SOME ASPECTS ON THE DESIGN APPROACHES FOR BOLTED MOMENT CONNECTIONS IN FRAMES

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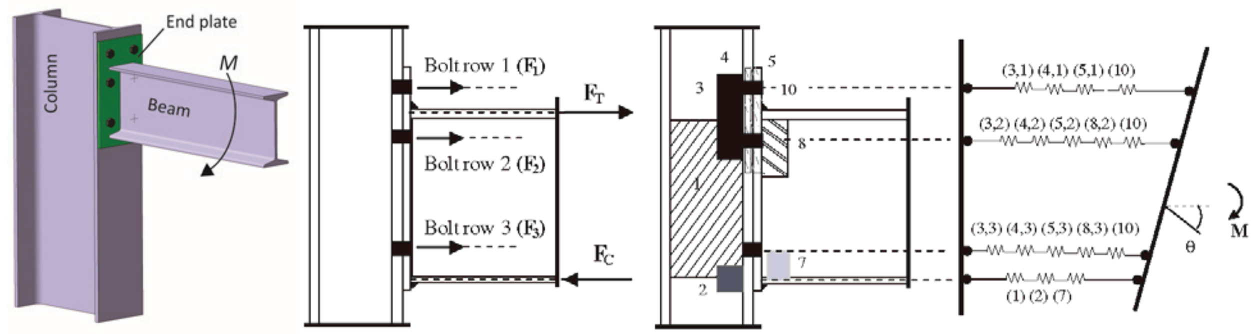
Summary: The end-plate bolted connections are widely used in the construction of metal buildings and steel portal frames and play a crucial role in the safety of steel structures. Studies agreed that joint rotational behavior should be considered in frame analysis due to the fact that majority of these joints are semi-rigid. This paper gives a survey on the progress in this topic, based on the studies in the last decade and main design approaches which are analytical, numerical and experimental. There are noted some principal characteristics of each method, along with some advantages and disadvantages. The illustrative example is given to describe the situation when all the mentioned methods are included on the single joint. It is proposed, as a good practice, to propose analytical model in that way to comply with experimental verification and to use numerical model in the form of validation in the last stages of joint design. Finally, it is noted that joint behavior under monotonic or cyclic loading, within the scope of the ductile failure modes of the joint, can be controlled with the design parameters of the end-plate and bolts.

Keywords: survey, end-plate joint, semi-rigid, moment-rotation, design method.

INTRODUCTION

The paper deals with the calculation methods of the end-plate bolted (EPB) moment connection-joint. They are widely present in steel buildings and framed structures and play important role in overall safety. The importance of this topic is accompanied with known fact that majority of structural failures are related to the bad design of its connections.

Primarily, the designers of structures deals with sizing of beams and columns to perform design check of structural members. Only in next stages, they design and calculate the joints in overall structure. As tradition, the designers are accustomed to consider the joints to be either pinned or rigid only. Within the framed structures, it was common to consider bolted moment connection as rigid ones which means that they provide full continuity between the connected members.



a) b)

***Figure 1**: a) Basic type of bolted moment connection, b) Component assemblage as mechanical model /17/*

However, most of the joints have behavior which is somewhere between that of pinned and rigid joints and this fact stands as semi-continuous approach in joint calculation. This is recognized by Eurocode 3 (EC3) and especcially intoroduced in EN 1993-1-8 /1/ which gave possibilites for better understanding of the joints behavior within the terms of stiffness, resistance and ductility. It offers analytical approach for the prediction of the joint response based on the mechanical and geometrical properties of the joint components and therefore termed as component method.

The subject of this paper are bolted moment end-plate connections in beam-to-column joints. They can be classified as flush or extended, with or without stiffeners, and with a different number of bolts at the tension zone. A basic example is given at fig. 1a. The calculation procedure of such joint, according to EC3, includes consideration of many parameters like column web in compression, column flange in bending, bolts in tension, end-plate in bending, etc. Hence, their design and mechanical behaviour are not so easy to analyze due to various components of different properties and geometrical discontinuities. One may see involved parts of joint on graphical presentation at fig. 1b.

In many surveys, researchers agree that in frame analysis, the rotational behavior of joints should be considered /2, 3/. Diaz et al. /4/ gave the significant and extensive review on the modelling of joint behaviour in steel frames, with research notes up to last decade.

This paper also emphasize the problem of calculation of joints at steel frames and is an attempt to give a review on up-to-date research in this topic. It deals with the three main accompanying approaches: analytical, numerical (finite element analysis) and experimental.

BRIEF SURVEY ON EXISTING DESIGN METHODS

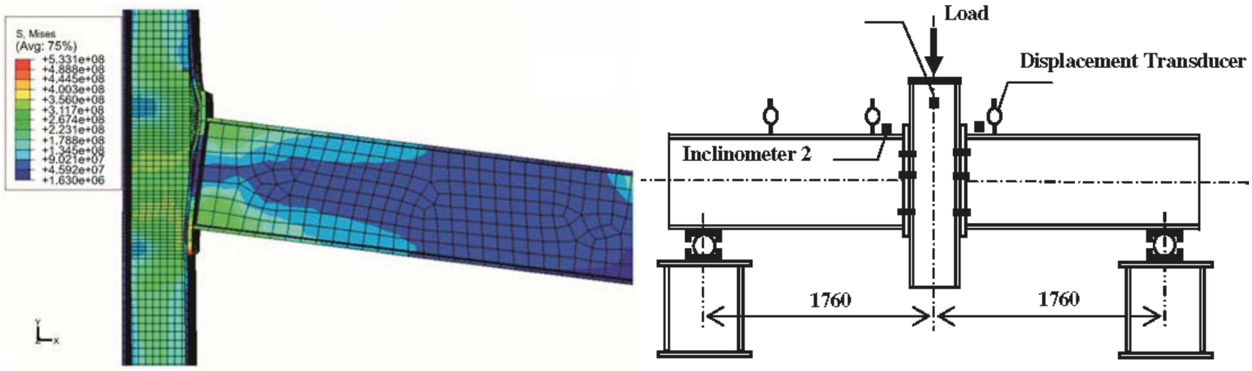
As mentioned before, analytical approach is covered with EC3 which gives design rules to predict connection flexural plastic resistance and initial stiffness. It propose the component method which is based on dividing the joint into its basic elements with defining their strength and stiffness characteristics. The stiffness of a joint is important characteristic which reflect the rotational resistance of a connection to applied moment. It is described with moment-rotation (M-Ø) diagram. The mechanical model consists of modelling a joint as an assembly of extensional springs, for each component, and rigid links (Figure 1b). The components which have to be considered in beam-to-column joints with bolted end-plate connections are the column web panel in shear, the column web in compression, the column web in tension, the column flange in bending, the end-plate in bending, the beam flange and web in compression, the beam web in tension and the bolts in tension.

Generally, the design procedure is composed of calculating the design resistances for a specified connection configuration, for the lowest mode of failure, and to ensure these are at least equal to the design beam/column moments. The rotational response is mostly governed by the deformation of the tension zone of the connection, which is formed by the column flange and the end-plate under tension and elongation of the bolts. The tension zone in EC3 is modeled by means of “equivalent T-stubs” concept. The standard only implicitly considers the prying effects when determining the design tension resistance. Analysis /5/ emphasizes the effects of prying action and compares formulae in several codes. It gives some conducive expresions which can be utilized to calculate prying forces and bending moment for end-plate in practical design. Also, it is proposed a simplified design procedure for end-plate connection which combines the advantages of several methods and could be easily programmed in the spreadsheet for efficient use by designers.

Wide theoretical postulation in this field is also given by Murrey and Sumner /6/ which is closely related to the American engineering practice /7/. They presented a unified method for the design of extended stiffened end-plate bolted (ESEPB) joints exposed to wind and seismic loading that applies yield line theory to predict the end-plate and column flange strength.

The influence of stiffeners at EPB joints in EC3 is not clearly implemented. D`Aniello et al. /8/ presented criticisms of current version of this standard due to missing specific provisions for a seismic design where extended stiffened end-plate joints are widely used. Herewith, along with general trend in engineering, the numerical approach-finite element (FE) analysis is highly present. Tartaglia et al. /9/ made extensive parametric FE simulations of the stiffened EPB joints using ABAQUS. Due to for monotonic and cyclic analysis, the yield line distribution and the variation of internal forces in the rib and bolts are monitored. Three-dimensional (3D) FE models that accounts both the geometrical and material non-linearities are developed in /10/, for EPB moment joints for beam splices with multiple row bolts. The behavior of beam-to-column connection using the FE analysis was successfully simulated by /11/, along with /12,13,14,15/.

The most reliable way and direct method of obtaining the moment-rotation curve are experimental investigations. Since experiments could often be very expensive, much more effort has been focused toward developing a well-defined analytical method that can be easily carried out. Shi et al. /16/ proposed a new model for the moment-rotation (M-Ø) relationship for extended stiffened beam-to-column end-plate joints and they verified the proposed analytical model conducting five corresponding joint tests. Abidelah /17/ presents the experimental results of eight specimens of joints, where four of them have stiffeners in the extended part. It is used column with low resistance to observe the competitions between the failure modes in the tension and compression zones. Often, the validation of experimental studies is done with numerical-FE analysis /18/.



a) b)

***Figure 2**: a) Von-Mises stress plot in connection /11/, b) The experimental set-up and measurement devices /17/*

It is obvious that the design of steel moment connections can be a laborious and time-consuming process due to different components involved if undertaken by hand according to existing standards. Especially, a large number of iterations may be required to obtain the optimum connection configuration. This is also valid for numerical-FE approach where one have to transform the physicality of the behaviour of the joint in correct way in standard FE softwares. Experimental research is of major importance because it provides the best verification of analytical or numerical models.

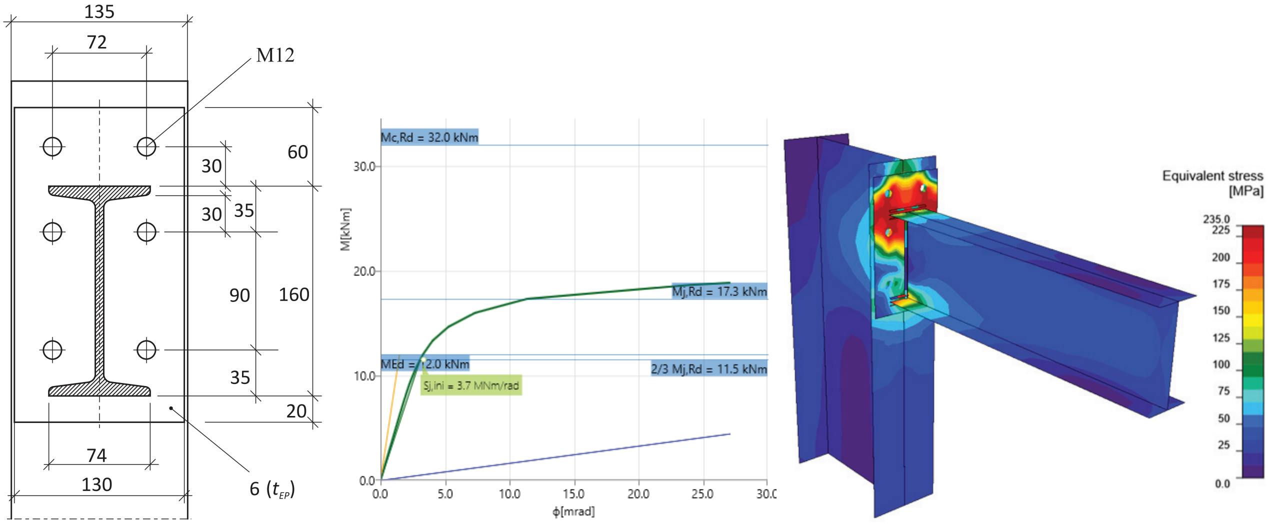
ILLUSTRATIVE EXAMPLE

All the three mentioned design approaches will be performed on the same object of the joint, in order to describe the correlation between them. It is used unstiffened extended end-plate bolted moment connection (Fig. 1a) with monotonic loading. The adopted testing model includes a beam IPN 160 (DIN) which is connected to the column IPE 270 (EURONORM). They are made of structural steel S235 with nominal characteristics: yield strength f_y = 235 MPa, ultimate tensile strength f_u = 360 MPa, modulus of elasticity E = 210000 MPa and Poisson's ratio v = 0.3. The bolted connection is non-preloaded with bolts M12-10.9 which have tension resistance of 60 kN each. The thickness of the end-plate is deliberately adopted as 6 mm, intended to include prying effects.

The analytical approach is implemented with EC3 rules, according to bolt arrangements as shown at Fig. 3a.

It is obtained rotational stiffness of the joint as $S_{j,ini}$=3.7 MNm/rad.

The numerical-FE model is done with same postulation and with applied moment of 12 kNm. It is used the software IDEA StatiCa Connection with a unique FE method /19/. Modeling considers an elastic-plastic material model for all the element of the joint while the steel members are meshed with 4-node shell elements. Among many of the responses, it is shown here the obtained moment-rotation diagram (Fig. 3b) and the stress state in the joint (Fig. 3c). One may found that value of the rotational stiffness obtained with the software is almost the same as the value obtained with analytical approach.



a) b) c)

***Figure 3**: a) Geometrical parameters, b) Moment-rotation diagram, c) Stress state in the joint*

Experimental set-up is depicted in Figure 4a. The input force (*F*) is applied with hydraulic press and goes from 1 kN to 20 kN on the arm of 600 mm. The strain measurements are realized with a rosette and strain gauges at 11 points and corresponding values of stress are obtained /20/. If compared with FE approach, one may find very good correlation of the stress values. The end-plate showed visual deformation for load intensity from 15 kN and ended test with plastic deformation, Fig. 4b.

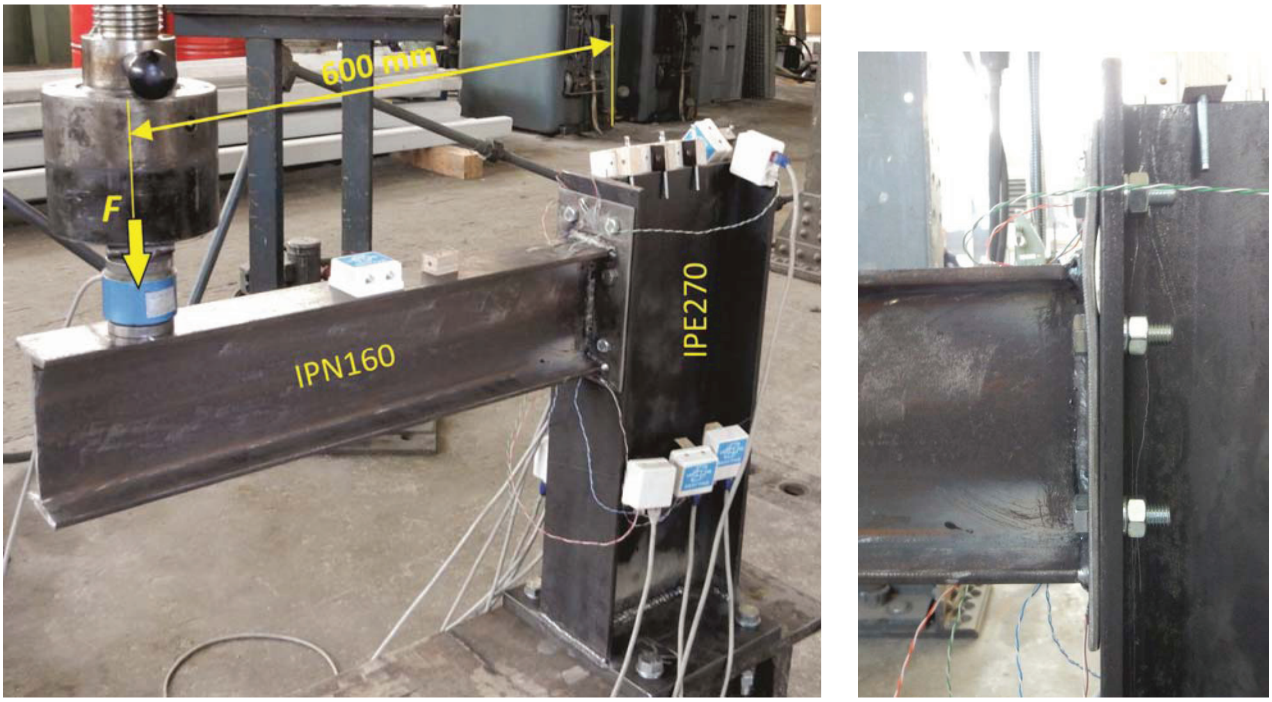


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***Figure 4**: a) Experimental set-up, b) End-plate plastic deformation*

DISCUSSION

First, all studies agree that the rotational behaviour of the joint should be considered when designers carry out the structural analysis of any frame i.e. traditional concept with assumption that joints are ideally pinned or fully rigid is conversative one. In the last thirty years, a large number of studies were carried out to investigate the performance of end-plate bolted moment connection.

It used here narrowed level of used methods with following approaches: analytical, numerical (finite element) and experimental. Apart from analytical models, /4/ discusses the mechanical models which formulation depends of following steps: (1) identification of the components of the joint that will provide significant deformation and failure, (2) determination of the constitutive laws for each component of the joint using any of the possible means, and (3) assembly of all the components in order to produce the moment-rotation curve for complete joint. However, this postulation is very close to analytical postulation. The backgound of analytical models are mainly postulated in the EC3 and AISC rules. Results in /21/ show that joints designed according to each of these rules provide similar response curves (elastic stifness and bending strenght) which is valuable for initial observation in this field.

Shi et al. /16/ proposed a new analytical model for the moment-rotation (M-Ø) relationship for extended stiffened beam-to-column end-plate joints. The contributions to the joint rotational deformation are provided of each component, such as shear deformation of the panel zone, the bolt extension, bending deformation of the end-plate and column flange. This analytical model can also provide the moment-shear rotation ($M\text{-}Ø_s$) and moment-gap rotation ($M\text{-}Ø_{ep}$) curves, thus provide a reliable foundation for analysing the detailed rotational behaviour of end-plate connections. They verified the proposed analytical model conducting five corresponding joint tests. In /5/ there is proposed revision for the current formulae in some codes for the end-plate thickness, prying forces and bending moment. From the study in that paper, the usage of equations which allow consideration of prying force is simple and feasible.

The finite element analysis are accompanying approach in the majority of studies because of following reasons: (1) due to lack of experimental results; (2) such models are inexpensive and robust; (3) to understand important local effects which are difficult to measure accurately physically; and (4) to achieve extensive parametric studies. The last is shown in /10, 15/, along with the fact the most considered parameters in studies are end-plate thickness, bolts diameter and influence of stiffeners. FEA can represent the complete picture of the stress, strain, deformation, bolt forces, etc.

However, if one considers the large number of variables related to connection geometry, connection components, and relationships for their materials, the task of determining simplified guidelines for the inclusion semi-rigid behavior into design is not that easy. Diaz et al. /12/, comparing numerical results with available experimental tests, pointed out some important directions that could lead to discrepancies in results: (1) the residual stresses in the welds are usually not considered in the FE models; (2) the tolerances in the dimensions of the sections and the geometrical imperfections in the experimental results used to validate and calibrate the FE model; and (3) the approximation used in incorporating the material stress-strain relationship into the FE model. One may notice that there are not an uniform procedure for selection the type of finite element in a mesh and the detail explanation of the contact finite elements between the components are often neglected.

The results of experimental testing is highly appreciated knowledge of the joint behaviour because there are not so frequently present in studies. In the researches, it is almost always inseparable from analytical approach. Some results show that EC3 gives safe proposals of the connection resistance but overestimates the initial stiffness of the connection, /17/. Due to small number of tests (8 in this case), this can serve only as guidance for possible studies. Also, the position of the compression center in the connection changes, with the presence of the stiffener in the compression zone, from the center of the beam flange to the centroid of the stiffener in the compression zone. Therefore, the value of the moment resistance of the connection is increased due to the increase of lever arm of the bolt rows in tension. The investigations /9, 18/ show that the slope and the thickness of the stiffener have a strong influence on the initial tensile stiffness of the joint.

CONCLUSION

Considerable number of papers have been published on the behavior of end-plate moment connections and agrees that joint rotational behavior should be considered in frame strucutral analysis. However, their design and mechanical behavior are complicated to analyze due to various components of different properties and geometrical discontinuities involved and is hard to simulate with simplified formulations. Analytical approach should always be the first step in joint design. The use of finite element analysis should be a potential tool for refinements in the current design approaches in order to improve the characterization of the actual behavior of connections. Moreover, numerical analysis has shown great importance in parametric studies where the lack of experimental testing is present. The real and most relevant behavior of single joint is obtained throughout experimental tests. It is not always cost effective, but this should be the price for propositon of new expressions or design methods.

The illustrative example is given here to show the application of all the mentioned approaches on the single joint. The effort ranking will put the experimental method on the first place, respecting that obtained results (even few of them) can be very important for the determination of the joint behaviour. Obviously, FE method is the leader when quantity of obtained results are the matter, but very good understanding of the phisicality is necessary prerequisition. The analytical approach is sufficient enough for the design of standard joints in steel frames and gives possibility for creating the easy-to-use algorithms in design process. According to the authors, the combination of approaches should always be present in studies. The most effective way is to present analytical model to comply with experimental verification and to use numeral model in the form of validation in the last stages of design.

Also, one may notice that joint behaviour can be controlled with two of his component, end-plate and bolts. With the change of their characteristics, it can be influenced on the level of the ductile failure modes of the joint. Similarly, the presence of welded stiffners, along with their shape, has influence on the joint behaviour. The design with extended end-plate should be prefered (vs flush) because it gives more possibilities for controlling the joint behaviour under monotonic or cyclic loadings.

This paper is a brief survey on up-to-date research in this topic, mostly from the last decade. With the narrowed level of design approach, it can serve as basic guidance for the method selection in design of the specific end-plate bolted moment connection.

ACKNOWLEDGEMENT

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