13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1282

A DESIGN FORMULA FOR PREDICTING THE SHEAR STRENGTH OF EXTERIOR BEAM COLUMN JOINTS UNDER SEISMIC LOADING

Gaetano RUSSO[1] and Giuliana SOMMA[2]

SUMMARY

The behavior at failure of 50 exterior beam-column joints tested by various authors has been examined to identify a model for computing the shear strength of exterior beam-column joints under severe seismic actions. This exam has pointed out that, during the cyclic loading, a large diagonal cracking comes together with a joint volumetric expansion. Three resisting contributions against the above mentioned expansion have been identified: the concrete one, the beam longitudinal reinforcement one, and the stirrup one. The overall shear strength has been taken as the sum of these three contributions, each dependent on a multiplying factor which has been univocally determined from the available experimental data. The so obtained expression predicts the shear strength in a much more accurate and uniform way than the Eurocode, New Zealand and ACI Codes expressions.

INTRODUCTION

Beam-column joints are critical regions in reinforced concrete frames subjected to severe seismic attack because beam moment reversals can produce high shear forces and bond breakdown into the joint, and hence its cracking. The consequent joint stiffness decreasing can lead to large overall story drift and damage of the structure.

Although the first experimental study on beam-column joints was done by Hanson and Conner [1] in the first sixties, only in the last years the researches on joints have been intensified. A lot of design code recommendations and analytical expressions for computing the exterior beam-column joints shear strength under seismic loading exist [2-7], but are not able to supply an accurate prediction, mainly because of the several parameters that take part and statically indetermination of the problem. There are different approaches followed by various codes and authors, trying to predict the real shear strength behavior of an exterior beam-column joint under earthquake loads.

[1] Full Professor, Department of Civil Engineering, University of Udine, Italy
[2] PhD Engineer, Department of Civil Engineering, University of Udine, Italy

On the basis of strength mechanisms which resist to joint expansion always observed in tests, an analytical expression is here proposed.

JOINT BEHAVIOR AT FAILURE

Experimental results of 50 exterior beam-column joints tested by various authors from 1967 to 2000 have been collected [1, 8-15]. These tests have been carried out by applying an horizontal alternate load at the top of the beam element, and often a vertical constant load on the column (Fig.1).

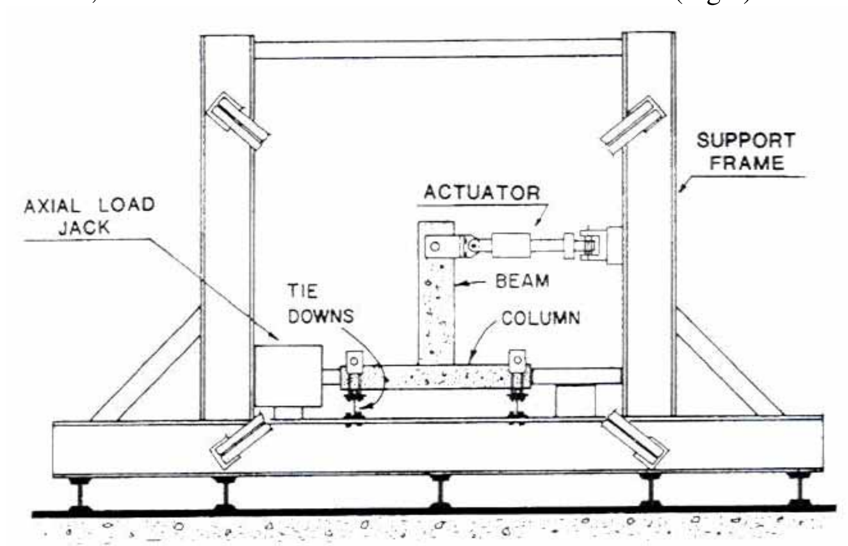

Fig.1: Usual test set-up for beam-column joint [10]

Because of the cyclically alternating forces, applied during the test, joints collapsed showing an appreciable diagonal crack opening. A photo of a joint tested by Milburn and Park [16] is shown in Fig.2: when failure occurs, a joint expansion is macroscopically apparent (Fig.2). Diagonal cracking evidences relative motion between crack sides originally in contact. Due to crack width increasing, the distance of opposite corners of the joint panel increases with horizontal load or with the number of cycles in the inelastic range. So it may be stated that, under the load actions which simulate the seismic action, within the joint there is the development of a diagonal cracking field with large crack width, leading to relative motions with components in both vertical and horizontal directions.

Fig.2: Joint cracking at failure [16]

The confinement action against the vertical component of the expansion is provided by the axial load and the column vertical reinforcement. This confinement action may reasonably be approximated by vertical compressive stresses σ_a and σ_V , respectively due to the axial load (active confinement) and to the vertical reinforcement (passive confinement), which is assumed to be distributed over all the section.
The horizontal component of the joint expansion is opposed by the passive confinement actions provided by beam longitudinal reinforcement bars and by the transverse (horizontal) reinforcement into the joint, respectively indicated with $v_{jh,l}$ and $v_{jh,h}$.

SHEAR STRENGTH COMPUTING MODEL

On the basis of previous considerations, an expression is proposed, which takes into account the following resisting mechanisms to joint expansion: (1) vertical stresses transmitted by column, (2) longitudinal beam reinforcement, and (3) passive confinement due to stirrups into the joint, if present. The proposed expression for shear strength of an exterior reinforced concrete joint is

$$v_{jh} = v_{jh,c} + v_{jh,l} + v_{jh,h} \qquad (1)$$

where $v_{jh,c}$ is the shear strength contribution provided by concrete and vertical stresses σ_a and σ_V , $v_{jh,l}$ is the strength contribution provided by beam longitudinal reinforcement, and $v_{jh,h}$ is the strength contribution provided by stirrups.

Concrete contribution

This contribution depends on the concrete tensile strength, on σ_a and on the confinement action provided by the column longitudinal reinforcement.
By considering on an horizontal plane between the upper and lower beam longitudinal reinforcements the action of a mean shear stress, $\tau_{h,c}$, a mean axial compressive stress σ_a, and a mean vertical confinement stress, σ_V, from Mohr's circle the principal tensile stress is expressed as

$$p_t = \frac{-\sigma_a - \sigma_v}{2} + \sqrt{\left(\frac{\sigma_a + \sigma_v}{2}\right)^2 + \tau_{h,c}^{\,2}} \qquad (2)$$

which gives

$$\tau_{h,c} = p_t \sqrt{1 + \frac{\sigma_a + \sigma_v}{p_t}} \qquad (3)$$

As the concrete tensile strength in a biaxial state of tension-compression is lower than that in a uniaxial stress state, f_{ct}, it follows that $p_t < f_{ct}$. Moreover the maximum vertical action is obtained when the bars are yielded, so that $\sigma_V = f_V$, where

$$f_V = k_V \frac{A_v f_{yv}}{A_g} \qquad (4)$$

where f_{yv} and A_v are respectively the yielding strength and cross section area of the vertical column reinforcement, A_g is the area of the joint transverse section, and k_V is a numerical coefficient to be determined.
By putting $p_t = f_{ct}$ and $\sigma_v = f_V$, Eq. (3) provides the limiting concrete shear strength contribution

$$v_{jh,c\,\mathrm{lim}} = f_{ct} \sqrt{1 + \frac{\sigma_a + f_V}{f_{ct}}} \qquad (5)$$

The real concrete shear strength contribution is lower than the limiting one, and hence it is expressed by

$$v_{jh,c} = k_0 \cdot v_{jh,c\,\mathrm{lim}} \qquad (6)$$

where $k_0 < 1$ is a numerical coefficient to be determined.

Beam longitudinal reinforcement contribution

Being beam reinforcement subjected to large alternate cyclic actions making non linear steel behavior, it is difficult to evaluate the maximum stress acting on the two reinforcement levels (at top and bottom), as far as the maximum confinement effect due to these bars.

It is assumed that the joint shear resistance due to the confinement action provided by beam longitudinal reinforcement, should be proportional to the yielding strength and to the average area of the beam longitudinal reinforcement, f_{yh} and A_{sh}. Consequently the shear strength due to beam reinforcement is

$$v_{jh,l} = k_1 \cdot \frac{f_{yh} \cdot A_{sh}}{A_g} \tag{7}$$

where k_1 is a numerical coefficient to be determined.

Stirrups contribution

The joint shear strength contribution due to the passive confinement action against expansion provided by stirrups present in the joint, is expressed as follows

$$v_{jh,h} = k_2 \cdot \frac{f_{yh,h} \cdot A_{sh,h}}{A_g} \tag{8}$$

where k_2 is a numerical coefficient to be determined, and $f_{yh,h}$ and $A_{sh,h}$ are respectively the yielding strength and cross section area of the stirrups in the joint.

On the basis of Eqs.(1), (5) and (6-8), the expression for computing the shear strength of an exterior beam-column joint is

$$v_{jh} = k_0 \left[f_{ct} \sqrt{1 + \frac{\sigma_a + f_V}{f_{ct}}} + c_1 \frac{f_{yh} A_{sh}}{A_g} + c_2 \frac{f_{yh,h} A_{sh,h}}{A_g} \right] \tag{9}$$

with $c_i = k_i / k_0$, f_V provided by Eq.(4), and f_{ct} expressed by the Oluokun [17] following formula

$$f_{ct} = 0.214 \cdot f'_c{}^{0.69} \tag{10}$$

where f'_c is the compressive concrete strength.

To evaluate the unknown parameters 50 specimens of exterior reinforced concrete joints tested by various authors have been considered. The values of the three unknown coefficients, k_V, c_1 and c_2 appearing in Eqs.(4) and (9) have been iteratively changed with the purpose to minimize the coefficient of variation, *COV*, calculated as the ratio between the standard deviation, *STD*, and the average value, *AVG*, of the experimental and computed shear strength ratio. The value of the unknown coefficient k_0 have been calibrated to obtaining the exact mean equality between experimental and computed shear strength, i.e. $AVG = 1$. So proceeding there have been found the values $k_0=1/3$, $k_V=1/2$, $c_1=3/2$ and $c_2=1/2$, which provided a $COV = 0.12$.

So the shear strength of an exterior reinforced concrete beam column joint is provided from Eq.(9) by

$$v_{jh} = \frac{1}{3} \left[f_{ct} \sqrt{1 + \frac{\sigma_a + f_V}{f_{ct}}} + \frac{1}{2A_g} \left(3 f_{yh} A_{sh} + f_{yh,h} A_{sh,h} \right) \right] \tag{11}$$

with f_{ct} provided by Eq.(10), and $f_V = A_v f_{yv} / (2A_g)$.

PROPOSED MODEL RELIABILITY

The reliability of the proposed model in predicting the shear strength of exterior reinforced concrete joints, is compared with the following shear strength Code expressions

New Zealand Standard 3101:1995 [2]

$$v_{jh} = \frac{f'_c}{6\alpha_j} \cdot \frac{f_{yh,h} A_{sh,h}}{f_{yh} A_s^*} \tag{12}$$

where A_s^* is the greater of the area of top or bottom beam reinforcement, and

$$\alpha_j = 1.4 - 1.6 \frac{\sigma_a}{f'_c} \geq \frac{1}{15} \cdot \frac{f'_c A_g}{f_{yh} A_s^*} \tag{13}$$

The shear strength v_{jh} must be such as $0.14 f'_c \leq v_{jh} \leq 0.20 f'_c$.

Eurocode 8 (1998) [3]

$$v_{jh} = 0.52 f'^{2/3}_c \qquad \text{for joints without stirrups} \tag{14}$$

$$v_{jh} = \sqrt{0.04 \cdot f'^{2/3}_c \cdot \left(0.48 \cdot f'^{2/3}_c + f_a \cdot f_{cd}\right)} + \frac{A_{sh,h} \cdot f_{yhd}}{A_g} \qquad \text{for joints with stirrups} \tag{15}$$

where f_{cd} and f_{yhd} are respectively the design concrete compressive strength and the design yielding strength of stirrups, expressed as $f_{cd} = f'_c / \gamma_c$ and $f_{yhd} = f_{yh,h} / \gamma_s$, where γ_c=1.5 and ?γ_s=1.15.

ACI Code 318-02 [4]

$$v_{jh} = 0.996 \sqrt{f'_c} \tag{16}$$

Theoretical joint shear strength has been computed for all the 50 tested specimens by means of Eqs.(11), (12), (14) or (15), and (16). The ratios between measured to calculated joint shear strength are shown in Fig.3 versus the concrete compressive strength f'_c. The coefficients of variation and average values, relative to each expression, are also indicated.

The measure of the prediction uniformity is given by the coefficient of variation, *COV*: the lower this value is, the greater the uniformity. From diagrams and *COV* values it is evident that the proposed expression leads to the most uniform prediction of the shear strength of exterior reinforced concrete beam column joints: a *COV* value at least 50% lower than those provided by the considered Codes is obtained. This result confirms the reliability of the mechanical model based on the confinement actions.

The comparison with the Paulay and Priestley [6] expression leads to *AVG* = 1.02 and *COV* = 0.18.

DESIGN FORMULA

The above mentioned reliability of the mechanical model leads to deduce from Eq.(11) a design formula, which meanly predicts shear strength values on the safe side. In fact, by multiplying Eq.(11) by a factor, only *AVG* changes, while *COV* doesn't.

A characteristic expression, leaving on the safe side 95% of the predicted values, is proposed for design. On the basis of the 50 here considered specimens, the multiplying factor, leading to 95% of safety, results 3/4. Consequently the design formula is

$$v_{jh,d} = \frac{1}{4}\left[f_{ct} \sqrt{1 + \frac{\sigma_a + f_V}{f_{ct}}} + \frac{1}{2A_g}\left(3 f_{yh} A_{sh} + f_{yh,h} A_{sh,h}\right)\right] \tag{17}$$

For the 50 considered specimens the mean measured to calculated shear strength ratio results 1.33.

CONCLUSIONS

By analyzing the reports of experimental tests carried out on 50 exterior beam column subjected to large seismic action, it has been noticed that a volumetric joint core expansion occurs at failure.
A mechanical model, based on the resisting mechanisms to this expansion, either in vertical and horizontal direction, has been shown to be very reliable. From this model an expression is derived, which takes into account the confinement action provided by the upper and lower column portions, by beam longitudinal reinforcements, and stirrup reinforcement.
The proposed expression for computing the joint shear strength exhibits a much more uniform prediction of experimental results than New Zealand Standards, Eurocode and ACI Code. This demonstrates the validity of the mechanical model, already proposed for interior joints [18 and 19], also for exterior ones.
The proposed design formula is affected by a mean safety factor of 33%.

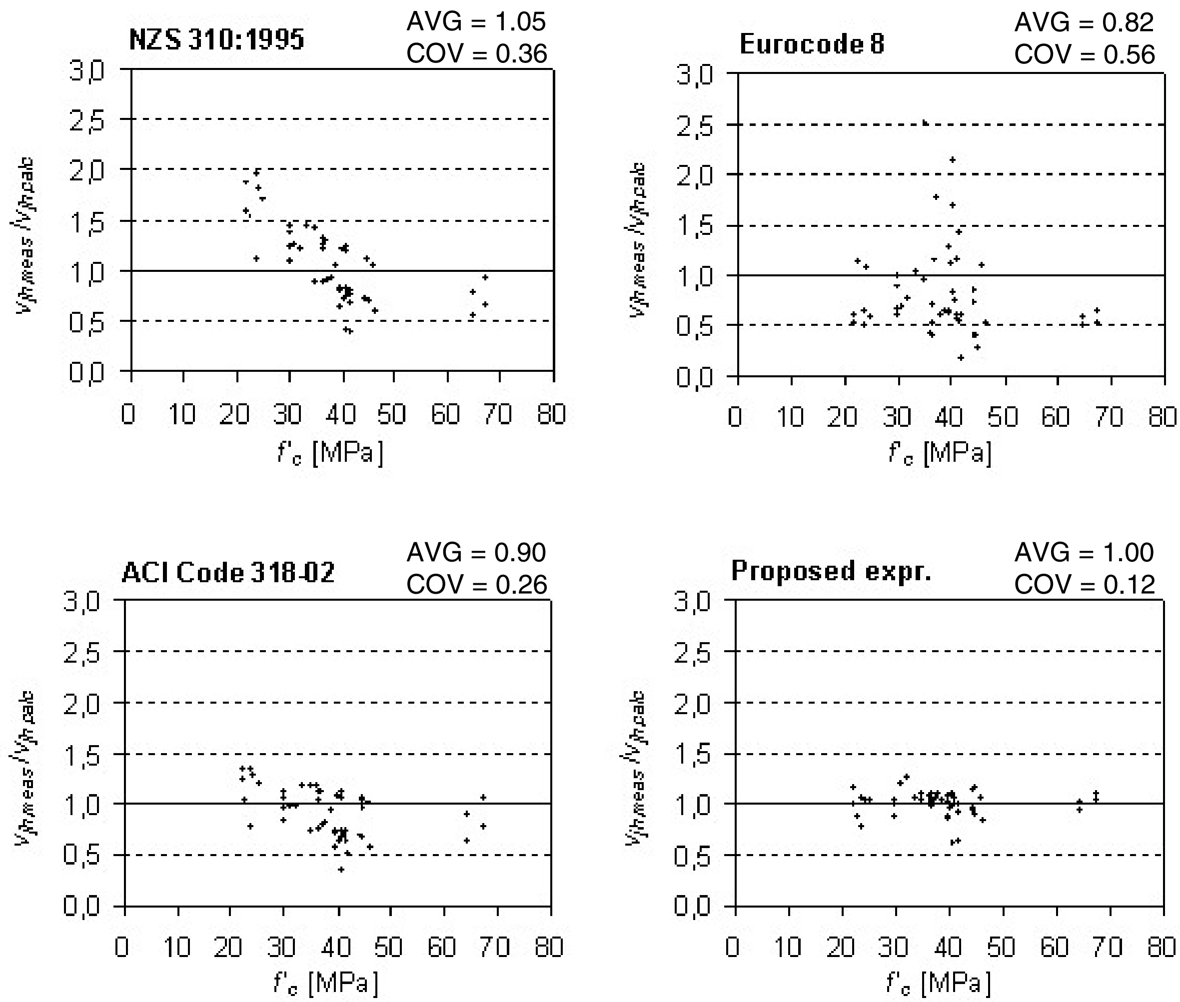

Fig.3: Measured to calculated shear strength ratio versus f'_c, for the 50 exterior joints

REFERENCES

1. Hanson NW, Conner HW. "Seismic resistance of reinforced concrete beam-column joints." Journal of the Structural Division, ASCE 1967; 93(5): 533-560.
2. NZS 3101:part 1:1995. "Concrete structures standard." Standard Association of New Zealand. Wellington, 1995.
3. ENV 1998-1-3. "Eurocode 8 - Design provisions for earthquake resistance of structures – Part 1-3: General rules-Specific rules for various materials and elements." Comitè Europeen de Normalization CEN, 1998.
4. ACI Committee 318-02. "Building Code Requirements for Structural Concrete and Commentary." ACI 318-02/ACI 318R-02. Detroit: American Concrete Institute, 2002.
5. Kurose Y. "Design of beam-column joints for shear". Earthquake resistance of concrete structures, 1993.
6. Paulay T, Priestley M.J.M. "Seismic design of reinforced concrete and masonry buildings". New York: John Wiley and Sons, 1992.
7. Hwang S.J., Lee H.J."Analytical model for predicting shear strengths of exterior reinforced concrete beam-column joints for seismic resistance. ACI Structural Journal 2000 ; 96(5): 846-857.
8. Hanson NW. "Seismic resistance of concrete frames with grade 60 reinforcement". Journal of the Structural Division, ASCE 1971; 97(6): 1685-1700.
9. Park R, Milburn JR. "Comparison of recent New Zealand and United States seismic design provision for reinforced concrete beam-column joints and test results from four units designed according to the New Zealand Code". Proceedings of the 3rd South Pacific Regional Conference on Earthquake Engineering, Wellington, New Zealand, 1983.
10. Ehsani MR, Wight JK. "Exterior reinforced concrete beam-to-column connections subjected to earthquake-type loading." ACI Structural Journal 1985; 92(4): 492-499.
11. Ehsani MR, Moussa AE, Vallenilla CR. "Comparison of inelastic behavior of reinforced ordinary and high-strength concrete frames". ACI Structural Journal 1987; 94(2): 161-169.
12. Bolong Z, Yuzhou C. "Behavior of exterior reinforced concrete beam-column joints subjected to bi-directional cyclic loading." Design of beam-column joints for seismic resistance. American Concrete Institute, Farmington Hills, Mich., 1991: 69-93.
13. Fujii S, Morita S. "Comparison between interior and exterior reinforced concrete beam-column joints behavior". Design of beam-column joints for seismic resistance. American Concrete Institute, Farmington Hills, Mich., 1991: 145-166.
14. Kaku T, Asakusa H. "Ductility estimation of exterior beam-column subassemblages in reinforced concrete frames". Design of beam-column joints for seismic resistance. American Concrete Institute, Farmington Hills, Mich., 1991: 167-185.
15. Clyde C, Pantelides CP, Reaveley LD. "Performance-based evaluation of exterior reinforced concrete building joints for seismic excitation". PEER Report 2000/05 University of California, Berkeley, July 2000.
16. Milburn JR, Park R. "Behavior of reinforced concrete beam-column joints designed to NZS 3101". Research Report, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, 1982.
17. Oluokun F. "Prediction of concrete tensile strength from its compressive strength: an evaluation of existing relations for normal weight concrete." ACI Material Journal 1991; 88(3): 225-239.
18. Russo G, Somma G. "Shear strength of interior beam-column joints under seismic loading". Proceedings of the 1st Fib Congress on Concrete Structures in the 21st Century, Osaka, Japan, 2002: 141-148.

19. Russo G, Somma G, Angeli P, Mitri D. “Contributi Resistenti a Taglio nei Nodi Interni Soggetti ad Azione Sismica”, Proceedings of the 11th National Congress “L’ingegneria Sismica in Italia”, Genova, Italy, 2004.