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TO DESIGN OF STIFFENERS IN STRUCTURAL STEEL JOINTS

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Abstract. *The paper presents research into the advanced stability analysis of stiffeners in structural steel joints. Stiffeners are investigated by component based finite element method (CBFEM). To avoid local buckling of slender plates in CBFEM a design procedure is proposed and verified on research finite element model (RFEM). RFEM is studied by material and geometrical nonlinear finite element analysis with imperfections. It is proposed to use a combination of material nonlinear analysis without imperfections with buckling analysis in CBFEM. The verification is shown on an example of web stiffener in welded portal frame joint. The stiffener is studied by numerical analysis, resistances and critical loads are determined in RFEM and CBFEM and results are compared. A numerical study illustrates the effect of the stiffener's thickness on the joint's resistance. Mesh sensitivity study is covered and the optimal number of elements along the stiffener's width is recommended.*

1 INTRODUCTION

Stiffeners have widely been used to increase the buckling resistance of shear panels in steel frames. However, due to major differences between plate girders and steel plate shear walls, use of plate girder equations often leads to uneconomical and, in some cases, incorrect design of stiffeners. The effect of stiffeners on the resistance of column web panel has been studied since 1970's. The research was supported by large experimental investigation [1]. Stiffeners are primarily provided to increase the buckling resistance of various plated structures. However, buckling and post-buckling of thin-walled stiffened plates are nonlinear phenomena and no design formulas for the design of stiffeners in steel shear walls have been suggested. Nevertheless, if optimum stiffener dimensions are provided, the stiffened plate should gain maximum buckling and post-buckling resistance. More recently have been investigated the various aspects of stiffened and unstiffened shear panels [2-5]. The optimisation of transverse stiffeners in plate girders was discussed in [6].

Hence, this paper uses finite element analysis (FEA) to describe the effect of the stiffener's thickness on the buckling resistance to avoid local buckling of the stiffener. Subsequently, curves and formulas for the design of slender stiffeners in design oriented FEM models are presented. The proposed design procedure is verified on the haunched beam-to-column joint [7, 8].

2 LOCAL BUCKLING OF COMPRESSED PLATES

In research FEA models the slender plates in compression are taking into account its plate geometrical imperfections, residual stresses and large deformations during analyses, see EN1993-1-5 [9]. This should be précised according to the different plate/joint configuration. The FEA procedure naturally offers the prediction of the buckling load of the joint. The design procedure for class 4 cross-sections according to reduced stress method is described in Annex B of EN1993-1-5. It allows predict the post buckling resistance of the joints. Critical buckling modes are determined by material linear and geometric nonlinear analysis. In the first step the minimum load amplifier for the design loads to reach the characteristic value of the resistance of the most critical point coefficient $\alpha_{ult,k}$ is obtained. Ultimate limit state is reached by 5 % plastic strain. 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 to the non-dimensional plate slenderness, which is determined as follows:

$$\overline{\lambda} = \sqrt{\frac{\alpha_{ult}}{\alpha_{cr}}} \tag{1}$$

Reduction buckling factor ρ is calculated according to Annex B of EN1993-1-5. Conservatively, the lowest value from longitudinal, transverse and shear stress is taken. Figure 1 shows the relation between plate slenderness and reduction buckling factor.

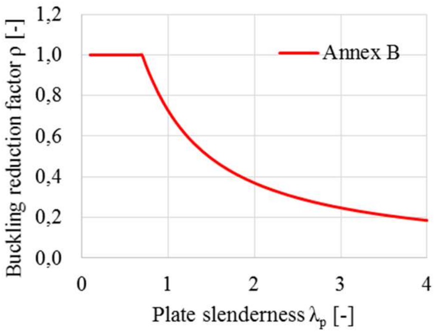

Figure 1. Buckling reduction factor ρ according to Annex B of EN1993-1-5.

The verification of the plate is based on the von-Mises yield criterion and reduced stress method. Buckling resistance is assessed as:

$$\frac{\alpha_{ult} \cdot \rho}{\gamma_{M1}} \geq 1 \tag{2}$$

where γ_{M1} is partial safety factor.

3 RESEARCH FEM MODEL

Research FEM model (RFEM) is used to verify the CBFEM model. The advanced FEM software Dlubal RFEM 5.0. [10] is used for the verification. In the numerical model, 4-node quadrilateral shell elements with nodes at its corners are applied with a maximum side length of 10 mm. Six degrees of freedom are in every node: 3 translations (u_x, u_y, u_z) and 3 rotations (φ_x, φ_y, φ_z). Material and geometric nonlinear analysis with imperfections (GMNIA) is applied. An ideal plastic material model with strain hardening, to overcome numerical instability, is chosen and the von Mises yield criterion is applied. Equivalent geometric imperfections are derived from the first buckling mode and the amplitude is set according to Annex C in EN1993-1-5. Large deformation analysis is used and the Newton-Raphson method for solving systems of equations is chosen. The number of loading steps is set to 50, the convergence criteria for tolerance to 1.0% and the maximum number of iterations to 50. Loading is applied through displacement increments, which better reflect the experiment conditions. The analysis stops at a certain limit of displacement. The numerical model is shown in figure 2.

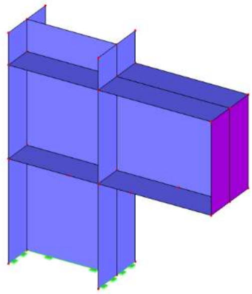

Figure 2. Research FEA model of a welded portal frame joint with slender column web stiffener.

3 COMPONENT BASED FEM MODEL

The component based FEM model is prepared in Idea Statica Connection software [11]. The calculation of the design resistances is done according to design procedure. F_{CBFEM} is interpolated by the user until $\rho \cdot \alpha_{ult,k}/\gamma_{M1}$ is equal to 1. A welded portal frame joint with a slender column web stiffener is studied. Same cross-section is used for the beam and the column. The thickness of the column web stiffener is changing. The geometry of the examples is described in table 1. The joint is loaded by bending moment.

Table 1. Examples overview.

	Column/beam flange		Column/beam web		Stiffener	
Example	b_f [mm]	t_f [mm]	h_w [mm]	t_w [mm]	t_s [mm]	Material
t3	400	20	600	12	3	S235
t4	400	20	600	12	4	S235
t5	400	20	600	12	5	S235
t6	400	20	600	12	6	S235

3.1 Mesh sensitivity study

There are some criteria of the mesh generation in the connection model. The connection check should be independent on the element size. Mesh generation on a separate plate is problem-free. The attention should be paid to complex geometries such as stiffened panels, T-stubs and base plates. The sensitivity analysis considering mesh discretisation should be performed for complicated geometries.

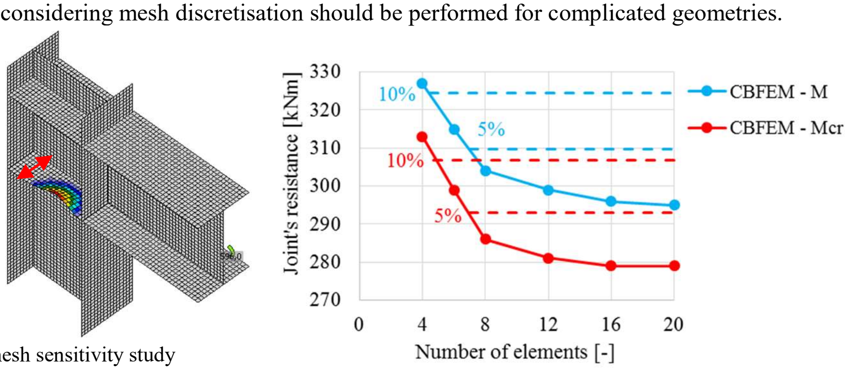

Figure 3. First buckling mode and influence of number of elements along the stiffener on the moment resistance.

Mesh sensitivity study of a slender compressed stiffener of column web panel is presented. The number of elements along the width of the stiffener is changed from 4 to 20. The first buckling mode and the influence of number of elements on the buckling resistance and critical load are shown in figure 35. The difference of 5% and 10% are displayed. It is recommended to use 8 elements along the stiffener width.

3.2 Global behaviour

The global behaviour of the welded portal frame joint with a slender column web stiffener of thickness 3 mm described by moment-rotation diagram in CBFEM model is shown in figure 4. Attention is focused to the main characteristics: design resistance and critical load. The diagram is completed with a point where yielding starts M_{yield} and resistance by 5 % plastic strain $M_{ult,k}$.

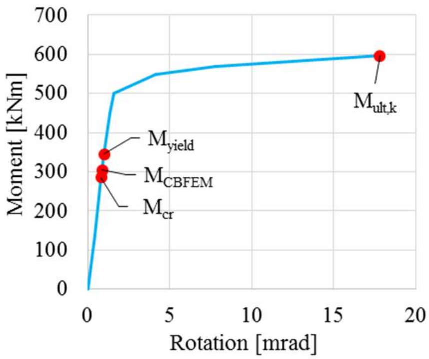

Figure 4. Moment-rotation curve of example t3.

3.3 Verification of resistance

The design resistance calculated by CBFEM Idea RS software is compared with RFEM. The comparison is focused on the design resistance and critical load. The results are ordered in table 2. The diagram in figure 5c shows the influence of the thickness of the column web stiffener on the resistances and critical loads in the examined examples. The results show very good agreement in critical load and design resistance. The CBFEM model of the joint with web stiffener thickness 3 mm is shown in figure 5a. The first buckling mode of the joint is shown in figure 5b. Verification studies confirmed the accuracy of the CBFEM model for prediction of a column web stiffener behaviour. Results of CBFEM are compared with the results of the RFEM. All procedures predict similar global behaviour of the joint. The difference in design resistance is in all cases up to 10%.

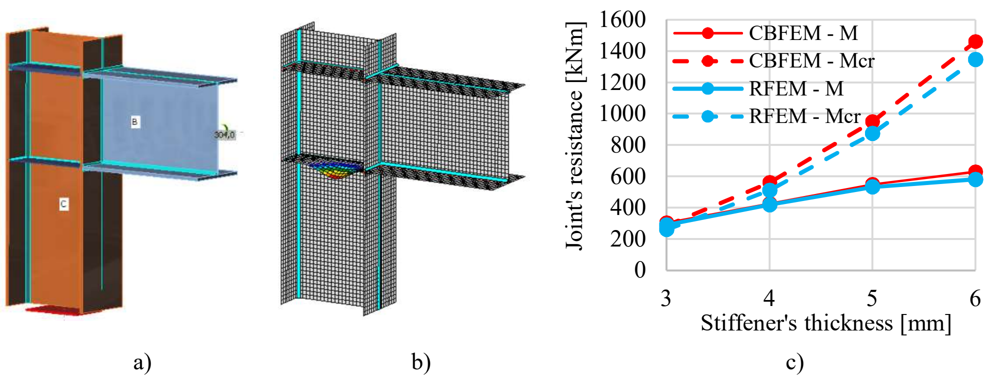

Figure 5. a) CBFEM model b) First buckling mode c) Influence of stiffener's thickness on resistances and critical loads.

Table 2. Design resistances and critical loads of RFEM and CBFEM.

	M_{cr}		α_{cr}	M_{Rd}		$\alpha_{ult,k}$	M_{CBFEM}
	RFEM	CBFEM	CBFEM	RFEM	CBFEM	CBFEM	/ M_{RFEM}
Example	[kNm]	[kNm]	[-]	[kNm]	[kNm]	[-]	[%]
t3	260	286	0.94	290	304	1.96	5
t4	511	561	1.32	419	426	1.43	2
t5	874	950	1.73	532	549	1.13	3
t6	1346	1460	2.32	580	629	1.00	8

3.4 Benchmark example

Inputs

Beam

- Steel S235
- Flange thickness $t_f = 20$ mm
- Flange width $b_f = 400$ mm
- Web thickness $t_w = 12$ mm
- Web height $h_w = 600$ mm

Column

- Steel S235
- Flange thickness $t_f = 20$ mm
- Flange width $b_f = 400$ mm
- Web thickness $t_w = 12$ mm
- Web height $h_w = 600$ mm

Upper column web stiffener

- Steel S235
- Stiffener thickness $t_w = 20$ mm
- Stiffener width $h_w = 400$ mm

Lower column web stiffener

- Steel S235
- Stiffener thickness $t_w = 3$ mm
- Stiffener width $h_w = 400$ mm

Outputs

- Load by 5% plastic strain $M_{ult,k} = 596$ kNm
- Design resistance $M_{CBFEM} = 304$ kNm
- Critical buckling factor (for $M_{CBFEM} = 304$ kNm) $\alpha_{cr} = 0.94$
- Load factor by 5 % plastic strain $\alpha_{ult,k} = M_{ult,k} / M_{CBFEM} = 596/304 = 1.96$

3.5 Limit slenderness

Although the process seems to be trivial it is general, robust and easily automated. The advantage of the procedure is the advanced FEM analysis of the whole joint, which can be applied to general geometry. Moreover it is included in valid Eurocode standards. The advanced numerical analysis gives quick overview of the global behaviour of the structure and its critical parts and allows fast stiffening to prevent instabilities.

The limit slenderness λ_p is provided in Annex B of EN 1993-1-5. The resistance is limited by buckling for plate slenderness higher than 0.7. With the decreasing slenderness is the resistance governed by plastic strain. The limit critical buckling factor for plate slenderness equal to 0.7 and buckling resistance equal to plastic resistance may be obtained as follows:

$$\alpha_{cr} = \frac{\alpha_{ult,k}}{\overline{\lambda}_p^{\,2}} = \frac{1}{0{,}7^2} = 2.04 \qquad (3)$$

It is recommended to check the buckling resistance for critical buckling resistance smaller than 3. The influence of plate slenderness on the plastic resistance $M_{ult,k}$ and buckling resistance M_{CBFEM} is shown in figure 6.

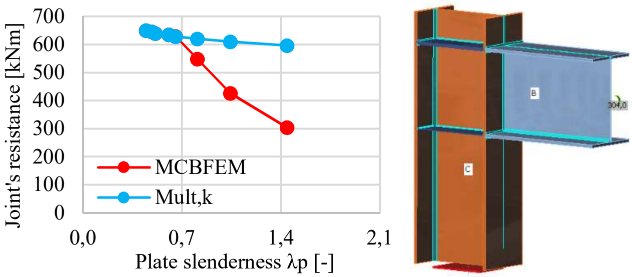

Figure 6. The influence of plate slenderness on the resistance of portal frame joint with slender stiffener

4 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.

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