Reliability of engineering methods of assessment the critical buckling load of steel beams

Katarzyna Rzeszut[1], Wiktor Folta[1], Andrzej Garstecki[2]

[1]*Faculty of Civil and Environmental Engineering, Poznan University of Technology, Piotrowo 5, 60-965 Poznań, Poland*
e-mail:katarzyna.rzeszut@put.poznan.pl

[2]*Stanisław Staszic University of Applied Sciences in Piła 64-920 Piła, ul. Podchorążych 10, e-mail:Andrzej.garsteckit@put.poznan.pl*

Abstract

In this paper the reliability assessment of buckling resistance of steel beam is presented. A number of parameters such as: the boundary conditions, the section height to width ratio, the thickness and the span are considered. The examples are solved using FEM procedures and formulas proposed in the literature and norms. In the case of the numerical models the following parameters are investigated: support conditions, mesh size, load conditions, steel grade. The numerical results are compared with approximate solutions calculated according to the standard formulas. It was observed that for high slenderness section the deformation of the cross-section had to be described by the following modes: longitudinal and transverse displacement, warping, rotation and distortion of the cross section shape. In this case we face interactive buckling problem. Unfortunately, neither the EN Standard nor the subject literature gives exact formulas to solve these problems. For this reason the reliability of the critical bending moment calculations is discussed.

Keywords: lateral torsional buckling, reliability, steel beam, critical bending moment

1. Introduction

The fact that steel structures are apt to fail by loss of stability belongs to the textbook's knowledge for decades. This tendency towards instability is a direct consequence of high slenderness of steel structural elements. Designers can find practical recommendations in design codes with theoretical and experimental background in the literature [4] how to overcome the problems of instability. Professional computer programs supporting design of steel structures implement many of these recommendations. However, modern light-weight steel structures gave rise to new stability problems [3]. Application of thin-walled cold formed sections and welded I sections with slender webs increased the importance of local instability phenomena which often appeared at a similar load level as global instability. The case when two or more different modes in stability and dynamic analyses are associated with the same or similar eigenvalues is termed a bimodal or multimodal solution. Designers' concern is that these solutions are very sensitive to imperfections [1]. Design codes contain recommendations with respect to global, local and distortional buckling, which can be taken into account separately. There is definitely not so much information about interactive buckling. Therefore the question of the reliability assessment of buckling resistance of steel beams is still unresolved issue.

2. Problem formulation

The primary objective of this work was to analyse the reliability of the critical bending moments for simply supported steel beams based on Vlasov beam theory using analytical procedures specified in the norms and Finite Element Method solving eigenvalue problem by application of a beam element with 7 degrees of freedom and shell elements.

The general theory of stability of a thin-walled bar with open cross-section was formulated by W. Z. Vlasov [2] basing on the following assumptions: a non-deformable contour, plane stress state, external load passes through the shear center of the bar. Using the equilibrium conditions describing the behavior of the bar, which switches from flexural to flexural-torsional equilibrium state, Vlasov derived the set of three differential equations of fourth order describing the global stability problem of thin walled beams.

Design of steel beams is highlighted by code EN-3. The first step in the procedure recommended in this code is assessment of critical buckling load. The code provides closed form formulas for critical buckling moment in several cases most often met in practice. The formulas stem from Vlasov theory. They are also implemented in common computer programs supporting the design. However, practical design engineers often meet problems beyond the set of cases specified in the code. Designers are not sure whether the critical bending moment incorporated in design procedure in EC-3, can be assessed using advanced FEM programs, when shell or solid elements are implemented. Stability analysis using these types of elements is not limited by Vlasov assumptions, hence different results can be expected. Erroneous values of critical buckling loads may result in unsafe or too conservative designs.

3. Numerical examples

The analyses included two different types of cross-sections namely IPE 300 and thin-walled Σ300x2 profile, various beam spans (3m, 6m, 12m) and load cases. There were considered uniformly distributed load, concentrated force in the middle of the beam span and bending moments imposed at the ends of the beam. Theoretical boundary conditions (so-called fork support) and solutions of simply supported beam, commonly used in engineering practice were taken into account (Fig. 1). Moreover the discussion of the problems concerning the numerical modeling of such boundary conditions was performed. In order to verify the reliability of the procedures available to computation the critical bending moment based on beam and shell theory was used. In first part of the study the critical bending moment was calculated using analytical procedures based on Vlasov beam theory included in the App. 1 to Polish Standard PN 90/B 03200 ($M_{cr,ref}$) and supplementary information to the Eurocodes - SN003a-EN-EU ($M_{cr,1}$). The results of this analysis will be used as the reference values. In

Financial support by the grant 01/11/DSPB/0805 is kindly acknowledged*

the second part, the critical bending moment was calculated using FEM solving eigenvalue problem by application of a beam element with 7 dof. in LTBeam program ($M_{cr,2}$) and shell elements S4R in Abaqus program ($M_{cr,3}$). It is worth to mention that beam element with 7 dof. so-called Vlasov beam element allows consideration of warping, while shell element deformation of the contour and thus local buckling. In case of shell model the mesh sensitivity was carried out. It proved that the model is sensitive to the adopted size of finite element. It follows that recommended size was approx. 1 cm (Fig. 2).

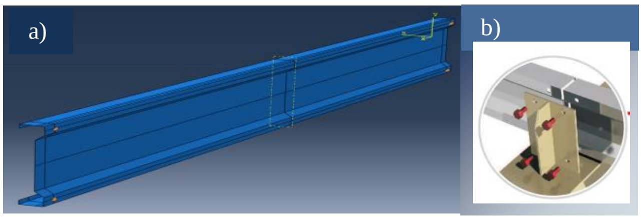

Figure 1: FEM model of Σ300x2 profile a) overall view of shell model, b) engineering solution of simply support conditions

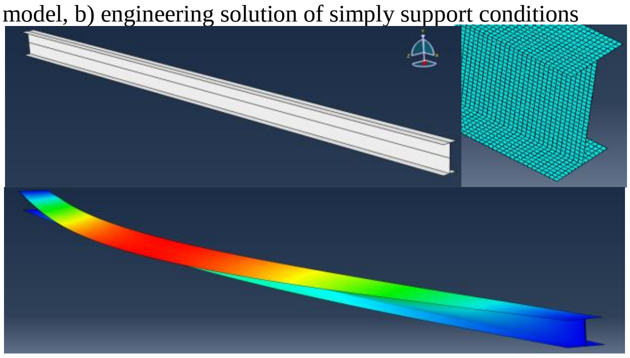

Figure 2: FEM model of IPE 300 a) overall view, b) shell element grid size, c) lateral torsional buckling mode

4. Results of calculations

In this paper, a number of comparative studies have been done, among which only four examples of critical bending moment calculation are presented in Figure 3 and 4.

Profile/ span	Static scheme	Load level	SN003a EN-EU $M_{cr,1}/M_{cr,ref}$	LT Beam $M_{cr,2}/M_{cr,ref}$	Abaqus (Shell) $M_{cr,3}/M_{cr,ref}$
IPE 300 6 m			99.47%	99.62%	96.66%
			98.86%	99.22%	-
			98.26%	98.74%	94.66%
			94.42%	98.57%	95.09%
			98.39%	99.35%	-
			102.54%	99.53%	95.74%
			100.00%	100.00%	96.82%
IPE 300 12 m			99.22%	99.63%	90.98%
			98.86%	99.09%	-
			98.49%	98.74%	91.26%
			96.02%	98.13%	89.24%
			98.41%	99.00%	-
			100.83%	99.47%	92.22%
			100.00%	100.00%	92.30%

Figure 3: $M_{cr,i}/M_{cr,ref}$ values for I cross-section and different calculational methods

Profile/ span	Static scheme	Load level	SN003a EN-EU $M_{cr,1}/M_{cr,ref}$	LT Beam $M_{cr,2}/M_{cr,ref}$	Abaqus (Shell) $M_{cr,3}/M_{cr,ref}$
∑ 300 3m			99.77%	99.83%	91.80%
			98.81%	99.27%	-
			97.94%	98.68%	92.09%
			92.63%	99.19%	92.91%
			98.40%	99.56%	-
			104.55%	99.46%	88.96%
			100.00%	100.00%	98.01%
∑ 300 6m			99.71%	99.78%	97.84%
			98.86%	99.31%	-
			98.00%	98.70%	96.31%
			98.39%	99.55%	-
			104.19%	99.46%	96.22%
			100.00%	100.00%	99.10%

Figure 4: $M_{cr,i}/M_{cr,ref}$ values for Σ cross-section and different calculational methods

The results of calculations obtained by analytical methods contained in standards and from the LTBeam program can be considered in most cases to be the equivalent. Whereas the results got using the shell model allow for a more advanced buckling analysis and enables the resignation of the classic Vlasov theory assumptions. Moreover it allows the contour deformation an global/local interactive buckling analysis as well. A very important observation is that using the shell model always lower values of critical bending moment are obtained. This proves that it is more secure estimation than based on the beam model. One can notice that in the case of stocky elements this difference grows with increasing span of beams, while for cross-section class 4 difference it is greater for shorter span of beams.

5. Concluding remarks

Expected and yet interesting was the observation that the FEM analyses with Vlasov beam elements using different computer programs provided the critical buckling moment in excellent agreement with the closed-form formulas given in EC - 3. Application of shell elements to beams with I and ∑ sections provided slightly lower critical buckling moments. It would result in slightly conservative design of beams.

References

[1] Garstecki A., Rzeszut K., Modeling of initial geometrical imperfections in stability analysis of thin-walled structures, Journal of Theoretical and Applied Mechanics, 2009, Vol. 47 (3), pp. 667–684.

[2] Vlasov V.Z., Thin-walled elastic rods (in Russian), Moscow, Izd. Akad. Nauk SSSR, 1963.

[3] Szymczak C., Sensitivity analysis of thin-walled members, problems and applications, Thin-Walled Structures, 2003, Vol. 41, pp. 271–290.

[4] Waszczyszyn Z., Cichoń C., Radwańska M., Stability of Structures by Finite Element Methods, Amsterdam, Elsevier, 1994.