



Stress distribution in the flanges of girders with corrugated webs

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ABSTRACT

The corrugated steel plate is a widely used structural element in many fields of application because of its numerous favorable properties. Due to the web corrugation the normal and shear stress distribution in the flange and web plates are different from the stress distribution of the conventional I-girders under in-plane bending and shear. The focus of this paper is the analysis of the stress distribution in the flanges of the girders with corrugated webs. Due to the corrugated web an additional transverse bending moment arises in the flange, which results in an additional normal stress distribution what has an effect on the bending moment resistance. The additional transverse bending moment comes from the shear force in the corrugated web and its value depends on the geometry of the corrugation profile. The effect and the tendency of this transverse bending moment are analyzed in the current paper. Based on experimental background a numerical model is developed to analyze the stress distribution in the flanges. Tendency of the additional normal stresses are determined and based on the numerical results an enhanced design method is proposed to determine the transverse bending moment and the additional normal stresses.

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1. Introduction

In the last 20 years the corrugated steel plate has been increasingly used as a beam web. This structural layout has spread in the field of bridges as well as in the field of industrial buildings. Numerous studies in the last years proved that the stress distribution in the girders with corrugated webs are different from the conventional stress distribution of the traditional I-girders with flat webs under in-plate bending and shear. The different characteristics of the stress distribution in the flange and web plates have an effect on the bending and shear resistance, which can be considered in the design.

Numerous studies detailed in [Section 2](#) investigate the bending and shear resistance of the girders with corrugated webs. It is well known from the previous investigations that the shear stress in the corrugated web indicates a transverse bending moment, which results in an additional normal stress in the flange. The current version of EN1993-1-5 Annex D [1] calls the attention of the phenomenon but does not give an application rule for it. In the international literature there are several proposals to solve the problem, but they do not cover the whole range of arrangements and loadings. The aim of the current research is the investigation of the flange stress distribution in the girders with corrugated webs and the development of a design method to determine the additional normal stresses for general cases.

The existing experimental, analytical and numerical investigations are analyzed, evaluated and compared in the current paper. To extend the previous investigations and to analyze the applicability of the

previous design proposals a numerical model is developed. The base of the numerical model development is the experimental investigations executed at the Budapest University of Technology and Economics on large scale test specimens with corrugated webs. The original aim of the tests was the determination of the fatigue behavior of the corrugated web girders but numerous strain measurements are also carried out which are good bases of the current investigations and numerical model verification.

Based on the developed numerical model the normal stress distribution in the flange plate is analyzed. The effect of the different geometric parameters, the corrugation profile and the loading conditions are studied in frame of a numerical parametric study. The tendencies in the transverse bending moment are determined and evaluated. The results of the numerical calculations are compared to the previous design proposals and an enhanced design method is proposed to determine the additional normal stresses coming from the shear in the corrugated web. The applied parameters used in the research are shown in [Fig. 1](#).

2. Literature overview

2.1. Previous studies on the stress distribution in the web and on the shear capacity

There are many previous investigations dealing with the stress distribution in the web and flange plates of the corrugated web girders. The normal stress distribution in the web was investigated by Elgaaly et al. [2,3] in 1997 and 1998. The typical stress distribution was determined by experimental and numerical investigations and the conclusion was drawn that the normal stresses are almost equal to zero in the main

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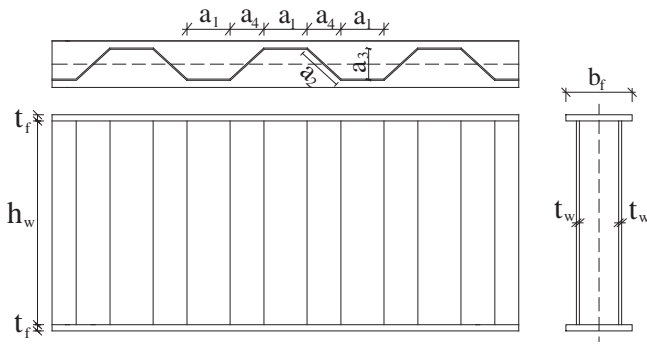


Fig. 1. Geometry of a girder with trapezoidally corrugated web.

part of the web except a localized area adjacent to the flanges, which are larger in the longitudinal folds and smaller in the inclined folds of the corrugation profile. Based on this observation they concluded that the contribution of the web in the moment carrying capacity of the girder is almost negligible.

The stress distribution of the corrugated web girders was also investigated by Huang et al. [4] in 2004. Girders with steel web and with concrete flanges were studied. Based on the experimental and numerical investigations they concluded that the corrugation profile has a significant effect on the axial stress distribution in the web. They described that the normal stress decreases rapidly under the flanges and its value is almost negligible in the largest part of the web. This phenomenon is called the “accordion effect”, which is typical for girders with corrugated webs. The same stress distribution was described by Mori et al. [5] in 2006. They investigated and characterized the stress distribution in girders with pre-stressed concrete flanges and with corrugated steel web. The focus of the research was to study the effect of the corrugated web on the pre-stressing force distribution.

There are also numerous studies, which are dealing with the determination of the shear buckling behavior of the corrugated web plate. Investigation was started by Easley and McFarland [6] in 1969. Since then numerous significant experimental, numerical and theoretical investigations are executed in this topic. The shear buckling resistance of the corrugated web girders was analyzed at first by Lindner and Aschinger [7,8] in 1988 and 1992. Significant numerical investigation was executed by Luo and Edlund [9]. Experimental and numerical investigations were done by Elgaaly et al. [10], the research was continued by Pasternak and Hannebauer [11], Yi et al. [12], Moon et al. [13] and by Eldib [14]. In these research studies the shear buckling behavior of the corrugated webs were studied in detail. Numerous experiments were executed and different numerical models were developed. Based on these investigations different design proposals were derived to determine the local and global shear buckling resistance.

2.2. Previous studies on the stress distribution in the flange and on the bending resistance

The bending resistance of the girders with corrugated web was investigated by Lindner [8] in 1992. Based on experimental investigation on large scale test specimens with corrugated webs it was proposed that the bending resistance should be calculated only from the contribution of the flanges with the additional normal stresses taken into account. To determine the additional normal stresses coming from the transverse bending moment experimental investigations are executed on large scale test specimens. The flange normal stresses were measured at several points in a cross-section of an inclined and a parallel fold and the tendency of the stress distribution and the value of the transverse bending moment were determined. The research was continued by Aschinger and Lindner [15] in 1997 and design proposal is derived to determine the

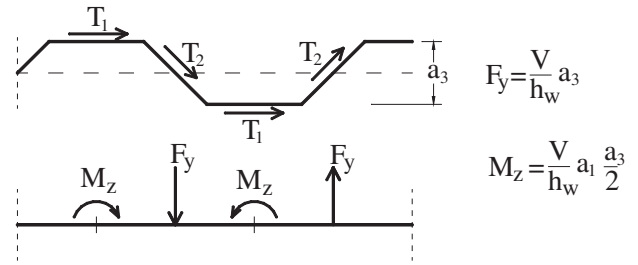


Fig. 2. Theoretical background of the transverse bending moment [2].

additional normal stresses. The theoretical background of the developed equation is that the additional normal stress comes from the shear flow of the corrugated web. The shear flow has different directions along the girder length in a parallel and in an inclined fold. Based on the theory of Aschinger and Lindner [15] the flange can be assumed as a girder loaded by the additional lateral force (F_y) and transverse bending moment (M_z), as shown in Fig. 2.

The shear flow has an alternating tendency therefore the additional stress distribution in the flange has also an alternating tendency along the girder length. These forces (F_y) and moments (M_z) result in a transverse bending moment in the flange and indicate the additional normal stresses. To determine the maximum transverse bending moment Eq. (1) is proposed in [15]

$$M_{z,\max} = C_1 \cdot F_y + C_2 \cdot M_z \quad (1)$$

where:

$$M_z = \frac{V}{h_w} \cdot a_1 \cdot \frac{a_3}{2} \quad (2)$$

$$F_y = \frac{V}{h_w} \cdot a_3. \quad (3)$$

C_1 and C_2 are constants which are depending on the loading conditions. The relevant values of C_1 and C_2 are given in Table 1.

The accuracy of the proposed equation is proved by laboratory test results. The above mentioned equation was implemented in the DAST-Richlinie 015 “Träger mit schlanken Stegen” [16]. Besides this transverse bending moment, two other, but much smaller effects can also be taken into consideration in the case of the corrugated web girders, which are related to the flange thickness. Due to the fact that these additional forces coming from the corrugation profile are acting on the lower or upper edge of the flange plate an additional torsion and bending moment also evolve, which can be also taken into account.

The bending resistance of the corrugated web girders was investigated also by Elgaaly et al. [2] in 1997. Based on the experimental investigations numerical model was developed and the stress distribution in the flange and in the corrugated web was studied in detail. Based on their investigations a conclusion was drawn stating that the contribution of the web to the ultimate moment capacity of the girder is negligible, and that the bending resistance can be calculated only from the contribution of the flanges. It was demonstrated that the shear force is carried only by the corrugated web. The flanges provide boundary support conditions to the web, which can be between simply supported

Table 1
Proposed values for C_1 and C_2 [15].

	C_1 [cm]	C_2
Uniformly distributed load	6.5	0.6
Concentrated load	13.0	1.5
Concentrated moment	13.0	2.0
Triangle distributed load	6.5	0.5

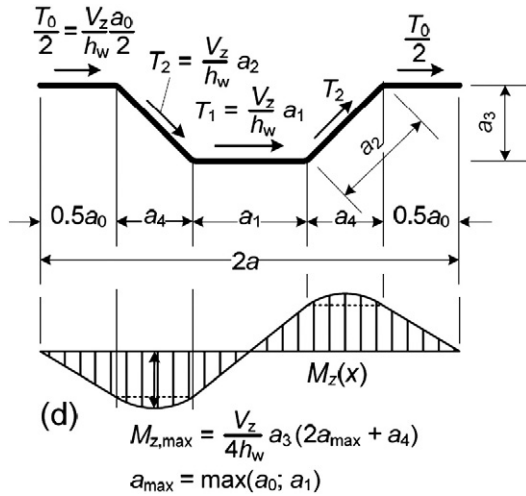


Fig. 3. Proposed amendment of Balaž for EN1999-1-1 [22].

and fixed depending on the flange and web thicknesses. Based on their observations they concluded that the bending moment is carried by the flanges and the shear is carried by the web, therefore there is no interaction between them. The stress distribution in the flanges and the effect of the transverse bending moment were not investigated.

Kuchta [17] investigated the structural behavior of the girders with trapezoidally corrugated webs under the combined loading situation of bending and shear in 2006. Based on the executed experimental research program a numerical model was developed. The interaction behavior and the stress distribution under the different loading situations were studied. The result of the investigation showed that there is a small reduction in the load carrying capacity under the combined loading situation and therefore an interaction equation is proposed which can be used for girders with trapezoidally corrugated webs. But the bending resistance model used in the proposed interaction equation does not take the effect of the transverse bending moment into account, and the additional normal stress was not studied in frame of this investigation.

Significant research activity is carried out by Abbas et al. [18,19,20] in 2006 and 2007 on this topic. The behavior of the corrugated web girders under in-plane loading was investigated and the stress distribution in the flanges was analyzed. Stress measurements were executed on large scale test specimens with trapezoidally corrugated webs. Based on the test results a numerical model was developed and the tendency of the transverse bending moment was studied on it. To determine the transverse bending moment of the trapezoidally corrugated web girders a so called

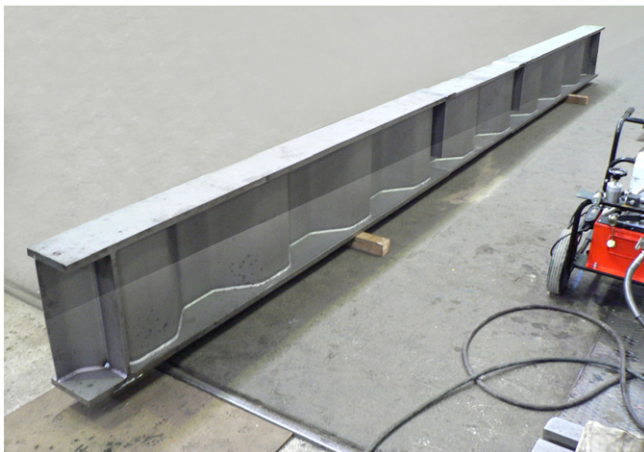


Fig. 4. Large scale test specimen.

“fictitious load method” is developed by Abbas et al. in [18]. This load is introduced as a tool for analyzing flange transverse bending of corrugated web I-girders. This load is defined as the transverse load that produces lateral force and transverse bending moment in the flanges. This load has the same meaning as F_y and M_z developed by Aschinger and Lindner [15]. In this method each flange is analyzed as a beam loaded with this transverse fictitious load (p_t) that has been mathematically described by Abbas et al. [19]. The proposed method is compared to strain measurements in laboratory tests made on large scale test specimens with trapezoidally corrugated web and to the results of numerical calculations. The comparison showed in all the analyzed cases a good agreement. Due to the complexity of the given proposal for the determination of the transverse bending moment, its usage in the praxis is quite difficult. Although manual calculation is also possible, the authors proposed that it is often more convenient to use commercial structural analysis software, especially as the number of corrugations increases.

Theoretical investigation has been also carried out by Abbas et al. in [19]. It was stated that the girders with corrugated webs cannot be analyzed by the conventional beam theory alone. Under the action of in plane loads a torsional moment is produced and the girder twists out-of-plane simultaneously as it deflects in-plane. The in-plane bending behavior can be analyzed by the conventional beam theory and the out-of-plane torsional behavior can be treated as a flange transverse bending problem, which is analogous to an I-girder warping torsion problem. The complete stress state can be determined by the superposition of the stresses due to in-plane bending and flange transverse bending. To derive a closed form equation to the transverse bending moment determination the trapezoidally corrugated web is replaced by a sinusoidally corrugated web, to make the analytical solution easier. The proposed equation is given in the form of Eq. (4), which is only applicable in case of uniformly distributed load along the girder length. All the details of the analytical solution and the relevant notations are given in [19]

$$M_t^{\sin} = \frac{p_y \cdot L^2 \cdot a_3}{2 \cdot h_w} \cdot \left\{ \frac{1}{\Pi^2} \cdot \left[\left(1 - 2 \frac{z}{L} \right) \cdot \Pi \cdot c_\zeta + 2 \cdot s_\zeta + (\Pi \cdot c_{\Pi} - 2 \cdot s_{\Pi} + \Pi) \cdot \frac{z}{L} - \Pi \right] \right\} \quad (4)$$

where:

p_y is the uniformly distributed in-plane load,
 L is the span of the analyzed girder, $\Pi = 2 \cdot \pi \cdot n$; $c_\zeta = \cos(2 \cdot \pi \cdot \frac{z}{L})$; $c_{\Pi} = \cos(2 \cdot \pi \cdot n)$; $s_\zeta = \sin(2 \cdot \pi \cdot \frac{z}{L})$; $s_{\Pi} = \sin(2 \cdot \pi \cdot n)$,
 n is the number of the corrugation waves, and
 z is the position of the analyzed cross-section along the girder axis.

Because the analytical solution can be used only for girders with sinusoidally corrugated webs, Abbas et al. [20] developed a so called “C factor”, which gives the relationship between the transverse bending moment of the sinusoidal and another corrugation profiles. Different corrugation profiles were studied (trapezoidal, triangular and rectangular) and different C factors were determined to be able to calculate the transverse bending moment in the form of Eq. (5).

$$M_t^{\text{trap}} = C \cdot M_t^{\sin} \quad (5)$$

Proposal to determine the maximal transverse bending moment can be also found in the “Commentary and worked examples to DIN-EN-1993-1-5 Plated Structural Elements” [21]. According to the description found in [21], if there is a substantial shear force in the cross-section of the maximum bending moment there may be an influence of the flange axial resistance from transverse bending. The theoretical basis of this model to calculate the secondary bending moment is the same as shown in Fig. 2. It means that the transverse bending comes from the shear flow in the corrugated web. The maximum

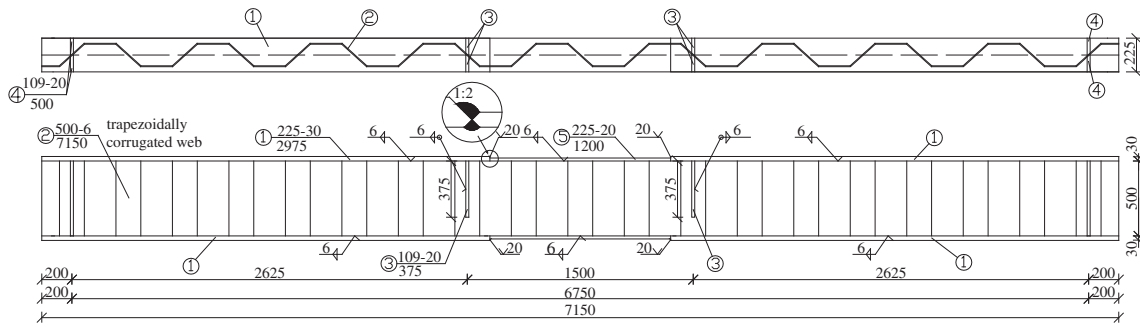


Fig. 5. Geometry of the specimen loaded under four-point-bending.

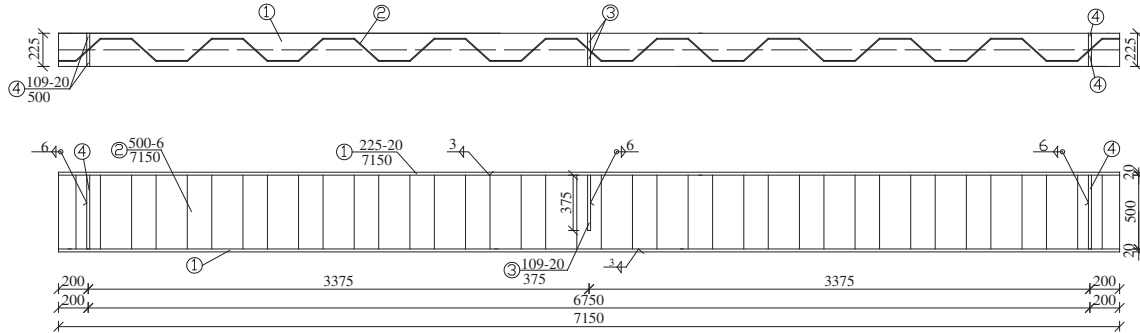


Fig. 6. Geometry of the specimen loaded under three-point-bending.

transverse bending moment $M_{z,max}$ occurs where the inclined part of the web intersects the centerline of the flange and its value can be calculated by Eq. (6).

$$M_{z,max} = \frac{V \cdot a_3}{4 \cdot h_w} \cdot (2 \cdot a_1 + a_4) \quad (6)$$

Balaž proposed to implement Eq. (6) into the EN1999-1-1 [22] and to modify the related figure (Fig. 3) to give more theoretical background to the given equation.

2.3. Evaluation of the previous research

All previous investigations have in common, that the ultimate bending resistance of the girders with corrugated webs can be calculated only from the contribution of the flanges. The contribution of the web can be neglected due to the “accordion effect”, that is typical for the corrugated web girders. It is also concluded that the shear buckling resistance can be calculated from the resistance of the web, and the flange contribution can be neglected.

In the bending moment resistance calculation, several studies take the influence of the transverse bending moment into account. Other studies neglect this effect and calculate the moment carrying capacity assuming a constant stress distribution in the flanges. All studies which are dealing with the effect of the transverse bending moment and which are taking the non-uniform stress distribution in the flanges into consideration are using the same theoretical background developed by Aschinger and Lindner [15] in 1997. However, although all design proposals found in the literature have the same background, the given equations to determine the maximum transverse bending moment are different. Therefore the focus of the current paper is to analyze and compare the previously developed design equations based on the recent experimental and numerical investigations.

3. Experimental investigations

3.1. Test specimens and arrangement

Laboratory tests were executed on 6 large scale test specimens with trapezoidally corrugated webs at the Budapest University of Technology and Economics in 2008. The original aim of the tests was the

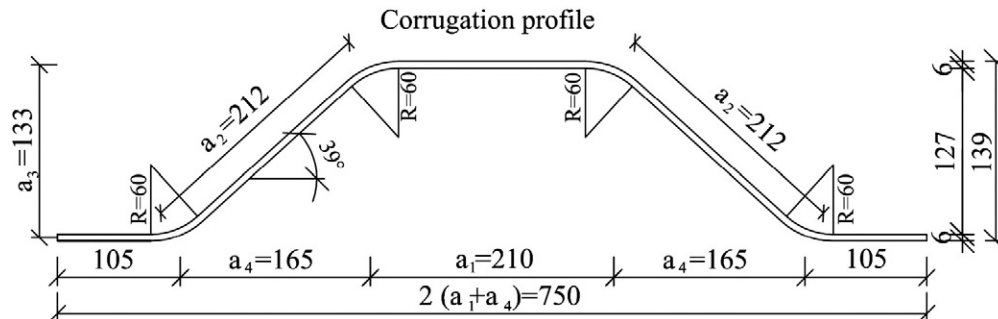


Fig. 7. Geometry of the corrugation profile.

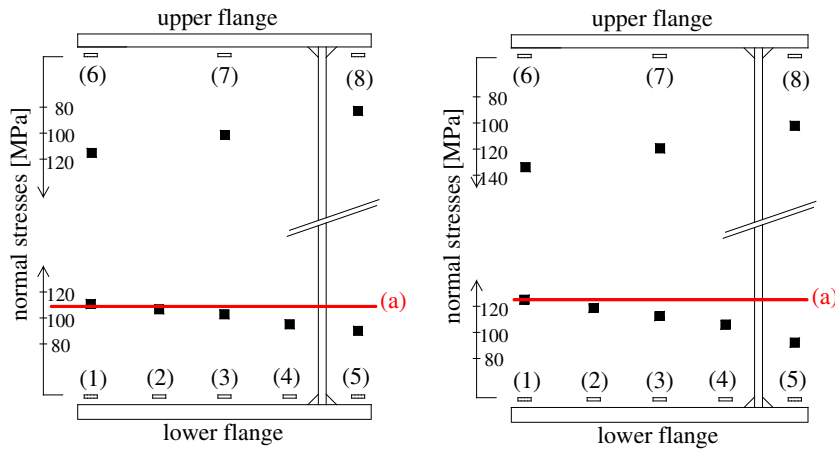


Fig. 8. Normal stress distribution in the flanges of specimens #1 and #2.

investigation of the fatigue behavior of the corrugated web girders. During the tests the stress distributions on different locations in the flange and in the web were measured and evaluated. These measurements provide an experimental background to the investigation of the stress distribution and to the numerical model development, which are the bases of the current analysis.

The test specimens are large scale I-girders with a total length of 7150 mm and a span of 6750 mm. The test specimen can be seen in Fig. 4. The girders have a 6 mm thick and 500 mm deep web. The flange width is 225 mm and the thickness is 20 mm. Two girders were loaded under a four-point-bending and four specimens under a three-point-bending arrangement. In the case of the specimens loaded under four-point-bending the flange thickness was 20 mm in the middle part of the girder in the constant bending moment region, and the flange thickness increased to 30 mm at both girder ends 600 mm from the load introduction locations to reduce the normal stresses in the end zones (note that the reduction was necessary due to fatigue aspects).

Under the load introduction places 20 mm thick stiffeners were applied. The used steel grade in the tests was S355. The yield and ultimate strengths were measured and in the case of the 20 mm thick plates these values are 379 MPa and 517 MPa, respectively; in the case of the web plate with a 6 mm thickness the measured values are 373 MPa and 542 MPa, respectively. The geometries of the specimens are shown in Figs. 5 and 6.

The corrugation profile was the same for all specimens, and the geometry is shown in Fig. 6. The fold lengths are $a_1 = 210$ mm, $a_2 = 212$ mm and the projected lengths of the inclined folds are $a_3 = 134$ mm and $a_4 = 165$ mm. The corrugation angle is 39° and the bending radius is 60 mm for all specimens. The geometry of the corrugation profile can be seen in Fig. 7.

3.2. Measured stresses

The main part of the strain measurements were made on the specimens loaded under four-point-bending and the stresses were measured in the constant bending moment zone, where the shear force was equal to zero. The measured stress distribution for specimen #1 and #2 can be seen in Fig. 8 in a cross-section with a parallel web fold.

The strains are measured on 8 points within the cross-section, 5 strain gauges were placed on the lower and 3 on the upper flange. Specimen #1 was loaded by two concentrated loads equal to 100 kN and specimen #2 by 115 kN. So the applied bending moments in the analyzed cross-sections are 262.5 kN m and 301.9 kN m, respectively. It was observed in the tests that in the cross-section of the parallel folds the normal stresses are smaller near to the web and larger far from it. The tendency of the stress distribution between the two flange edges

is nearly linear and the difference between the stresses at the flange edges changes between 18 and 27% in the cases of the analyzed girders.

It was found that in the constant moment zone there is also a linear stress distribution between the two flange edges, what comes not from the shear flow in the corrugated web, it has another reason. The reason of this phenomenon can be explained by the structural characteristic of the corrugated web. In the cross-section of the parallel folds the interlock between the upper and lower flanges are better than in the cross-section with an inclined fold. Therefore the web contribution in the load bearing is more dominant in the cross-section with a parallel fold than in a cross-section with inclined folds. This explanation is proved by the strain measurements in the web plate as well. The measured normal stress distribution in an inclined and in a parallel fold can be seen in Fig. 9. The diagram shows the well-known “accordion effect” and furthermore that the normal stresses in the inclined folds are smaller than in the parallel folds. The previous two establishments are in correlation with each other and it results in the difference in the normal stress distribution in the flanges.

Lines (a) in Fig. 8 represent the calculated normal stresses under the applied bending moment using the assumption that only the flanges are taken into consideration in the inertia calculation and the web part is neglected. This assumption is recommended by several researchers (see Section 2.2) and also by the EN1993-1-5 Annex D [1]. In the cross-section of the inclined folds the normal stress distribution is approximately constant along the whole flange width in the constant bending moment zone and the stresses are just a little bit smaller than the calculated value represented by line (a). It means that the current tests also prove the assumption that the normal stresses in the flange of a corrugated web girders can be calculated neglecting the web part from the inertia calculation. The stresses in the cross-section

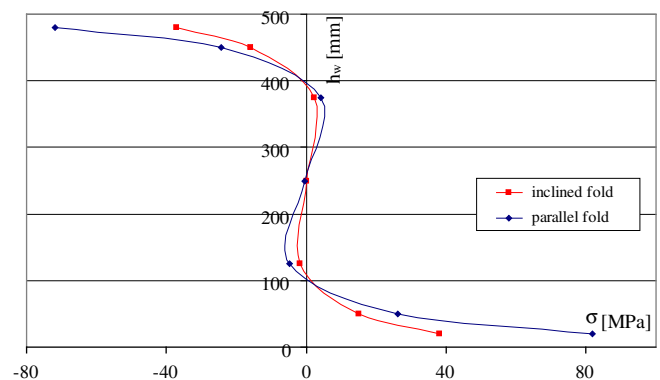


Fig. 9. Longitudinal normal stresses in the web along the depth (specimen #1).

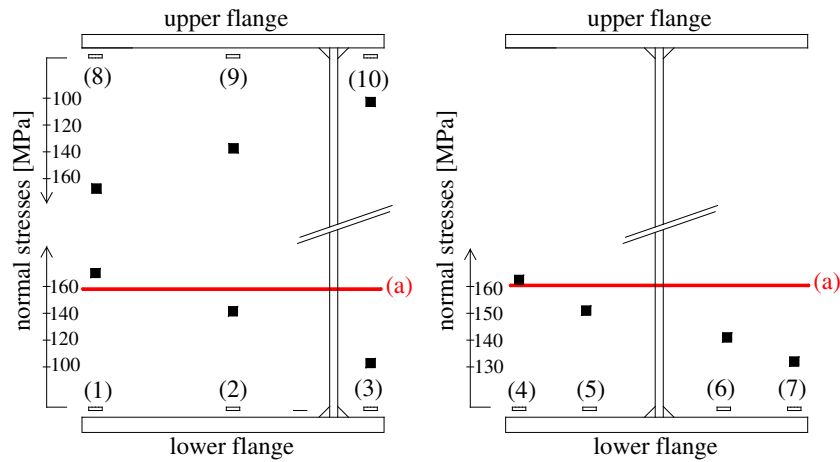


Fig. 10. Typical stress distribution under bending and shear.

with a parallel fold are smaller near the web but the largest stress can be determined using the above mentioned assumption. To determine the average stresses in the flange with a parallel fold an effective cross-section with 3/20 of the whole web depth can be taken into account to get the average normal stress with adequate accuracy, but the effective section depends on the stiffness ratio of the flange and web plates and on the corrugation profile.

By summarizing the evaluation of the strain measurements in the constant bending moment zone the following conclusion can be drawn:

- The stress distribution in the cross-section with an inclined fold is almost constant within the flange width.
- The stress distribution in the cross-section with a parallel fold is nearly linear.
- The measurements proved that the largest normal stress from pure bending in a cross-section with inclined or parallel fold can be determined by neglecting the web from the inertia and the linear stress distribution comes not from the transverse bending but from the better interlock between the flange and web in the parallel fold region.

Strain measurements are also executed on specimens #3–#6, which were loaded under three-point-bending. The measured typical stress distributions in a cross-section with parallel and with inclined folds are shown in Fig. 10. Specimen #3 was loaded by a concentrated force of 230 kN at the midspan, which resulted in the middle cross-section and bending moment of 388.12 kN m. The lines (a) show the calculated nominal normal stresses in the analyzed cross-sections neglecting the web contribution from the inertia calculation. It can be seen that the tendency of the normal stress distribution in the cross-section with parallel fold is the same as described above by the constant bending moment zone without shear forces. But the stress distribution in the cross-section with an inclined fold shows also a linear tendency, which can be explained by the effect of the shear flow in the corrugated web.

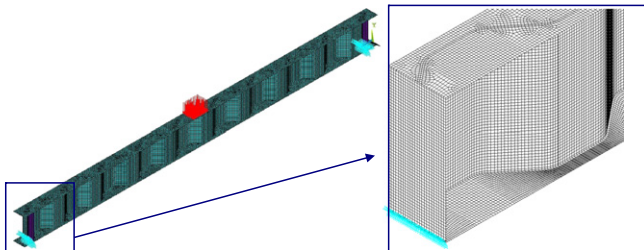


Fig. 11. Developed numerical model for specimen #3.

To analyze the stress distribution under the combined loading situation, a numerical model is developed. The model verification is executed on the bases of the laboratory tests. The stress distribution in the flange plate is analyzed in different cross-sections under different loading conditions to compare the previously proposed design equations detailed in Section 2.2.

4. Numerical research program

4.1. Numerical model development and verification

Based on the experimental background, a numerical model is developed with the finite element program Ansys 10.0 [23]. The aim of the numerical investigations is to determine the stress distribution of the corrugated web girders under different loading conditions, extending the range of the experimental results. The corrugated web, the flanges and stiffeners are modeled using eight node thin shell elements. The developed numerical model, the applied finite element mesh, and the loading and support conditions can be seen in Fig. 11.

The stresses in the numerical model are calculated by a linear analysis using linear elastic material model ($E = 210,000$ MPa; $\nu = 0.3$). Convergence study is executed to ensure and check 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 15 and 25 mm. The numerical model is verified by the comparison of the measured and calculated stresses and deflections of all the 6 test specimens. The comparison of the flange stresses for one specimen can be seen in Fig. 12. The finite

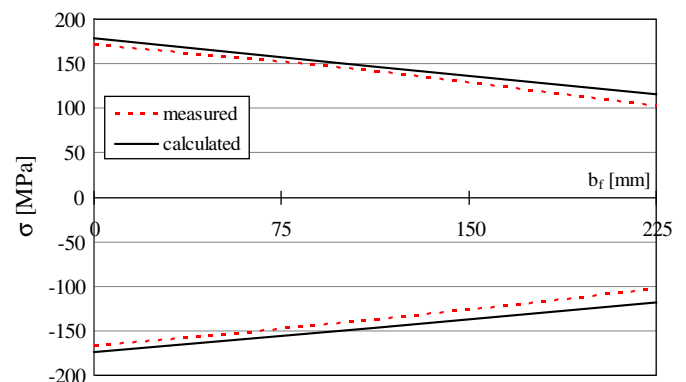


Fig. 12. Comparison of the measured and calculated stresses in the flange.

element model exhibited the same elastic structural behavior as observed in the tests, and the comparison showed a good agreement between the test and the numerical results.

4.2. Numerical study program

Based on the verified finite element model a numerical study is executed. In its frame, different loading conditions are analyzed, as shown in Fig. 13.

Three point bending is used to analyze the stress distribution under combined bending and shear with a constant shear distribution along the girder length. The results of the numerical calculations are compared to the previously proposed calculation methods of the additional transverse bending moments. The difference between the proposals are analyzed and evaluated.

Four point bending is used only to the model verification and to analyze the stress distribution in the flanges under pure bending. The previous conclusions are proved and confirmed by the numerical results.

Bending by uniformly distributed load is used to investigate the effect of the shear force diagram on the transverse bending moment. According to the proposal of Aschinger and Lindner [15] the additional transverse bending moment changes according to the applied load type, but according to the proposal of the “Commentary to EN1993-1-5” [21] its value depends only on the current shear force in the analyzed cross-section and not on the load distribution. Therefore, besides the fact that the analytical method proposed by Abbas et al. [20] is usable only in this loading condition, this effect is studied in detail in the current research.

4.3. Normal stress distribution in the flanges in case of constant shear distribution along the girder length

4.3.1. Stress distribution tendencies

The flange stress distributions in the middle of each web folds along the whole girder length are investigated and evaluated in the frame of the current numerical investigations. The lines where the normal stresses are studied are shown in Fig. 14. All analyzed cross-sections are located in the middle of a web fold and are numbered from the end of the girder. The results showed that the stress distributions in both type of cross-sections with parallel and inclined folds show a linear tendency, as illustrated in Fig. 10. It means that an additional transverse bending moment develops in both cross-sections. The assumption used for the explanation of the transverse bending moment (Fig. 3) shows that its value should be zero at the middle of the parallel fold, but the numerical calculations do not confirm it.

Furthermore on the basis of the numerical investigations it is observed that the tendency of the normal stress distribution in the flanges depends on the analyzed specimen geometry (number of the corrugation waves), on the position of the load introduction place and on the support position. Four different loading and support positions can be

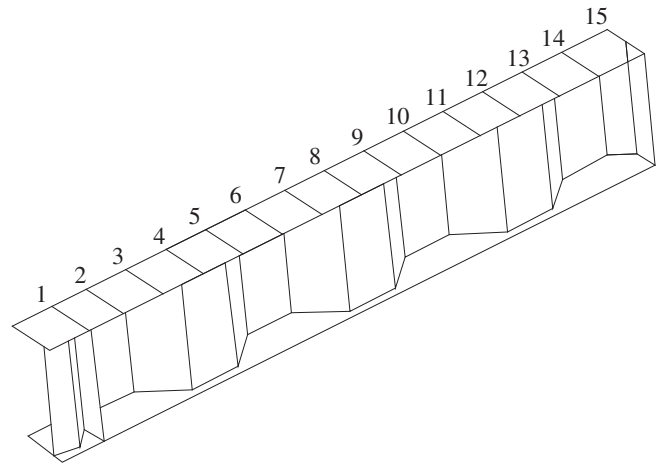


Fig. 14. Sections where the normal stresses are analyzed.

identified from the point of view of the stress distributions, as shown in Fig. 15:

1. Girder type 1: Support and loading at the middle of a parallel fold; not full corrugation waves between the support and load introduction place (Fig. 15a).
2. Girder type 2: Support and loading at the middle of a parallel fold; full corrugation waves between the support and load introduction place (Fig. 15b).
3. Girder type 3: Support and loading at the middle of an inclined fold; not full corrugation waves between the support and load introduction place (Fig. 15c).
4. Girder type 4: Support and loading at the middle of an inclined fold; full corrugation waves between the support and load introduction place (Fig. 15d).

The stress differences ($\Delta\sigma$) between the two flange edges along the half girder length is studied in all the four different girder types. The results of the numerical calculations are shown in Figs. 16 and 17. The analyzed girder has the same geometry as the test specimen described in Section 3 and a 100 kN concentrated force is applied at the midspan. The horizontal axis of the diagrams show the number of the analyzed cross-section in accordance with Figs. 14 and 15.

The stress differences ($\Delta\sigma$) presented on the vertical axis are in linear relationship with the transverse bending moment, therefore these diagrams show its tendency as well. In the cases of the first two girder geometries (girder type 1–2) the stress distribution tendencies are the same, as shown in Fig. 16. It means that the number of the modeled corrugation waves has no influence on the additional flange stresses. The position of the maximal additional normal stresses are located in the middle of the inclined folds (point nos. 2, 4, 6, 8, etc.), and the values of the extreme points are constant along the girder length, because the shear

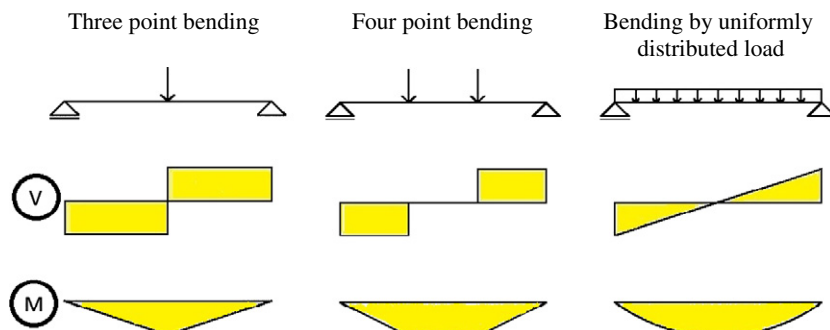


Fig. 13. Analyzed loading conditions.

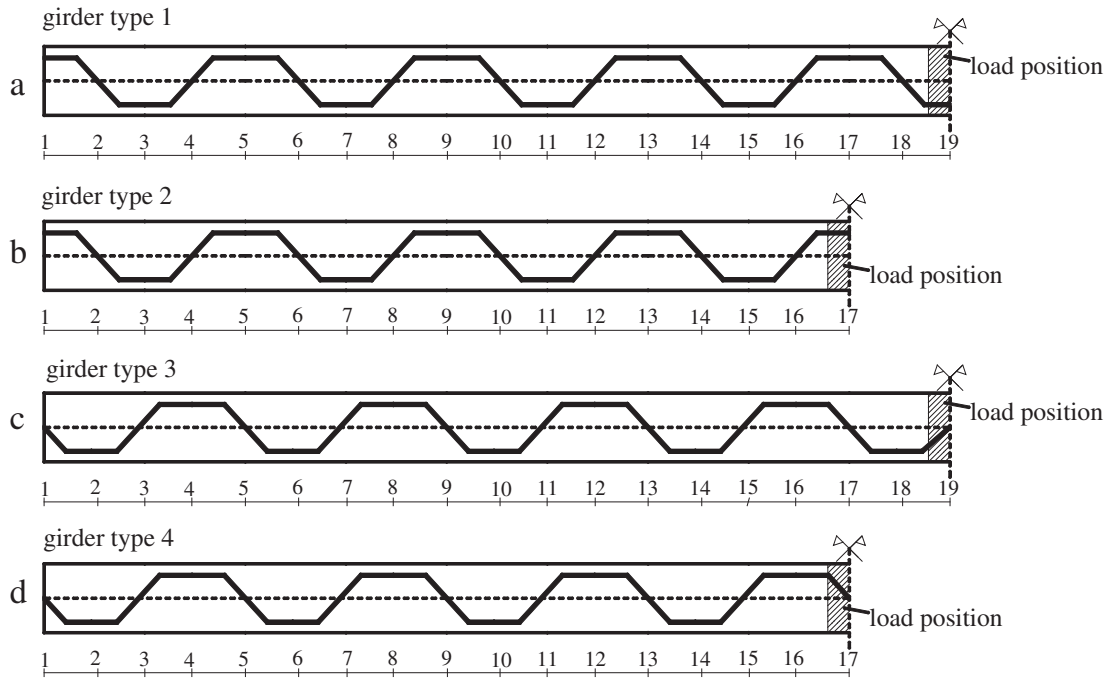


Fig. 15. Analyzed girder geometries, and support and loading positions.

force diagram is constant. The additional bending moment has an alternating tendency, in the first parallel fold its direction is positive and in the next fold negative. The diagram shows that the stress differences in the middle of the inclined folds are always zero, as shown in Fig. 3.

The stress differences between the two flange edges according to [21] are calculated as follows:

$$M_{z,max} = \frac{V}{h_w} \frac{a_3}{4} (2a_1 + a_4) = \frac{50 \text{ kN}}{50 \text{ cm}} \cdot \frac{13.3 \text{ cm}}{4} \cdot (2 \cdot 21 \text{ cm} + 16.5 \text{ cm}) \quad (7)$$

$$= 194.5 \text{ kN cm}$$

$$I_{z,flange} = \frac{22.5^3 \cdot 2}{12} = 1898.43 \text{ cm}^4 \quad (8)$$

$$\Delta\sigma = \frac{194.5}{1898.43} \cdot 22.5 = 23.1 \text{ MPa} \quad (9)$$

The numerical calculation resulted in 22.5 MPa, it means that the proposed equation gives a good approximation in the above mentioned loading and supporting conditions.

The numerical calculation, however, showed that in the cases of girder types 3–4 the stress distribution tendencies are different, as

illustrated in Fig. 17. The red curve (girder type 4) shows the tendency of the additional transverse bending moment distribution along the girder length if support and load introduction places are located at the middle of an inclined fold and the girder has a number of full corrugation waves between the support and loading positions. It can be seen, that the tendency of the diagram is totally different from the tendency shown in Fig. 16. The stress difference does not have an alternating tendency, the minimum value is near zero, and the maximum value (41.2 MPa) is almost double the above mentioned maximum (22.5 MPa). Based on the evaluation of these results the minimum and maximum values of the transverse bending moments are always in the middle of the inclined fold but they are not zero in the middle of the parallel folds.

The diagram also shows that the maximum and minimum values are almost constant along the girder length, which can be explained by the full number of the corrugation waves. In the case of girder type 3 the number of the analyzed corrugation waves is not a round value and it results in a non-uniform tendency in the transverse bending moment diagram. The maximum value is located at the girder end which almost reaches the maximum value of girder type 4, and it is much smaller in other folds. The reason for this is the unbalanced shear forces in the corrugated web.

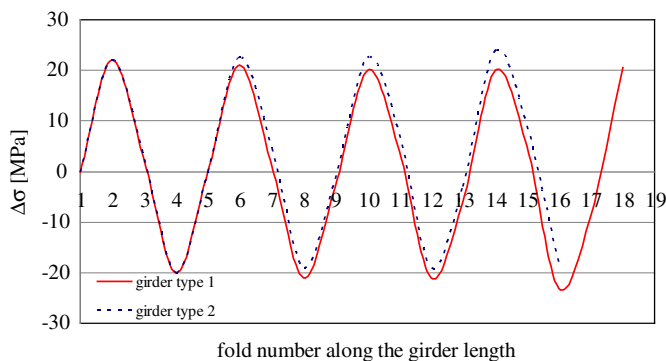


Fig. 16. Normal stress differences in the different cross-sections along the girder length.

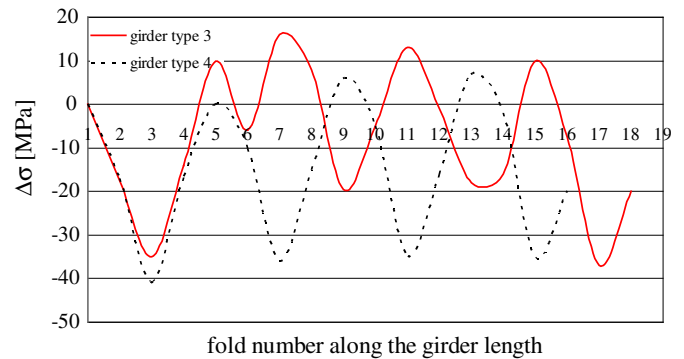


Fig. 17. Normal stress differences in the different cross-sections along the girder length. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

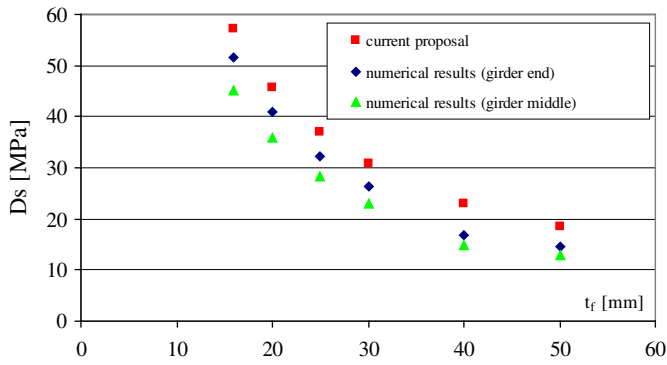


Fig. 20. Effect of the flange thickness on the maximum stress difference.

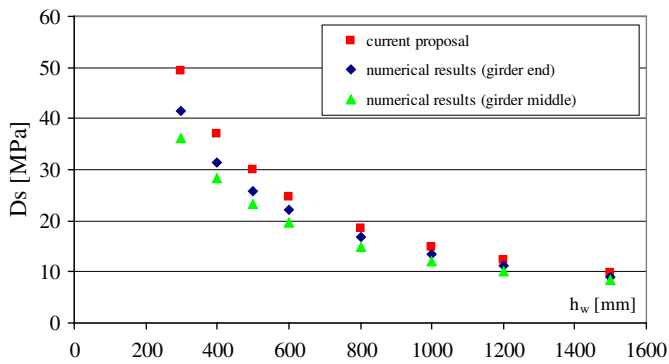


Fig. 21. Effect of the web depth on the maximum stress difference.

flange. The diagram shows that the tendencies found in the numerical parametric study are the same as the tendency of the enhanced transverse bending moment determination method, according to Eq. (12).

The results of the numerical calculations are compared to the proposal of Aschinger and Lindner [15] and to the proposal of [21] in Fig. 24. Based on the numerical results the maximum additional stress in the flange coming from the shear flow in the corrugated web can be determined using the proposal of Aschinger and Lindner [15] or by the enhanced design method according to Eq. (12), if the shear force diagram is constant along the girder length.

In the numerical parametric study it is also observed that the proposal of Ashinger and Lindner [15] does not follow the tendencies of the numerical calculations if the parallel and inclined fold lengths are different ($a_1 \neq a_2$). Fig. 25 shows the stress differences in the function of the a_2 keeping the value of a_1 constant. The diagram shows that the

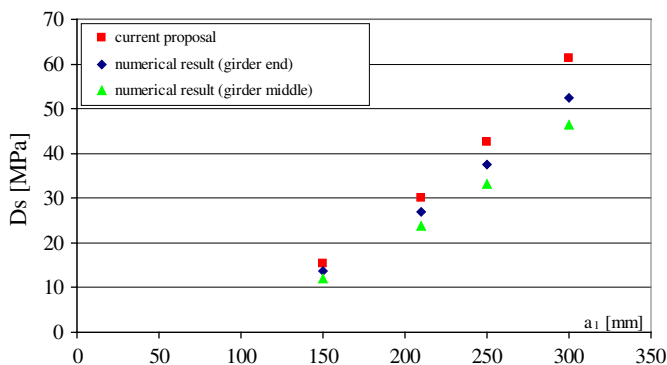


Fig. 22. Effect of the fold length on the maximum stress difference.

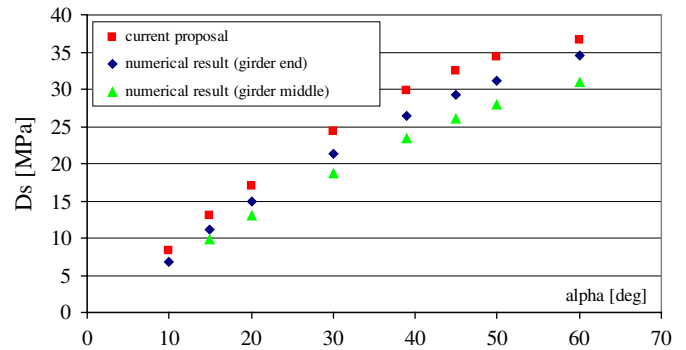


Fig. 23. Effect of the corrugation profile on the maximum stress difference.

current modification proposal follows the calculated tendencies in the analyzed parameter range, but the values calculated by the proposal of Aschinger and Lindner gives in several cases smaller values.

If the load type is different from that mentioned above, then the proposal of Aschinger and Lindner changes (C_1 and C_2 values are different), but the proposal of [21] does not change only in the value of the shear force. To determine the stress distribution tendencies and the value of the maximum transverse bending moment under uniformly distributed load a numerical parametric study is also carried out in the current paper.

4.4. Normal stress distribution in the flanges in case of linear shear distribution along the girder length

The calculations are executed in the most unfavorable loading and supporting conditions (girder type 4). The results of the numerical calculations can be seen for one girder in Fig. 26. The uniform change in the shear force diagram can be also observed in the diagram of the transverse bending moments. The maximum values of the diagram changes along the girder length nearly linearly and the function has a sinusoidal character. The same observation was done by Abbas et al. in [20]. The diagram of the transverse bending moment according to their analytical solution [19] has the same tendency and the same character as presented in the current paper. This observation suggests that the additional normal stresses can be calculated in each cross-section from the shear force acting in the analyzed cross-section. The numerical calculations proved that this assumption results in always conservative values.

The same parametric study as presented in Section 4.3.2 is executed in the case of bending by a uniformly distributed load by changing

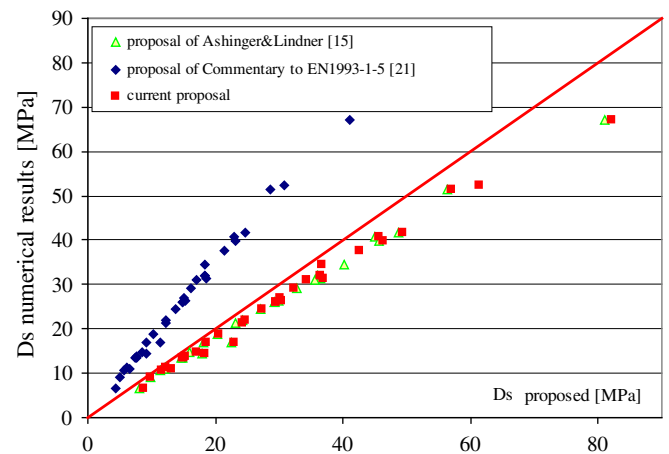


Fig. 24. Comparison of the different design proposals for load type 1.

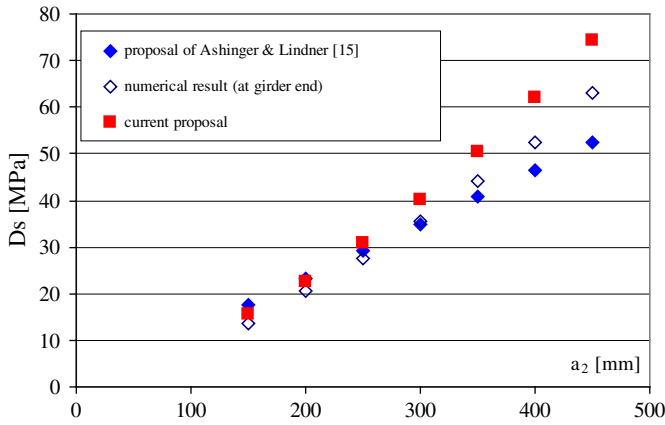


Fig. 25. Effect of the different fold lengths on the maximum stress difference.

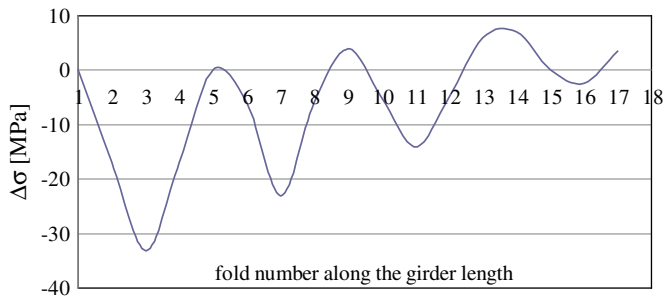


Fig. 26. Normal stress differences in the different cross-sections along the girder length.

the same geometric parameters in the same parameter range. The evaluation of the results is extended by the calculation of the maximum transverse bending moment also according to the proposal of Abbas et al. [20]. The relevant values are calculated using the analytical solution according to Eq. (5) taking the effect of the corrugation profile (factor C) according to Table 2 into account. All results are summarized in Fig. 27.

The diagram shows that the proposal of Aschinger and Lindner [15] and the proposal of [21] gives smaller values in the case of a uniformly distributed load, if the shear forces acting in the analyzed cross-section are taken into account in the calculation of the additional normal stresses. Furthermore the result show that the proposal of Abbas et al. [20] leads exactly to the same transverse bending moment as the currently proposed enhanced design method.

5. Conclusions

The focus of the current paper is the investigation of the stress distribution in the flange of the girders with corrugated webs. The different design proposals found in the literature are studied and compared. The stress distributions are analyzed under different loading and supporting conditions by numerical and experimental studies. The

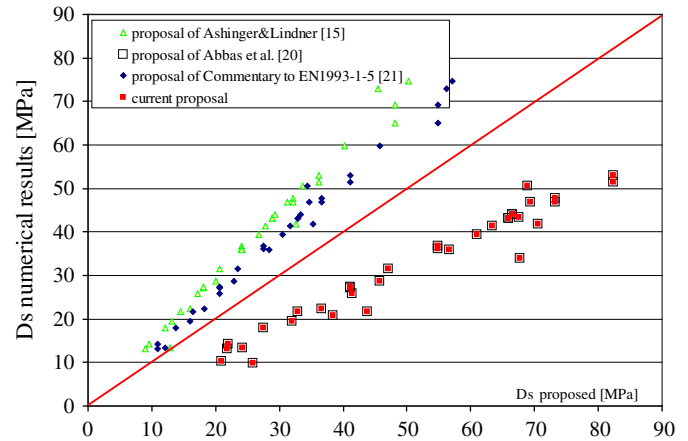


Fig. 27. Comparison of the different design proposals for load type 3.

previous design methods are compared to the numerical calculations and as a result the following conclusions can be drawn:

1. The test results showed that the stress distribution under pure bending in a cross-section with inclined fold is almost constant within the flange width and in a cross-section with a parallel fold is nearly linear. The measurements proved that the largest normal stress in a cross-section under pure bending can be determined by neglecting the web part from the inertia calculation.
2. The test results and the numerical calculations showed that the normal stress distribution in the flange under combined bending and shear depends on the analyzed specimen geometry (number of the corrugation waves), on the position of the load introduction place and on the support position. The results show that the most unfavorable girder geometry, loading and support conditions from the point of view of the additional transverse bending moment are in girder type 4 (support and loading at the middle of an inclined fold; full corrugation waves between the support and load introduction place).
3. Analyzing the most unfavorable case the numerical calculations showed that the value of the maximal transverse bending moment can be double the value proposed in [21], therefore an enhanced design equation is derived. The average value in the most unfavorable case can be calculated by the proposal of [21] and the extreme

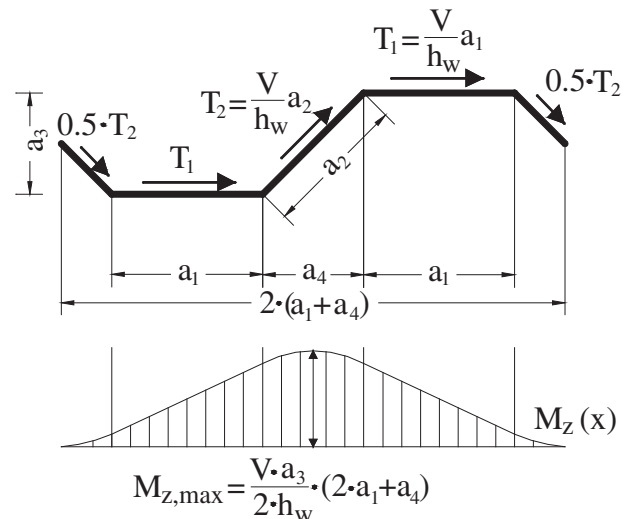


Fig. 28. Proposal for the illustration of the transverse bending moment calculation.

Table 2
Determination of the C factor.

Corrugation profile	C factor
Sinusoidal	1
Trapezoidal	$\pi \cdot \left(\frac{a_1 + 0.5 \cdot a_4}{2 \cdot a_1 + 2 \cdot a_4} \right)$
Triangular	$\pi/4$
Rectangular	$\pi/2$

value can be calculated by the currently proposed enhanced design method, as follows:

$$M_{z,max} = \frac{V \cdot a_3}{2 \cdot h_w} \cdot (2 \cdot a_1 + a_4) \quad (16)$$

4. The numerical calculations showed that the proposal of Aschinger and Lindner [15] gives a good approximation of the maximum additional transverse bending moment, if the shear force diagram along the girder length is constant. This design proposal gives smaller values than the numerical calculations in the analyzed parameter range, if the shear force diagram is not constant, or if the fold lengths (a_1 and a_2) of the corrugation profile are not equal.
5. The numerical parametric study showed that the tendencies of the numerical calculations and the proposed equation in [21] or in the current proposal are the same in the analyzed parameter range. It proves that the theoretical background of the calculation method is correct.
6. The numerical calculations showed that the value of the maximum transverse bending moment can also be determined according to the proposed closed form solution by Abbas et al. [19,20], if the girder is loaded by a uniformly distributed load. But the application range of this method is relative narrow, because there are no closed form solutions for other loading conditions (for concentrated loads or for nonuniform loading situations). The values according to the proposal of Abbas et al. resulted in exactly the same transverse bending moment as the currently proposed enhanced design method.
7. Fig. 28 is proposed to illustrate the theoretical background of the developed enhanced design method. This diagram follows the same theory as the proposal of Balaž (Fig. 3), but it belongs to the most unfavorable case and it gives the value of the maximum possible transverse bending moment.
8. If the determination of a more accurate value of the transverse bending moment is necessary and the possible maximum value that can be determined by the current proposal is not enough, the authors propose to use the finite element software.

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