TO PREDICTION OF THE CONNECTION DEFORMATION CAPACITY BY COMPONENT BASED FINITE ELEMENT METHOD

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Abstract: This paper introduces the prediction of deformation capacity of structural steel connections by the component based finite element method (CBFEM). The distribution of internal forces in connection is analysed by FEA. The connectors' behaviour is modelled by analytical models as components. The prediction of deformation capacity is verified on behaviour of the T-stub, the column web panel in shear, and the beam splices. The influence of the limits of materials strain and the estimation of the strain hardening and upper values material yield stress is described on the beam to column welded connection. The sensitivity study of connection deformation capacity shows applicability for practical design solutions.

1. Introduction

The prediction of deformation capacity of connections is currently offered by component method (CM), which builds up on standard procedures of evaluation of internal forces in connections and their checking. Zoetemeijer [1] was the first who equipped this model with prediction of stiffness and deformation capacity. The elastic stiffness was improved in the work of Steenhius, see [2]. Basic description of components behaviour in major structural steel connections was used by Jaspart for beam to column connections [3] and by Wald et al for column bases [4]. Method, which is implemented in the current European structural standard for steel and composite connections see [5] and [6] can be applied in majority of software for structural steel used in Europe. The model was generalised by da Silva [7]. Procedure starts with decomposition of a joint to components followed by their description in terms of normal/shear force deformation behaviour. After that, components are grouped to examine joint moment-rotational behaviour and classification/representation in a spring/shear model and application in global analyses. Advantage of the component model is integration of current experimental and analytical knowledge of connections components behaviour, bolts, welds and plates. This provides accurate prediction of behaviour in elastic and ultimate level of loading for simple configurations of joints. Disadvantage of component method is that experimental evaluation of internal forces distribution is available only for limited number of joint configurations. In temporary scientific papers, description of atypical components is either not present or has low validity in description of background materials. The CM´s is not developed for hand calculation but as a method for preparation of the design tables or tools.

Development of modern general-purpose software and decreasing cost of computational resources facilitate the trend of prediction of behaviour of structures by FEA. As the computational tools become more readily available and easier to use, even to relatively inexperienced engineers. Steel and steel and concrete connections are one of the last parts of structural design where the FEA is not commonly use. Finite element analyse (FEA) for connections is used from 70s of last century for research purposes. Their ability to express real behaviour of connections is making it a valid alternative to testing and current source of knowledge of connection's behaviour. Material model of structural steel for the research FEA uses true strain stress-strain diagram. Component based finite element method (CBFEM) is a multilevel FEA model developed to analyse and design connections of steel structures with features advanced analyses [8]. The distribution of internal forces in connection is analysed by FEA method. The resistance of steel plates design is evaluated by limiting the strain to 5% as it is recommended in cl. C.8(1) EN 1993-1-5 [9]. The proper behaviour of connectors, of bolts, welds etc., is treated by introducing them as components representing well its behaviour in term of initial stiffness, ultimate resistance and deformation capacity, see [10]. Standard procedure with partial safety factors for material/connections is applied.

The study is prepared in CBFEM IDEA RS, which uses for steel plates the most common MITC4 quadrangular element given by four nodes. Each node has all 6 degrees of freedom in translation and rotation. Deformation along the element are divided into membrane and flexural components. For membrane behaviour are also contemplated rotation perpendicular to the plane of the element. This provides full 3D formulation of element. Bolts are modelled as three subcomponents. The first sub-component is the bolt shank, which is represented as a bilinear spring transmitting the compression force only. Its force-deformation diagrams in tension is prepared based on the experiments and standardised values for resistance. Initial stiffness, design tensile resistance, initialisation of yielding and deformation capacity are the main characteristics required of its tensile behaviour. Second subcomponent is connecting the bolt shank to the plates by restrains taking into account the bolt shear resistance. Third subcomponent modelled by restrains is limiting the bearing resistance.

Ductility with strength and stiffness belongs to the three basic parameters describing the behaviour of connections. In moment resistant connections, the ductility is achieved by a sufficient rotation capacity. Compare to well accept methods for determination of the initial stiffness and resistance of many types' structural joints, there are no generally accepted standardised procedures for the determination of the rotation capacity. The deemed to satisfy criteria are selected to help the engineers in EN1993-1-8 [5]. The estimation of the rotation capacity is important in many applications namely in connections exposed to seismic, see [11] and [12], and extreme loading, see [13] to [15]. The deformation capacity of components has been studied from end of last century [16]. Faella et al [17] carried out tests on T-stubs and derived for the deformation capacity the analytical expressions. Kuhlmann and Kuhnemund [18] performed tests on the column web subjected to transverse compression at different levels of compression axial force in the column. Da Silva et al [19] predicted deformation capacity at different levels of axial force in the connected beam. Based on the test results combined with FE analysis deformation capacities are established for the basic components by analytical models by Beg at al [20]. In the work are represented components by non-linear springs, and appropriately combined in order to determine the rotation capacity of the joint for the end-plate connections, with an extended or flush end-plate, and welded connections. For these connections, the most important components that may significantly contribute to the rotation capacity column were recognised as the web in compression, column web in tension, column web in shear, column flange in bending, and end-plate in bending. Components related to the column web are relevant only when there are no stiffeners in the column that resist compression, tension or shear forces. The presence of a stiffener eliminates the corresponding component, and its contribution to the rotation capacity of the joint can be therefore neglected. End-plates and column flanges are important only for end-plate connections, where the components act as a T-stub, where also the deformation capacity of the bolts in tension is included. The questions and limits of deformation capacity of connections of high strength steel was studied in [21].

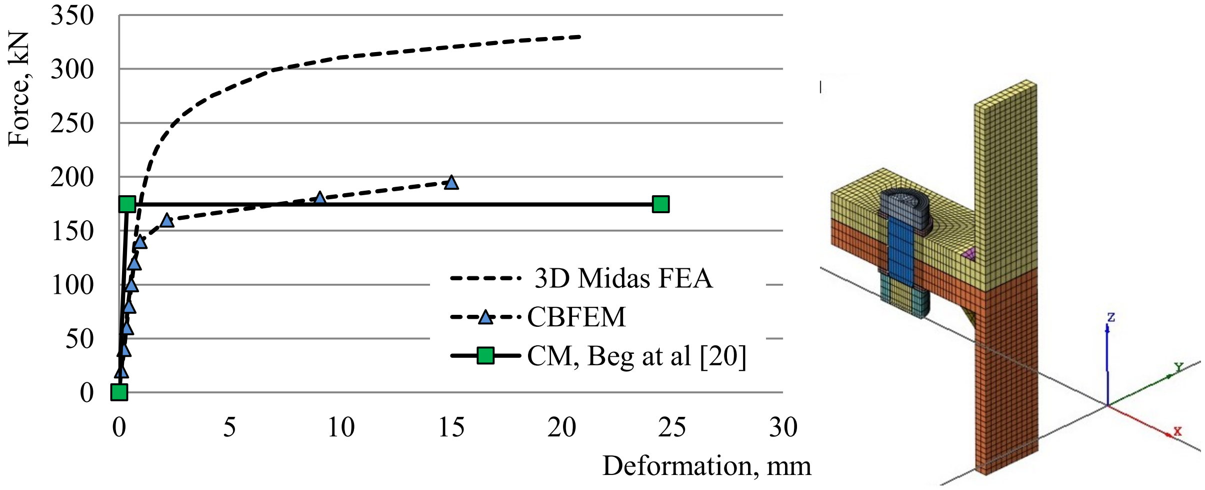

Fig. 1: a) Prediction of deformation capacity for a T stub $t_f = 20$ mm,
b) mesh and bolt representation for research FEA model by FEM MIDAS code

2. Verification

The detailed procedure for verification of proposed method was prepared [22]. The procedure contains Benchmark studies for connectors and major connections. In cases, where gives the CBFEM method higher resistance, initial stiffness or deformation capacity, the advanced FEM model validated on experiments is used, to approve physically good results of modelling. The quality of prediction of deformation capacity was validated on the T stub behaviour and on the column web panel in shear, which was calculated by CM according to [20].

In Fig. 1 is compared the prediction of the deformation capacity by CM and CBFEM to FEM research model [8]. The mesh of research model is includes. A T stub with flanges thickness $t_f = 20$ mm and width $b_f = 300$ mm, web thickness $t_w = 10$ mm, radius $r = 14{,}1$ mm for steel S235 is modelled. The limits for principal stain are expected 20 % for plates and 5 % for bolts. By CM is calculated the initial stiffness as 485 kN/mm and deformation capacity as 24,47 mm, see Tab. 1. By the research model using FEM MIDAS validated on experiments and using measured material characteristic, see [10], is the deformation capacity 21,07 mm. Using CBFEM is the deformation capacity predicted as only 15,02 mm. The Table 1 shows the influence of the flanges thickness t_f for the prediction of deformation capacity.

For flange thickness of 10 and 12 mm, the plastification of flange only, is the predicted deformation capacity by CBFEM higher then by CM. In CBFEM is taken into account the membrane behaviour of the plate. For flange thickness 15 to 25 mm limits the bolt deformation capacity the behaviour of the T stub already and the CBFEM in these cases is more conservative. The prediction by CM according to [20] seems to be not realistic. For flange thicker than 30 mm has the limiting strain no influence to the deformation capacity of the T stub due to failure of the bolts.

Table 1 Deformation capacity of the T stub

Flange thickness t_f (mm)	Deformation capacity by CBFEM δ_{Cd} $\delta_{Cd,CBFEM}$ (mm)	Deformation capacity by CM $\delta_{Cd,CM}$ (kN)
10	37,50	24,47
12	35,10	24,47
15	23,77	24,47
20	15,02	24,47
25	11,16	13,86
30	3,99	15,71
35	3,66	17,55
40	3,84	19,40
45	4,05	11,50
50	2,59	12,50

Fig. 2 shows the plastic strain of the unstiffened welded beam-to-column connection, which was selected for comparison of prediction of deformation capacity by CBFEM to CM for beam IPE330 and column HEB260 in Fig. 3. The values for model by CM according to [20] were reached by FE analyses and validated on experiments for strain 10 %. In cl. 6.4.3(2) of EN1993-1-8 [5] is for an unstiffened welded beam-to-column joint assumed a rotation capacity φ_{Cd} at least 15,0 mrad. Conservative prediction by estimation in standard is hence confirmed.

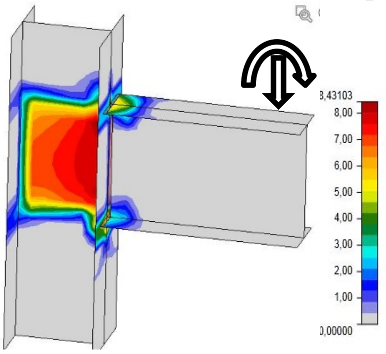

Fig. 2: Distribution of strains in welded connection

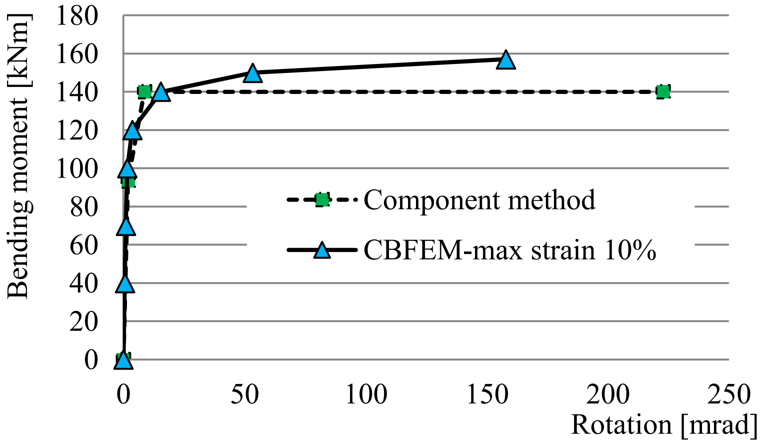

Fig. 3: Moment rotation diagram for beam to column welded unstiffened connection by CBFEM and CM

The bolted beam splice connection of two IPE 300 in Fig. 4 shows the influence of the T stub to behaviour of the connection, which exhibits a limited deformation capacity. The end plates with steel S355 were here designed 12 mm thick with bolts M16 4.8. The sensitivity of the end plate thickness to the resistance and changes in the failure modes are demonstrated in Fig. 5. In the moment rotational diagram in Fig. 6 is visible the difference of the prediction of the rotational capacity by CBFEM and CM according to [20].

EN1993-1-8 [17] in cl 6.4.2(2) limits the plastic distribution between the bolt rows, for joints with a bolted end-plate connection provided that the design moment resistance of the joint is governed by the design resistance of the column flange or the beam end-plate in bending or the thickness t of either the column flange or the beam end-plate or tension flange cleat satisfies

$$t \leq 0{,}36\, d \sqrt{f_{ub}/f_y} \tag{1}$$

where d and $f_{\mathrm{u.b}}$ are the diameter and strength of the bolt and f_y is the yield strength of the relevant plate. This criterion is in CBFEM taken into account naturally by checking/limiting the deformation capacity of each connector. The development of plastic zones round the bolts and limited plastification till failure of the second bolt row in tension is shown in Fig. 6b.

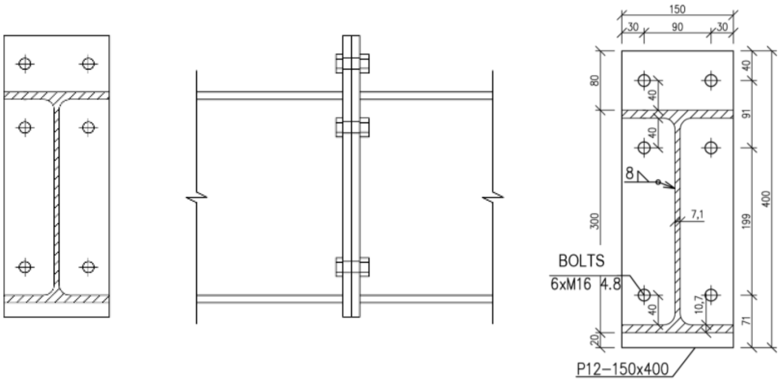

Fig. 4: Geometry of the studied bolted end-plate connection, IPE 300, S355

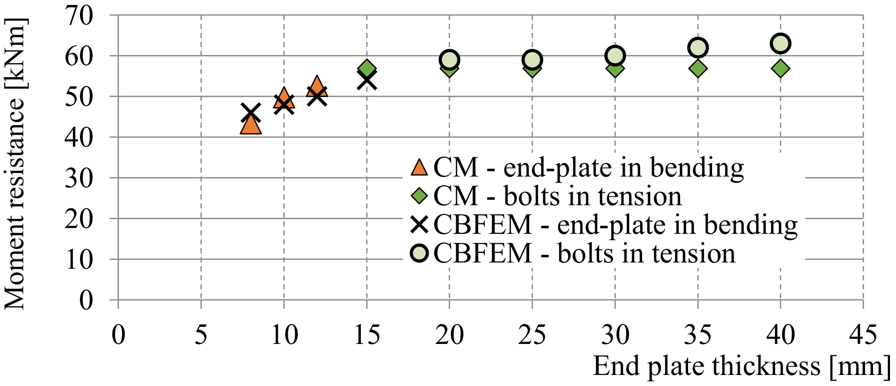

Fig. 5: Comparison of moment resistance predicted by CBFEM and CM for different plate thicknesses

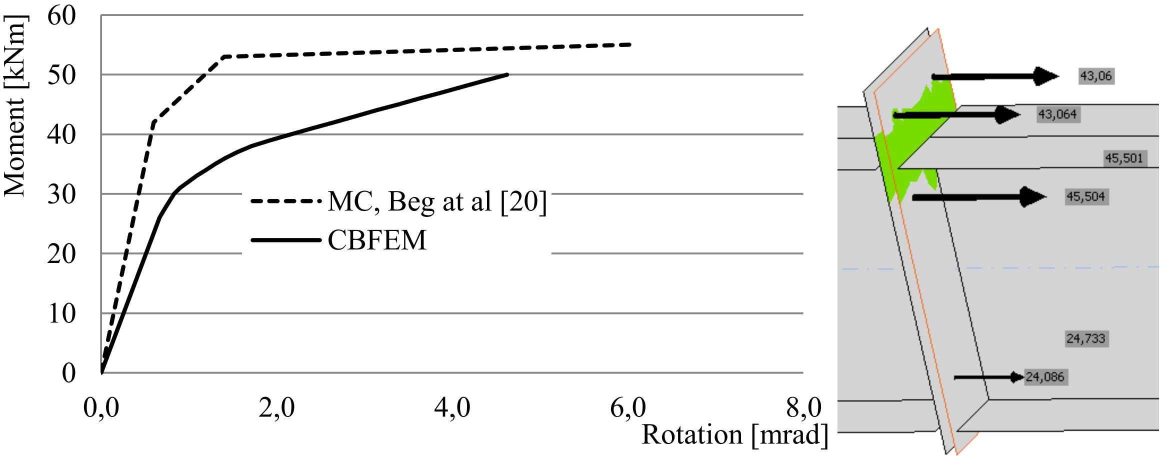

Fig. 6: a) Moment - rotational diagram for the end plate connection predicted by CBFEM and CM
b) distribution of forces between bolts with controlled deformation of each connector

3. Sensitivity study

It is commonly known, that the relative strength of individual components is of great importance for ductility of connections. The already available knowledge and good engineering practice in seismic design [23] introducing the parameters for overstrength of parts of joints may be utilised in the methodology for prediction of deformation capacity of connections.

The influence of not guaranteed values of yield strength of the structural steel to the ductility of connections is demonstrated in Fig. 7 for beam to column welded unstiffened connection in Fig. 2 described in previous paragraph. The rotation capacity reduces for example from 170 mrad for column with f_y = 235 MPa to 7 mrad for column with $f_y = 1.5 \cdot 235$ MPa. For bolted connection it was shown in previous paragraph the good and safe estimation of 5 % limit of strain. For column panel zone in shear is the limiting strain changed from 3 % till 20 %. Currently is guaranteed for structural steel. 15 % strain. Such or specific value of steel strain for particular steel may be recommended for prediction of ductility of connection.

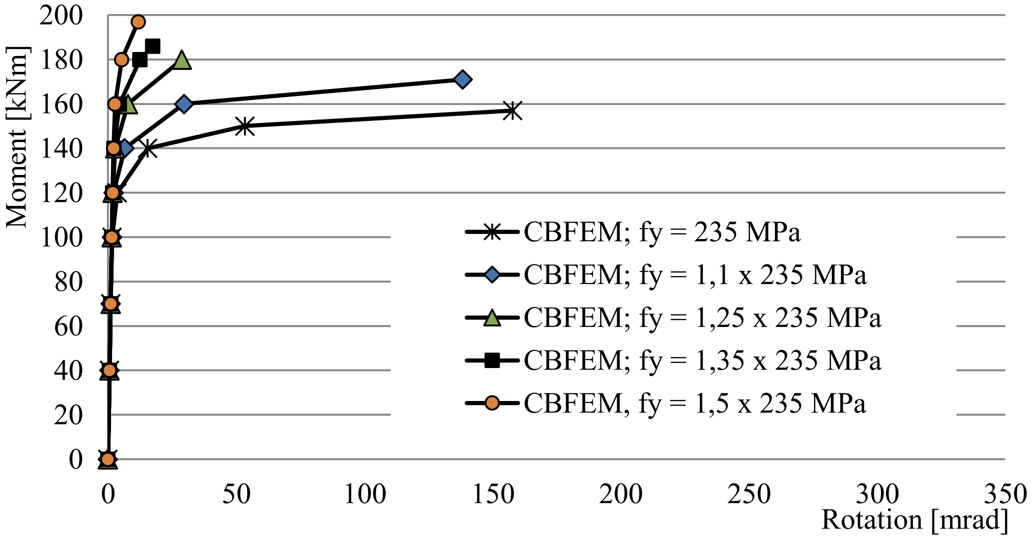

Fig. 7: Moment - rotational diagram for beam to column welded unstiffened connection calculated by CBFEM for changed material properties of column only

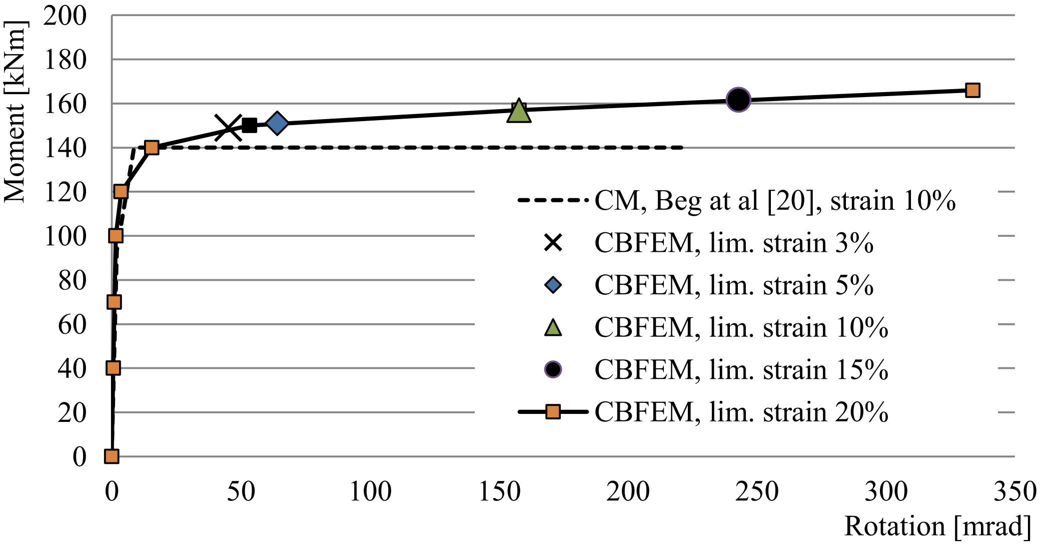

Fig. 8: Moment - rotational diagram for beam to column welded unstiffened connection calculated by CBFEM with limits in strain

4. Conclusions

In current models for prediction of the rotational capacity of structural steel connections by component method is the behaviour of steel plates implemented from finite element analyses FEA. The quality of prediction limits also dissimilarity of assembly procedures for stiffness and resistance, the estimation of the lever arm of internal forces, and neglecting the interaction of internal forces.

The multilevel FEA, component based finite element method CBFEM, gives naturally a realistic prediction of ductility of connections, represented by its deformation and rotational capacity, based on model of steel plates including its membrane action and analytical model of connectors behaviour. The changes of position of internal forces during loading of connection is taken into account. A comparison with the test results shows good agreement.

This contribution is not focusses to welds ductility, which may be of course simply examined by CBFEM, where this component has its stiffness, strength and deformation capacity. The study of this question is under preparation.

Next necessary step for the further studies is validation of CBFEM for prediction of ductility of different types of connections to experiments. For correct application of advanced models in everyday practice is necessary to prepare benchman cases and to standardise the advanced models of connections similar to already published cases in another parts of structural engineering, like in plated structures, fire engineering or structural dynamics.

Acknowledgments

The work was prepared under the project MERLION supported by Technology Agency of the Czech Republic, project No. TA02010159.

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