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Design of full-strength full-ductility extended end-plate beam-to-column joints

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ABSTRACT

The analysis and modelling of the ultimate behaviour of beam-to-column connections is certainly one of the most studied topics in the field of steel structures. In particular, seismic design of steel frames is commonly carried out to assure the dissipation of the seismic input energy in so-called "dissipative zones". The location of such zones depends on the connection ultimate behaviour. Therefore, connections have to be properly detailed in order to assure wide and stable hysteresis loops. Once avoided the yielding of columns, beam-to-column joints play a role of paramount importance. In fact, beam-to-column joints can be designed either as Full Strength (FS) or as Partial Strength (PS). In the first case, depending on the overstrength level, the input seismic energy should be dissipated by means of plastic cyclic excursions of the beam ends. In the second case, dissipation requires the plastic engagement of ductile joint components.

This paper addresses the design criteria to be adopted to assure full-strength full-ductility behaviour of Unstiffened Extended End-Plate (U-EEP) beam-to-column joints. The validation of the design procedure is accomplished by three-dimensional finite element analyses with ABAQUS 6.13 software. Finally, in order to clarify the design procedure in detail, a worked numerical example concerning the design of an external joint is presented.

1. Introduction

Within the analysis of steel structures, the modelling of the ultimate behaviour of beam-to-column joints is one of the most studied topic. As well known, before the introduction of the *semi-rigidity* concept [1,2], steel frame design was accomplished by properly considering a limit assumption regarding the joint behaviour. Depending on the beam-to-column joint typology, it was either assumed that all the ends of the members converging in the joint are subjected to the same rotation and the same displacements or assumed that the joints are able to permit free rotations. The first case leads to *continuous frames*, while the second one to *pinned frames*. The application of the semi-rigidity concept has required the development of a general methodology allowing the evaluation of the rotational stiffness and the flexural resistance of joints starting from their geometrical and mechanical properties. This resulted in a strong effort, in Europe more than in United States, which has led to the complete definition and codification of the component method [3,4]. This allows the analysis of actual semi-continuous structural systems, accounting for the rotational behaviour of beam-to-column joints.

The component method is essentially based on mechanical models constituted by the assembling of spring elements modelling the joint components. The non-linearity of the moment-rotation response of joints is obtained starting from the non-linear constitutive laws adopted for the components. The method is suitable for the modelling of any kind of joint provided that the components are properly identified and their constitutive law is appropriately modelled.

Even though some authors have already investigated some aspects related to the prediction of the plastic deformation capacity [5–8,39,40] and of the cyclic behaviour of connections [9–13,41], past experimental and theoretical researches have often focused their attention mainly on the prediction of the stiffness and resistance of joint components. Therefore, the theoretical prediction of the plastic deformation capacity of connections is still an open research field.

Moreover, it cannot be denied that the classification of beam-to-column joints as full-strength or as partial-strength is too simplistic, because it is rigorous only in the pure theoretical case occurring when both the joint that the connected member exhibit a perfectly plastic behaviour. Unfortunately, this is not the case of actual connections whose ultimate behaviour is always significantly affected by strain hardening which can give rise to the shearing of yielding between the joint and the connected member as it will be described in the following. As soon as the distinction between the joint and the connection is made (Fig. 1), allowing the definition of the joint as the combination in series of the connection and of the column web panel zone, also the concept of ***beam-joint system*** becomes noticeable, being constituted by the combination in series of the beam-to-column joint and the beam end [14].

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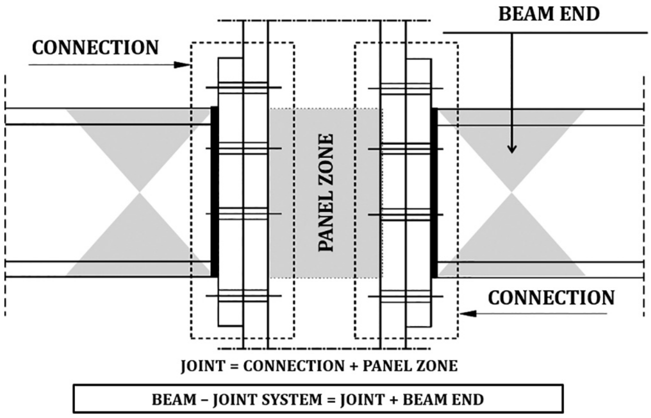

Fig. 1. Beam-joint system.

This concept is of primary importance under the point of view of the yielding location and, therefore, for seismic design purposes. This statement can be easily explained considering a tri-linear modelling of the moment-rotation curve of both the beam-to-column joint and the beam end (Fig. 2). In fact, generally the plastic rotation supply Θ_{pu} of the beam-joint system can be regarded as the sum of two contributions ($\Theta_{pu} = \varphi_p + \vartheta_p$): the plastic rotation of the beam-to-column joint φ_p and the plastic rotation provided by the beam end ϑ_p. Therefore, an accurate evaluation of the moment-rotation curve of the beam-to-column joint is required, because the plastic rotation provided by the beam end is strictly dependent on the flexural resistance that the beam-to-column joint is able to develop [14].

Concerning the beam-to-column joint, $M_{j.\,y}$ is the value of the bending moment leading to first yielding, $M_{j.\,p}$ is the conventional plastic moment defining the knee of the moment-rotation curve according to Eurocode 3, $M_{j.\,u}$ is the theoretical ultimate flexural resistance of the beam-to-column joint. Regarding the beam, $s\ M_{pb}$ is the maximum bending moment corresponding to the occurrence of local buckling of the beam compressed flange.

The parameter s is the non-dimensional buckling stress depending on the width-to-thickness ratios of the plate elements constituting the beam section and on the longitudinal stress gradient. Starting from the analysis of available experimental data [15,16], by means of a multiple regression analysis, Mazzolani and Piluso [17] defined the following empirical relationship:

$$s = \frac{1}{0.546321 + 1.632533\lambda_f^2 + 0.062124\lambda_w^2 - 0.602125\frac{b_f}{L_e} + 0.001471\frac{E}{E_h} + 0.007766\frac{\varepsilon_h}{\varepsilon_y}} \le \frac{f_u}{f_y} \tag{1}$$

where λ_f and λ_w are, respectively, the normalized slenderness parameters of the flange and of the web equal to:

$$\lambda_f = \frac{b_f}{2\,t_f}\sqrt{\frac{f_{ym.bf}}{E}} \quad \text{and} \quad \lambda_w = \frac{d_w}{2\,t_w}\sqrt{\frac{f_{ym.bw}}{E}} \tag{2}$$

where b_f is the flange width, t_f is the flange thickness, d_w is the depth of the beam web, t_w is the web thickness, L_e is the shear length of the beam, E is the Young modulus, $f_{ym.\,bf}$ is the average value of the yield stress of the beam flange, $f_{ym.\,bw}$ is the average value of the yield stress of the beam web, E_h is the hardening modulus, ε_y is the strain corresponding to first yielding, ε_h is the strain corresponding to the end of the yield plateau and f_u and f_y are, respectively, the ultimate and the yielding stress of the material composing the beam.

Four significant cases can arise [14] (Fig. 2):

$M_{j.u} \ge s\ M_{pb}$

In this case the ultimate resistance of the beam-to-column joint allows the complete exploitation of the beam plastic reserves, so that:

$$\vartheta_p = \vartheta_{pu} \quad \text{and} \quad \varphi_p \le \varphi_{pu} \tag{3}$$

where ϑ_{pu} is the ultimate plastic rotation of the beam and φ_{pu} is the theoretical value of the ultimate plastic rotation of the beam-to-column joint.

Therefore, the plastic rotation supply of the beam-joint system is given by the sum of the beam plastic rotation supply and a part, for $M_{j.\,u} > s\ M_{pb}$, or the total value, for $M_{j.\,u} = s\ M_{pb}$, of the plastic rotation supply of the beam-to-column joint. As the plastic rotation supply of the beam-joint system is greater than the plastic rotation capacity of the connected beam, in this case the beam-to-column joints can be defined as full-strength full-ductility.

$M_{pb} \le M_{j.u} < s\ M_{pb}$

In this case, even though the beam end can be engaged in plastic range, the ultimate resistance of the beam-to-column joint is not sufficient to completely exploit the beam plastic reserves, so that:

$$\vartheta_p < \vartheta_{pu} \quad \text{and} \quad \varphi_p = \varphi_{pu} \tag{4}$$

Therefore, the plastic rotation supply of the beam-joint system is given by the sum of the plastic rotation supply of the joint and a part of that of the connected beam. The beam-to-column joint can be defined as full-strength (because $M_{j.\,u} > M_{pb}$), but cannot be defined "a priori" as full-ductility, because the plastic rotation capacity of the beam-joint system is strictly dependent on the contribution (φ_{pu}) due to the beam-to-column joint.

$M_{j.u} \le M_{pb}$

In this case, the ultimate resistance of the beam-to-column joint is not sufficient to engage the beam in plastic range, so that:

$$\vartheta_p = 0 \quad \text{and} \quad \varphi_p = \varphi_{pu} \tag{5}$$

Therefore, the ultimate plastic rotation of the beam-joint system is coincident with the plastic rotation of the beam-to-column joint. The beam-to-column joint can be defined as partial-strength. Nothing can be said, a priori, about the degree of restoration of rotation capacity, because the plastic rotation capacity of the beam-joint system is strictly dependent on φ_{pu}.

$M_{j.y} > sM_{pb}$

In this case, the elastic flexural resistance is sufficient to completely exploit the plastic reserves of the beam, so that:

$$\vartheta_p = \vartheta_{pu} \quad \text{and} \quad \varphi_p = 0 \tag{6}$$

Consequently, the plastic rotation of the beam-joint system is equal to the plastic rotation of the beam end. The beam-to-column joint can be referred as full-strength full-ductility. The difference with respect to case a) is that the beam-to-column joint remains in elastic range ($\varphi_p = 0$).

Regarding the evaluation of the plastic rotation of the beam end, simple relations are available in literature [18–21]. In addition, the plastic rotation of the beam-to-column joints can be determined starting to the knowledge of the plastic deformation of each component, through an advanced modelling of their force-displacement law (up to