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Proposals of beam column joint reinforcement in reinforced concrete moment resisting frame : A literature review study

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Abstract

That the failure of large beam column specimens occurs in the joint rather than in the adjoining members or the beam proves that the joint shear strength of the current methods are inadequate. Moreover, the addition of transverse shear reinforcement in the joint up to a certain limit will increase the shear strength and otherwise it would result in a decrease, if this limit is exceeded. So to increase the shear strength to a greater value, other means are required. With the simplifying assembling and the ductile performance of steel, it is proposed that the use of King-cross steel profile implants at beam-column-joints as a shear reinforcement could be expected to replace the transversal reinforcement and enhance the joint shear strength, ductility and stiffness of the structure.

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Keywords: beam-column joint; joint shear reinforcement; joint shear strength; steel reinforced concrete; steel profile shear reinforcement

1. Introduction

Indonesia is an area that is vulnerable to earthquake disasters; therefore, earthquake resistant buildings are necessary to reduce the damage caused. One of the characteristics of earthquake resistant buildings is having an adequate design on the beam-column joint. Generally, when large forces occur during earthquakes, joints are severely damaged. Unsafe design and detailing within the joint region endangers the entire structure. The beam-

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Nomenclature

A_{ch}	cross-sectional area of a structural member measured to the outside edges of transversal reinforcement
A_g	gross area of concrete section
A_j	effective area of beam-column-joint
A_{sh}	total cross sectional area of rectangular hoop reinforcement
A_v	area of shear reinforcement
b_c	cross sectional dimension of member core measure to the outside edges of the transverse reinforcement composing area A_{sh}
C_2	concrete compressive force due to positive moment
C_c,C_c',C_c"	compression concrete force
d	distance from extreme compression fiber to centroid of longitudinal tension reinforcement
d_b	nominal diameter of bar
D_c	diagonal strut force
$\Delta T'$, $\Delta T''$	vertical compressive component
D_{si}	diagonal compresisive component
f'_c	specified compressive strength of concrete
f_{yt}	specified yield strength f_y of transverse reinforcement
h_x	maximum center to center horizontal spacing of crossties or hoop legs on all faces of the column
s	center to center spacing of transverse reinforcement
T,T',T"	tensile steel force
T_1	tensile force in the steel reinforcement in the beam due to negative moment
T_2	tensile force in the steel reinforcement in the beam due to positive moment
V_b	shear force from the beam
V_c	nominal shear strength provided by concrete
V_{col},V'_{col}	shear force from the column
V_{column}	shear force in column at the top and bottom of the beam-column-joint
V_{jh}	total horizontal joint shear force
V_n	nominal shear strength provide by concrete

column joints must be designed to resist earthquake effects. Hence the adjoining flexural members (beams and columns) could develop their inelastic capacities to dissipate high seismic energy.

Seismic design focuses on the ductility of a frame as the main structure to resist the lateral force. This condition is determined by the structural members, especially beams and columns. Therefore, the joint must be sufficiently ductile till beams and columns achieve their load capacity. During the inelastic deformation of the beams and columns outside the elastic range, large deformation will be involved resulting in clearly visible damage. These force effects are called plastic hinges. The inelastic rotation spreads at certain areas. When the joint suffers inelastic rotation, the ductility capacity of all members are transferred to the joint so that the damage at the joint is will be substantial and should be avoided. The formation of a plastic hinge is expected, where permitted structural damage occurs. Thus, it is very important in seismic design that the damage of a plastic hinges occurs in the beam, rather than in the column.

During horizontal earthquakes, moments and shear forces acting on the beams and columns of the frame building are resulting in internal-vertical and horizontal forces on the face of the joint core. The internal forces produce a resultant acting in the joint core, either a diagonal tensile or compression stress. Diagonal tensile stresses and compressive forces result in cracking and crushing of the concrete core. If the shear resistance at the joint core is insufficient, there will be failures along the diagonal of the joint core. The design of the shear beam-column joint of steel reinforced concrete (SRC) contributed much to the design of joints under seismic loads. Chen et al. [3] adopted the concept of superposition for the analysis and design of beam-column joints. The use of an H cross-section in the SRC column generates significantly more strength when compared to a wide flanges cross-section. When compared with conventional reinforced concrete joints, the joint strength of SRC is more significant and generates greater energy dissipation. By using the superposition techniques, the shear strength of SRC beam-column joint is a contributions of web longitudinal shear strength, longitudinal flange, and reinforced concrete.

Since the mid-1960s, numerous experimental tests and analytical studies have been carried out to investigate the performance of reinforced concrete beam-column-joints under seismic loading. The extensive experimental reinforced concrete beam-column joint reviews were classified as in-plane geometry, without out of-plane geometry and joint eccentricity. This paper presents a review of the various designs and types of the beam-column-joint, joint shear performance and alternative design.

2. Mechanism of force and cracks development in the joint

The mechanism of force action in the joint-cores due to earthquake loads and cracking has been described by Paulay and Scarpas [1] as follows.

The internal actions assumed to be generated at the core of an exterior beam-column-joint when a plastic hinge develops in the beam due to earthquake loads are shown in Fig. 1(a). The tensile and compression steel forces, introduced by the beam and column reinforcement to the concrete of the joint core, are labeled as T, T', T" and C_s, C_s', C_s" respectively. The compression forces, i.e., resultants of the concrete compression stresses, applied by the

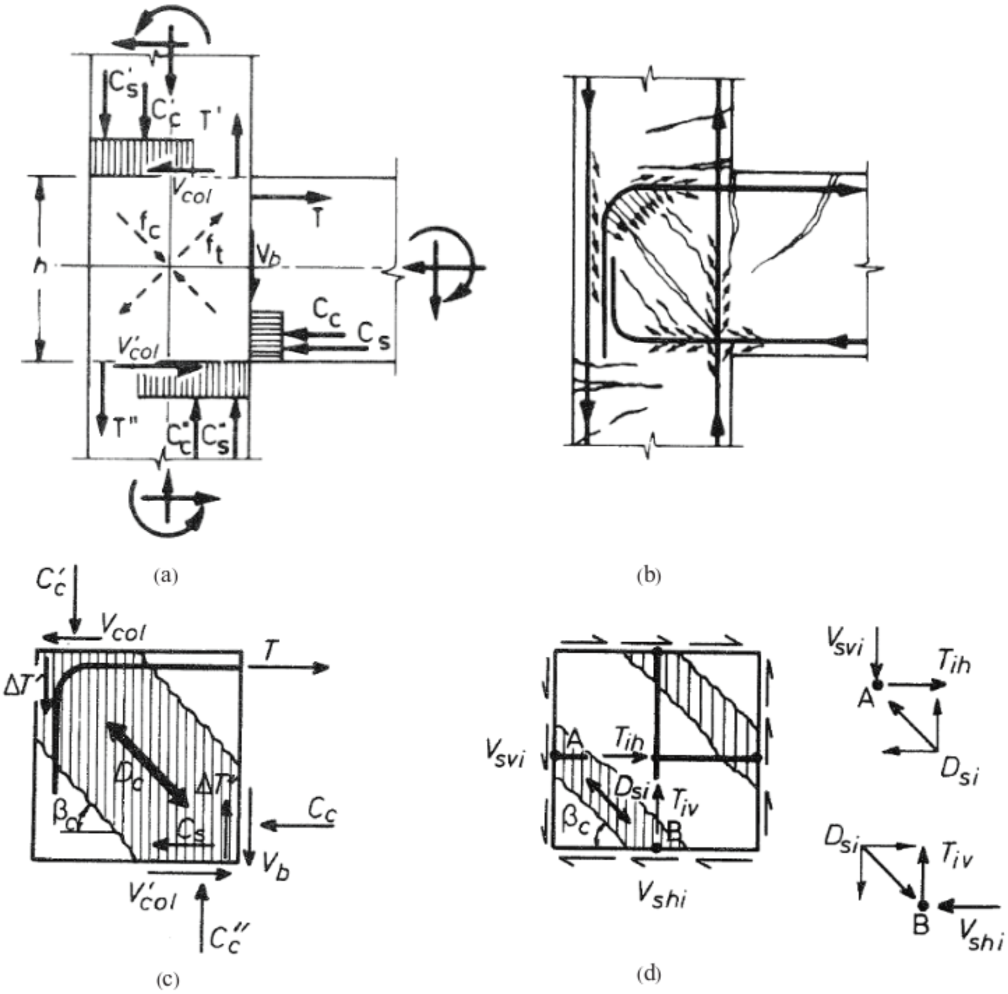


Fig. 1. (a) Force acting in the joint core [8] (b) crack development in the joint core [8] (c) Concrete strut mechanism (d) Truss mechanism [8]

three adjacent members to the joint core, are in turn shown as C_c, C_c' and C_{cc}". At the boundaries of the joint core, shear forces from the beam V_b, and the columns, V_{col} and V'_{col}, are also introduced. The total horizontal joint shear force

$$V_{jh} = T - V_{col} \tag{1}$$

and a similar vertical joint shear force generally lead to excessive diagonal tensile stresses in the concrete core so that diagonal tension cracks, such as shown in Fig. 1(b), develop.

The diagonal cracked concrete in the joint core can efficiently transfer diagonal compression forces, approximately parallel to the cracks.

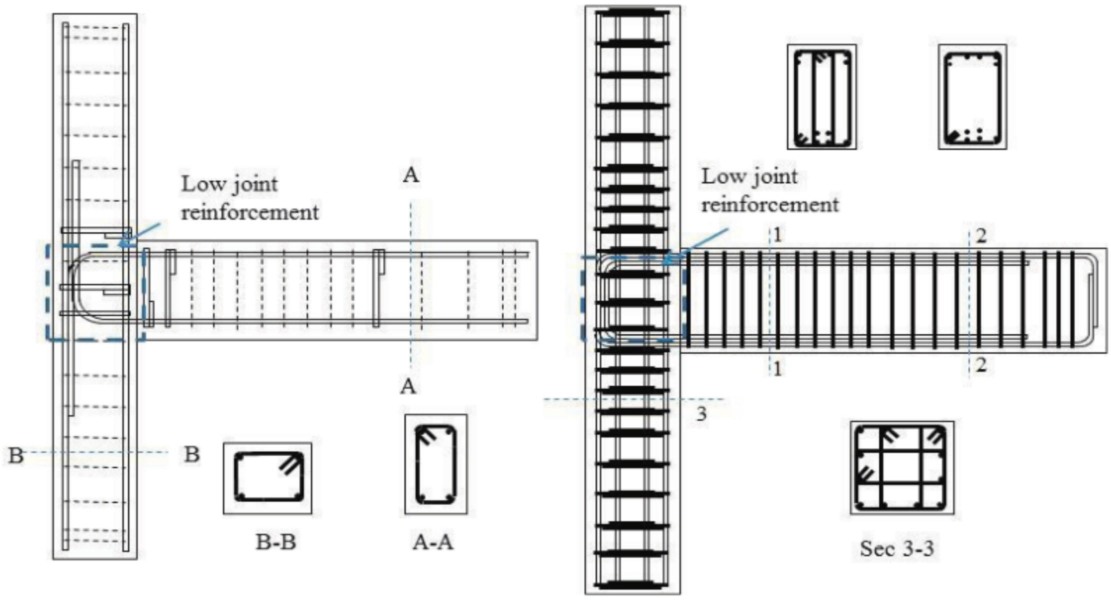
Forces from the beam and column reinforcement are transferred to the core concrete by bond stresses and by bearing stresses within the bend of the anchorage of top bars. These actions are qualitatively shown in Fig. 1(b).

Fig. 1(c) shows, for example, that at the lower right hand corner of the joint, the horizontal concrete force C_c, together with the major part of the horizontal steel compression force Cs and the column shear force V'_{col} can combine with similar vertical forces, C_c, $\Delta T"$ and V_b, to introduce the diagonal strut force D_c. For this system to be in equilibrium, it does not require any contribution from horizontal or vertical joint shear reinforcement. This system is called a strut mechanism.

As shown in Fig. 1(d), the shear force introduced at a node point at the face of the joint can be resolved into a diagonal compressive component D_{si} acting along the strut, and a vertical or horizontal tension component T_i which needs to be carried by steel reinforcement. Because of the relatively long tension path of the internal forces, usually involving large steel strains, this system is called a truss mechanism and is much more flexible than the one shown in Fig. 2(a).

3. The transversal joint shear reinforcement

The detailing of beam-column joints of RC frame structures in regions with a high earthquake risk is normally governed by code provisions (GB 50010 2010, ACI 318-11, NZS 3101 2006, EC8 2003). This detailing consists of a considerable amount of transverse reinforcement to resist the horizontal joint shear forces.



(a) (b)

Fig. 2. Typical Layout of transversal joint Shear Reinforcement (a) Park and Paulay (1972) (b) Paulay and Scarpas (1981)

Since 1973, studies of transverse reinforcement in the beam-column joint have been carried out. As shown in Fig. 2(a), Park and Paulay [2] conducted a study with a variation in the number of transverse reinforcement to the amount of transverse reinforcement according to ACI 318-71. From the test results it was concluded that the transverse reinforcement in the joint placed for the shear in accordance with the recommendations of ACI 318-71 proved to be inadequate. In the absence of substantial axial compression on the columns it appears that no reliance can be placed on thoroughly cracked joint concrete under cyclic loading to resist shear forces [2]. Joint failure occurred also in those specimens in which full or excess transverse reinforcement were assembled. It was observed that transverse steel at the level of the compression zone of the beam was not yielding and that the critical diagonal tension crack in the joint formed along one of the diagonals [2].

In 1981 Paulay and Scarpas [1] conducted similar studies by varying the number of horizontal shear reinforcement in the joint. As shown in Fig. 2(b), only half of the horizontal joint shear reinforcement of the requirements of the DZ3101 2nd Draft New Zealand Standard would be provided. In spite of this low shear steel content, excellent performance was observed because of the larger stiffness, as indicated by the beam deflection being lower than what was observed in other specimens. The test indicated that the joint shear reinforcement was well utilized in spite of the small quantity used, so that the response of the specimen was fully controlled by the plastic hinge region of the beam. The test was terminated when 137% of the theoretical strength of beam was reached.

Six exterior beam-column joints, which were designed according to British Standard BS 8110 were tested by Kaung and Wong [3]. The variables examined were the transverse steel stirrup ratio in the joint core and the moment capacity of the beam. Based on the findings from the tests, the conclusion can be drawn that horizontal stirrups in beam-column joints with a non-seismic design can effectively improve the seismic behavior and enhance the joint shear strength. It is recommended that the upper limit of the horizontal stirrup ratio in non-seismically designed exterior beam-column joints under low to moderate seismicity for enhancing the shear capacity be 0.4%. Additional transverse reinforcement provided to the joint may have less effect in the joint shear strength enhancement.

Similar to previous studies, Sasmal [4] conducted a comparison between the Indian standard of seismic design without any special ductile detailing (SP3) and the Eurocode (SP4). The Indian Standard design has a higher beam moment capacity combined with a lower shear reinforcement ratio than the Eurocode. From the load-displacement envelop constructed from the test results it was shown that SP-3 performed better than SP-4 under positive (upward) displacement cycles, whereas under downward displacement cycles the difference was negligible. It is also clear that the load-displacement envelop for the ‘non ductile’ specimens are very close to the ‘ductile’ ones, which signifies that the strength of the ‘Non Ductile’ specimens is not much different from the ‘Ductile’ specimens.

All of the five studies mentioned above have a similarity in that there is a limit in the optimum number of transverse shear reinforcement in the joint. The addition of transverse shear reinforcement in the joint up to a limit will increase the shear strength, and a reduction on the other hand would result in a reduction of shear strength if the limit is exceeded.

A study on the variation in the amount of joint shear reinforcement in the various axial load values toward the behavior of beam-column-joint was carried out by Masi et al. [5]. Experimental results show how the value of the axial load acting on the columns can change the collapse modes, spreading damage from the beam to the joint panel. The variation of the stress state in the joint panel due to the lower axial load value in the column caused a decrease in its shear strength, resulting in diagonal cracking, which in turn affects the bond between steel bars and concrete. Cracking in the joint panel increased the loss of bond of the longitudinal beam bars in the joint panel, rapidly reducing the flexural strength of the beam. This is different to those already carried out by Asthiani et al. [6]. According to Ashtiani et al. [2], the joint stirrups in the HSSCC specimen with a lower quantity of shear reinforcement experienced higher strain compared with the other two specimens due to the lower axial load value in the column.

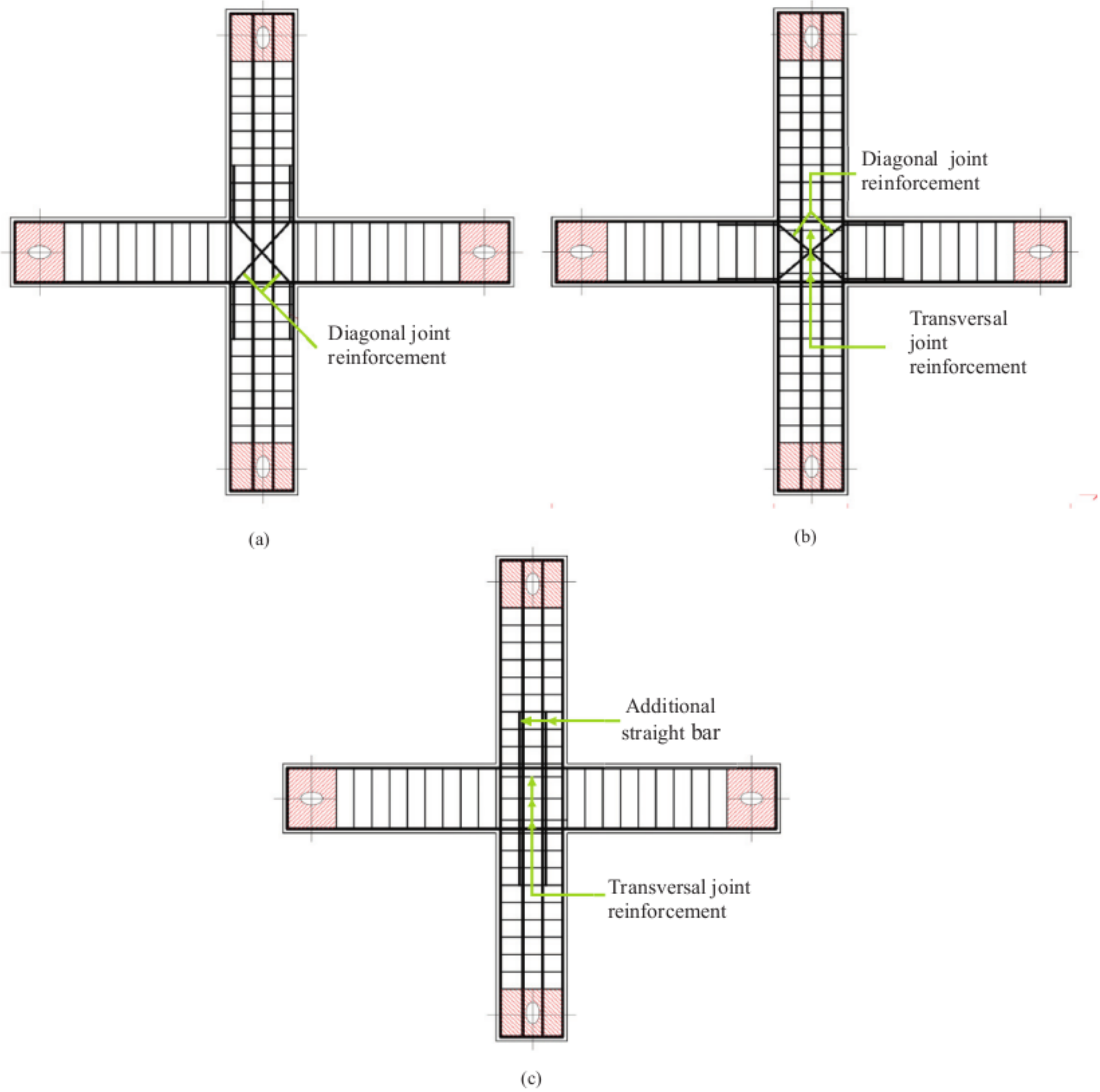


Fig. 3. Joint shear reinforcement with additional bars by Lu et al. (2011) (a) additional diagonal bars along the column (b) additional diagonal bars along the beam (c) additional straight deformed bars

4. Diagonal cross bracing bars joint shear reinforcement

In the development of joint reinforcement, diagonal cross bracing bars have been used to increase the shear strength. As shown in Fig. 3(a), Lu et al. [7] added a reinforcement bars with an overlap approximately 400 mm towards the column's end from the top longitudinal bars in the beam. The test specimen has lower strength when compared to the specimen without additional diagonal bars. The cracks initially developed diagonally, but at higher loading the cracks propagated towards the geometric direction of the diagonal additional bar. Obviously, these joint types are not acceptable in practice both for seismic loading and for gravity loading design.

Another design has diagonal additional reinforcement bars fixed along the beam instead of the column, as shown in Fig. 3(b). Cracks had diagonal patterns but were centralized at the beams and the joint core region. There were minor cracks at the intersection between the beam and column but were of extreme distance away from the joint region. This showed that the additional diagonal bars added sufficient strength to the beam closer to the joint region, which reasonably protected the beam-column-joint interface. This test-specimen has greater strength than the specimen without additional diagonal bars, but the curves are not closer to each other than the previous specimen. Thus at this stage, this specimen is weaker than the rest, as explained above.

The next design has additional straight deformed bars of 12 mm in diameter fixed at the central vertical reinforcement bars of the column on opposite faces. The additional straight deformed bars overlap about 400 mm away from the joint region towards the column ends, as shown in Fig. 3(c).

The crack propagated in the beam was centralized at a distance away from the joint. The joint region happened to have minor obvious cracks. From the cracks observed, this proposed new design was the best. However, additional diagonal bars prevented cracks at the edges of the joint interface between the column and beam. Furthermore, these joints have been proven to behave in a ductile manner as beams undergo plastic hinging earlier than the columns. The strength capability showed by this arrangement happened to be higher, but too slightly.

Different to that Lu et al. [7], Asha and Sundararajan [8] performed tests on specimens with square-spiral confinement in the joint region and additional inclined bars from column to beam (SS2), as shown in Fig. 4. From the lateral load-displacement hysteresis loops of specimens, it is observed that SS2 possessed spindle shaped curves without pinching showing. SS2 is the specimen with the highest load carrying capacity of 15.6 kN. SS2 experienced hairline 'X' shaped cracks in the joint region and full depth cracks in beam region approximately at a distance of 1.5D from the face of column. This confirmed that plastic hinge formed in the beam approximately at the location where the additional inclined bars were curtailed.

Apart from Lu [7], Rajagopal and Prabavaty [9] recommended the use of hair-clips (U-bars) and X-cross bars in combination with T-type mechanical anchorage for the joint details, as shown in Fig. 5. The detail offers a better moment carrying capacity, thereby improving the seismic performance without compromising the ductility and stiffness. Specimen A1 with T-type mechanical anchorage (ACI-352, mechanical anchorage) in combination with hair clips (U-bars) and additional X-cross bars shows lesser cracks and much better control of crack capacity with an improvement in seismic performance compared to other specimens.

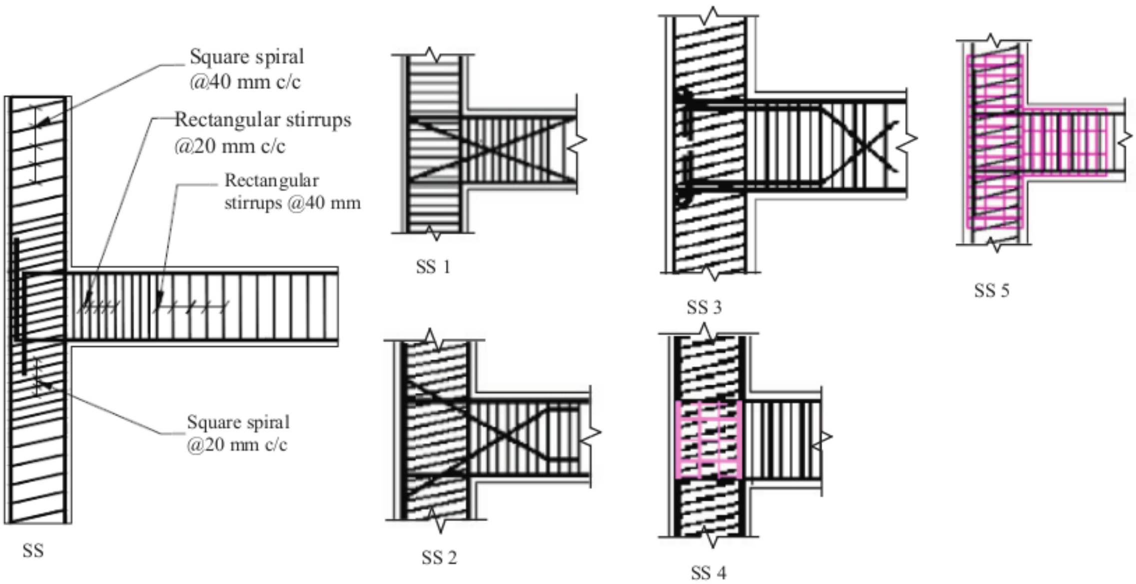


Fig. 4. Typical layout joint shear reinforcement with square spiral confinement and types of anchoring beam bars [8]

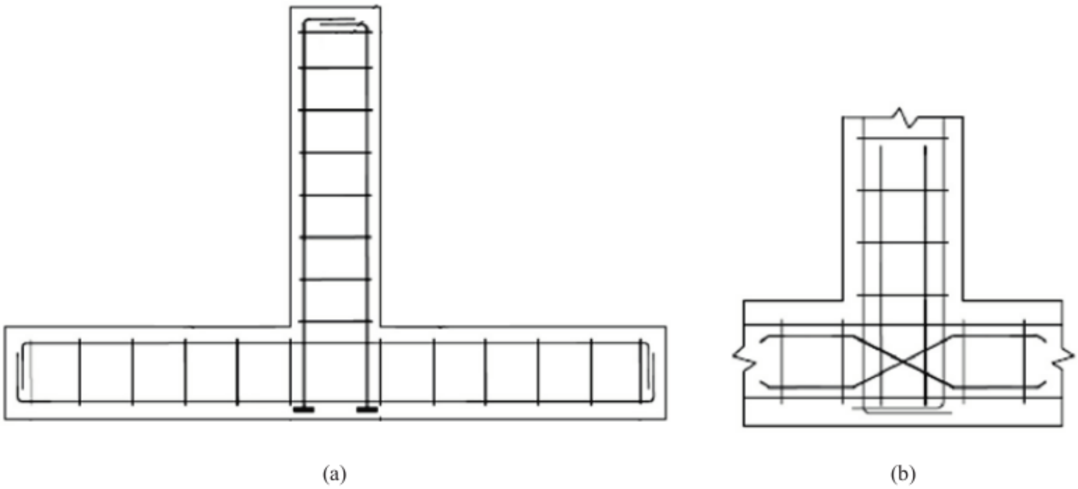


Fig. 5. Typical layout joint shear reinforcement additional hair clip (U-bar) and X-cross bar (a) with the combination of T-type mechanical anchorage joint (b) [9]

5. Steel reinforced concrete beam-column-joint

The next review was conducted on steel reinforced concrete (SRC) beam-column-joints. Chen and Lin [10] and Chen et al. [11] carried out researches of SRC. From the researches performed by Chen and Lin [10] specimen SRC-XH (as shown in Fig. 6(a)) contained a steel beam-column joint where the column cross-sectional steel shape used a cross-H section. Specimens SRC-XH developed diagonal cracks in the joints. The maximum load of the SRC-XH specimen (588 kN) was higher than that of S-XH, SRC-H-SB and SRC H. Where the S-XH specimen is the steel beam column assembly, SRC-H-SB is the SRC with steel beam and SRC H is the SRC with a H profile column. The use of a H cross-section provided significantly more strength than the wide flange section. Compared to the RC beam column specimen, the load-drift angle hysteresis loops of the SRC specimens were developed to a more advanced state and generated a resistant to more energy.

Following Chen and Lin [10], Chen et al. [11] carried out a research of SRC in which the column cross-sectional steel shape used a cross-H section with joint elevation and detail as shown in Fig. 6(b) and Fig. 6(c). From the research it was concluded that the anchorage position of beam longitudinal bars has an influence in the joint shear strength and crack pattern. It is shown that a 6% of the maximum load increase in SRC-XH2-A2 (as shown in Fig. 6b) was resulted, when compared to SRC-XH2. The SRC-XH2-A2 anchorage beam bars are deeper than those of SRC-XH2. Stressed beam-column-joints with the anchorage position A2 (longer development length) had steeper diagonal cracks than those of with the anchorage position A1. The increased depth of cross-sectional steel leads to a higher shear strength for the beam-column-joint. The value of joint shear force is higher in SRC-XH2 than in SRC-XH1, while the column cross sectional of SRC-XH2 is deeper than SRC-XH1.

6. Design of beam-column-joint base on SNI 2847:2013

The standard design of beam-column joints has been proposed in SNI 2847:2013. Therefore, this study will compare the design and performance of the previously discussed method to beam-column-joint based on SNI 2847:2013. The following paragraph deals with beam-column-joint design based on SNI 2847:2013.

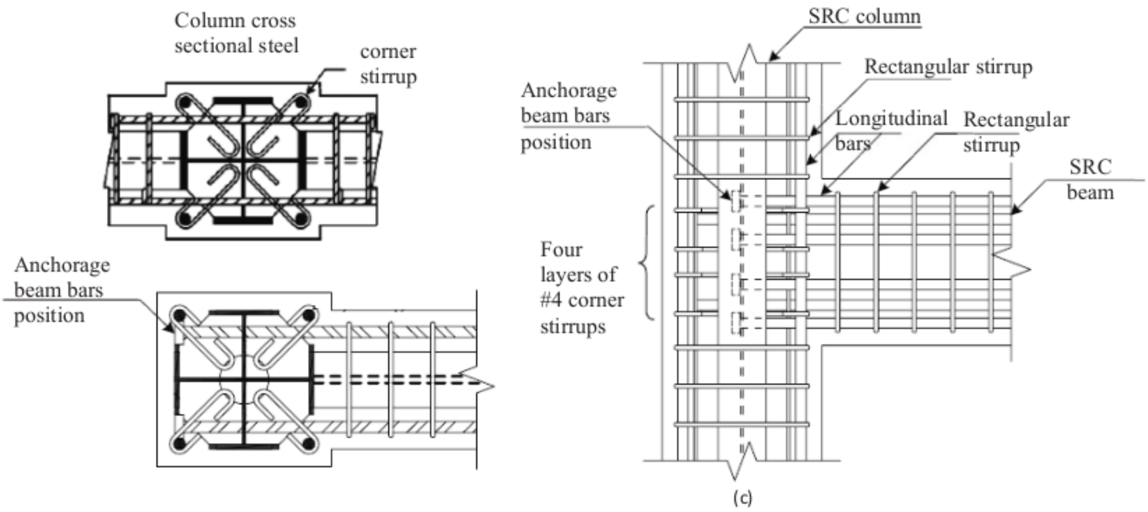


Fig. 6. Specimen SRC contained a steel beam–column joint which the column cross-sectional steel shape used a cross-H section (a) Interior joint [10] (b) exterior joint [11] (c) Joint elevation specimen with A1 anchorage position beam bars [11]

Base on SNI 2847-2013 [12] which refers to ACI 318M-11, the joint design for seismic moment resisting frames has a special detail. Joint transverse reinforcement shall satisfy either requirement of the total cross-sectional area or spacing of reinforcement stirrups. The total cross-sectional area of rectangular hoop reinforcement shall not be less than:

$$A_{sh} = 0.3 \frac{s b_c f'_c}{f_{yt}} \left[\left(\frac{A_g}{A_{ch}} \right) - 1 \right] \tag{1}$$

and

$$A_{sh} = 0.09 \frac{s b_c f'_c}{f_{yt}} \tag{2}$$

Spacing of transverse reinforcement along the length of the member shall not exceed the smaller of:

a. One quarter of the minimum member dimension
b. Six times the diameter of the smallest longitudinal bar
c. s_o, as defined

$$s_0 = 100 + \left(\frac{350 - h_x}{3} \right) \tag{3}$$

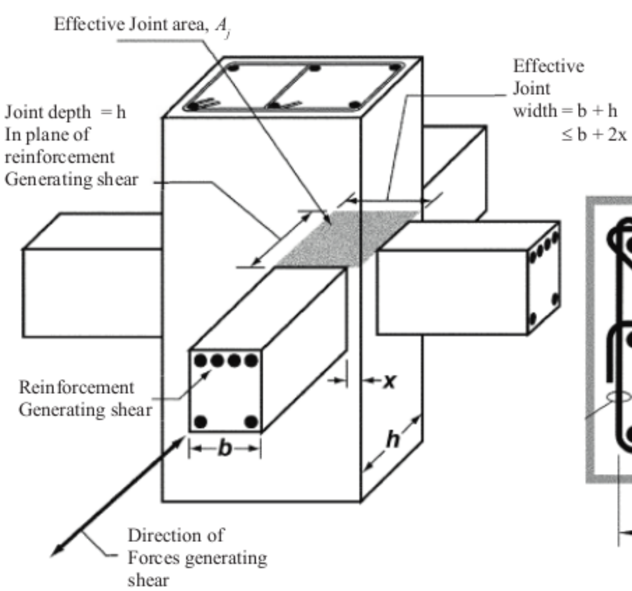


Fig. 7. Effective joint area [12]

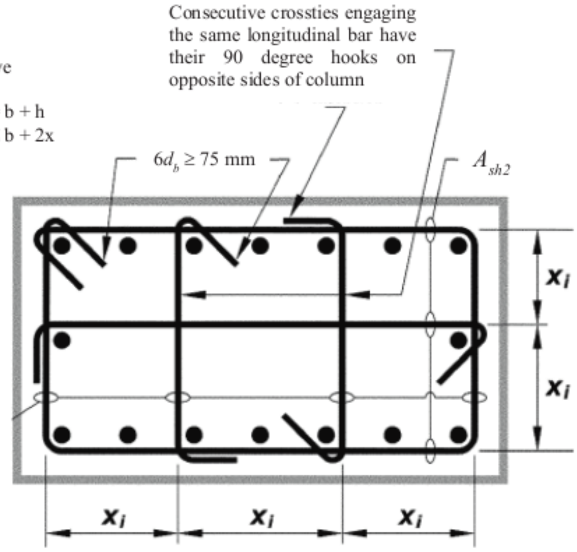


Fig. 8. Example of transversal reinforcement in columns [12]

In terms of designing shear strength V_n, the nominal shear strength of the beam-column joint should exceed the greater of following provisions:

a. For joints confined by beams on all four faces :

$$1.7\sqrt{f'_c}A_j \tag{4}$$

b. For joints confined by beams on three faces or on two opposite faces :

$$1.2\sqrt{f'_c}A_j \tag{5}$$

c. For other cases :

$$1.0\sqrt{f'_c}A_j \tag{6}$$

The guide to determine the effective area of beam-column-joint A_j is shown in Fig. 7 and Fig. 8.
The factored shear force acting on the beam-column joint, V_u, is calculated as follows:

$$V_u = T_1 + C_2 - V_{column} \tag{7}$$

$$= T_1 + T_2 - V_{column}$$

The design of the cross section subject to shear shall be based on

$$\phi V_n \geq V_u \tag{8}$$

where V_u is the factored shear force at the section considered, as Equation (7) and V_n is nominal shear strength computed by

$$V_n = V_c + V_s \tag{9}$$

where V_c is the nominal shear strength provided by concrete calculated in accordance with Equation (4), (5), (6) and V_s is the nominal shear strength provided by shear reinforcement.
When V_u exceeds V_c, shear reinforcement shall be provided. V_s shall be computed in accordance with

$$V_s = \frac{A_v f_{yt} d}{s} \tag{10}$$

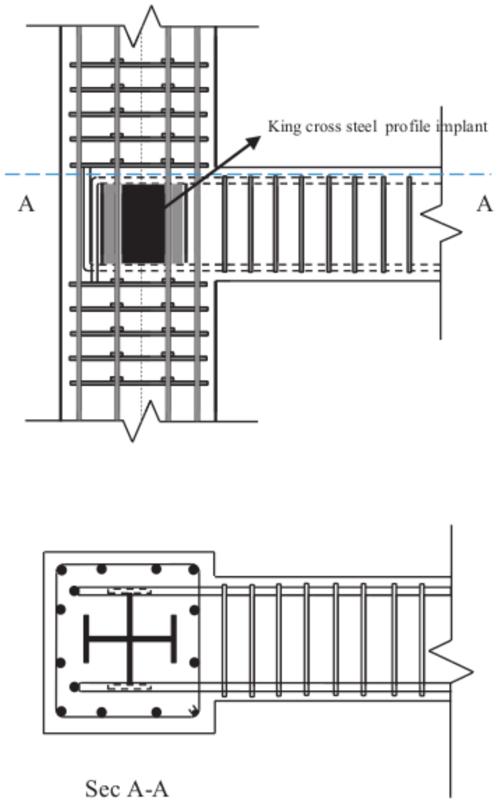


Fig. 9. Detail of exterior beam-column-joint design proposed

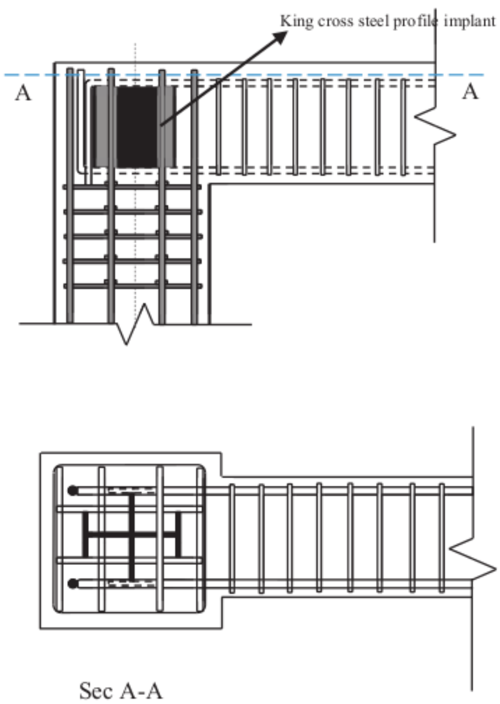


Fig. 10. Detail of corner beam-column-joint design proposed

7. Further study of beam-column-joint design

Evaluating the data base, several flaws in the design of beam-column-joint were detected, namely the low shear strength and ductility, and shear failure in the joint should be avoided. The use of stirrups in the joint reinforcement is limited by the maximum value of the ratio of joint reinforcement. When exceeded, this will result in an over reinforced design and decrease in the shear strength of the joint. In the past it was shown that the use of diagonal cross bracing as joint shear reinforcement has had various results. The test specimen has the lower strength while compared to the test specimen without additional diagonal bars [7]. The research conducted by Chen et al. [11] showed a good performance of the SRC structure when compared to steel or reinforced concrete structure in term of strength, ductility and stiffness of the structure. Therefore, in this study it was proposed to use the assemblies of SRC in the joint core using a King-cross steel profile. The assemblies can be applied in the corner joint, exterior joint and interior joint. As a comparison the used of conventional joint design based on SNI 2847 : 2013 [12] was presented.

A King-cross steel profile is embedded in the joint to increase the shear strength and ductility of the joint. The cross-section configuration of a King-cross resembles two Hs crosses. A King-cross steel profile is selected because it can provide a higher shear strength contribute to the joint when compared to a H section. This is because the shear force is not only carried by the longitudinal web but also the longitudinal flange.

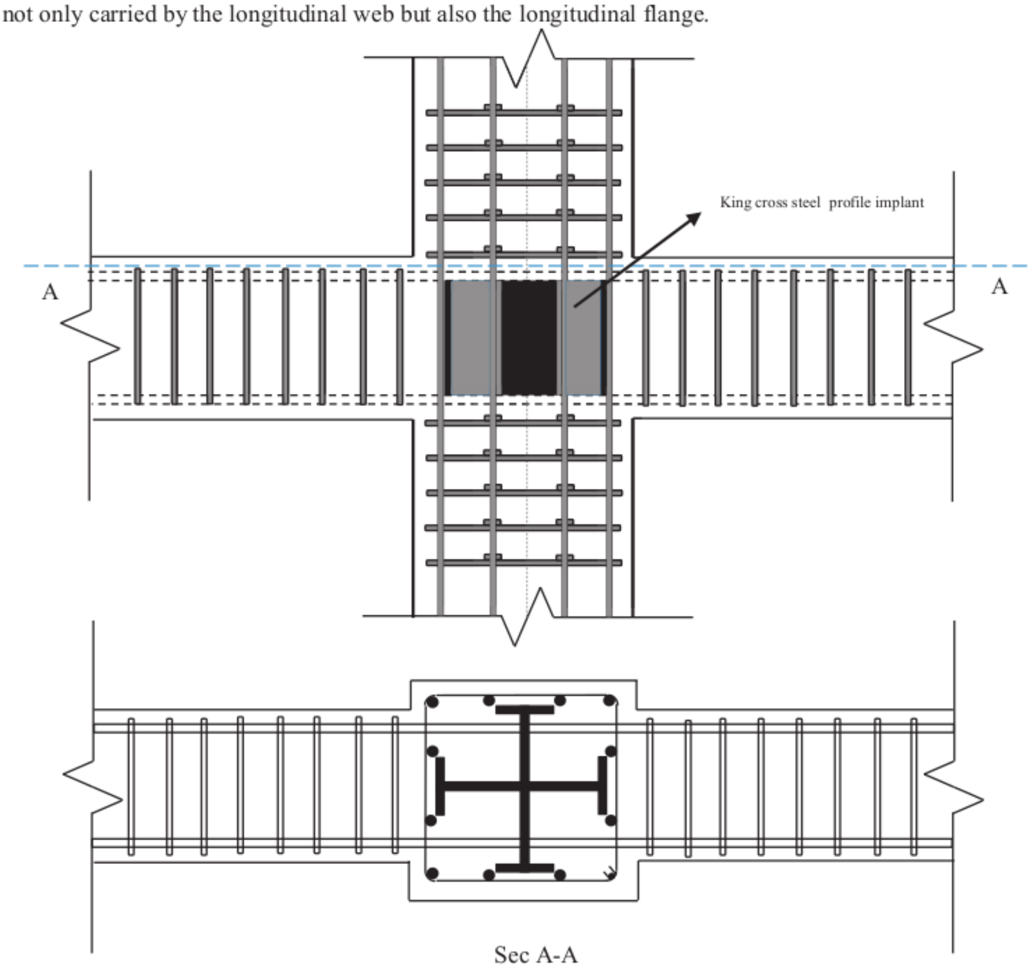


Fig. 11. Detail of interior beam-column-joint design proposed

Fig. 9 shows details of the proposed exterior beam-column-joint design. There is an anchorage and it also presents the development length of beam bars in the specimen. The implant of the steel King-cross profile within the joint has a height not exceeding the maximum space between the top and the bottom beam bars. And the width of the King-cross steel profile does not exceed the width of the space between the anchorage of the bars and column bars.

Fig. 10 shows details of the proposed corner beam-column-joint design. This specimen there has an anchorage of beam bars on the side edge and an anchorage of column bars on the top edge. This configuration yields in a smaller joint space compared to the two other specimens. To determine the influence of the dimension of the King-cross profile towards the performance of the joint, the experiment will use various dimensions of the King-cross. To increase the performance of the joint towards the shear force, a King-cross steel profile is attached to the steel bar by means of welding of the contact area between the King-cross profile and the bars.

Fig. 11 shows details of the proposed interior beam-column-joint design. This specimen has no anchorage in the beam and column bars. The space formed in this specimen is the greatest compared to the joint space formed by the other specimen, thus allowing the use of a larger King-cross profile.

8. Conclusions

From the studies above, the method and the performance of reinforced concrete (RC) beam-column-joints can be concluded. Further studies are highly encouraged. The important points of suggestion are:

- The failure of large beam column specimen occurred in the joint rather than in the adjoining members or beam, proved that the joint shear strength methods have been carried out inadequately.
- An upper limit of the horizontal stirrup ratio in designed beam-column joints under seismicity exists. Additional transverse reinforcement provided to the joint may have less effect in the joint shear strength enhancement.
- T-type mechanical anchorage joint detail offers a better moment carrying capacity, thereby improving the seismic performance. The anchoring method was used in the purpose study.
- In the past it was shown that diagonal cross bracing bars as joint shear reinforcement have had various result. The test specimen has a lower strength when compared to the test specimen without additional diagonal bars.
- Compared to the RC beam column specimen, the load-drift angle hysteresis loops of the SRC specimens were more saturated and dissipated more energy.
- Based on the performance of beam-column-joint in the previous experimental research that proposed the utilizing of a King-cross steel profile within joint core, it was shown that this configuration provided significantly more strength and ductility than the conventional shear reinforcement joint. Hence its application can be suggested to be studied further for providing a design alternative of beam-column-joint.

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