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A beam–column joint element for analysis of reinforced concrete frame structures

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ABSTRACT

Earthquake reconnaissance and laboratory tests reveal that the beam–column joints of existing RC frame structures in China are susceptible to failure, leading to severe structural damage. However, the inelastic response of joint elements is rarely considered in structural analysis or design. A new joint element considering shear deformation and bar-slip behaviour was proposed and verified using an extensive experimental data set. Two RC frame specimens with different details were modelled with the joint element and their simulated seismic responses were compared with experimental results in terms of global and local performance. Based on the simulation, the joint element proved to be reliable and suitable for 2D structural modelling. Finally, two reinforced concrete frame structures with the same dimensions and reinforcement ratios but different ductility are modelled with and without the proposed joint elements. The proposed joint element was shown to accurately predict the mechanical behaviour of such structures and their components, especially the hysteresis behaviour. Analysis shows that joint failure tends to happen in low-ductility structures and will reduce the ductility and the energy dissipation ability of the structure, even cause structural collapse. Compared with the new designed structures, seismic performance of the low-ductility ones is worse, with poor energy dissipation, weak collapse resistance and brittle failure modes.

1. Introduction

Earthquake reconnaissance and laboratory tests reveal that old beam–column joints of reinforced concrete (RC) frame structures built in China or other countries tend to suffer severe earthquake damage [1–5]. The typical failure modes include shear failure of joints and bond failure of the longitudinal beam in the joint panel, which may cause severe structural damage [6,7]. In order to consider the potential impact of joint failure on structural seismic response, researchers have developed various implicit explicit models of joint elements [8–15].

In the implicit ones the joint region is indirectly represented by nonlinear springs or plastic hinges in adjacent beams or columns. Such elements make it computationally efficient to determine the global influence of nonlinear joints on structural responses, but their shear deformation and bond-slip are hard to predict [16]. Explicit elements consider an explicit representation of the joint region and satisfy joint kinematics. They can easily be calibrated. The "BeamColumnJoint" element in OpenSees proposed by Lowes and Altoontash [12] in 2003 is one of elements widely used. The element was updated by Mitra and Lowes [13] in 2007 to make it easier to simulate the response of joints with a wide range of design parameters. However, there are still some limitations in its application. For example, it is difficult to consider complex cross sections of the adjacent beams and it is also difficult to account for different bond-slip relationships, such as behaviours of corroded reinforcing bars. Additionally, too many springs in this element may cause numerical convergence problems when applied in structural analysis, especially for the dynamic one, which is also described in Ghannoum's research [17].

A new beam–column joint element considering shear deformation and bar-slip behaviour is therefore proposed, and 16 interior joint specimens and two RC frame tests are presented to confirm its effectiveness and reliability at both the component and the structure level. The proposed joint element is applied to a study of the seismic performance of the low-ductility structures built before the 1990s in China.

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2. The proposed beam–column joint element

2.1. Formulation

The Mitra–Lowes element comprises one shear panel component, eight bar-slip springs and four interface shear springs, as illustrated in Fig. 1. The shear panel simulates strength and stiffness loss due to failure of the joint panel; the bar-slip springs simulate strength and stiffness loss due to anchorage-zone damage; and the interface-shear springs simulate the shear transfer through friction at the beam or column ends. However, it is difficult for bar-slip springs to consider complex beam cross sections and account for different bond-slip behaviours in the joint panel. Moreover, too many bar-slip springs at the joint perimeter can easily cause numerical convergence problems in structural nonlinear analysis.

The joint element shown in Fig. 2 is proposed to overcome these limitations. It keeps the shear panel component but replaces the bar-slip springs by zero-length elements at the beam ends and it removes the bar-slip springs at the column ends for simplification. The constitutive model of reinforcing steel in a zero-length element can be defined by various stress–slip relations to introduce the additional angles $\Delta\theta_{bl}$ and $\Delta\theta_{br}$ at the beam ends accounting for different bond-slip behaviours, as described in Fig. 3. The additional angles calculated by section analysis are determined by the yield strength of the beam rebar f_y, the bond strengths τ_E and τ_Y for elastic and yielding steel, and beam rebar slip s. The shear forces V_{br}, V_{bl}, V_{ct}, V_{cb}, the axial forces N_{br}, N_{bl}, N_{ct}, N_{cb}, and the moments M_{br}, M_{bl}, M_{ct}, M_{cb} at the joint perimeter are used to describe the force equilibrium. θ_{bl} and θ_{br} at the beam ends are the rotation angles associated with the moments M_{bl} and M_{br}. b and h are the width and the height of the joint panel. The total moment M_j and rotation angle θ_j for joint panel are defined by Eq. (1).

$$\theta_j = (u_{Vbr} + u_{Vbl})/b + (u_{Vct} + u_{Vcb})/h \tag{1a}$$

$$\begin{aligned} M_j = {} & M_{ct} + M_{cb} - M_{bl} - M_{br} + (N_{ct}/2 - V_{br} - N_{cb}/2) \cdot b \\ & + (N_{bl}/2 + N_{ct} - N_{br}/2) \cdot h \end{aligned} \tag{1b}$$

where u_{Vbr}, u_{Vbl}, u_{Vct}, u_{Vcb} are the displacements associated with the shear forces V_{br}, V_{bl}, V_{ct}, V_{cb} respectively, as shown in Fig. 3.

2.2. Shear panel response

Research has shown that the force-transfer mechanisms in a beam–column joint panel can be represented by diagonal compression strut, truss and confined mechanisms [18], as shown in Fig. 4. Modified compression field theory (MCFT) [19], diagonal compression strut model (DCSM) [13], and a simplified strut-and-tie model (STM) [20] can be used to represent them. Together they can be applied to predict the relationship of M_j and θ_j for the rotational spring. Modified compression field theory is a general theory for the load–deformation behaviour of two-dimensional cracked RC structures subjected to shear. It was developed through testing of multiple RC panels subjected to uniform strain states. However, the uniform pure shear stress assumed by the theory is different from the complex stress state of a beam–column joint, so MCFT is not suitable for defining a joint's shear stress–strain relationship. Another approach is the diagonal compression strut model, in which a main strut is adopted to allow considering the diagonal compression strut and confined mechanisms without the truss mechanism.

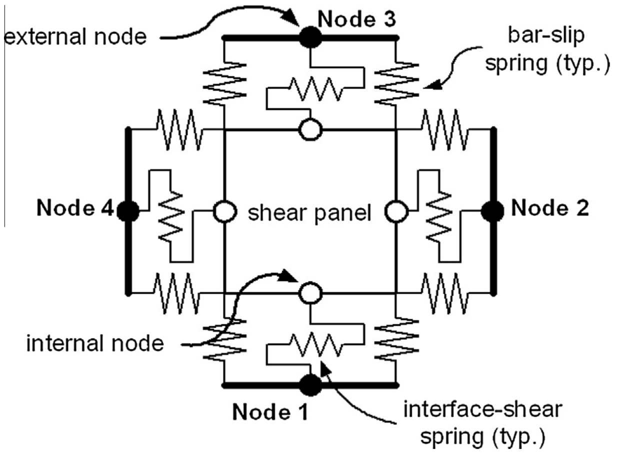

Fig. 1. Mitra–Lowes element (from Ref. [13]).

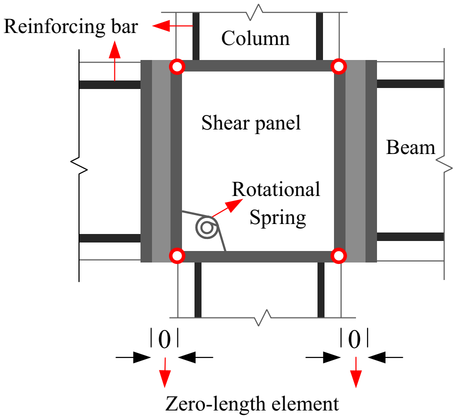

Fig. 2. Proposed joint element.

The simplified strut-tie model was developed to account for all these mechanisms by adding a sub-strut to simulate the shear effect of stirrups, as shown in Fig. 5. The truss mechanism is formed by the main strut, sub-strut and stirrup together. The STM was applied in this study to predict the joint's shear stress-rotation ($\tau_{j.STM}, \gamma_{j.STM}$) relationship. The Pinching4 material model [12] is recommended to describe any hysteresis, pinching, energy dissipation, and cyclic degradation of the joint's shear response. They are defined using a response envelope, an unload–reload path, and three damage rules that control how the joint's response path evolves, as shown in Fig. 6. This material model is particularly useful for simulating any pinched hysteresis of critical elements such as joints with low stirrup ratios.

The key points of the backbone curves ($M_{j.STM}, \theta_{j.STM}$) are defined by Eq. (2), which represents four damage states of the joint panels. State I is the crack opening state of concrete; state II is the strength yielding state of the stirrups; state III represents the joint shear stress reaching its maximum value; state IV means the shear failure of the joint region, as indicted in Fig. 6. The hysteresis rule is defined according to the approach of Mitra and Lowes [13].

$$\theta_{j.STM} = \gamma_{j.STM} \tag{2a}$$

$$M_{j.STM} = \tau_{j.STM} \cdot h_c \cdot h_b \cdot b_j \tag{2b}$$

where h_c and h_b are the width and the height of the joint; and b_j is the maximum out-of-plane dimension of the beam or the column.

2.3. Bond-slip response

The most direct approach for defining bond-slip relations is to use the moment-rotation relationship to account for rotation caused by rebar slip [21]. Its properties can easily be determined.