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Numerical modelling of the contact problem on the end-plate connections of the steel structures

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This paper presents method, procedure and the developed mechanism for experimental determination of the F-Δ diagram for high strength bolts with 10.9 class of strength, which are used in the end-plate connections of the steel structures. The F-Δ diagram is essential as an input parameter for the "SOFISTIK" software package users, and for the real numerical modelling of contact problems in the end-plate connections of the steel structures and obtaining the M-F diagram using FEM. As well, it presents the comparison between the numerical method obtained from the M-Φ diagram and the M-F diagram obtained from EUROCODE 3 under the given rules within the procedure.

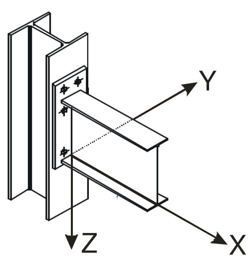
Keywords: End-plate connection, steel structure, high strength bolts, experimental F-Δ diagram.

Introduction

The behaviour of the end-plate connections with high quality bolts is very complex and complicated. Some of the paper works (Waznek and Gebbeken, 1999; Butterworth, 1995) emphasize that the behaviour of these connections depends on many parameters. Main parameters include the beam dimensions - width and thickness of the flange; the web thickness; the column dimensions - width and thickness of the flange; the end-plate dimensions which are in function of the beam dimensions; the number and the disposition of the bolts. The end-plate thickness, material characteristics, bolt type and quality influence the behaviour of the connection as well.

The behaviour of the end-plate connections (Figure 1) is represented by tree curves: the moment-rotation (M-F) curve, moment-axial force (M-N) curve, and moment-transversal force (M-Q) curve. Because of the small deformation occurring as a result of the axial and the shear force, the impact may be neglected. So the best representation of the behaviour of the end-plate connections is using the moment-rotation (M-F) curve.

FIGURE 1. END-PLATE CONNECTION OF THE STEEL CONSTRUCTION



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All attempts for numerical modelling are based on numerous suppositions, and very often the obtained results are not accurate, so they correspond only in limited work area of the connection. The bolt state is particularly important because of the great influence on the behaviour of the connection. It should be emphasized that the bolts, beside the influence upon the capacity, as well have an essential influence upon the stiffness of the connection. The bolts consist of several different elements such as a head, shank, nut and two washers. The bolt shank is cylindrical and consists of threaded and non-threaded part. Each of the parts mentioned, divided and as a whole, defines the bolt behaviour. Other parameter that is of crucial importance for the bolt behaviour is the "nonmaterial" parameter, representing the bolt pretension upon the behaviour of the connection.

Most of the estimation methods have numerous suppositions and simplifying in the modelling, not only of the behaviour, but also in the bolt geometry modelling. One of the most used and efficient method for analysis of this connection type is FEM. Butterworth (1995) uses two types of elements in modelling of the bolt: beam element in modelling the bolt body, and 3D elements in modelling the head and the nut. The pretension is a subject to special investigations and modes of modelling for its application into the bolts. Citipioglu, Haj-Ali, and White (2002) present such original mode where the thickness of adequate bolt pretension plates was taken into consideration during force determination. Waznek and Gebbeken (1999) and Citipioglu et al. (2002) emphasized that a good and accurate approximation of the bolt is if the bolt is modelled by non-linear spring, where its stiffness characteristics are inserted through F-Δ bolt diagram. For real modelling of the bolt behaviour the diagram F-Δ should be obtained in experimental way, in conditions equal to the real connection. During experimental determination of F-Δ bolt diagram, all influences which could hardly numerically be modelled in reality are taken into consideration and replaced by only one curve.

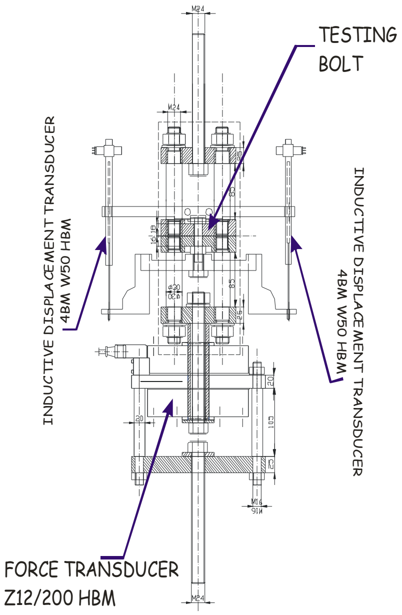
The influences included in the F-Δ curve are as follows: the influence from deformation on head and bolt, the influence from deformation on both different parts of the bolt shank, on the part without a thread, and on the part with a thread. The deformations occurring in the flat washers, the deformations due to compaction of the thread profiles occurring under the influence of a force, as well as the deformations of the plates which create the package. However, the previously cited papers emphasize the fact that the influence of the deformation on the bolt head and the bolt body on F-Δ diagram is insignificant, so that the problem of obtaining F-Δ diagram is reduced practically to bolt body extension measurement.

Description of experimental appliance

All influences taken into consideration with F-Δ diagram were previously mentioned. In order for all of them to be correctly modelled, it is necessary to make such type of measuring appliance and to use adequate measuring equipment where the force and deformations of obtained F-Δ diagram correspond to real behaviour. Girao Coelho, Bijlaard, Gresnigt, and da Silva (2004) present a measuring appliance consisted of two parts: part through which the force acts and part through which the deformation is measured. The paper does not include the way of force measurement as well as detailed description of the process of deformation measurement, except measures with an appliance from the "horseshoe" type.

For the purpose of our measurements, an appliance was prepared (Figure 2) including series of experiments conducted for the purpose of obtaining F-Δ diagram of M16 bolts with 10.9 class of strength. In general, the appliance consists of three elements (systems) functionally connected: first - a system through which the deformation upon the bolt body acts, second - a system through which the force is measured, and third - a system through which the deformation is measured.

FIGURE 2. DEVICE FOR TESTING THE SCREWS WITH THE SYSTEM FOR MEASURING THE STRENGTH AND DEFORMATION



System through which the deformation upon the bolt body acts

This system consists of two parts between which the deformation of the bolt is carried out. The upper and lower parts are identical, except in the parts of the plates which are fastening with the bolt being under examination. On the upper plate the thickness of bolt opening being examined is 18 mm, while on the lower plate the thickness of bolt opening is 16 mm. In this way, the thickness of the both plates is 34 mm, a thickness equal to the thickness of the front plate and the belt of the column that is tightening; so that the F-Δ diagram as well includes the influence of their deformation. The bolt deformation is obtained by separation of the plates. Because of their great stiffness the plates move parallel, one plate upwards and the other plate downwards, making a relative movement; hence presenting the displacement Δ of the bolt body, including the deformations of all elements specified above between the level of the bolt lower surface and the nut lower surface.

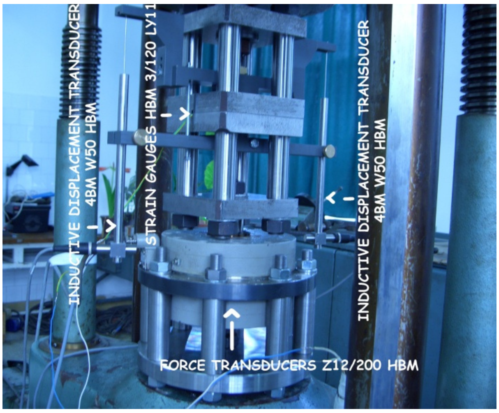
System through which force acts and is measured

A main element of the system is the force measurement instrument "Force transducer Z12/200kN", produced by the Hottinger Baldwin Messtechnik GMBH (HBM) Company. The maximum force of measurement is 200 kN with accuracy of 0.1%.

System for bolt displacements measurement

This system consists of two parts stiffly fastened for the bolt head from the upper side and for the body bolt. The parts are made of PVC and they are characterized with a great stiffness and small weight. At the end of these parts there are instruments for measuring the displacements in specially prepared holes. The displacements are measured by inductive displacement transducers produced by the Hottinger Baldwin Messtechnik GMBH (HBM) Company, type W 50. The entire length of the instrument is 223 mm, and the part taken out is 123 mm long. The instrument is measuring ±50 mm (total 100 mm) with accuracy of 1 micron, including an error in linearity of ±0.2%. Figure 3 presents the appliance for bolt examining including all mentioned elements.

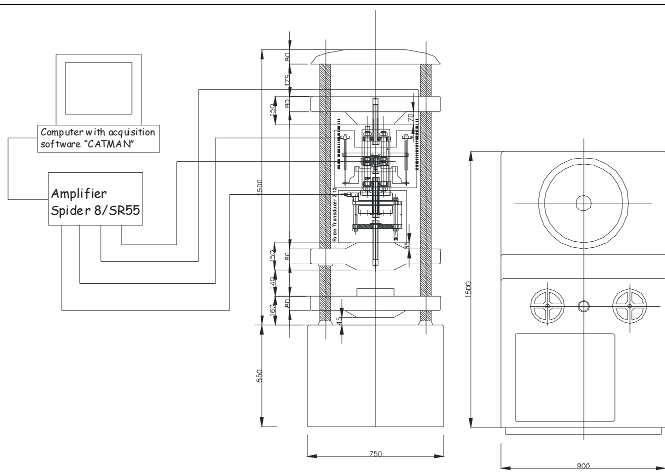
FIGURE 3. THE DEVICE PHOTO FOR TESTING THE SCREWS WITH THE SYSTEM FOR MEASURING THE STRENGTH AND DEFORMATION



Acting the force

The entire appliance is fastened on static hydraulic tensile testing machine ZD 40 of Eastern German production with final twisting off force of 400 kN. (Figure 4) The velocity of loading is 10 kN for 20 sec (30 kN per minute) and the time for twisting off for one bolt is 5 - 6 minutes.

FIGURE 4. STATIC HYDRAULIC TENSILE TESTING MACHINE ZD 40 WITH THE INSTRUMENTS



System for data collection and data acquisition

The goal of this experimental investigation is to obtain the F-Δ diagrams of examined bolts. That indicates that at one place the displacements of the bolt axis should be obtained, while on the other place - the applied force. Because the displacements of the bolt axis are obtained as a mean value in measuring of the displacements on the left and right side, it should follow three signals: two for displacements and one for force. Strain gauges are adhered on three bolts implying the need of parallel following of four signals. For that purpose the eight canal digital amplifier "Spider8/55" produced by the Hottinger Baldwin Messtechnik GMBH (HBM) is used. The process is permanently followed on computer through "Catman" software developed by the same company for this type of amplifier (Figure 4). All data are processed 10 times per second, and the software creates "Excel" tables, which could be processed later on and used as inlet in another programs.

Description of experimental procedure and results

For the purpose of obtaining F-Δ bolt diagrams experiments were made for eight bolts M16 with a strength class of 10.9 produced by "Wurth" Company. On three from eight bolts, marked by 3-ml, 4-ml, 5-ml strain gauges are adhered on the bolt body. A diagram is obtained by the strain gauges force-dilatation (F-ε). The strain gauges are produced by the HBM Company and consist of initial resistance of 120 Ω. The measuring length is 3 mm. The bolts are loaded up to twisting off, i.e. the loss of capacity is due to twisting off the bolt in the thread (Figure 5). The results from examination are presented in Table 1.

TABLE 1. THE RESULTS FROM EXAMINATION OF THE BOLTS

No	Mark	Type	Δy(μm)	Fy(N)	Du(mm)	Fu(N)
1	1N	M16 10.9	307.80	160 092	1028.10	177 300
2	2N		256.25	157 212	1104.68	177 867
3	3N-ML		283.06	158 040	1026.56	173 244
4	4N-ML		360.90	159 252	1092.20	173 880
5	5N-ML		359.38	157 908	1181.25	171 936
6	6N		332.81	158 736	1110.93	173 736
7	7N		284.37	157 212	1076.56	174 456
8	8N		295.31	148 944	1131.25	163 500

FIGURE 5. TWISTED BROKEN BOLTS

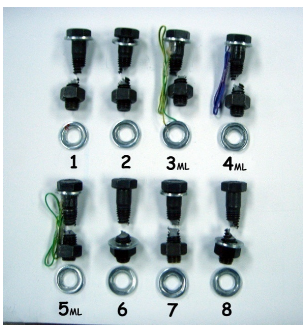


Table 1 and F-Δ diagrams suggest that all bolts have greater values of the loading force and twisting off force from forces obtained by valid technical code; where for a bolt M16 with a strength class 10.9 and a pitch of thread of 2 mm the examining force is 130000 N, and the twisting off force is 163000 N. All bolts have linear part to the limit of loading, marked by (Δy, Fy). From this point, there is distinctly non-linear part with maximum largest recorded force, force Fu achieved for the adequate extension marked by Δu. This force and this extension are taken as a force of twisting off and adequate deformation of twisting off. After this extension, the plastic extensions greatly increase and the force permanently but monotonously decreases approximately up to 5000 μm (5mm) when occurs twisting off the bolt. Figure 6 presents F-Δ diagram of one of the eight examined bolts (diagram for bolt No.5) directly obtained on "Excel" tables formed by previously mentioned software for data acquisition. The point of loading (Δy, Fy) that refers to the limit of proportionality and the point of twisting off (Δu, Fu) is marked on the diagrams.

FIGURE 6. F-Δ DIAGRAM OF ONE OF THE EIGHT EXAMINED BOLTS
(diagram for bolt No.5)

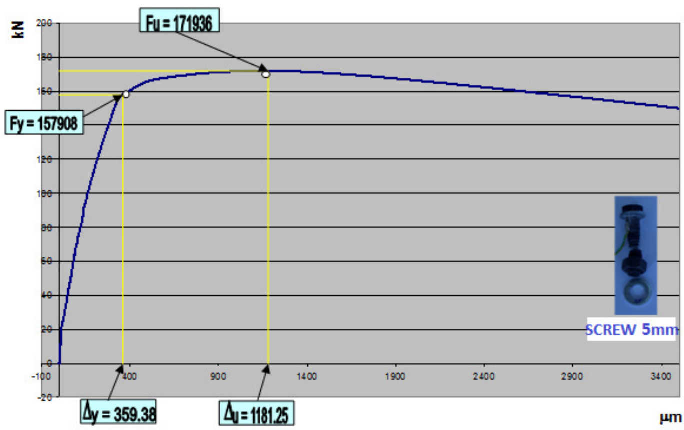
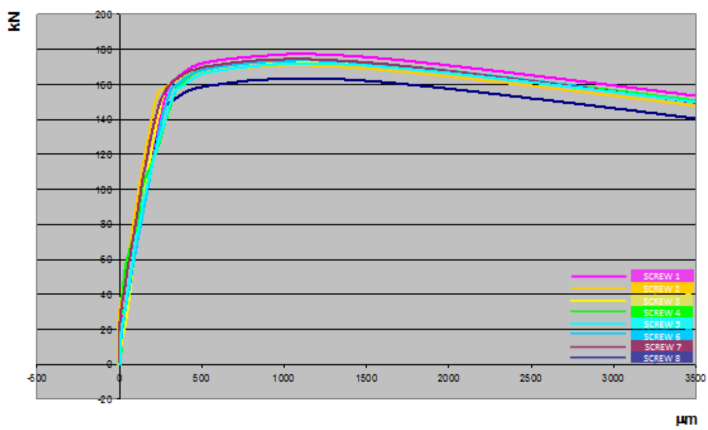


FIGURE 7. ALL SINGLE F-Δ DIAGRAMS ON AXIS TOGETHER WITH THE SAME SCALE



The way of measuring the deformations was previously described in details and the axis deformation of the bolt was obtained as a mean value from the deformations measured on the left and right appliance side for measurement.

The diagram (Figure 7) presents all single F-Δ diagrams on axis together with the same scale. These diagrams as well as the other diagrams confirm the former statement that the linearity exists to the point of the beginning of the loading force Fy. It is within the limits of 148994 N for the 8th bolt up to 160092 N for the first bolt. The extensions of loading are within the limits of Δy_2 = 256.25μm for the second bolt to Δy_5 = 359.38 μm for the 5th bolt.

All bolts reach the maximum of the twisting off force approximately at the same place: Δy_3 = 1026.56 μm for the 3rd to Δy_5 = 1181.25 μm for the 5th bolt. The goal of experimental obtaining of F-Δ diagrams is to obtain F-Δ diagram which will really model the bolt behaviour. But the diagrams obtained may present such ones not covering each other; so one diagram should be obtained where the sufficient accuracy will replace the model of all F-Δ diagrams. And it will be inserted in the numerical analysis by the program package "SOFISTIK". There are many possibilities in the above mentioned package about the way of insertion of the F-Δ diagram. The most adequate possibility in this case is inserting the F-Δ diagram through its characteristic points. The maximum number of points that may be accepted by the program package is twenty. But the nature of the diagrams is such that 13 points are quite enough. For each of the 8th diagrams 13 points with adequate (Δi, Fi) are selected from several thousand points (in average per 2500) obtained by the experiment according to the above specified criterion. In this way, a system is created of 8 x 13 = 104 points, presented on (Figure 8); due to the nature of the point system, it is difficult to interpolate only one curve. But the distribution of the points is such that in the part between (Δy, Fy) and (Δu, Fu) where the greatest number of the points are grouped the cubic parabola is interpolated. In the part of (Δu, Fu) to (Δ_{5000}, F_{5000}), i.e. to the end of the diagram a quadratic parabola is interpolated; and the quadratic parabola, characteristics of which are close to a straight line, is interpolated in the part of (0.0) to (Δy, Fy). This part is interpolated with quadratic parabola with the only aim to include the small breaking that occurs in all diagrams, somewhere about 40 kN (Figure 8).

FIGURE 8. INTERPOLATED WITH QUADRATIC PARABOLA WITH THE ONLY AIM TO INCLUDE THE SMALL BREAKING

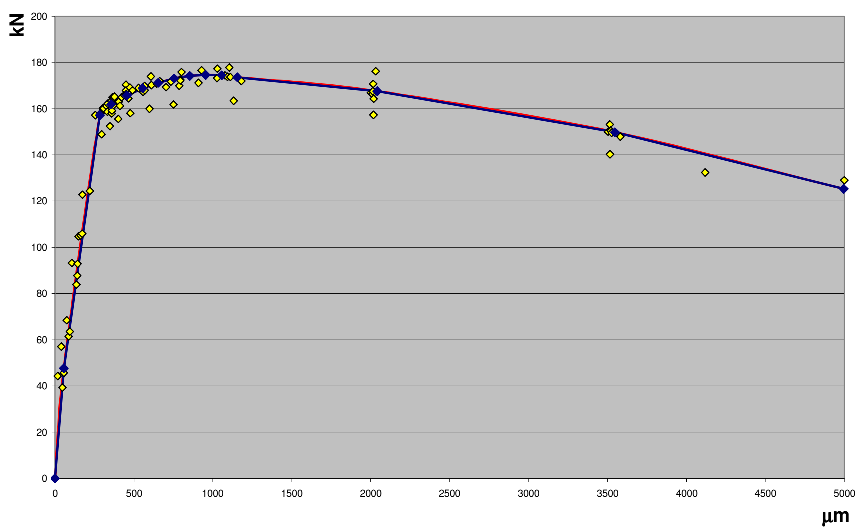


FIGURE 9. ALL EIGHT F-Δ DIAGRAMS, THE INTERPOLATED F- Δ DIAGRAM MARKED IN WHITE COLOUR AND WELL MATCHING OF EXPERIMENTALLY OBTAINED F- Δ CURVES

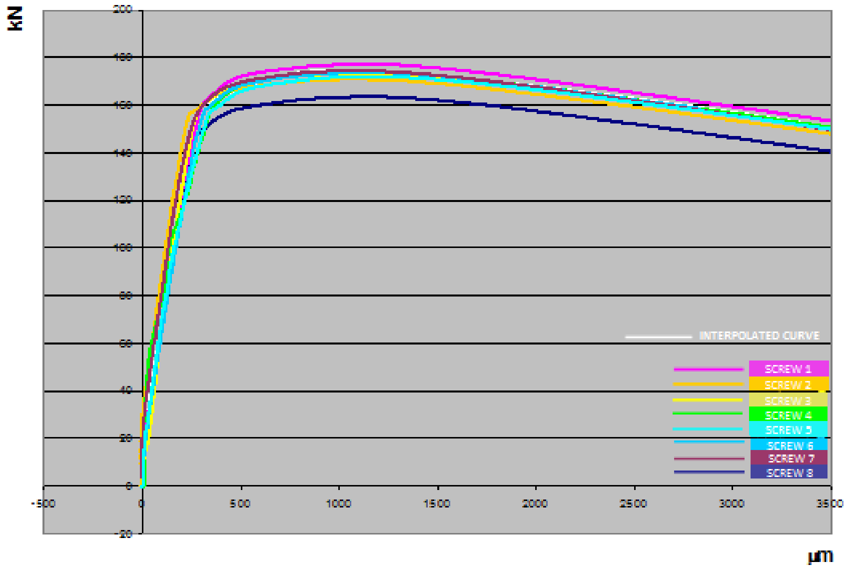


TABLE 2. DATA FOR THE DERIVED F- Δ DIAGRAM OF THE 14 CHARACTERISTIC VALUES

Di	0	56.25	284.37	355	455	555	655	755	855	955	1055	1155	2041.1	3546.8	4996.8
Fi	0	4	157.2	161.9	165.7	168.81	171.26	173.1	174.1	174.6	174.4	173.5	167.592	149.7	125.3

From interpolated three curves, the derived F-Δ diagram of the characteristic values of F-Δ diagram is obtained (Table 2). This curve completely models the behaviour of the examined bolts in the numerical model realized by the program package "SOFISTIC".

Figure 8 presents insertion of the points (Table 2) together with the points through which the curve is interpolated. It can be presented by the diagram well matching of interpolated points with the points as basis of interpolation.

Figure 9 presents all eight F-Δ diagrams, the interpolated F-Δ diagram marked in white colour, and well matching experimentally obtained F-Δ curves.

Numerical modelling using FEM and the results

FEM was used for the purpose of obtaining the moment-rotation (M-F) diagram of the end-plate connection. The FEM model of the whole construction is presented in the Figure 10. Numerical model is made by using SOFISTIK commercial FEM program. Three numerical investigations on same type of construction were made. The difference is in the thickness of the end plate. The thickness of the end-plate is changing and it is d_p=12mm, d_p=14mm and d_p=16mm.

Three types of elements for the modelling of the construction were used: shell element and two types of spring elements for modelling the contact and the bolts.

FIGURE 10. USED COORDINATE SYSTEM P- Δ

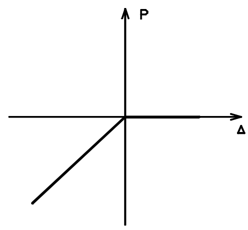


FIGURE 11. THE FEM MODEL OF THE WHOLE CONSTRUCTION

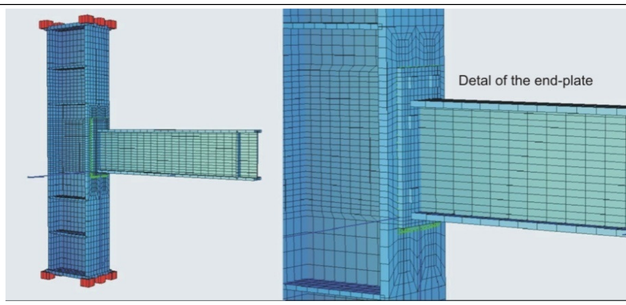
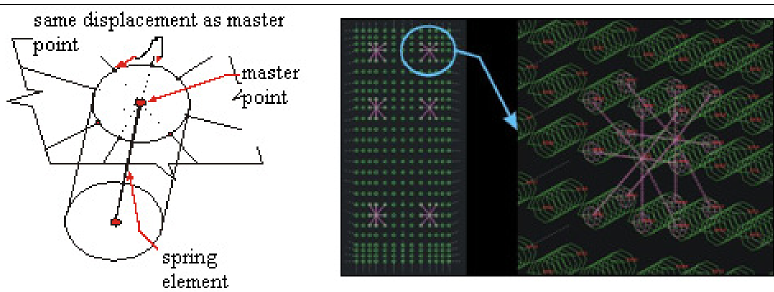


FIGURE 12. MOMENT-ROTATION (M-Φ) DIAGRAM OF THE END-PLATE IS OBTAINED BY THE HORIZONTAL DISPLACEMENTS OF THE TWO CHARACTERISTIC POINTS OF THE END PLATE



The shell elements are QUAD4 bilinear shell elements with thin leer. 3937 shell elements connected in 3707 joints are used. 338 spring elements are used for modelling the contact between the end-plate end the column (Figure 11).

Specific spring elements are used for bolt modelling (Figure12). The numerical modelling of the bolts in this can of connection is specific; the state of the bolts is particularly of the great influence on the behaviour of the connection. F-Δ diagram presents this bolt. The F-Δ diagram of the bolt is experimentally obtained. The influences included in the F-Δ curve are as follows: the influence from deformation on head and bolt, the influence from deformation on both different parts of the bolt shank, on the part without a thread, and on the part with a thread. 15-teen characteristic point presents the F-Δ diagram of the bolt. At this point the SOFISTIC program is used for calculation of the deformation of the bolt for each increment of the load.

The acting of the load is in increment of one kN at the moment when the nonlinear effect in the end-plate appears. After this point the SOFISTIC program automatically changes the load increment.

Moment-rotation (M-Φ) diagram of the end-plate is obtained by the horizontal displacements (Figure 12) of the two characteristic points of the end plate.

The two characteristic point of the end-plate from which the moment-rotation diagram is obtained are the points in the centre of the two flange (Figure 13).The rotation is obtained by the relation

$$\varphi = \frac{Ux_{17} - Ux_{20}}{d} \text{ [rad]}$$

The Figure 7 and Figure 8 present M-F diagram for end plate. The same diagram presents the rules regarding the M-F diagram obtained from EOROCODE 3.

FIGURE 13. THE TWO CHARACTERISTIC POINTS OF THE END-PLATE

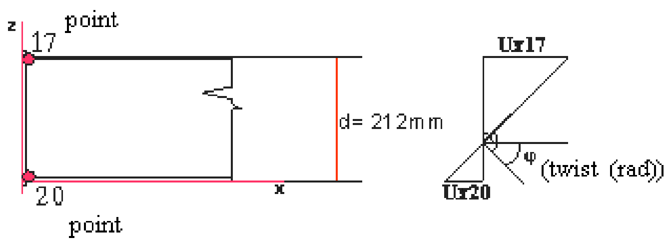


FIGURE 14. FIGURE14. M-Φ DIAGRAM FOR END PLATE WITH DP=12 MM (BLUE LINE) AND THE M-Φ DIAGRAM OBTAINED FROM EOROCODE 3 RULES (YELLOW LINE)

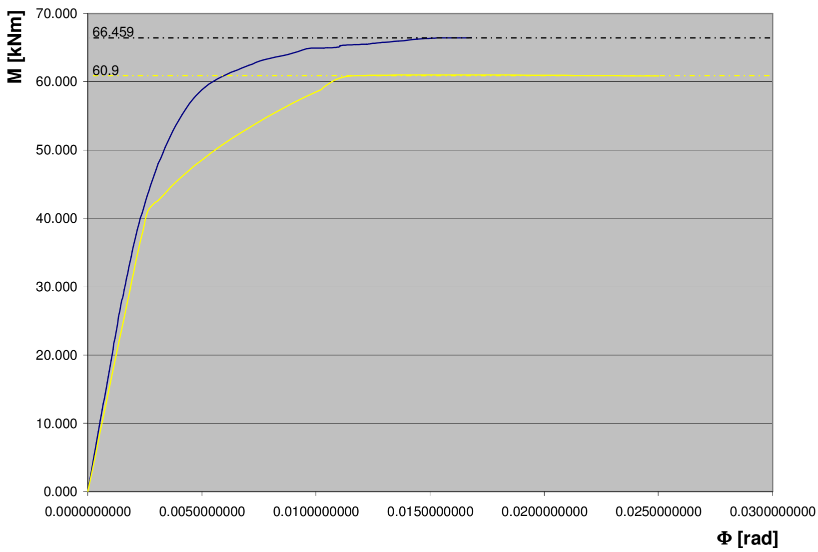
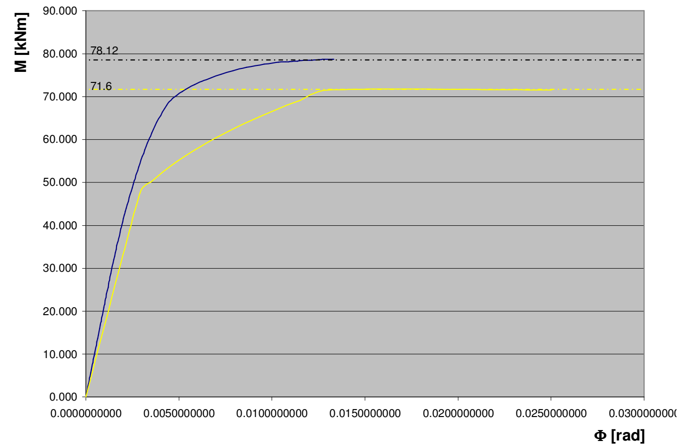


FIGURE 15. M-Φ DIAGRAM FOR END PLATE WITH DP=16 MM (BLUE LINE) AND THE M-Φ DIAGRAM OBTAINED FROM EOROCODE 3 RULES (YELLOW LINE)



The Figure 13 and Figure 14 present the numerical M-Φ diagram obtaining bigger moment resistant and initial stiffness then M-Φ diagram obtained from the Eurocode 3. The difference is bigger in the area of high moment and high rotation. That means that the stress-strain condition of the end plates hewed strong influence on the behaviour of the whole construction. The reason is that the limit state of the construction is determination of the stress-strain condition of the end plate. This means that the stress in the end plate is linear for working condition. For higher moment, the condition of the end plate is strongly nonlinear.

Conclusion

The numerical model of contact problem obtained by FEM, including incorporated experimental obtained F-Δ diagram for the bolts, gives the better real solutions for maximum loading of the end-plate connection of the steel construction than EUROCODE 3. According to the results shown on Figures 13-15 we strongly recommend it for future implementation in constructor's work.

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