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FUTURE DESIGN PROCEDURE FOR STRUCTURAL CONNECTIONS IS COMPONENT BASED FINITE ELEMENT METHOD

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Abstract: This paper introduces component based finite element model (CBFEM) which is a method to analyse and design connections of steel structures with features demonstrated here on a portal frame eaves bolted connection. The connection in CBFEM procedure is analysed by FEM. The proper behaviour of components is treated by introducing a components representing well its behaviour in term of initial stiffness, ultimate resistance and deformation capacity, of bolts, welds etc. As for another FEM design procedures a special care is given the Validation and Verification procedures which is here in this contribution demonstrated on example of portal frame eaves welded connection.

1 Introduction

Four decades ago computational analysis of structural connection was treated by some researchers as a non-scientific matter. Two decades later it was already a widely accepted addition or even extension of experimental and theoretical work. Today computational analysis, in particular computational mechanics and fluid dynamics, is commonly used as an indispensable design tool and a catalyst of many relevant research fields. The recommendation for design by advanced modelling in structural steel is already hidden but ready to be used in Chapter 5 and Annex C of EN 1993-1-5:2005, see [1]. Development of modern general-purpose software and decreasing cost of computational resources facilitate this trend. As the computational tools become more readily available and easier to use, even to relatively inexperienced engineers, more scepticism and scrutiny should to be employed when judging one's computational analysis. The only way to prove correctness of simulated results is through a methodical verification and validation process. Without it the analysis is meaningless and cannot be used for making any decisions. In the case when the analysed event is too complex or overly expensive to test experimentally, hierarchical validation is recommended.

However for structural connections with thousands experiments available the validation process may be executed. But even in such situation the verification process performed through benchmark tests gains crucial importance. Seeing the need of making the results of research more transparent to the public, the office of science and technology policy in the United States issued a memorandum stipulating increased access to the results of federally funded scientific research. Such data can be easily verified or used for verification (or benchmarking), of some other work. The trend of making extended data available together with a report or publication persists in order to build confidence in growing number of performed numerical simulations. To achieve this goal it seems beneficial at this point to develop a standard set of smaller benchmark tests that can be used as a reference in the verification pro-cess of simulations. The source and the extent of such benchmark tests for the field of structural connections is yet to be established. The considerations emphasize questions encountered in the V&V process, principles of comparison of numerical results and experimental data, the importance of sensitivity study, new ideas regarding the relationship between the research and design finite element model, differences between the Component based model and the Design finite element model.

2 Component method and FEM

Component model of connections builds up on standard procedures of evaluation of internal forces in connections and their checking. Zoetemeijer [2] 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 [3]. Basic description of components behaviour in major structural steel connections was used by Jaspart for beam to column connections [4] and by Wald et al for column bases [5]. Method implemented in the current European structural standard for steel and composite connections see [6] and [7] can be applied in majority of software for structural steel used in Europe. The model was generalised by da Silva [8]. 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 very accurate prediction of behaviour in elastic and ultimate level of loading. Verification of the model is possible using simplified calculation. Disadvantage of component model is that experimental evaluation of internal forces distribution can be done only for limited number of joint configurations. In temporary scientific papers, description of atypical components is either not present or has low validity and description of background materials. Models of hollow section connections are described in Ch. 7 of EN1993-1-8 [6] by curve fitting procedures; their compatibility with component model is till now unreliable. The CM´s is not developed for hand calculation but as a method for preparation of design tables or tools.

Finite element models (FEM) for connections are used from 70s of last century as research-oriented. Their ability to express real behaviour of connections is making them a valid alternative to testing – standard and expensive source of knowledge of connection’s behaviour. Material model for FEM uses true strain stress-strain diagram, see Fig. 1. Native process of computer based design is V&V of models, see [9]. Application of V&V to steel connections design is limited to a few published benchmark studies, see [10]. Comparison of V&V to different engineering application is still to be done [11]. Strain is recommended to be limited to 5%, see cl. C.8(1) EN 1993-1-5 [1]. Implementation of safety into advanced design models under ultimate limit state design is summarised in cl. C.9(2) EN1993-1-5 [1]. Standard procedure with partial safety factors for material/connections may be applied. More advanced and accurate solution, which takes into consideration the accuracy of model and material separately, gives more accurate and economical solution of structural connections, see [12] to [15]. The CBFEM development was forced by development of information technologies, see [16].

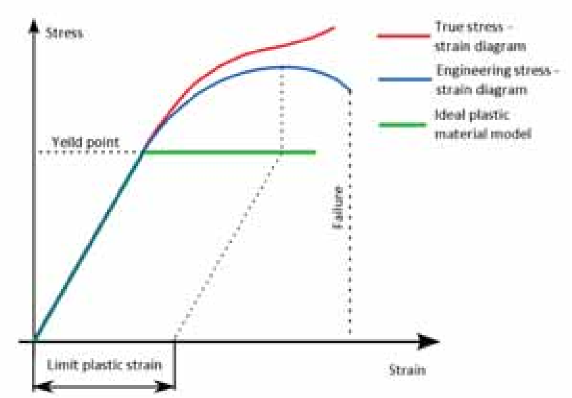


Fig. 1: Material models of steel for research and design oriented methods

3 Connection behaviour

The advantages of FEM analyses of steel plates may be documented on behaviour of a well-designed portal frame eaves moment bolted connection developed based on US best practice and applied in good European practice represented by British and German design books. The composition of the connection geometry of the bolted connection in the CBFEM IDEA SR code is demonstrated in Fig. 2. The rafter of cross section IPE 400 column is connected to column HEA 320 by the full depth end plate of thickness 25 mm by 12 bolts M24 8.8. The haunch 700 mm long is 300 mm high with flange 15x150 mm. The stiffeners are designed from P20. Material S355. The results of analyses show in Fig. 3 the development of plastic zones in connection by CBFEM analyses, from first yielding under the bolt in tension, through development of full plasticity in the column web panel in shear, till reaching the 5 % strain in panel. After reaching this strain the plastic zones propagate rapidly in the column web panel in shear and for small steps in bending moment the rotation of the joint rise significantly, see Fig. 4.

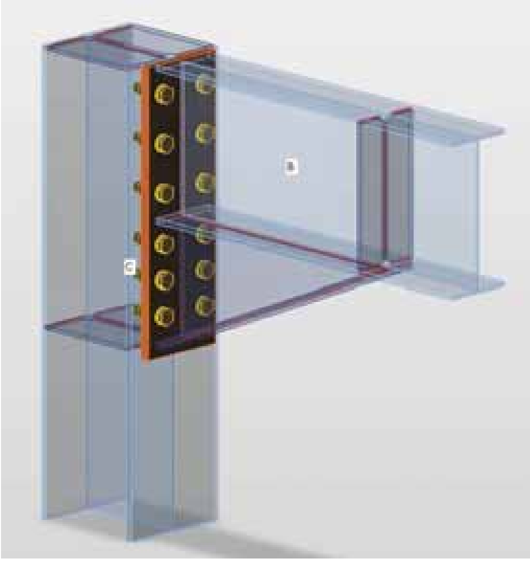
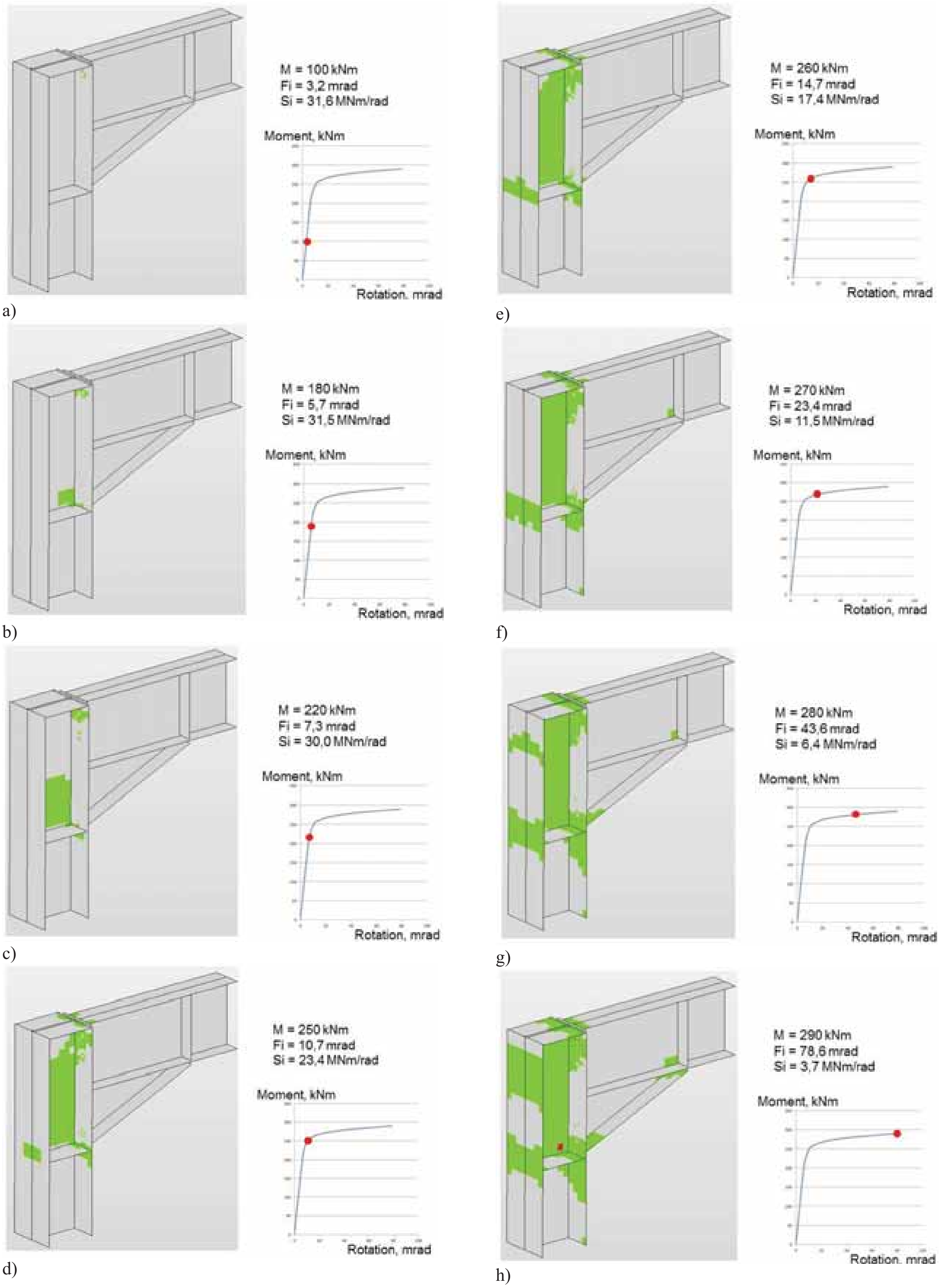


Fig. 2: Composition the bolted connection
selected for analyses in the CBFEM IDEA RS code



a) e) b) f) c) g) d) h)

Fig. 3: Development of plastic zones in connection by CBFEM analyses, from firs yielding under the tensile bolt a), through development of full plasticity in the column web panel loaded in shear e)-f), till reaching the 5 % strain in panel h)

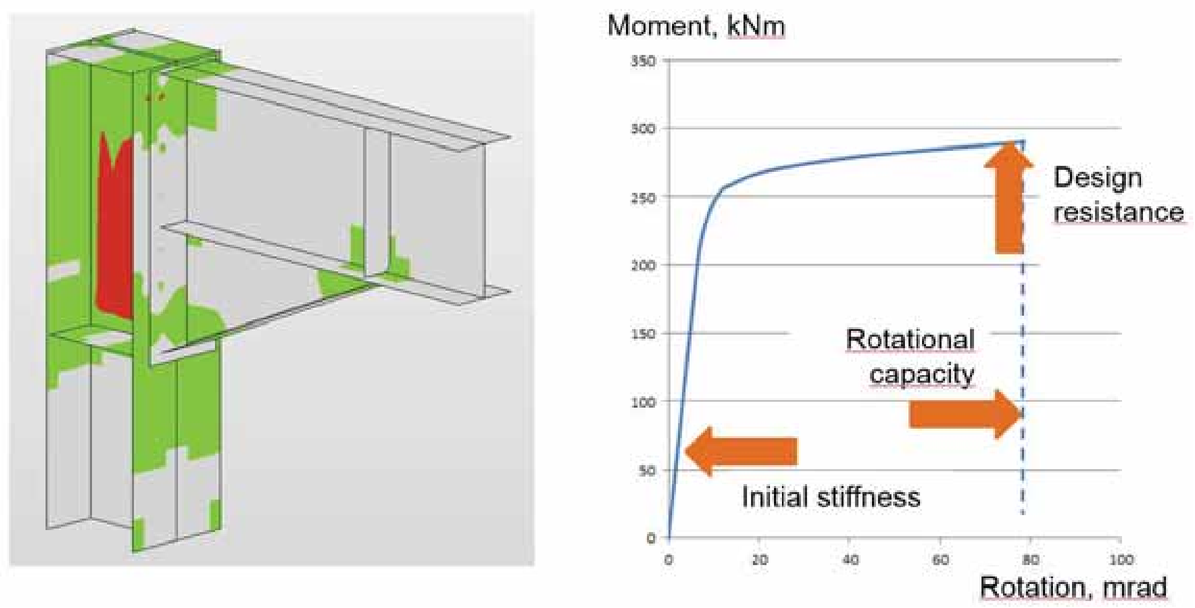


Fig. 4: After reaching the 5 % strain in the column web panel in shear the plastic zones propagate rapidly

As is commonly known even in well-designed connections starts the plastification early, see Fig. 3a). The column web panel in shear bring the deformation capacity of connection and guide the nonlinear part of behaviour, see Fig. 3e-f). Fig. 4 demonstrates the fast development of yielding in the column web panel after reaching the 5 % strain.

4 Validation and Verification

The detailed procedure for verification of proposed method and its application in design tool IDEA RS Connections was prepared. The procedure consist of preparation of Benchmark studies for used components, e.g. bolts, welds, slender plates in compression, anchor bolts, and concrete block in compression. Three different types of welded connections were selected for benchmark studies, connections loaded in shear, in bending, and welded to flexible plate. For bolted connections are prepared benchmark studies for T-stub in tension, the splices in shear and the generally loaded end plate connection. For slender plate in compression is studied the triangular haunch in compression, the slender stiffener of column web and the plate in compression between bolts. For hollow section joints are studied the welded joints between CHS or RHS members and RHS/CHS diagonals welded to the open section chords in shape of T, K and TT joints. For column bases are prepared verifications for T stubs in tension and compression and for the generally loaded columns of open and hollow sections. Benchmark study consist of description of selected joint, results of CBFEM and CM, differences described in term of global behaviour on the force-deformation/rotation curve, and verification of initial stiffness, resistance, deformation capacity. At the end of each Benchmark study is prepared a Benchmark case to allow the user to check his results. In some cases gives the CBFEM method higher resistance, initial stiffness or deformation capacity. Advanced FEM model from the bricks element validated on own or from literature experiments is used in these cases, to get proper results. CBFEM is approved by this procedure.

As a simple example was verified the model of the portal frame eaves moment connection with parallel stiffeners. Results show a good agreement between two models. After that, sensitivity study was performed. Beam IPE cross-section size is shown in Fig. 5. Column of cross section HEB 260 was considered.

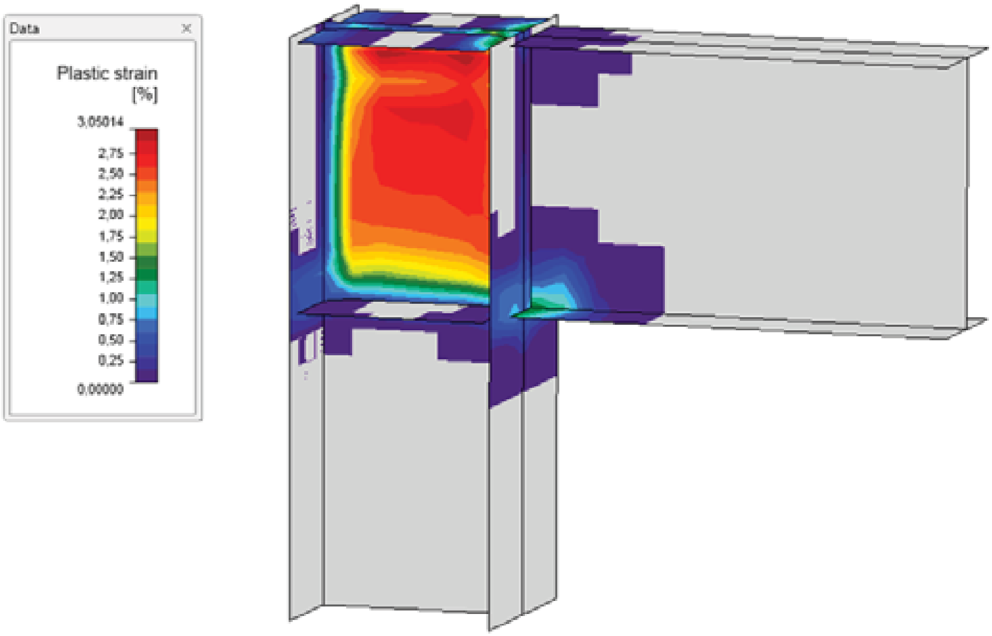


Fig. 5: Welded connection IPE 330 rafter to column HEB 260 selected for verification

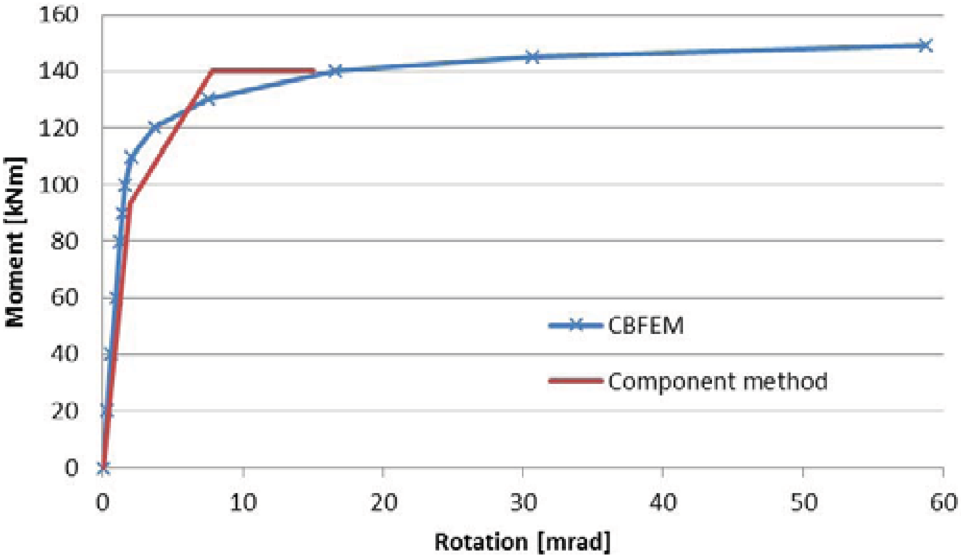


Fig. 6: The moment rotational behaviour of welded eaves moment connection for beam IPE330 to column HEB260 calculated by CBFEM and by CM

Comparison of the global behaviour of the joint is described on moment-rotation diagrams for CBFEM and for CM in Fig. 6. Attention was focused on the main characteristics of the moment-rotation diagram: initial stiffness, elastic resistance and design resistance. Connection of the beam IPE330 to column HEB260 was chosen as a sample. Both procedures give for initial stiffness, elastic resistance and design resistance similar results, see Tab. 1. In addition, the rotational capacity is compared. Component method guarantee the rotational capacity in EN 1993-1-8 in cl. 6.4.3(2), only value 15 mrad. That is lower value compared to prediction by CBFEM, where the 5 % strain is checked in plates and welds. The deformation capacity depends on upper limit of steel properties, which is taken into account by material amplifier γ_{Cd} =1,25 recommended for seismic design.

Table 1: The differences in moment rotational behaviour calculated by CBFEM and CM

Characteristics		CM	CBFEM	CM/CBFEM
Initial stiffness	[kNm/rad]	48423.7	66889.6	0.72
Elastic resistance	[kNm]	93.3	90.0	1.04
Design resistance	[kNm]	140.0	149.0	0.94
Rotation capacity	[mrad]	15.0	58.8	0.26

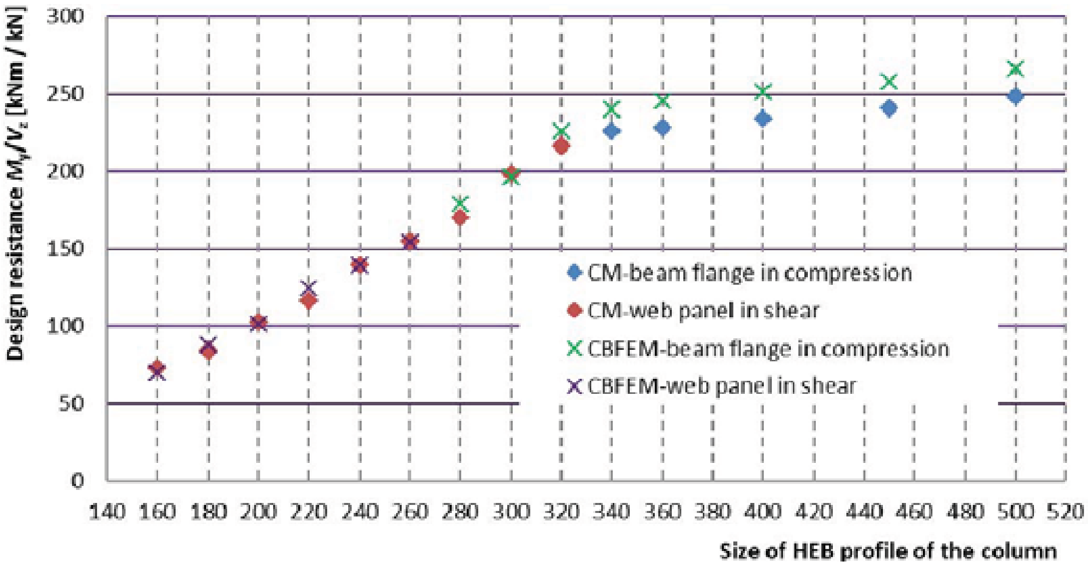


Fig. 7: The sensitivity study for column size

The sensitivity study for column size shows a good agreement of both methods, see Fig. 7. The columns up to HEB 320 shows higher resistance also for advanced model due to membrane action of the relatively thin column web.

Results of sensitivity study for rafter size, column size and column web thickness are shown in Fig. 8. 5% differences are marked by lines. The column web thickness study was performed for IPE 330 rafter and column cross-section dimensions corresponding to HEA 320. The differences are due to weld sizes as was approved by research FEM analyses.

5 Conclusion

As the global analyses of steel structures is today carried out by FEM and all the traditional procedures are not used any more (like force method, three moment equation, Cremon´s pattern, the Cross method or the distribution of moments). Due to fast development of software will be designed very soon the connections by the component based finite element method instead of today used curve fitting and component method.

For proper use of CBFEM is necessary to develop and standardise a good Validation and Verification procedures to allow a safe use of design tools. This procedures are already well developed in another areas of civil engineering like in structural fire design, see [17] and [18]. An important tool is the hierarchy of V&V.

The presented results shows the good accuracy of CBFEM verified to CM and to advanced calculations/experiments in cases where the CBFEM gives higher stiffness / resistance / deformation capacity.

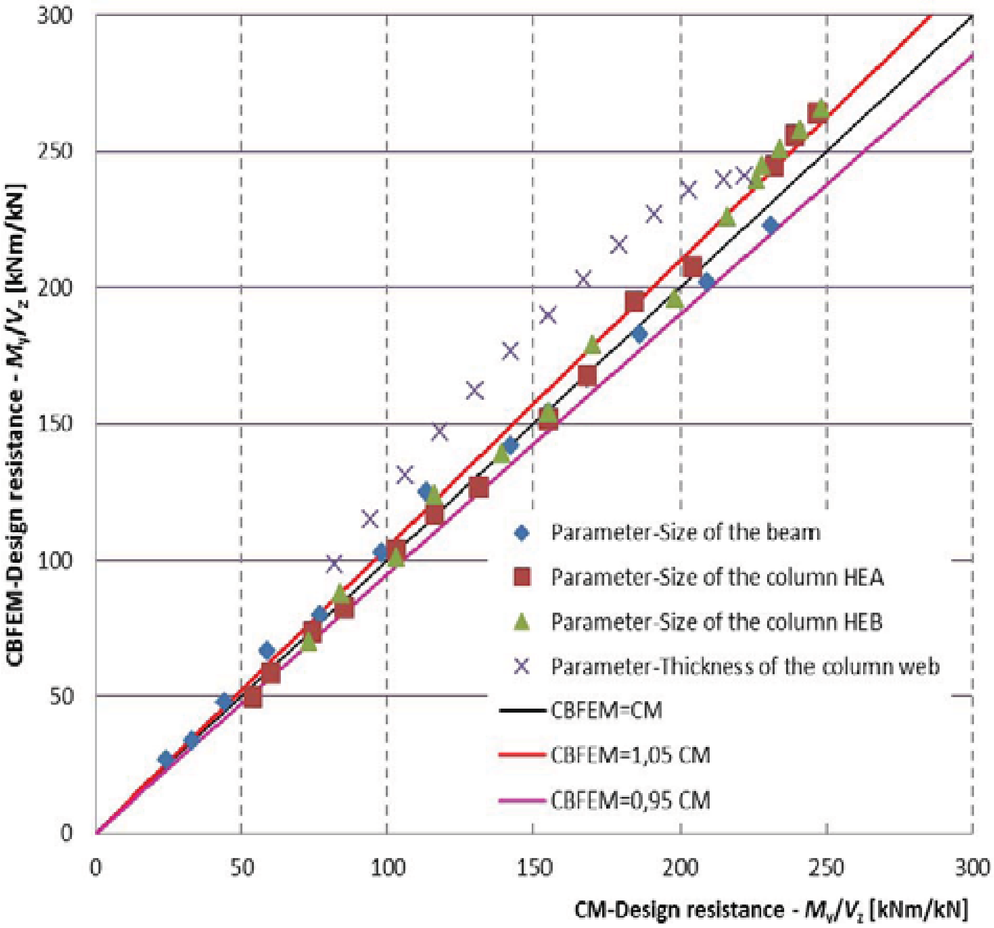


Fig. 5: The summary of the sensitivity study of the portal frame eaves welded moment connection

Acknowledgments

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