ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

Simplified Model for Shear Strength Prediction of RC Exterior Beam-Column Joints

[1] Kanak N. Parate, [2] Dr. Ratnesh Kumar
[1] Research Scholar, [2] Assistant Professor,
Department of Applied Mechanics, Visvesvaraya National Institute of Technology,
Nagpur, India.

***Abstract:*— Poor performance RC beam-column joints have been recognized as the main cause of failure of many RC framed buildings in the past earthquakes. The techniques to determine the strength of joints have been proposed by many researchers; however, the significant difference observed between the results of experimental and analytical models. The experimental database consisting of 100 exterior joints from the literature have been considered for the parametric analysis. In present study the influence of various significant parameters such as concrete compressive strength, beam longitudinal reinforcement, column axial load, dimensions of interconnecting beam and column, and joint shear reinforcement have been evaluated and an empirical joint shear strength model has been proposed. The model considers the appropriate contribution of various aforementioned parameters. The predictions of proposed joint shear strength model along with the earlier proposed six empirical models have been compared with the experimental database. It has been observed that the prediction of the proposed model is more precise than other previously proposed models. Moreover, the proposed model is comprehensive and simplified, and can be readily used in design offices.**

***Index Terms*— reinforced concrete, beam-column joint, joint shear strength, parametric study**

I. INTRODUCTION

Even though, the study of behavior of RC beam column joints under seismic loading and endeavors for predicting the joint shear strength has started long back [1], the collapse of many RC buildings in recent past under seismic loading has been attributed to failure of beam-column joints [EI Asnam 1980, Mexico 1985, LomePrieta1989, Izmit Turkey 1999, Chi-Chi Taiwan 1999]. As a matter of fact, the prediction of accurate joint shear strength is difficult task since it depends on complex interactions of various parameters. Many researchers have proposed analytical and empirical models for predicting joint shear strength; however, theses analytical models are generally based on limited set of experimental test results.

From literature, parameters such as beam width, beam depth, column width, column depth, concrete compressive strength, yield strength of reinforcement, amount of column and beam reinforcement, shear reinforcement inside joint zone and axial compressive load from column have been identified as crucial parameters affecting joint shear strength [2,3]. Considering some of the aforementioned parameters, various analytical models for computing joint shear strength have been proposed. Empirical models are generally developed by assessing the effect of various parameters influencing the joint shear strength using experimental database. In the early years, experiments by Taylor in 1974 paved the way for formulation of recommendations of BS8110 [as reported by Scott et al. 1994]. Later Sarsam and Philips (1985) proposed a model considering several influencing parameters i.e. concrete strength, column longitudinal reinforcement ratio and column axial load based on the calibration of experimental database. In the same way, Bakir and Boduroğlu (2002) considered the additional parameter of beam longitudinal reinforcement in the formulation but neglect the effect of column reinforcement and axial load. Based on the regression analysis of experimental database for different parameters, Hegger (2003) proposed an empirical model. Russo and Somma (2006) developed model, considering contribution of strength of both concrete and reinforcement based on evaluation of experimental database. Based on probabilistic analysis method, Kim et al. (2009) proposed empirical model for reinforced exterior joint using large experimental database. Recently, Tran et al. (2014) proposed empirical model for both interior and exterior joint considering the additional new parameter of bond strength in parametric analysis and validated with huge experimental database. Based on the experimental test results database from the past, Lima et al. (2012) performed the relative study of different joint shear strength models.

In present study the empirical joint shear strength predictive models presented by six researchers viz. Sarsam and Phillips (1985), Vollum and Newman (1999), Bakir and Boduroğlu (2002), Hegger et al. (2003), Kim et al. (2009),

IFERP
connecting engineers... developing research
ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

and Tran et al. (2014) have been considered for investigation. These analytical models are then compared with a collected experimental database of exterior beam-column joint results. This report brings out the limitations of the aforementioned six models and identifies the effect of different parameters considered in the formulation. The new empirically determined model for the joint shear strength has been presented and found more efficient than earlier proposed model for the considered experimental database.

II. REVIEW OF PREVIOUS EMPIRICAL MODELS

Various approaches towards the exact prediction of joint shear strength have been made in the past. In this, the existing six empirical models by various researchers viz., Sarsam and Phillips (1985), Vollum and Newman (1999), Bakir and Boduroğlu (2002), Hegger et al. (2003), Kim et al. (2009), and Tran et al. (2014) have been evaluated in detail along with their applicability and limitations.

Sarsam and Phillips (1985) proposed an analytical model for the design of monotonically loaded exterior beam column joints. This model considers mainly the effect from concrete compressive strength, percentage of column reinforcement, axial stress from column, yield strength of reinforcement and joint shear reinforcement.

$$V_j = 5.08 f_c \rho_c 0.33 \frac{h_c}{h_b} 1.33 b_c h_c \sqrt{\left(1 + 0.29 \frac{N}{A_C}\right)} + 0.87 f_{yj} A_{sj} \quad (1)$$

Here the parameter of joint shear reinforcement is considered to give additional strength to joint. In this the effect of beam longitudinal reinforcement is neglected.

Vollum and Newman (1999) developed a semi empirical model based on analysis of available test results under monotonic loading.

$$V_j = 0.642\,\xi[1 + 0.552(2 - h_b/h_c)] b_j h_c \sqrt{f_c'} + A_{sj} f_{yj} \quad (2)$$

Where, ξ represents the detailing of reinforcement, =1.0 for L bend and =0.9 for U bend. This analytical model considers joint aspect ratio, concrete compressive strength, effective width of joint, area of joint stirrups, and yield strength of reinforcement. But neglect the effect of column axial load effect and amount of reinforcement in beam and column. In the same way the shear strength without shear reinforcement can be calculated from the same equation.

Bakir and Boduroğlu (2002) proposed an empirical model based on regression analysis of 58 experimental test data. This model considers the parameters like, joint aspect ratio, beam longitudinal reinforcement, concrete compressive strength and joint shear reinforcement. The detailing of longitudinal beam bars inside the joint region is mainly focused here.

$$V_j = \frac{0.71\beta\gamma\left(100 * \frac{A_{sb}}{b_b d_b}\right)^{0.4289} \left(\frac{b_c + b_b}{2}\right) h_c \sqrt{f_c'}}{\left(\frac{h_b}{h_c}\right)^{0.61}} + \alpha A_{sje} f \quad (3)$$

where, β = 0.85 for the joints detailed by U type bars and =1.00 for L type bars. γ= 1.37 for inclined bars inside joint and = 1.00 for other cases. α = 0.664 for joints with low amount of stirrups; = 0.60 for joints with medium amount of stirrups; and = 0.37 for joints with low amount of stirrups. In this the joints are consider to have low amount of stirrups when the stirrups ratio is below 0.003, for medium amount of stirrups when ratio ranges between 0.003 to 0.0055, and for high amount of stirrups for ratio exceeds 0.0055. This model lacks in some cases as it does not consider the effect of parameters like column axial load and column reinforcement.

Hegger et al. (2003) suggested an empirical model based on regression analysis of experimental database. The model considers the parameters like column reinforcement ratio, joint aspect ratio, concrete compressive strength, effect of column and joint reinforcement ratio,

$$V_{jh} = \alpha_1 A\, B\, C\, b_j h_c + \alpha_2 A_{sj} f_{yj} \quad (4)$$

From the regression analysis the following expressions are proposed. The term f_c' is the compressive strength of concrete (MPa). The coefficient α_1 are 0.85 and 0.95 for 180^0 and 90^0 bend bars. The term *A* denotes the effect of joint aspect ratio.

$$A = (1.2 - 0.3\, h_b/h_c)$$

The effect of column longitudinal reinforcement ratio is,

$$\left(1 - \frac{\rho_C - 0.5}{7.5}\right)$$

and the term C is for concrete compressive strength as,

$$2\sqrt[3]{f_c'}$$

with limiting concrete grade from 20 MPa to 100Mpa. The coefficient α_2 denotes the efficiency of shear reinforcement.

Kim et al., (2009) developed an empirical joint shear strength model using the Bayesian parameter estimation method for exterior joint. Earlier model developed by Kim et al. (2007) was not suitable for evaluating the shear strength in unreinforced beam-to-column joints. Now this model is considered suitable for both interior and exterior types of joints.

$$V_{jh} = 1.3 \alpha_t \beta_t \eta_t (JI)^{0.15} (BI)^{0.3} (f_c')^{0.75} A_{jh} \quad (5)$$

where, αt and βt are parameters for describing the in-plane and out-of-plane geometry, respectively; η_t is a parameter to account for the influence of beam eccentricity; JI is the joint transverse reinforcement index depending mostly on the volumetric joint shear reinforcement ratio; BI is the beam reinforcement index depending mostly on the beam reinforcement ratio, ρ_{sb}.

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

$$\eta_t = \left(1 - \frac{e_b}{b_c}\right)^{0.67} \quad BI = \frac{\rho_j f_{yb}}{f_c} \qquad JI = \frac{\rho_j f_{yj}}{f_c} > 0.139$$

Beam reinforcement ratio ρb and the volumetric joint transverse reinforcement ratio ρj needed for evaluating the beam and transverse reinforcement index, respectively, can be evaluated as follows;

$$\rho_b = \frac{A_{sb,sup} + A_{sb,inf}}{b_b h_b} \quad \rho_j = \frac{A_{sjh} + h_c}{h_c b_c (h_b - 2d_b)}$$

Tran et al. (2014) considers the contribution of bond strength in the formulation of empirical model. The model is based on the regression analysis base on the large experimental database. The four parameters are considered such as concrete grade, column axial load ratio, shear reinforcement and the bond strength.

$$V_{jh} = \left(\gamma_1 + \frac{N}{b_c h_c f_c} + 1.2\chi_b\right) A_{jh} f_c^{0.5} + \gamma_2 \left(A_{sjh} f_{yjh} + A_{sjv} f_{yjv}\right) \tag{6}$$

Where, the coefficients γ_1 =0.34 and γ_2=0.22 for exterior joints. The additional new parameter of bond strength is defined as,

$$\chi_b = \frac{n_b d_{sb} h_c}{b_b h_b} \leq 0.4$$

In this equation the effect of parameter of column reinforcement is not considered. The beam reinforcement is considered in terms of bond strength.

III. EXPERIMENTAL DATABASE

The test results of exterior beam-column joints from various research groups are collected here from the literature. The joint specimens considered here neglects the joints having the eccentricity, headed bar reinforcements, and axial load from column. The exterior beam-column joint test specimen collected includes the tests under monotonic or cyclic loading. A total 70 experimental results are collected from 18 research groups viz., Ehsani et al (1985), Tsonos (1992, 1999, 2007), Scott (1996), Parker and Bullman (1997), Clyde et al. (2000), Hakuto et al (2000), Calvi et al (2002), Gencoglu and Eren (2002), Pantelides et al (2002), Hegger et al. (2003), Alva (2004, 2007), Kuang and Wong (2006), Karayannis et al. (2008), Bindu and Jaya (2008), Kusuhara and Shiohara (2008), Wong and Kuang (2008), Kaung and Wong (2011) and Chun and Shin (2014). These test specimens have been collected such that the parameter should consists of all the ranges. The equation which is proposed in this study is calibrated with the test results of this experimental database. The range of all the selected parameters is shown in the Table 1.

Table I Minimum and maximum range of experimental database

	Beam			Column			Joint				
	b_c	h_c	A_{sc} %	b_b	h_b	A_{sb} %	A_{sjh} %	A_{sjv} %	f_c	f_v	$N_c/A_c f_c$
Min	100	150	0.8	100	150	0.5	0	0	23	308	0
Max	460	460	3.8	457	610	3.2	1.0	1.3	86	630	0.5

IV. PROPOSED NEW EMPIRICAL MODEL

Based on influence of each significant parameter a new empirical model is proposed for predicting the joint shear strength of exterior joint based on the statistical analysis of experimental database [2]. The proposed joint shear strength predictive model considers the influence of beam width, beam depth, column width, column depth, concrete compressive strength, yield strength of steel, beam longitudinal reinforcement, joint shear reinforcement and column axial load ratio. Based on the analysis of aforementioned parameters, the corresponding factor have been developed based on the trend line as shown in following subsection. The model is calibrated based on seventy test results collected from literature. The influence of each parameter on joint shear strength is described in the following sections.

Influence of concrete strength (fc)

The concrete strength is directly related with the shear strength of joint. The influence of concrete grade on the joint shear strength has been represented in the Fig. 1. The relation between concrete compressive strength and joint sear strength have been evaluated empirically as shown in Equation (7). Fig. 1 shows that the increase in concrete strength increases the joint strength.

The regression analysis yields the relation of concrete grade with joint strength as,

$$V_j = 0.30 f_c^{0.80} \qquad \text{............(7)}$$

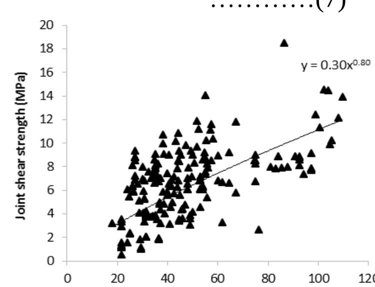


Fig. 1 Influence of concrete grade Influence of depth ratio and width ratio

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

While analyzing this parameter the interesting variation is observed that is the joint shear strength, which shows the joint shear strength is directly proportional to aspect ratio upto 1.5, but for high aspect ratio it behaves in contrast manner (Fig. 2). The same observations are observed in the case of joint width ratio such as the width of beam should not exceed the column width to prevent the effect of eccentricity which reduces the joint shear strength (Fig. 3).

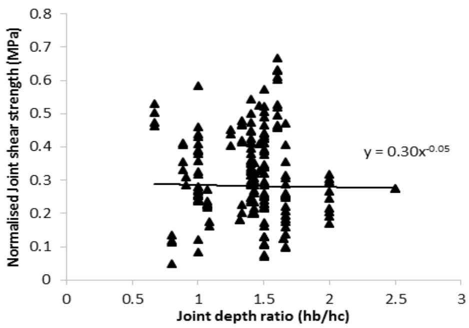


Fig. 2 Influence of depth ratio

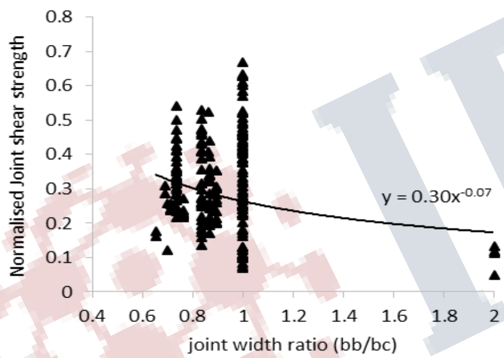


Fig. 3 Influence of width ratio

From the regression analysis the formulation for both depth ratio and width ratio are given (Equation 7 and 8) below,

Joint depth index = $$\frac{0.30}{\left({h_b}/{h_c}\right)^{1/20}} \qquad (8)$$

Joint width index = $$\frac{0.30}{\left({b_b}/{b_c}\right)^{0.7}} \qquad (9)$$

Influence of column axial load ratio (N_c/A_cf_c)

It is evident from the past studies [2,3] that the column axial load increases the joint shear strength. The similar observations based on experimental results shows (Fig. 4) minor rate of increase with joint shear strength. The mathematical expression of the trend line is given in Eq 10.

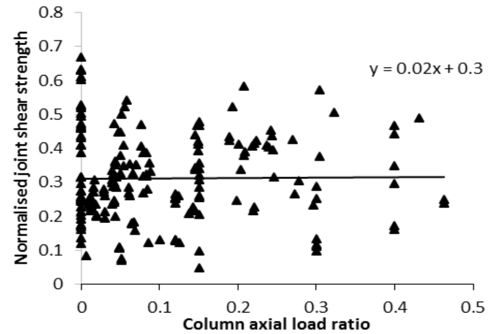


Fig. 4 Influence of column axial load ratio

The influence of column axial load ratio is in the form of linear expression as given as below,

Column axial load ratio index = $$0.30 + 0.02\left({N}/{A_c f_c}\right) \qquad (10)$$

Influence of beam longitudinal reinforcement

The beam reinforcement gives the significant contribution for the joint shear strength [2]. The longitudinal reinforcement from the beam affects the bond strength inside the joint panel. The beam reinforcement are bent inside the joint zone either upward or downward into the column. The beam bar provide additional strength to the joint if properly anchored. The effect of beam reinforcement on normalized joint shear strength is shown in Fig. 5. The effect of beam longitudinal bars are considered here as per the regression analysis of experimental test results as shown in Eq. (11),

Beam R/f index = $$0.80\left(\frac{A_{sbtotal} f_{yb}}{b_b h_b}\right)^{0.90} \qquad (11)$$

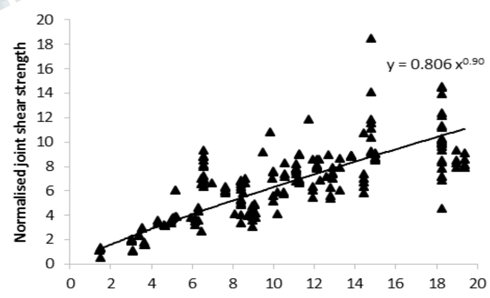


Fig. 5 Influence of beam longitudinal reinforcement

Influence of Joint shear reinforcement

It has been observed that the presence of joint shear reinforcement increases the joint strength as seen in the earlier section and in the Fig. 6.

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

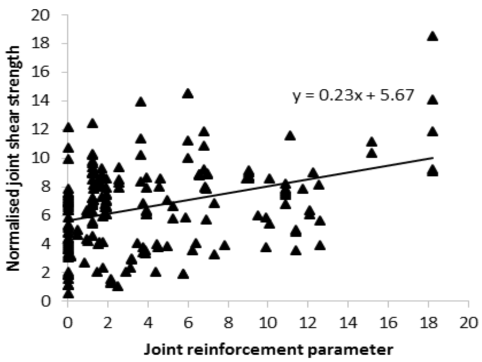


Fig. 6 Influence of joint shear reinforcement

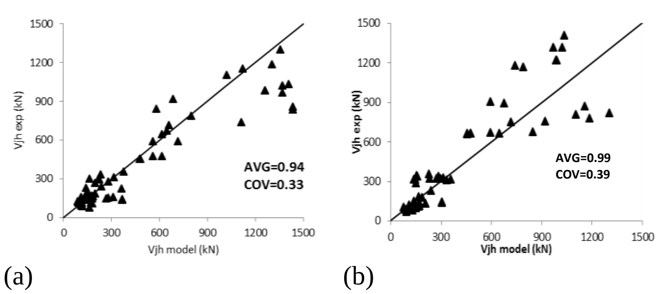
The effect of shear reinforcement considered here through regression analysis in the form of linear expression (Eq. 12) as,

$$\text{Joint shear R/f index} = 5.67 + 0.23\left(\frac{[A_{sjh}+A_{sjv}]f_{yj}}{b_j h_c}\right) \quad (12)$$

The final expression for predicting the shear strength of joint is in the form as described below,

$V_j = 0.30 f_c^{0.80}$ (Depth Index) (Width Index) (Column axial load ratio) (Beam R/f Index) (Joint shear R/f)

The calibration of proposed empirical joint shear strength model is presented along with the other models as shown in the Fig. 7 (a-g). In this the comparison have been made based on the ratio of experimental shear strength to the model shear strength (V_{jexpt}/V_{jmodel}). The average (AVG) and coefficient of variation (COV) values for individual models have been presented in the Fig (7). It has been observed that the models of Sarsam and Phillips (1985), Vollum and Newman (1999), Hegger et al. (2003), and Kim et al. (2009) gives higher prediction than experimental results. However, the models of Bakir and Boduroğlu (2002), and Tran et al. (2014) predicts the joint shear strength lower than experimental results. The prediction of proposed model shows accurate results with lesser variation than other models.



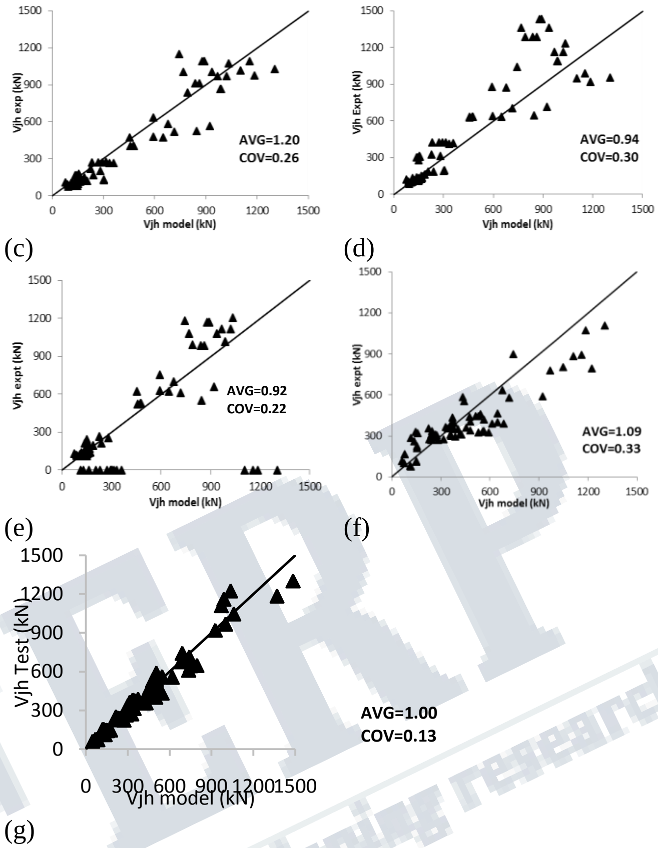


Fig. 7 (a-g) Comparison of shear strength prediction of proposed model (g) with six empirical models as, (a) Sarsam and Phillips (1985), (b) Vollum and Newman (1999), (c) Bakir and Boduroğlu (2002), (d) Hegger et al. (2003), (e) Kim et al. (2009), (f) Tran et al. (2014)

V. CONCLUSION

Based on the statistical analysis of experimental database, a new model for joint shear strength has been proposed for the exterior beam-column joint. In this the influence of various parameters have been considered for the development of proposed model. Especially the width and depth of interconnecting members have been introduced which gives realistic prediction with the experimental results. The prediction of proposed empirical model have been compared with the experimental results. To verify the efficacy, the proposed model have been verified with the other empirical models and it has been observed that the proposed model gives more precise results with the test results. The proposed model is based on limited parameters makes it simple for design purpose.

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 2, Issue 3, March 2017

REFERENCES

1) N. W. Hanson, and H. W. Connor, "Seismic resistance of reinforced concrete beam–column joints," Journal of Structural Division, ASCE, 93, No. ST5, pp. 533–559, 1967.
2) K. Parate and R. Kumar, "Investigation of shear strength models for exterior RC beam-column joint", Structural Engineering and Mechanics, 58(3), 475-514, May 2016.
3) K. Parate, R. Kumar and S. V. Bakre, "A review on seismic behavior of RC beam-column joints", 15th Symposium on Earthquake Engineering, IIT Roorkee, Paper No. A134, December 11-13, 2014.
4) H. P. J. Taylor, "The Behavior of In-situ Concrete Beam-Column Joints," Cement and Concrete Association, Wexham Springs, UK, Technical Report 42.492, 1974.
5) R. H. Scott, I. Feltham, and R. T. Whittle, "Reinforced Beam-Column Connections and BS 8110," The Structural Engineer, 72(4), 55-60, 1994.
6) K. F. Sarsam, and M. E. Phillips, "The shear design of in-situ reinforced beam-column joints subjected to monotonic loading", Magazine of Concrete Research, 37(130):16–28, 1985.
7) P. G. Bakir, and H. M. Boduroğlu, "A new design equation for predicting the joint shear strength of monotonically loaded exterior beam-to-column joints", Engineering Structures, 24(5) 1105–1117, 2002.
8) J. Hegger, A. Sherif, and W. Roeser, "Nonseismic design of beam-column joints", ACI Structural Journal, 100(5):654–664, 2003.
9) G. Russo, and G. Somma, "Shear Strength of Exterior Beam-Column Joints under Seismic Loading", Proceedings of the 2nd fib Congress, Naples, Italy. Napoli: fib Italia, Paper No. 9-38, 2006.
10) J. Kim, J. M. LaFave, and J. Song, "Joint Shear Behavior of Reinforced Concrete Beam-Column Connections", Magazine of Concrete Research, 61-No.2, pp. 119-132, 2009.
11) T. M. Tran, M. N. S. Hadi, and T. M. Pham, "Anew empirical model for shear strength of reinforced concrete beam-column connections", Magazine of Concrete Research, 66(10):514–530, 2014.
12) C. Lima, E. Martinelli, and C. Faella, "Capacity models for shear strength of exterior joints in RC frames: state-of-the-art and synoptic examination", Bull Earthquake Engg., 10:967–983, 2012.
13) R. L. Vollum, and J. B. Newman, "The design of external, reinforced concrete beam-column joints", Journal of Structural Engg., 77(23–24):21–27, 1999.
14) M. R. Ehsani, and J. K. Wight, "Exterior Reinforced Concrete Beam-to- Column Connections Subjected to Earthquake-Type Loading", Technical Paper, ACI Structural Journal, Title no. 82-43, pp. 492-499, 1985.
    A. G. Tsonos, I. A. Tegos, and G. G. Penelis, "Seismic resistance of type 2 exterior beam–column joints reinforced with inclined bars", ACI Structural Journal, 89(1):3–11, 1992.
15) A.G. Tsonos, "Lateral Load Response of Strengthened RC Beam-to- Column Joint", ACI Structural Journal, 96(1), 46–56, 1999.
    A. G. Tsonos, "Cyclic load behavior of reinforced concrete beam- column sub assemblages of modern structures", ACI Structural journal, 104(4): 468-478, 2007.
16) R. H. Scott, "Intrinsic mechanisms in reinforced concrete beam column connection behavior", ACI Structural Journal, 93(3), 1-11, 1996.
17) D. E. Parker, and P. J. M. Bullman, "Shear strength within reinforced concrete beam-column joints", The Structural Engineer, 75(4), 53–57, 1997.
18) C. Clyde, C. P. Pantelides, and L. D. Reaveley, "Performance-based Evaluation of Exterior Reinforced Concrete Building Joints for Seismic Excitation", Pacific Earthquake Engineering Research Center, PEER Report 2000/05, University of California, Berkeley, CA, 2000.
19) S. Hakuto, R. Park, and H. Tanaka, "Seismic load tests on interior and exterior beam column joints with substandard reinforcing details", ACI Structural Journal, 97(1), 11-25, 2000.
20) G. M. Calvi, G. Magenes, and S. Pampanin, "Relevance of beam-column damage and collapse in RC frame assessment", Journal of Earthquake Engineering, 6-S1, 75-100, 2002.
21) M. Gencoglu, and I. Eren, "An experimental study on the effect of steel fiber reinforced concrete on the behavior of the exterior beam-column joints subjected to reversal cyclic loading", Turkish J. Eng. Env. Sci., 26, 493-502, 2002.
22) C.P. Pantelides, J. Hansen, J. Nadauld, and L. D. Reaveley, "Assessment of Reinforced Concrete Building Exterior Joints with Substandard Details", PEER Report 2002/18, University of California, Berkeley, CA, 2002.

23) J. Hegger, A. Sherif, and W. Roeser, "Nonseismic design of beam-column joints", ACI Structural Journal, 100(5):654–664, 2003.
24) G. M. S. Alva, A. L. H. D. C. Debs, and M. K. E. Debs, "An experimental study on cyclic behavior of reinforced concrete connections", Canadian Journal of Civil Engineering 34(4): 565–565, 2007.
25) J. S. Kuang, and H. F. Wong, "Effects of beam bar anchorage on beam–column joint behavior", Proceedings of the Institution of Civil Engineers–Structures and Buildings, 159(2): 115–124, 2006.
26) C. G. Karayannis, and G. M. Sirkelis, "Strengthening and rehabilitation of RC beam–column joints using carbon-FRP jacketing and epoxy resin injection", Earthquake Engineering and Structural Dynamics, 37(5): 769-790, 2008
27) K. R. Bindu, and K. P. Jaya, "Performance of exterior beam column joints with cross- inclined bars under seismic type loading", Journal of Engineering and Applied Sciences, 7, 591-597, 2008.
28) F. Kusuhara, and H. Shiohara, "Tests of R/C beam-column joints with variant boundary conditions and irregular details on anchorage of beam bars", The 14th World Conference on Earthquake Engineering, Beijing, China, 2008.
29) H. F. Wong, and J. S. Kuang, "Effects of beam-column depth ratio on joint seismic behavior", Structures and Buildings 161(2), 91-101, 2008.