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# RC Beam-Column joints, discussion of the provisions in the second generation Eurocode 8

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**Abstract**

This paper reviews the provisions given in the draft of the second-generation Eurocode 8 (EC8) for the design and assessment of RC beam-column joint against seismic conditions. The analytical bases were recently published by Michael Fardis. A critical discussion of the analytical models, supported by a numerical example, is given. Validation against an independent database of exterior joints is made. A final comparison with respect to (i) current EC8 provisions and (ii) other Building Codes is presented.



*Keywords:* Beam-Column Joint; Eurocode 8; Modified-Compression-Field-Theory; Strut-and-Tie.

## 1. Introduction

According to Paulay and Priestley (1978), overstrength of RC beam-column joint with respect to the members it connects is fundamental for the application of seismic capacity design. In this regard, accurate evaluation of joint shear strength becomes necessary.

The strength limits proposed by Eurocode 8 (EC8) changed between its first ENV draft, i.e. EC8 (1996) and the current version EC8 (2004). The former proposed to limit the concrete tangential stress demand to a value equal to 20 or 15 times the tangential strength ( $\tau_{rd}$ ) for interior and exterior joints, respectively. Currently, the Principal Stress Method (Fardis (2009)) applies. Specifically, shear strength is obtained from the concrete compressive strut resistance.

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A reduction of the concrete compressive strength applies to account for cracked condition. Design of the joint's horizontal reinforcement is made such that yielding occur at concrete cracking.

Recently, Fardis (2021), (2020) presented a combination of Strut-and-Tie method (STM, Schlaich et al. (1987)) and Modified Compression Field Theory (MCFT, Vecchio and Collins (1986)) to solve the joint's stress state in closed-form. Such method has been adopted in the draft of the new generation of EC8 CEN/TC250/SC8 (2022a). Besides, (i) simplified provisions for minimum amount of horizontal reinforcement are given alternatively and (ii) Principal Stress Method applies for the assessment of existing structures (CEN/TC250/SC8 (2022b)).

This paper briefly reviews the analytical background of the Fardis' model at Section 2 along with other design formulas. An independent validation is presented at Section 3 using a database of exterior joints. Finally, some conclusions summarize the work.

**Nomenclature**

| | |
|---|---|
| $A_{sh}, A_{sv}$ | Steel area yielding stress of horizontal and vertical reinforcement within the joint panel. |
| $E_s$ | Steel Young Modulus. |
| $f_{cd}$ | Concrete cylindrical compressive strength. |
| $f_{ctd}$ | Concrete tensile strength. |
| $f_{yhd}, f_{yvd}$ | Steel yielding stress of the horizontal and vertical reinforcement within the joint panel. |
| $\varepsilon_1, \varepsilon_2$ | Principal stresses in the joint panel: (1) tension; (2) compression. |
| $\varepsilon_v$ | Strain of the vertical reinforcement within the joint panel. |
| $\sigma_{sh}, \sigma_{sv}$ | Stress of the horizontal and vertical reinforcement within the joint panel. |
| $\theta$ | Inclination angle of the compression field within the joint panel. |
| $\beta$ | Inclination angle of the joint panel's diagonal. |
| $\nu$ | Normalized axial force of the column, i.e. $\nu = N_v / (f_{cd} A_c)$ . |

## 2. RC beam-column joint design formulas

### 2.1. Second generation EC8

Latest draft of EC8 (CEN/TC250/SC8 (2022a)) provides the horizontal shear strength ($V_{jh,d}$) of an RC beam-column joint as the result of the following Equation :

$$V_{jh,d} = \max\left(V_{jh,cr} ; V_{jh,\min} + V_{jh,MCFT}\right) \tag{1}$$

where,

$$V_{jh,cr} = f_{ctd} \sqrt{1 + \frac{\nu f_{cd}}{f_{ctd}}} b_j h_c \tag{2}$$

$$V_{jh,min} = \alpha f_{ctd} b_j \sqrt{h_c h_b} , \alpha = 0.50[exterior], 1.20[interior] \tag{3}$$

Equation (2) gives the "cracking load", that is the joint shear resistance when principal tensile stress reaches $f_{ct}$ , as it is represented via Mohr's circle in Fig. 1.

Derivation of Equation (3) is unclear. Fardis justified it as minimum horizontal shear strength to add to the $V_{jh,MCFT}$ to solve the issue of zero strength in case of un-reinforced joints.

The term $V_{jh,MCFT}$ , in the Equation (1), is obtained from two alternative sets of equations. As can be inferred from Fig. 2, the geometry of the compressive strut depends both on the compression field angle (θ) and on the diagonal angle (β). Specifically, for the case θ < β (compression field steeper than joint diagonal):

$$V_{jh,MCFT}=min\left(\frac{max\left[N_v+A_{sv}\sigma_{sv};0\right]}{cot\theta};A_{sh}\sigma_{sh}+(cot\theta\text{-}cot\beta)sin^2\theta v_j f_{cd} h_c b_j\right) \tag{4}$$

$$\nu_j=\frac{1}{1.4(1+100\varepsilon_1)} \tag{5}$$

$$\varepsilon_1=\varepsilon_v+(\varepsilon_v+\varepsilon_2)\cot^2\theta>0 \tag{6}$$

$$\varepsilon_v=\sigma_{sv}/E_s \tag{7}$$

$$\sigma_{sv}=\frac{V_{jh,MCFT}\cot\theta-N_v}{A_{sv}}<f_{yvd} \tag{8}$$

$$\sigma_{sh}=E_s[(\varepsilon_v+\varepsilon_2)\cot^2\theta-\varepsilon_2]\le f_{yhd} \tag{9}$$

Where all the symbols used in the equations above are explained in the "Nomenclature" section at the beginning of this paper. Similar expressions can be obtained for the case of θ < β (compression field shallower than joint diagonal), which are omitted for the sake of synthesis. Besides, they are comprehensively reported in Fardis (2021).

The presented equations are based on the following assumptions easily derivable from the background of MCFT: (i) concrete fails in compression at a stress value equal to $\nu_j f_{cd}$ ; (ii) the direction of principal stresses coincidences with direction of principal strains; (iii) the horizontal ( $\varepsilon_h$ ) and vertical ( $\varepsilon_v$ ) strains for reinforcement are the same for concrete due to perfect bond.

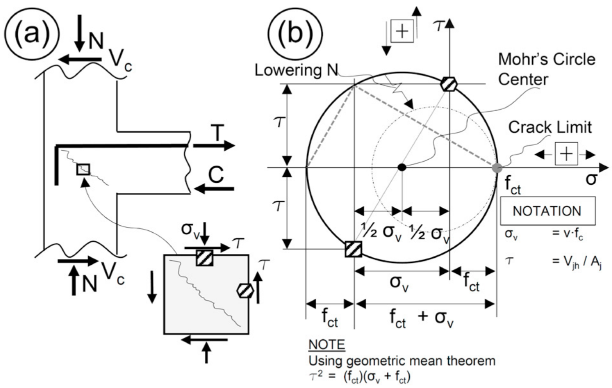


Fig. 1. Cracking load state for a RC beam-column joint: (a) Free-body diagram; (b) Mohr's Circle.

The set of equations (from Equation (4) to Equation (9)) has six unknowns, i.e. $\varepsilon_v$, $\varepsilon_h$, $\sigma_{s_h}$, $\sigma_{sv}$, $\theta$ , $V_{jh,MCFT}$ . In particular, Equation (4) and Equation (8) impose the equilibrium. Equation (7) and Equation (9) impose the reinforcement constitutive law. Compatibility is inherently assumed with perfect bond condition. As a result, the mathematical problem has 2 degrees of freedom and it is non-linear. Non-linearity is due to both (i) elastic-perfect plastic steel and (ii) to sine and cosine functions (and their derivatives) which apply to $\theta$ .

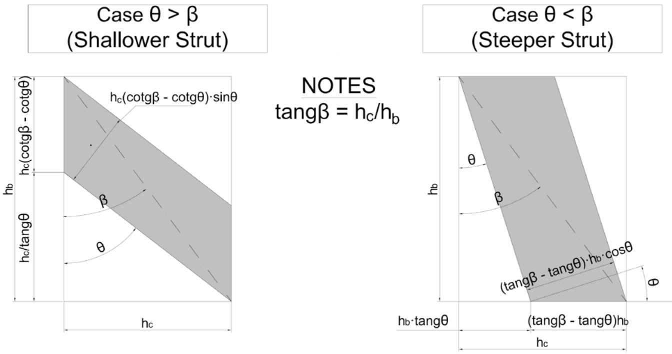


Fig. 2. Geometry of the concrete strut for different cases of compression field angle according to Fardis (2021).

The solution path might include the following steps:

- The principal compressive stress $\varepsilon_2$ is set to a fixed value, e.g. Fardis (2021) proposed equal to -0.001.
- $\theta$ is set to a reference value. Fardis (2021), proposed an empirical relation depending on mechanical reinforcement ratios ($\omega_v$, $\omega_h$) and on the $\beta$ angle, i.e.:

$$\tan\theta = 1.15 + 2.30\omega_h - 1.30\min\left(0.40; \omega_h; \frac{N_v}{f_{cd} b_c h_c}\right) - 0.275\cot\beta \tag{10}$$

- In general, $\theta$ should be swapped until the maximum resistance is attained. Such assumption is not thoroughly justified neither in Fardis (2021) nor in Fardis (2020). However, the validation was carried out by Bentz et al. (2007) dealing with RC panels having two-dimensional grid of reinforcement subjected to shear test. After yielding of the transverse reinforcement, the angle $\theta$ will become smaller, causing an increase in the $\sigma_{sv}$ and, in case of hardening, also in $\sigma_{sh}$. At the same time, the resulting large increase in $\varepsilon_1$ will decrease the concrete contribution to strength. Therefore, assuming $\theta$ when concrete strength is at its maximum contribution will result conservative.
- By combining the previous steps, solution can be obtained. It is worth mentioning that iterations are needed to comply with the yielding threshold of the reinforcement.

Alternatively to the solution of Equation (1), the EC8 draft currently allows conservatively to assume the shear strength as the maximum between $V_{jh,cr}$ and $V_{jh,\min}$.

### *2.2. First Generation EC8*

EC8 in its current version (EC8 (2004)) applies the Principal Stress Criterion. Specifically, when the principal stress in tension reaches the concrete tensile strength ($f_{ct}$) the normalized shear stress ($v_{j,t}$) is written as it follows:

$$v_{j,t} = \frac{f_{cd}}{\sqrt{f_{cd}}}\sqrt{\left(\nu\rho_h + \frac{f_{ctd}}{f_{cd}}\right)\left(\nu + \frac{f_{ctd}}{f_{cd}}\right)} \tag{11}$$

Similarly, using Mohr's circle, when the principal stress in compressions reaches the reduced concrete compressive strength ($\eta f_{cd}$) the normalized shear stress ($v_{j,c}$) is written as it follows:

$$v_{j,c} = \eta\frac{f_{cd}}{\sqrt{f_{cd}}}\sqrt{1 - \frac{\eta}{\nu}} \tag{12}$$

Where $\eta$ is a reduction factor taking into account the detrimental effect of tensile strains. The minimum between Equation (11) and (12) is taken as nominal shear strength. Besides, by assuming $\rho_h$ equal to zero, Equation (11) is identical to Equation (2).

### *2.3. ASCE 41-17*

ASCE 41-17 (ASCE (2017)), prescribes a fixed values of the normalized shear stress ( $v_j$ ), i.e. 0.49 $\sqrt{f_c}$ and 0.99 $\sqrt{f_c}$ for "non-conforming" and "conforming" joint, respectively. The notion of conformity refers to the presence of hoops within the joint panel.

### *2.4. Model Code 2020 (draft)*

MC-2020(draft, FIB (2020)) gives a two levels-of-approximation(LoA) models. LoA-1 is based on pure STM. LoA-2 assumes Equation (1) identically. The former was presented by Fardis (2020) and its formulation is not repeated here for the sake of synthesis. It is worth to mention, though, that a fixed width of the concrete strut is assumed, that is equal to 0.11 or 0.09 times the length of the diagonal, depending on the presence of horizontal reinforcement within the joint panel.

## 3. An independent validation

MATLAB® environment was used to implement the equations presented in the Section 2 of this paper. The following additional assumptions were considered:

- Mean values obtained from database collection were used for the material parameters.
- The reference value of the cylindrical compressive strength $f_{cd}$ was divided by a factor equal to 1.60, to consider strength degradation for the cyclic load condition according to Biskinis and Fardis (2020).
- The limit for the principal compressive strain of concrete ( $\varepsilon_2$ ) was assumed equal to -0.001.
- The joint effective width ( $b_j$ ) was defined as the mean value between the beam and the column width, i.e. $b_j = 1/2(b_w + b_c)$ . Such assumption was compared by Fardis (2021) with other definitions of $b_j$ concluding that the results were comparable.
- The "swapping- $\theta$ " procedure has been carried out considering the following assumptions: (i) the range of $\theta$ angle is set as $\beta - 20° < \theta < \beta + 20°$ ; (iii) iterations of reinforcement stress (bounded by yielding strength) are carried out per each $\theta$; (iv) stop criteria considers the Euclidean norm of Equation (4) (or its corresponding one for the case $\theta > \beta$ ), calculated at two consecutive steps and tolerance set to $10^{-3}$; (v) the "optimal" $\theta$ angle is obtained when the concrete strut reaches maximum resistance.

### *3.1. Database of Exterior Joints*

An experimental database spanning a wide range of design parameters was constructed for 2D exterior joints. The database comprises the experimental results of almost 130 units. The limitation criteria were: (i) sub-assemblage of with at least 1/3 scale; (ii) joint shear failure mode either in conjunction with beam yielding [BY-JS] or joint failure [JS] without; (iii) conventional types of reinforcement anchorage (no headed bars).

For the sake of synthesis, the database is not presented in this paper but online available at: https://polimi365-my.sharepoint.com/:b:/g/personal/10342861_polimi_it/EcR0sjyDxG9Mu0D_y2XgajMBDT-3gxNVyQRZR13Noy-KBw?e=nTqCpn.

### *3.2. Results of Validation*

After screening the database, eighty tests had failure mode compliant with 'JS' or 'BY-JS'. Results of the validation are shown in Fig. 3 (a)-(f). The sub-figures are described as it follows:

- (a). The points representing pure shear failure fall to the left side of the bisector thus the model behaves conservatively. After performing simple statistic, T-t-P ratio resulted to have: (mean) 1.08; (median) 1.07; (CoV)

0.31. Those values are comparable with what Fardis (2021) declared. However, it is noteworthy that mean values have been used for material parameters. Differently, Fardis assumed nominal characteristic values (e.g $f_{ck} = f_{cm} - 8MPa$ and $f_{yk} = f_{cm} / 1.15$). Nonetheless, database contents might be different as well.

- (b). When the maximum of the Equation (1) is given by $V_{jh,cr}$, "CRACK" marker with a dark circle is shown in the plot. Conversely, if the maximum is attained either from Equation (4) (or its corresponding one for the case $\theta > \beta$ ) the result is labeled as "MCFT" and grey square marker appears in the plot. The latter applies to 43 cases, being this sub-class characterized by the following simple statistic: (mean) 1.03; (median) 1.00; (CoV) 0.29. The normalized shear stress ( $v_j$ , having dimension equal to $\sqrt{f_c}$ ) favors the comparison with respect to other simpler formulations. For instance, ASCE 41-17 (ASCE (2017)) prescribes, at most, 0.99 $\sqrt{f_c}$ for exterior joints. Furthermore, results show that cracking prediction is dominant for an interval of $v_j$ between 0.5 $\sqrt{f_c}$ to 1.0 $\sqrt{f_c}$ , with few exceptions.
- (c) and (d). The influence of $\varepsilon_1$ on the T-t-P ratio can be partly recognized for the Equation (4). Large tensile strains reduce the compressive strength according to Equation (5). As a result, the model tends to behave conservatively. Furthermore, it is evident that cracking prediction is dominant for $\varepsilon_1$ lower than 0.5\%.
- (e) and (f). An increase of reinforcement ratio, considering horizontal bars, promotes the MCFT prediction with respect to cracking. The same cannot be sustained for vertical reinforcement.

An insight on the sub-class of joints predicted Equation (4) (or its corresponding one for the case $\theta > \beta$ ) is represented in Fig. 4. The cases of $\theta > \beta$ need an explanation. For an exterior joint, it goes out of the common perception to imagine the compressive field shallower than the diagonal. Indeed, the compressive stresses cannot be transferred from the joint panel at the external side which is un-loaded. For those cases, horizontal reinforcement resulted un-yielded. Conversely, yield largely occurred for $\theta < \beta$ .

Finally, the predicted joint shear stress ( $v_j$ ) is given as a function of the mechanical reinforcement ratios in the Fig. 4 (b). A simplified strength envelope is suggested as it follows:

$$\begin{aligned} v_j &= 0.5 + 2.5\rho_h f_{yh} / f_c \quad \left(\sqrt{f_c}\right) \qquad with(\rho_h f_{yh} / f_c < 0.20) \\ v_j &= 1.0 \qquad \left(\sqrt{f_c}\right) \qquad with(\rho_h f_{yh} / f_c \geq 0.20) \end{aligned} \tag{13}$$

The extremes values for strength given by the Equation (13) are comparable with those currently assumed by ASCE41-17 for 2D exterior joints. Besides, the need for simplification of MCFT as a design tool has been claimed often (e.g. Bentz et al. (2007)).

### *3.3. Comparison with other design formulas*

Design formula reviewed in Section 2 were applied to the database of exterior joints. Results of the T-t-P ratio are shown in Fig. 5. All the formulas show CoV almost equal to 0.30. Median value obtained with Equation (1) is the lowest, apart from ASCE41-17 which has value lower than one. Summarizing, results obtained with design formulas are comparable with Equation (1), which has a larger computational effort that might not be necessary for preliminary design (or assessment) phases.

## 4. Conclusions

This paper reviewed the calculation method for shear strength of RC beam-column joint included in the draft of new generation Eurocode 8, as widely circulated in the scientific community. The method, as proposed by Michael Fardis in two background documents, combines Strut-And-Tie method and Modified-Compression-Field-Theory. The key analytical aspects were critically reviewed. An application to a database of more than one hundred exterior joint was presented. Comparable results of the T-t-P were obtained with respect to what declared by Fardis, although mean values for material parameters were used instead of characteristic ones. If compared with other building codes, the CoV of the T-t-P ratio was comparable. In this light, the increased computational effort might be not necessary for preliminary design phases

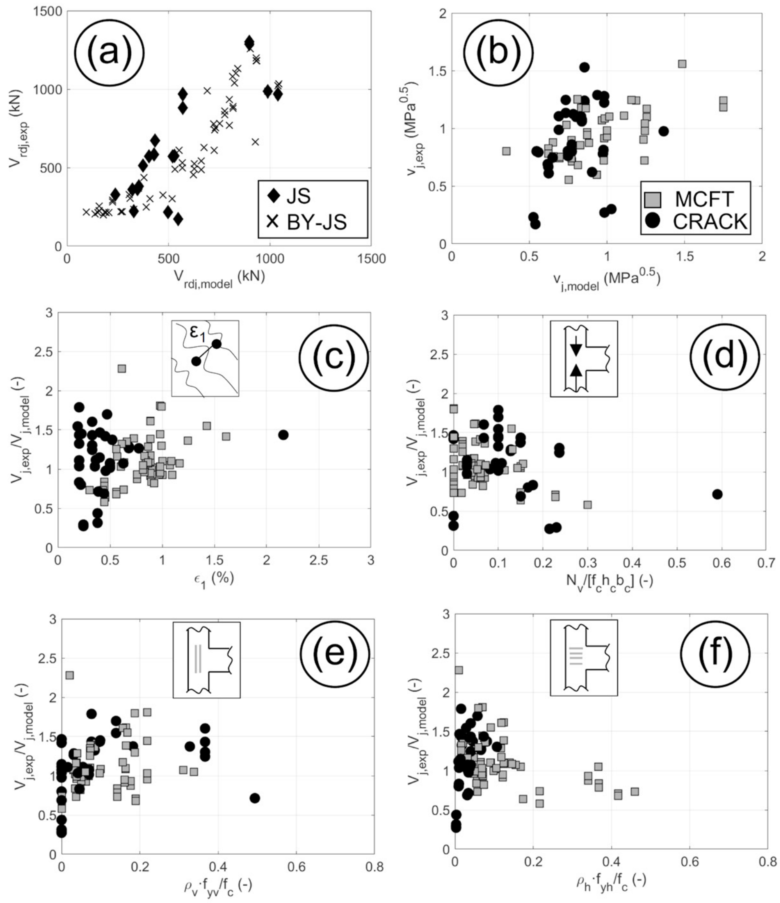


Fig. 3. Results of the application of Equation (1) to the database of 2D exterior joints. Test-To-Predicted charts: (a) joint shear force; (b) normalized shear stress; (c) influence of principal tensile strain; (d) influence of normalized axial force; (e) influence of horizontal reinforcement ratio; (f) influence of vertical reinforcement ratio.

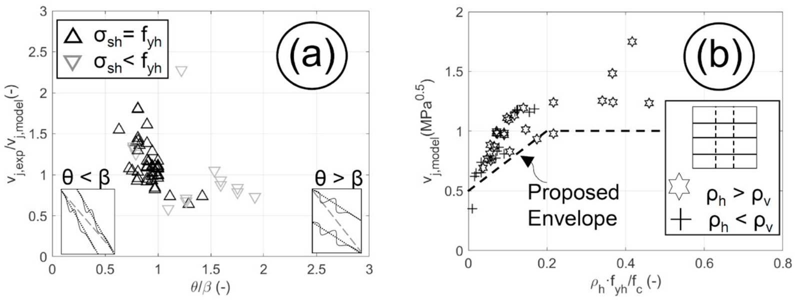


Fig. 4. Results of Equation (4) applied to the database of exterior joints: (a) T-t-P as a function of the ratio $\theta / \beta$ ; (b) Influence of the horizontal reinforcement ratio on the predicted shear stress.

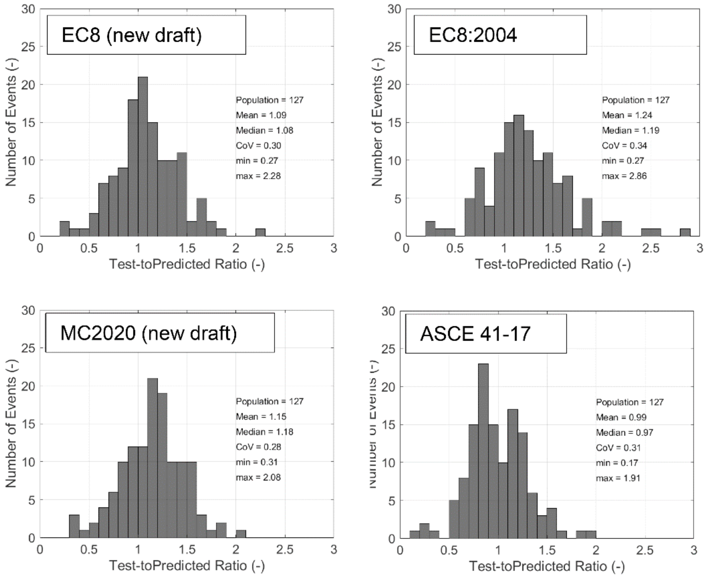


Fig. 5. Comparison of T-t-P ratios using different design formulas for the prediction of beam-column joint strength.

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