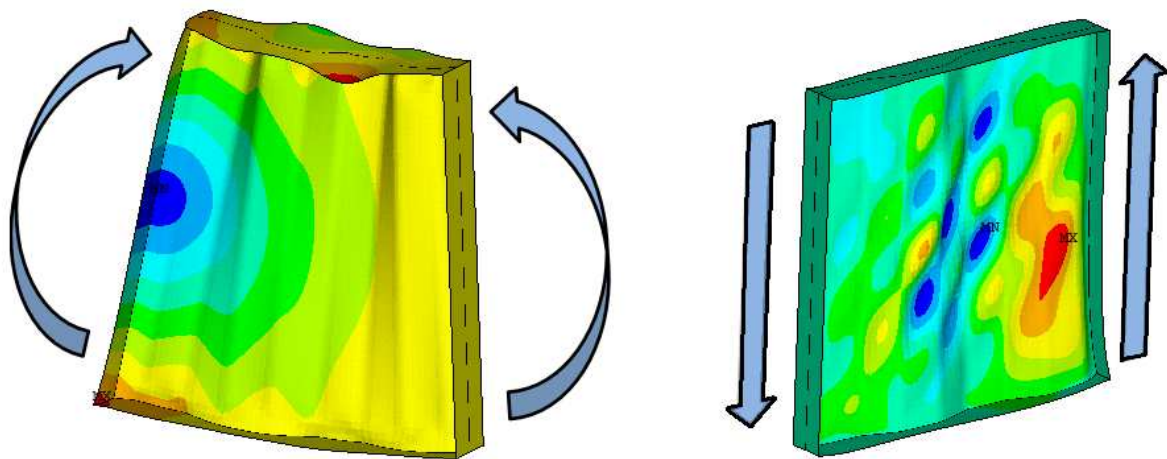




ANALYSIS OF GIRDERS WITH CORRUGATED WEBS SUBJECTED BY COMBINED MOMENT AND SHEAR

Scientific Students' Paper



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MSc 2012

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Budapest, November 2013

TABLE OF CONTENTS

1. Problem statement	4
2. Bending resistance according to EN1993-1-5 Annex D	6
3. Literature overview	9
3.1. Previous studies on the stress distributions and on the bending resistance	9
3.2. Previous studies on the shear buckling resistance	13
3.3. Previous studies on the bending and shear interaction	13
3.4. Evaluation of the previous result and research aims	15
4. Effect of the additional normal stresses according to the Eurocode	17
5. Finite Element Models	24
5.1. Experimental background	24
5.2. Geometric model	26
5.3. Material models	27
5.4. Finite element mesh	27
5.5. Loads and boundary conditions	29
5.6. Analysis types	31
5.7. Applied imperfections	31
5.8. Verification of the numerical models	32
6. Effect of different support conditions on the additional normal stresses	36
6.1. Research strategy and goals	36
6.2. Results of the numerical calculations	36
7. Effect of the geometric parameters on the pure bending resistance	43
7.1. Research strategy and goals	43
7.2. Results of the numerical calculations	43

8. Effect of the transverse bending moment on the bending resistance	48
8.1. Research strategy and goals.....	48
8.2. Numerical research program	48
8.3. Results of the numerical calculations	51
9. Conclusions	54
Acknowledgement.....	56
References	57

ABSTRACT

Corrugated sheets have been used for a long time in geotechnical engineering and for roof covering, but corrugated web girders have been used in the previous 30 years in industrial buildings and bridges. Previous research activities related to the girders with corrugated webs showed that the structural behaviour of the corrugated web girders is different from the conventional I-girders, especially the stress distribution in the flanges and in the web due to the corrugation profile. An additional transverse bending moment develops in the flanges which comes from the shear flow in the corrugated web plate. Due to this additional transverse bending moment additional normal stresses occur in the flanges. Previous research investigations studied the normal stress distributions in the flanges and proposed analytical equations to determinate the maximum possible additional normal stresses coming from the transverse bending moment. But there is a lack of investigations analyzing the effect of the additional normal stresses on the in-plane-bending resistance of the corrugated web girders. There are several recommendations in the international literature regarding to take the effect of the shear force on the in-plane-bending resistance into account, but there are contradictions in the results of the previous studies. Therefore the subject of this paper is the determination of the additional normal stresses in the flanges due to the transverse bending moment and analyzing its influence on the load carrying capacity.

1. Problem statement

The corrugated web plates have been used for 30 years in bridge engineering as the web of a hybrid superstructure and also have been used in building engineering, especially in industrial buildings and halls. Typical layout of a hybrid superstructure can be seen in Fig. 1.

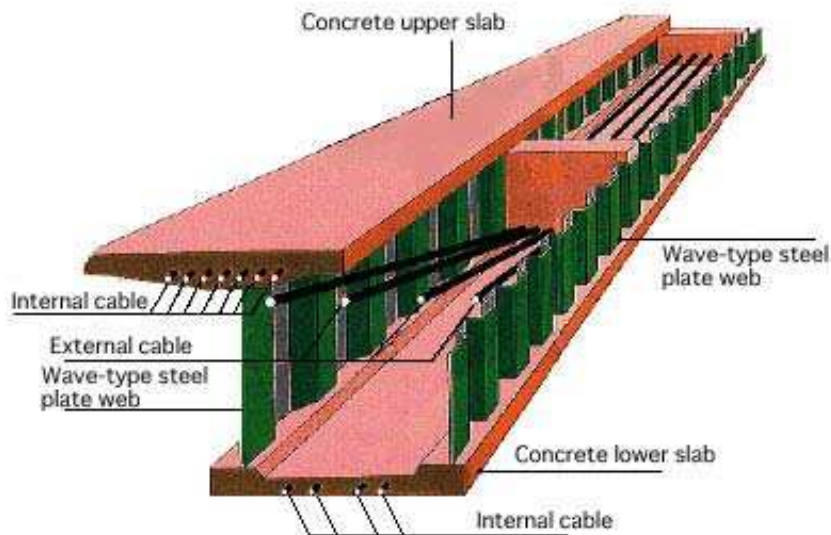


Fig. 1: Typical layout of a hybrid superstructure.

Numerous experimental and numerical investigations can be found in the international literature related to girders with corrugated webs. These investigations are dealing with the strength, stability and fatigue problems of such structures. Several papers investigate the bending and shear resistance of corrugated web girders. Numerous investigations had the focus on the determination of the shear buckling resistance of the corrugated webs taking into account the different buckling failure modes such as local buckling of web folds, global buckling of adjacent web folds and the interaction of two aforementioned phenomena. Further investigations are intended to determine the in-plane-bending resistance of girders with corrugated webs. The main purpose of such investigations is generally the determination of the buckling resistance of the compressed flange plate under bending. Moreover there are many researches regarding to the fatigue behaviour of corrugated web girders.

It is commonly accepted among researchers and designers that the flanges of corrugated web girders are carrying the major part of the bending moment and normal forces and the corrugated web plate is carrying the major part of the shear force. It is also known from previous investigations that the shear flow in the corrugated web indicates transverse bending moment in the flanges resulting additional normal stresses. Numerous papers are dealing with the normal stress distribution in the flanges due to shear force. The purpose of these papers

are mainly the determination of the maximum transverse bending moment in case of different layouts, but there are just a very small number of investigations focusing on the bending moment resistance affected by the modified normal stress distribution. Thus the purpose of this research activities is the analysis of the bending moment resistance reduction of trapezoidally corrugated web girders due to modified normal stress distribution in the flanges. The applied parameters and notations used in this paper are shown in Fig. 2.

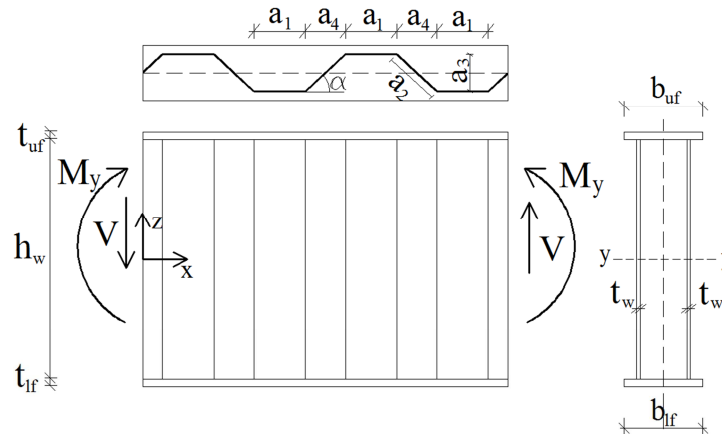


Fig. 2: Geometry of a girder with trapezoidally corrugated web.

In the Eurocode there is recommendation how to calculate the bending resistance of girders with corrugated webs. In this design equation the in-plane-bending moment resistance is reduced by the effect of shear force using a reduction factor. Previous investigations, experimental and analytical studies showed contradictions in this topic, and several researchers had the opinion, that the effect of the transverse bending moment on the bending resistance could be neglected.

In the frame of the recent research work the resistance reduction of the in-plane-bending resistance is analyzed due to the shear force. For analyzing the aforementioned resistance validated numerical models are used verified by test results taken from the international literature. The bending moment reduction factors calculated by the Eurocode standard design formula and the numerical simulations are compared and the importance of the resistance reduction factor is discussed and evaluated.

The purpose of this study is the analysis of the transverse bending moment on the in-plane-bending resistance and harmonizing the previous research results.

2. Bending resistance according to EN1993-1-5 Annex D

There are several contradictions in the international literature considering the influence of the additional normal stresses on the bending resistance. The design rule of EN1993-1-5 Annex D [1] gives a reduction factor for the bending resistance of the corrugated web girders, if the girder is also subjected by shear force. The pure bending resistance of the corrugated web girders according to [1] can be determined by the Eq. (1).

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

The used notations can be seen in Fig. 2. The χ factor considers the plate buckling phenomenon of the compressed flange. The EN1993-1-5 Annex D suggests using buckling coefficient assuming an equivalent rectangular plate supported along three edges. The buckling coefficient can be calculated as follows:

$$k_{\sigma} = \max(0,6; 0,43 + (c/a)^2) \quad (2)$$

where: c the greatest outstand from weld to free edge,

a the greatest length of the assumed plate ($a = a_1 + 2a_4$, see Fig. 2).

The flange buckling is considered in EN1993-1-5 by the buckling coefficient given above in Eq. (2). After determination of the buckling coefficient the relative slenderness and the reduction factor related to the outstand compression elements can be determined on the same way as for the conventional I-girders.

If the girder is subjected also by shear force the bending resistance should be reduced by a reduction factor (f_T) which depends on the flange size and on the maximum normal stress coming from the transverse bending moment. The reduced bending resistance can be determined by Eqs. (3)-(4), if the value of χ is equal by 1,0.

$$M_{V,Rd} = f_T \cdot M_{Rd} \quad (3)$$

$$\text{where: } f_T = 1 - 0,4 \sqrt{\frac{\sigma_x(M_z)}{f_{yf}}} = 1 - 0,4 \sqrt{\frac{6M_{z,\max}}{f_{yf} b_f^2 t_f}} \quad (4)$$

f_{yf} yield strength of the flange plate,

γ_{M0} partial factor for stress check,

$\sigma_{x(M_z)}$ maximum value of the additional normal stresses coming from transverse bending moment,

$M_{z,max}$ maximum value of the transverse bending moment.

According to the EN1993-1-5 Annex D [1] the maximum value of the transverse bending moment can be calculated by the Eq. (5). The theoretical background of the calculation of the maximum transverse bending moment due to shear force is shown in Fig. 3. It can be seen that this theory assumes that the girder is supported under a parallel fold of the corrugated web, the number of the web corrugation is odd and the shear force along a corrugation is constant.

$$M_{z,max} = \frac{V}{h_w} \frac{a_3}{4} (2a_1 + a_4) \quad (5)$$

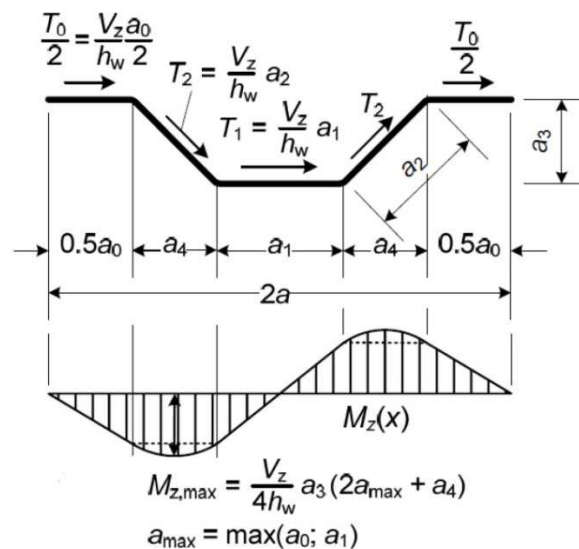


Fig. 3: Calculation of the maximal transverse bending moment.

The reduction factor in Eq. (4) was developed by Lindner [2] and it was also implemented in the DAST-Richtlinie 015 [3]. However the same reduction factor is not considered in the Austrian and Swedish design rules, because it was stated that the effect of the additional normal stresses on the bending resistance is not too large. The commentary document of the EN1993-1-5 [1] also emphasizes that from theoretical point of view these bending moments are required for reasons of equilibrium, but it is questionable how important they actually are in real life [4]. Elgaaly et al. investigated the bending and shear resistance of the trapezoidally corrugated web girders in 1997-98 [5], [6] and [7]. Their conclusion was that there is no interaction between the bending and shear resistance of the trapezoidally corrugated web girders. It was proved by Pasternak and Hannebauer [8] in 2003 that in case of sinusoidal

corrugation profiles the effect of the additional bending moment can be neglected, and the reduction factor f_T can be set to 1.0. Against it Kuchta proposed in 2006 an M-V interaction equation for girders with sinusoidally corrugated webs [9], however it has to be mentioned that only a small interaction behaviour is observed during the investigations.

Due to the contradictory observations on the importance of the additional normal stresses on the bending resistance this paper focuses on the analysis of the structural behaviour of the trapezoidally corrugated web girders under combined bending and shear. The aim of the investigation is to analyse the effect of the transverse bending moment on the bending resistance and to harmonize the previous research results. The necessary consideration method of the transverse bending moment in the design is also discussed.

3. Literature overview

In this section the previous investigations are presented in the field of girders with corrugated web. Numerous experimental and numerical investigations can be found in the international literature related to girders with corrugated webs. These investigations are dealing with the strength, stability and fatigue problems. Several papers investigate the stress distributions and the bending and shear resistance of corrugated web girders. Numerous investigations focus on the determination of the shear buckling resistance of the corrugated webs taking into account the different buckling failure modes such as local buckling of web folds, global buckling of adjacent web folds and the interaction of two aforementioned phenomena. Further investigations are intended to determine the in-plane-bending moment resistance of girders with corrugated webs. In the following subsections the different fields of investigations are presented in detail.

3.1. Previous studies on the stress distributions and on the bending resistance

The international literature includes many investigations on the stress distributions of the flange plates and web plate of girders with corrugated web. The stress distributions in the web and in the flanges were investigated by different researchers in the past such as Linder [2] in 1992, Aschinger and Linder [10] in 1997, Elgaaly et al. [5] in 1997, Huang et al [11] in 2004, Mori et al. [12] in 2006, Abbas et al. [15], [16], [17] in 2006 and 2007, Hannebauer [13] in 2008 and Kövesdi et al. [14] in 2012.

The **normal stress distribution in the web** is almost negligible in the greatest part of the web depth, only very close to the flanges it has a considerable value but it decreases rapidly towards to the axial centerline of the web folds. Some papers suggest considering the lower and upper 15% of the web depth when the normal stresses are calculated in a cross section with a parallel fold, however it is also negligible at an inclined fold of the corrugated web. This phenomenon is called as “accordion effect”. Therefore the web is neglected in the calculation process of the bending moment resistance of corrugated web girders in the praxis.

The **normal stress distribution in the flanges** of corrugated web girders is not constant along the width of the flange plate length. There is a significant difference between the two edges of the flange plate in a cross section and this normal stress difference has an alternating tendency along the girder length. This stress difference can be explained by two different effects. The first reason is the different interlock between the flange and the web plates at the parallel and at the inclined folds and the second one is the effect of the shear force. The

normal stress difference between the two edges is relatively small due to the effect of the different interlock. In a cross section at a parallel fold the interlock is more efficient than in a cross section at an inclined fold of the corrugated web. The normal stress difference in the flanges will be much more dominant if the girder is affected by combined bending and shear.

The normal stress distribution and the bending moment resistance of girders with corrugated web were investigated firstly by Linder [2]. It was proposed that the bending moment resistance reduction is theoretically calculated only from the additional normal stresses due to shear flow in the corrugated web and the design proposal was developed by this way. According to Linder the direction of the shear flow follows the shape of the web corrugation and based on this the flange can be assumed as a girder loaded by additional lateral forces (F_y) and transverse bending moments (M_z) coming from the shear flow, as shown in Fig. 4. This mechanical model is proved by all the previous investigations.

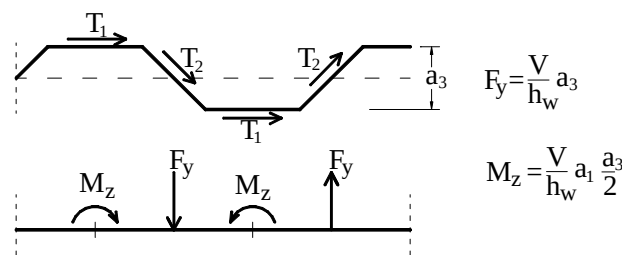


Fig. 4: Theoretical background of the transverse bending moment [2].

In the field of this research topic Abbas et al. carried out similar results. The stress distribution in the flanges was analyzed under in-plane loading. The so called “fictitious load method” was developed which is similar to the mechanical model of Linder.

According to the „Commentary and worked examples to DIN-EN-1993-1-5 Plated Structural Elements” [4] the maximal transverse bending moment can be calculated with the Eq. (5) which is relevant to the mechanical model of Linder. The theoretical background of the calculation of the maximum transverse bending moment resistance can be seen in Figs. 3-4.

The theoretical investigations of Balaz [18] proved also the applicability of this theory and it is proposed to implement the Eq. (5) into the EN1999-1-1 [19].

In 2012 Kövesdi et al. [14] analyzed girders with corrugated web from point of view of the additional normal stresses in the flanges with different girder geometries, corrugation profiles, loading and support conditions. In the Fig. 5 the different girder can be seen which were analyzed.

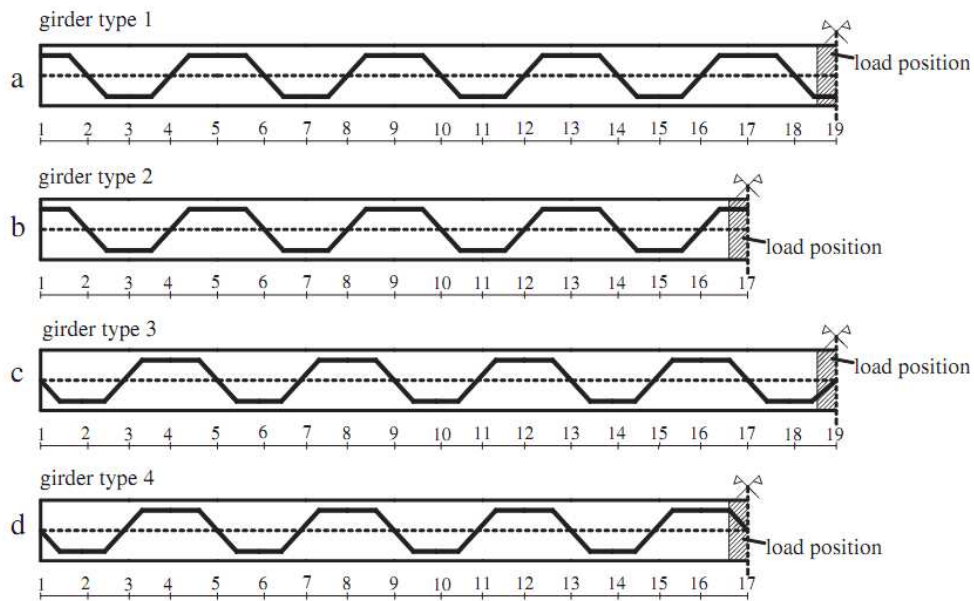


Fig. 5: Analyzed girder geometries, and support and loading conditions.

The numerical results show that the aforementioned variables have significant effect on the structural behaviour of trapezoidally corrugated web girders. At first the most unfavorable geometric layout is when the girder is supported under at an inclined fold of the web instead of the recommendation of the Eurocode where the girder is started and ended with a parallel fold of the web. According to Kövesdi et al. the maximum possible transverse bending moment can be calculated by the Eq. (6) which is twice as large as obtained from Eq. (5) and the maximum possible transverse bending moment diagram can be seen in Fig. 6.

$$M_{z,\max} = \frac{V}{h_w} \frac{a_3}{2} (2a_1 + a_4) \quad (6)$$

Furthermore the numerical calculations showed that the proposal of Linder and Aschinger [10] will give a good approximation for the maximum additional transverse bending moment in the flanges if the shear force diagram along the girder length is constant, but it will give smaller values comparing to the numerical results if the shear force diagram is not constant or the fold lengths of the corrugation profile are not equal.

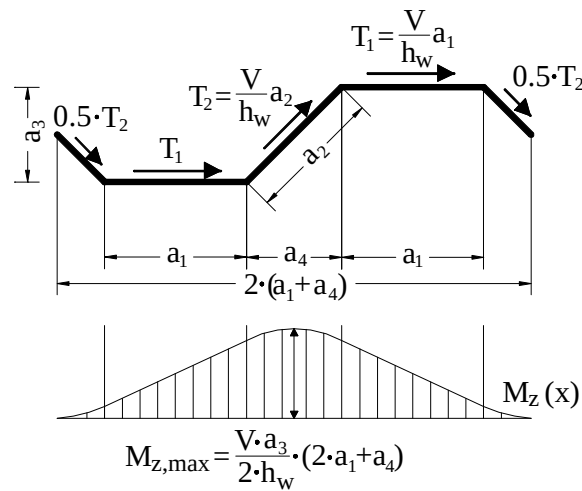


Fig. 6: Proposal for the maximum possible transverse bending moment calculation [14].

Moreover the proposed closed form solution of Abbas et al. gives exactly the same result as the Eq. (6) proposed by Kövesdi et al., but the applicability is relatively narrow, because it can not consider different loading conditions. If the girder is loaded by uniformly distributed load the obtained maximum transverse bending moment from the proposal of Abbas et al. will give a good approximation in comparison with the numerical results.

Due to the numerous investigations it is known that the shear force causes additional transverse bending moment in the flanges of corrugated web girders. The theoretical background and the calculation methods are clarified, but there is a lack of investigations dealing with the effect of this transverse bending moment on the in-plane-bending resistance of corrugated web girders.

3.2. Previous studies on the shear buckling resistance

Numerous studies are dealing with the shear buckling resistance of the corrugated web girders. In this field the first investigation was done by Easley and McFarland [20] in 1969. They suggested a formula for the calculation of the global shear buckling resistance for corrugated webs. In this study the corrugated web was supposed as an orthotropic flat web. After that several experimental, numerical and theoretical investigations have been performed in this field. In 1988 and 1992 Linder and Aschinger [21], [10] analyzed the shear buckling resistance of girders with corrugated web. Experimental investigations were done by Bergfelt et al. [23] in 1984, Elgaaly et al. [7] in 1996, Yamazaki [22] in 2001, Driver et al. [24] in 2006, Scheer [25] and Moon et al. [26] in 2009.

Numerical investigations were executed by Luo and Edlund [27] in 1996 and by Yi et al. [28] in 2008 where all the geometric parameters of the corrugation profile were analyzed including the span length and web depth and thickness. Other experimental and numerical investigations were carried out by Pasternak and Hannebauer [8], [29] in 2003 and 2004, Moon et al. [26] in 2009, Eldib [31] in 2009 and Hassanein and Kharoob [30], [32] in 2013. Based on these investigations different design proposals were derived to determine all the three type of shear buckling failure modes, namely the local, global and interactive shear buckling resistances.

3.3. Previous studies on the bending and shear interaction

In the international literature there are many papers dealing with the bending resistance and shear buckling resistance of corrugated web girders separately and there is just a few numbers of investigations paying attention to the combined bending and shear loading.

Both bending and shear buckling resistance of the corrugated web girders was investigated by Elgaaly et al. in 1997 and 1998 [5]-[7]. Based on the experimental investigations a numerical model was developed on which the stress distribution in the flanges of girders with corrugated web was analyzed in detail. The experimental and numerical results showed that the contribution of the web to the ultimate moment capacity of such girders is negligible, thus the in-plane-bending resistance can be calculated only from the contribution of the flanges. It was also demonstrated that the shear force is carried only by the corrugated web. Based on their investigations they also stated that there is no interaction between the shear and bending resistance of the trapezoidally corrugated web girders.

The EN1993-1-5 [1] recommends how to consider the effect of the shear force on the bending resistance. It suggests taking the reduction factor (f_T) according to the formulas of Eqs. (3)-(5)

into account as a multiplication factor of the pure bending resistance of a given girder. As far as the authors know, this reduction factor was calibrated based on experimental results on specimens tested by combined bending and shear, where the failure mode was lateral torsional buckling of the specimens. Based on my opinion, it is an important task, because the current paper focuses only on the combined bending and shear resistance of the corrugated web girders and the lateral torsional buckling resistance determination is not the topic of this paper.

Sinusoidally corrugated web girders have been intensively studied on this research field by Pasternak and Hannebauer [8] in 2003. They investigated the effect of the shear force on the in-plane-bending resistance of the sinusoidally corrugated web girders. According to their results the additional normal stresses indicated by the shear force have no significant effect on the in-plane-bending resistance in case of usual girders with sinusoidal corrugations used in the praxis. The ratio of the corrugation depths and the usually used flange widths are relatively small, therefore the reduction of the in-plane-bending resistance due to the transverse bending moment in the flanges can be neglected. This statement is noted in the EN1993-1-5 Annex D [1], that the reduction factor (f_T) can be set to 1,0 in case of sinusoidally corrugated web girders.

Another research was carried out by Kuchta [9] in 2006 investigating the structural behaviour of sinusoidally corrugated girders under combined bending and shear. Based on the executed experimental investigations a numerical model was developed. In this research program the interaction behaviour and the stress distributions under the different loading situations were analyzed. As a result of the investigation an interaction equation is proposed for girders with sinusoidally corrugated web under the combined loading situation. According to the aforementioned interaction equation there is a small reduction in the load carrying capacity of such girders. In the model of Kuchta related to the investigation of the bending resistance the effect of the transverse bending moment is not considered thus the magnitude of the additional normal stresses in the flanges were not studied. Furthermore the shear resistance and bending resistance of the girders were determined separately based on the plastic resistance of the web and the plastic resistance of the flanges neglecting the possible shear buckling or flange buckling phenomena. According to the proposal of Kuchta [9] the maximum reduction of the bending or the shear resistance in the M-V interaction is 1/12 (8,33%). The proposed interaction diagram can be seen in Fig. 7.

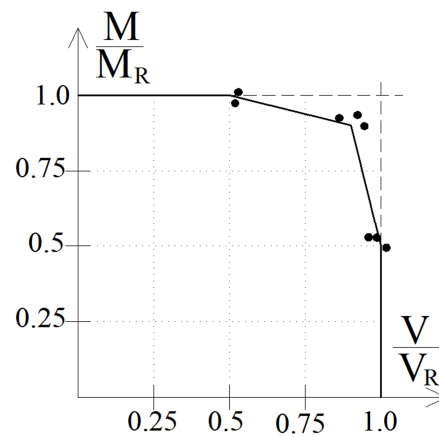


Fig. 7: M-V interaction diagram for sinusoidally corrugated web girders [9].

3.4. Evaluation of the previous result and research aims

Based on the previous investigations, it can be stated that the effect of the transverse bending moment on the in-plane-bending moment resistance of girders with corrugated web is still not clarified until now. The different research results from different authors should be harmonized. The reduction factor in the EN1993-1-5 [1] is still questionable in the practice design according to several researchers in the past. That is why further investigation is needed in this field to clarify the structural behavior of corrugated web girders under combined moment and shear.

The following questions which should be answered in this paper that what is the magnitude of the additional normal stress and which parameters influence the the additional normal stresses in case of typical girders used in the praxis. Furthermore how significant can be the effect of the shear force on the in-plane-bending moment resistance, and moreover is it necessary to consider the transverse bending moment in the practical design and how can it be considered in the design formula.

To give answers to the above questions, the following research strategy is carried out. Firstly numerous existing experimental and numerical investigations on the research field of corrugated web girders are collected in this paper. Data base have been made with more than 1900 girder geometries which were found in the international literature. For each girder the bending moment reduction factors according to the EN1993-1-5 [1] are calculated and compared. This comparison gives an overview about the importance of the reduction factor in the case of typical girders used in the practice or investigated by researchers in the past.

Numerical investigations showed, that the support conditions have a large influence on the additional normal stresses in the flanges. In the case of real structural elements, the transverse bending moment is influenced by the support conditions and its value can be significantly smaller than the theoretically determined maximum value. To give overview about the effect of the lateral and longitudinal support conditions on the normal stress distribution, girders with different support conditions are investigated and the normal stress distributions are compared.

Finally the recent research program contains the analysis of the structural behavior of girders with corrugated web under pure bending and combined bending and shear using numerical simulations (GMNIA). Based on test results found in the literature and own experiments [14] numerical model is developed and verified on which the M-V interaction behavior is studied, and the effect of the shear force on the bending resistance is determined on various girder geometries. The numerically calculated resistances are compared to the design equations. The aim of the recent paper is to give proposal how to handle the M-V interaction for girders with trapezoidally corrugated web for the practical design.

4. Effect of the additional normal stresses according to the Eurocode

This Section is meant to analyse the magnitude of the transverse bending moment in the flanges of typical corrugated web girders which are used in the practical design and determine their in-plane-bending moment resistance reduction factors (f_T) according to the EN1993-1-5 [1]. The reduction factor which can be calculated by Eq.(4) depends on the applied shear force, therefore this formula represents the M-V interaction curve which can be seen in Fig. 8.

It can be observed that the interaction equation has different character than in case of usual steel structures. The maximum possible value ($f_{T,max}$) is related to the shear force applied on the structure equal to the shear resistance of the given girder. The maximum transverse bending moments in the flanges can be calculated in two different ways depending on the support conditions (see Fig. 5). If the girder is supported under at the parallel fold of the web the maximum transverse bending moment in the flanges can be determined analytically with the Eq. (5) (see Fig. 3) representing by line II., otherwise the maximum transverse bending moment can be determined with Eq. (6) (see Fig. 6) representing by line I. The transverse bending moment calculating with Eq. (6) (line I. in Fig. 8) is two times greater than calculating with Eq. (5) (line II. in Fig. 8), thus the Eq. (6) gives the maximum possible value representing by line I.

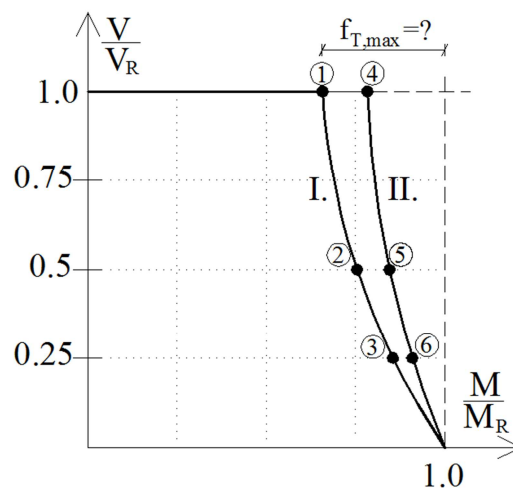


Fig. 8: M-V interaction diagrams according to EN1993-1-5 [1] and evaluation strategy. Hereafter the interaction diagram which is characterized by this maximum possible value (line I. in Fig. 8) is presented in detail, because this is the basis of the current comparison (point 1 in Fig. 8). Due to the data base which consists of 1900 collected girder geometries found in the international literature the maximum value of the in-plane-bending resistance reduction factor ($f_{T,max}$) is determined for each geometries. For all the analyzed girders firstly the shear

resistance is calculated according to the EN1993-1-5 [1] and then the maximum reduction factors ($f_{T,max}$) are determined from this shear resistance as the maximum possible applied shear force on the structure. This maximum value of the applied shear force (equal to the shear resistance) acts on the real structures very rarely, therefore the reduction factor of the in-plane-bending resistance is also determined in case of shear force levels equal to the 25% and 50% of the shear resistance (points 2-3, in Fig. 8). These situations can frequently occur on real structures. In the Fig. 8 the point 4-6 means the corresponding values with regarding to the line II. where the transverse bending moment is determined by Eq. (5).

It can be seen that in case of one girder geometry 6 different values are calculated representing the bending reduction factors at three different shear force levels using two different support conditions (points 1-6 in Fig. 8). It has to be mentioned, that the reduction factor of Lindner [2] is calibrated by using the maximum value of the additional normal stresses. The theoretically derived equation consisted a factor of 0.816, but its value has been reduced to 0,4 in Eq. (4) for design purposes. The background of it is that the value of the transverse bending moment has large changes along the girder length, even its sign can be changed.

The maximum additional normal stresses in the flanges are also calculated and compared to the yield strength of each analyzed girder. The comparison shows that how much does the transverse bending moment increase the normal stress field in the flanges. It means that if the girder is designed based on the allowable elastic stresses, and its bending utilization ratio for in-plane-bending is 1.0, the effect of the transverse bending moment can be characterized by the ratio of σ_x/f_y . This ratio represents the overstress ratio in case of elastic design, if the additional normal stresses are neglected from the design and the bases of the design is the yield strength. This comparison is just a fiction, gives not real utilization values, but it characterizes the importance of the transverse bending moment in the practical design.

In the frame of this study typical girder geometries with trapezoidally and sinusoidally corrugated webs are also collected and evaluated. An equivalent trapeze profile is prepared in case of sinusoidal web corrugation to evaluate the geometrical properties and to determine the additional normal stresses indicated by the shear force. The evaluation is carried out separately for trapezoidally and sinusoidally corrugated web girders. The girder geometries of the experimental and numerical calculations which were executed in the past are also collected for both girder types.

In case of trapezoidal corrugation 115 different girder geometries are found which were tested experimentally and 292 different girder geometries are found which were analyzed numerically.

12 different girder geometries are collected from existing bridge structures with corrugated web girders. These bridges are the Altwipfergrund bridge [33] [34], Shinkai bridge [30], Matsunoki bridge [30], Hondani bridge [30], Cognac bridge [30], Maupre bridge [30], Dole bridge [30], Maetani bridge [11], Ilsun bridge [30] and the Móra Ferenc bridge [36][37]. In case of several bridges only the geometry of the corrugation profile and the web depths were available from the literature. In these cases fictitious flange sizes are assumed, which are usually used for these kind of bridges.

In case of sinusoidal corrugation 1519 different girder geometries are found in the product catalog of the company Zeman [38]. In most of the papers in the international literature the authors analyze the same geometries as can be found in the product catalog, however Hannebauer [13] and Kuchta [9] analyzed girders with sinusoidally corrugated web slightly different geometries in comparison with the girder geometries in the product catalog.

In total of 1941 different girder geometries are collected from the international literature and product catalogs and the transverse bending moment is calculated and its effect is evaluated for each girders. In case of sinusoidally corrugated web girders the corrugation depths are small (40 – 43 mm) in comparison with the flange width, and the fold lengths of the equivalent trapeze profiles are also relatively small (30 - 60 mm), and the thickness of the web is also small (1,5 – 6 mm). These girders are used in building structures as shown in Fig. 9.

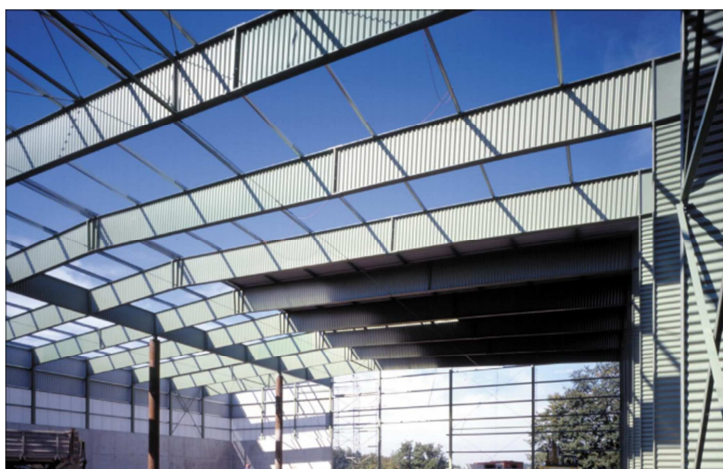


Fig. 9: Corrugated web girders used in industrial buildings, from [38].

In case of girders with trapezoidally corrugated web the size of the corrugation profile extremely different. The folds lengths which are applied are mostly between 150 – 400 mm are larger and the sizes of the flanges are also larger than in case of sinusoidal corrugation profiles. This can be attributed to that fact that the trapezoidally corrugated web girders are mostly used in bridge structures as shown in Fig. 10.



Fig. 10: Corrugated web girders used in bridges, from [39].

Due to the differences between the applied geometrical sizes of the sinusoidally and trapezoidally corrugated web girders the transverse bending moment coming from the shear force are significantly different, therefore the magnitude of the bending resistance reduction factor (f_T) are also significantly different.

Table 1: Girder geometries collected from international literature.

	corrugation angle (α) [°]			fold length (a_1) [mm]			fold length (a_2) [mm]		
	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average
Sinusoidal corrugation	20	38	37,9	26	100	26,5	65	220	66,1
Trapezoidal corrugation	10	90	39,4	20	750	245,1	14	707	237,1
Existing bridges	25	39	33,3	250	430	334,8	250	430	340,3

In Table 1 the minimum, the maximum and the average values of the corrugation angle and the fold lengths can be seen which are calculated with the help of the available data base containing the collected girder geometries. The different statistical values with regarding to the sinusoidal and trapezoidal corrugations and the existing bridges are separately calculated. In case of trapezoidal corrugation the difference between the minimum and maximum values is much larger than in the other two cases, because this kind of girders was widely analyzed by different researchers, however the average values can be more comparable. It can be observed that the corrugation angles are almost the same for all the three groups. The average

fold lengths are smaller in case of sinusoidal corrugation and larger in case of the existing bridges.

The Table 2 shows the maximum, minimum and average values of the calculated additional normal stresses and the bending resistance reduction factors of sinusoidal, trapezoidal and existing bridge corrugations with 3 different load situations using the maximum possible transverse bending moment (points 1-2-3 in Fig. 8).

The average value of the additional normal stresses indicated by the shear force equal to shear resistance is 9,18 MPa in case of typical girders with sinusoidal corrugation. The same value for girders with trapezoidal corrugation and existing bridges are 107,9 MPa and 159,6 MPa, respectively. It can be observed that the effect of the transverse bending moment in case of existing bridges or trapezoidal corrugation is much larger, than in case of sinusoidal corrugation.

Table 2: Calculated additional normal stresses and reduction factors using the maximum transverse bending moment (Eq. 6).

Evaluation of Line I. using the maximum transverse bending moment		additional normal stress $\sigma_{x,(Mz)}$ [MPa]			bending resistance reduction factor f_T [-]		
		Min.	Max.	Average	Min.	Max.	Average
Point #1 (100% shear force)	Sinusoidal corrugation	0,34	65,68	9,18	0,79	0,98	0,93
	Trapezoidal corrugation	0,8	488,9	107,9	0,58	0,99	0,81
	Existing bridges	60,4	651,7	159,6	0,46	0,84	0,75
Point #2 (50% shear force)	Sinusoidal corrugation	0,2	32,8	4,6	0,85	0,99	0,95
	Trapezoidal corrugation	0,4	244,4	54,1	0,71	0,99	0,87
	Existing bridges	30,2	325,9	79,8	0,62	0,88	0,82
Point #3 (25% shear force)	Sinusoidal corrugation	0,1	16,4	2,3	0,89	0,99	0,97
	Trapezoidal corrugation	0,2	122,2	27,2	0,79	0,99	0,90
	Existing bridges	15,1	162,9	39,9	0,73	0,92	0,88

The large differences between sinusoidal and trapezoidal corrugations are attributed to the sizes of the geometric parameters and not the shape of the corrugation (sinusoidal or trapezoidal). The average of the bending resistance reduction factors related to the maximum applied shear force situation (shear resistance) are 0,93, 0,81 and 0,75 for the the three different groups, which means that the in-plane-bending resistances are reduced on an average with 7% for the sinusoidally corrugated web girders and 19% and 25% for the trapezoidally corrugated web girders and existing bridges. It can be observed that in case of trapezoidally corrugated web girders and in case of the existing bridges the maximum bending resistance reduction can reach a value close to 50% according to the EN1993-1-5 [1] if the shear

resistance is applied as the shear force on the structure which is extremely high. These aforementioned values are corresponding to the point 1 in the Fig. 8.

The additional normal stresses and the bending reduction factors can be significantly smaller if the 50% or 25% of the shear resistances are applied on the structure as shear force. These values are corresponding to the point 2 and 3 in the Fig. 8. The values of the additional normal stresses are in linear relationship with the applied shear force, which means that if the half of the shear resistance is applied as shear force on the structure then the additional normal stresses will be the half of original one. In the last three rows of the Table 2 in which only the fourth of the shear resistance is applied as shear force it can be seen that the average values of the additional normal stresses are 2,3 MPa for sinusoidal corrugation, 27,2 MPa for trapezoidal corrugation and 39,9 MPa in case of the existing bridges. These last two values are still dominant and can have a significant effect on the structural behavior of the bending resistance.

Table 3: Calculated additional normal stresses and reduction factors using the transverse bending moment determined by Eq. (5).

Evaluation of Line II. using the average transverse bending moment		additional normal stress $\sigma_{x,(Mz)}$ [MPa]			bending resistance reduction factor f_T [-]		
		Min.	Max.	Average	Min.	Max.	Average
Point #4 (100% shear force)	Sinusoidal corrugation	0,2	32,8	4,6	0,85	0,99	0,95
	Trapezoidal corrugation	0,4	244,4	54,1	0,71	0,99	0,87
	Existing bridges	30,2	325,9	79,8	0,62	0,88	0,82
Point #5 (50% shear force)	Sinusoidal corrugation	0,1	16,4	2,3	0,89	0,99	0,97
	Trapezoidal corrugation	0,2	122,2	27,2	0,79	0,99	0,90
	Existing bridges	15,1	162,9	39,9	0,73	0,92	0,88
Point #6 (25% shear force)	Sinusoidal corrugation	0,1	16,6	1,2	0,92	0,99	0,98
	Trapezoidal corrugation	0,1	98,1	13,7	0,80	1,00	0,93
	Existing bridges	7,5	81,5	20,0	0,81	0,94	0,91

The bending resistance reduction factors are in nonlinear relationship with the applied shear forces, however the same tendencies can be observed. In the last three rows of the Table 2 in which only the fourth of the shear resistance is applied as shear force it can be seen that the average values of the reduction factors can reduce the in-plane-bending resistance with 3% in case of sinusoidally corrugated web girders and 10% and 12% in case of trapezoidally corrugated web girders and existing bridges, while the maximum reduction in case of existing bridges can reach the 27% of the bending resistance which is a significant reduction in the bending resistance for typical bridge girders.

The same evaluation procedure can be seen in Table 3 where the transverse bending moment in the flanges are determined with the help of the Eq. (5) instead of Eq. (6), thus this Table is corresponding to the line II. in the Fig. 8. It can be seen from the results that the average value of the bending resistance reduction factors for girders with sinusoidally corrugated web is 0,95 and for trapezoidally corrugated web girders and existing bridges these values are 0,87 and 0,82. If only the fourt of the shear resistance is applied as shear force on the structure the reduction factors are on an average between 0,91 – 0,98.

In the Table 4 the additional normal stresses indicated by the transverse bending moment are in comparison with the yield strength of the flange plate when the 50% and the 25% of the shear resistance as shear force are acting on the structure. The results show the effect of the additional transverse bending moment on the bending resistance, if elastic design method is used with maximum allowable normal stress. The values in the Table 4 show the difference in the bendind utilization. The results represent that if the 50% of the shear resistance is applied as shear force on the structure that the average effect of the additional normal stresses can be 3,6% for sinusoidally corrugated web girders, however it can be 14%-20% for trapezoidally corrugated web girders and existing bridges.

Table 4: Differences between bending utilization ratios considering or neglecting the effect of the transverse bending moment.

Evaluation of Line I. using the maximum transverse bending moment		$\sigma_{x,(Mz)} / f_y$ [%]		
		Min.	Max.	Average
Point #2 (50% shear force)	Sinusoidal corrugation	0,35	17,47	3,61
	Trapezoidal corrugation	0,06	54,04	14,18
	Existing bridges	6,89	91,79	19,80
Point #3 (25% shear force)	Sinusoidal corrugation	0,2	8,7	1,8
	Trapezoidal corrugation	0,0	27,0	7,1
	Existing bridges	3,4	45,9	9,9

5. Finite Element Models

The finite element models are developed in ANSYS 14.5. The developed finite element models (geometric, mesh, load and boundary conditions) are introduced in this section. The experimental background, the analysis type and the verification of the numerical models are also presented in this section. Most of the subsections are divided into two parts according to the additional normal stress analysis in the flanges and the in-plane-bending moment resistance analysis including the M-V interaction analysis of girders with corrugated web.

5.1. Experimental background

Additional normal stress analysis in the flanges

Large scale tests have been done in the last few years to analyze the fatigue and patch loading resistance of girders with corrugated web by the BME Department of Structural Engineering. From these experiments the measured results of one specimen which is loaded by static load are used to verify the numerical model for the analysis of the additional normal stresses in the flanges. The geometric parameters of this specimen (specimen number 3) can be seen in Fig. 11 and Fig. 12. During the loading of the specimen the deflection of the midspan and the stresses in some cross sections were measured with the help of strain gauges.



Fig. 11: Experimental layout. [14]

Geometric parameters of the specimen number 3:

-	length:	7147 mm
-	span:	6765 mm
-	web depth:	499.39 mm
-	web thickness:	6.01 mm
-	flange thickness:	20.53 mm
-	flange width:	224.62 mm

- weld size: 6 mm
- angle of the inclined fold of the web: 39 degree
- bending radius of the corrugation: 60 mm

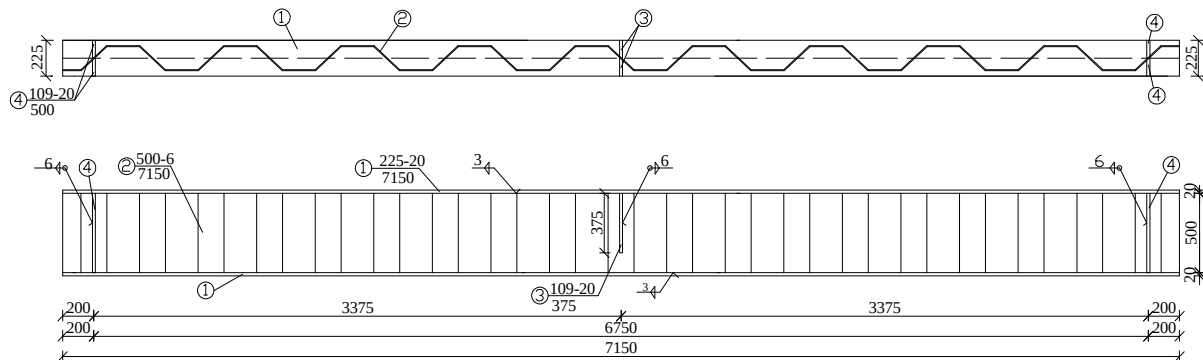


Fig. 12: Geometry of specimen number 3.

The geometrical differences between the specimen and the numerical model are that there is no stiffener in the numerical model and the length of the model is equal to the span length. The profile of the trapezoidal corrugation can be seen in Fig. 13 below.

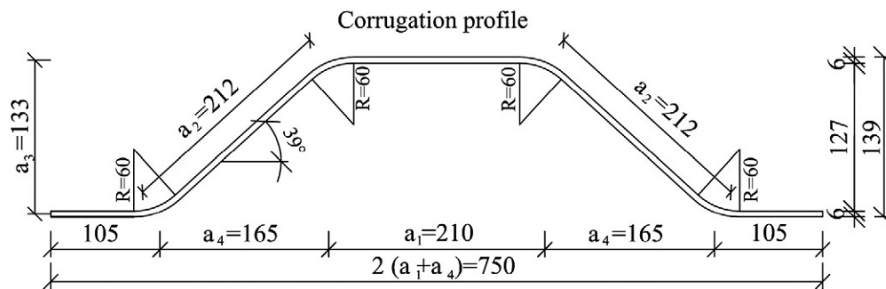


Fig. 13: Profile of the corrugation.

In-plane-bending moment resistance analysis

In the international literature more than 150 experimental tests can be found in case of trapezoidally corrugated web girders. Model verification is executed by recalculations of experimental results found in the literature. From these specimens 8 specimens were chosen to verify the numerical model. Six large scale specimens are chosen from the 4-point-bending tests of Elgaaly et al. [5] in 1997. The failure mode occurred in all cases in the “pure” bending zone (middle part of the test specimens) by the buckling of the flange plates. The aim of the investigations of Elgaaly et al. [5] was to determine the bending resistance of girders with trapezoidally corrugated web. Therefore these test results are optimal to the numerical model verification. The numerical model of all the 6 test specimens is developed and the bending resistances are recalculated.

Thus the aim of the current investigation is the study of the M-V interaction, the determination of the shear resistance is also an important task. Therefore the numerical model is also verified by test results where the observed failure mode was the shear buckling of the corrugated web. Test specimens taken from two independent previous research programs are selected and the model verification is made for both test results. Experimental research program on corrugated web girders was made by Moon et al. in 2009 [26] on three large scale test specimens. From the three specimens one specimen is selected (M14) to the model verification. Independent experimental research program was also executed by Hannebauer [13] in 2008. One girder with trapezoidally corrugated web was investigated in this research program. The numerical model of these test specimens is developed and the shear buckling resistances are determined by the numerical simulations.

Thus the model verification is based on three different research programs in the current paper, the detailed description of the test layouts and test specimens are not given here. All the necessary information can be found in the relevant papers [5], [13] and [30]. But all the geometrical and material properties of the analysed specimens, which are necessary to the model development and recalculation of the test results are listed in Table 6.

5.2. Geometrical model

In this subsection only one geometric model is presented because the geometry of all models are similar. The geometrical model can be seen in Fig. 14, where four and a half corrugations are applied with parallel folds at both ends of the beam. In this case the length of the beam is 5400 mm, thus the length of one corrugation is 1200 mm in which the length of the parallel fold is 400 mm and the depth of the corrugation is 200 mm with an angle of 45° .

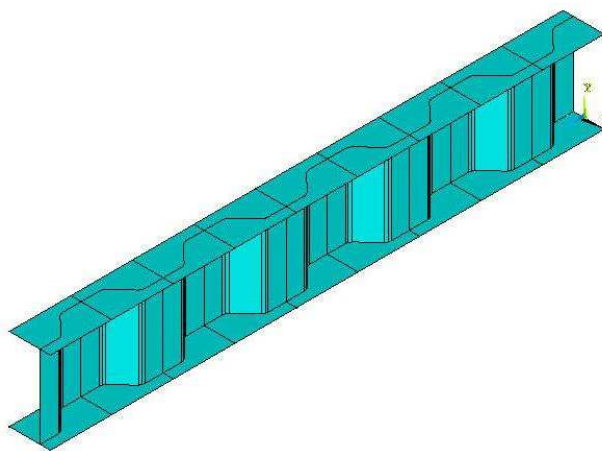


Fig. 14: Geometric model of trapezoidally corrugated web girder.

5.3. Material model

Additional normal stress analysis in the flanges

For the additional transverse bending moment analysis in the flanges linear elastic material model is applied. The Young modulus is taken to $E=210\,000$ MPa and Poisson ratio equal to $\nu=0.3$.

In-plane-bending moment resistance analysis

For the in-plane-bending moment resistance analysis two different material models are applied. The first model is used for the numerical model verification according to the measured material properties and the second model is used for the numerical parametric study. The character of the applied material models are a linear elastic - hardening plastic material model using von Mises yield criterion. This material model has in the plastic domain an isotropic hardening behaviour. The material is assumed to behave linearly elastic and to obey Hook's law with a Young' modulus equal to $210\,000$ MPa up to the yield stress. Thereafter and until it reaches the ultimate stress, the material is assumed to behave linearly with a reduced modulus. The ultimate strength is defined by $e=10\%$, which usually fits to the material tests. The material is assumed to be perfectly plastic when it reaches the ultimate stress.

The first material model follows the measured material properties observed in the tests, to ensure the best agreement of the numerical calculations to the measured resistances. In the numerical parametric study the characteristic value of the yield and ultimate strength are used in the calculations instead of the measured values. In the second part only girders made from S355 steel material are analysed in the frame of the calculations, where the yield strength (f_y) is equal to 355 MPa and the ultimate strength (f_u) is equal to 510 MPa.

5.4. Finite element mesh

Convergence study is executed to ensure the model reliability. As a principle it is concluded that one fold should be modeled by minimum of 8-10 elements along the fold length to determine the stresses with adequate accuracy. It means that in case of the analyzed girders the applied finite element size varies between $2 - 40$ mm.

For representing the process of the convergency study, one geometry is chosen which can be seen in Subsection 5.2. Proving the accuracy of the numerical model different mesh sizes were applied and analyzed. During the investigation the computational time was also measured for each case. In the Fig. 15 it can be seen that using smaller and smaller mesh size

the obtained value of the numerically calculated bending moment resistance has a better and better accuracy.

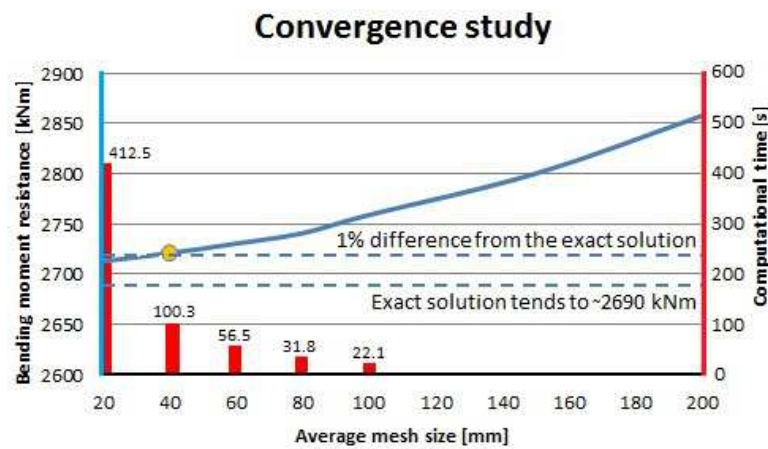


Fig. 15: Convergence study of the mesh size.

The tendency of using different mesh sizes is represented by the blue line. According to the Microsoft Excel software in this case the exact solution tends to the bending moment resistance equal to 2690 kNm which is represented by the lower dashed line. The one percentage difference from the assumed exact solution is demonstrated by the upper dashed line. The intersection point of the upper dashed line with the continuous blue line is close to the mesh size 40 mm which is marked by a yellow dot in the Fig. 15. It is shown by red columns that the computational time is more time-consuming in case of mesh size 20 mm and this is the main reason why mesh size 40 mm was judged to be accurate enough for the application for the numerical calculation. In the below Fig. 16 you can see the finite element model after the mesh generation.

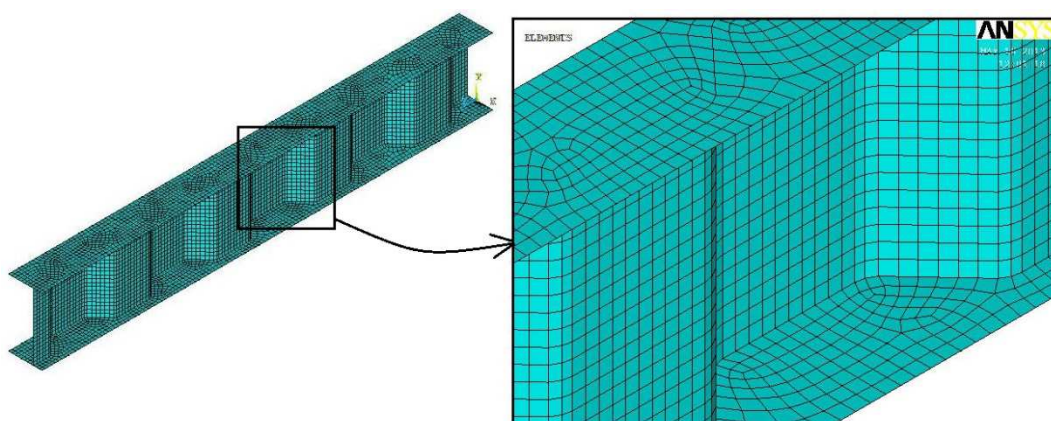


Fig. 16: Finite element mesh.

In the finite element model the SHELL181 element was applied which can be seen in the Fig. 17. The attributes of the mentioned element is written after the Fig. 17.

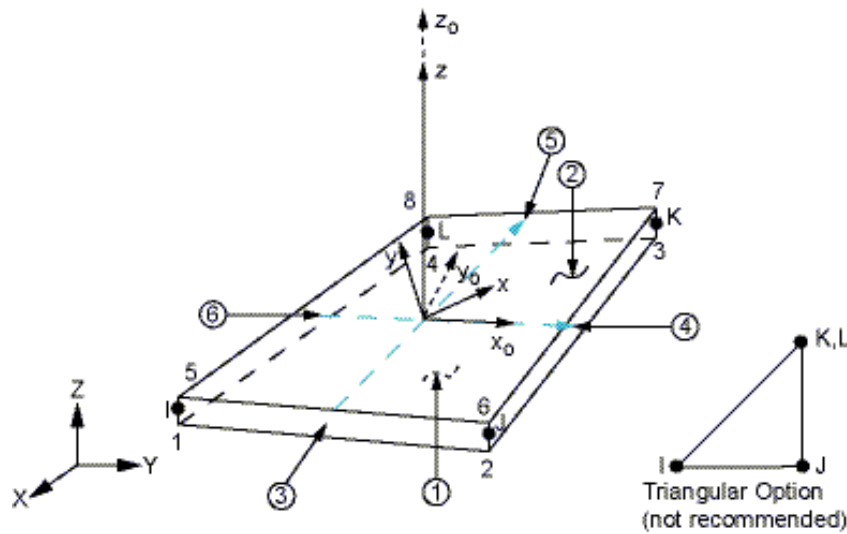


Fig. 17: SHELL181 finite element. [40]

SHELL181 finite element attributes:

- four-node thin shell element,
- bending and membrane capabilities, so both in-plane and normal loads are permitted,
- six degrees of freedom at each node, translations in the nodal x , y and z direction and rotations around the nodal x , y and z -axis,
- large strain and large deflection capabilities are also included,
- it can be applicable for stability analysis (critical stress level determination),
- well-suited for linear or nonlinear applications.

In this geometry with mesh size 40 mm the number of applied nodes is 4963, thus the degrees of freedom of the whole model is 29778.

5.5. Loads and boundary conditions

Additional normal stress analysis in the flanges

The developed numerical model for the verification and analysis can be seen in Fig. 18 with the applied finite element mesh, the loading and support conditions. The girder is simply supported at the two ends and the uniform load is acting on the upper flange in the midspan. This model is meant to recalculate numerically the results of the large scale specimen 3 [14] which is described in Section 5.1 to verify the numerical model by comparing the measured and computed results.

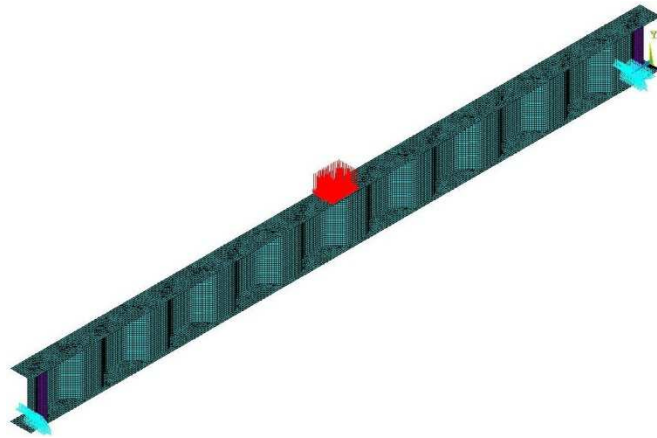


Fig. 18: Developed numerical model for the verification and analysis.

In-plane-bending moment resistance analysis

For the in-plane-bending moment resistance and M-V interaction analysis the support and load conditions are applied in the numerical model which are demonstrated in Fig. 19. In the numerical calculations only the half of the simply supported girder is modelled. It can be seen that on the right side of the girder simply support is defined and on the left side of the girder symmetry condition is defined. At both ends of the girder lateral supports are applied on the upper and lower flanges.

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 supplemented by two normal forces applied in the center of gravities of the upper and lower flanges. The shear force is constant along the girder length, therefore the shear resistance can be determined on a definite way. The in-plane-moment diagram has a linear character along the girder length, which has the minimum value at the simply support and the maximum value at the midspan. The analyzed girder and the support and loading conditions can be seen in Fig. 19.

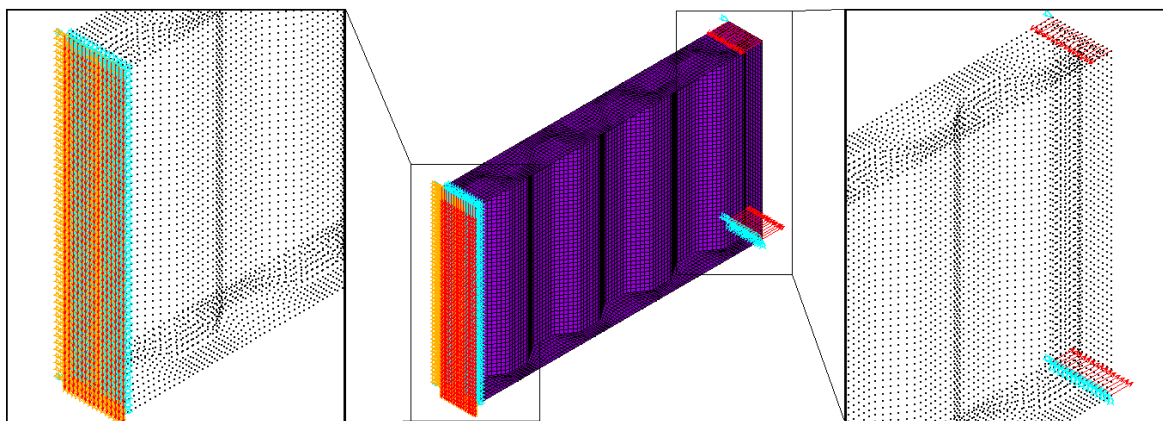


Fig. 19: Boundary conditions and applied forces in the numerical model.

In the Fig. 20 a schematic figure can be seen with the applied forces and defined boundary conditions. The figure emphasizes that the most critical cross section related to the bending failure of the flange is localized in the middle of the first parallel fold close to the symmetry condition.

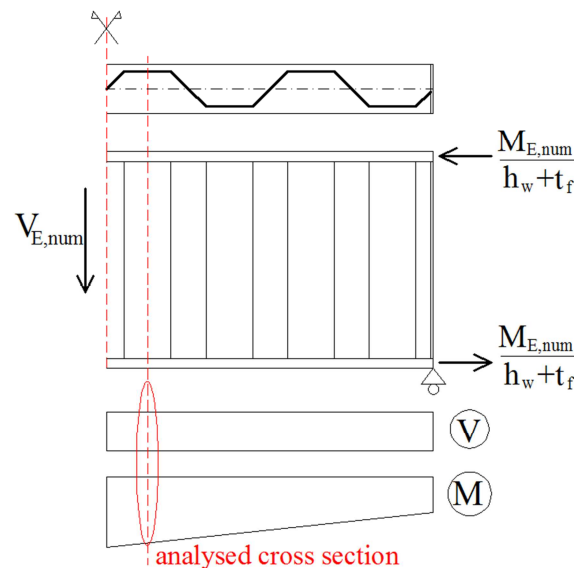


Fig. 20: Support and loading conditions of the analyzed model.

5.6. Analysis type

Additional normal stress analysis in the flanges

The stresses in the numerical model are calculated by a linear analysis using linear elastic material model ($E=210000$ MPa; $\nu=0.3$).

In-plane-bending moment resistance analysis

For the analysis of the in-plane-bending resistance of corrugated web girders under pure bending and combined bending and shear geometrical and material nonlinear analysis using equivalent geometric imperfections (GMNIA). The Newton-Raphson approach is used in the nonlinear analysis.

5.7. Applied imperfections

The aim of this research work is the determination of the bending and shear buckling resistances of the analyzed girders. In case of both failure modes buckling can govern the structural behaviour, therefore the application of the imperfections is a key point of the calculation. There are different possibilities to define the equivalent geometric imperfection according to EN1993-1-5 [1]. Thus in the current research work different failure modes are studied separately and also on a combined way (M-V interaction), the best and always a safe

side solution is ensured by using eigenmode imperfections. This imperfection type can handle the change of the failure mode in the interaction domain. Maybe the usage of the first eigenmode imperfection shape leads to a conservative design, but it is sure, that all the calculations are on the safe side. Furthermore in the current investigations not the exact values of the resistances are studied, only the resistance reductions. Therefore all the numerical parametric studies are executed using the first eigenmode imperfection shape scaled to the proposed amplitude of EN1993-1-5 [1]. In the Fig. 21 a typical first buckling mode can be seen due to bending.

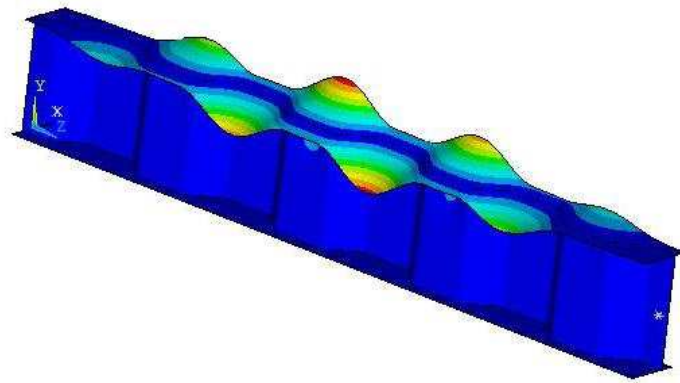


Fig. 21: First buckling modes due to pure bending.

5.8. Verification of the numerical models

Additional normal stress analysis in the flanges

With the help of the experimental background due to the large scale test in the Department of Structural Engineering the verification of the numerical model is performed. The measured deflections and the normal stresses in the flanges are compared with the numerically recalculated results.

Table 5: Measured and computed stresses of the flanges in the parallel fold of the web.

At the first parallel fold of the web in the midspan.						
	Bottom flange			Upper flange		
Strain gauge number	G1	G2	G3	G8	G9	G10
Measured stresses [Mpa]	171.0	141.5	102.9	-167.1	-137.4	-102.8
Computed stresses [Mpa]	178.3	148.0	112.2	-179.1	-145.2	-116.7
Differences [%]	4.27	4.59	9.04	7.18	5.68	13.52
Averages of the differences [%]	5.97			8.79		

In the above Table 5 shows the comparison of the measured and computed normal stresses. In the last row of the table you can see that the differences between the stresses are more than 5%. The difference related to the bottom flange is 5.97% and the difference related to the upper flange is 8.79%. In the Fig. 22 the stress distributions in the bottom and in the upper

flanges can be seen. It can be observed that the computed stresses are slightly higher, thus the computed results are in the save side.

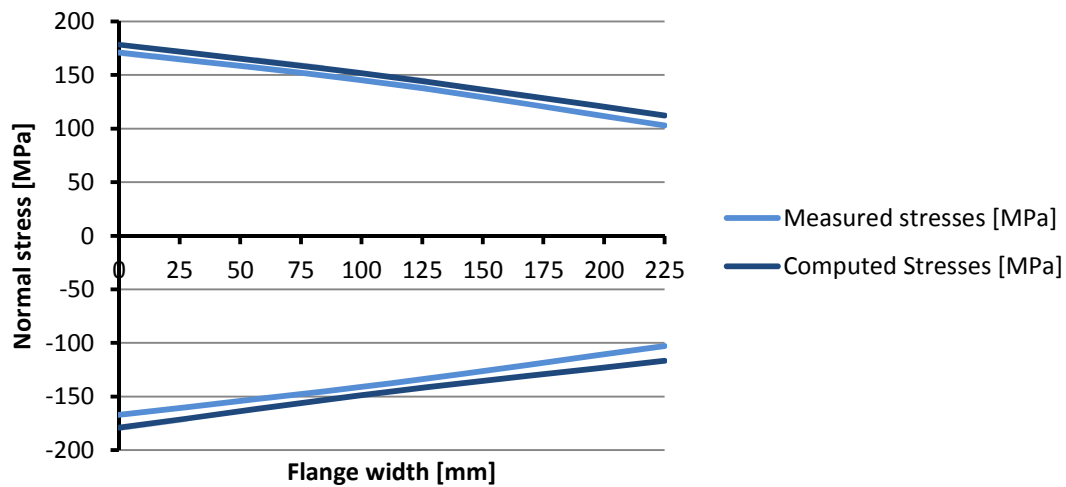


Fig. 22: Measured and computed normal stresses in the flanges.

In the Fig. 23 you can see the deflection of the numerical model due to three point bending. This geometry and loading condition of the model is identical to the loading layout of specimen number 3 (see Subchapter 6.1.). The difference between the deflection of the specimen and the numerical model is 4.9%. The deflection of the specimen was 13.66 mm and the deflection of the numerical model is 12.983 mm as you can see in the Fig. 22.

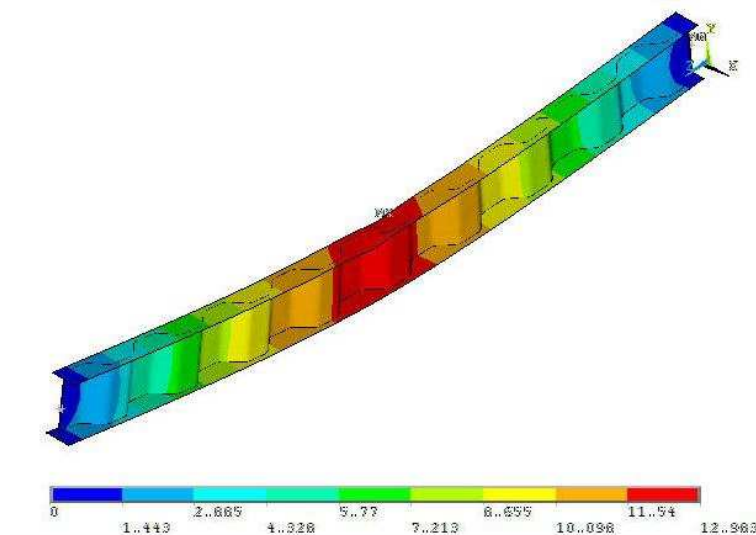


Fig. 23: Deflection of the numerical model.

After the comparison it can be stated that the developed numerical model is judged to be accurate enough or gives results always in the save side in case of the normal stresses in the flanges, therefore further analysis can be performed on it.

In-plane-bending moment resistance analysis

The applied numerical models, boundary conditions and typical failure modes can be seen in the Fig. 24. The boundary conditions applied for the specimens of Elgaaly et al. [5] are simply supported and loaded by bending moments at the two ends of the girder. Only the middle part of the test specimen is modelled in the current investigation and the two sides of the girder are supplemented by the applied forces. In case of the test specimens of Moon et al. [30] only the half of the girder is modeled which is discussed previously in Section 5.5.

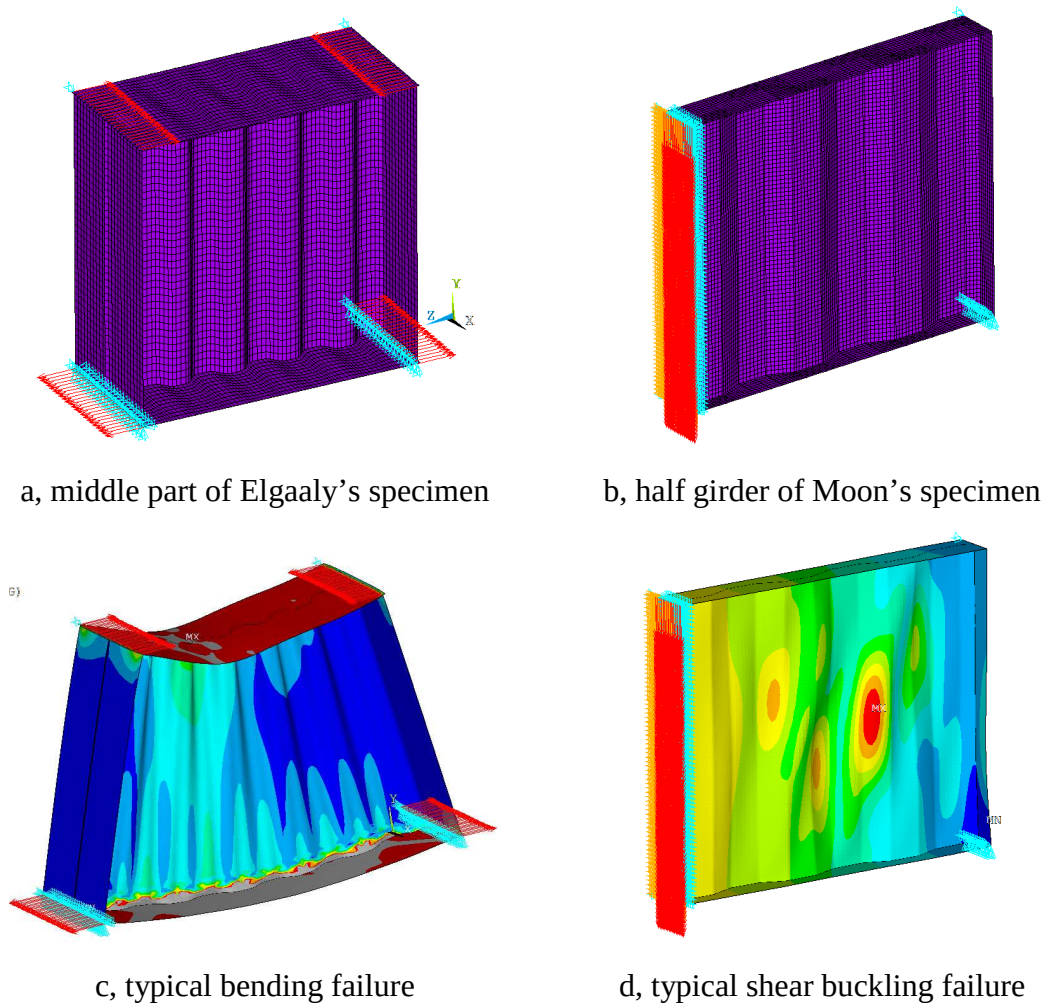


Fig. 24: Applied numerical models and typical failure modes.

All the geometrical and material properties, the results of the tests and the numerical calculations are summarized in Table 6.

The comparison show, that there is a good agreement between the test results and the numerical calculations. In case of the bending tests the difference is between $\pm 3\%$. The observed failure modes in the tests and in the numerical models are the same, yielding of the flanges and the plastic buckling of the compressed flange.

A slightly larger difference (5-6%) between the test results and the numerical calculations can be observed in case of the shear buckling tests. The observed failure modes are the same, global shear buckling of the whole web panel, but the shear buckling resistance calculated by the numerical simulations are 5-6% smaller than the test results. The reason of it is the application of the first eigenmode imperfection with standard magnitudes, which results in safe solution for the shear buckling resistance. The test specimen could have smaller imperfections, which results the slightly larger resistance.

Table 6: Comparison of the experimental and numerical results.

	tf [mm]	bf [mm]	hw [mm]	tw [mm]	L/2 [mm]	α [°]	a1 [mm]	a2 [mm]	a4 [mm]	a3 [mm]	f_{yf} [MPa]	f_{yw} [MPa]	V_{test} [kN]	M_{test} [kN]	V_{num} [kN]	M_{num} [kN]	V_{test} / V_{num}	M_{test} / M_{num}
Bending tests of Elgaaly et al. [5]																		
1	12.7	152.4	304.8	0.607	304.8	50	19.8	18.53	12	14	289	682	-	180.9	-	178.9	-	1.01
2	12.7	152.4	304.8	0.607	304.8	45	38.1	35.92	25	25	289	682	-	193.3	-	181.4	-	1.07
3	12.7	152.4	304.8	0.607	304.8	55	41.9	40.7	23	33	289	682	-	175	-	178.8	-	0.98
4	12.7	152.4	304.8	0.607	304.8	62.5	49.8	57.25	26	51	289	682	-	175.2	-	178.7	-	0.98
5	12.7	152.4	304.8	0.76	304.8	55	41.9	40.7	23	33	376	682	-	237.8	-	231.1	-	1.03
6	12.7	152.4	304.8	0.76	304.8	62.5	49.8	57.25	26	51	376	682	-	223.2	-	229.4	-	0.97
Shear test of Moon et al. [26]																		
7	30	300	2000	4	3110	22.6	220	195	180	75	296	296	1052.8	-	1003	-	1.05	-
Shear test of Hannebauer [13]																		
8	15	200	500	2.5	1000	40	30	62	47	40	270	270	206.5	-	195.6	-	1.06	-

6. Effect of support conditions on the additional normal stresses

6.1. Research strategy and goals

The aim of this part of the research program is to analyse numerically the effect of the different support conditions on the additional normal stress distribution in the flanges indicated by shear. With the help of the Ansys 14.5 [40] finite element package the numerical model is developed with linear elastic material model and linear analysis. Previous investigations of Kövesdi et al [14] in 2012 the effect of the geometric parameters, corrugation profile and different girder layouts (see Fig. 5) on the maximum transverse bending moment are studied in detail. These investigations represented that the maximum possible value of the additional normal stresses in the flanges can be determined by the Eq. (6) with adequate safety. In that paper it is stated that the influence of the lateral and longitudinal support can have a significant effect on the maximum transverse bending moment. Thus the purpose of the current investigation is to provide complementary investigation on the variation of the transverse bending moment along the girder length due to the effect of the different support conditions.

It has to be mentioned, that the investigations in [14] showed that the most unfavorable situation from point of view of the additional normal stresses is if the supports and load introduction places are located at the middle of an inclined fold and a full number of corrugation waves are between these two places as shown in Fig. 25. The possible layouts can be seen in Fig. 5. Because the corrugation layout related to the Fig. 25 is the most unfavorable from point of view the transverse bending moment, all the further calculations are made on this geometry to get results always on the safe side.

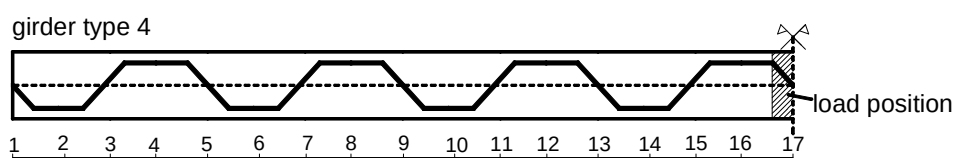


Fig. 25: Analyzed corrugation layout, support and load introduction locations.

6.2. Results of the numerical calculations

In this subchapter the results of the numerical calculations is presented. The analysis is extended to girders with typical bridge geometries and with typical industrial building geometries, however only the results of a typical bridge girder is presented because the tendencies which are observed are the same for both girder types. The analyzed trapezoidally corrugated web girder which is chosen to present here has geometric parameters very close to

the average parameters used in the existing bridges. The applied geometric parameters are the followings: the width and thickness of the flange are 400 mm and 30 mm, the depth and thickness of the web are 2500 mm and 10 mm, the length of the folds ($a_1=a_2$) are 350 mm and the corrugation angle is 39° . For this geometry the analytically calculated maximum possible value of the transverse bending moment, the maximum value of the additional normal stress and the bending resistance reduction factor are determined with the Eqs. (7)-(9). The applied shear force at the midspan is 1000 kN which is about the 25% of the shear resistance of the given girder.

$$M_{z,\max} = \frac{V \cdot a_3}{2 \cdot h_w} \cdot (2 \cdot a_1 + a_4) = \frac{1000 \text{ kN} \cdot 220 \text{ mm}}{2 \cdot 2500 \text{ mm}} \cdot (2 \cdot 35 \text{ cm} + 272 \text{ cm}) = 4281,9 \text{ kNcm} \quad (7)$$

$$\sigma_x(M_z) = \frac{M_{z,\max}}{I_z} \cdot \frac{b_f}{2} = \frac{4281,9 \text{ kNcm}}{\frac{(40 \text{ cm})^3 \cdot 3 \text{ cm}}{12}} \cdot 20 \text{ cm} = 53,5 \text{ MPa} \quad (8)$$

$$f_T = 1 - 0,4 \cdot \sqrt{\frac{\sigma_x(M_z)}{f_y}} = 1 - 0,4 \cdot \sqrt{\frac{53,5 \text{ MPa}}{355 \text{ MPa}}} = 0,845 \quad (9)$$

During the whole investigation the additional normal stresses indicated by the shear force are also computed numerically using different longitudinal and lateral support conditions and compared with the analytical solutions. The analyzed 6 different support conditions are presented in the followings:

- model 1: simply supported girder with lateral supports at both ends (modeling the worst case as reference),
- model 2: simply supported girder with 5 lateral supports along the girder length (modeling the effect of transverse girders or purlins),
- model 3: simply supported girder with 5 lateral supports with rotational constrains (modeling the effect of transverse girders with fixed connections),
- model 4: simply supported girder with 7 lateral supports along the girder length (modeling the effect of transverse girders or purlins),
- model 5: simply supported girder with continuous lateral supports (modeling the effect of concrete slab, what is usually used in bridges with corrugated webs),
- model 6: fixed supports at both ends without lateral restrains (modeling the effect of the longitudinal support conditions).

In the followings the results related to the 6 models are presented in the Figs. 26-31. In the figures below the horizontal axis represents the number of the individual web folds along the girder length as demonstrated in Fig. 5 and Fig. 25. The vertical axis represents the magnitude

of the additional normal stress distribution in the flanges at a given web fold. For this geometry the horizontal red line demonstrates the analytically calculated maximum possible value of the additional normal stress according to the Eqs. (7)-(9). The model 1 is taken as reference model with simply support conditions and with lateral support conditions at both ends. It can be seen in Fig. 26.

It can be observed that the additional normal stress in the flanges has a cyclic development along the girder length and this additional normal stress diagram in the lower and also in the upper flange is point symmetric to the midspan of the structure where the concentrated force is acting. It can be clearly seen that the analytical solution proposed by Kövesdi et al. [14] gives result in a very good agreement with the numerically computed maximum values in the lower and in the upper flange as well. This model with simply support condition and without intermediate lateral supports is taken as reference model with which the further models are compared and evaluated.

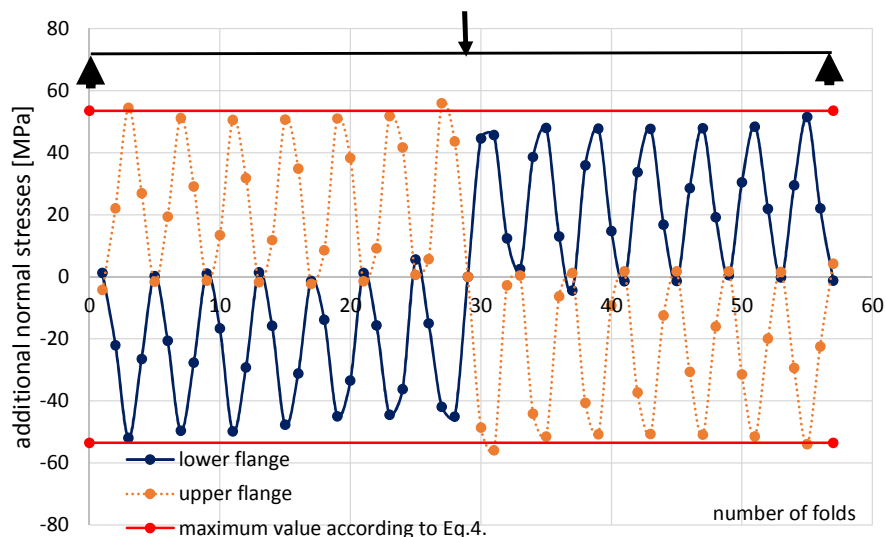


Fig. 26: Additional normal stresses ($\Delta\sigma$) for model 1.

The model 2 is the first model which is meant to analyse the effect of the intermediate lateral supports on the additional normal stresses along the girder length. In the model 2 the lateral supports do not provide constraints against rotation as it can be seen in Fig. 27. In this case 3 additional intermediate lateral supports is applied from which one is located at the midspan where the concentrated force is acting. The dashed orange line in the Fig. 27 represents the results of the reference model (see Fig. 26) and the continuous blue line represents the additional normal stresses using 5 lateral supports.

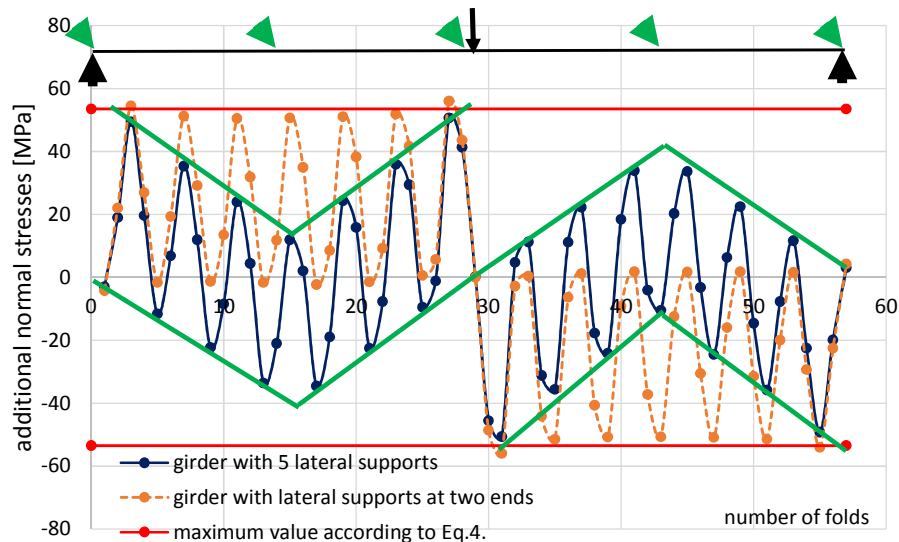
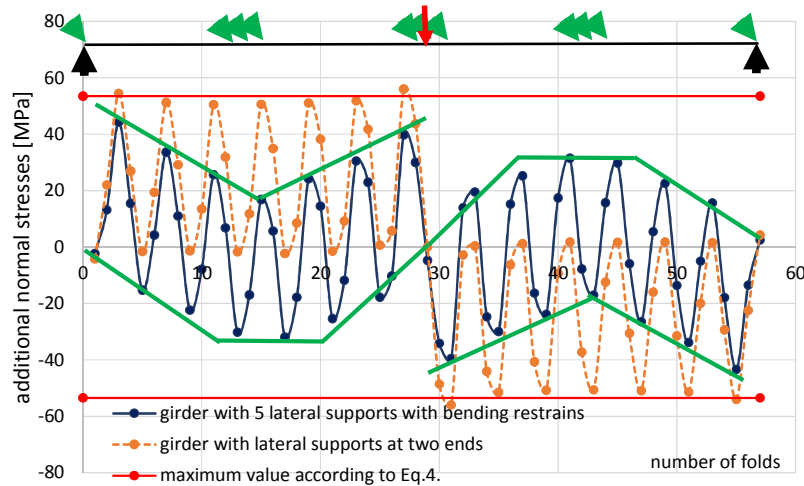


Fig. 27: Additional normal stresses ($\Delta\sigma$) for model 2.

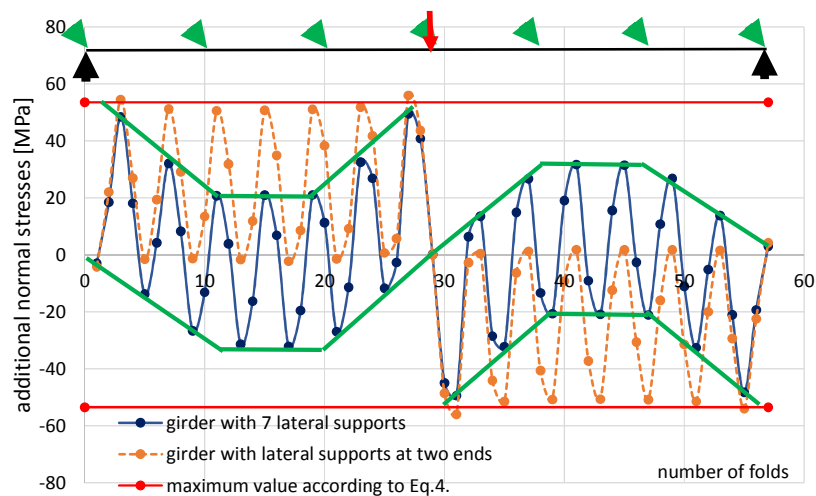
In the Fig. 27 it is very conspicuous that the lateral supports have a significant effect on the additional normal stresses in the flanges along the girder length. This significant effect is attributed to the fact that the transverse bending moment is derived from the lateral and eccentric longitudinal forces according to the mechanical model of Linder [2] in 1992 (see Fig. 4). The lateral forces are supported by the lateral constraints and the transverse bending moment is developed only from the eccentric longitudinal forces (see Eq. (6) and Fig. 6). This is the reason why the additional normal stresses in the flanges can be reduced significantly close to the lateral supports.

In Fig. 27 the green continuous lines represent the modified tendency of the maximum additional normal stresses along the girder length. It can be observed that around the intermediate lateral supports the maximum value of the additional normal stresses are reduced by 30%, however if the intermediate lateral support is located in a cross section in which the lateral forces can be neglected (at the midspan cross section) then the lateral support has no any influence on the additional normal stresses.

The model 3 demonstrates the case when the intermediate lateral supports provide constraints against rotation. In the Fig. 28. it can be observed that this rotational constrain has a larger influence on the maximum additional normal stresses. This larger effect is attributed to the fact that the transverse bending moment is coming from the eccentric longitudinal forces which can be also reduced around the lateral supports. It can be clearly seen in the Fig. 28 that at the midspan the maximum value of the additional normal stresses are also reduced due to the constraints against rotation.

Fig. 28: Additional normal stresses ($\Delta\sigma$) for model 3.

The same tendency as shown in Fig. 28 can be observed if more lateral supports are applied along the girder length. Figure 29 demonstrates the additional normal stress distribution for model 4 where 5 intermediate lateral supports are applied without rotational constrains. The results show that the additional normal stresses are significantly reduced ($\sim 40\%$) by both support conditions.

Fig. 29: Additional normal stresses ($\Delta\sigma$) for model 4.

In case of hybrid superstructures where the flanges of the box girder are prestressed concrete and the web is usually trapezoidally corrugated steel plate. In this case the concrete slab provides continuous lateral support to the corrugated web, thus this continuous lateral constrain (model 5) is necessary to be investigated in this paper. In the Fig. 30 the additional normal stresses coming from the model 1 (reference model) and from model 5 are compared. It is very conspicuous that due to the effect of the continuous lateral support the maximum value

of the additional normal stresses is reduced by about 75%, however the tendency is remained the same along the girder length.

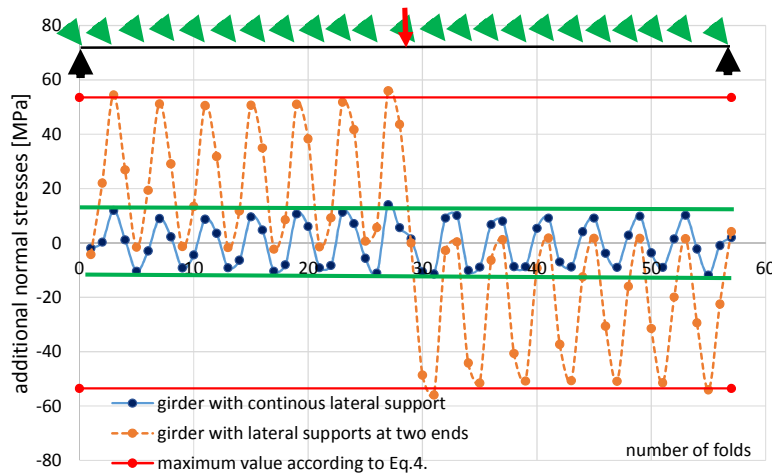


Fig. 30: Additional normal stresses ($\Delta\sigma$) for model 5.

The above investigations show that the lateral supports can have significant effect on the additional normal stresses in the flanges of corrugated web girders. The results show that due to the intermediate lateral supports (transverse girders, purlins) the maximum value of the additional normal stresses can be reduced by about 35-40% around the lateral supports in case of the analyzed girder. Furthermore the continuous lateral support can be more significant, in case of the analyzed girder the reduction is about 75%. It can be stated that these reductions depend on the corrugation profile (see Fig. 6) while the conclusion is that the effect of the lateral supports is also very significant.

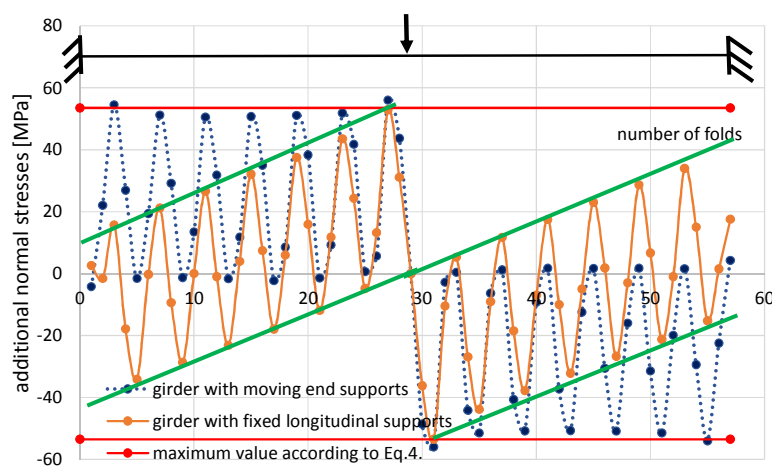


Fig. 31: Additional normal stresses ($\Delta\sigma$) for model 6.

In Fig. 31 the effect of the longitudinal supports on the additional normal stress is presented. The numerical results show that the longitudinal supports greatly influence the additional

normal stress distribution along the girder length. The dashed blue line represents the results of the model 1 and the continuous orange line represents the results of the model 6 in which the girder has fixed supports at both ends. The numerical results show that close to the fixed supports the maximum value of the additional normal stresses can be reduced.

The numerical investigation on the effect of the different support conditions shows that both longitudinal and lateral support can reduce the maximum value of the additional normal stresses, therefore in case of real structures with real boundary conditions the maximum value of the additional normal stresses can be significantly smaller than the analytical solutions according to the proposals of the EN1993-1-5 [1] and Kövesdi et al. [14].

In case of corrugated web girders the maximum value of the normal stress in the flanges depends on the corrugation profile, the sizes of the flanges, the web depth, the applied forces and the support conditions as well, thus the determination of this value for a given girder is very hard by analytical ways, only the maximum possible values can be determined quite well in some cases without taking into account the effect of the different support conditions and the effect of the different loading conditions. The author suggests using finite element simulation if a more accurate value of the maximum normal stress in the flanges of corrugated web girders is needed.

7. Effect of geometrical parameters on the bending resistance

7.1. Research aims and solution strategy

In this section the pure bending resistance of trapezoidally corrugated web girders is analyzed with the variation of different geometric parameters and girder geometries. It was written in Section 3.1 that the girder geometry has a significant effect on the transverse bending moment in the flanges indicated by the shear force. Despite the girder is affected only by bending the effect of the girder geometry is also studied. The different girder geometries can be seen in Fig. 5. First of all the effect of different girder end layouts are analyzed on the in-plane-bending resistance and then a parametric study for analysing the different geometric parameters on the in-plane-bending resistance.

The design code recommends the calculation of the bending resistance only from the contribution of the flanges. According to the EN1993-1-5 Annex D [1] the pure in-plane-bending resistance can be calculated with Eqs. (1)-(2) and with the 4.4 (1) and (2) of the EN1993-1-5. The flange buckling is considered in EN1993-1-5 by the buckling coefficient given above in Eq. (2) (see Section 2). After determination of the buckling coefficient the relative slenderness and the reduction factor related to the outstand compression elements can be determined with the 4.4 (2) of EN1993-1-5 formulas and after the effective area of the compression zone can be obtained with the 4.4 (1) of EN1993-1-5. In this Section the accuracy of the reduction factor with respect to the compression flange stability is studied.

The calculated bending resistances according to the design code are compared with the obtained numerical results. Numerically the resistances of the analyzed girders are determined by geometrical and material nonlinear analysis using equivalent geometric imperfections (GMNIA). In the parametric study the web depth, the web thickness, the flange width, the flange thickness and the corrugation angle of the web are the varied parameters. The fold lengths of the corrugation profile is remained unchanged in the whole analysis ($a_1=400$ mm, $a_2=282.8$ mm). During the investigation the web depth varies from 200 mm to 4000 mm, the web thickness varies from 4 mm to 20 mm, the flange width varies from 220 mm to 1200 mm, the flange thickness varies from 10 mm to 40 mm and the corrugation angle varies from 26.5 to 51.3 degree.

7.2. Results of the numerical calculations

For each analyzed girder the numerically calculated resistances and the calculated resistance according to EN1993-1-5 [1] are compared. Firstly the effect of the girder geometry on the

bending resistance is analyzed. The different girder geometries can be seen in Fig. 5. As it is expected that the analysis shows that the different layouts have practically no effect on the pure in-plane-bending moment resistance.

After that a numerical parametric study is carried out to analyse the effect of the other geometrical parameters. In the figures the horizontal continuous red lines represent the ratio of the numerically calculated bending resistance divided by the recommendation of the EN1993-1-5 [1] (M_{num}/M_{Rk}) equal to 1,0. In the Fig. 32 the ratios of the web depth and thickness can be seen with the M_{num}/M_{Rk} ratios. The typical failure modes are shown in Fig. 33 related to 4 mm and 16 mm web thicknesses. In case of small web thickness the failure mode (see Fig. 33.a) is buckling of the compressed flange and local buckling of the web folds. In case of 16 mm web thickness the failure mode (see Fig. 33.b) is the pure buckling of the compressed flange.

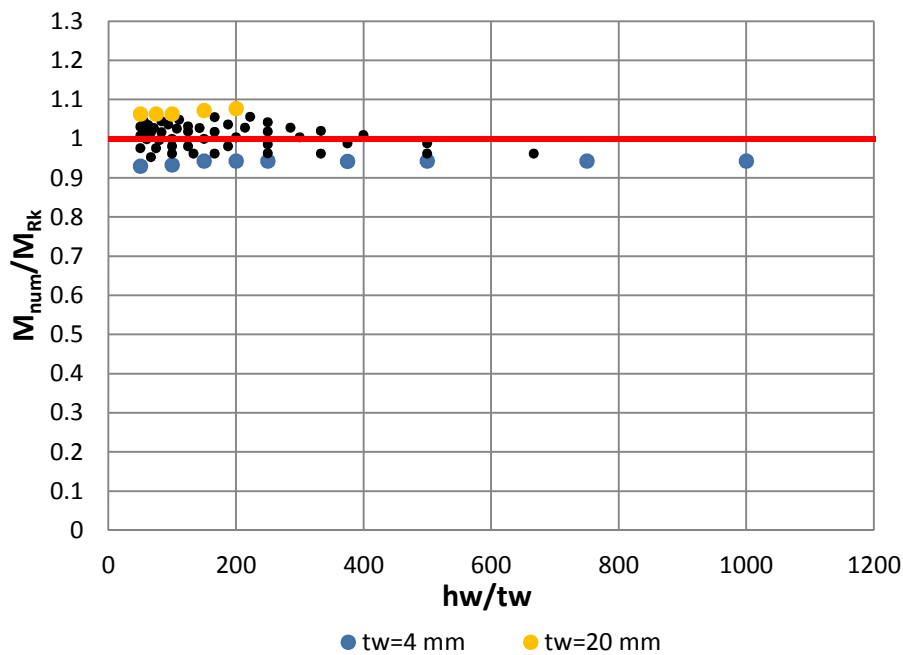


Fig. 32: The effect of the web depth and thickness.

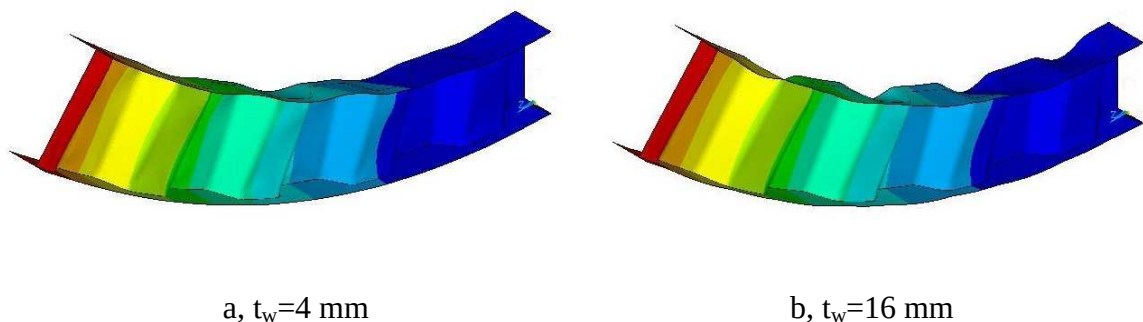


Fig. 33: Failure modes related to different web thicknesses.

It can be observed that in case of smaller web thickness the $M_{\text{num}}/M_{\text{Rk}}$ ratios become also smaller. This effect is attributed to the contribution of the corrugation web to the in-plane-bending resistance due to its smaller and smaller stiffness. Furthermore if the web is not stiff enough it can not support the flange against rotation in the transverse direction, thus compressed flange buckling can occur easier. The results show a very good agreement, because the differences between the numerically calculated bending reistances and the proposal of the EN1993-1-5 [1] are less than 6%.

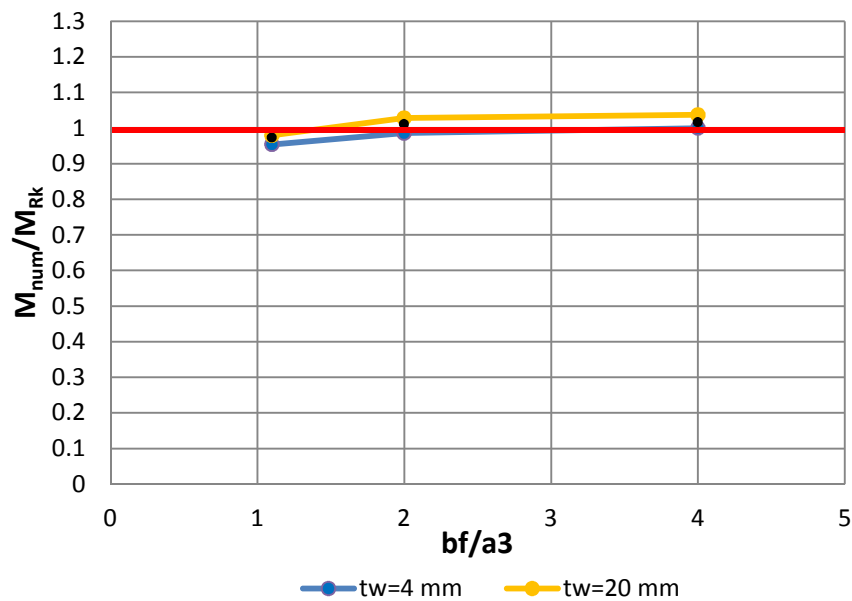


Fig. 34: The effect of the flange outstands.

In Fig. 34 the effect of the flange outstands is shown in case of different web thicknesses. The horizontal axis demonstrates the b_f/a_3 ratio and the vertical axis demonstrates the $M_{\text{num}}/M_{\text{Rk}}$ ratio. It can be seen, that using a girder with b_f/a_3 ratio close to 1.0 the $M_{\text{num}}/M_{\text{Rk}}$ ratio becomes smaller, however the differences are less than 5% in all cases. This phenomenon is attributed to the effect of the relatively large web corrugation on the relatively small width of the flange. It is also observed which is stated before that using smaller web thickness the $M_{\text{num}}/M_{\text{Rk}}$ ratio is getting smaller, because the corrugated web can not contribute so much to the load carrying due to its smaller stiffness.

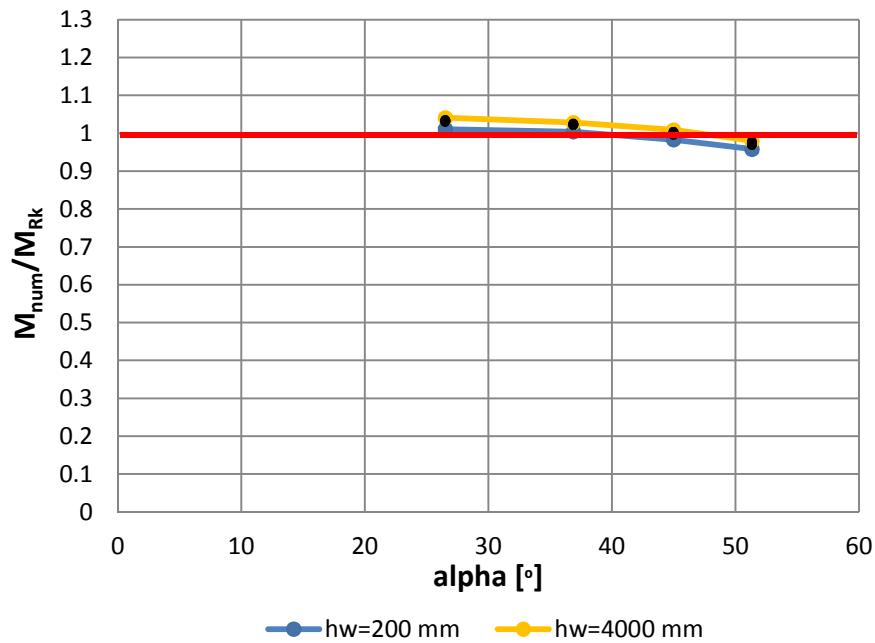


Fig. 35: The effect of the corrugation angle with different applied web depths.

In the followings the effect of the corrugation angle and the effect of the flange thickness are studied with different corrugation web depths. Firstly in the Fig. 35 the effect of the alpha corrugation angle can be seen. It is observed and expected that in case of smaller alpha the corrugation depth is smaller (a_3) thus the contribution of the web to the real in-plane-bending resistance is larger. The differences are also less than 5% in both directions.

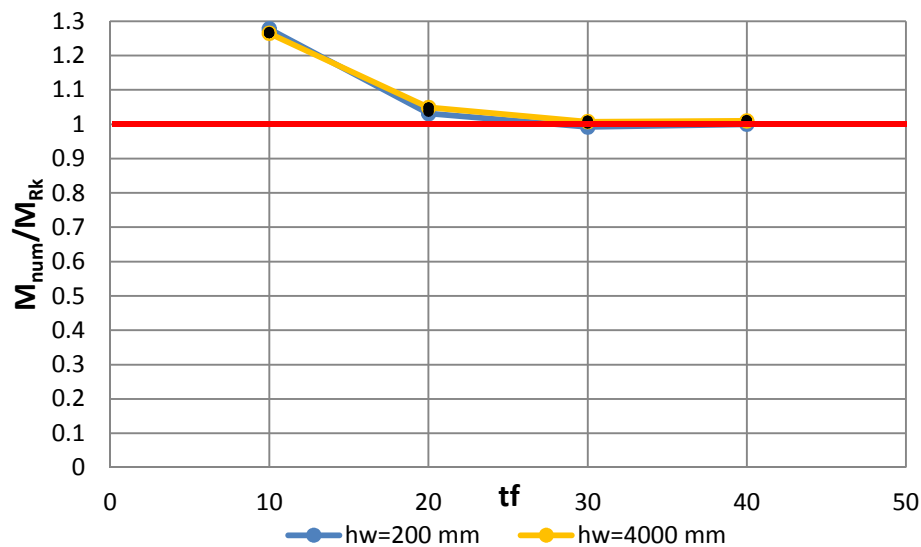


Fig. 36: The effect of the flange thickness.

In Fig. 36 the effect of the flange thickness is analyzed with different web depths. It can be seen that in case of web thickness larger than 20 mm the recommendation of the EN1993-1-5 [1] gives a very good agreement with the numerical results. In case of web thickness smaller than 20 mm the M_{num}/M_{Rk} ratio becomes larger so the EN1993-1-5 Annex D [1] gives a

conservative result which is attributed to the proposed formula of the reduction factor related to the compression flange buckling, thus further investigation is needed in this direction.

It can be clearly seen from the results that the proposal of the EN1993-1-5 [1] gives results in good agreement with the numerical results. The differences are not larger than 5-6%. in the analysed cases The design rule recommends calculating the bending resistance only from the contribution of the flanges. Despite of the proposal of the design rule the numerical calculations show that the corrugated web has a slight contribution in the load carrying capacity but due to its slight contribution it can be negligible. However further analysis is needed for the reduction factor related to the effective flange width because the standard gives very conservative results in case of thin flanges.

Except small flange thicknesses the results from the analysis of the in-plane-bending resistance without the effect of shear are judged to be acceptable, therefore the further investigations focusing on the load carrying capacity of trapezoidally corrugated web girders affected by combined bending and shear can be carried out.

8. Effect of the transverse bending moment on the bending resistance

8.1. Research strategy and goals

The previous results in the recent paper in Section 4 and 5 demonstrated that the transverse bending moment can have a significant influence on the normal stress distribution in the flanges of corrugated web girders, however the effect of this modified stress distribution on the bending resistance needs further investigations. This Section is dealing with the in-plane-bending moment resistance determination of corrugated web girders affected by combined bending and shear in case of typical geometries used in the practical design. The bending resistance reductions in the function of the applied shear force are determined and compared to the proposed reduction factor of EN1993-1-5 [1]. The resistances of the analyzed girders are determined by geometrical and material nonlinear analysis using equivalent geometric imperfections (GMNIA).

The numerical models are verified based on test result found in the literature. Based on the verified numerical model a numerical parametric study is executed to analyze the effect of the shear force on the bending resistance. The previous calculations showed that girders with typical geometries used in bridges and in industrial buildings can have different structural behaviour under combined bending and shear, therefore girders with both typical geometries are investigated. The geometric parameters which have influence on the transverse bending moment in the flanges (fold length, corrugation angle, web depth) are varied in the numerical parametric study. For all the analyzed girders the bending and shear buckling resistances are determined as a first step and after that the M-V interaction behaviour is analyzed with 8 calculations for each specimen.

8.2. Numerical research program

The numerical model is verified by test specimens from the international literature, therefore it is applicable for the determination of the bending and shear buckling resistances of the analyzed girders. Due to the developed numerical model a parametric study can be carried out to investigate the structural behavior of girders with corrugated web under combined loading situation.

In this part of the recent research program firstly the ultimate load carrying capacity of typical girder geometries are calculated numerically. A total of 20 specimens are chosen and investigated, 11 with typical bridge geometries and 9 with typical geometries of building structures. The analyzed geometries and material properties are summarized in Table 7.

Further investigation is carried out on a chosen geometry in which the effect of the variation of the different geometric parameters (fold length, web depth, web thickness, corrugation angle) on the load bearing capacity affected by combined bending and shear is studied. This girder geometry (C.P.1) is coming from the article of Moon et al. [35] in 2009. In [35] the author studied the lateral-torsional buckling behaviour of trapezoidally corrugated web girders. In the frame of this study the variation of the fold lengths are taken with a multiplication factor into account which varies from 0,6-1,4. The corrugation angle varies between 20 and 60 degree, the web depth varies between 1000 and 2000 mm and the web thickness varies from 4 to 12 mm. The basic geometric and material properties of the analyzed girder are presented in Table 8.

Table 7: Analyzed girder geometries in the numerical parametric study.

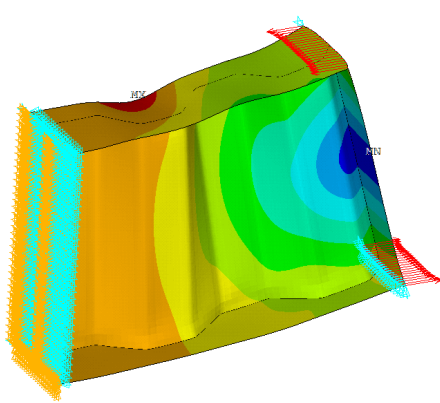
	bf [mm]	tf [mm]	hw [mm]	tw [mm]	L/2 [mm]	alpha [°]	a1 [mm]	a2 [mm]	f _{yt} [MPa]	f _{yw} [MPa]
Typical bridge geometries										
1	300	30	2000	4	3200	23	220	200	296	460
2	300	20	1000	4	1000	45	150	150	355	510
3	400	40	1500	6	1365	45	200	200	355	510
4	400	40	1000	10	2000	45	200	200	355	510
5	450	40	2500	9	2440	32	330	330	355	510
6	450	40	2500	9	2250	45	330	330	355	510
7	450	40	2500	9	1960	60	330	330	355	510
8	300	20	2500	9	2440	32	330	330	355	510
9	300	30	2500	9	2440	32	330	330	355	510
10	350	30	2000	8	2440	32	330	330	355	510
11	350	30	1200	9	1800	36,8	250	250	355	510
Typical building geometries										
12	200	15	500	2,5	922	40	30	62	270	430
13	300	20	1000	4	1000	45	50	50	355	510
14	250	16	750	5	887	45	65	65	355	510
15	250	16	750	5	780	60	65	65	355	510
16	250	16	750	5	960	30	65	65	355	510
17	250	16	750	5	820	45	120	120	355	510
18	250	16	750	5	1365	45	200	200	355	510
19	250	16	750	5	546	45	40	40	355	510
20	220	12	1000	1,5	760	45	140	70	270	360

Table 8: Analyzed girder geometries in the numerical parametric study.

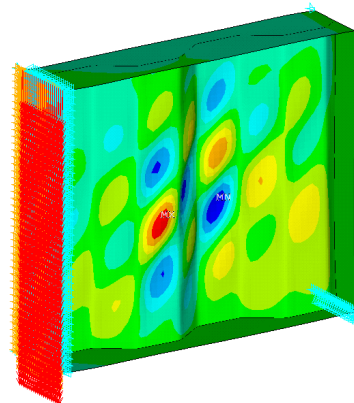
	bf [mm]	tf [mm]	hw [mm]	tw [mm]	L/2 [mm]	alpha [°]	a1 [mm]	a2 [mm]	f _{yt} [MPa]	f _{yw} [MPa]
1	300	25	1500	8	1200	35.5	180	172	250	250

The numerical calculations show that the bending failure occurs in the compressed flange at the middle of a parallel fold of the web, where the flange outstand is the greatest and the bending moment is also relatively large. In the Fig. 20 the red line is representing the location

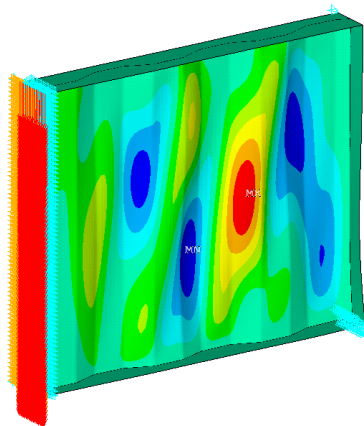
of the bending failure under combined loading situation. In this cross section the bending resistance of the analyzed girders can be determined from the applied bending moment and the applied accompanying shear force. In the Fig. 37 four typical failure modes can be seen. The first failure mode representing by Fig. 37.a is a typical bending failure due to pure bending. The Fig. 37.b-c are representing the two typical shear buckling failure modes. Local shear buckling of the individual web folds is dominant in case of typical bridge structures, however global buckling mode of adjacent folds is dominant in case of typical building structures. In the Fig. 37.d a typical failure mode can be seen under combined loading situation. It can be observed what is mentioned above that the flange buckling is localized in the cross section at the middle of the first parallel fold of the web, because this cross section is the weakest from point of view of the the combined loading situation.



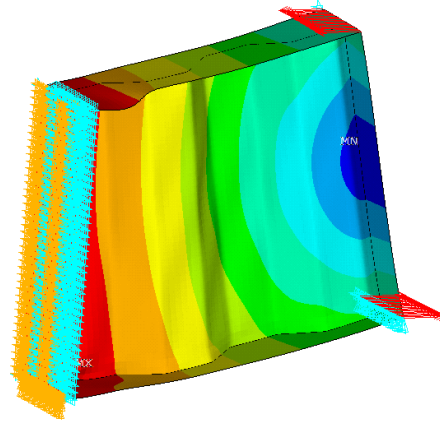
a, bending failure



b, shear buckling failure (local buckling)



c, shear buckling failure (global buckling)



d, failure under combined loading

Fig. 37: Observed typical failure modes.

It is shown from the linear calculation of the stress distributions that the geometry of the girder and the layout of the corrugation profile have a significant effect on the transverse bending moment. To take the unfavorable situation from point of view of the transverse

bending moment to obtain the largest reduction in the in-plane-bending resistance due to the shear force, the girder geometry is modeled as it can be seen in Figs. 18 and 25 according to Kövesdi et al. [14]. In the parametric study firstly the bending and shear buckling resistances of each analyzed girders are determined numerically and then further 6 calculations are carried out under combined bending and shear by varying the values of the applied bending moment and shear force. A total of 232 numerical calculations are executed.

8.3. Results of the numerical calculations

The resistances are determined and compared numerically and analytically according to the proposal of the EN1993-1-5 [1] for each analyzed girders. From the analyzed 20 specimens two is chosen for illustrating how the results are compared. In the Fig. 38 the results of a typical bridge girder geometry and a typical building girder geometry can be seen. In the figure the horizontal axis represents the bending resistance and the vertical axis represents the shear resistance of the analyzed girder and the points show the numerically calculated results. The proposed interaction equation of the EN1993-1-5 [1] is also presented in both diagrams by green line.

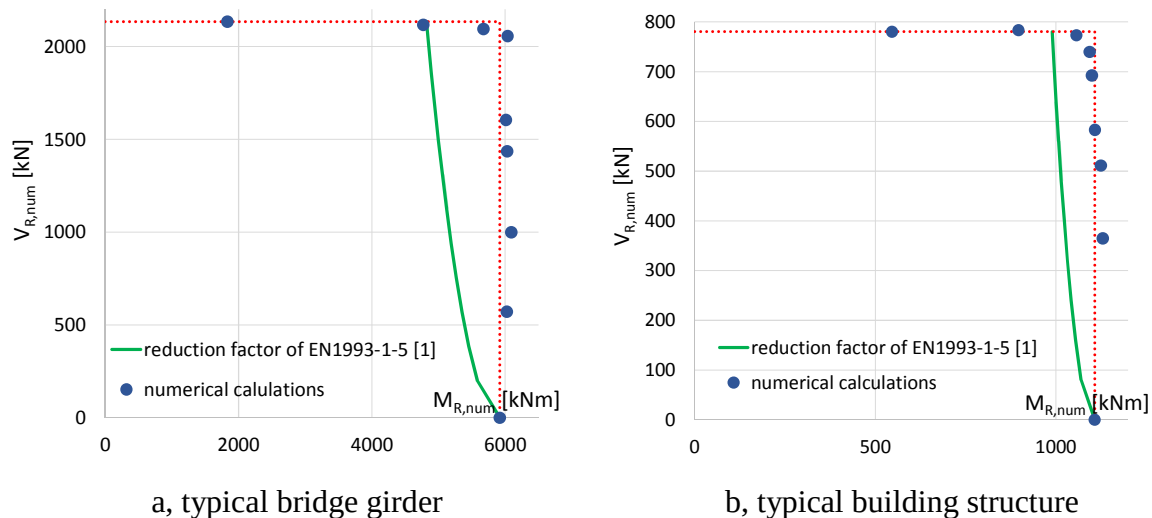


Fig. 38: Typical M-V interaction behaviour.

The results of the combined bending and shear interaction analysis show that there is just a very small resistance reduction developed. The numerical results follow the red dotted lines which demonstrate the pure bending and shear buckling resistances of the analyzed girder. It can be seen that the bending resistance reduction formula of EN1993-1-5 [1] representing by the green line does not result a large resistance reduction in case of typical building structure, however in case of bridges the reduction can be more significant. The figures show that the proposal of the EN1993-1-5 [1] gives a very conservative design which is not needed

according to the numerical results. All the results of the analyzed 20 specimens are presented in the Fig. 39. It can be seen that maximum bending resistance reduction due to the combined bending and shear interaction is 4,7%.

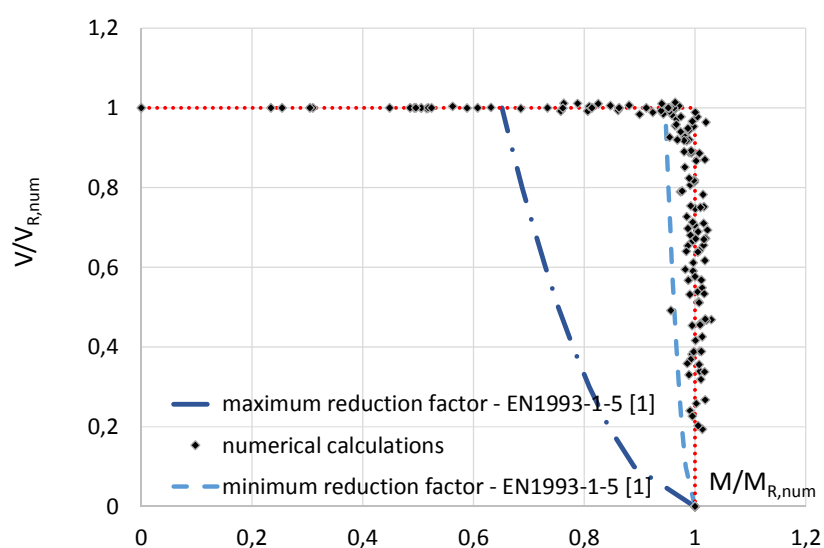


Fig. 39: Observed M-V interaction behaviour.

In the Fig. 40 the results of the numerical calculations can be seen respect to the specimen of Moon et al. [35]. The green continuous line represents the reduced M-V interaction and the yellow continuous line represents the determined shear and bending resistances according to the EN1993-1-5 [1]. It can be observed that in case of this girder there is no interaction between bending and shear and the recommendation of the design rule gives a very good agreement with the numerically calculated shear and bending resistances.

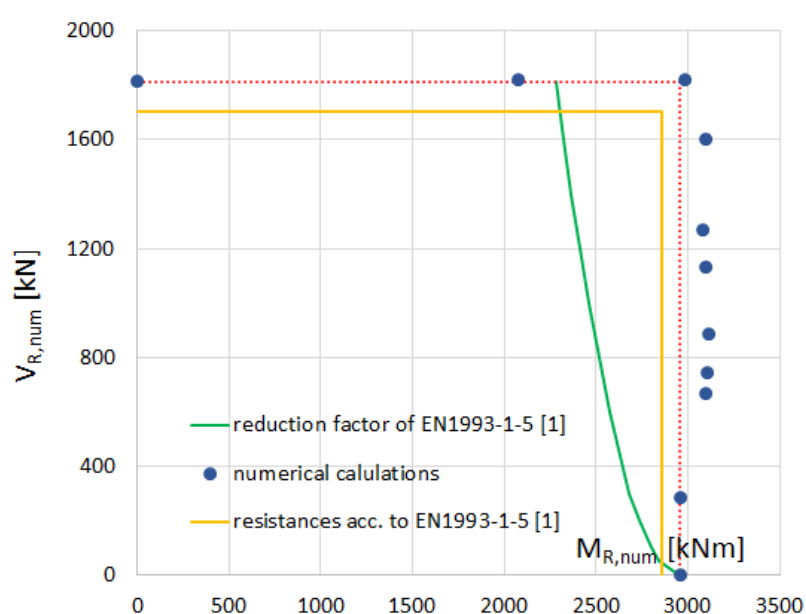


Fig. 40: M-V interaction behaviour of specimen C.P.1.

Based on the numerically calculated results which can be seen in Fig. 41 it can be stated that there is just a small interaction behaviour come out during the parametric study. It has to be mentioned that all of the results are outside of the unsafest solution of the bending and shear resistances according to the EN1993-1-5 [1]. It is also observed as in the previous results that the current Eurocode based reduction factor leads to a too conservative design.

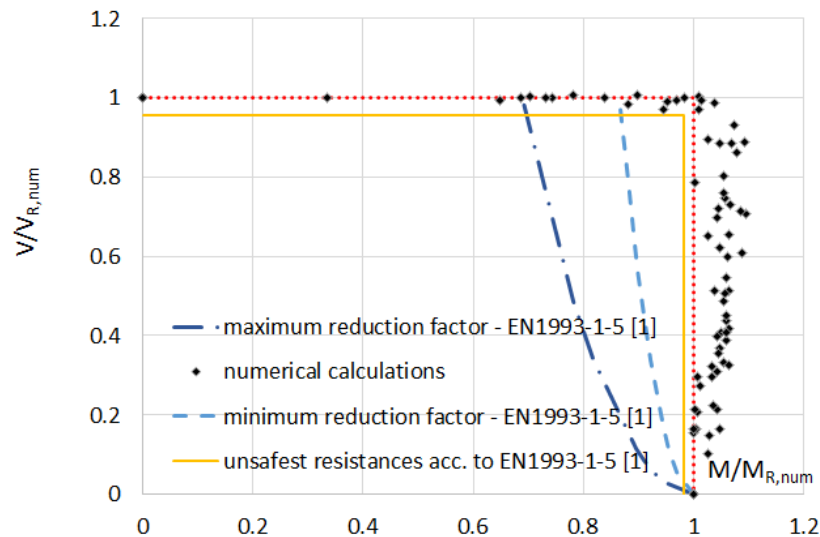


Fig. 41: Results of the parametric study on the specimen C.P.1.

These computed prove the results of Kuchta [9] who suggested also just a small resistance reduction due to the combined M-V loading situation and proves the statement of Elgally [5] that the interaction behavior of trapezoidally corrugated web girders could be neglected.

The observed resistance reduction is not larger than the web contribution in the bending resistance or the flange contribution in the shear buckling resistance. But these contributions are neglected in the design of the corrugated web girders.

Based on the numerical calculations another important observation is also noticed that the interaction behavior does not depend on the corrugation profile, but the additional normal stress distribution in the flanges are largely dependent on the corrugation profile of corrugated web girders. According to the results of the numerical calculations there is no relationship existing between the transverse bending moment in the flanges indicated by the shear force and the in-plane-bending resistance reduction, if plastic design is used.

9. Conclusions

Previous investigations in the field of corrugated web girders are dealing with the effect of the shear force on the normal stress field in the flanges. It is known that the shear force results an additional transverse bending moment in the flanges which indicates additional normal stresses. There are different proposals existing in the international literature how to consider the effect of shear on the calculation of the in-plane-bending moment resistance of girders with corrugated web. The reduction factor (f_T) in the EN1993-1-5 [1] is still questionable in the practice design according to several researchers in the past. That is why further investigation is needed in this field to clarify the structural behavior of corrugated web girders under combined moment and shear.

The evaluation according to EN1993-1-5 [1] of the analyzed girder geometries found in the international literature shows that in case of sinusoidal corrugation the applied corrugation depth is usually smaller in comparison with the flange width than in case of trapezoidal corrugation. Another observation is that the fold lengths of the equivalent trapeze profiles of sinusoidal corrugation are also relatively small, however the applied fold lengths of trapezoidal corrugation profiles are 5-7 times larger and the applied web thicknesses are also larger. These different applied geometrical dimensions are the reasons why the value of the transverse bending moment in the flanges can be significantly larger in case of trapezoidally corrugated web girders, than in case of sinusoidally corrugated web girders.

The reduction factor (f_T) of EN1993-1-5 [1] depends on the applied shear force, thus this formula expresses an M-V interaction diagram. This interaction diagram is extremely different from the usual M-V interaction formulas used for conventional steel structures. The evaluation of the reduction factor shows that it has a significant reduction effect on the in-plane-bending moment resistance of trapezoidally corrugated web girders with typical geometries used in the practical design. It can be observed that in case of the most unfavorable girder layout the average reduction in the bending resistance can be around 5% for sinusoidal corrugations and 13-18% for trapezoidal corrugations when the 50% of the shear resistance is applied as shear force on the structure. This analysis demonstrates that the transverse bending moment indicated by the shear force can have a significant effect on the in-plane-bending resistance reduction of girders with corrugated web in the practical design according to the EN1993-1-5 [1], therefore the investigation is necessary in this field.

In this paper the additional normal stresses and the normal stresses coming from the in-plane-bending are compared and evaluated. The results show that the difference between the

maximum values of the flange normal stresses can be significant by considering or neglecting the effect of the transverse bending moment. If the limit state of the design is the maximum allowed stress, the effect of the transverse bending moment could have importance.

Kövesdi et al. [14] carried out investigations focusing on the effect of the support conditions on the maximum value of the transverse bending moment in the flanges. The results of the investigations showed that the effect of the support conditions have a large influence on the maximum value of the transverse bending moment. In the recent paper the results of the numerical calculations have revealed that both the longitudinal and the lateral supports can reduce significantly the theoretically determined maximum value of the transverse bending moment in the flanges close to the support locations. It means that in case of real structures with real support conditions the maximum value of the transverse bending moment can be significantly smaller than its theoretically determined maximum. The transverse bending moment in the flanges are influenced by many parameters, therefore the determination of its value is very hard with analytic ways. However the maximum possible values can be determined by analytical solutions proposed by the EN1993-1-5 [1] and Kövesdi et al. [14], but if a more accurate value of the transverse bending moment is needed the author suggests using finite element software for taking the real boundary conditions into account.

For analyzing the effect of the additional normal stresses on the in-plane-bending moment resistance of girders with corrugated web, firstly the pure bending resistance and then the M-V interaction are analyzed with the help of numerical simulations. The results of the pure bending resistance analysis demonstrate that the EN1993-1-5 [1] gives proposal in a very good agreement with the numerical results except small flange thicknesses where the recommendation of the EN1993-1-5 [1] gives a very conservative design. The results of the combined bending and shear interaction analysis show that a very small resistance reduction is developed and the EN1993-1-5 [1] results in a conservative design.

The results show that in case of the analyzed girders the maximum reduction on the bending resistance due to the combined loading situation is 4,7%. These results are close to the results of Kuchta [9] who suggested also just a small resistance reduction due to the combined M-V loading situation and proves the statement of Elgaaly [5] that the interaction behavior of trapezoidally corrugated web girders could be neglected. The observed resistance reduction is not larger than the contribution of the web in the bending resistance or the contribution of the flange in the shear buckling resistance, however these contributions are neglected in the design of girders with corrugated web.

The numerical calculations demonstrate that the M-V interaction behavior does not depend on the corrugation profile, but the maximum value of the transverse bending moment depends on it. If plastic design is applied the numerical results do not show any relationship between the transverse bending moment and the bending resistance reduction.

Acknowledgement

The author wish to express his gratitude to Dr. Balázs Kövesdi and Dr. László Dunai for their accompanying useful advices, their helpfulness and their patience during the whole preparation of the recent paper.

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