Lateral-torsional buckling resistance of cold-formed high strength steel rectangular hollow beams

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ABSTRACT: Hollow sections have been widely used for steel structures. Applications of High Strength Steel (HSS) on cold-formed hollow sections lead to thinner and lighter structures. This paper presents numerical investigations on the lateral-torsional buckling resistance of the cold-formed high strength steel rectangular hollow beam. Results from finite element analysis using Abaqus software are compared to calculations according to Eurocode 3. First, buckling analyses are carried out to investigate buckling behaviors of the rectangular hollow beams. In this step, elastic critical moments have been investigated and compared to calculations according to SN003. Buckling shapes have been also obtained in this step. Secondly, nonlinear analyses using Riks method have been performed. Buckling resistances of the beams with various thicknesses, various high strength materials S460, S650 and S960 have been compared to calculations according to EC 3. Further investigations on geometric imperfection sensitive have been carried out with different amplitudes $L/1000$, $L/750$, $L/500$ and $L/250$.

1 INTRODUCTION

Resistance of beams under bending is governed by Lateral Torsional Buckling (LTB). Some studies on LTB have been presented in [1–3]. Meftah et al. have published a study on lateral buckling of box beam under combined axial and bending loads in [1]. In this paper, authors have used Ritz and Galerkin's methods to develop an analytical model. Results have been compared to calculations according to Eurocode 3. D. Sonck and J. Belis have presented investigation on lateral torsional buckling resistance of cellular beams under constant bending moment in [2]. Using finite element analysis and Eurocode 3 (EC 3) approach, authors have proposed a design approach for LTB. New design curves for lateral torsional buckling have been investigated by A. Taras et al. [3]. The authors have proposed a new formulaic description of the buckling resistance.

High Strength Steel (HSS) have been widely studying and applying on steel structures because of its advanced characteristics [4–5]. Particularly, application of HSS on cold-formed hollow sections leads to thinner and lighter structures. To supplement and get better understand of lateral torsional buckling of cold formed high strength steel hollow beam, a numerical investigation using finite element analysis program Abaqus [6] has been performed. Firstly, buckling analysis has been carried out. Elastic critical moments have been investigated and compared to calculations according to

EC 3. Buckling shapes have been also obtained in this step. Secondly, nonlinear analyses using Riks method have been performed. Buckling resistances of the beams with various thicknesses, various high strength materials S460, S650 and S960 have been compared to calculations according to EC 3. Further investigations on geometric imperfection sensitive have been carried out with different amplitudes $L/1000$, $L/750$, $L/500$ and $L/250$.

2 FINITE ELEMENT MODELS

2.1 Geometry of models

Rectangular hollow beams with end moments have been considered. Length (L) of the beam is 6000 mm. Dimensions at center of the beam cross section is presented in Fig. 1. The height and width of cross section are 300 mm and 100 mm respectively. Radii at the corner is 25 mm. Various thicknesses (t) 6 mm, 8 mm, 10 mm, 12 mm, 14 mm have been taken into this study. Various lengths of beam have been used to construct a buckling curve of the rectangular hollow section.

2.2 Analysis method

In this study, buckle analysis and Geometrically and Materially Nonlinear Analysis with imperfection models (GMNIA) have been considered. Buckle analysis have been initially performed in order to get buckling shape and elastic critical

Figure 1. Geometry of beam.

moment for lateral-torsional buckling. Then, nonlinear analysis using Riks method has been carried out. The riks method has been mentioned in [7–9].

2.3 Finite element type and mesh

Commercial finite element analysis program Abaqus [6] has been used for the buckle analysis and the nonlinear analysis in this study. In Abaqus, there are various 3D-dimentional solid elements such as C3D4 (4-node linear tetrahedron), C3D8 (8-node linear brick), C3D8R (8-node linear brick, reduced integration with hourglass control), C3D10M (10-node modified tetrahedron, with hourglass control). In this study, 3D-dimentional solid elements C3D8R have been used. Figure 2 presents typical FE mesh of the models.

2.4 High strength steel materials

With development of steel production and processing technology, High Strength Steel material (HSS) have been studying and widely applying on steel structures. Particularly, applications of high strength steel on cold-formed hollow sections lead to thinner and lighter structures. Steel grades up to S460 have been using in Eurocode 3, part 1-1 to part 1-11. Eurocode 3 part 1-12 recommend rules for steel material up to S700. In this study, high strength steel materials S460, S650 and S960 have been considered in order to investigate influences of HSS on buckling behavior of beams. The materials have been referred in [13–14] and material data at Luleå University of Technology. The Young's modulus $E = 210000$ (N/mm²), the shear modulus $G = 81000$ (N/mm²) and the Poisson's ratio $\nu = 0.3$ have been used for calculations. In abaqus, the true stress and true plastic strain are used as material characteristic. Relation between true stress and true plastics strain is defined in [6] as follows:

$$\sigma_{true} = \sigma_{nom}(1 + \epsilon_{nom}) \quad (1)$$

$$\epsilon_{true} = \ln(1 + \epsilon_{nom}) - \frac{\sigma_{true}}{E} \quad (2)$$

where σ_{nom} is engineering stress, ϵ_{nom} is engineering strain, σ_{true} is true stress, ϵ_{true} is true plastic

Figure 2. Mesh of numerical model.

Figure 3. True stress and true plastic strain curves of the materials.

strain. Figure 3 shows true stress and true plastic strain curves of high strength materials S460, S650 and S960.

3 BUCKLING ANALYSIS

Buckling analysis is the first step of the analysis sequence. The buckling analysis is performed in order to obtain buckling shape and elastic critical moment. Figure 4 presents typical buckling shape of the numerical models. According to SN003 [10], elastic critical moment of doubly symmetric sections can calculate as follows:

$$M_{cr} = C_1 \frac{\pi^2 EI_z}{L^2} \left\{ \sqrt{\frac{I_w}{I_z} + \frac{L^2 GI_t}{\pi^2 EI_z} + (C_2 z_g)^2} - C_2 z_g \right\} \quad (3)$$

where I_z is the second moment of area about the weak axis, I_t is the torsion constant, I_w is warping constant, L is the beam length between points which have lateral restraint, z_g is the distance between the point of load application and shear center. This equation was used for calculation of elastic critical moments of box beams in [1].

Figure 4. Typical buckling shape of numerical models.

Table 1. Elastic critical moments according to FEA and EC3.

Specimen	Thickness mm	Elastic critical moment M_{cr} (kNm)		
		FEA	SN003	FEA/SN003
HRC-6	6	1330	1083	1.2
HRC-8	8	1934	1446	1.3
HRC-10	10	2640	1811	1.5
HRC-12	12	3395	2179	1.6
HRC-14	14	4173	2549	1.6

Table 1 presents comparison of the elastic critical moments between Finite Element Analysis (FEA) and SN003. The FEA results are higher than those according to SN003. Elastic critical loads from FEA of the 6 mm and 14 mm thick specimens are 20% and 60% higher than those from SN003, respectively.

4 PARAMETRIC ANALYSIS

4.1 Buckling resistance analysis

According to EN1993-1-1 [11], buckling resistance moment is recommended as follows:

$$M_{b,Rd} = \chi_{LT} W_y \frac{f_y}{\gamma_{M1}} \quad (4)$$

where W_y is the approximate section modulus as follows:

$$\begin{aligned} W_y &= W_{pl,y} && \text{for Class 1 or 2 cross sections} \\ W_y &= W_{el,y} && \text{for Class 3 cross sections} \\ W_y &= W_{eff,y} && \text{for Class 4 cross sections} \end{aligned}$$

χ_{LT} is the reduction factor for lateral-torsional buckling.

According to EN 1993-1-3 [12], influence of cold forming are calculated as increasing average yield strength f_{ya} in following equation:

$$f_{ya} = f_{yb} + (f_u - f_{yb}) \frac{knt^2}{A_g} \text{ but } f_{ya} \leq \frac{(f_u + f_{yb})}{2} \quad (5)$$

Where f_{yb} is the basic yield strength, f_u is tensile strength, A_g is the gross cross sectional area, k is a numerical coefficient, n is the number of 90° bends, t is the thickness.

Table 2 presents resistances moments of specimens with different thicknesses and materials. Comparison between buckling resistance moments according to FEA and EC3 are also presented in this table. Resistance moments according to EC3 equal approximately 75% those according to FEA. Failure mode of 8 mm thick numerical models is illustrated in Figure 5.

Figure 6 presents resistance moment—rotation curves with various thicknesses 6 mm, 8 mm, 10 mm, 12 mm and 14 mm. Thickness significantly affects resistance moments of the beams. Resistance moment of the beam with 6 mm thickness equals 413 kNm and reaches 995 kNm with 14 mm thickness (241%). Resistance moments of the beam with 8 mm, 10 mm and 12 mm are

Table 2. Buckling resistances according to FEA and EC3.

Specimen	Material	Thickness (mm)	Buckling resistance $M_{b,Rd}$ (kNm)		
			EC3	FEA	EC3/FEA
HRC-6	S460	6	183	233	0.8
	S650	6	237	316	0.8
HRC-8	S460	8	246	327	0.8
	S650	8	317	428	0.7
HRC-10	S460	10	311	396	0.8
	S650	10	397	532	0.7
HRC-14	S460	14	444	580	0.8
	S650	14	558	755	0.7

Figure 5. Failure mode of 8 mm thick numerical model.

Figure 6. Influence of various thicknesses on resistance moment.

Figure 7. Influence of high strength steel on resistance moments of 12 mm thick numerical model.

562 kNm, 700 kNm and 847 kNm respectively. It must be emphasized that the material used is the high strength material S960.

4.2 Using high strength steel

Figure 7 illustrates resistance moment-rotation curves of the beam with 12 mm thick cross section with various high strength materials S460, S650 and S960. Using high strength steel considerably increase resistance moments of the beams. The resistance moment of the beam with the material S460 reaches 486 kNm. It increases 75% in using the high strength steel S960.

Applications of high strength steel on cold-formed hollow sections lead to thinner and lighter structures. Resistance moment of the beam with thickness 12 mm using material S460 is 486 kNm. While resistance moment of the beam with thickness 8 mm using material S960 is 564 kNm. The thickness decreases approximately 33%.

Table 3. Resistance moments with various geometric imperfection amplitudes.

Specimen	Thickness (mm)	Buckling resistance $M_{b,Rd}$ (kNm)			
		L/1000	L/750	L/500	L/250
HRC-6	6	415	413	410	402
HRC-8	8	564	562	559	554
HRC-10	10	703	700	695	685
HRC-12	12	851	847	841	830
HRC-14	14	1000	995	989	975

4.3 Geometric imperfection sensitive analysis

In order to investigate influence of geometric imperfection on resistance moment, amplitudes of geometric imperfections L/1000, L/750, L/500 and L/250 have been considered. Buckling resistance of specimens with geometric imperfection amplitudes L/1000 are higher approximately 3% than those with geometric imperfection L/250.

5 CONCLUSION

In this paper, numerical investigations of lateral torsional buckling resistance of cold formed high strength steel rectangular hollow beams are presented. Buckling behaviors of the beams under constant bending moments were analyzed. Results from the analyses showed that resistance moments of the beams according to EC 3 are approximately 70% of those using FEA. Using high strength steel significantly reduces thickness of beams (approximately 33%). Using high strength steel S960 considerably increases resistance moment 75% in comparison with using the steel material S460. The resistance moments were also affected by geometric imperfection amplitudes. Resistance moments of specimens with geometric imperfection amplitudes L/1000 are higher approximately 3% than those with geometric imperfection L/250.

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