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Flange buckling behavior of girders with corrugated web Part II: Numerical study and design method development

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ABSTRACT

Girders with trapezoidally corrugated web are widely used structural elements in the civil engineering praxis due to their numerous advantages. Despite, there are a relatively small number of previous investigations focusing on the determination of the bending moment resistance and the flange buckling behavior. Previous experimental and numerical investigations confirmed that the flange buckling resistance model provided by the EN1993-1-5 predicts often unsafe resistances. The summary of the previous investigations on the flange buckling behavior is presented in the companion paper (Part I) Jáger et al. [1] coupled with the introduction of an executed experimental research program investigating the flange buckling resistance of girders with corrugated web. Based on the test results an advanced FE model is developed, validated and presented in the current paper. In the first part of the study an imperfection sensitivity analysis is performed to develop proposals for applicable equivalent geometric imperfections for FEM based design method. In the second part of this paper an intensive parametric study is performed to investigate the buckling coefficient and the relationship between the relative slenderness and the reduction factor for corrugated web girders. The current paper also focuses on a new design method development for the determination of the flange buckling resistance.

1. Introduction

The flange buckling resistance of trapezoidally corrugated web girders has been investigated in the last two decades. All of the available previous research activities are collected and discussed in the companion paper Jáger et al. [1] in a detailed manner covering the results of the previously and currently performed experimental and numerical research programs. In the international literature a total number of 22 laboratory test results could be found. In the frame of the current research program further 16 laboratory tests are performed at the Budapest University of Technology and Economics, Department of Structural Engineering investigating the flange buckling behavior of trapezoidally corrugated web girders. In the international literature there are some proposals available for flat web I-girders and for unstiffened plated elements which are also discussed and their applicability for corrugated web girders are studied. Several papers deal with the determination of the elastic buckling coefficient of flat web girders by considering the flange-to-web thickness ratio [2,3] what is usually neglected in the design codes and specifications such as in the EN1993-1-5 [4]. For trapezoidally corrugated web girders the existing proposals [4–7] give different upper limits for the theoretically [8] calculated buckling coefficient with considering the buckled shape of the subpanel of the compression flange bounded by the inclined folds of the web. For the relative slenderness and reduction factor determination of the outstand plated elements the EN1993-1-5 [4] recommends to use the same Winter-curve based formula for trapezoidally corrugated web girders as for flat web girders. Furthermore, additional formulas called reduced stress based effective equations were developed for unstiffened outstand plated elements by Bambach and Rasmussen [9] in 2004 considering the stress gradient in the flange. For trapezoidal web girders Koichi and Masahiro [7] proposed similar equation for the effective width determination in 2006. These aforementioned formulas are collected in Section 2 and evaluated based on the numerical parametric study.

To investigate the flange buckling resistance an advanced numerical model is developed and validated based on the current experimental investigations presented in the companion paper (Part I). Based on previous and current test results the magnitude of the equivalent geometric imperfection using the first eigenmode shape is calibrated to give applicable proposals promoting FEM based design method for corrugated web girders. The EN1993-1-5 [4] prescribes a rotational imperfection magnitude equal to 1/50 for flange twisting. With the help of the calibrated imperfection magnitude the applicability of the FEM based design method is presented. On the validated numerical model

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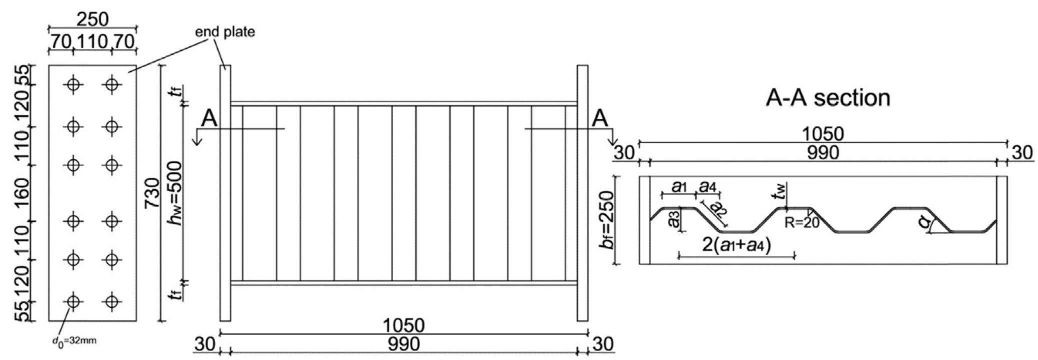

Fig. 1. Used notations for girders with corrugated webs.

parametric study is performed to determine the buckling coefficient (k_σ) of the outstand part of the compression flange. The relationship between the relative slenderness ratio and the reduction factor for outstand compression element is also investigated by geometrical and material nonlinear imperfect analysis (GMNIA). Based on the numerical results design equation is proposed for the determination of the buckling coefficient (k_σ) and the buckling curve for flange buckling of trapezoidally corrugated web girders. The layout of the tested girders, the applied dimensions and notations used in the current paper are shown in Fig. 1.

2. Literature overview

2.1. Determination of the buckling coefficient (k_σ)

It is commonly accepted by researchers [4,6–8,10], that for trapezoidally corrugated web girders the theoretically derived equation shown by *Eq.* (1) can be applied with adequate safety for flange buckling. This equation, however, does not consider the rotational support effect of the trapezoidal web and the non-uniform stress distribution in the flange, which may have significant effect on the flange buckling resistance [1].

$$k_\sigma = 0.43 + \left(\frac{c_f}{a}\right)^2, \tag{1}$$

where c_f is the large flange outstand width, $a = a_1 + 2a_4$ is the estimated buckling wave length, where a_1 and a_4 are the length of the parallel web fold and the length of the longitudinal projection of the inclined web fold [4,10], shown in Fig. 1. Different researchers prescribe different limits for this theoretically considered buckling coefficient. The DASt-Richtlinie 015 [5] and the EN1993-1-5 [4] prescribe a maximum value of 0.6. Sayed-Ahmed [6] proposed a limit of 0.7 while Koichi and Masahiro [7] proposed a value of 1.28. In addition Li et al. [11] recommended a new formula for the buckling coefficient calculation based on the average flange outstand in the form of *Eq.* (2). The formula was calibrated by a numerical parametric study.

$$k_\sigma = 0.425 + \frac{6}{12 + \beta_{Li}}, \tag{2}$$

where β_{Li} is a theoretically derived factor representing the rotational restraint of the web on the compression flange, as given in *Eq.* (3). If β_{Li} is equal to zero, the web has infinite rotational restraint. If β_{Li} is larger, then it approximates the solution of a plate simply supported at three edges.

$$\beta_{Li} = \frac{16\cdot(a_1 + a_4)\cdot t_f^3\cdot h_w}{b_f\cdot t_w\cdot a_3^2\cdot(a_2 + 3a_1)}, \tag{3}$$

where b_f and t_f are the compression flange width and thickness, h_w and t_w are the web depth and thickness, a_2 and a_3 are the length of the inclined web fold and the corrugation depth. The non-uniform stress distribution along the flange width is considered in the EN1993-1-5 [4] and also proposed by Bambach and Rasmussen [9] for flat web girders with the assumption that the outstand element is simply supported by the web. The calculation method of the buckling coefficient according to the EN1993-1-5 [4] is given by *Eq.* (4).

$$k_\sigma = \frac{0.578}{\psi + 0.34}, \tag{4}$$

where $0 \le \psi \le 1$ is the ratio of the normal stresses at the free edge (σ_2) and at the web-to-flange junction (σ_1). By substituting $\psi = 0$ and $\psi = 1$, $k_\sigma = 1.7$ and $k_\sigma = 0.43$ are obtained, respectively. Johnson [2] proposed a new formula for the buckling coefficient based on test results of unstiffened flat web girders in 1985. The provided buckling coefficient takes the moderate rotational restraint of the web into account according to *Eq.* (5).

$$k_\sigma = \frac{4}{\sqrt{h_w/t_w}} = 0.43\cdot\left(\frac{86.5\cdot t_w}{h_w}\right)^{0.5}. \tag{5}$$

Similar formula has been derived by Park et al. [3] for flat web girders in 2016. The bending resistance of plated girders with longitudinal stiffeners was numerically studied focusing on the supporting effect of the flange and web plates. Based on the results of Park et al. [3] a modified buckling coefficient was proposed in the form of *Eq.* (6) where the web-to-flange thickness ratio is also considered.

$$k_\sigma = 3.0\cdot\left(\frac{c_f/t_f}{h_w/t_w}\right)^{0.6} = 0.43\cdot\left(25.5\cdot\frac{c_f}{h_w}\cdot\frac{t_w}{t_f}\right)^{0.6}, \tag{6}$$

where $c_f = b_f/2$.

2.2. Determination of the buckling curve (λ-ρ)

In most of the previously developed design methods for unstiffened plated elements, the relative slenderness may be calculated according to *Eq.* (7).

$$\bar{\lambda}_p = \frac{c_f/t_f}{28.4\cdot\sqrt{k_\sigma}}\sqrt{\frac{f_{yf}}{235MPa}}, \tag{7}$$

where f_{yf} is the yield strength of the flange material (detailed description found in [1]). In the international literature different types of design curves can be found regarding plate buckling. In the current EN1993-1-5 [4] the Winter-curve based formula is implemented in the form of *Eq.* (8) where the relative slenderness limit (plateau length) is equal to 0.748. The experimental results clearly show that this design buckling curve does not give always safe side resistances, therefore it is not applicable in the current form for trapezoidally corrugated web girders [1].

$$\rho = \frac{c_{f,eff}}{c_f} = \frac{\bar{\lambda}_p - 0.188}{\bar{\lambda}_p^2} \le 1.0. \tag{8}$$

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