Mechanical behavior of joints with cellular beams

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RÉSUMÉ. Toutes les études existantes considèrent que les poutres ajourées sont simplement appuyées. Par conséquent, les assemblages poutre-poteau sont conçus pour être nominalement articulés. Si les caractéristiques des assemblages ne sont pas affectées par les ouvertures situées au voisinage de la connexion, l'utilisation des assemblages semi-rigides ou rigides pourrait augmenter la capacité portante des poutres ajourées. L'objectif de cet article est d'étudier l'effet des ouvertures d'âme des poutres sur les caractéristiques des assemblages boulonnées par platine d'about en utilisant un modèle éléments finis 3D. Les simulations numériques ont été réalisées avec le logiciel ABAQUS 6.14. Le modèle EF a été validé par des résultats expérimentaux disponibles dans la littérature. Une étude paramétrique a été réalisée pour étudier l'effet de la forme, la taille et la position des ouvertures sur les courbes moment-rotation des assemblages poutre-poteau par platine d'about boulonnée.

ABSTRACT. In all existing studies, castellated beams are considered as simply-supported. Therefore, beam-to-column joints are designed to be nominally pinned. If the characteristics of the joints are not affected by the openings situated in the vicinity of the joint, the use of semi-rigid or rigid connections would increase the load carrying capacity of castellated beams. This study investigates the effect of openings on the characteristics of bolted end plate connections by using a three-dimensional finite element model. Analysis simulations were performed using the commercial finite element analysis software ABAQUS, version 6.14. The FEM model was validated with experimental results available in the literature. A parametric study was carried out to examine the effect of shape, size and location of the openings on the behaviour of end plate connections.

MOTS-CLÉS : platine d'about, courbe moment-rotation, ouvertures d'âme, poutres ajourées , modélisation par élément finis.

KEY WORDS: End plate connection, Moment-rotation curve, Openings, Castellated beams, Finite element modelling.

1. Introduction

Castellated beams are widely used to pass underfloor services ducts (water and sewage pipes, air ducts, cables etc.). The use of such beams leads into an increase in bending capacity and a reduction of weight, compared to solid webbed sections. Thus, they are an ideal solution for long and medium spans. In the current design procedures [1, 2] beams with perforated web are considered as simply supported at their ends. The connections between beams and columns must then be pinned. Double angle web connections are usually considered as simple shear connections. They transfer only shear to the supporting structural elements, even though this type of connection can transfer little moments.

Behavior of a joint is represented by moment-rotation characteristics relating the moment transmitted by the joint to the relative rotation between the members it connects [MOT 05]. The main features of this curve, as specified in Eurocode 3, part 1.8 [EUR 05], are: the initial stiffness, Sj.ini, the moment resistance of the joint, Mj.Rd, the capacity of rotation (ductility).

Classifications of EC3-1-8 [EUR 05] indicate that the rigidity of the beam is one of the main parameters affecting classification of beam-to-column joints. The purpose of this paper is to investigate the effect of the presence of web openings of various shapes and size in the vicinity of the bolted end plate joints on the moment-rotation curves Mj-ϕ. To accomplish this objective, a finite element study was performed by means of the general purpose software Abaqus, version 6.14. If the joint configuration has an appropriate rigidity to behave as a semi-rigid, it will increase the shear/moment capacity of castellated beams instead of considering them as simply supported.

2. Experimental tests used for the validation of the numerical model

Numerical models are required to be carefully validated against experimental data in order to determine the accuracy of the modeling. For this purpose, test results of two double-sided beam-to-column joints conducted by Abidelah et al [ABI 12] in the laboratory of Blaise Pascal University, named BC1 and BC2 were numerically analysed. The two test specimens consisted of an IPE 240 beam, without openings, connected with an HEA 120 and an end-plate with a thickness of 15mm, all of class S235 steel grade. Beams of test specimens were connected to the column with three rows of bolts. The two connections had two high tension bolts M16 per horizontal row with grade 8.8 in 18 mm drilled holes.

A vertical load was applied to the upper end of the column by one hydraulic actuator and was monotonically increased under displacement control at the rate of 0.02 mm/s.

The main features of the test set-up and the location of the displacement transducers are illustrated in figure 1. The complete details of the experimental program are available in [ABI 12]

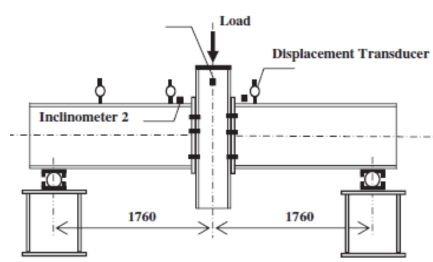


Figure 1. *Test set-up and location of the displacement transducers [ABI 12]*

3. Numerical Modeling

The numerical simulations are performed by using the general-purpose finite element software Abaqus, ver. 6.14. Material nonlinearities, large deflection, large strain and contact between different joint surfaces were included in the model. Taking advantage of the bi-axial symmetry, only one-fourth of the test specimens were modelled to reduce computational time. Solid twenty-noded hexahedral elements (Abaqus designation C3D20) with quadratic shape functions and full integration scheme (27 integration points) were employed to model all components of the connection. The nut, the bolt-head, and the two washers placed on both ends of the bolt (nut and bolt-head) were considered as a single body. Different mesh densities were adopted according to stress concentration, fine mesh in the connection zone and around the web openings and coarse mesh for the other parts. The contact between the column flange and the back of the end plate was modeled as frictionless by ensuring non-penetration and permitting separation of the individual parts. The interactions washer/end plate, bolt shank/ bolt-hole and washer/column flange were modeled as tangential frictional contact using penalty stiffness with the penalty value of 0.3. Overall views of typical meshed connections are shown in figure 2.

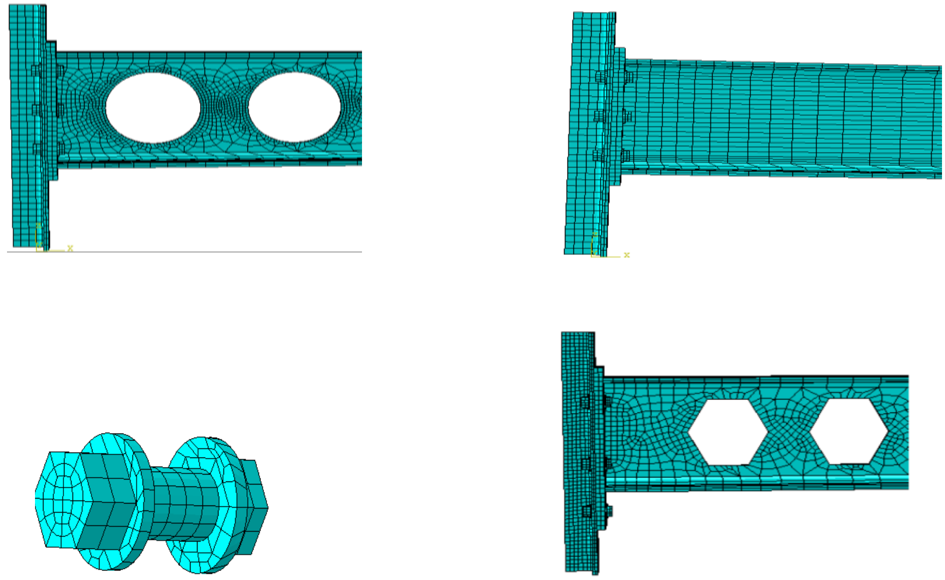


Figure 2. *Typical finite element models*

Nodes on the two planes of symmetry were restrained from displacing in the directions normal to these planes. Vertical displacements of the beam ends were restrained at the lower flange.

The stress–strain relationship for all elements of the connection is defined by using bilinear isotropic hardening models. The von Mises yielding criterion was used in conjunction with the associative flow rule. Young modulus of 210 GPa and Poisson's ratio of 0.3 were assumed. In ABAQUS, the material response to unidirectional stress is input through σ_t vs. ε_t, the true stress and the true strain respectively which account for large strains. The true stresses and strains were calculated in terms of measured stresses and strains obtained from uniaxial tensile tests performed on coupons, extracted from the joints components , and on some bolts.

To generate a bending moment at the connection, loading was applied monotonically by assigning vertical displacements at the mid plane of the column. The effects of pretension in the bolts were ignored.

The joint moment was taken as the product of the beam reaction by its distance to the front column flange. End plate and column flange separation values were recorded for each step load and used to generate the applied moment versus the relative joint rotation connection curve. Joint rotation ϕ of the beam-to-column end plate connection was defined in [BUR 98, YUA 07] as the relative rotation between the center lines of the beam top and bottom flanges and is illustrated in figure 3.

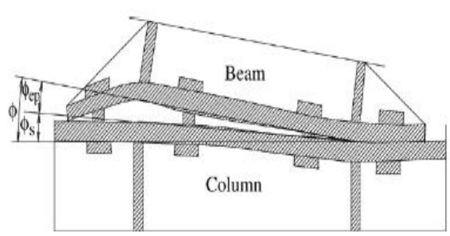
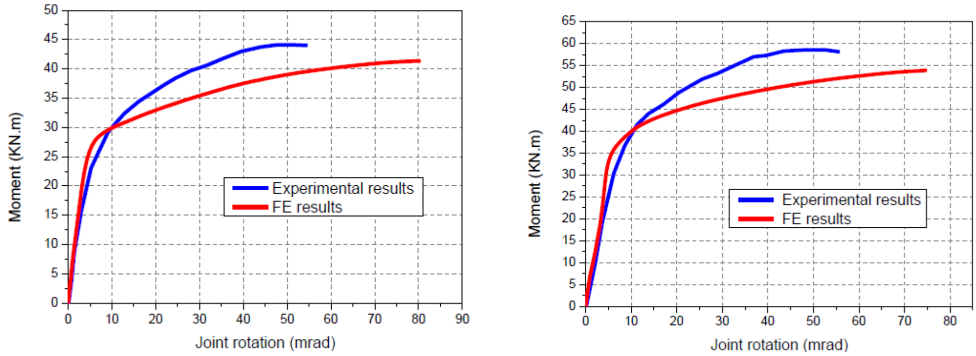


Figure 3. *Definition of joint rotation [YUA 07]*

4. Assessment of the numerical model

In order to assess the accuracy of the numerical model, test specimens BC1 and BC2 [ABI 12] were analysed by the numerical model described above. The numerical modeling and the experimental results were compared in terms of moment versus rotation curve and reported in figure 4. It can be observed that throughout the early stages of loading the numerical M-ϕ curves coincide with the experimental ones. Thus, the FE model can accurately predict the initial stiffness of the end-plate connection. As the moment increases, it can be observed a relative discrepancy between the experimental and the numerical curves as well as the maximum rotations.

Nevertheless, the maximum bending moment obtained numerically for the two test specimens are very close to the test results. Disagreement between numerical predictions and experimental data may be explained by the neglecting of geometrical imperfections and residual stresses, the materials are represented by simplified stress-strain curves and pretension in the bolts were not taken into account.



(a) Specimen BC1 *(b) Specimen BC2*

Figure 4. *Comparison of numerical and experimental results in terms of moment versus joint rotation of the test specimens [ABI 12]*

Figure 5 shows that at failure, the deflected shapes of the two connection specimens BC1 and BC2 obtained from the FEA are close to those obtained from the experimental data.

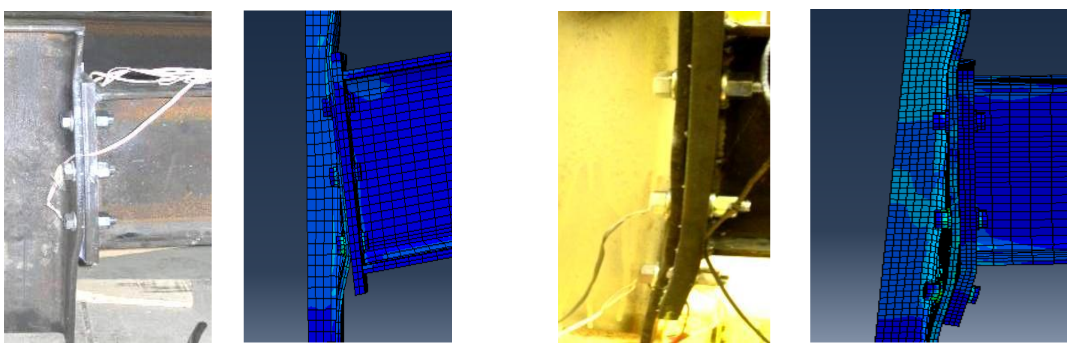
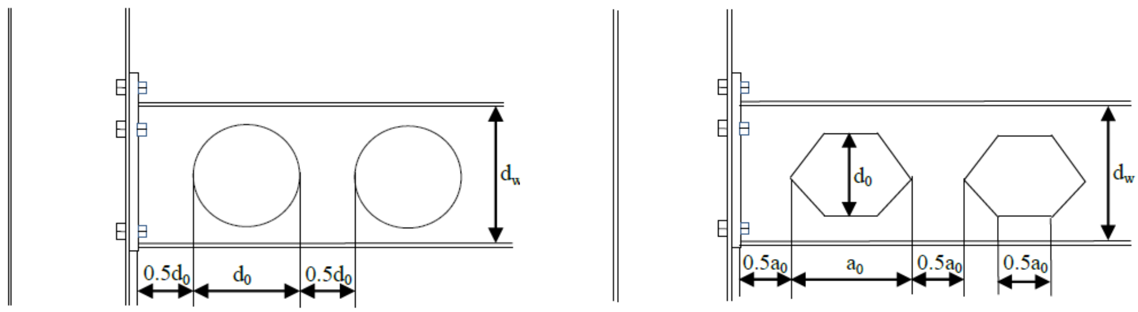


Figure 5. *Comparison of ultimate failure mode of connection of the test specimens in [ABI 12]*

Therefore, it can be concluded that the proposed finite element modeling can predict with acceptable accuracy the main characteristics of bolted end-plate connections.

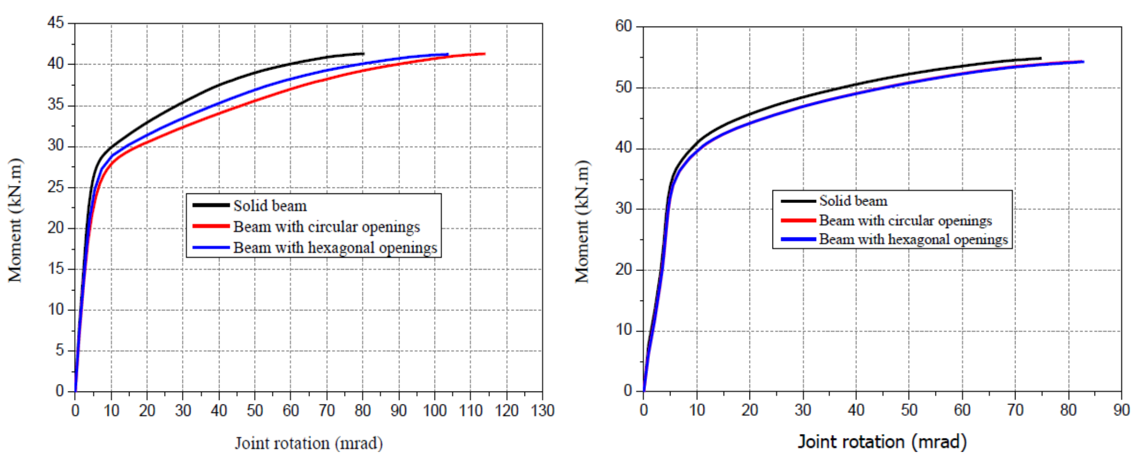
5. study of the influence of web openings in the beam on the bolted end-plate connection characteristics

Using the validated finite element modeling discussed above, a parametric study was conducted to assess the impact of the beam web openings on the behavior of end-plate connections. To achieve this objective, numerical analyses were carried out on connections with solid and perforated beams. In addition to the tested specimens BC1 and BC2, tested specimens RA1, RA4 and RA4T [ARI 05], which have a similar connection configuration of the specimen BC1 and BC2, were used in this comparative study. Six further specimens were considered by transforming the solid webbed beams of the tested specimens mentioned above to a perforated beams formed by closely spaced and uniformly distributed circular and hexagonal shaped web openings. Size and spacing of the openings adopted for each specimen were within the limits recommended by the design guidelines prescribed in the Annex N of ENV 1993-1-1 [ENV 93]. The geometrical parameters of the perforated beams adopted for the present study are shown in figure 6. Parameters for the web opening layout were adopted in an attempt to minimize the characteristics of the connection without causing a premature failure by web-post buckling mechanism of the beam. This was realized by considering the maximum required size and spacing of the openings and the minimum required distance between the column face and the edge of the first opening as can be seen from figure 6. Results of the numerical analyses are displayed as joint moment-rotation curves as shown in figures 7a to 7e. Figures 7c to 7e indicates clearly that the moment versus rotation curves of the connections with solid beams [ARI 05] virtually coincide with those of connections with perforated beams whether the openings have circular or hexagonal shapes with comparable sizes and locations. The nonlinear part of the moment-rotation curve for specimen BC1 with flush end-plate connection (figure 7a) is somewhat affected by the presence circular or hexagonal openings, but without altering substantially the main mechanical characteristics of the connection obtained from this curve, except for the ultimate rotation which is slightly increased. The influence of the openings on the nonlinear moment-rotation curve part is insignificant if extended end-plate is used instead of flush end-plate (figure 7b). These results may indicate that flush end-plate connections are more sensitive to the presence of openings in the beam web than extended end-plate connections.

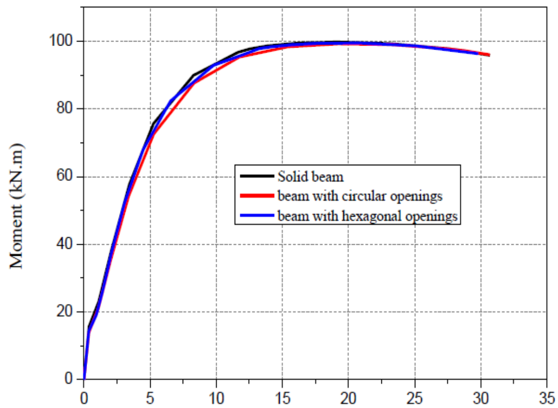


d0 = 0.8dw (depth of the web) *d0 = 0.75dw a0 = d0*

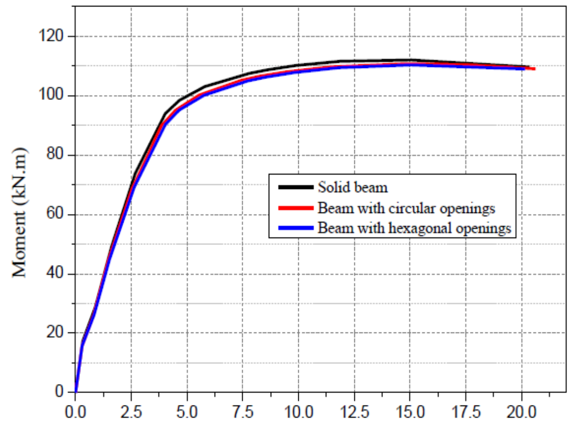
Figure 6. *Geometry of the beams with web openings*



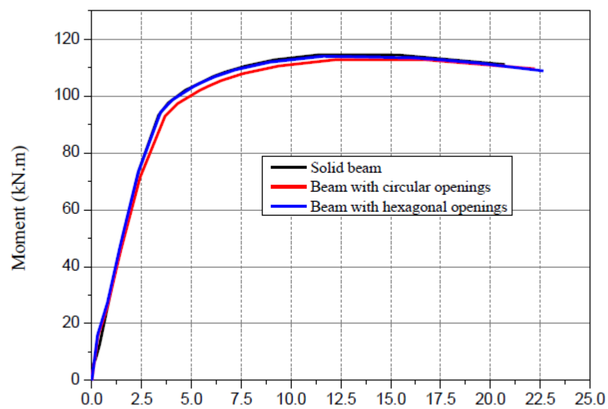
a) Specimen BC1 *b) Specimen BC2*



c) Specimen RA1



d) Specimen RA4



e) Specimen RA4T

Figure 7. *Moment-rotation curves for joints with solid beams and perforated beams*

Conclusions

In the present research the impact of the presence of the conventional hexagonal and circular web openings in the beams on the behavior of extended end-plate connections was investigated by means of numerical simulations. The results of two test specimens, available in the literature, were used to validate the numerical model developed in this study. Comparison between experimental and numerical moment versus rotation curves revealed that the numerical can predict with sufficient accuracy the initial rotational stiffness and the maximum moment. Nonetheless, the model should be improved to obtain more accurate results in terms of the rotational ductility, the joint moment resistance and the variation of the moment-rotation curve in the post-elastic range. The study conducted on 10 FE models has shown that the presence of l openings, and particularly near the connection zone, does not affect significantly the characteristics of the end-plate connections. Thus the use of semi-rigid connection for castellated beams may enhance their performance, without altering the performance of the bolted end-plate connections. However, further investigations are required to endorse the results of the present study.

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