Slender Compressed Plate in Component Based Finite Element Model

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Abstract. The paper presents an advance design model of a slender plate in the structural steel joint. Finite element methods and material models are described and design procedure for slender plates in numerical models of steel joints is proposed. The design procedure is demonstrated on examples. The results are verified with an analytical model according to European standards. A compressed beam with slender web and beam-to-column joint are studied by numerical analysis, buckling resistances are determined and results verified. The verification shows very good agreement.

1. Introduction

The analytical model represented by component method (CM), which is described in EN 1993-1-8, gives good prediction of behaviour for typical structural steel joints [1]. However, many components are limited by plate slenderness, because the design procedure is valid for the third class cross section and better, see [2] and [3]. Buckling of slender plates should be assessed in a separate step according to EN 1993-1-5 [4]. The code also contains recommendations for design by numerical modelling as an alternative to the analytical model. The use of numerical models is today widely spread in design practice and especially buckling analysis of plated structures gets special attention [5]. Finite element models (FEM) give very good prediction of global behaviour of joints, although the accuracy of the results is closely connected to the meshing, element types, interfaces and sub-modelling. When using FEM tools, special attention should be paid to the selection of software, modelling of material properties, the use of imperfections and modelling of boundary conditions and loads.

2. Finite element method in plate stability analysis

With respect to the ultimate limit state, the code provides five categories of numerical analysis with the following assumptions:

- Material and geometric linear;
- Material nonlinear and geometric linear -> plastic resistance;
- Material linear and geometric nonlinear -> buckling;
- Material linear and geometric nonlinear with imperfections;
- Material and geometric nonlinear with imperfections -> ultimate resistance.

Plastic resistance is determined by material nonlinear and geometric linear analysis. Material diagram is elastic with strain hardening and the structure is modelled with its theoretical geometry without imperfections. Ultimate limit state is reached by 5% plastic strain. The coefficient $\alpha_{ult,k}$ is obtained, where $\alpha_{ult,k}$ is the minimum load amplifier for the design loads to reach the characteristic value of the resistance of the most critical point.

Critical buckling modes are determined by material linear and geometric nonlinear analysis. The critical buckling factor α_{cr} is determined and stands for the load amplifier to reach the elastic critical load under complex stress field.

The load amplifiers are related with the non-dimensional plate slenderness, which is determined as follows:

$$\bar{\lambda} = \sqrt{\frac{\alpha_{ult}}{\alpha_{cr}}} \quad (1)$$

Reduction buckling factor ρ is calculated according to EN 1993-1-5 Annex B. Conservatively, the lowest value from longitudinal, transverse and shear stress is taken. Figure 1 shows the relation between plate slenderness and reduction buckling factor.

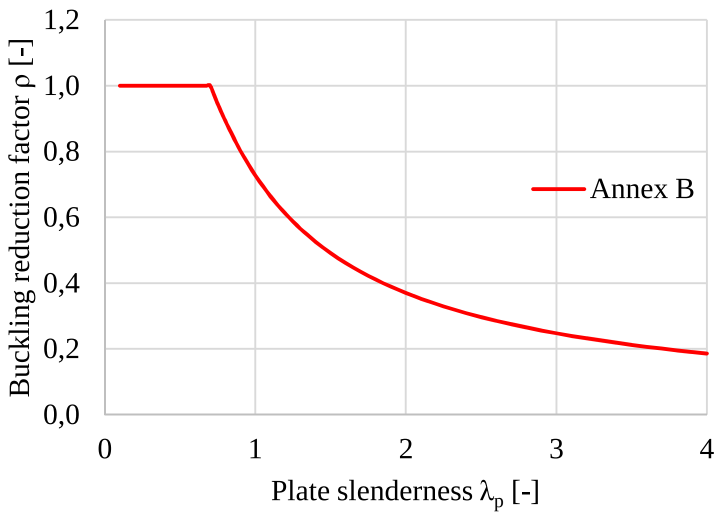


Figure 1. Buckling reduction factor ρ according to EN 1993-1-5 Annex B.

The verification is based on the von-Mises yield criterion and reduced stress method and sums up the load effects of normal and shear stresses. Buckling resistance is assessed as:

$$\frac{\alpha_{ult} \cdot \rho}{\gamma_{M1}} \geq 1 \quad (2)$$

where γ_{M1} is partial safety factor.

It should be noted that the first critical buckling mode in the joint may not be in terms of the previous condition crucial. More buckling modes need to be assessed in a complex joint, because they are related to different parts of the joint. The procedure is sufficiently general, robust and can be quite easily automated. Its advantages are in the advanced joint FEM analysis. In addition, it is part of the Eurocode standards. The design tool gives a quick overview of the joint behaviour, its critical components and allows fast stiffening to prevent instabilities.

The above described design procedure is used in component based finite element model (CBFEM), which combines the advantages of finite element models and the component method. The stress distribution in the joint is close to the real behaviour and the components bolt, weld and plate are assessed according to analytical models approved by experiments, see [6] and [7]. Compared to research finite element model (RFEM), which uses material and geometric nonlinear analysis with imperfections, CBFEM is time-saving in modelling, FEM analysis and evaluation of ultimate limit state. CBFEM is an innovative design method for steel joints with complex geometry and stress field, see [8]. Material model uses true stress-strain diagram, which is obtained by tensile tests, in RFEM and ideal plastic or elastic with strain hardening for design FEM, see figure 2.

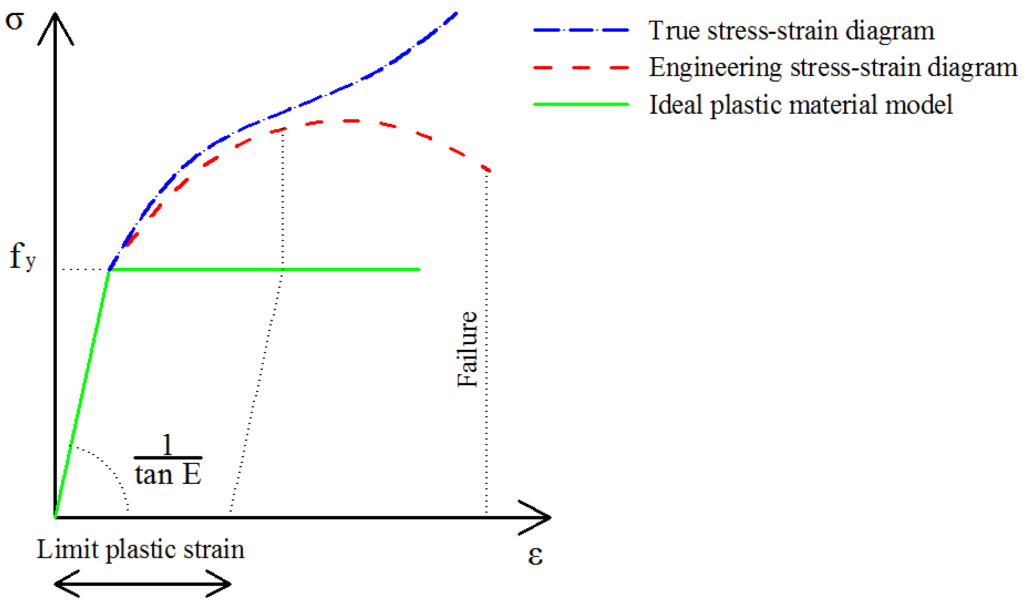


Figure 2. Material models of steel for research and design numerical models.

Validation and Verification (V&V) is a native process of computer based design, see [9], where validation means comparison of numerical models to experimental data and verification comparison of the numerical solution with the accurate analytical or numerical solution. Application of V&V to steel connections design is limited to a few published benchmark studies, see [10]. System response quality (SRQ) contains a description of a selected joint, results of CM and CBFEM, comparison of resistances and Benchmark case to allow the user to check his results. In some cases the CBFEM method gives higher resistance. Advanced FEM model with shell elements validated on own experiments or experiments from literature is used in these cases to get proper results. CBFEM is approved by this procedure. The proposed procedure for slender plate in CBFEM model is based on Annex B in EN1993-1-5 and verified on two examples.

3. Verification of the compressed beam web

First verification example shows a welded beam loaded in compression. Four beams B2-B5 are studied and the ultimate resistances are calculated. The beam dimensions are fixed, only the web thickness t_w is changing between 2 and 5 mm. A plate 200x10 mm is used for flanges and a web height is set to 380 mm. The range of web's slenderness is set from 1 to 2.5. Yield strength of the beam is set to S235. Figure 3 shows the first buckling mode of the compressed beam.

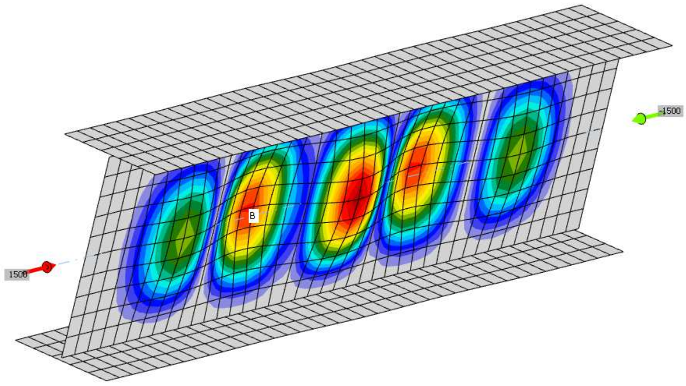


Figure 3. First buckling mode of the compressed beam.

A comparison of compressed beam's ultimate resistance for analytical calculation according to EN 1993-1-5 and CBFEM is shown in table 1. It is observed that the resistances are in good accordance with the CBFEM calculations.

Table 1. Ultimate resistance of compressed beam – Comparison.

	t_w	$\alpha_{cr,CBFEM}$	$\alpha_{ult,k,CBFEM}$	$\lambda_{p,CBFEM}$	F_{CBFEM} [kN]	F_{Rd} [kN]	$(F_{CBFEM} - F_{Rd}) / F_{CBFEM}$ [%]
B2	2	0,12	0,77	2,53	338	330	2
B3	3	0,30	0,83	1,66	553	553	4
B4	4	0,56	0,89	1,26	777	758	2
B5	5	0,91	0,95	1,02	1016	1004	1

A comparison of ultimate resistances for the compressed beam is shown in figure 4. The vertical axis of the diagram shows the ultimate resistance by CBFEM model, while the horizontal axis shows the results of an analytical solution. An allowed deviation of 10% is marked by dotted lines. A very good agreement is observed in the diagrams.

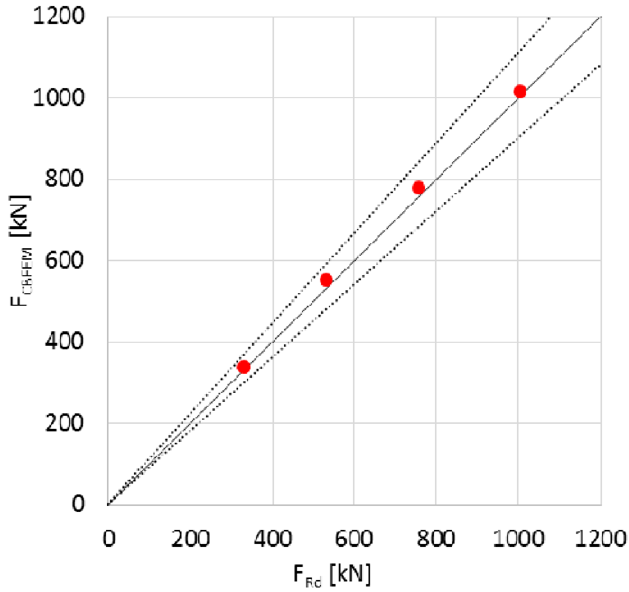
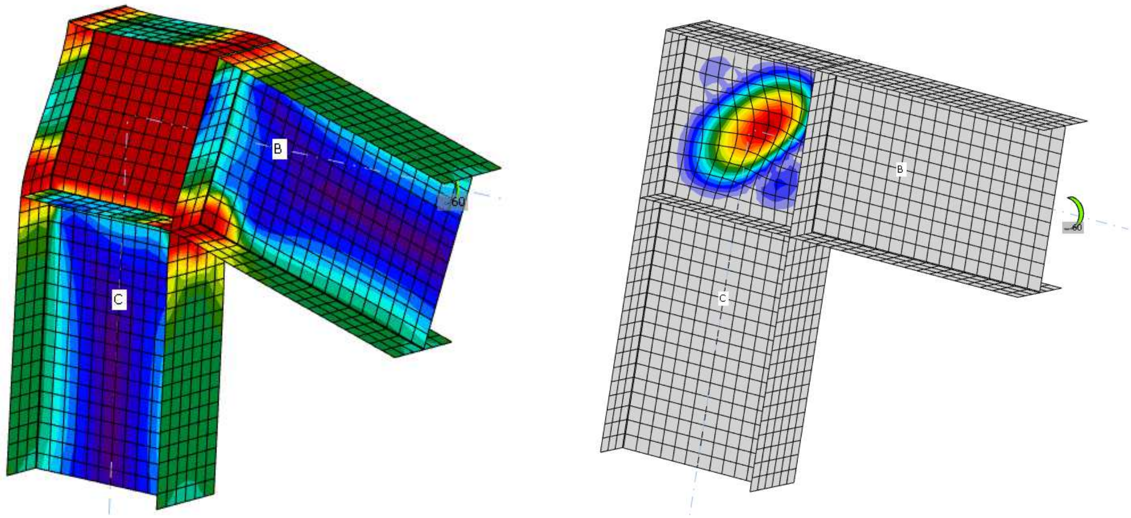


Figure 4. Comparison of compressed beam's ultimate resistances for CBFEM and CM.

4. Verification of the beam-to-column joint

The second verification study covers a beam-to-column joint. Four joints W2-W5 are studied and the ultimate resistances are calculated. Beams and columns are welded cross sections with flange 300x8 mm and web height 584 mm. Only the thickness of a column web panel t_w is changing from 2 to 5 mm in the verification study. The range of column web panel's slenderness is set from 0.8 to 2.0. The joint is loaded in bending and yield strength is set to S235. A plastification of the column web panel and the first buckling mode are shown in figure 5.



(a) (b)

Figure 5. Yielding in column web panel (a) and the first buckling mode (b).

A comparison of beam-to-column joint's ultimate resistance for analytical calculation according to EN 1993-1-5 and CBFEM is shown in table 2 and in figure 6. It can be found that the maximum deviation of ultimate resistances between CBFEM model and analytical solution is 7%, which means good agreement exists.

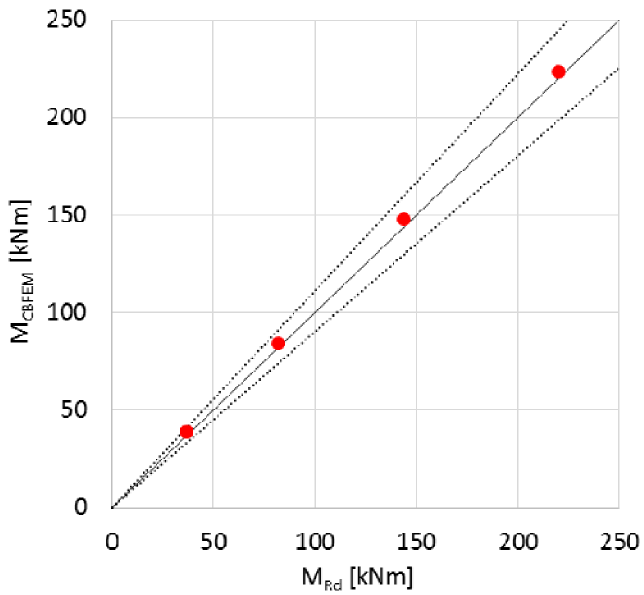


Figure 6. Comparison of beam-to-column joint's ultimate resistances for CBFEM and CM.

Table 2. Ultimate resistance of beam-to-column joints – Comparison.

	t_w	$\alpha_{cr,CBFEM}$	$\alpha_{ult,k,CBFEM}$	$\lambda_{p,CBFEM}$	M_{CBFEM} [kNm]	M_{Rd} [kNm]	$(M_{CBFEM} - M_{Rd})$ / M_{CBFEM} [%]
W2	2	0,10	0,41	2,02	39	36	7
W3	3	0,33	0,59	1,34	84	81	4
W4	4	0,77	0,79	1,01	148	141	4
W5	5	1,48	0,97	0,81	223	216	3

5. Conclusion

It is proposed to use the reduced stress method for the design finite element model (DFEM) or component based finite element model (CBFEM) of compressed plates in structural steel joints. The verification examples show that compressed plates could be designed in finite element models without applying imperfections. Essential part of the following research is the verification of buckling curve for non-regular plate shapes. Using the buckling curve instead of nonlinear analysis will reduce the calculation time. The design procedure covers local buckling of the compressed plates, shear buckling of a slender web panel and local buckling of a compressed plate between the bolts.

Acknowledgments

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