes.

It has been identified that the deficiencies of joints are mainly caused due to inadequate design to resist shear forces (horizontal and vertical) and consequently by inadequate transverse and vertical shear reinforcement and of course due to insufficient anchorage capacity in the joint. Therefore, inadequate transverse reinforcement and insufficient anchorage in the joint are two major problems of the joints designed as per non-seismic guidelines [7]. These problems have been highlighted, in recent past, by the damage observed in devastating earthquakes in different countries. The two major failure modes for the failure at joints are (a) joint shear failure and (b) end anchorage failure (Fig. 1). A typical example of a beam–column joint failure during the 1999 Turkey earthquake is shown in Fig. 2 [8].

While designing a structure, conventionally, the joint core is considered as rigid and the frame members are assumed to be connected forming a single node that symbolizes the joint. New codes [4,5,9] suggest an indirect approach to design the joint by limiting the joint shear stresses. However, again in older codes, no such provisions existed. Even in the case of nonlinear displacement based analysis (e.g. Pushover) all the plastic rotations are assumed to occur in the beams and/or columns forming the joint core. Although this assumption is reasonable for the structure subjected to static gravity loads, the same assumption does not hold good for the structures subjected to seismic loads, since under earthquake loads, high shear forces gradually soften the joint core making it non-rigid.

Even though now it is well-known that the beam–column joints, especially the poorly designed ones, behave highly nonlinearly during the earthquakes, still the analysis approach mainly

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(a) Joint shear failure.

(b) Inadequate reinforcement anchorage.

Fig. 1. Major failure modes for a RC beam–column joint.

Fig. 2. Typical beam–column joint failures (Turkey earthquake).

revolves around considering concentrated plasticity at the member ends and assuming the joint core as rigid. This is not due to negligence of the designers or analysts but is attributed to the fact that the models available in the literature generally are not simple enough to be used in commercial programs while being at the same time able to predict the shear behaviour of the joints nicely. Moreover, the models either require large computational efforts so that they are not practically useful for analyzing the global structural behaviour or they need a special element with various nodes and springs or a special purpose program to implement the joint's nonlinearity. This makes it difficult for the designers and analysts to follow the recommended approaches using the commercial programs.

In this work, a new model for predicting the nonlinear shear behaviour of beam–column joints is suggested that can reasonably accurately capture the shear behaviour of the joints and also is practical enough to be used with existing available commercial software programs. The model is based on practical deformational behaviour of the joint sub-assembly in a structure and follows the principal stress failure criteria so that due consideration may be given to the axial load acting on the column. The formulations needed to generate the joint characteristics are given and the model is validated and shown to be applicable for analysing the joints with different detailing aspects.

2. Mechanics of exterior joints

When RC moment frames are subjected to lateral seismic loading, high shear forces are generated in the joint core [1,2,10,11]. Fig. 3 shows the mechanics of an exterior joint when subjected to seismic forces. The lateral seismic loading on a frame leads to bending moments and shear forces that can be simulated in the joint as shown in Fig. 3(a). Here the length of the beam L_b is half of the bay width and L_c is the storey height. The other dimensions are explained in the figure. Fig. 3(b) shows the joint shear forces generated due to these external actions.

From the equilibrium of the joint, as shown in Fig. 3(b), we get,

$$V_{jh} = T_b - V_c. \tag{1}$$

Now, we have

$$T_b = M_b/Z_b = V_b L_b/Z_b \tag{2}$$

where Z_b is the lever arm.

Also, from the equilibrium of external actions, we have,

$$V_c = V_b(L_b + 0.5h_c)/L_c. \tag{3}$$

Substituting (2) and (3) in (1), we get,

$$V_{jh} = V_b\left(\frac{L_b}{Z_b} - \frac{L_b + 0.5h_c}{L_c}\right). \tag{4}$$

The horizontal joint shear stress can be obtained as

$$\tau = \frac{V_{jh}}{h'_c b'_c} \tag{5}$$

where, h'_c and b'_c are the length and width of joint core respectively.

In general, for sufficient accuracy, we can consider,

$$Z_b = d_b - d'_b \tag{6}$$

where,

d_b = Effective depth of the beam

d'_b = Effective cover to compression reinforcement.

Similarly, from equilibrium in vertical direction, we can get vertical joint shear. Now, vertical joint shear stress is given by,

$$\sigma = \frac{V_{jv}}{h'_c b'_c}. \tag{7}$$

However, it has been shown that [2,9,10,12]

$$\frac{V_{jv}}{V_{jh}} = \frac{h_b}{h_c} = \alpha \tag{8}$$

where, α is the joint aspect ratio.

The principal compressive stress, p_c and tensile stress p_t can be calculated as [12]

$$p_{c,t} = \frac{\sigma}{2} \pm \frac{\sigma}{2}\sqrt{1 + \frac{4\tau^2}{\sigma^2}}. \tag{9}$$

A system of diagonal compression strut and tension tie is developed in the concrete core to transmit the joint shear forces.