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Analysis and design of reinforced concrete beam-column joint using king cross steel profile

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Abstract

The limitation or the neglecting of concrete role in resisting the shear stress causes the need of high amount of steel bars reinforcement in beam-column joints. This will cause problem if the steel bars reinforcement congestion occurs where the steel bars reinforcement may not be easy to be installed.This paper discuss the analysis and design of king cross steel profile to be implemented as alternative reinforcement in reinforced concrete beam-column joints. With the simplifying assembling 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. Therefore various arrangements of beam-column reinforcement are studied analytically.
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Keywords: beam-column joint, joint shear force, joint shear reinforcement, concrete shear strength of joint, king cross profile

1. Introduction

The beam column joint is a crucial area where the transfer of loads from the beams and columns occur. Seismic load causes great shear force that occurs at the joint. This behavior is very different when is compared to the behavior of the joint due to gravity loads. Due to seismic load, the beams which assamble in the joint, resist the moment that is opposite direction. Thus the increase of the shear force in the joint occures. So that the design capacity of the joint must be strong enough to ensure that the adjoin mambers achieve plastic deformation. In the interior joint, action occurs in the both directions, so it requires a complex design.

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In the design of the conventional beam-column joint, the shear forces that occur in the joint, are resisted by joint stirrup together with concrete through the truss and the strut mechanism. The failure of the joint should be avoided so that the requirement for the joint shear stirrups becomes very large. The large requirement of the joint stirrup causes the space of the stirrups is too dense hence the minimum allowable distance between reinforcement. When the space between the reinforcement bars is too dense, it will cause incomplete consolidation, increased permeability and strength reduction of the concrete [1].

The use of king cross steel profiles on reinforced concrete columns can increase the shear capacity of the beam column joint 40% higher than the use of H steel profiles [2]. Based on these research and the existing problems, the use of king cross steel profiles in the joint is expected can reduce the use of joint stirrup to solve the congesten problem in the joint.

The use of king cross steel profiles in the joint to increases the shear capacity without enhance the number of stirrups to avoid failure in the joint so that result the strong column weak beam mechanism. With adequate joint shear capacity is expected to reach inelastic capacity of flexural beam and the mechanism of plastic deformation in design can develop and be maintened.

2. The shear requirement of the beam column joint

The beam column joint resists the shear forces (V_j) that are calculated base on the shear capacity of the adjoining beam. And the capacity of the joint stirrup should not be less than the shear requirement of the joint that is supported. Thus the requirement for the joint stirrup is by calculate the horizontal shear force that through the beam column joint as

$$V_j = (f_sA_s)_1 + C_2 - V' = (f_sA_s)_1 + (f_sA_s)_2 - V' \qquad (1)$$

Where $(f_sA_s)_1$ and $(f_sA_s)_2$ = top and bottom longitudinal beam reinforcement and V' = column horizontal shear force.

3. The shear capacity of the beam column joint

3.1. The Joint shear capacity based Park and Paulay, 1974 [3]

1. The concrete shear capacity of joint

The concrete shear capacity of joint (v_c) according to Park and Paulay are calculated by a beam shear design without stirrups that sustain the shear forces and the axial compression (Figure 1a). Conservative prediction of the beam shear strength without the shear reinforcement (stirrup), which incorporate various factors that are tensile strength of concrete which is measured by the parameters $\sqrt{f'_c}$, crack control $\rho_w = A_s/b_w d$ and the ratio of shear span to depth M/Vd in the equation

$$v_c = \frac{V_c}{b_w d} = 1.9\sqrt{f'_c} + 2500\rho_w \frac{V_u d}{M_u} \le 3.5\sqrt{f'_c} \qquad (2)$$

Because of Equation (2) is often difficult to apply in the design, ACI 318-71 permit the use of more simple equation to calculate V_c that undergo the column axial force (N_u) in column area (A_g) into

$$v_c = 0.2905\sqrt{f'_c}\sqrt{1 + 0.2903\frac{N_u}{A_g}}\ (MPa) \qquad (3)$$

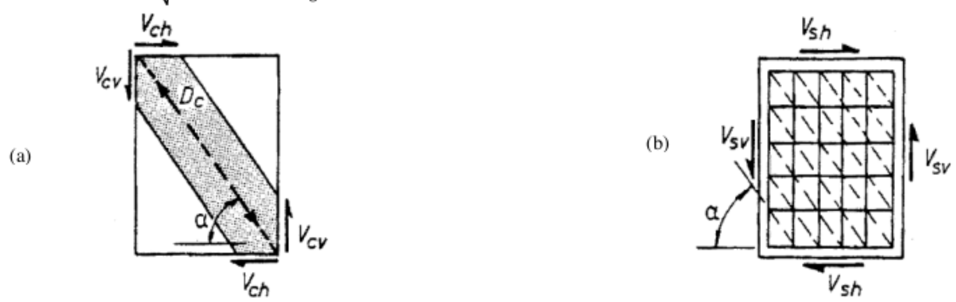

Figure 1. Portion of joint shear capacity by (a) diagonal concrete strut (b) diagonal compression field parallel to the diagonal concrete strut with stirrup reinforcement proposed by Park and Paulay (1974) [4]

If the axial compressive force in the column (N_u) causes the stress on the gross cross-section is less than 0,12f'_c, the contribution of the shear resistance of concrete should be ignored.

2. The shear capacity of the joint stirrup

The shear capacity of the joint stirrup (V_s) that described in Figure 1b is calculated using two methods:

1) The shear capacity of the joint stirrup based on the truss mechanism

The analogy between the shear resistance of the truss and the beam stirrups are concept in concrete structures. The analogy defined that the truss is equivalent to the stirrups and acts as a tensil element. While the concrete strut parallel to the diagonal cracks, generally the concrete strut angle is 45^o to the beam axis.

Where A_v is the area of the stirrups reinforcement that is at s distance along the beam and f_s is the stress of the stirrups. The area requirement of the stirrup reinforcement area (A_v) on ideal strength if $f_s = f_y$ be

$$A_v = v_s \frac{sb_w}{f_y} \quad (4)$$

2) In the interior joint, the intire stirrup at the joint core will participate in the shear resistance. Then the stirrup requirement is

$$A_v = \frac{V_s s}{(d-d')f_y} \quad (5)$$

Where in (d-d') is the distance between the center point of the top and the bottom beam reinforcement

3.2. The Joint shear capacity based on SNI 03-2847-1992 [5]

1. The concrete shear capacity of joint

The joint mechanism to continu the horizontal shear force passes through the joint are the diagonal concrete strut and the truss panel mechanism. The shear force that is carried by the strut concrete V_c should be taken equal to zero except the compressive stress of column section satisfy. The minimum average of compressive stress on the gross cross section of concrete column above the joint should exceed 0.1f'_c. So that the shear resistance of the strut concrete joint is taken by

$$V_{ch} = \frac{2}{3}\sqrt{\left(\frac{N_{u,k}}{A_g}\right) - 0.1f'_c}\, b_j h_c \quad (6)$$

2. The shear capacity of the joint stirrup

The mechanism of truss panel consists of the horizontal stirrups with the shear capacity V_{sh}. If the concrete diagonal strut has the shear capacity V_{ch}, so that the shear force design which is retained by horizontal shear reinforcement of joint is

$$V_{sh} = V_{jh} - V_{ch} \quad (7)$$

While the total effective area of the stirrups that are placed in the joint can not be less than

$$A_{jh} = \frac{V_{sh}}{f_y} \quad (8)$$

4. The shear strength of the steel structure component based on AISC 360-10 [6,7]

The nominal shear strength, V_n of the area of unstiffened or stiffened webs (A_w) according to the limit states of the shear yielding and the shear buckling is

$$V_n = 0.6F_y.A_w.C_v \quad (9)$$

For webs of all other doubly symmetric shapes and singly symmetric shapes and channels, except round *HSS*, the web shear coefficient, C_v, is determined as follows:

(i) When $h/t_w \leq 1{,}1\sqrt{k_v E/F_y}$ so $C_v = 1.0$ (10)

(ii) When $1.10\sqrt{k_v E/F_y} < h/t_w \leq 1.37\sqrt{k_v E/F_y}$ so

$$C_v = \frac{1.10\sqrt{k_v E/F_y}}{h/t_w} \quad (11)$$

(iii) When $h/t_w > 1.37\sqrt{k_v E/F_y}$ so $C_v = \frac{1.5 k_v E}{(h/t_w)^2 F_y}$ (12)

5. The shear strength of Steel Reinforced Concrete (SRC) of interior joint [2]

The evaluation method of the shear strength that is the most commonly used method and suitables the for beam column joint is the method of superposition strength. Where the shear strength are contributed either by cross-section of steel profile and reinforced concrete that are counted separately initially, then these two forces are superposed to obtain SRC joint strength.

The shear strength contributions of the king cross steel profile are

(1) The contribution of the web of the king cross cross section

For columns with the king cross steel section as in Figure 2, the shear strength of the joint along the plane of the web is mainly retained by the web. According to the specifications of AISC - LRFD, the shear strength is retained by the web V_{sw} as

$$V_{sw} = 0.6 F_{yw} d_c t_w \quad (13)$$

where F_{yw} = yield stress of web, d_c = height of the web, dan t_w = thickness of the web.

(2) The contribution of the flange of the king cross cross section

No method of calculation of the shear strength is provided by the design specifications for the king cross steel cross section that is used in the column. The shear strength contribution of longitudinal web can be calculated according to Equation (13). In addition it is also proposed the shear strength that is provided by two longitudinal flanges V_{slf} which is estimated at

$$V_{slf} = 2 \times \left[\frac{2}{3}\left(0.6 F_{yf} \times A_f\right)\right] \quad (14)$$

The shear strength calculation V_s defined as the sum of V'_{sw} and V_{slf}. The V_t/V_s ratio is very close to 1, this proves that the calculation of the shear strength is in accordance with the test results. V_{slf}, contributed 57% of the shear strength of the joint.

6. The analysis and design of beam column joint

Step by step beam column joint design is

1. Determine the material properties and the beam column joint dimension
2. Calculate the design shear force of beam column joint
3. Calculate the concrete shear resistance of beam colum joint
4. Calculate the design shear force of the horizontal shear stirrup of the joint
5. Calculate the design shear force of the king cross steel profile of the joint
6. Create the type of the beam column joint design
7. Calculate the amount of the horizontal shear stirrup of the joint
8. Calculate the dimension of the the king cross steel profile of the joint
9. Calculate the nominal shear capacity of the beam column joint design

6.1. Determine the material properties and the beam column joint dimension

The dimensions and material properties of the beam column joint (Figure 2) that is designed based on the analysis of two-storey structures in seismic regions [8] are as follows:
The concrete compressive strength f'_c = 28.31 MPa
The yield strength of longitudinal bar f_y = 393.19 Mpa
The yield strength of transversal bar f_y = 373.72 Mpa
The yield strength of king cross profile f_y = 245 Mpa
The column axial load P_u = 180 kN
The concrete cover = 25 mm

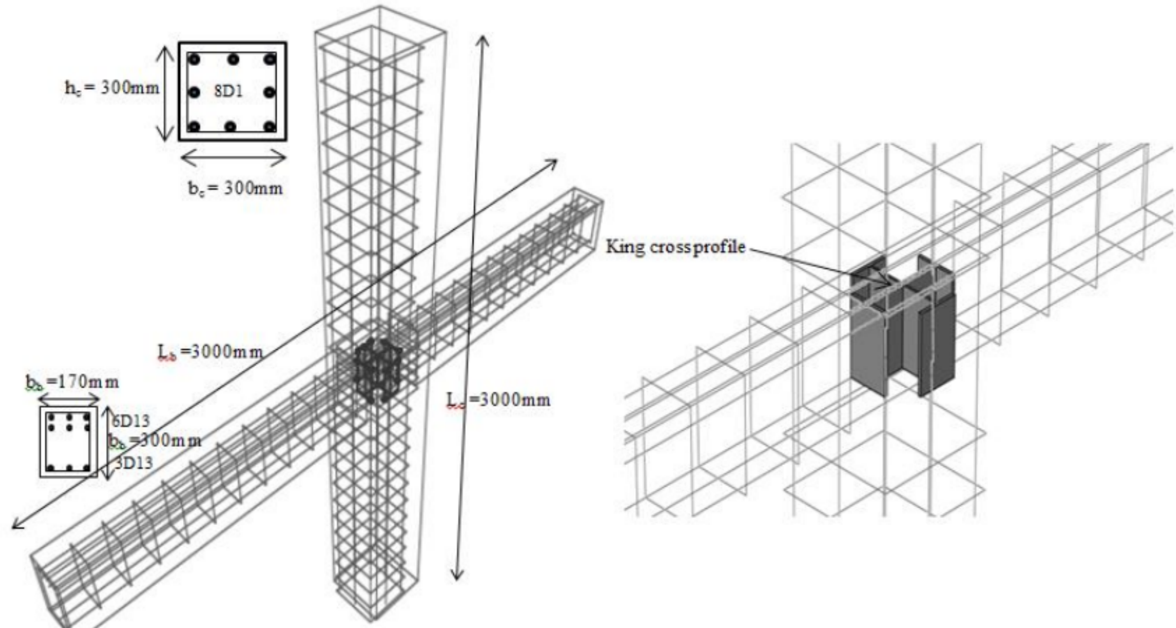

Figure 2. Dimension of beam column joint with king cross profile

6.2. Calculate the design shear force of beam column joint

The magnitude of the shear force of the joint is the difference in the amount of the beam tension and the compression force to the horizontal shear force that works on the column.

$$V_u = T_s + C_s - V_c \quad (15)$$

The amount of the shear force design is calculated by various method and are tabelated as follows:

Table 1. The joint shear force design (V_u)

Analysis method	M beam ($M_{pr,b}$)	Column shear force (V_c)	Beam tension (T_s) and compression force (C_s)	The joint shear force design (V_u)
ACI- ASCE (352R-02) [9]	$M_{pr,b1} = A_{s1}\alpha f_y\left(d - \frac{a}{2}\right) = 46.3\ kNm$ $M_{pr,b2} = A_{s2}\alpha f_y\left(d - \frac{a}{2}\right) = 75.8\ kNm$	$V_c = V_{c1} + V_{c2} = \left(M_{pr,b1} + M_{pr,b1}\right)\left(\frac{1}{l_c} + \frac{h_c}{2 l_b l_c}\right) = 45.22\ kN$	$T_s = \alpha f_y A_{s1} = 195.709\ kN$ $C_s = \alpha f_y A_{s2} = 391.418\ kN$	$V_u = T_s + C_s - V_c = 541.9033\ kN$

Park dan Paulay, 1974	$M_{pr,b1} = A_{s1}\alpha f_y(d_1 - d'_2) = 39.53\ kNm$ $M_{pr,b2} = A_{s2}\alpha f_y(d_2 - d'_1) = 79.066\ kNm$	$V_c = V_{c1} + V_{c2} = (M_{pr,b1} + M_{pr,b1})\left(\frac{1}{l_c} + \frac{h_c}{2l_b l_c}\right) = 43.926\ kN$	$T_s = \alpha f_y A_{s1} = 195.709\ kN$ $C_s = \alpha f_y A_{s2} = 391.418\ kN$	$V_u = T_s + C_s - V_c = 543.200\ kN$
Response 2000	$M_{pr,b1} = 47.9\ kNm$ $M_{pr,b2} = 73\ kNm$	$V_c = V_{c1} + V_{c2} = (M_{pr,b1} + M_{pr,b1})\left(\frac{1}{l_c} + \frac{h_c}{2l_b l_c}\right) = 44.778\ kN$	$T_s = 255\ kN$ $C_s = 359\ kN$	$V_u = T_s + C_s - V_c = 569.222\ kN$
Analisis layer	$M_{pr,b1} = C_c\left(C - \frac{a}{2}\right) + C_s f'_s(C - d') + T_{s1} f_s(d" - C) + T_{s2} f_y(d - C)$ $M_{pr,b2} = 41.486\ kNm$ $M_{pr,b1} = C_c\left(C - \frac{a}{2}\right) + C_s f'_s(C - d') + T_{s1} f_Y(d" - C) + T_{s2} f_y(d - C)$ $M_{pr,b2} = 67.25\ kNm$	$V_c = V_{c1} + V_{c2} = (M_{pr,b1} + M_{pr,b1})\left(\frac{1}{l_c} + \frac{h_c}{2l_b l_c}\right) = 40.273\ kN$	$T_s = A'_s f'_s + A_s f_y = 256.364\ kN$ $C_s = A'_s f'_y + A_s f_y = 313.134\ kN$	$V_u = T_s + C_s - V_c = 529.226\ kN$
SAP 2000	$M_{pr,b1} = 44.695\ kNm$ $M_{pr,b2} = 67.77\ kNm$	$V_c = 41.98\ kN$		

The analysis results show that the calculation of the beam moment ($M_{pr,b}$), the column shear force (V_c), the beam tension force (T_s) and the beam compression force (C_s) of all the method are similar saficiently. So that the calculation result of the joint shear force design (V_u) can be consider significant. And to avoid the joint failure than is taken the largest V_u value is $V_u = 569.222$ kN.

6.3. Calculate the concrete shear capacity of joint

The joint shear capacity (V_u) contributed by the concrete shear capacity (V_c) and the shear capacity of the joint stirrup (V_s), so formulated as follows:

$$\boldsymbol{V_u = V_c + V_s} \tag{16}$$

The concrete shear capacity of joint is calculated using Equation (3) based on ACI 318-71 and Equation (6) based on SNI 03-2847-1992 by ignoring the column axial load minimum limit.
The amount of the concrete shear capacity of joint (V_c) are tabulated in Table 2.

Table 2. The concrete shear capacity of joint

Method of the joint concrete shear strength	V_c (kN)
ACI 318-71	174.89
SNI 03-2847-1992	0

From all of the values, the value of Equation (3) based on ACI 318-71 is considered more closer to the actual of the concrete shear capacity of joint so that is used as the concrete shear capacity of joint V_c = 174.89 kN.

6.4. Calculate the design shear force of the joint stirrup and the king cross steel profile

The amount of the design shear force that must be resisted by stirrups according Equation (16) is

$$\boldsymbol{V_s = V_u - V_c} \tag{17}$$

So that the design shear force that must be resisted by stirrups is V_s = 394.3304 kN and the the design shear force that must be resisted by king cross profile that replaces stirrup is

$$V_k = V_s = 394.3304 \text{ kN} \tag{18}$$

6.5. Create the type of the beam column joint design

The types of the beam column joint design are created as in Table 3.Variety on the design shear force of the joint stirrup and the king cross steel profile is conducted by the purpose to find out the change of the profile dimension and the amount of stirrup that are installed on the joint. The increases of the design shear force involve enhancement of the amount of the stirrup and steel. The number of stirrups that are required can be reduced with the use of king cross steel profiles, because the use of stirrups in large numbers will complicate the joint installation. And the use of stirrups with large diameter will induce the difficulty process of bending stirrups.

Table 3. The type of the beam column joint design

Types of joint design	Joint shear capacity		
	Contribution of concrete shear capacity (kN)	Contribution of stirrup shear capacity (kN)	Contribution of king cross profile shear capacity (kN)
DS-1	V_c	V_s	-
DS -2	V_c	$3/4V_s$	$1/4V_k$
DS -3	V_c	$1/2V_s$	$1/2V_k$
DS -4	V_c	$1/4V_s$	$3/4V_k$
DS -5	V_c	-	V_k

Chen and Lin, 2009 calculated the shear strength of SRC interior joint using the strength superposition method. Under this method, the design shear force of beam column joint (V_u) will be calculated by combining the concrete shear capacity (V_c), the stirrup shear capacity (V_s) and the king cross shear capacity (V_k) as follows:

$$V_u = V_c + V_s + V_k \tag{19}$$

6.6. Calculate the amount of the joint stirrup and the dimension of the the king cross steel profile

To calculate the joint stirrup is used Equation (4) based on the truss mechanism (Park and Paulay, 1974), Equation (5) based on force mechanism (Park and Paulay, 1974), and Equation (8) based on SNI 03-2847-1992. The amount of joint stirrup based on that equations are shown in the formation of stirrup bar diameter and spacing in Table 4.

Table 4. The horizontal shear stirrup of joint design

Types of joint design	Shear capacity of stirrup	Eq. 4	Eq. 5	Eq. 8
DS-4	¼ Vs	ϕ8-80	ϕ 8-60	ϕ 8-120
DS-3	½ Vs	ϕ 8-48	ϕ 8-30	ϕ 8-48
DS-2	¾ Vs	ϕ 8-30	ϕ 8-24	ϕ 8-35
DS-1	Vs	ϕ 8-24	ϕ 8-16	ϕ 8-24

And to avoid the failure of the joint then is taken the greatest value of A_{sn}.

To calculate the king cross steel profile of the joint (Figure 2) used Equation (9), (10), (13) and (14). Equation (9) and (13) are modified into

$$V_{sw} = F_{yw}.H.t_1.C_v \quad (20)$$

And Equation (14) is modified into

$$V_{sf} = 2 \times (F_{yw}.B.t_1) \quad (21)$$

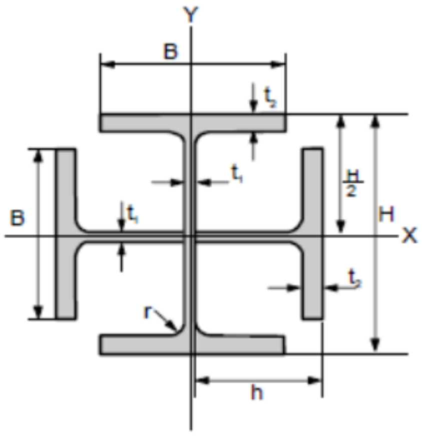

Figure 2.. King cross profile cross section

Both Equation (20) and (21) will provide the smaller dimension of king cross steel profile because the equation does not consider the shear factor reduction. So the shear strength of king cross profile (V_k) becomes

$$V_k = V_{sw} + V_{sf} \quad (22)$$

Based on the value of V_k obtained from equation (2.4), the dimension of king of cross profile can be seen in Table 5.

Tabel 5. The dimension of king of cross profile

Types of joint design	Shear capacity of profile	H (mm)	B (mm)	t_1 (mm)	t_2 (mm)
DS -2	¼ V_k	85	40	2	3
DS -3	½ V_k	110	60	3	4
DS -4	¾ V_k	130	70	4	5
DS -5	V_k	165	80	4	6

6.7. Calculate the nominal shear capacity of the beam column joint design

Shear capacity of joint design is a superposition of the the concrete shear capacity, stirrup nor king profile cross. From the fifth of the design type, the nominal shear capacity (V_n) is fully satisfy the design shear force (V_u). But the design types of DS1 and DS2 have stirrups spaced too tightly, so it is less than the required space of reinforcement. In the design of DS3 and DS4, by application of the king cross profile the use of the stirrup can be reduced so that the stirrup space can qualify the minimum distance of stirrup reinforcement.

Tabel 6. The nominal shear capacity of the beam column joint design

Types of joint design	The amount of the joint stirrup (stirrup bar diameter – spacing in mm)	The dimension of the king cross steel profile	The concrete shear resistance (V_c) (kN)	The nominal shear force of the stirrup design (V_{sn}) (kN)	The nominal shear force of the king cross steel profile design (V_k) (kN)	The nominal shear capacity of the beam column joint design (V_n) (kN)	The design shear force of beam column joint (V_u) (kN)
DS-1	ϕ8-16	-	174.892	474.33	-	649.222	569.22
DS -2	ϕ8-24	85.2.40.3	174.892	316.22	100.450	591.562	
DS -3	ϕ8-30	110.3.60.4	174.892	252.97	198.450	626.312	
DS -4	ϕ8-60	130.4.70.5	174.892	126.49	298.90	591.282	
DS -5	-	165.4.80.6	174.892	-	396.9	571.792	

7. Conclusion

From analysis and design of both the conventional and the beam-column joint using king cross profile above can be taken several conclusions as follows :

1. Joint strength superposition method not only consider the capacity of concrete shear joint. In this method there is no limitation in minimum dimensions of the concrete joint. In the method of superposition, the joint shear capacity is a combination of the concrete joint shear capacity, the stirrup joint shear capacity and the shear capacity of steel profile.
2. The design shear capacity is calculated based on the methods of ACI-ASCE R-02, Park Paulay 1974, Response 2000, Layer analysis produce the shear capacity design that approach one another. While the results of the calculation for the column shear force approach to calculation with SAP 2000.
3. The shear capacity of the joint concrete is calculated based on ACI 318-71 generate the shear force capacity much greater than the shear capacity of joint concrete that is calculated based on SNI 03-2847-1992 (ACI 318-83).
4. Number of stirrup generated from the calculation based on the Equation (4), (5), (8), produce the number of stirrups which approach one another
5. In conventional design of beam-column joint, the joint space stirrups is from 16 to 24 mm in stirrup diameter by 8 mm. Spacing is less than the minimum distance allowed between two rebars, so it will cause congesten problem. when the clear spacing between rebar is less than 1⅓ times the maximum size of coarse aggregate.
6. DS-3 and DS-4 is an ideal design, with a spacing stirrup eligible.
7. From design and analysis has been done, then suggestions for future research is to conduct experimental research to determine the strength of the joint superposition method validation against experimental results.

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