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Girders with trapezoidally corrugated webs subjected by combination of bending, shear and path loading

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ABSTRACT

Steel girders with corrugated webs are increasingly used in the field of bridges, especially in case of composite bridges. During launching of a bridge structure the girder can be subjected by the combination of bending moment (M), shear (V) and transverse forces (F) which result in a complex stress field in the girder and in an interacting stability problem. Previous research activities related to the corrugated web girders showed that the structural behavior of the girders with corrugated webs differ from the conventional I-girders, especially in the stress distribution of the flanges and the web. On the other hand the stability behavior of the corrugated web girders are also different from the flat web girders due to the corrugation profile therefore the interaction equations developed for conventional I-girders cannot be used for corrugated web girders. There is a lack of investigations analyzing the effect of the complex loading situation for corrugated web girders, therefore the current paper focuses on the investigation of the structural behavior under all of the aforementioned actions and their combinations. Based on the previous and current investigations design interaction equation is developed for the combined M–V–F loading situation.

1. Introduction

During the incremental launching of a bridge girder almost all the cross-sections are launched through an intermediate support where concentrated force is introduced with accompanying bending moment and shear force. The combination of these three actions leads to an interacting stability phenomenon for both flat and corrugated web girders. Previous research activities showed that the local and global stability behavior of the girders with corrugated webs differ from the conventional I-girders due to the corrugation profile. Therefore the interaction equations developed for I-girders with flat webs cannot be applied for corrugated web girders [1]. It is to be noted that the M–V–F interaction behavior of the conventional I-girders with flat web was also just recently investigated, and design equation was proposed by Braun in 2010 [2] and by Kövesdi et al. in 2014 [3]. Based on a deep literature overview it can be observed that there is a lack of investigations analyzing the effect of the combined loading situation for the corrugated web girders. The latest investigations on this research field clearly shows that the interactions are not negligible in the design of the girders with corrugated web [4]. Resistance formulas to determine the pure bending and shear buckling resistances are given in the EN1993-1-5 Annex D [5]. There are no recommendations, however, in the current standard to determinate the patch loading resistance, therefore a design method was developed by Kövesdi et al. in 2010 [6,7]. Interaction type equation for the combined M–V loading situation can be found in the EN1993-1-5 Annex D [5], but there are no design recommendations on the M–F, V–F and M–V–F interaction behavior.

The individual interaction planes M–V, M–F and V–F were separately investigated by several researchers in the past as detailed in Section 2. The authors, however, could not find any previous investigations regarding the M–V–F interaction behavior of the corrugated web girders, and have the aim to study this combined loading deeply. At first the existing experimental, analytical and numerical investigations in this topic are studied, evaluated and summarized. To extend the previous investigations and to analyze the applicability of the previous design proposals an advanced numerical model is developed and verified by experimental results. By the application of the numerical model the bending moment, shear buckling and patch loading resistances are determined and evaluated by the comparison to the above mentioned resistance models. As a final results an interaction equation is developed for the M–V–F interaction behavior of corrugated web girders.

The research work is completed according to the following research strategy:

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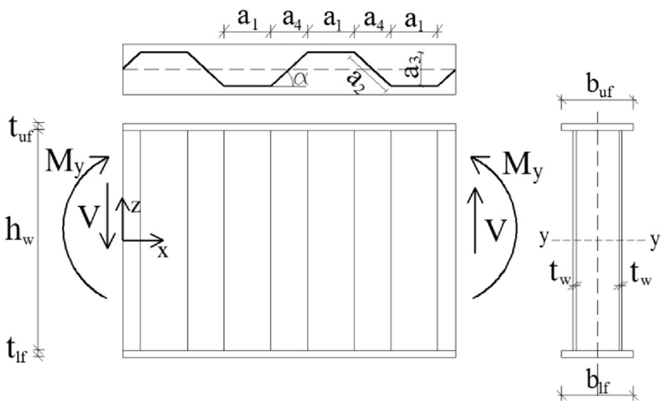

Fig. 1. Used notations for corrugated web girders.

1. Literature overview in the topic of the M–V, M–F, V–F and M–V–F interaction behavior for corrugated web girders.
2. Advanced numerical model development considering the geometric and material nonlinearities and equivalent geometric imperfections.
3. Verification of the numerical model based on test results found in the literature.
4. Numerical parametric study using different geometric parameters to investigate the pure resistances and the individual interaction planes (M–V, M–F and V–F) and the M–V–F interaction surface.
5. Comparison of the numerical results with the proposals related to the interaction planes and development of new proposals if needed.
6. Development of new M–V–F interaction surface based on the numerical calculations.
7. Statistical evaluation to determine the applicability and accuracy of the new M–V–F interaction equation.

The applied notations in the current paper are shown in Fig. 1.

2. Literature overview

2.1. General

Due to the small number of previous research activities in the field of the M–V–F interaction behavior a deep literature overview is executed in the topic of the individual interaction planes (M–V, M–F and V–F planes) separately. This section gives a short overview on the latest proposals to determine the bending, shear buckling and patch loading resistance of the girders with corrugated webs. These resistance models are used for the evaluation of the current numerical simulations and to evaluate the developed interaction surface. Furthermore, the previously developed interaction curves for the individual interaction planes (M–V, M–F and V–F) are also separately analyzed and summarized in the followings.

2.2. Applied resistance models for M, V and F

According to the EN1993-1-5 Annex D [5] the bending resistance can be determined from the contribution of the flanges presented by Eq. (1).

$$M_{Rd} = min\left\{\frac{b_{lf}\cdot t_{lf}\cdot f_{yf}}{\gamma_{M0}}\cdot\left(h_w + \frac{t_{uf}+t_{lf}}{2}\right); \frac{b_{uf,eff}\cdot t_{uf}\cdot f_{yf}}{\gamma_{M0}}\cdot\left(h_w + \frac{t_{uf}+t_{lf}}{2}\right); \frac{b_{uf,eff}\cdot t_{uf}\cdot f_{yf}\cdot\chi}{\gamma_{M1}}\cdot\left(h_w + \frac{t_{uf}+t_{lf}}{2}\right)\right\} \quad (1)$$

where $b_{f,eff}$ and t_f are the smallest effective width and the related thickness of the lower and upper flanges, t_{uf} and t_{lf} are the upper and lower flange thicknesses, h_w is the web depth, f_{yf} is the flange yield strength, γ_{M0} and γ_{M1} are partial safety factors and χ is the reduction factor related to the buckling (see details in EN1993-1-5 [5]).

Design formula for the shear buckling resistance of corrugated web girders is given in the form of Eq. (2) according to EN1993-1-5 [5] Annex D.

$$V_{bw,Rd} = \chi_c \frac{f_{yw}}{\gamma_{M1}\sqrt{3}} h_w t_w \quad (2)$$

where h_w and t_w are the web depth and thickness, f_{yw} is the yield strength of the web, χ_c is the smaller reduction factor regarding to local and global buckling and γ_{M1} is the partial factor for buckling (further details can be found in EN1993-1-5 [5]).

The patch loading resistance can be dtermined according to the proposal of Kövesdi et al. [7] which can be calculated according to Eq. (3).

$$F_{Rd} = \frac{2\cdot\sqrt{4\cdot M_{pl,f}\cdot\chi\cdot t_w\cdot f_{yw}} + f_{yw}\cdot\chi\cdot t_w\cdot s_s}{\gamma_{M1}^{**}} \quad (3)$$

where t_w is the web thickness, f_{yw} is the yield strength of the web, s_s is the loading length, χ is the reduction factor for web crippling, $M_{pl,f}$ is the plastic moment resistance of the flange alone and $\gamma_{M1^{**}}$ is the partial factor equal to 1.35 derived by Kövesdi [7].

The above mentioned three resistance models are used in the current study as reference resistances. The detailed determination methods and the backgrounds of these design methods can be found in [5–7,11].

2.3. Previous studies on the M–V interaction behavior

In the international literature there are numerous papers dealing with the in-plane-bending and shear buckling resistances of the corrugated web girders separately but there are only a few investigations dealing with the combined bending and shear. Based on numerical results the stress distributions in the flanges and in the corrugated web was analyzed by Elgaaly et al. [8] in 1997. It was concluded that the moment resistance can be calculated from the contribution of the flanges alone and the shear force is carried only by the corrugated web. Therefore it was stated that there is no need to consider interaction behavior between bending and shear for girders with trapezoidal corrugated webs.

The EN1993-1-5 Annex D [5] recommends a design method to consider the effect of the shear force in the in-plane-bending moment resistance by using a reduction factor (f_T). This factor can be calculated from the maximum additional transverse bending moment in the flanges coming from the shear flow in the web. The reduced moment capacity can be calculated according to Eq. (4) and the character of the interaction diagram can be seen in Fig. 2, presented by blue dashed line.

$$M_{V,Rd} = f_T\cdot M_{Rd} \quad (4)$$