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# PERFORMANCE OF STEEL END-PLATE CONNECTIONS WITH TWO AND FOUR BOLTS PER ROW

BY

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**Abstract.** Any building structural system should be designed as to ensure structural stability and resistance for usual loading conditions but also for potential accidental loading situations. In the case multi-story steel building frames, the second requirement can be achieved considering special design situations in case of key structural member loss, such as a column element. In this case, the behaviour of elements and their connections should be adequate to avoid structural failure by assuring the development of alternate load paths. In this paper, a study on beam-to-column end-plate connections with four bolts per row is presented, in view of enhancing the local behavior of the connection and also the overall behavior of the new structural system. The study assessed the viability and behaviour of such connections under extreme loading situations, where the robustness of the structure represents a critical parameter. It is based on parametric advanced FEM analyses considering the relevance and impact of several geometrical parameters.

**Keywords:** end-plate connection; four bolts per row; robustness; FEM analysis; ductility.

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## 1. Introduction

According to EN1991-1-7 (CEN 2006), robustness represents „the ability of a structure to withstand extreme loading events without being damaged to an extent disproportionate to the original cause”. Especially in urban areas, events like explosions, impact, or fire can pose significant risks to the integrity of a structure, generating local degradation of the mechanical properties which may trigger progressive collapse.

Avoiding such risks requires building to be designed with enhanced local strength and alternative load paths in order to reduce its vulnerability. This can be achieved either by identifying the accidental load and designing the structure in order to resist the action, or by limiting the damage and redistributing the loads to the undamaged elements. In a scenario where a structure is subjected to an extreme loading and damage occurs, the connections need to assure the transfer of the loads from the damaged area to the undamaged elements. This requires a connection which has adequate levels of strength, stiffness and ductility, as well as a good post-flexural behaviour (Mărginean, 2017).

In the last decades, various studies investigated the behaviour of steel and composite steel-concrete frame connections (Jaspart and Weynard 2005) (Jaspart & Weynard 2016). The results led to the development of several types of connections and new design guides which were progressively integrated in the corresponding design standards. In Europe, Eurocodes 3 and 4 (CEN 2005) (CEN 2004) have been enriched with approaches regarding the integration of several types of connections in the design of frame assemblies (Dubina *et al.*, 2011).

In the particular case of steel and composite frame connections, the extended end-plate configuration is widely used throughout Europe. Although not present in modern design norms, the use of four bolts per row proves to bring important advantages to overall behaviour of beam-to-column connections (Demonceau *et al.*, 2010; Pisarek & Kozlowski, 2005). This technical detail has the potential to be an efficient solution in order to comply with robustness performance demands for buildings, by providing an appropriate ductility and post-critical behaviour.

The present study aims to analyse the behaviour of four bolts per row extended endplate connection against a more typical solution with two bolts per row. The analysed connections are retrieved from a spatial 2-storey, 2- bays on 2-span steel structure (Fig. 1) conceived as a full scale model for a blast testing.

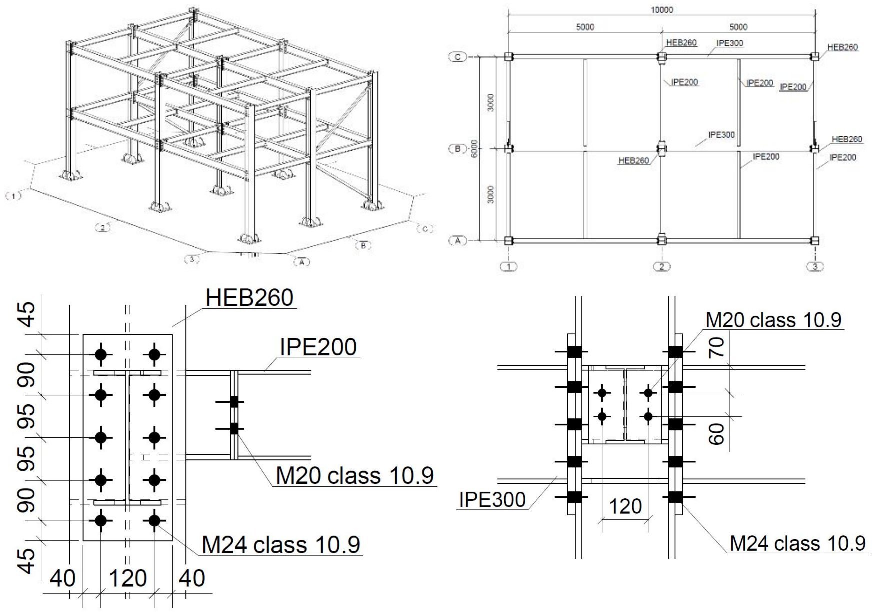


Fig. 1 – Geometry of the full-scale model.

The building was designed for permanent and live loads, and to seismic loads corresponding to a Romanian low seismicity zone of ag=0.10g. The following structural elements resulted from design: columns HEB260, main beams IPE300 and secondary beams IPE200, by considering a structural steel grade S275. The beam-to-column connection, which is the main focus of this study, features an extended end-plate of 20mm thickness, and 10 M24 bolts, grade 10.9 (Fig. 1).

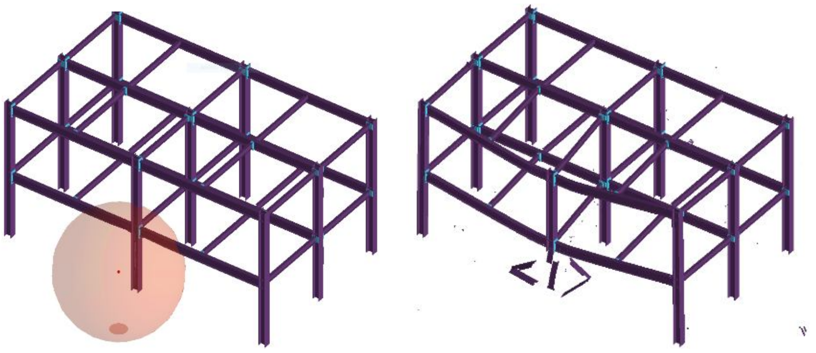


Fig. 2 – Simulation of the blast loading (Dinu, et al. 2017)

The main purpose of the research is to study the behaviour of the end-plate connections in case of the loss of the central perimetral column of a transversal frame due to blast loading as presented in Fig. 2. The blast is considered enough powerful to severely damage the column (considered as removed), but without producing considerable damage or dynamic impact to other structural elements.

## 2. Numerical Model and Parametrical Study

The behaviour of the beam-to-column connection, considered as a sub-assembly retrieved from the main structure was simulated by FE models in order to depict the behaviour of the end-plate beam-to-column connection with four bolts per row in comparison with the original design of the connection typology with two bolts per row. The selected sub-assembly comprises both 1st story beams and a segment from top and bottom connected columns corresponding to "zero-moment" zones, and corresponding joints, as shown in the static representation in Fig. 3.

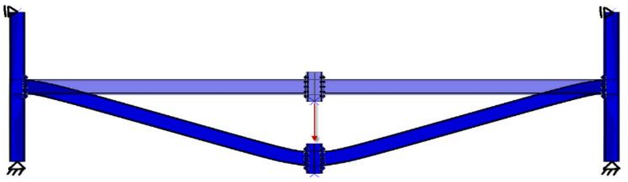


Fig. 1 – Static representation of the numerical model.

The main geometry of the connection was kept in case of two bolts per row and adapted to the case of four bolts per row (Fig. 4). The material characteristics of steel for beam, column and bolts were considered identical for all analysed cases. However, a parametrical study was investigated, considering as variables the end-plate thickness and bolt diameter: Table 1 presents the parameter variation in FE models.

The sub-assemblies were modelled in 3D FEA software ABAQUS (Dassault Systèmes 2016). The elements were modelled using solid geometry (C3D8R-type finite elements with reduced integration), using nominal material curves for plates and profiles, and experimental-based material curves for bolts (Dreveny 2014). The columns were restrained both in the out-of-plane direction as well as to torsion. The material characteristics considered S275 steel for structural elements and high strength characteristics HR10.9 for bolts (Fig. 5), for which the plastic behaviour was modelled using a true stress - true strain curve, obtained from tensile tests. In addition, failure was defined for the bolt material via damage evolution parameters in order to obtain failure in the bolts in tension.

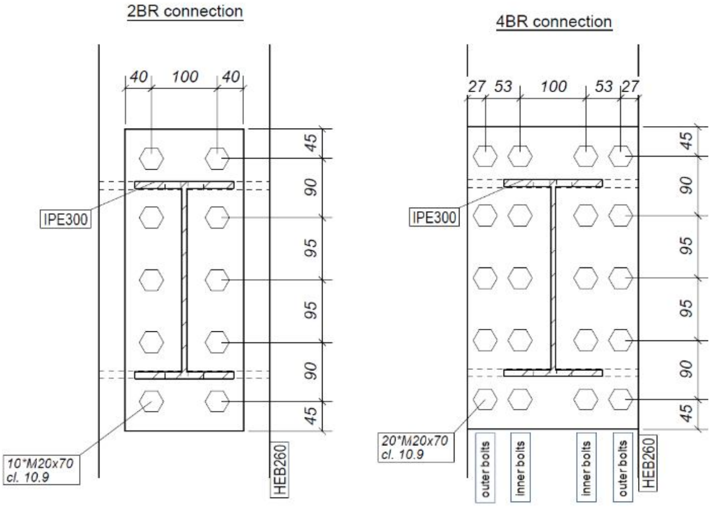


Fig. 2 – Adapted connection geometry for 2 and 4 bolt configurations respectively.

**Table 1**

*Parameter Variation* (BR = bolt per row)

| | | End-plate thickness | | |
|---|---|---|---|---|
| | | t = 20 mm | t = 15 mm | t = 12 mm |
| Bolt diameter | M24 | 2BR* | 2BR | – |
| | M20 | 2BR, 4BR | 2BR, 4BR | 2BR, 4BR |
| | M16 | – | 2BR, 4BR | 2BR, 4BR |

*Original joint configuration used in structural design

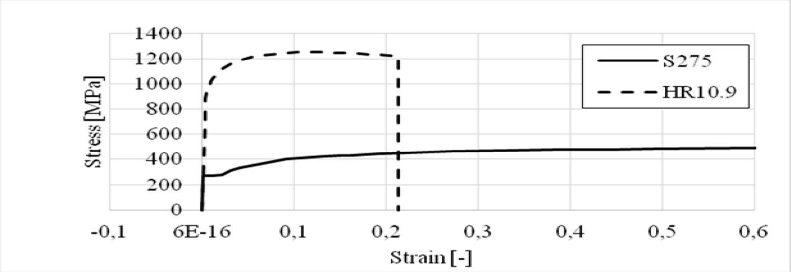


Fig. 3 – Trues stress-strain characteristic curves of materials used in FEA.

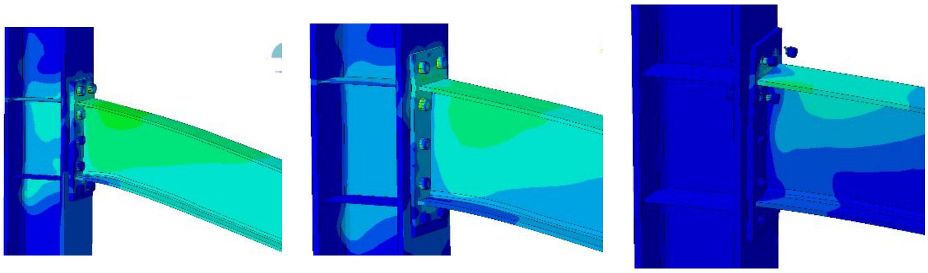
In order to optimize time of computation, a preliminary symmetry study was conducted. The results showed little difference between a full model (composed of two beams) and a symmetric version (composed of only one beam), for which the later was chosen.

## 3. Numerical Results

In order to simulate the columns loss, the middle column was subjected to an imposed downward displacement. Table 2 presents the failure mechanisms recorded for analysed models:

a) mainly, for bolt diameters of 20 to 24 mm, the failure is recorded in the beam and not in the connection;

b) in case of smaller diameters of bolts (M16), the general failure is recorded in the connection due to bolts failure in tension – mode 3 in accordance to EN 1993-1-8.



a) Beam yield (M24_2BR_20mm)

b) Beam and endplate yield (M20_2BR_12mm)

c) Bolts in tension (M16_2BR_12mm)

Fig. 4 – Failure modes.

**Table 2**

*Failure Modes*

| | | | End-plate thickness | | |
|---|---|---|---|---|---|
| | | | *t* = 20 mm | *t* = 15 mm | *t* = 12 mm |
| Bolt diameter | M24 | 2BR | Beam yield (Plastic hinge) | Beam yield (Plastic hinge) | – |
| | M20 | 2BR | Beam yield (Plastic hinge) | Beam yield (Plastic hinge) | Beam and end-plate yield |
| | | 4BR | Beam yield (Plastic hinge) | Beam yield (Plastic hinge) | Beam yield (Plastic hinge) |
| | M16 | 2BR | – | Bolts in tension | Bolts in tension |
| | | 4BR | – | Beam yield (Plastic hinge) | Inner bolts in tension |

In the particular case of the model considering M16 bolts, four bolts per row and the end-plate thickness of 12mm, the failure was characterized by an initial failure of the top inner bolts in tension (rows 1 and 2) followed by the outer bolts of row 1, and in a later stage, the outer bolts of row 2 also failed.

Fig. 7 presents the interpretation of results under the form of bending moment - rotation diagrams (M16 bolt case). The behaviour of the models using 4BR present both higher ultimate bending moment and higher ductility, allowing thus the development of catenary forces in the connection. The absence of damage evolution behaviour of the beam's steel material also contributed to these high values.

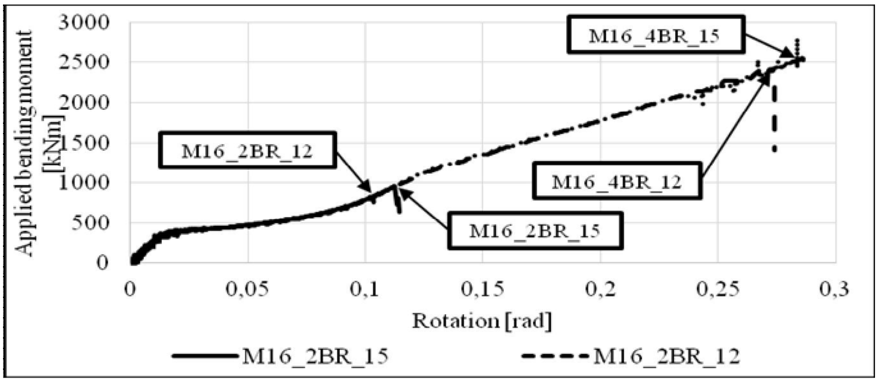
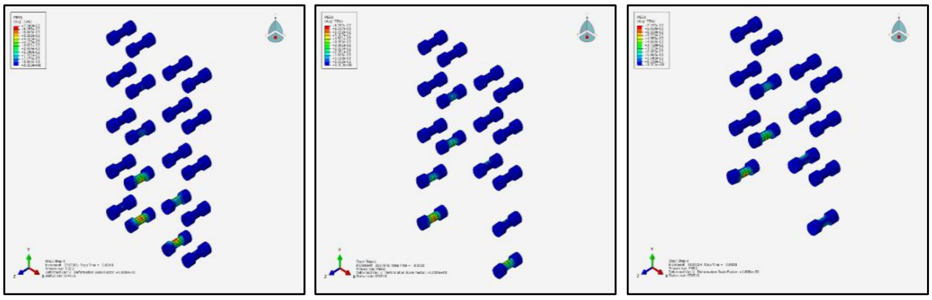


Fig. 5 – Moment – rotation diagram for the models using M16 bolts.

Fig. 8 presents the Equivalent Plastic Strain (PEEQ) strains at different imposed vertical displacements of the middle column: 1,330, 1,350 and respectively 1,380 mm . The PEEQ values show a small level of strain in the outer bolts in the moment when the first failure occurs in the inner bolts: this is



a) 1,330 mm b) 1,350 mm c) 1,380 mm

Fig. 8 – Strain states before different stages of vertical displacement in case M16 4BR $t$ = 12 mm.

due to a lack of adequate stiffness in the beam/end-plate assembly, which does not assure an even stress distribution. Fig. 9 shows the maximum recorded strain in the bolts for all analysed cases at different vertical deflection values: 200, 500, 800 and 1,200 mm respectively. In the same manner, Fig. 10 presents the maximum strains recorded in the end-plate.

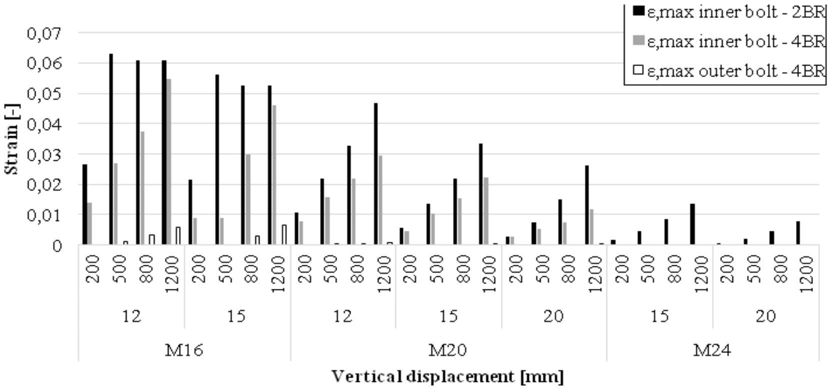


Fig. 6 – Maximum strain levels in the bolts.

The strain levels were also recorded in the end-plate, see:

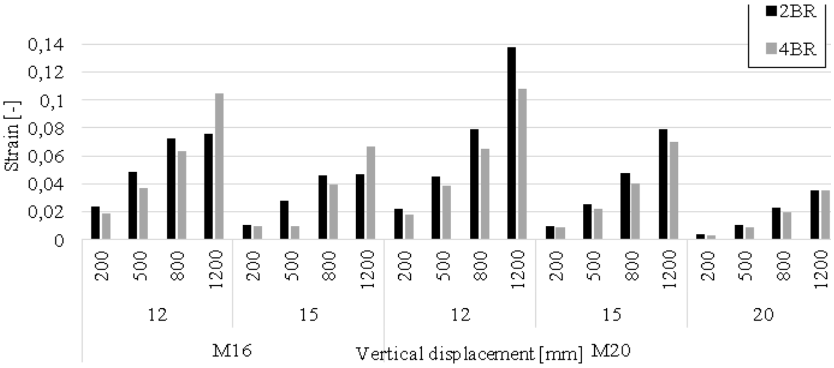


Fig. 7 – Maximum strain levels in the endplate.

## 4. Conclusions

The paper presented a numerical parametrical study, aimed to investigate the behavior of end-plate beam-column connections in a two-span, two-storey frame configuration affected by the middle column loss. The parametric study included several variations of an end plate bolted connection with two bolts per row, by modeling different bolt-row configuration, bolt diameter and end-plate thickness. The parametric study has shown the following:

a) for all the parallel cases analyzed, the strains recorded in bolts of four bolts per row are smaller than in the usual end-plate connections having two bolts per row;

b) in 4BR cases, an uneven stress distribution was observed, leading to a staggered response of bolts: the outer bolts are properly activated after the inner bolts have reached the ultimate strains: these may act as safety bolts in case of important loads;

c) in case of thicker end-plate connections ($t_{ep}$ = 15,...,20mm) and bolts of M20 to M24, the failure mechanism is the formation of a plastic hinge in the beam and fracture of the beam flange in tension;

d) the failure mechanism by bolts failure was recorded for small end-plate thicknesses and lower diameters of 16 mm.

In extreme loading scenarios, where structural integrity needs to be assured, reducing the strain level in the connection components can delay the joint failure and avoid its premature collapse of the structure.

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## PERFORMANȚA ÎMBINĂRILOR METALICE CU PLACĂ DE CAPĂT CU DOUĂ ŞI PATRU ŞURUBURI PE RÂND

### (Rezumat)

Orice sistem structural ar trebui proiectat pentru a asigura stabilitatea structurală şi rezistența în condiții normale de încărcare, dar şi pentru situațiile deosebite de încărcare. În clădirii multi-etajate din oțel, a doua cerință poate fi realizată prin proiectarea structurii, astfel încât stabilitatea structurală să fie menținută atunci când se pierde un element structural cheie, cum ar fi un stâlp la parter. În acest caz, comportamentul elementelor şi îmbinărilor acestora ar trebui să fie adecvate pentru a evita avarierea structurii prin asigurarea dezvoltării căilor alternative de încărcare. În această lucrare este prezentat un studiu privind îmbinări cu placă de capăt cu patru şuruburi pe rând. Studiul a evaluat viabilitatea şi comportamentul unor astfel de îmbinări în situații extreme de încărcare, unde robustețea structurii este un parametru critic. Studiul se bazează pe analize parametrice avansat FEM având în vedere relevanța şi impactul mai multor parametri geometrici.