NUMERICAL ANALYSIS OF INFLUENCE OF AXIAL FORCE ON RESISTANCE OF COLUMN WEBS IN TRANSVERSE COMPRESSION

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Abstract. *Steel members of double-symmetrical open cross-sections are often used in engineering structures and structures of buildings as columns and beams. Due to connections of the members, transverse compression of the cross-section webs can occur and is subject to structural assessment. The resistance of the column web is influenced by structural solution of the joint (welded, bolted, with end plates) and possible interaction with axial force in the column or shear. The paper focuses on numerical investigation and quantification of the influence of axial force in the column on behaviour and resistance of the column web in transverse compression. The analysis was performed using finite element method based computation system and included both rolled and welded cross-sections with various values of relative slenderness of the web. The results were compared with results of transverse compression resistance calculated using actual standard for design of steel structures.*

Keywords

Column web, resistance, steel, transverse compression.

1. Introduction

The application of members of double symmetrical open cross-section in steel structures is very wide. They can be used e.g. as columns and beams in buildings and engineering structures. Besides of the stress caused by global internal forces of the structure, the attention should be paid to joint components where local stress can arise due to connection to other members. One of the typical example is connection of a beam to a column using welds, bolts or end plates. As the beam can introduce transverse force to the column web, the transverse resistance of the web should be verified in the structural design of the column. This resistance is affected by number of factors, e.g. structural solution of the joint and possible interaction with axial force and shear.

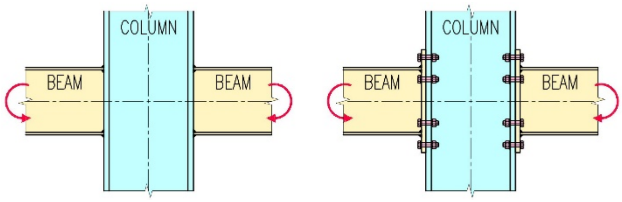

Fig. 1: Examples of typical beam-to-columns connections.

The paper focuses in detail on problem of resistance of the column web in transverse compression (taking into account stability effects) with interaction of axial compression force in the column which can practically arise there in some load cases (or combination of load cases). It is assumed that this interaction will, to a certain extent, negatively influence the resistance in transverse compression. The quantification of this effect using advanced finite element models can result in discussion of the accuracy of its consideration in the actual standard.

In the current European standard for design of joints in steel structures [1] two formulas for design resistance in transverse compression $F_{c,wc,Rd}$ are available: Eq. (1) and Eq. (2) – first one for the yielding of the web and second one for buckling of the web which is taken into account using reduction factor ρ for plate buckling.

$$F_{c,wc,Rd} = \frac{\omega \cdot k_{wc} \cdot b_{eff,c,wc} \cdot t_{wc} \cdot f_{y,wc}}{\gamma_{M0}}, \quad (1)$$

$$F_{c,wc,Rd} = \frac{\omega \cdot k_{wc} \cdot \rho \cdot b_{eff,c,wc} \cdot t_{wc} \cdot f_{y,wc}}{\gamma_{M1}}. \quad (2)$$

In these equations, $f_{y,wc}$ is the yield strength of the web, t_{wc} is thickness of the web, $b_{eff,c,wc}$ is the effective breadth over which the transverse load is distributed in the column web, k_{wc} is a factor for taking the axial force into account, ω is a factor for consideration of shear and γ_{M0} and γ_{M1} are partial safety factors for steel. The effective breadth is based on assumption of load distribution with distribution angle as displayed in Fig. 2.

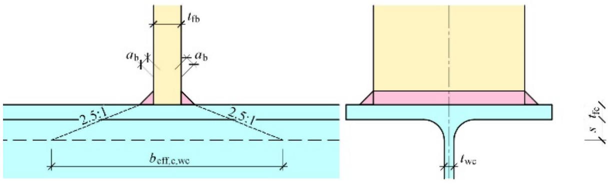

Fig. 2: Effective breadth of the web in transverse compression.

According to [2], Eq. (2) covers any possible failure modes of the web in transverse compression including buckling and crippling. These effects are taken into account using reduction factor ρ resulting from the value of relative slenderness of the web. The effect of the axial force in the column is considered using k_{wc} factor. In terms of the standard [1], the effect of the axial force is considered only in the cases where longitudinal normal stress resulting from axial force (or bending moment) $\sigma_{com,Ed}$ exceeds 70% of the web yield strength $f_{y,wc}$. In that case, Eq. (3) for k_{wc} factor applies (otherwise k_{wc} = 1.00):

$$k_{wc} = 1{,}7 - \frac{\sigma_{com,Ed}}{f_{y,wc}}. \quad (3)$$

The problem of column webs exposed to transverse compression was in the past subject of number of studies. In [3] a summarization of test results of double symmetrical steel rolled cross-sections performed in various laboratories is presented together with resistances calculated using different approaches, both empirical and analytical. Paper [4] presents results of full-scale tests of double-symmetrical columns subjected to transverse compression (with no axial load) and compares the results with resistances obtained using standards (including European standard for steel structures valid at that time). Commenting the results, it is concluded that the provisions of the standard are safe but sometimes conservative. Another comment is provided to the effective breadth where the load distribution angle is introduced to the calculation not based on theory but in such a way that it should provide safe results. Results of another full-scale tests of columns subjected to transverse compression are presented in [5]. Double symmetrical cross-sections of depths ranging from approx. 200 mm to approx. 300 mm were used. Based on comparison with results of European design standard calculation it is concluded that standard provisions are on the safe side. Tests of column webs in transverse compression presented in [6] are particularly relevant as they were performed under axial load of the columns. Significant influence of the axial load was observed. Nevertheless, only rolled cross-sections with depths of approx. 200 mm were used for the test program.

The aforementioned literature outcomes indicate relevance of the influence of axial load on the resistance of webs in transverse compression and need for further investigation.

2. Subject of the Study

For the investigation of behaviour of column webs with various values of relative slenderness (affecting the buckling behaviour) in transverse compression, series of cross-sections were selected. As it is assumed that the geometry of the flange-web transition influences the resistance of the web (by affecting the area where the applied transverse load distributes to the web), both rolled and welded cross-sections were selected for the analysis to cover both types. In case of rolled cross-sections, a series of IPE profiles were investigated. Welded cross-sections with depths of 100 and 550 mm and thickness of the web 10 mm were selected. Strength class of steel S355 were used in all cases. Dimensions of the cross-section are listed in Tab. 1 including radius r of the web-flange transition or thickness of the fillet weld a, respectively.

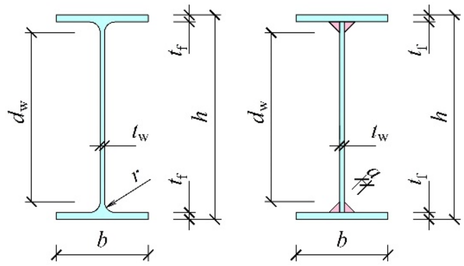

Fig. 3: Rolled and welded cross-sections.

Tab. 1: Dimensions of the cross-sections.

Cross-section	h (mm)	b (mm)	t_f (mm)	t_w (mm)	r / a (mm)
IPE 100	100	55	5.7	4.1	7.0
IPE 200	200	100	8.5	5.6	12.0
IPE 300	300	150	10.7	7.1	15.0
IPE 400	400	180	13.5	8.6	21.0
IPE 500	500	200	16.0	10.2	21.0
IPE 600	600	220	19.0	12.0	24.0
wI 100/100/10/10	100	100	10.0	10.0	3.0
wI 550/300/10/20	550	300	20.0	10.0	4.0

To investigate the effect of axial load on resistance in transverse compression, besides the transverse load axial compressive load is considered as well which results in longitudinal normal stress $\sigma_{com,Ed}$. Several levels of this normal stress related to the yield strength are considered and applied as axial loads corresponding to the respective level of the compressive longitudinal stress. The levels selected for the analysis are equal to 0% (no axial load), 10%, 30%, 50%, 70% and 90% of yield strength $f_{y,wc}$. The corresponding force was calculated using cross-section area of the considered profiles and yield strength of steel. The scheme of analysed member with loads is in Fig. 4.

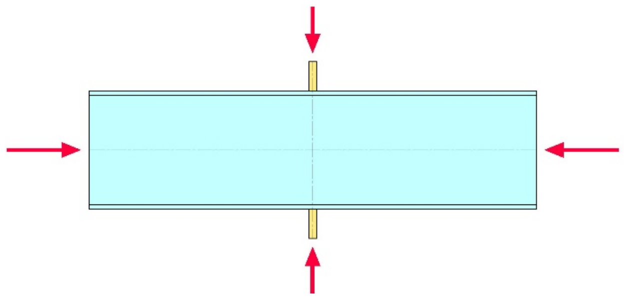

Fig. 4: Transverse and longitudinal loads.

3. Numerical Analysis

3.1. Model and Analysis Description

The investigation was performed using ANSYS 19.2 [7] system based on finite element method. The models were created using solid (volume) finite elements. The length of each column was set to four times the member depth (preliminary models confirmed that for this length the effect of overall length on results for transverse compression is insignificant which is in compliance with findings presented in [5]).

At midspan of the member short plates of thickness identical with thickness of the flange were attached to both upper and lower flanges. The lower one was used to support the member, on the upper one the load was applied.

On the plate attached to the lower flange all the faces were fully prevented from displacement. Lateral displacements were prevented at both ends of the member. To ensure support in the longitudinal direction of the member, displacement in the respective direction was prevented at faces at midspan of the member.

The finite element mesh was in all cases assigned in such a way that there were four finite elements across the thickness of flanges and web of the column. The central parts of the member on both sides from the centre (up to length equal to member depth h on both sides) were divided into 50 divisions (i.e. 50 finite elements per given length) and the end parts were divided into 10 divisions. Along the height of the web, 32 finite element divisions were defined in all cases. The finite element mesh was created using SOLID186 elements.

For the analysis, bilinear material model of steel with recommended value of modulus of elasticity $E = 210$ GPa and slight linear strain hardening from yield strength onwards was used. The numerical analysis consisted of several consecutive phases. In the frame of the first phase, materially nonlinear and geometrically linear analysis was performed (MNA analysis). The loads were applied in two load steps: axial compression load in the first step (applied on both end faces of the member) and persisting into the next step, transverse load was applied in the second load step on the upper short plate attached to the member. The resistance in transverse compression was then considered as maximum applied load or force necessary to reach 5% plastic strain. This resistance is comparable to the yielding of the web as defined using Eq. (1).

After completion of the MNA analysis, linear buckling analysis (LBA analysis) was performed to obtain buckling modes and loads at bifurcation levels in terms of theory of stability of structures. Typical buckling mode is in Fig. 5.

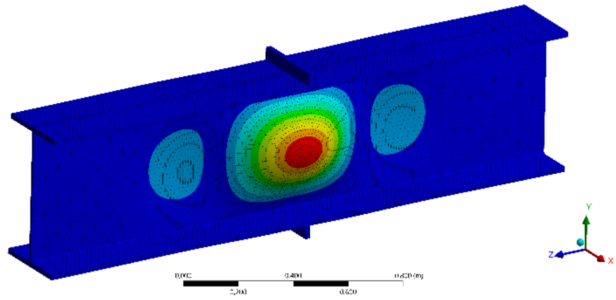

Fig. 5: Buckling mode of column web.

In the last phase of the numerical analysis, the geometrically and materially nonlinear analysis with imperfections (GMNIA analysis) was performed. Transverse load was applied on the upper plate attached to the member as specified enforced vertical displacement. The reaction force corresponding to the applied displacement was considered as the transverse load. To implement the initial imperfection, the geometry was modified by the respective buckling mode obtained from the LBA analysis. The amplitude of the initial imperfection was specified as $d_w/200$ [8] where d_w is depth of the column web excluding round corners of rolled profiles or fillet welds of welded profiles. The resistance of the web in transverse compression was determined in the same manner as in the first phase of the analysis. The results of the GMNIA analysis are to be compared with Eq. (2) which includes the effect of buckling.

3.2. Results of the Analysis

In the frame of the evaluation, variations of the plastic strain and equivalent stress were particularly observed. In Fig. 6, relationships between plastic strain and applied load from the MNA analysis for IPE 400 profile are displayed for investigated levels of axial load as an illustration of typical curves obtained from the analysis. The respective results of the GMNIA analysis are in Fig. 7.

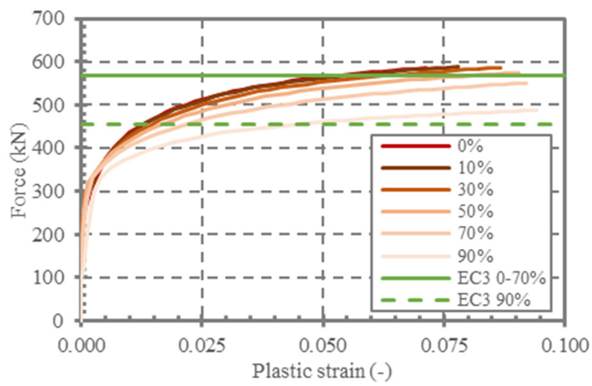

Fig. 6: Relationship between plastic strain and applied load (MNA).

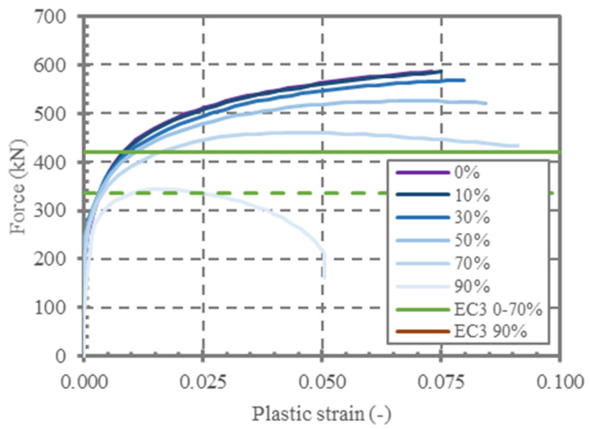

Fig. 7: Relationship between plastic strain and applied load (GMNIA).

Resistances in transverse compression in both MNA and GMNIA analysis were determined using the aforementioned procedure. In Fig. 8 and Fig. 9, typical variations of equivalent stress caused by axial force at levels of 10% and 90% of web yield strength are displayed. Equivalent plastic strains for these levels are in Fig. 10 and Fig. 11 for one of the investigated cross-sections. All these variations are results of the GMNIA analysis. They are related to the magnitude of load corresponding to the resistance of the member in transverse compression.

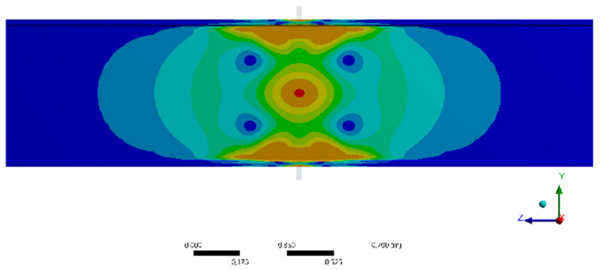

Fig. 8: Equivalent stress – level of 10% of yield strength.

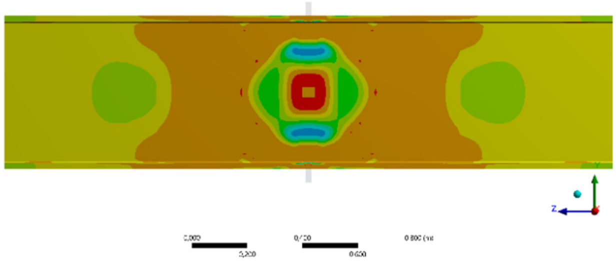

Fig. 9: Equivalent stress – level of 90% of yield strength.

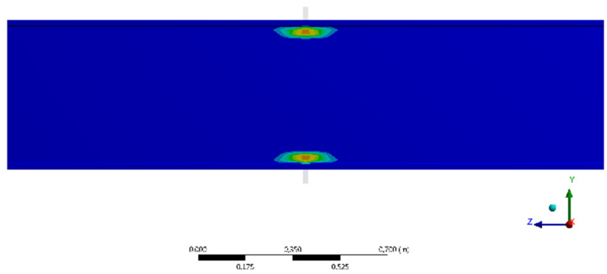

Fig. 10: Equivalent plastic strain – level of 10% of yield strength.

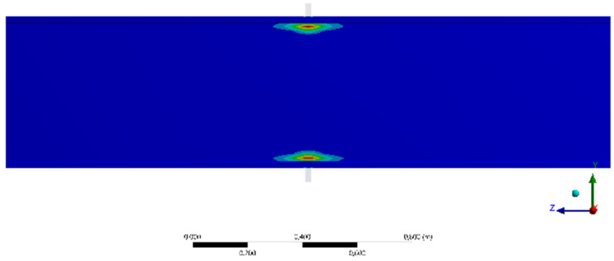

Fig. 11: Equivalent plastic strain – level of 90% of yield strength.

4. Evaluation and Comparison with Results Obtained Using Standard for Design of Steel Structures

Essential results of the numerical analysis (resistances obtained from MNA and GMNIA analysis) together with results of standard calculations (design resistances in terms of [1]) are listed in Tab. 2 for welded cross-sections and Tab. 3 for rolled cross-sections. The resistances are related to considered levels of longitudinal normal stress. In terms of the standard [1], the level of this stress is taken into account using k_{wc} factor as Eq. (3). For the investigated cases, this factor is non-unit in case of 90% of yield strength with value of 0.80, otherwise its value is 1.00 (no influence of axial load on resistance in transverse compression).

Tab. 2: List of results – welded cross-sections.

Cross-section	$\sigma_{com,Ed} / f_{y,wc}$	k_{wc}	EN 1993-1-8 yielding	EN 1993-1-8 buckling	Numerical analysis MNA	Numerical analysis GMNIA
			$F_{c,wc,Rd}$	$F_{c,wc,Rd}$	$F_{MNA,Rd}$	$F_{GMNIA,Rd}$
		(-)	(kN)	(kN)	(kN)	(kN)
wI 100/100/10/10	0.00	1.00	288	288	278	281
	0.10	1.00	288	288	281	282
	0.30	1.00	288	288	284	284
	0.50	1.00	288	288	279	278
	0.70	1.00	288	288	267	266
	0.90	0.80	231	231	236	225
wI 550/300/10/20	0.00	1.00	526	408	902	900
	0.10	1.00	526	408	898	886
	0.30	1.00	526	408	881	844
	0.50	1.00	526	408	855	779
	0.70	1.00	526	408	810	671
	0.90	0.80	421	327	724	452

Tab. 3: List of results – rolled cross-sections.

The comparison of the results with standard provisions is performed using ratios between yielding (or buckling) resistances in terms of the standard [1] and resistances obtained using numerical finite element analysis (MNA or GMNIA). The outcomes are in Fig. 12 – ratio between yielding resistance $F_{c,wc,Rd}$ (yielding) calculated using Eq. (1) and corresponding resistance obtained from the MNA analysis – and in Fig. 13 – buckling resistance $F_{c,wc,Rd}$ (buckling) calculated using Eq. (2) and resistance obtained from the GMNIA analysis.

Cross-section	$\sigma_{com,Ed} / f_{y,wc}$	k_{wc}	EN 1993-1-8		Numerical analysis	
			yielding	buckling	MNA	GMNIA
			$F_{c,wc,Rd}$	$F_{c,wc,Rd}$	$F_{MNA,Rd}$	$F_{GMNIA,Rd}$
		(-)	(kN)	(kN)	(kN)	(kN)
IPE 100	0.00	1.00	101	101	91	92
	0.10	1.00	101	101	90	91
	0.30	1.00	101	101	89	89
	0.50	1.00	101	101	87	86
	0.70	1.00	101	101	82	81
	0.90	0.80	81	81	72	69
IPE 200	0.00	1.00	221	189	209	210
	0.10	1.00	221	189	208	209
	0.30	1.00	221	189	205	204
	0.50	1.00	221	189	199	197
	0.70	1.00	221	189	189	183
	0.90	0.80	177	152	168	145
IPE 300	0.00	1.00	351	280	350	350
	0.10	1.00	351	280	349	348
	0.30	1.00	351	280	344	341
	0.50	1.00	351	280	334	329
	0.70	1.00	351	280	317	300
	0.90	0.80	282	225	285	200
IPE 400	0.00	1.00	568	421	564	563
	0.10	1.00	568	421	561	560
	0.30	1.00	568	421	553	547
	0.50	1.00	568	421	539	519
	0.70	1.00	568	421	512	460
	0.90	0.80	455	337	460	344
IPE 500	0.00	1.00	728	542	745	741
	0.10	1.00	728	542	742	735
	0.30	1.00	728	542	731	719
	0.50	1.00	728	542	711	690
	0.70	1.00	728	542	676	600
	0.90	0.80	585	436	611	423
IPE 600	0.00	1.00	997	738	1018	1014
	0.10	1.00	997	738	1015	1006
	0.30	1.00	997	738	1001	985
	0.50	1.00	997	738	974	944
	0.70	1.00	997	738	927	801
	0.90	0.80	801	593	842	565

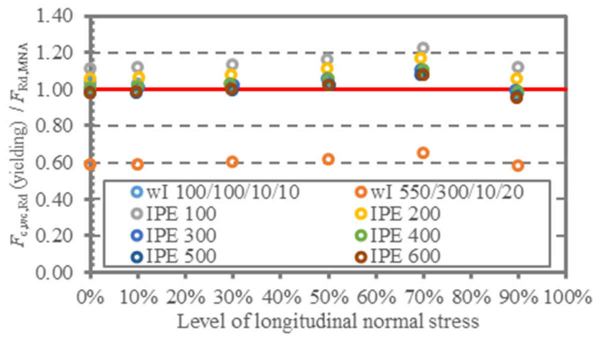

Fig. 12: Ratio between yielding resistance and resistance from MNA.

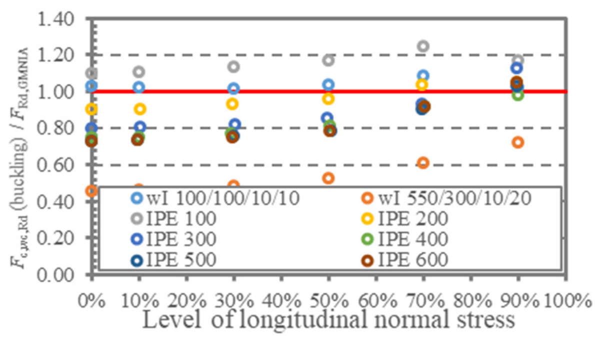

Fig. 13: Ratio between buckling resistance and resistance from GMNIA.

Particular attention was paid to quantify the influence of the axial load on resistance in transverse compression at various levels of the longitudinal compression stress and comparison of the results with standard provisions where this influence is considered using k_{wc} factor. To evaluate the results, the resistances at certain longitudinal stress levels were related to the resistances at zero level of longitudinal normal stress which resulted in a series of ratios. This procedure was applied both on results based on standard provisions, i.e. Eq. (1) for yielding and Eq. (2) for buckling and on results of MNA and GMNIA analysis. As the ratio between the resistance at certain axial load and zero axial load is comparable with the k_{wc} factor which takes into account possible reduction of the resistance due to the axial load, these ratios together with the variation of the k_{wc} reduction factor depending on the level of axial load are plotted in one chart for comparison. The results are separately plotted for MNA and GMNIA analysis in Fig. 14 and Fig. 15.

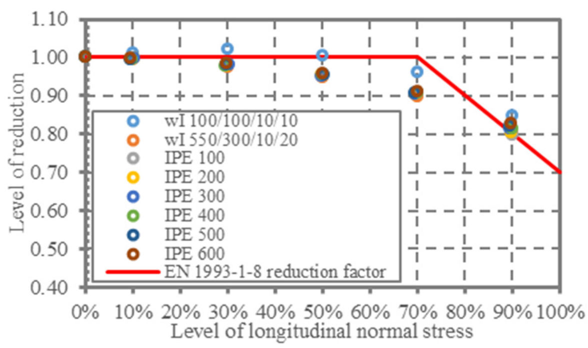

Fig. 14: Reduction due to axial load (Eurocode and MNA analysis).

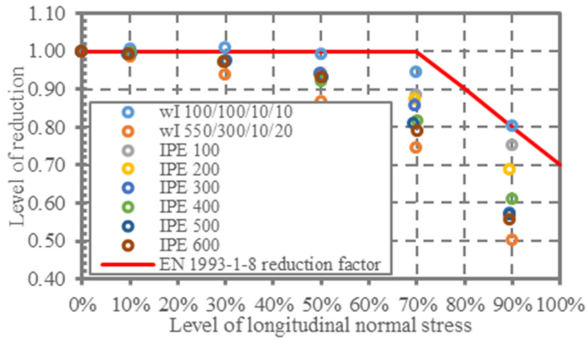

Fig. 15: Reduction due to axial load (Eurocode and GMNIA analysis).

Based on results in Fig. 12 and Fig. 13, it can be stated that the standard gives in some cases unsafe results related to the results of the numerical analysis. Relatively great difference for one of the welded columns can be explained by the fact that for this cross-section, small fillet-welds (in comparison with the rounding area of usual rolled profiles) were used which affected the effective breadth in terms of the design code and hence the resistance. Nevertheless, the resistance according to the standard is on the safe side. Besides aforementioned findings, in the frame of evaluation of results of the numerical analyses it was found out that the limit value of 5% plastic strain was in all investigated cases first reached in the region of the web-flange transition (under the attached plates for load application). It applies to the GMNIA too, where initial imperfection with amplitude at the middle of depth was implemented. The fact that the most crucial point is located at this web-flange transition can be explained by relatively small load distribution area of the transversal force (located at the flange) at the web-flange transition while in the middle of the web depth the transverse load distributes to much larger area. Another reason is the consequence of boundary conditions of the web which can be considered as, to a certain extent, fixed to the flanges which results in additional stress due to end moments on the web caused by the imperfection at the centre of the web.

Within preliminary studies, the influence of the imperfection amplitude on the resistance in transverse compression was investigated. It was found, as mentioned above, that the decisive point for determination of the resistance was in the web-flange transition and the influence of the imperfection amplitude was insignificant. It should also be noted that the loads applied within the numerical analysis should be, according to [8], amplified by the α_u factor that covers finite element model uncertainties and scatter of the load and resistance models. It can result in lower resistances obtained from the numerical analysis. Nevertheless, the resistances obtained from standard calculations would in some cases still be on the non-conservative side.

5. Conclusion

The analysis of columns of selected rolled and welded cross-sections subjected to transverse compression and axial load provided number of findings. It confirmed significant influence of the axial load on resistance of column webs in transverse compression. Although the European standard considers the reduction due to the axial load only in cases when the longitudinal normal stress exceeds 70% of web yield strength, based on the results of the analysis this unfavourable influence is also relevant for lower levels of the longitudinal stress. This is especially notable from the results of the GMNIA analysis. The numerically determined resistances in some cases deviate from the resistances in terms of the design code by tens of percent on the unsafe side. It might indicate considerable inaccuracy of the reduction factor in the standard.

Acknowledgements

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