INFLUENCE OF LOCAL BUCKLING ON THE SHEAR RESISTANCE OF BOLTED CONNECTIONS FOR TUBULAR RACKING STRUCTURES

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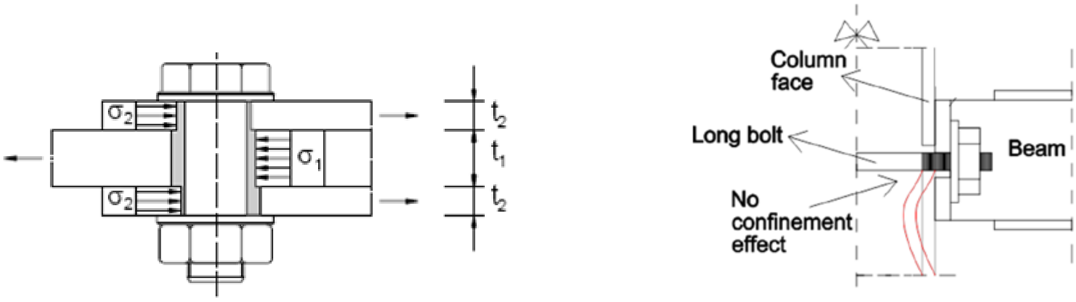
Abstract: The competition in the field of storage racking structures is so that companies are always looking for new structural solutions aiming at containing construction time and expenses. This paper focuses the bearing failure of shear joint using long bolts through thin tubular members with the purpose to check the reliability of Eurocode 3 formulation. The used hollow sections are free to buckle inward leading to a bearing resistance lower than the one predicted using EC3. In fact EC3 does not account for the possible occurrence of out-of-plane deformations in shear connection assuming that the connected plates are restrained by the bolt head and the nut. In order to investigate this phenomenon, an experimental campaign has been developed, a FE model Abaqus/CAE has been validated and a parametric study has been performed. The present paper introduces the conducted investigations.

1. Introduction

Storage racking structures are often considered less important than traditional steel structures mainly due to their use in industrial warehouse and due to the mass production with standardized components [1]. Nevertheless the competition in the field of storage racking structures leads the companies to search for new solutions to streamline the structural elements through the use of thin wall members, with the aim of optimising, in term of time and expenses, the fabrication and assembly procedure. For these structures, connections play a key role on the overall behaviour, even more significant compared to normal steel frames. The actual formulation in Eurocode 3 covers shear connections between two or more plates, assuming that the plates are always laterally restrained by the bolt head and the nut (Fig. 1a). Using long bolts passing through hollow section members, only one side of the section walls is in contact with the bolt head or nut; thus, only this side can be assumed as laterally restraint. In the herein studied connections, the tubular profile is free to buckle inward (Fig. 1b); this could lead to a decrease of resistance, in particular, the bearing one. Hence it is important to understand if the formulations present in the current formulation of EC 3, for the bearing resistance of steel plates, can also be applied to tubular members in racking structures. The bearing resistance of bolted connections has been often investigated with the aim to extend the application of the EC3 rules to cases not covered by the code, such as the case of high strength steel [2, 3, 4] or stainless steel [5, 6] or the case of connections of cold formed strips and hot rolled steel plates [7]. The approach followed in this paper is similar to that provided in [3, 5], in which the accuracy of the application of the codified approach to new cases is firstly investigated by means of a parametric analysis based on FE simulations calibrated on the results of experimental tests.

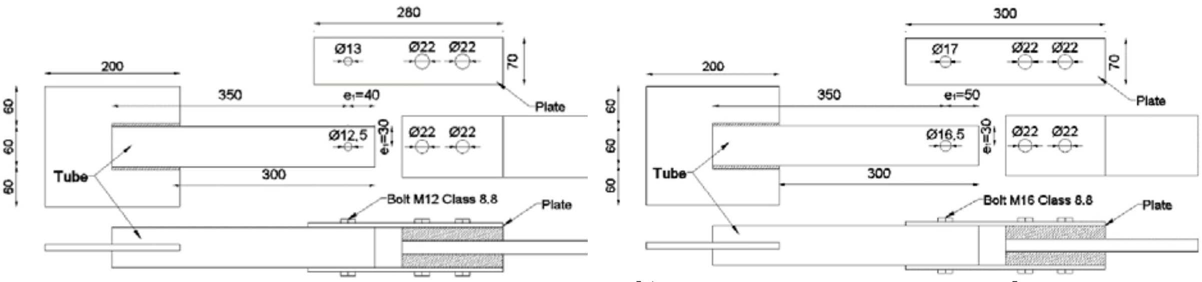


a) Plate connections b) Tube-to-plate-connections

Fig. 1: Shear connections

2. Experimental Campaign

Monotonic tensile tests on 24 assembly, divided into six groups, according to material and geometry properties, were carried out at the Laboratory of the University of Liège. Two different materials for the tube, namely HX420LAD (f_y=min.420/max.520 MPa) and S235 (f_y=235 MPa), three different tube thicknesses (2 mm, 2.5 mm and 4 mm) and two bolt diameters (M12 and M16) were tested. All the bolts were 8.8 class ones and were not preloaded before executing the tests. The specimens were connected to the loading machine by means of steel plates, on one side welded to the tube and, on the other side, bolted to the specimen (Fig. 2). The tube's walls were marked with letters, the hole sides were called A and C and the two other sides were called B and D. In Table 1, the material grade and the actual dimensions of all the specimens are summarized. In particular, in this table, the values of the parameters d_A and d_C, which are the minimum dimensions of the hole diameters (on side A and C respectively) and of the parameter d_N, which is the nominal dimension of the hole, are given. Also some information about the holing procedure (drilling or punching) are given.



a) HX-2-M12, HX-2.5-M12 and S235-4-M12 b) HX-2-M16, HX-2.5-M16 and S235-4-M16

Fig. 2: Layout of the tested specimens

Table 1: Specimens' actual geometrical and nominal mechanical properties

	TUBE		L[mm]	B[mm]	d_N[mm]	*Holing procedure*	d_A[mm]	d_C[mm]	t[mm]	e_1[mm]	e_2[mm]
HX-2-M16	HX420LAD Thickness 2mm, bolts M16	1	399	60.15	16.5	Punched	16.59	16.66	2.04	50.26	29.67
		2	398.8	60.16	16.5	Punched	16.50	16.51	2.11	48.66	29.68
		3	399.5	60	16.5	Punched	16.50	16.53	2.06	49.02	29.72
		4	399.3	59.8	16.5	Punched	16.53	16.50	2.07	49.11	29.76
HX-2-M12	HX420LAD Thickness 2mm,bolts M12	5	389.9	60	12.5	Punched	13.28	12.9	2.03	39.27	29.92
		6	390.2	59.8	12.5	Punched	12.89	13.05	2.06	40.00	30.21
		7	390.1	59.9	12.5	Punched	12.84	12.93	2.09	39.93	30.15
		8	389.6	59.9	12.5	Punched	12.97	12.93	2.04	39.86	30.15
HX-2.5-M12	HX420LAD Thickness 2.5mm,bolts M12	9	391.2	60	12.5	Punched	12.55	12.64	2.57	39.60	29.84
		10	388.7	60.1	12.5	Punched	12.46	12.56	2.55	40.00	29.99
		11	390.4	60	12.5	Punched	12.46	12.85	2.51	41.94	29.70
		12	390.3	60.1	12.5	Punched	12.66	12.30	2.55	40.82	29.69
HX-2.5-M16	HX420LAD Thickness 2.5mm,bolts M16	13	399	59.9	16.5	Punched	16.59	16.49	2.57	49.58	29.93
		14	399	60.1	16.5	Punched	16.98	16.45	2.54	51.67	30.02
		15	398.9	60.1	16.5	Punched	16.99	16.50	2.62	50.87	30.00
		16	399.1	60	16.5	Punched	16.76	16.45	2.55	49.45	30.00
S235-4-M12	S235 Thickness 4mm,bolts M12	1	391.7	60.5	12.5	Drilled	12.39	12.53	3.85	33.17	30.30
		2	391.3	60.4	12.5	Drilled	12.41	12.51	3.87	33.36	30.39
		3	391.6	60.4	12.5	Drilled	12.57	12.56	3.85	33.05	30.49
		4	391.5	60.4	12.5	Drilled	12.46	12.53	3.79	34.07	30.35
S235-4-M16	S235 Thickness 4mm,bolts M16	5	391.4	60.3	16.5	Drilled	17.24	17.29	3.8	41.48	30.39
		6	391.5	60.6	16.5	Drilled	17.27	17.40	3.8	37.61	30.40
		7	391	60.5	16.5	Drilled	17.31	17.37	3.8	40.61	30.49
		8	390.1	60.6	16.5	Drilled	17.26	17.28	3.8	41.27	30.25

2.1 Results

The tests on the connections have been performed using a Schenck RME 600 under monotonic loading conditions. The load has been applied under displacement control mode following a quasi-static protocol aimed at defining the initial stiffness of the connection and the force-displacement response up to failure. In Fig. 3 the experimental results of all the tests have been represented in terms of force and displacement calculated at the external transducer directly applied in correspondence of the tube holes.

3. Application of EC3

In order to evaluate the possibility to simply extend EC3 formulation to the connections analyzed in this work, a comparison between the bearing resistance provided by the code and the one obtained from the experimental tests is given herein. According to Eurocode 3, the resistance of the connection is provided by the minimum value between bolt and bearing resistances.
The bolt resistance can be calculated according to Eq. (1), while the bearing resistance can be evaluated in Eq. (2),

$$F_{v,Rd} = \frac{\alpha_v f_{ub} A_b}{\gamma_{M2}} \tag{1}$$

$$F_{b,Rd} = \frac{k \alpha_b f_u t d}{\gamma_{M2}} \qquad \alpha_b = Min\left(\frac{e_1}{3d_0}; \frac{f_{ub}}{f_u}; 1\right) \tag{2}$$

where, f_u and f_{ub} are respectively the plate and bolt ultimate strength, d and d_0 are respectively the bolt and hole diameter, e_1 is the distance of the hole from the plate free edge and k is equal to 2,5 provided that the distance of the hole from the lateral edge of the plate e_2 is greater than 1,5d. These last equations, account for all the basic failure modes normally arising in a simple bolted connection. The comparison between the resistance provided by the experimental tests and the one predicted by EC3 formulation is reported in Fig. 4, where the ratio between the predicted and the experimental values of the bearing resistance (respectively $F_{b,EC3}$ and $F_{b,exp}$) are represented for each test.

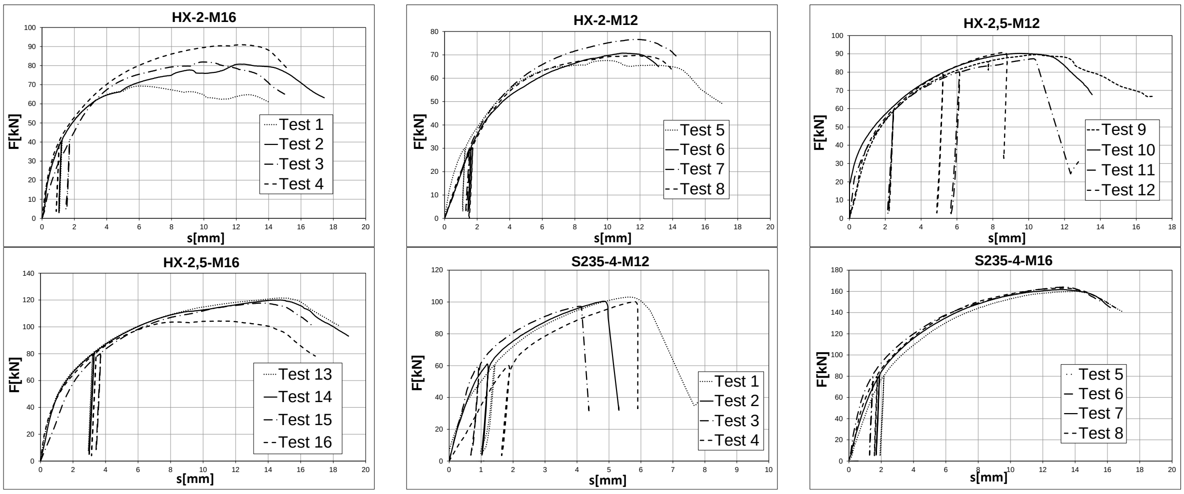
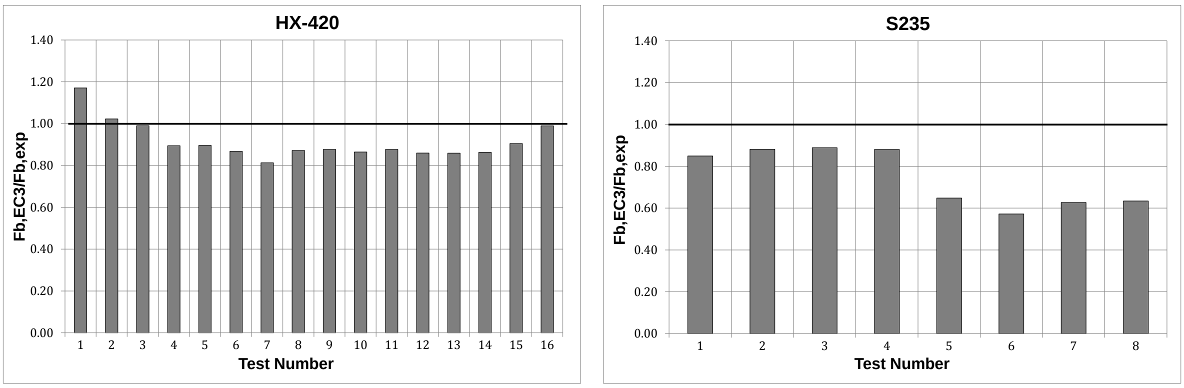


Fig. 3: Experimental force-displacement curves

On average a good prediction is observed (average value of the ratio is equal to 0.9 and 0.74 and the standard deviation is equal to 0.08 and 0.13 for HX420LAD and S235 respectively), nevertheless the comparison highlights a lower safety of EC3 formulation for the specimens characterized by a low value of thickness/hole diameter ratio (Fig. 4). This result can be due to the fact that the EC3 formulation does not account for the local buckling failure mode especially when the local slenderness of the tube's plate is high. Therefore this first comparison points out the need of a further investigation when low values of tube's thicknesses are used.



a) Tubes made of steel HX420LAD b) Tubes made of steel S235

Fig. 4: Accuracy of EC3 model

4. Application of EC3

In order to further investigate the accuracy of EC3 formulation and to extend the results obtained through the experimental program, a Finite Element model has been developed in

Abaqus/CAE software. The required steps to develop the model are the followings: geometrical characterization of the parts, definition of the material properties, definition of the elements’ interaction, definition of the boundary conditions and choice of the elements and size of the mesh. To decrease computational time, a quarter of the assembly has been modelled keeping into account the symmetry conditions (Fig. 5) and following a three-dimensional approach. In particular, the geometric non linearity has been properly considered, in order to include the typical buckling phenomena of the plate composing tube arising at high displacements. Regarding the ***element type***, eight-node brick elements with full integration and first order approximation have been adopted (C3D8). Such elements, as reported in [4], are particularly accurate for analysis where buckling effects are significant. The ***material properties*** of tubes and plates have been described by means of an elastic-plastic isotropic model by adopting simplified equivalent bi-linear or quadri-linear true stress-true strain laws defined using the results from the coupon tensile tests. Conversely, considering the absence of the experimental data for the bolts, the behaviour of the material composing the bolts has been modelled using a simplified bi-linear model based only on literature data for strength and deformation. All the ***interactions*** between the different parts have been defined using the surface-to-surface contact. The ***mesh size*** of the elements composing the model has been defined after performing several preliminary analysis and by following some of the guidelines available on the topic [10]. With the aim to reduce the computational effort, the number of elements has been increased only in areas where great stress gradients were expected. Therefore, in order to obtain accurate and stable results the following mesh average geometry has been adopted: the tube mesh starts from 0.8 mm in the zone of the tube subjected to high stress concentrations up to 8 mm and by defining at least six elements within thickness of the plates (Fig. 6); the bolt has been meshed with elements from 0.8 mm up to 2mm; the loading plate has been modelled with a larger mesh adopting only two elements within the thickness of the plate.

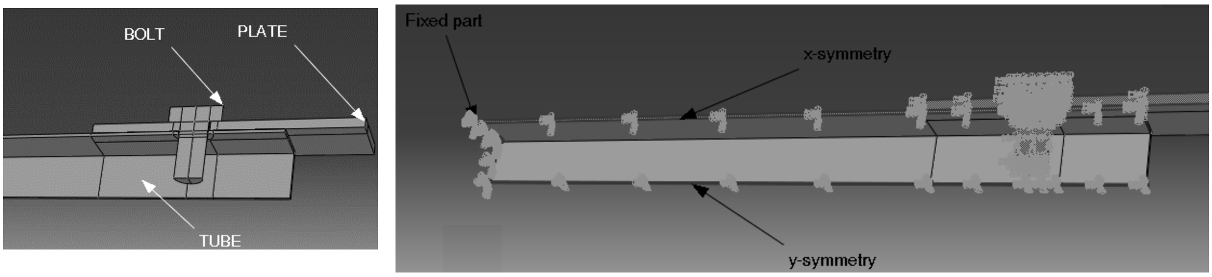


Fig. 5: Modelled parts and symmetry conditions

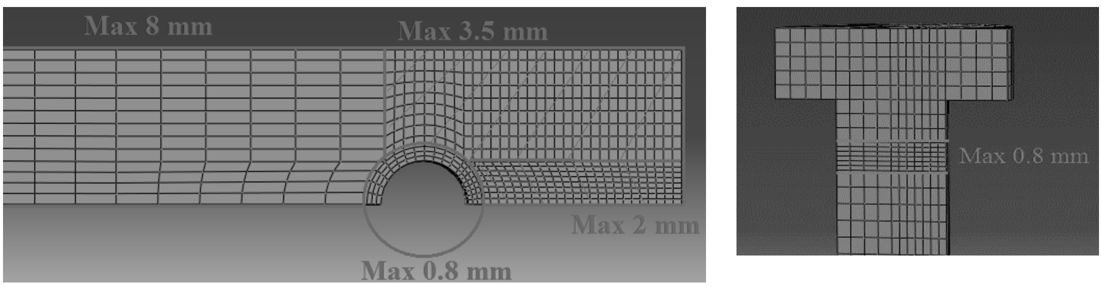


Fig. 6: Tube and bolt element size

4.1 Finite element results vs experimental one

Two different FE models have been developed, one called “ideal”, defined according to the nominal geometry of the specimens and considering the nominal diameter of the bolt; and the second one, called “initial”, defined accounting for the geometrical imperfections of the holes related to the manufacturing process and considering the net diameter of the bolt (EN1090-2).

In Fig. 7 the comparison between the two FE models is given. The "ideal" model provides an overestimation of the initial stiffness and a good accuracy in predicting the resistance. The "initial" model instead reproduces with high accuracy the stiffness accounting for the hole imperfections. The comparison between the FE model and the experimental tests, in terms of deformation at the end of the test, is shown in Fig. 8.

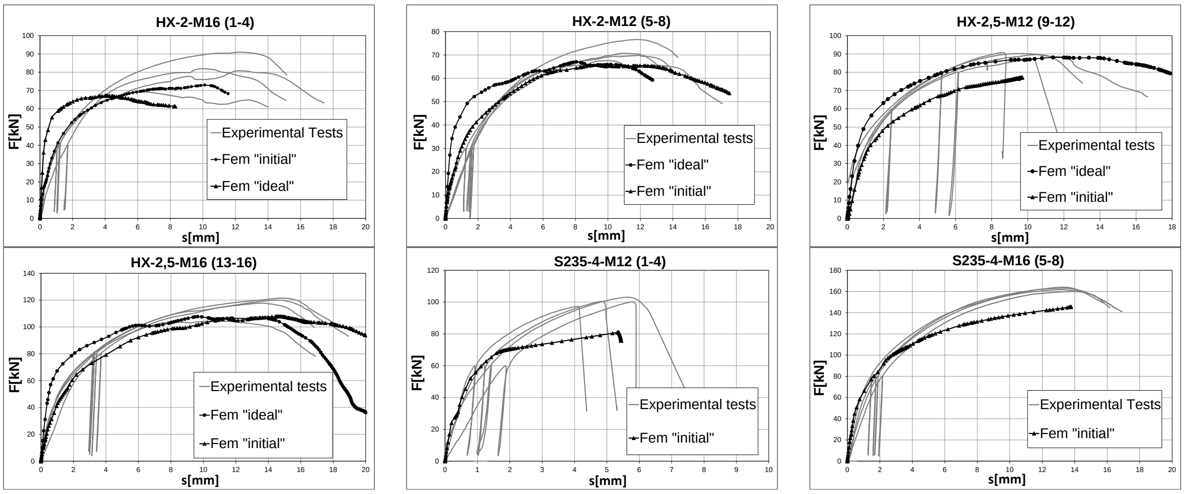
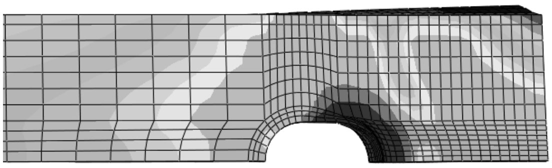
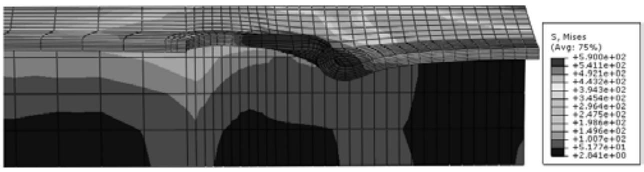


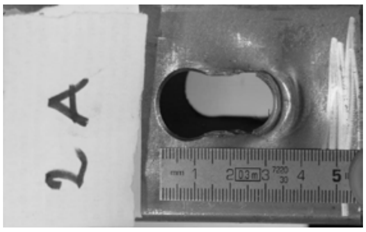
Fig. 7: FEM vs Experimental



a) Hole elongation in FE model



c) Local buckling in FE model



b) Hole elongation at the end of the test

d) Local buckling at the end of the test

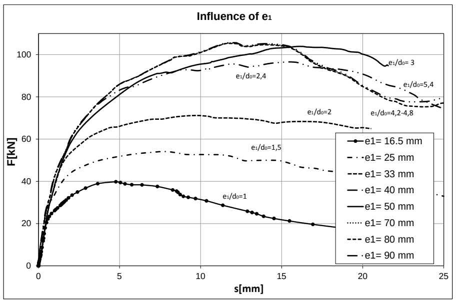
Fig. 8: Results series 1-4 HX420LAD

5. Parametric Study

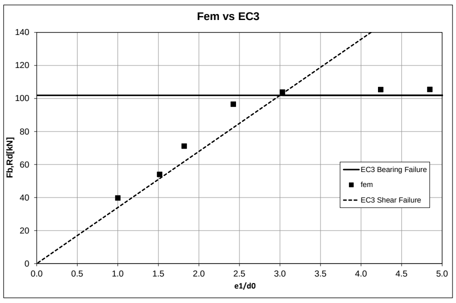
The bearing resistance of the steel connections is mainly influenced by the geometrical parameters e_1, e_2, d, d_0 and t. A parametrical study has been performed starting from the FE model HX420-2.5-M16, by varying the three considered geometrical parameters one by one.

5.1 Influence of e_1 and e_2

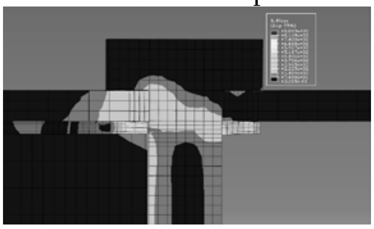
Due to the presence of the tube lateral walls, the influence of the edge distance e_2 is less important in this study. On the contrary, e_1 influences the bearing resistance, and, in this work, eight values have been investigated in a range from 16.5 up to 90 mm (Fig. 10).



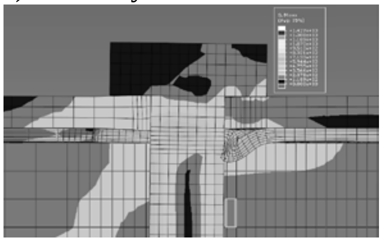
a) Influence of e1: force displacement curve



b) Accuracy of EC3 formulation



c) Influence of e1 (e1=16.5);



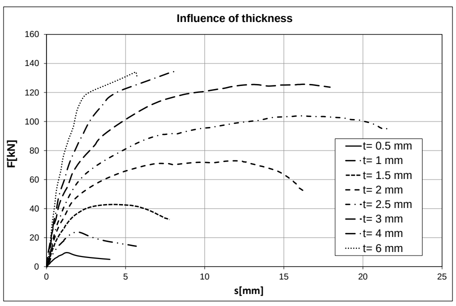
d) Influence of e1 (e1=90mm)

Fig. 9: Influence of e_1 and Accuracy of EC3 formulation

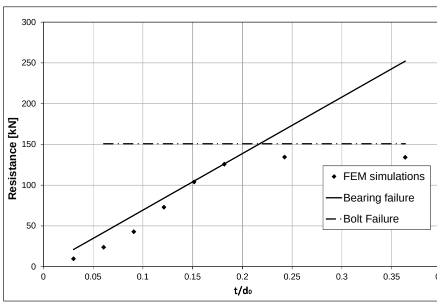
The results of simulations, in terms of load-displacement curves, for each value of e_1/d_0, are depicted in Fig. 9(a) while in Fig. 9(b) the application of the design formulation, provided by EC3, is represented. It is possible to observe that the code equation is slightly conservative in the shear failure mode range, while it is very accurate in the bearing range. In addition, it can be also recognised that the boundary value separating the two failure mode ranges appears well predicted by EC3 formulation.

5.2 Influence of *t*

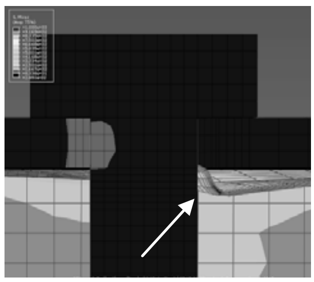
Clearly, the thickness of the plate also plays a significant role on the bearing resistance. In particular, the decrease of the tube's thickness leads to a decrease of the connection resistance with the progressively appearance of buckling phenomena (Fig. 10(a)). In the performed analysis, eight values of the thickness varying from 0.5 mm up to 6 mm have been considered. In Fig. 10(b) the resistance provided by the model is compared with the resistance predicted by EC3. Above all, in such a graph the FE and EC3 resistance values have been charted versus the t/d_0 ratio. For values of the t/d_0 ratio higher than 0.15 the EC3 formulation provides an adequate prediction of the resistance, on the contrary, for values of t/d_0<0.15, EC3 formulation provides an overestimation of the resistance since it does not account for the local buckling (Fig. 10(c)).



a) Influence of t, force displacement curve;



b) Accuracy of EC3 formulation



c)Local buckling (e_1=16.5mm)

Fig. 10: Influence of geometrical parameters and accuracy of EC3

6. Conclusions

The main conclusions are:

1. The numerical analyses, conducted in ABAQUS, can accurately predict the ultimate resistance if an appropriate mesh is used, while the prediction of the initial stiffness is strongly influenced by the hole's imperfection and the actual bolt's diameter.
2. The parametric study allowed to recognize that the distance e_1 and the thickness t of the tube influence the prediction of the connection resistance while the distance e_2 is not significant in the examined case. In particular, the developed parametric analyses evidenced that in case of low values of tube thickness and hole diameter ratio a more accurate formulation for predicting bearing resistance is advisable, by properly accounting for the influence of the local buckling of the tube plate in contact with the bolt shank.

Notation

L	Length of the specimen	d_c	Hole diameter (on the side C)
B	Width of the specimen	t	Thickness of the specimen
d_N	Nominal hole diameter	e_1	Distance from the centre of the hole to the edge
d_A	Hole diameter (on the side A)	e_2	Distance from the centre of the hole to the lateral edge

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