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Flange buckling behavior of trapezoidally corrugated web girders subjected to bending and shear interaction

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Abstract
Steel girders with trapezoidally corrugated web are widely used structural members in the civil engineering praxis due to their favorable behavior. The stress distributions and the bending-shear interaction of trapezoidally corrugated web girders have been already investigated in the case of compact flanges. Furthermore, the flange buckling behavior and resistance of slender flanges has been recently studied and design proposal has been developed based on the effective width method. In addition the shear buckling resistance is still a very active research field in the case of corrugated web girders. There is, however, a lack of research in the international literature regarding the investigation of the combined bending and shear interaction behavior of trapezoidally corrugated web girders having slender flanges. In the current supplementary study the stress distribution in the flanges under combined loading, the combined imperfection sensitivity and the interaction behavior at ultimate are investigated and presented. To investigate these girders with slender flanges, a recently validated advanced FEM model is used for parametric studies. In the analysis different levels of sophistication is applied for the investigation of the normal stress distribution. Geometric and material nonlinear imperfect analysis using only equivalent geometric imperfections is applied for the determination of the ultimate bending and shear interaction behavior. To promote FEM based design method, imperfection sensitivity analysis is performed using the combination of the pure flange buckling and pure shear buckling eigenmodes together as equivalent geometric imperfections. Based on the FEM results design proposals are developed and proposed for the determination of the most unfavorable additional transverse bending moment in the flanges and the interaction resistance of trapezoidally corrugated web girders having slender flanges.

Keywords: corrugated web; trapezoidal corrugation; flange buckling resistance; shear buckling resistance; interaction.

1. Introduction
The investigation of the special structural behavior of steel corrugated web girders has been started for 30 years and the first research results had been implemented into the German specifications for steel beams with slender webs (DASt-Richtlinie 015 1990) including the flange

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buckling, shear buckling and combined bending-shear interaction resistance models based on the “accordion effect”. It means that the web contribution to longitudinal load bearing is negligible; the shear force is carried by the corrugated web and the axial forces are carried by the flanges only. The accordion effect based design resistance models are also implemented into the Annex D of EN 1993-1-5 standard. Due to the special structural behavior of corrugated web girders additional normal stresses, however, arise in the flanges caused by transverse bending coming from the shear flow in the web. Since the shear force is practically carried only by the corrugated web, it indicates that the bending-shear interaction may be limited to the flanges in conjunction with the special transverse bending moment caused by the web corrugation in the presence of shear. This phenomenon was first recognized by Lindner (Lindner 1992) and Aschinger and Lindner (Aschinger and Lindner 1997). After that some researchers investigated the tendency and maximum value of the transverse bending moment in the flanges along the girder length. For trapezoidally corrugated web girders having compact flanges it is proved that the transverse bending moment caused by shear has no provable influence on the bending moment resistance reduction, furthermore the bending-shear interaction is quite small and could be negligible in the design (Kövesdi, Jáger and Dunai 2016). The effect of the transverse bending moment on corrugated web girders having slender flanges have not been, however, studied. The flange buckling resistance under pure bending is recently studied (detailed references can be found in Jáger, Dunai and Kövesdi 2017b; 2017c) but the effect of the transverse bending on the flange buckling resistance – namely the flange buckling resistance under linear normal stress distribution – of corrugated web girders have not been investigated according to the authors’ best knowledge. Therefore the aim is to study the normal stress distribution in the flanges and the flange buckling resistance of corrugated web girders having slender flanges under combined bending and shear interaction. In the investigation, FE simulations is used by previously validated numerical models. The used notations are shown by Fig. 1.

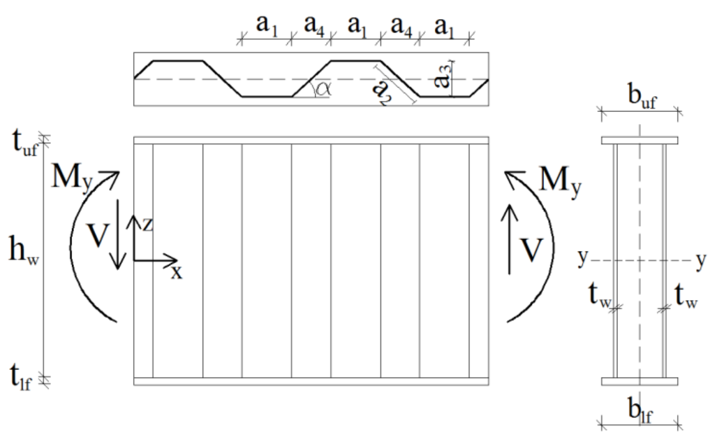


Figure 1: Used notations

2. Previous researches

2.1 Normal stress distribution

The special normal stress distributions in the flanges of corrugated web girders caused by the shear flow in the web were investigated at first by Lindner (Lindner 1992) and Aschinger and Lindner (Aschinger and Lindner 1997). They stated that the additional normal stresses in the flanges are caused by the transverse bending moment due to the shear flow in the web and it has a significant reduction effect on the in-plane-bending moment resistance of corrugated web girders. They gave a proposal considering different load cases for the determination of the maximum transverse bending moment in the flanges. A significant research program was executed on the stress distributions in the flanges of corrugated web by Abbas et al. (Abbas, Sauce and Driver 2006; 2007a; 2007b). They developed a "fictitious load method" for the determination of the maximum transverse bending moment in the flanges. In addition, Baláž and Koleková (Baláž and Koleková 2012) investigated the transverse bending moment distribution in the flanges along the beam length and developed an analytical method for the determination of the possible maximum transverse bending moment. The latest researches in this field were completed by Kövesdi et al. (Kövesdi, Jáger and Dunai 2012; 2016). Different corrugated profiles and layouts considering different boundary and loading conditions are studied. Based on a comprehensive experimental based numerical and analytical investigations a new proposal was developed for the determination of the possible maximum transverse bending moment in the flanges coming from the shear flow in the corrugated web. In the numerical investigation only linear analysis and compact flanges were used, thus the flange buckling was not considered. It was revealed that the most unfavorable layout from point of view of the transverse bending moment is when the web of a simply supported girder subjected to three-point-bending has even number of half corrugations in the web and supported under the inclined web folds. The mechanical model is presented by Fig. 2 assuming permanent shear flow along one corrugation.

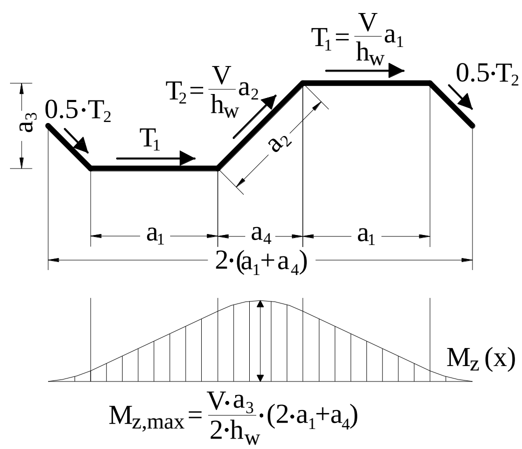


Figure 2: Analogy for the calculation of the maximum transverse bending moment

2.2 Flange buckling resistance

The flange buckling resistance of corrugated web girders under pure bending was investigated experimentally and numerically by Johnson and Cafolla (Johnson and Cafolla 1997). They developed a design procedure for the determination of the flange buckling resistance. Watanabe and Masahiro (Watanabe and Masahiro 2006) studied experimentally and numerically the local flange buckling behavior of corrugated web girders and a new relationship was developed based on the effective width method. Li et al. (Li, Jiang and Zhu 2015) also performed experimental and numerical investigations on the local flange buckling of corrugated web girders having wide flanges. Based on their results an outstand-to-thickness slenderness limit formula was developed using the average flange outstand. By executing a large number of experimental test program coupled with a comprehensive FE parametric study and considering the previous proposals an effective width method based proposal was developed for the determination of the flange buckling resistance of corrugated web girders by Jáger et al. (Jáger, Dunai and Kövesdi 2017b; 2017c). The reduction factor on the flange outstand widths may be calculated according to Eq. 1:

$$\rho = \left(14 \cdot \varepsilon \cdot \frac{t_f}{c_f}\right)^{\beta} \leq 1.0 \tag{1}$$

where ε depends on the material quality ($\sqrt{235/f_y}$), t_f and c_f are the thickness and width of the outstand compression element and the index β considers the enclosing effect of the web (R), the corrugation angle (α) and the flange-to-web thickness ratio (t_f/t_w) which clearly define a specific profile for a given flange width. The index can be determined according to Eqs. 2-4:

$$\beta = 5 \cdot \eta \cdot R \cdot \left(\frac{a_4}{a_3}\right)^{\eta} \text{ where } 0.5 \leq \beta \leq 1.0 \tag{2}$$

$$\eta = 0.45 + 0.06 \cdot \frac{t_f}{t_w} \tag{3}$$

$$R = \frac{(a_1 + a_4) \cdot a_3}{(a_1 + 2a_4) \cdot b_f} < 0.14 \tag{4}$$

2.3 Shear buckling resistance of the web

The shear buckling behavior of corrugated webs is still a very active research field (Moussa, Samer, Salah, Talha and Mohamed 2017). In the current paper the used design model for the shear buckling resistance is given by Eq. 5 according to EN1993-1-5 Annex D.

$$V_{bw,Rd} = \chi_c \frac{f_{yw}}{\gamma_{M1}\sqrt{3}} h_w t_w \tag{5}$$

where t_w is the web thickness, f_{yw} is the yield strength of the web panel, χ_c is the reduction factor considering both the local and global buckling behavior of the corrugated web and γ_{M1} is the partial safety factor for stability check (Further details regarding the calculation of the reduction factors can be found in EN1993-1-5).

2.4 Bending-shear interaction

The bending and shear interaction behavior of corrugated web girders was started to be investigated in connection with the transverse bending moment in the flanges caused by the web corrugation due to shear. In the EN1993-1-5 standard the recommendation of the German specification (DASt-Richtlinie 015 1990) has been implemented using a reduction factor on the bending moment resistance due the accompanying shear force. Based on experimental test results and numerical investigations Elgaaly et al. (Elgaaly, Seshadri and Hamilton 1997) stated that the bending-shear interaction behavior is negligible for trapezoidally corrugated web girders having compact flanges. It was confirmed by Pasternak and Hannebauer (Pasternak and Hannebauer 2003) for sinusoidally corrugated web girders. Another research was carried out by Kuchta (Kuchta 2006) investigating the combined bending moment and shear force interaction behavior of sinusoidally corrugated web girders. Based on experimental and numerical investigations an interaction equation was proposed with maximum reduction in the bending and shear resistance of 8.33%. Including experimental and numerical investigations a comprehensive research program was executed on trapezoidally corrugated web girders having compact flanges by Jáger, Kövesdi and Dunai (Jáger, Dunai and Kövesdi 2015; 2017a; Kövesdi, Jáger and Dunai 2016). The results confirmed the previous proposals that just a minor interaction was observed which could be negligible in the design of corrugated web girders if plastic design of the flanges is used. Furthermore it was revealed that there is no relationship between the transverse bending moment caused by shear and the in-plane-bending moment resistance reduction of trapezoidally corrugated web girders having compact flanges. Fig. 3 shows the previous proposals for the bending-shear interaction.

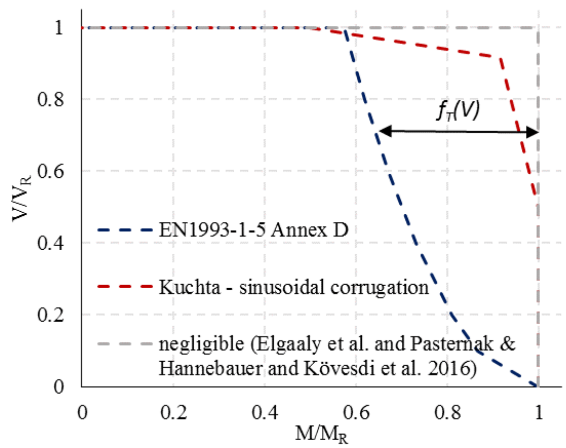


Figure 3: Proposals for the M-V interaction

2.5 Modelling issues

In the current paper the ultimate strength are determined by FE simulations applying geometric and material nonlinear imperfect analysis (GMNIA) where the imperfections are considered by equivalent geometric imperfections – involving residual stresses and initial geometric imperfections – using eigenmode shapes. For the determination of the FEM based flange buckling resistance the scaling factor $c_f/50$ as flange twist – proposed also by the EN1993-1-5 Annex C – on the flange buckling eigenmode shape can be applicable for trapezoidally corrugated web girders having slender flanges (Jáger, Dunai, Kövesdi 2017c). In terms of shear buckling Driver et al. (Driver, Abbas and Sause 2006), Hassanein and Kharoob (Hassanein and Kharoob 2013), Jáger et al. (Jáger, Dunai and Kövesdi 2016) and the EN1993-1-5 Annex C proposed the web depth over 200 ($h_w/200$), while Yi et al. (Yi, Gil, Youm and Lee 2008) and Nie et al. (Nie, Zhu, Tao and Tang 2013) proposed the web thickness t_w as scaling factor on the shear buckling eigenmode shape as equivalent geometric imperfection magnitude, respectively. In addition the imperfection sensitivity of corrugated web girders in the presence of patch load is studied by Kövesdi and Dunai (Kövesdi and Dunai 2011).

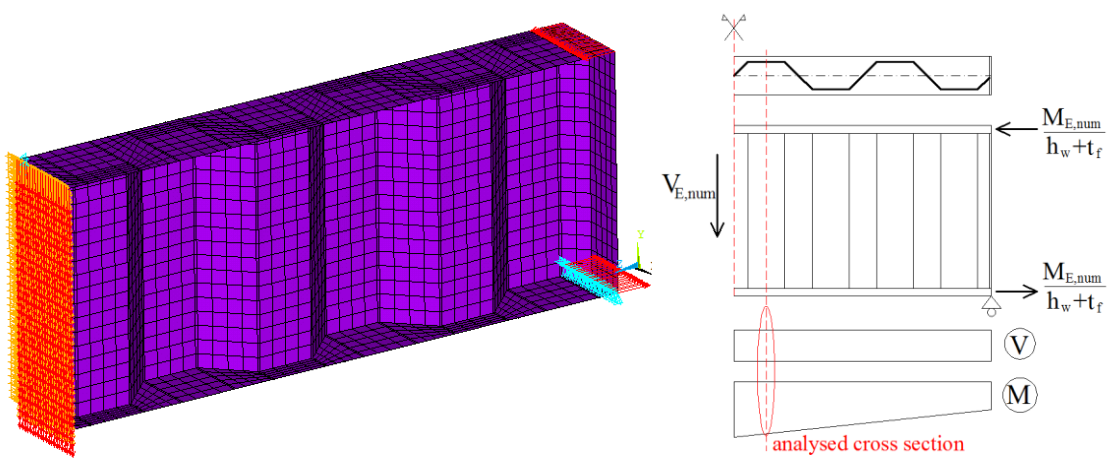
3. Investigated parameter ranges

From point of view of the maximum transverse bending moment only the most unfavorable girder layout is investigated and presented in the current paper. Based on the previous researches this layout is when the web of a simply supported girder has even number of half corrugations and supported at the inclined folds. The analogy of the mechanical model is presented by Fig. 2.

In the current research more than 200 numerical simulations have been carried out having steel grade S355. In the numerical analysis the following geometric parameter domains are analyzed: (i) flange slenderness c_f/t_f=11.5-18.5, (ii) corrugation angle α=30-60 degree, (iii) enclosing effect of the web R=0.19-0.43 and (iv) flange-to-web thickness ratio t_f/t_w=2-3.5. These parameters are the most influential from point of view of flange buckling (Jáger, Dunai and Kövesdi 2017c).

4. Numerical model development

An advanced numerical model is developed in ANSYS 15.0 finite element program. It is based on a full shell model using eight-node-thin (SHELL281) shell elements with serendipity base functions. Fig. 4 presents the meshed geometric model with the boundary and loading conditions and the location of the evaluated cross-section at ultimate. In the current paper only the most unfavorable corrugation layout is used discussed in Section 2.1 and shown by Fig. 2. In the numerical simulations only the half of a simply supported girder is modeled. Symmetry conditions are defined at the left end of the model and simply support at the right end. There are two loads applied which ratios are varying in the parametric study. The shear force ($V_{E,num}$) is introduced at the midspan of the girder and the bending moment ($M_{E,num}$) is substituted by a force couple applied in the center of gravities of the upper and lower flanges. The shear force is permanent along the girder length while the bending moment envelope has a linear character along the girder length. The internal forces are evaluated where the flange outstand is the biggest since this cross-section is the most sensitive to flange buckling.



a) boundary and loading conditions b) evaluation of the internal forces

Figure 4: Numerical model and evaluation of the internal forces

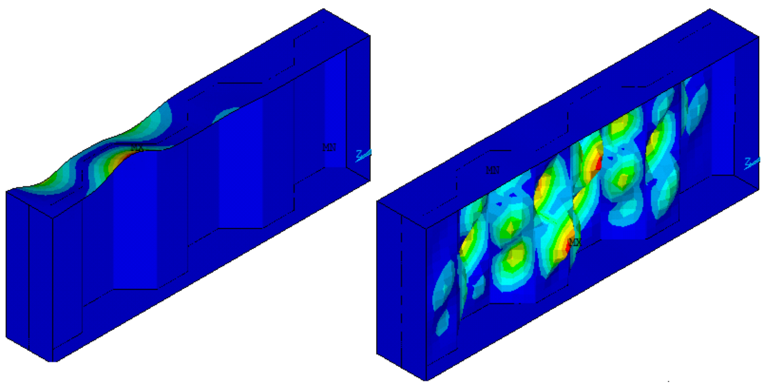
4.1 Applied analysis and material model

Five analysis types are applied considering different levels of sophistication with force control, namely linear analysis (LA), material nonlinear analysis (MNA), geometrical nonlinear analysis (GNA) and geometrical and material nonlinear analysis without imperfections (GMNA) and with imperfections (GMNIA). The normal stress distributions in the flanges are studied by all levels of analysis. In addition on the imperfect structure the pure and combined bending and shear buckling interaction strengths are studied, beside the execution of an imperfection sensitivity analysis. The applied numerical model can apply the eigenmode shapes as equivalent geometric imperfections. More details regarding the setup of the nonlinear solver and mesh sensitivity analysis are presented in Jáger et al. (Jáger, Dunai and Kövesdi 2017c). A linear elastic -

hardening plastic material model with von Mises yield criterion is used in the numerical model. The material model behaves linear elastic up to the yield stress (f_y) by obeying Hook's law with Young's modulus equal to 210000 MPa. The yield plateau is modeled up to 1% strains with a small increase in the stresses. By exceeding the yield strength the material model has an isotropic hardening behavior with a hardening modulus until it reaches the ultimate strength (f_u). From this point the material is assumed to behave as perfectly plastic. The validation of the FE model is detailed in corresponding papers (Jáger, Dunai and Kövesdi 2015; 2017a; 2017c; Kövesdi, Jáger and Dunai 2012; 2016)

4.2 Applied imperfections

In the GMNIA eigenmode shapes are applied as equivalent geometric imperfections. Two types of eigenmode shapes are combined in each simulations presented in Fig. 5, namely the flange buckling and shear buckling eigenmode shapes.



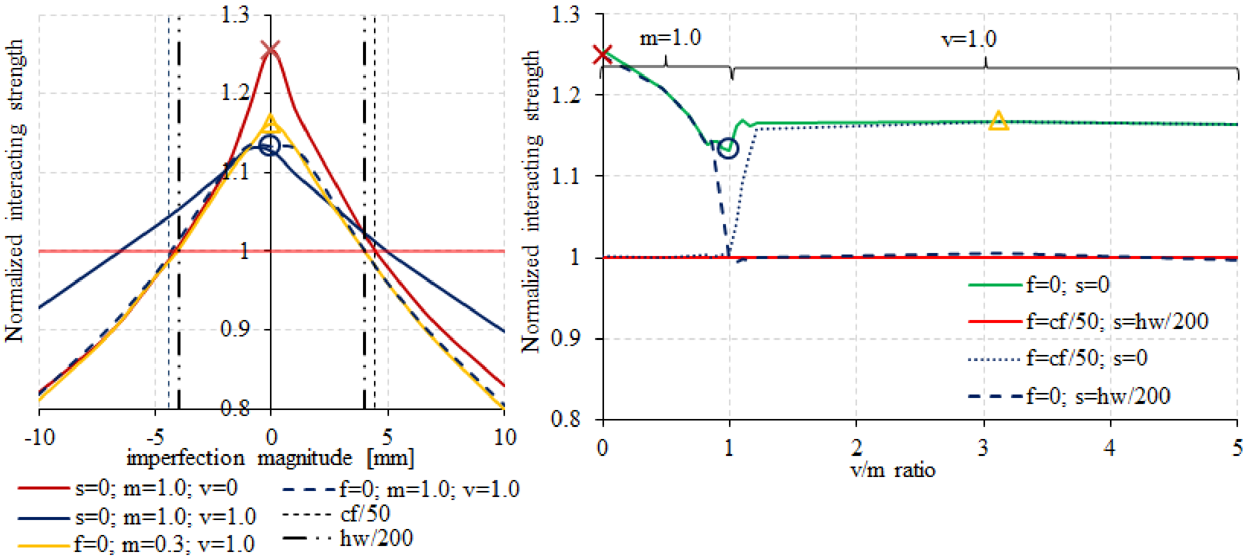
a) flange buckling eigenmode b) shear buckling eigenmode

Figure 5: Applied typical eigenmode shapes for imperfections

5. Combined imperfection sensitivity

The detailed imperfection sensitivity analyses on the flange buckling and shear buckling can be found in the relevant papers (Jáger, Dunai and Kövesdi 2016; 2017c). In the current paper the combined imperfection sensitivity is studied by varying the FEM based bending (m tends from 0 to 1.0) and the FEM based shear (v tends from 0 to 1.0) utilizations focusing on the separated influences of the shear buckling and flange buckling eigenmode imperfections on the interaction strength. The aim is to determine the possible interaction domain from point of view of the choice of the corresponding imperfection shape. For analyzing the imperfection sensitivity geometrical and material nonlinear analysis is performed on the perfect (GMNA) and imperfect models (GMNIA). The notations f and s represent the applied magnitude on the flange buckling and shear buckling eigenmode shapes, respectively. In the case of flange buckling the value of f is interpreted in the analyzed cross-section shown by Fig. 4b if accompanying shear force is acting; since the flange buckling eigenmode shape has typically the maximum magnitude at the second flange subpanel shown by Fig. 5a.

Fig. 6 presents the combined imperfection sensitivity analysis. The vertical axes represent the interacting strength normalized to the FEM based interaction strength using $f=+c_f/50$ and $s=+h_w/200$ imperfection magnitudes simultaneously. In Fig. 6a the imperfection sensitivity under different m and v utilizations are presented using only the flange buckling or shear buckling eigenmode shapes. The corresponding peak points of the curves – representing the perfect model – can be found in Fig. 6b with the same cross, triangle and circle markers, respectively. The green line represents the development of the interaction strength of the perfect model in the function of the ratio of the bending and shear utilizations (*v/m*). It is to be noted that in the case of *m=1.0* and *v=0-1.0* the interaction strength of the perfect model reduces parallel with the reduction of the imperfection sensitivity (peakedness and steepness of the corresponding curves in Fig. 6a) and the sum of both effects, however, results in the same FEM based interaction strength. Fig. 6b shows separately the effect of the flange buckling (with $f=+c_f/50$) and shear buckling (with $s=+h_w/200$) imperfections to any *v/m* ratios represented by the dotted and dashed lines, respectively. It can be seen that the flange buckling imperfection has practically no effect on the FEM based shear buckling strength (*v=1.0* range) and vice versa (*m=1.0* range) represented by the V-shape. It means that the use of both imperfections together have no further reduction effect on the FEM based interaction strength and their influences are independent.



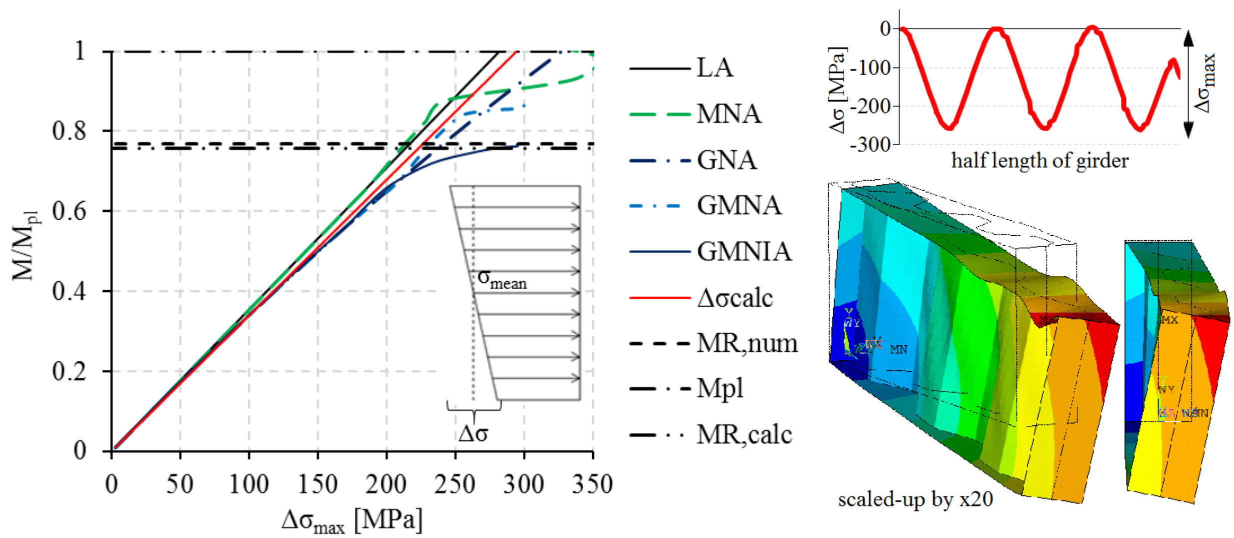
a) sensitivity analysis b) effect of bending and shear utilizations

Figure 6: Combined imperfection sensitivity

6. Normal stress analysis in the compression flange

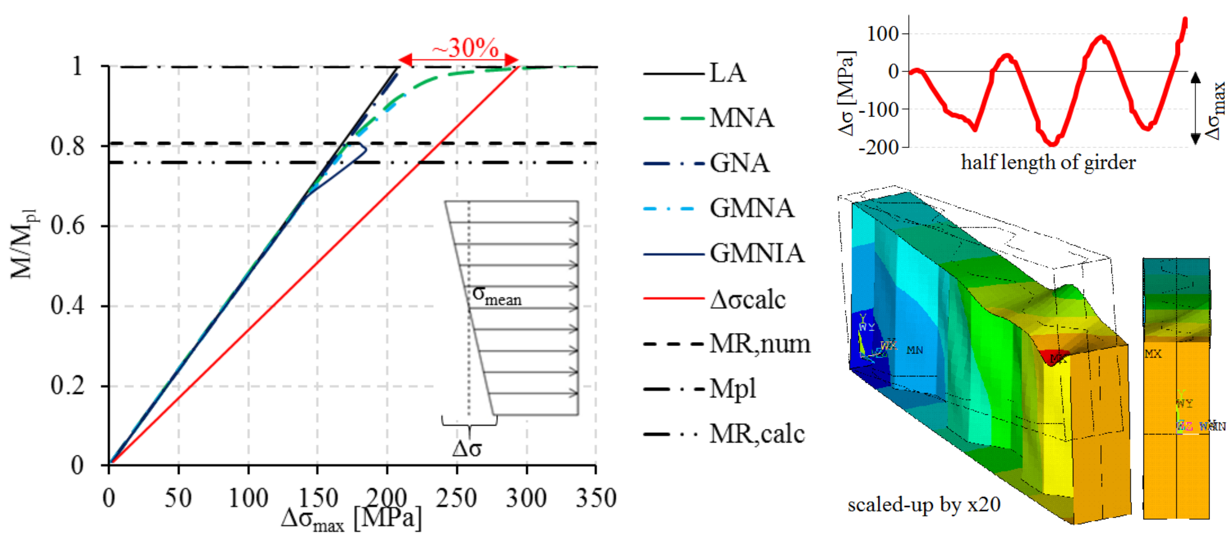
Previously the normal stress distribution in the – compact – flanges was investigated with only linear analysis by different researchers and the occurrence of flange buckling was not considered. Since the imperfections – in shape and size – and nonlinearities (Section 4.1) may have notable effect on the flange buckling behavior, the stress distribution is studied by different analysis levels. In addition the effect of lateral supports is also studied on the normal stress distribution in the compression flange. For sake of simplicity the stress evaluation is performed by means of assuming linear stress distribution along the flange width, even if geometrical and material nonlinearities are active. Their effects are arbitrarily ignored in the stress check. The aim is to give an insight in the tendency of the additional normal stress development. The stress evaluation is represented by the maximum normal stress difference ($\Delta\sigma_{max}$) between the edges of the compression flange.

The transverse bending moment analysis of a simply supported girder without lateral support at the load introduction place (only half of the girder is modeled) is presented by Fig. 7. The bending and shear utilizations are $m=1.0$ and $v=0.7$, respectively, at ultimate. The development of the maximum normal stress difference ($\Delta\sigma_{max}$) between the edges of the compression flange using different analysis levels is presented in Fig. 7a in comparison with the applied in-plane-bending moment. The different lines represent different analysis levels. It is to be noted that the analytically calculated $\Delta\sigma_{calc}$ (from the transverse bending moment according to Fig. 2) – represented by the red line – has a very good agreement with the FEM results at elastic state. The calculated $\Delta\sigma_{calc}$ provides slightly greater values than the linear analysis, however, with the consideration of geometrical nonlinearity slightly greater values are obtained. The tendency of $\Delta\sigma$ along the half of the girder is shown in Fig. 7b from linear analysis. Since no lateral support is applied at midspan the value of amplitudes in all period is nearly the same and the girder displaces to the lateral direction shown in Fig. 7b with a scaled-up diagram from GMNIA. Therefore the failure mode is flange buckling coupled with lateral-torsional-buckling.



a) different levels of analysis b) Δσ distribution and ultimate failure mode

Figure 7: Maximum normal stress difference w/o lateral support under three-point-bending (v=0.7, m=1.0)



a) different levels of analysis b) Δσ distribution and ultimate failure mode

Figure 8: Maximum normal stress difference w/ lateral support under three-point-bending (v=0.7, m=1.0)

To avoid lateral-torsional-buckling failure lateral support is needed to be placed in the load introduction place at the midspan. The previous researches revealed that it may have notable reduction effect on the transverse bending moment, so thus on the maximum $\Delta\sigma$. The influence of the lateral support is presented by Fig. 8. It can be seen that pure flange buckling failure of the compression flange is occurred and the maximum value of $\Delta\sigma$ is reduced by 30% in comparison with the analytical proposal which confirms the observation of the previous investigations (Kövesdi, Jáger and Dunai 2016). Due to the prevention of lateral displacement the tendency of $\Delta\sigma$ along the girder length is chanced (Fig. 8b), in addition the geometrical nonlinearity has a smaller increasing effect on $\Delta\sigma$ (Fig. 8a).

7. Interaction strength analysis

The interaction behavior at ultimate are studied by geometrical and material nonlinear imperfect analysis. Fig. 9 summarizes the overall FEM results normalized to the pure FEM based bending and shear buckling resistances and presents the typical failure modes by von-Mises stresses for different bending and shear utilizations. During the investigations it is observed that the flange buckling and shear buckling failure can develop independently from each other as shown in Fig. 9; the same behavior is observed in the imperfection sensitivity analysis presented in Section 5. The overall results show that the actual interaction behavior can be negligible. The statistical evaluation of the results are tabulated in Table 1. The maximum deviation is obtained only 2% on the unsafe side with average equal to 1.00 found in the 2nd, 5th, and 7th columns of Table 1 regarding the dominant bending, shear and combined loading failures, respectively.

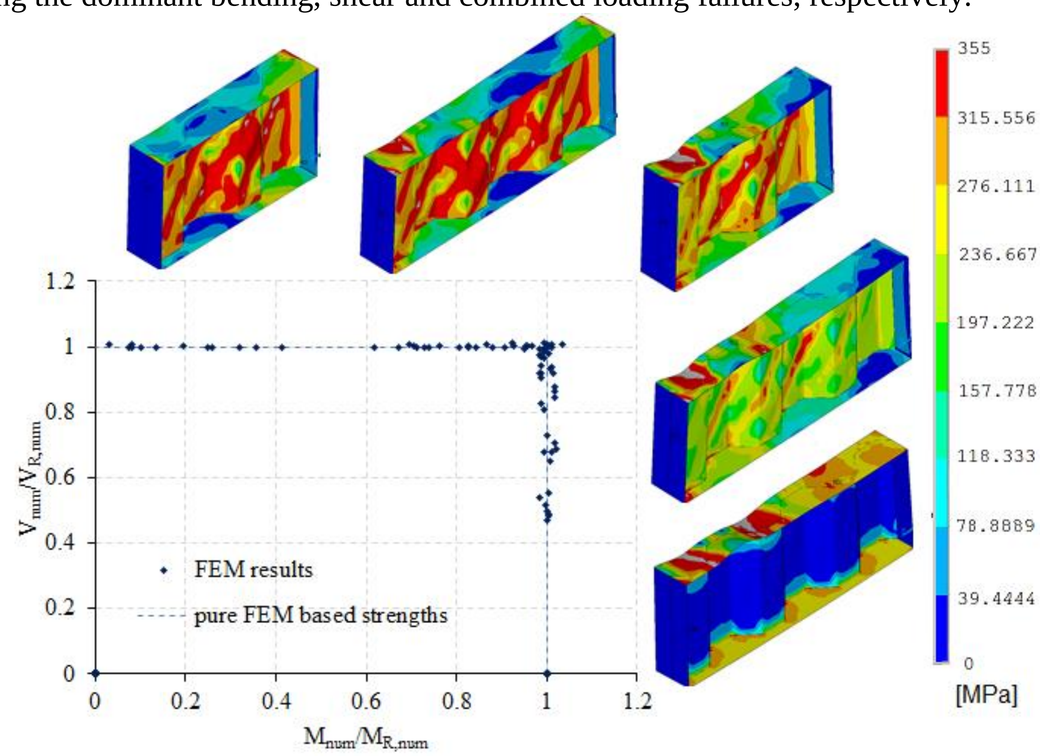
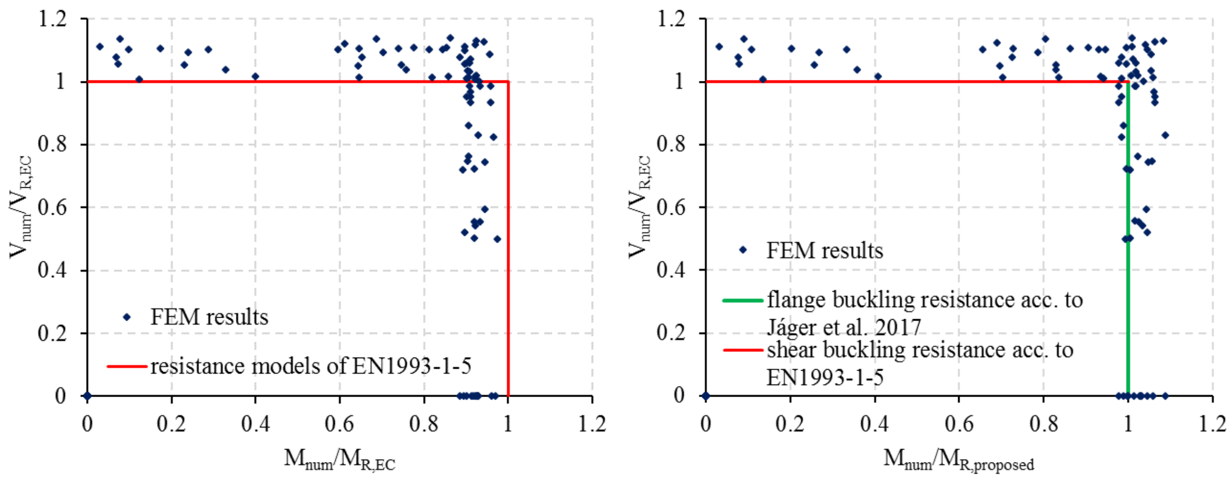


Figure 9: Actual bending-shear interaction behavior with typical failure modes and von-Mises stresses

The FEM based results are also presented in Fig. 10 normalized to the corresponding resistance models of EN1993-1-5 standard and normalized to the recently developed flange buckling resistance model presented by Eqs. 1-4. It can be seen in Fig. 10a that the flange buckling resistance model of EN1993-1-5 provides unsafe solutions for slender flanges. The average is obtained to 0.92 with maximum deviation equal to 11% on the unsafe side shown by the 3rd column of Table 1. However, the shear buckling resistance model of EN1993-1-5 provide results on the safe side shown by 6th column.



a) normalized to the resistance models of EN1993-1-5 b) normalized to the proposed resistance models

Figure 11: Bending-shear interaction

Fig. 10b presents the results when the proposed flange buckling resistance model is used. It can be seen that almost all of the results are on the safe side, the maximum deviation is 2% on the unsafe side shown by 4th column in Table 1. By using this resistance model the statistical evaluation of the interaction resistance is found in the last column of Table 1. The average is obtained to 1.05 with variation coefficient equal to 0.04.

Table 1: Statistical evaluation

	Bending strength			Shear strength		Interaction strength		
	$M/M_{R,num}$	$M/M_{R,EC}$	$M/M_{R,proposed}$	$V/V_{R,num}$	$V/V_{R,EC}$	R/R_{num}	R/R_{EC}	$R/R_{proposed}$
Average	1.00	0.92	1.03	1.00	1.08	1.00	1.02	1.05
Std. Dev	0.01	0.02	0.03	0.00	0.04	0.01	0.08	0.04
CoV	0.01	0.02	0.03	0.00	0.04	0.01	0.08	0.04
Min	0.98	0.89	0.98	0.99	1.01	0.98	0.89	0.98
Max	1.03	0.97	1.09	1.01	1.14	1.03	1.14	1.14

8. Conclusions

In the current research the bending-shear interaction behavior of trapezoidally corrugated web girders having slender flanges is investigated. Girders with compact flanges have been already studied previously. A validated finite element model is used for the investigation of the imperfection sensitivity, the normal stress distributions in the flanges and the interaction behavior at ultimate. Based on the results the following conclusions are drawn:

(i) the imperfection sensitivity analysis shows that the design shear buckling imperfection has no reduction effect on the flange buckling strength and vice versa;

(ii) the results confirmed that the lateral supports has notable reduction effect on the transverse bending moment in the flanges coming from the shear flow in the web;

(iii) no relationship between the transverse bending moment and the reduction in the flange buckling resistance is observed;

(iv) the bending and shear interaction of trapezoidally corrugated web girders having slender flanges is very small and can be negligible in the design. This observations correspond to the interpretation of the “accordion effect” based design, since the shear force is carried by the web and the axial forces are carried by the flanges;

(v) thus the proposed flange buckling resistance model of Jáger et al. (Jáger, Dunai and Kövesdi 2017c) is applicable in the presence of accompanying shear force as well.

Acknowledgments

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