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МУЛТИ-НИВЉЕНИ ЧЛАН И ЦОННЕЦТИОН ДИЗАЈН

Резиме

Глобална анализа челичних конструкција врши Анализа финих елемената (ФЕА) и све традиционалне процедуре се више не користе. У новој генерацији конструкцијског челика Еурокодови после 2021. Организоваће се знање запремине ЕН 1993-1-4: 2021 Пројектовање челичних конструкција методом коначних елемената. Дизајн чланова је под утицајем заједничког дизајна. Сензитивност на крутост савијања је најједноставнији пример. То је изазов за инжењера из првих систематских тестова 1917. године. У овом доприносу је приказан напредни дизајн удружења и његова валидација и верификација и како ће се дизајн чланова, укључујући зглобове, третирати у наредној будућности.

Кључне речи: **челичне конструкције, дизајн везе, компонента метода, метода коначних елемената**

MULTI LEVEL MEMBER AND CONNECTION DESIGN

Summary

The global analysis of steel structures is carried out by Finite Element Analyses (FEA) and all the traditional procedures are not used any more. In new generation of structural steel Eurocodes after 2021 will be organised the knowledge in volume EN 1993-1-4:2021 Design of steel structures by finite element method. The member design is influenced by joint design. The sensitivity to bending stiffness is the simplest example. It is challenge for engineer from first systematic tests in 1917. In this contribution is shown the advanced design of joint and its Validation and Verification and how the member design including joints will be treated in next future.

Key words: ***steel structures, connection design, component method, finite element method***

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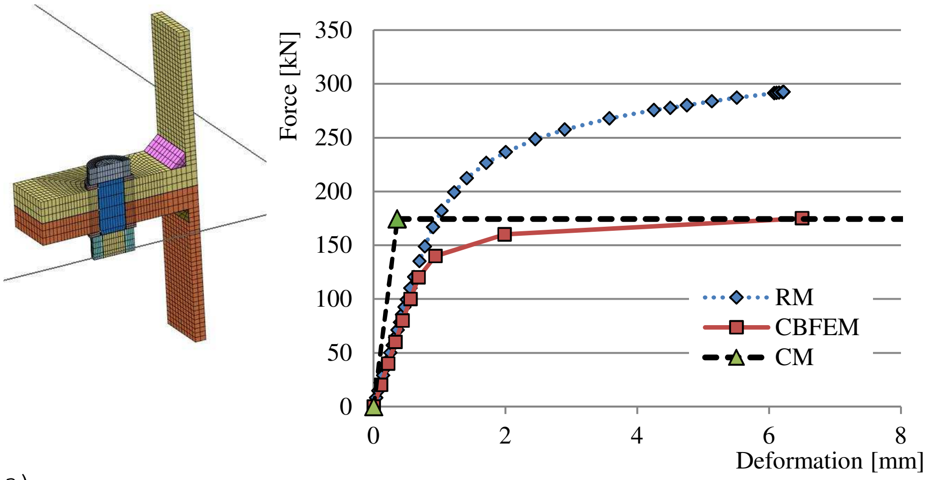
1. INTRODUCTION

Experimental evidence and curve fitting procedures were and still are used for safe and economical design of connections [1]. Based on analytical models of resistance of connectors, as welds, bolds, and plates, and the estimated lever arm of internal forces is predicted resistance of connection. Zoetemeijer [2] was the first who equipped this model with estimation 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 prepared 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 the steel and composite connections [6] and is applied in majority of software for structural steel in Europe. The idea was generalised by da Silva [7] for 3D behaviour including nonlinear parts of behaviour. 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 this often called Component Method (CM) 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 CM is that experimental evaluation of internal forces distribution is available only for limited number of the open section joint configurations. In temporary scientific papers, description of atypical components is either not present or has low validity and description of background materials. The CM is not developed and standardised for hand calculation but for preparation of design tables or software tools. For hollow section connections is still used curve fitting procedures based on mechanical and numerical experiments with its low quality of prediction and big restrictions, see for example Ch. 7 of EN1993-1-8:2006 [6].

2. VALIDATION AND VERIFICATION

FEA´s for connections are used from 70s of last century as research-oriented FEA (RFEA). Their ability to express real behaviour of connections is making numerical experiments a valid alternative to testing and source of additional information about local stresses. Material model for FEA uses true strain stress-strain diagram. Validation and Verification (V&V) process of models is integral part of the procedure, see e.g. [8], and the FEA studied are based on the researcher's own experiments. During preparation of CM for EN 1998-1-3:2006 were deeply modelled all basic components, see [9]. Special attention was given to modelling of the T stub, which represents the end plate connections beam to column joints, beam splices and column bases. Last generation of FEA models of connections is utilised in studies focussed to application of high strength steel in the connections [10].

V&V of the FEA design models (DFEA) of steel connections design is native part of its preparation, see [11]. The detailed procedure for verification of CBFEM and its application in design tool IDEA RS Connections was prepared, see [12]. The procedure consists 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, see Figure 1. 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.



a)

b)

Figure 1 - ***The bolted T stub in tension a) mesh for research FEM,***
b) force-deformation diagram

The research FEA of the bolted T stubs in tension was prepared Midas FEA code, see Figure 1a, and validated on experiments [13]. T-stub of steel S235, with flange thickness t_f = 20 mm, web thickness t_w = 20 mm, flange width b_f = 300 mm, length b = 100 mm, double fillet weld a_w = 10 mm, bolts 2 x M24 8.8 with pitch w = 165 mm was modelled and selected for sensitivity study. The research FEM using the true stress true stain material diagram represents the experimental behaviour was used for verification of the CBFEM model of T stub, see Figure 1b. For thin plates gives CM unrealistic low value due to neglecting of membrane action of end plates, see Figure 2. For regular plates predict CM higher resistance by neglecting the shear and bending interaction on deformed endplate. For very thick plates is for CM calculated the limit of deformation capacity separately and its estimation may not fit into shear and tension interaction in bolt. The sensitivity study of flange thickness width and material quality, bolt size, pitch and material quality, shows good prediction resistance by CBFEM on asked design level. Summary of verification of CBFEM to CM for the bolted T stub in tension is presented in Figure 3, where are recapitulated the studies for bolt size, material and pitches, the flange thickness and width. The results show that the difference of the two calculation methods is mostly up to 10 %. In cases with CBFEM/CM > 1,1 accuracy of CBFEM was verified by the results of RM which gives highest resistance in all selected cases.

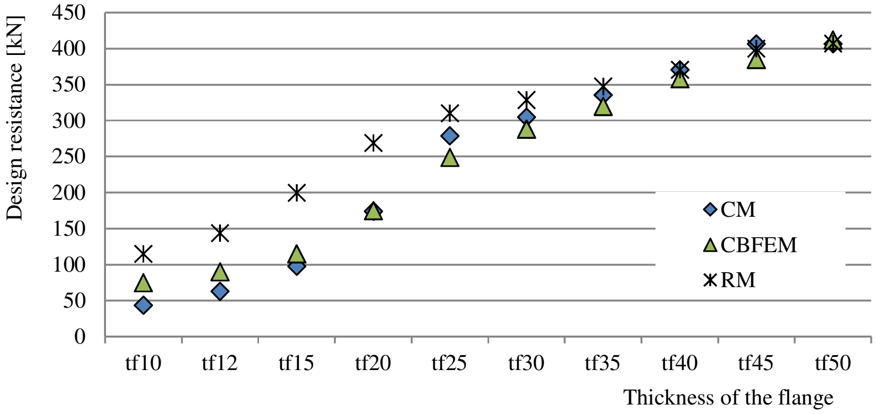


Figure 2 - ***Sensitivity study of flange thickness***

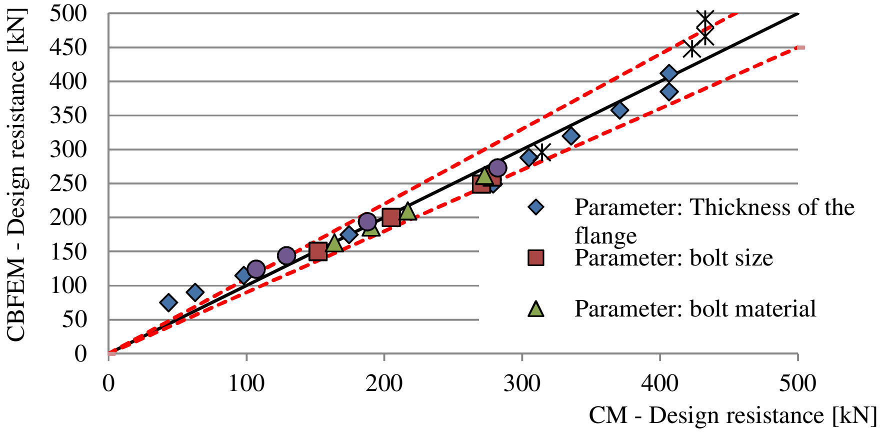
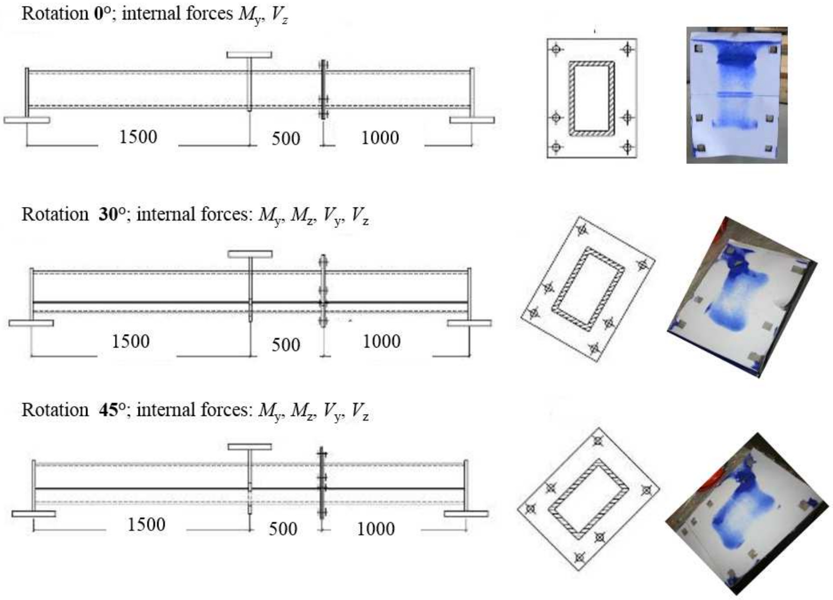


Figure 3 - ***Summary of verification of CBFEM to CM for the bolted T stub in tension***

Experimental investigation of three samples of the generally loaded end plate joints was performed [13]. End plates were welded on two RHS 250 x 150 x 16 beams of different lengths 2000 mm and 1000 mm. The beams and plates were designed from S355, with measured values of $f_{y,m}$ = 410 MPa and $f_{u,m}$ = 582 MPa. The end plates P10 – 400 x 300 were connected by M20 8.8 bolts, with the vertical distances 35 – 230 – 100 – 35 mm and horizontal ones 30 – 240 – 30 mm. The beam with connection 500 mm from its centre was loaded in its centre through P20 by hydraulic jack, see Figure 4. The configuration creates in the connection shear forces and bending moments. The results of the contact imprints on paper placed between the end plates is included on right side of the Figure 1b. The inclination of the specimens varied from 0°; 30° till 45°. The test set up with 0° inclination is documented at Figure 5.


Rotation **0**°; internal forces M_y, V_z

Rotation **30**°; internal forces: M_y, M_z, V_y, V_z

Rotation **45**°; internal forces: M_y, M_z, V_y, V_z

Figure 4 - ***Position of the beam splice joins on beam, inclination and contact imprints***

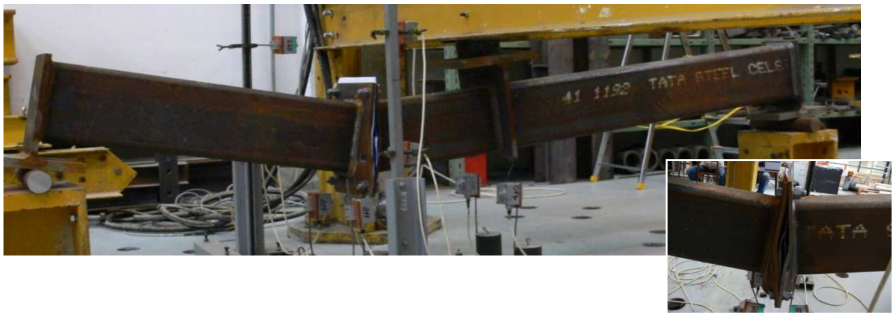


Figure 5 - ***The test sample with 0° inclination***

Connections were designed according to EN 1993-1-8:2006 [6]. Four components are guiding the behaviour the fillet welds, the beam flange in compression and in tension, the end plate in bending and the bolts in tension. Effective lengths for circular and noncircular failures are considered according to EN 1993-1-8:2006 cl. 6.2.6. Three modes of collapse according to cl. 6.2.4.1 are considered. Bolts are designed according to cl. 3.6.1. Design resistance considers punching shear resistance and rupture of the bolt. For component method is in EN1993-1-8:2006 recommended a linear interaction. The quadratic interaction curve according to [14] is included in verification study.

Samples 30° and 45° with strong axis bending moment were chosen to present of the global behaviour described by moment-rotation diagram, see Figs 6 and 7. CM with quadratic interaction gives higher initial stiffness compared to CBFEM and experimental data. In all cases are resistances by CM and CBFEM similar and corresponds to asked characteristic design level. Experimentally measured resistance is higher including hardening of the materials after reaching yield strength. Resistance calculated by CBFEM was compared with the results of CM and experimental results, see Figure 8. CM with linear interaction gives conservative values of resistance. CM with quadratic interaction gives the highest resistances, which are to experimental results still rather conservative. CBFEM gives similar results as CM with quadratic interaction. The verification of the prediction of the resistance of the CBFEM to CM for inclination of°0° and changing the end plate thickness is presented in Figure 9 and Table 1. The verification of the prediction of the resistance of the CBFEM to CM for inclination of°0° and changing the bolt material is presented in Table 2. The results show good agreement between both models.

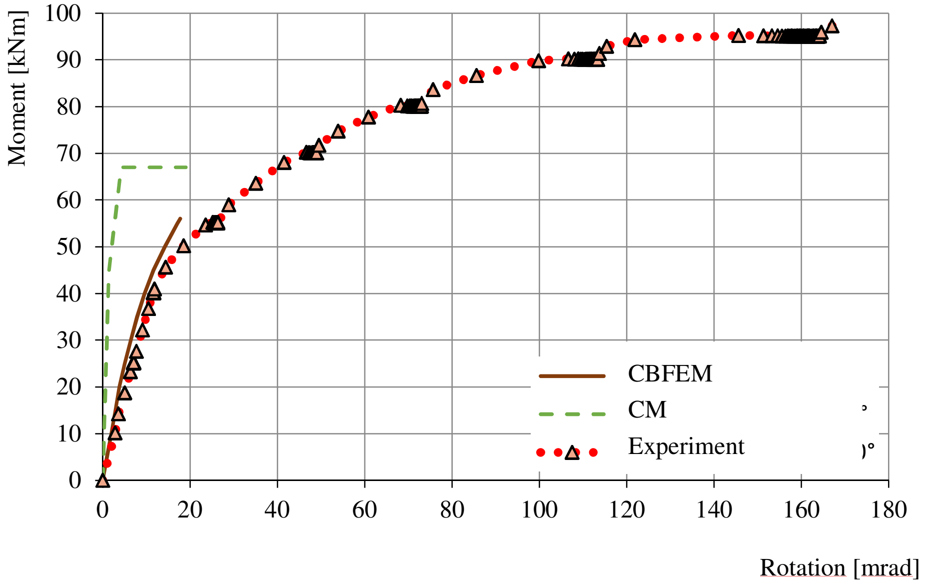


Figure 6 - ***Validation of moment rotational curve of numerical model (CBFEM) and analytical model (CM) to experiments for inclination 30°***

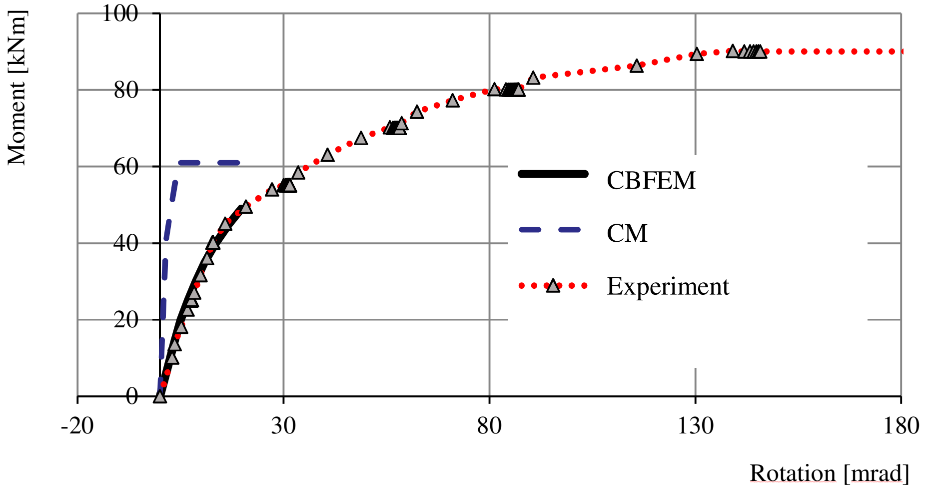


Figure 7 - ***Validation of moment rotational curve of numerical model (CBFEM) and analytical model (CM) to experiments for inclination 45°***

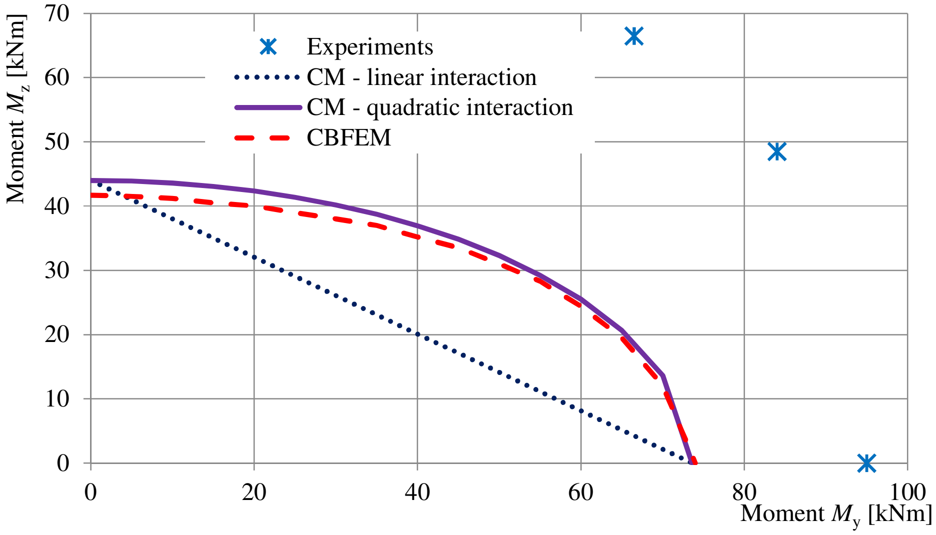


Figure 8 - ***Validation of resistances for numerical model (CBFEM) and analytical model (CM) to experiments***

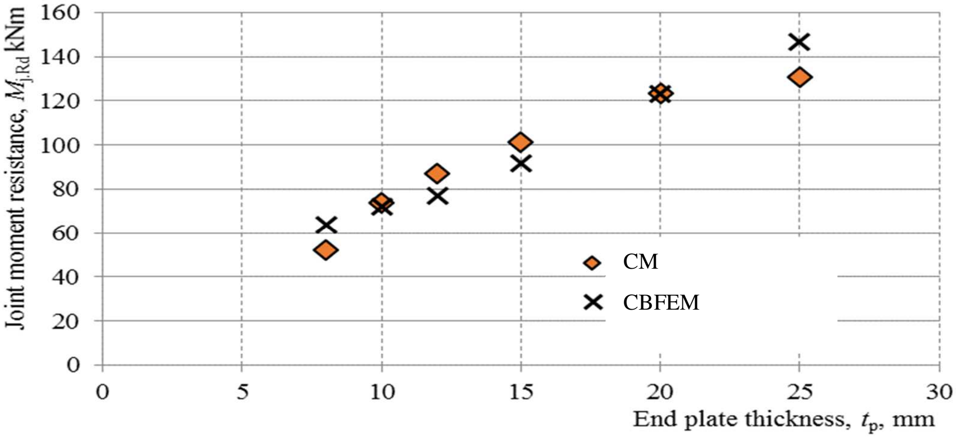


Figure 9 - ***Verification of numerical model (CBFEM) to analytical model (CM) for the end plate thickness***

Table 1 – ***Verification of numerical model (CBFEM) to analytical model (CM) for the end plate thickness***

Parameter	Numerical model, CBFEM		Analytical model, CM		Ration CBFEM/ CM
End plate thickness, f_p, mm	Bending resistance, kNm	Decisive component	Bending resistance, kNm	Decisive component	
8	64	End plate in bending	52	End plate in bending	1,22
10	72	End plate in bending	74	End plate in bending	0,98
12	77	End plate in bending	87	End plate in bending	0,88
15	92	End plate in bending	101	End plate in bending	0,91
20	123	End plate in bending	124	End plate in bending	1,00
25	147	Bolts in tension	131	Bolts in tension	1,12

Table 2 – ***Verification of numerical model (CBFEM) to analytical model (CM) for inclination of°0° and bolts 8.8***

Parameter	Numerical model, CBFEM		Analytical model, CM		Ration CBFEM /CM
Bolt class	Bending resistance, kNm	Decisive component	Bending resistance, kNm	Decisive component	
4.8	49	End plate in bending	48	End plate in bending	1,01
5.8	50	End plate in bending	56	End plate in bending	0,89
6.8	55	End plate in bending	64	End plate in bending	0,86
8.8	72	End plate in bending	74	End plate in bending	0,98
10.9	75	End plate in bending	79	End plate in bending	0,94

3. MEMBER BEHAVIOUR INCLUDING CONNECTIONS

The discrete evaluation of members may be based on the same procedure as for joints. For joints it is expected no recalculation of global analyses due to design is necessary. For members the iterative procedure is obvious to reach a satisfactory result. It the first step are solved the internal forces and deformations in the 3D FEM with 1D elements with global imperfections, Geometrically Non-linear Elastic Analysis with Imperfections, on the structure with selected cross-sections of members, see Figure 10a. Selected member with its internal force is then analysed by FEM using 3D Geometrically and Materially Non-linear Analysis with Imperfections including joints, see Figure 10b. It allows to introduce buckling of member in both planes and lateral torsional buckling. The member is checked according to ULS and SLS and the cross-sections are modified, see EN 1993-1-1:2005 [15]. The structure with modified member is recalculated by 3D FEM with global imperfections. The procedure is repeated to achieve a satisfactory accuracy in prediction.

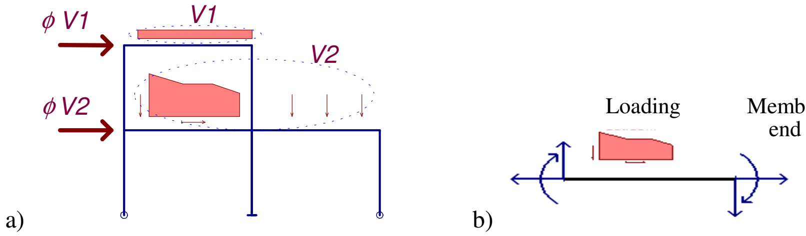
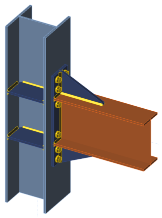
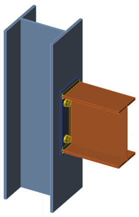


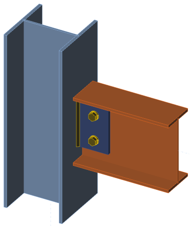
Figure 10 - ***a) Sketch of Geometrically non-linear elastic global analysis with imperfections with separate member and joint***
a) Geometrically and Materially Non-linear Analysis with Imperfections

Geometrically non-linear elastic global analysis with imperfections a) is equipped with separate member and joint Geometrically and Materially Non-linear Analysis with Imperfections.

$$k_b = S_{j,ini} L_b / (I_b E) \tag{1}$$


a) Extended plate connection


b) End plate connection


c) Fin plate connection

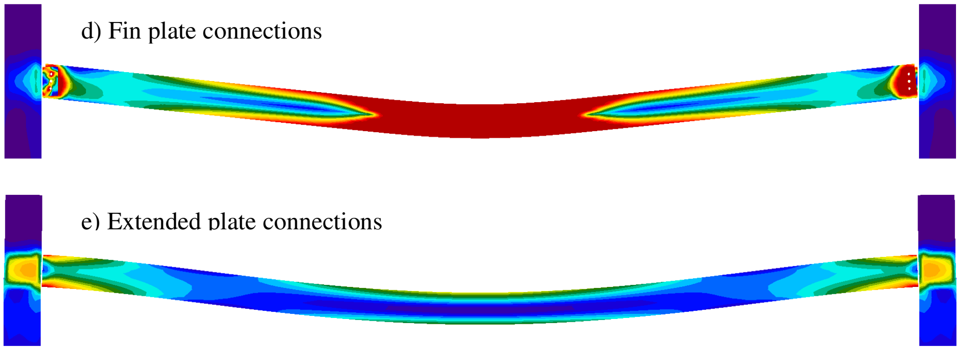


*Figure 11 -**a) Extended end plate, b) End plate connection, c) Fin plate connection, d) Von Misses' stresses along the beams with fin plate and e) with extended plate connections, Idea Member [17]***

The influence of joint stiffness k_b to beam of cross-section IPE 330 is shown in Figure 12. There are three areas of the stiffness classification of the joint according to EN 1993-1-8:2006 [6] hinged joints k_b < 0,5 and rigid one k_b > 25. The beam is designed for the bending moment at ULS and deflection at SLS. The limits of accuracy in prediction are expected to be 5 % for ULS and 20% for SLS.

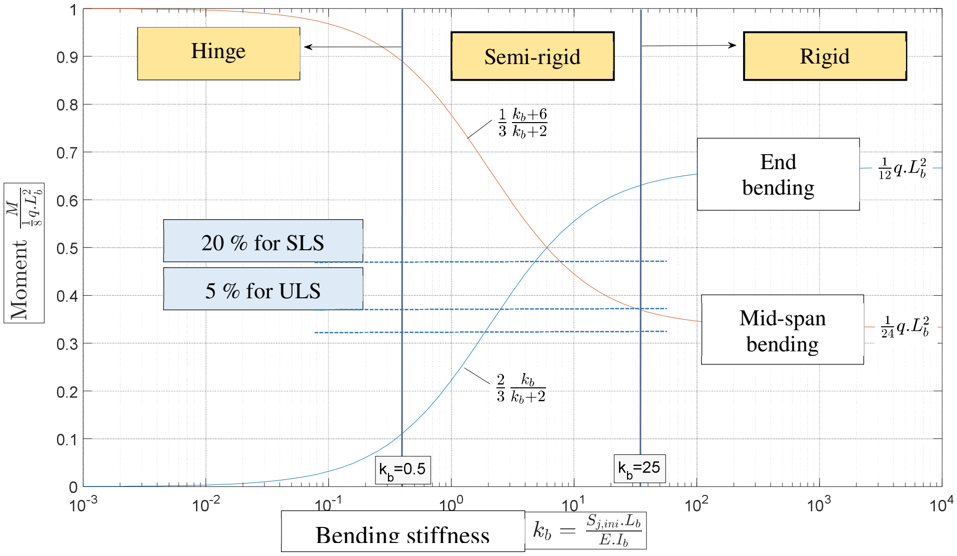


*Figure 12 - **Influence of the relative bending stiffness of the joint in logarithmic scale to the relative mid span bending moment***

4. SUMMARY AND ACKNOWLEDGMENT

The presented results show the good accuracy of CBFEM verified to CM and to advanced calculations/experiments in cases where the CBFEM gives higher stiffness, resistance, or deformation capacity, see [12].

The member 3D analyses including connections allows prediction of behaviour of complex member, with haunches, openings etc., including connection and loading.

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