Research on seismic design method of a beam-column joint in reinforced concrete space frame

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Abstract: Earthquake action is multi-dimensional and random. Under bidirectional horizontal direction loading, the seismic capability of beam-column joints in reinforced concrete (RC) frame may be lower than the design capability under unidirectional main direction loading. Detailed calculation methods for the shear bearing capability and shearing performance of RC space joints in frames under bidirectional horizontal direction loading have not been reported. In this work, the shear mechanism and internal force calculation method of an RC space joint under bidirectional horizontal direction loading are analyzed. Furthermore, a shear capacity calculation model is established based on the strut-and-tie model. The prediction of the shear capability in this work are in good agreement with the reported experimental results. This study provides a design method for the seismic design of RC space frame joints, and provides a supplement for the seismic design method of RC space frame with "strong joints and weak members", when they are subjected to bidirectional horizontal direction loading at the same time.

1. Introduction

Under arbitrary horizontal direction seismic action, an RC space joint experiences loading from two horizontal spindle directions simultaneously; under these conditions, insufficient resistance may be one of the main reasons leading to the failure of the joint.

In the current seismic design code, seismic calculations of RC frames are carried out only along the main axis direction, but the direction of actual seismic action may not coincide with the principal direction of the frame. Moreover, under bidirectional horizontal direction loading, both beam-column joints and columns in an RC frame are loaded in two directions at the same time, and their mechanical and seismic performance may be greatly reduced as a consequence.

Burguieres and Jirsa (1979) conclude that the strength and stiffness may deteriorate rapidly with load cycling; and the performance under cycling did not markedly improve with a large increase in the transverse rebar in the core area of the joints. Beckingsale (1980) tested one interior RC space joint from a space frame. Fujii and Morita (1987) demonstrate that the shear bearing capacity of RC
beam-column joints significantly degrade under bidirectional cyclic loading, and the shear strength of joints significantly improved by utilizing unloaded transverse beams, and that bidirectional loading has a significant effect on the deformation of joints. Zhang (1987) believe that the core area of a joint are more likely to be destroyed and that the ultimate strength and stiffness of joints are significantly degraded under bidirectional cyclic loading. Kitayama et al. (1988) find that the shear bearing capacity of an RC beam-column joint is enhanced by the inclusion of slabs subjected to bidirectional cyclic loading. Chen et al. (1995) studied the shear capacities and bonding behaviors of the longitudinal rebars of several RC space joints under bidirectional cyclic loading. Hwang and Lee (1999, 2000) established a softening strut-and-tie model of RC beam-column joints based on the strut-and-tie model and calculated the shear bearing capacity of plane joints. Based on an analysis of the stress and strain in the core area of joints, a general calculation model for the shear bearing capacity of an RC beam-column joints was established by Attaalla (2004) in consideration of the softening effect of cracked concrete. Sun et al. (2014) investigated the shear performance of three-dimensional (3D) RC beam-column joints subjected to bidirectional cyclic loading based on the results of nonlinear finite element analysis and verified the existence of a significant deterioration in the shear strength. Cui et al. (2014) tested several RC corner joints under bidirectional cyclic loading and proposed a strut-truss model for beam-column joints. Kim et al. (2017) develop a 3D macroelement model for beam-column joints that can better estimate the 3D seismic response; however, this method requires a moderate amount of computational effort, and it must be carried out on a PC. Methods for calculating the shear capacities of RC beam-column joints are also given in American code (ACI 318-11, 2011), Europe code (MC90, 1993), Japanese code (AIJ, 2004) and Chinese code (GB 50010-2010, 2010), but these code methods take an unloaded transverse beam as the premise and consider only the favorable influence of transverse beam.

Nevertheless, the RC beam-column joints response when it is subjected to bidirectional loading has not been explicitly reported. The abovementioned calculation methods for the shear capacities of joints are mainly applied along the main principal axis rather than under bidirectional horizontal direction loading. Hence, no clear research results have been reported on the possible adverse effects of simultaneous (i.e., bidirectional horizontal direction) loading on the shear capacities of RC beam-column joint, and no specific visual method for predicting the max shearing capacity of an RC space joint under bidirectional horizontal direction loading has been developed. Therefore, in this paper, the shear mechanism and internal force calculation method of a joint in an RC frame under bidirectional horizontal direction loading are ascertained, and a design method for the max shearing capacity of a joint in an RC frame is established.

2. Internal force calculation
According to the research on RC palne joints conducted by Paulay et al. (1978, 1984), the horizontal shear and vertical shear of a joint can be calculated. The beam bars and column rebars throughout the joint are either in tension or in compression, and compression zones are formed at the compressed sides of the beam ends and column ends adjacent to the joint.
Fig 1. Internal force calculation in an RC space joint.

Under the tension of $T_{bs}$ and the compression $C_{bs}$ provided by the beam rebars in joint, $T_{cs}$ and $C_{cs}$ provided by the column rebars, and the compression of $C_b$ and $C_c$ provided by the concrete at the end of the beam and the column adjacent to the joint, a tension zone and a compression zone are formed. Under the pressure of the compression zone in the joint, a diagonal compression strut is formed (Fig 1). The pressure of the concrete diagonal compression strut forms a balance relationship with $V_h$ and $V_v$, making the strut resist both horizontal and vertical shearing in the joint. The horizontal shear in joint can be calculated as

$$V_h = \left( M_{bl}^R + M_{bl}^L \right) / h_{bo} - V_c$$

where $V_h$ = the horizontal shear in joint; $M_{bl}^R$, $M_{bl}^L$ = the bending moments at the right and left ends of the joint, respectively; $h_{bo}$ = the distance between the extreme longitudinal rebar in the beams; and $V_c$ = the horizontal column shear force above the joint. The vertical shear in joint $V_v$ can also be calculated.

Under bidirectional horizontal direction loading, the angle between the horizontal direction of loading and the x-direction of the structure is $\alpha$, the horizontal joint shear forces $V_{hx}$ and $V_{hy}$ (Fig 2) are formed in the x-direction and y-direction, respectively, of the joint core region. The horizontal joint shear forces in both directions can be further synthesized as a horizontal composite shear force $V_{jh}$, while the vertical shear forces in both directions can be synthesized as a vertical composite shear force $V_{jv}$.

Fig 2. Internal force calculation in an RC space joint under bidirectional horizontal direction loading.

3. Calculation method
3.1. Shear-resisting mechanism

The core area of the RC joint belongs to the D-region, where the stress distribution and the strain distribution are significantly nonlinear. A strut-and-tie model for calculating the shearing capacity of the D-region in RC members has been established by Schlaich and Schäfer (1991). Considering the softening effect of cracked concrete proposed by Vecchio and Collings (1986), Hwang and Lee (1999, 2000) established a softening strut-and-tie model, which can be calculated the shearing capacity of an RC plane joints.

Fig 3. Shearing mechanism in an RC space joint under bidirectional horizontal direction loading.

According to the abovementioned analysis of the shear mechanism of joints, oblique compression zones are formed at the ends of the upper and lower columns of the joint under the simultaneously loadings in the two horizontal spindle directions. It is assumed that a concrete bottle-shaped compression strut is formed in the core area of the joints, as represented by the shaded area in Fig 3. The combined shear acting plane of the joint is the vertical plane where the horizontal shear force $V_{jh}$ and the vertical shear force $V_{jv}$ are located in. The concrete strut, stirrups and column rebars form a strut-and-tie model to bear the joint shear force in the combined shear acting plane of the joint.

In Fig.4, $\alpha$ = the angle between the combined shear acting plane and the x-axis; $\theta$ = the inclination angle of the oblique compression strut; $h_b$, $b_c$, and $h_c$ = the beam height, column width and column height, respectively; and $h_b'$, $h_c'$, and $h_c''$ = the distance between the extreme longitudinal rebar of the corresponding side in the beams or column.

3.2. Oblique compression strut

The concrete compression zone of a square column under bidirectional horizontal direction loading can be obtained. To simplify the study, the loadings of two main directions are the same in this paper.

Under bidirectional horizontal direction loading, the equivalent oblique compression strut can be obtained (Fig 4). The cross section of the oblique compression strut is perpendicular to the diagonal (AE) in the core area of the joint, and the angle of the oblique compression strut can be assumed as $\theta$. Because the area of compression zone $S_c$ ($\Delta ABC$) is much larger than the compression zone in the beam adjacent to the joint, the area of cross section of the oblique compression strut $A_{str}$ ($\Delta BCD$) can be determined by $S_c$, and $S_c$ is the horizontal projection of $A_{str}$.
Fig 4. Oblique compression strut in an RC space joint under bidirectional horizontal direction loading.

\[
\theta = \tan^{-1}\left(\frac{h_{c}^{2}}{h_{b}^{2} + b_{c}^{2}}\right)
\]

\[
A_{sw} = \frac{S_{c}}{\cos\left(\frac{\pi}{2} - \theta\right)} = \frac{S_{c}}{\sin \theta}
\]

3.3. Calculation model

The max shearing capacity of the joint can be expressed as \(C_d\).

\[
C_d = K\xi f' c A_{sw} \cos \theta
\]

\[
\xi \approx 3.35 / \sqrt{f' c} \leq 0.52
\]

The softening effect of cracked RC members was confirmed by Vecchio and Collings (1986). Hsu (1996). Hwang and Lee (2002) proposed the softening coefficient \(\xi\) of the core area in RC plane joints. In the strut-and-tie model of the joint, which has both stirrups and column rebars, for the constraint of stirrups and column rebars, the increased degree of the oblique compression capacity is expressed as \(K\).

\[
K = K_s + K_c - 1
\]

The more stirrups there are, the higher the oblique compressive capacity of the concrete in joint will be. But the oblique compressive capacity will not be infinitely enlarged. If the number of stirrups is adequate, additional stirrups will not influence the shear strength. The coefficient \(K_h\) can be determined according to stirrups, representing the beneficial effect on the shear strength by the horizontal tie.

\[
K_h = 1 + \left(\frac{K_h - 1}{F_{yh}}\right) \leq K_h
\]

If the stirrups in the joint has been sufficiently allocated, then the stirrup reaches yielding during the failure of joint. The coefficient representing the beneficial effect of the stirrups on the shear strength \(K_h\), and the tensile of horizontal tie \(F_{yh}\) can be expressed as

\[
K_h = \frac{(1 - \gamma_h) + \gamma_h}{(1 - \gamma_h) + \gamma_h} \approx \frac{1}{1 - 0.2(\gamma_h + \gamma_h^2)}
\]

\[
F_{yh} = \gamma_h \times \left(K_h \xi f' c A_{sw} \cos \theta\right)
\]

In the combined shear acting plane of the joint, the tension of the horizontal tie can be synthesized by the tensions of the stirrups in the two main directions (Fig 5). Furthermore, \(F_{yh}\) = yielding force of the horizontal tie, and \(F_{yh} = \sqrt{2} A_{th} f_{th}\), where \(A_{th}\) is the cross area of the stirrups in the one main
direction, which is the cross area of the stirrups in the effective layers (Hwang and Lee, 2000) and \( f_{yh} \) is the yield strength of the stirrups in joint.

![Fig 5. Tie forces of rebars in an RC space joint.](image)

The coefficient representing the beneficial effect of the intermediate column rebars on the shear strength \( K_v \) can be obtained by the same method.

\[
K_v = 1 + \frac{(K_v - 1)F_{vu}}{F_v} \leq K_v
\]  

(10)

In the combined shear acting plane of the joint under bidirectional horizontal direction loading, \( F_v \) can be synthesized by the tensions of all the middle column rebars. Additionally, \( f_{vu} = \) the yielding force of the vertical tie, and \( F_{vu} = A_{tv}f_{vu} \), where \( A_{tv} \) = the cross area of the middle column rebars, and \( f_{vu} \) = the yield strength of the intermediate column rebars.

According to the research of Schäfer (1996), the coefficient \( \gamma_h \) and \( \gamma_v \) can be calculated, and the same method also has been given in the Europe code (MC2010, 2010).

\[
\gamma_h = \frac{2\tan\theta - 1}{3} \quad \text{and} \quad 0 \leq \gamma_h \leq 1
\]  

\[
\gamma_v = \frac{2\cot\theta - 1}{3} \quad \text{and} \quad 0 \leq \gamma_v \leq 1
\]  

(11)  

(12)

4. Calculated and experimental results

The shear bearing capacities of many RC space joints are calculated under bidirectional horizontal direction loading, and the two horizontal spindle directions of the joints bear the same force. The selected specimens are all square cross-sectional columns, the loadings in the two spindle directions are identical, and shear failure occurs in all core areas of the joints.

The calculated results of the shear bearing capacities of the joints are in good agreement with the experimental results (Fig 6). In Fig.6, \( C_{d,c} \) = the calculated result of ultimate shear bearing capacity in an RC space joint, \( C_{d,t} \) = the experimental result of ultimate shear bearing capacity in an RC space joint.
5. Design method

The calculated result is the average value of theoretical prediction, and the safety factor $\phi$ of design has not been considered. Under bidirectional horizontal direction loading, if the demand of horizontal composite shear force of the joints is $V_{jh,u}$, the design formula for the seismic design of RC space frame joints can be expressed as Equation (13).

$$\phi C_d = \phi K \xi f_c A_{sp} \cos \theta \geq V_{jh,u}$$  \hspace{1cm} (13)

An illustrative Example is shown schematically as follows.

$$\theta = \tan^{-1} \left( \frac{h_b}{\sqrt{h_e^2 + h_c^2}} \right) = \tan^{-1} \left( \frac{399}{\sqrt{239^2 + 239^2}} \right) = 50^\circ$$

$$A_{sp} = \frac{S}{\cos \left( \frac{\pi}{2} - \theta \right)} = \frac{S}{\sin \theta} = \frac{38726}{\sin 50^\circ} = 50753 \text{ mm}^2$$
\[ \xi \approx \frac{3.35}{\sqrt{f_c}} = \frac{3.35}{\sqrt{1.194 \times 29.65}} = 0.56 > 0.52 \]

Take \[ \xi = 0.52 \]

\[ \gamma_h = \frac{2 \tan \theta - 1}{3} = \frac{2 \tan 50^\circ - 1}{3} = 0.454 \]
\[ \gamma_v = \frac{2 \cot \theta - 1}{3} = \frac{2 \cot 50^\circ - 1}{3} = 0.231 \]

\[ \bar{K}_h = \frac{1}{1 - 0.2(\gamma_h + \gamma_h^2)} = 1.152 \]
\[ \bar{K}_v = \frac{1}{1 - 0.2(\gamma_v + \gamma_v^2)} = 1.060 \]

\[ F_h = \gamma_h \times (\bar{K}_h \xi f'_{cH} A_{ph} \cos \theta) = 316 \text{ kN} \]
\[ F_v = \gamma_v \times (\bar{K}_v \xi f'_{cH} A_{ph} \cos \theta) = 175 \text{ kN} \]
\[ F_{jh} = \sqrt{2} A_{ph} f_{ph} = \sqrt{2} \times 4 \times 33.183 \times 436 \times 10^{-3} = 327 \text{ kN} \]
\[ K_h = 1 + \frac{(\bar{K}_h - 1)F_{jh}}{F_h} = 1.157 > \bar{K}_h \]

Take \[ K_h = 1.152 \]

\[ F_{ev} = A_{ph} f_{ev} = 8 \times 254.47 \times 432.5 \times 10^{-3} = 880 \text{ kN} \]

\[ K_v = 1 + \frac{(\bar{K}_v - 1)F_{ev}}{F_v} = 1.304 > \bar{K}_v \]

Take \[ K_v = 1.060 \]

\[ K = K_h + K_v - 1 = 1.212 \]

\[ C_d = K \xi f'_{cH} A_{ph} \cos \theta = 734.69 \text{ kN} \]
\[ \phi C_d = 0.85 C_d = 624.48 \text{ kN} > V_{ph,\alpha} = 600 \text{ kN}, \text{ OK} \]

6. Conclusions

(1) The bearing mechanism and internal force calculation method of an RC space joint in frame subjected to bidirectional horizontal direction loading are analyzed. Under biaxial loading, the angle and cross section area of the diagonal compression strut are determined, and the shear contributions of stirrups and column rebars in joints are clarified.

(2) The method of the strut-and-tie model for calculating the shear bearing capacity of an RC space joint is presented. The shear capacities of many joints under bidirectional horizontal direction loading are calculated by the abovementioned method. The calculated results are in good agreement with the experimental results.

(3) The design method for the seismic design of RC space frame joints is provided, and an illustrative example is also provided.

The paper only studies the shear bearing capacity of an RC space joint for square section columns,
and the two main direction loadings are the same. In the future, further studies will investigate the corresponding research for general rectangular section columns, and the two main direction loadings are not identical.

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