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Flange buckling behavior of girders with corrugated web Part I: Experimental study

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ABSTRACT

Application of the corrugated web girders has been widely spread due to their numerous advantages in the field of bridges and buildings in the civil engineering praxis. This girder type has a special stress distribution and buckling behavior compared to conventional steel I-girders. Despite, there are a relative small number of previous investigations dealing with the bending moment and the flange buckling resistance of the trapezoidally corrugated web girders. Previous experimental and numerical investigations confirmed that the bending moment resistance according to the EN1993-1-5 often results in unsafe resistances if the compressed flange belongs to cross-section class 4. Therefore, improved design models are developed by different researchers in the past, but there are contradictions in the previous design models regarding the consideration of the flange width and the clamping effect of the web. The current paper collects all the previous research results on the flange buckling resistance and introduces an additional experimental research program investigating the flange buckling behavior and the bending moment capacity. The companion paper (Part II) [1] introduces the executed numerical research program and the design method development for the flange buckling resistance.

1. Introduction

Research on steel girders with corrugated web was started in 1956 by NACA [2] for wings of airplanes where the sections were built up by riveted angle connections. After that the application of the corrugated web girder was spread in the civil engineering praxis as well, especially in the field of bridges. Numerous researchers investigate the special structural behavior of this girder type, however, hardly any research was done on the flange buckling behavior and on the bending moment resistance of girder with thin flanges.

The EN1993-1-5 [3] standard contains design model for the determination of the bending and shear buckling resistances and taking their interaction (M + V) into account for corrugated web girders. The shear buckling resistance model was calibrated based on a large number of experimental and numerical investigations, the resistance model related to bending, however, was developed based on a significantly smaller number of experimental and numerical investigations [4]. The standard does not contain design formulas for patch loading and for the combined loading conditions (M + F and M + V + F) of trapezoidally corrugated web girders. In the frame of the current research new resistance models were developed by the authors based on experimental and numerical investigations [5–10]. Applicability of the corrugated web girders as built-up sections was investigated by Dubina et al. [11] in 2015 and as arch structures by Guo et al. [12] in 2016.

Due to the numerous advantages of corrugated web girders the application field is growing nowadays in the civil engineering praxis. There are companies specialized for the production and design of corrugated web girders [13,14]. Preliminary investigations by the authors confirmed that the proposal of the EN1993-1–5 can result in large scatter in the bending moment resistance for trapezoidally corrugated web girders having slender flanges. Therefore, the improvement of the design method related to flange buckling has a high priority.

The current paper collects all the available previous investigations on the flange buckling resistance for trapezoidally corrugated web girders. The detailed literature review includes the existing experimental and numerical investigations with the existing design proposals. Due to the small number of previous experimental investigations on the flange buckling resistance a new experimental research program is designed and executed on 16 large scale test specimens; the results are presented in the current paper. The numerical model development is presented by the companion paper (Part II) Jáger et al. [1] coupled with the performance of imperfection sensitivity analysis and numerical parametric study in order to develop design proposals. The layout of the tested girders, the applied dimensions and notations used in the paper are shown in Fig. 1.

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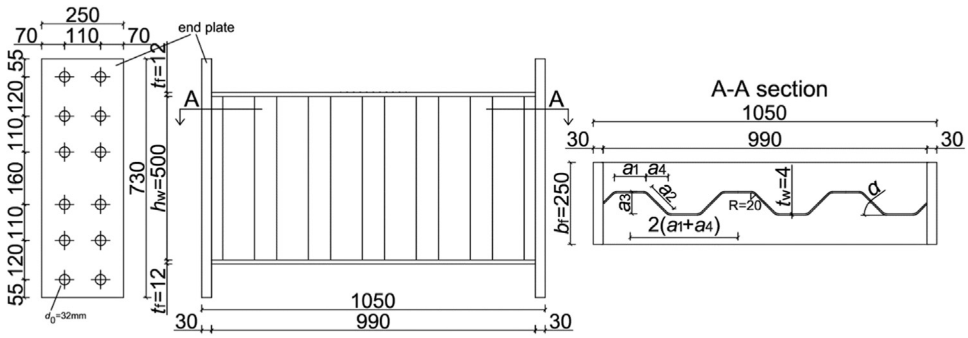

Fig. 1. Used notations for girders with trapezoidally corrugated webs.

2. Literature overview

2.1. Investigations on the elastic stress distribution in the flanges

The normal stress distribution in the flanges of conventional steel I-girders is assumed to be constant along the flange width under pure bending moment (assuming that the shear lag effect is negligible). In case of corrugated web girders, however, the presence of shear force results in additional normal stresses in the flanges. This special normal stress distribution was firstly investigated experimentally and theoretically by Lindner in 1992 [15] and Aschinger and Linder in 1997 [16]. They developed a design procedure to calculate the additional normal stresses depending on the loading conditions. A significant research program was also executed by Abbas et al. [17–19] in 2006 and 2007. The main aim of their research program was the determination of the distribution and the magnitude of the transverse bending moment. Further investigations were executed on the determination of the maximum transverse bending moment in the flanges by Kövesdi et al. [6] in 2012 and by Baláž and Koleková [20] in 2012. It was also recognized that the loading conditions and the location of the lateral supports have also a significant effect on the maximum transverse bending moment, which makes the determination of the flange stress distribution more complex. Analytical calculation method was derived for the most unfavorable situation by Kövesdi et al. [6]. Further numerical investigation on the stress distributions in the flanges under different boundary and loading conditions was analyzed by Kövesdi et al. [7] in 2016.

2.2. Investigations on the flange buckling resistance

Previous research results showed that the reduction of the bending moment resistance due to accompanying shear force is negligible [7,8,10,23] and the bending resistance should be calculated only from the contribution of the flanges [15,21,23]. The previous research activities to determine the bending resistance were mainly focusing on the investigation of the buckling behavior of the compressed flange, on the determination of the critical outstand-to-thickness ratio and on the determination of the effective flange area. The DASt-Richtlinie 015 [21] proposes a design resistance model for the determination of the bending moment resistance according to Eq. (1).

$$M_{Rd} = \min\begin{cases} \dfrac{f_{yf}\cdot b_{cf,eff}\cdot t_{cf}}{\gamma_M}\cdot\left(h_w + \dfrac{t_{cf}+t_{tf}}{2}\right) \\ \dfrac{f_{yf}\cdot b_{tf}\cdot t_{tf}}{\gamma_M}\cdot\left(h_w + \dfrac{t_{cf}+t_{tf}}{2}\right)\end{cases}, \tag{1}$$

where $b_{f,eff}$ and t_f are the effective width and the thickness of the flanges (notations c and t refer to the compression and tension flanges), h_w is the web depth, f_{yf} is the yield strength of the flange material, γ_M is the partial safety factor. This design method considers the accordion effect which is typical for corrugated web girders, thus the effect of the web is neglected from the moment capacity. The effective width of the compression flange can be calculated by Eq. (2) assuming the buckling coefficient equal to $k_\sigma = 0.6$.

$$b_{cf,eff} = 30.7\cdot t_{cf}\cdot\sqrt{\frac{240}{f_{yf}}} \le b_{cf}, \tag{2}$$

where b_{cf} is the total width of the compression flange. In addition, the DASt-Richtlinie 015 provides maximum slenderness for the trapezoidal web to be capable to prevent flange induced buckling in the form of Eq. (3).

$$\bar{\lambda}_{pw} = 0.8\cdot\frac{h_w}{t_w}\cdot\sqrt{\frac{f_{yw}}{E}\frac{1}{k_\tau}} \le \bar{\lambda}_{pw,\,\max} = 0.316\cdot\sqrt{\frac{E}{f_{yw}}}, \tag{3}$$

where E is the Young's modulus, t_w is the web thickness and k_τ is the shear buckling coefficient equal to 5.34. According to the EN1993-1-5 Annex D [3] the bending moment resistance can be calculated by Eq. (1) but with applying γ_{M1} instead of γ_M for flange buckling and by calculating the effective width of the compression flange using Eq. (4).

$$b_{cf,eff} = c_{f,eff,1} + c_{f,eff,2}, \tag{4}$$

where $c_{f,eff,1}$ and $c_{f,eff,2}$ are the Winter-formula based effective width of the large and small outstand compression elements of the flange according to Eq. (5).

$$\rho = \frac{c_{f,eff}}{c_f} = \frac{\bar{\lambda}_p - 0.188}{\bar{\lambda}_p^2} \le 1.0, \tag{5}$$

where c_f is taken as the width of the larger and smaller outstand of the compression flange part ($(b_{cf} \pm a_3)/2$). For the calculation of the $\bar{\lambda}_p$ relative slenderness ratio Eq. (6) should be considered.

$$\bar{\lambda}_p = \frac{c_f/t_{cf}}{28,4\cdot\sqrt{k_\sigma}}\sqrt{\frac{f_{yf}}{235}}, \tag{6}$$

where k_σ is the buckling coefficient according to Eq. (7). By substituting outstand-to-thickness ratio equal to 14ε (limit for cross-section class 4) and $k_\sigma = 0.43$ the relative slenderness limit is obtained to $\bar{\lambda}_{p,\,\lim} = 0.752$ which is modified to 0.748 in the EN1993-1-5.

$$k_\sigma = \min\left(0.6;\, 0.43 + \left(\frac{c_f}{a_1 + 2\cdot a_4}\right)^2\right), \tag{7}$$

where a_1 and a_4 are geometric properties of the web profile shown in Fig. 1. The bending resistance of the corrugated web girders was investigated by Elgaaly et al. [23] in 1997 on six test specimens subjected by four-point-bending. The failure mode of the specimens was buckling of the compression flange. The main conclusion based on the experiments and additional numerical investigation was that the web is completely negligible in the longitudinal load bearing capacity due to the accordion effect. Five specimens were tested by Johnson and Cafolla [24] in 1997 from which three specimens failed by local flange buckling and two specimens failed by shear buckling of the web. Based on the test results the authors proposed that the average flange outstand (b_{cf}/