New Design Methods for Trapezoidally Corrugated Web Girders

Bence Jáger [1] ✉, *Balázs Kövesdi* [1], *László Dunai* [1]
✉ e-mail: jager.bence@emk.bme.hu
[1] Budapest University of Technology and Economics, Department of Structural Engineering, Budapest, Hungary

DOI: https://doi.org/10.14459/icbdb24.41

Abstract Steel corrugated web girders are increasingly used in buildings, industrial halls and in bridges due to their well-known advantages. Numerous researchers highlighted and studied the advantages and favorable properties of the trapezoidally corrugated web girders in the past. However, there are only a limited number of available design proposals for the resistance calculation of trapezoidally corrugated web girders. The current research focuses on the authors' contribution to recover this lack of information and to improve the economic design of corrugated web girders. In frame of the research activity standard conform design procedures are developed providing both analytical resistance models and proposals for FEM based design approaches for the design of corrugated web girders. The design proposals are developed based on comprehensive experimental, analytical and numerical studies. The current paper collects and introduces the completed and on-going research activities and the improved design proposals developed by the BME Department of Structural Engineering within the last 15 years.

1 Introduction

Research on steel I-girders with corrugated web was started in 1956 by NACA [1] for wings of airplanes where the sections were built up by riveted angle connections. Later on the application of the corrugated web girder has been spread in the civil engineering praxis as well, especially in the field of industrial halls and bridges. Design codes and specifications, however, do not provide proposals for the design of steel corrugated web girders under different loading conditions. In the EN1993-1-5 [2] Annex D there are only recommendations for the determination of the bending moment and shear buckling resistances and for the bending-shear interaction behavior. The bending and shear buckling resistance models are based on the so called accordion effect, meaning that the flanges carry the longitudinal forces while the corrugated web carries the shear force. Nonetheless, the bending-shear interaction resistance model results in a conservative design ignoring the accordion effect. Furthermore, the flange buckling model developed for flat web girders is proposed for corrugated web girders as well, which is a rough simplification of the buckling phenomena.

Despite the detailed standardization of traditional I-girders, due to the lack of investigations on corrugated web girders there is no recommendation in the EN1993-1-9 [3] for fatigue detail classification. Research results, however, proved that longer fatigue life can be expected using corrugated web girders as stiffened flat web girders. In addition, the EN 1994-1-1 [4] standard for steel-concrete composite structures does not provide design resistance models for corrugated web girders having concrete flanges. Therefore, it can be concluded, that there is a need to study the structural behavior of corrugated web girders and to improve or develop reliable design methods, which can be economically used in different types of structures.

The current paper collects the design improvements developed at the Department of Structural Engineering, Budapest University of Technology and Economics in the last 15 years for trapezoidally corrugated web girders. The research work is initiated by extradosed bridge projects which are completed on the Tisza and Danube rivers in Hungary. The research covers the investigations on the stress distributions within the flanges, fatigue behavior, patch loading resistance, bending moment resistance and interaction behavior. In addition, an on-going research project is focusing on the design of embedded shear connectors, on the behavior of steel-concrete composite hybrid girders and on the lateral torsional buckling resistance of steel corrugated web girders. Based on the recent comprehensive studies new design proposals are developed providing FEM based design and conventional semi-empirical design procedures for trapezoidally corrugated web girders. Considering the large number of research fields to be introduced, the current paper collects all the final results of the research activities, however, the background and all the details of the executed research programs are not introduced. Details to each topic can be found in the cited references.

2 Literature review

Stress distributions in the flanges

Previous research results highlighted that due to the presence of shear flow in the corrugated web transverse bending moments act in the flanges causing additional normal stresses. This phenomenon was first revealed by Lindner [5] and Aschinger and Lindner [6] based on experimental results. A tabulated method for the determination of the additional normal stresses coming from the shear flow in the web is developed using the composition of a fictitious additional lateral force (F_y) and transverse bending moment (M_z). Significant research activity was carried out by Abbas et al. [7,8,9] on this research field in 2006-2007. An expressive schematic drawing about the reason of the additional bending moment and about the background of the calculation process is proposed by Balaž and Koleková [10], as shown in Figure 1.

Patch loading resistance

Research on the patch loading resistance of corrugated web girders was started in 1987 by Aravena and Edlund [11]. The patch loading resistance was discussed theoretically based on the experimental results of Kähönen [12] in 1988. A new design model has been developed, which is the improved version of the model proposed for flat web girders developed by Rockey and Roberts [13] in 1979, where the contribution of the web and the flange to the patch loading resistance was separated. Significant investigations were performed by Elgaaly and Seshadri [14] and by Luo and Edlund [15]

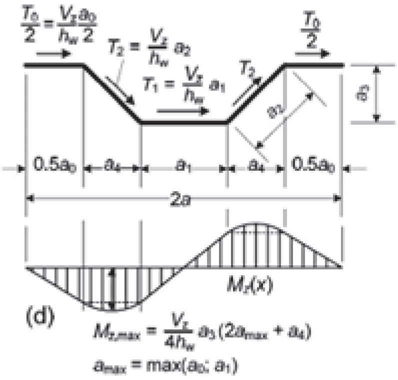


Figure 1: Proposed improvement of Balaž and Koleková [10].

in the past. The proposed design formulas are decomposed into the contribution of the web and flange resistances against transverse force.

Flange buckling resistance

It is proved and widely accepted according to the previous research results that due to the accordion effect, only the flanges contribute to the bending resistance of corrugated web girders. However, the bending resistance of slender flanges, namely the local flange buckling resistance has been investigated in a small extent. At first, Johnson and Cafolla [16] investigated the flange buckling behavior in 1997. Later on Watanabe and Masahiro [17] and Li et al. [18] performed significant research programs on this research field in 2006 and 2015, respectively. In addition, the DASt-Richtlinie 015 [19] and the EN1993-1-5 [2] Annex D provide analytical model for the effective width determination of the corrugated web girder flanges. The DASt-Richtlinie prescribes a value of 0.6 for the buckling coefficient, while the EN1993-1-5 prescribes a range from 0.43 to 0.6. Both resistance models are based on the buckling curves developed for flat web girders, which need improvements.

Bending and shear interaction

Based on the experimental and numerical investigations of Elgaaly et al. [20] it was concluded that the moment resistance can be calculated from the contribution of the flanges alone and the shear force is carried only by the corrugated web. Therefore, it was stated that the interaction could be negligible for girders with trapezoidal corrugated webs. The EN1993-1-5 Annex D [2] recommends a conservative design approach to consider the effect of shear force in the in-plane bending moment resistance by using a reduction factor (f_T). This factor can be calculated from the maximum additional transverse bending moment in the flanges produced by the shear flow in the web. The interaction diagram is shown in Figure 2 presented by blue dashed line.

Bending, shear and transverse force interaction

In the literature the authors could not find any research result on the bending, shear buckling and transverse force interaction behavior of corrugated web girders. Elgaaly and Seshadri [21], however, investigated separately the bending and transverse force interaction and the shear and transverse force interaction in 1997. Based on a limited number of experiments and numerical calculations interaction equations were proposed for both interaction planes separately.

Fatigue behavior of steel and hybrid girders

In 2001 six specimens with trapezoidal corrugations were tested under four-point-bending by

Ibrahim [22]. All the test specimens failed by fatigue cracks within the constant moment region and the initiation of the cracks arose at the web-to-flange weld toe along an inclined fold and propagated in the tension flange. Significant experimental and numerical research program was executed by Sause et al. [23] in 2006. Eight specimens with trapezoidal corrugations were tested under four-point-bending. Based on the test results it was concluded that corrugated web girders have longer fatigue life time than ordinary flat web girders made with transverse stiffeners, however, they have shorter lifetime than those of without stiffeners. Further experimental and numerical investigations were conducted by Ibrahim et al. [24] in 2006. Six specimens were tested under four-point-bending where the cracks initiated at the pure bending zone. Notable experimental and numerical investigations were carried out by Wang et al. [25] in 2014. Fillet welded joints with corrugated plate specimens were tested. The fatigue cracks initiated close to the intersection point of the inclined fold and the bended web part (S-point) depending on the corrugation angle and the bend radius.

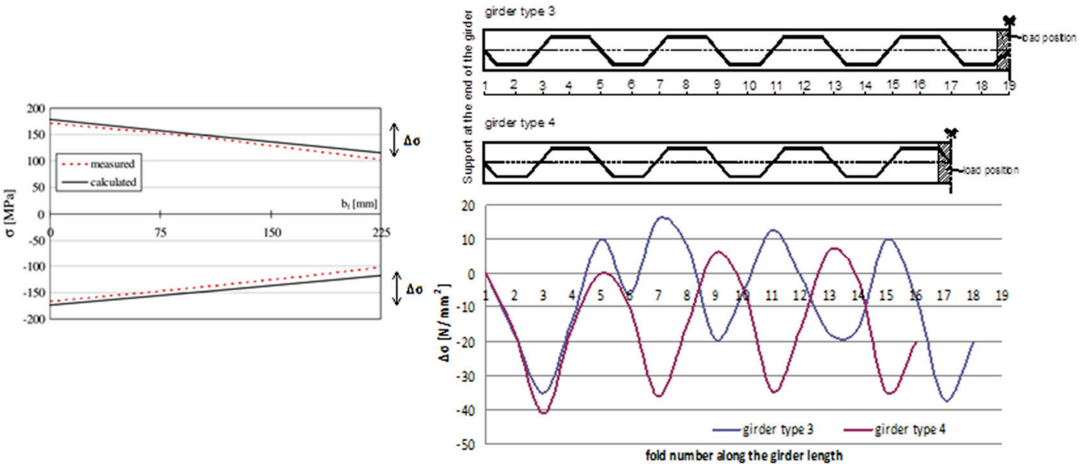
3 Design method improvements

3.1 Stress distributions in the flanges

Previous research results highlighted that due to the presence of shear force in the web additional normal stresses act in the flanges of corrugated web girders. The authors conducted a research program including experimental and numerical investigations in 2012 [26] to study the distribution of the additional normal stresses in the flanges. Figure 2a presents the comparison of the measured and calculated normal stress distributions along the width of the upper and lower flanges from the experimental and numerical analysis. It was concluded that the normal stress distribution along the flange width can be assumed to be linear and it is confirmed that the additional normal stresses are caused by the shear flow in the web generating additional alternating transverse bending moments in the flanges. The mechanical model shown in Figure 1 is based on the assumption that the corrugated web starts and ends by a parallel web fold and the shear flow is constant along the corrugation. The results, however, pointed out that the value of the additional normal stresses can be the double of the previously proposed value, if the corrugated web starts and ends by an inclined fold. Figure 2b presents the variation of the additional normal stress in the flanges along the girder subjected by three-point-bending. It is to be noted that the variation of the maximum additional normal stresses in the flanges follow the variation of the web in such a way that the amplitudes are obtained at the middle of the inclined fold.

Considering these findings an improved mechanical model and an enhanced analytical solution was developed for the determination of the maximum additional transverse bending moment in the flanges as shown in Figure 3.

Further investigations were performed on the stress distribution by the authors [27] in 2016. It was revealed that lateral supports connected to the flanges can significantly reduce the maximum additional normal stresses in the flanges, which can be neglected in the bending moment resistance calculation, it should be, however, considered in the fatigue design.



a) in the cross-section b) additional normal stresses along the girder

Figure 2: Normal stress distribution in the flanges [26].

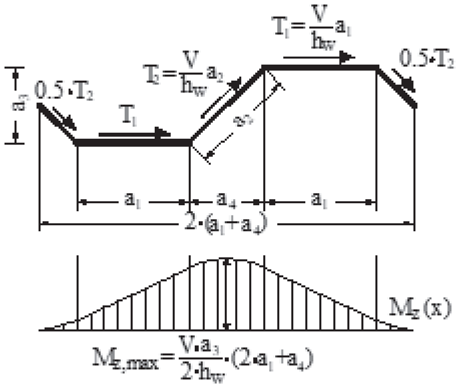


Figure 3: Mechanical model for the maximum additional transverse bending moment [26].

3.2 Patch loading resistance

The previous investigations on the patch loading resistance focused on the typical geometrical parameter range of frame structures. Therefore, an experimental and an extended numerical parametric study were executed by Kövesdi et al. [28] in 2008 in order to investigate the typical geometric parameter range used in bridges. The experimental and numerical results proved that modified version of the design proposal of Kähönen [12] fits best to the numerical results for longer loading lengths. To harmonize the design method with the principle of the EN 1993-1-5 for buckling analysis, a new buckling curve was derived which consider the effect of the corrugation angle in the resistance model. The applicability of the derived formula for bridge structures was confirmed by Kövesdi et al. [29] in 2010. In addition, imperfection sensitivity analysis using equivalent geometric imperfections was performed by Kövesdi and Dunai [30] to promote the FEM based design approach. It was concluded that the fold length divided by the scaling factor of 200 is applicable as imperfection magnitude using the web crippling type eigenmode shapes, if the failure mode is local buckling of the folds under the transverse force. The investigated type failure observed in the tests and in the numerical model is presented in Figure 4.

Figure 4: Experimental and numerical investigations on patch loading resistance.

A new resistance model is proposed to determine the patch loading resistance by Kövesdi et al. [29] in form of Equation 1.

$$F_{Rd} = \frac{2 \cdot \sqrt{4 \cdot M_{pl,f} \cdot \chi \cdot t_w \cdot f_{yw}} + f_{yw} \cdot \chi \cdot t_w \cdot s_s}{\gamma_{M1}^{**}} \tag{1}$$

where t_w is the web thickness, f_{yw} is the yield strength of the web, s_s is the loading length, χ is the reduction factor for web crippling, $M_{pl,f}$ is the plastic moment resistance of the flange alone and γ_{M1**} is the partial safety factor equal to 1.35. Further details can be found in [29].

3.3 Flange buckling resistance

Experimental and numerical studies on the bending resistance of trapezoidally corrugated web girders with slender flanges are performed by the authors [31,32]. Sixteen full scale test specimens were investigated under pure bending, where the obtained failure mode was the flange buckling. During the tests the initial geometric imperfection and residual stresses were measured. The results revealed that based on the accordion effect the web contribution to the bending moment resistance is negligible. Based on the experimental results advanced FE model was developed in order to investigate the flange buckling resistance by an extended numerical parametric study. In addition, imperfection sensitivity analysis is also performed to provide design guidelines to the FEM based design approach. The results show that for the flange outstand the scaling factor of 1/50 could be applicable as equivalent geometric imperfection. Figure 6 presents the experimental and numerical failure modes.

Based on the extended numerical parametric study it was concluded that the relative slenderness limit cannot be assumed as a specific constant value on the same way as for flat web girders, since the buckling coefficient varies by the change of the corrugation geometry. In addition, the results proved that the best approximation for the buckling curve can be given in form of Equations 2 and 3, where the slope of the curve (β) is not a constant value but it should depend on the corrugation angle (α), on the enclosing effect of the web (R) derived by Johnson and Cafolla [16] and on the web-to-flange thickness ratio.

$$\rho = \left(\frac{\overline{\lambda}_{p,lim}}{\overline{\lambda}_p}\right)^{\beta} = \left(14 \cdot \varepsilon \cdot \frac{t_f}{c_f}\right)^{\beta} \leq 1.0 \tag{2}$$

$$\beta = 5 \cdot \eta \cdot R \cdot \left(\frac{1}{tg(\alpha)}\right)^{\eta} = 5 \cdot \eta \cdot R \cdot \left(\frac{a_4}{a_3}\right)^{\eta}, \; where\; 0.5 \leq \beta \leq 1.0 \; and\; \eta = 0.45 + 0.06 \cdot \frac{t_f}{t_w} \tag{3}$$

where t_w is the web thickness, t_f is the flange thickness, c_f is the flange outstand, a_4 and a_3 are the perpendicular and parallel lengths of the inclined fold, α is the corrugation angle and ε is a material property depending on the steel grade. Further details can be found in [31,32].

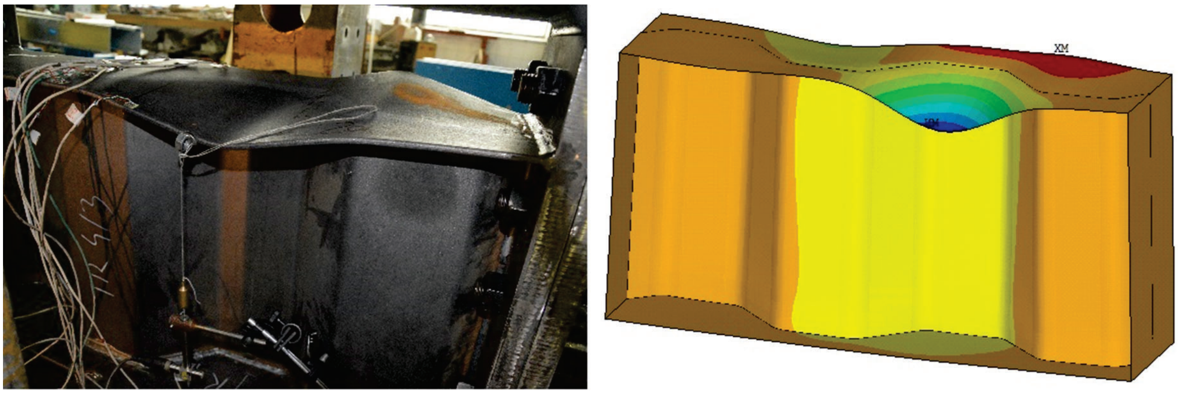


Figure 5: Experimental and FE investigations.

3.4 Bending and shear interaction

Due to the numerous contradictions found in the international literature regarding the bending and shear interaction behavior of corrugated web girders, numerical parametric study is performed by the authors on trapezoidally corrugated web girders including non-slender [27] and slender flanges [33] as well. It is shown that due to the shear flow in the corrugated web additional alternating transverse bending moment acts in the flanges of corrugated web girders. Therefore, the purpose of the research was to investigate the effect of additional normal stresses on the bending moment resistance reduction. Based on the numerical results it was concluded that the developed mechanical model shows good agreement with the numerical calculations in the elastic range, if the girder is subjected by three-point-bending and it is supported laterally only at the two ends. This numerical research program proved the previous results presented in Section 3.1. Numerical simulations are also executed to study the M-V interaction behavior and to characterize the interaction curve for corrugated web girders. The numerical results presented in Figure 6 showed that even for slender flanges the additional alternating transverse bending moments have no further reduction effect on the bending resistance of the corrugated web girders. The shear flow within the corrugated web does not reduce the flange buckling resistance and the accompanying bending moment does not reduce the shear buckling resistance of the corrugated web girder. Therefore, based on the current results the bending and shear buckling interaction can be negligible in the design.

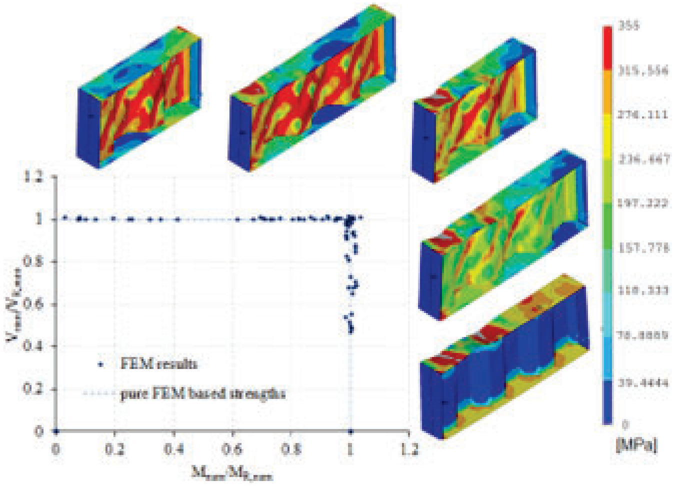


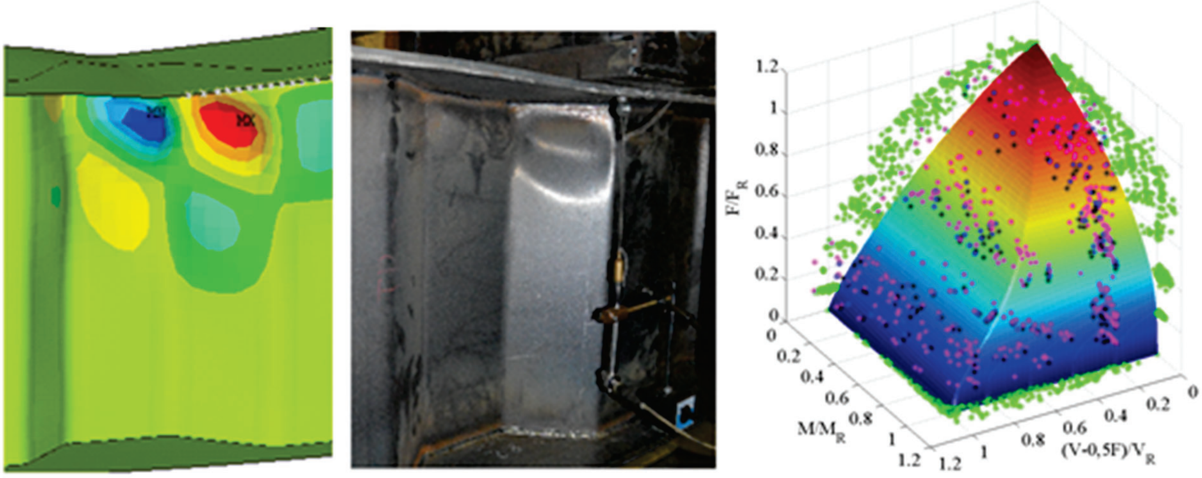
Figure 6: M-V interaction behavior and obtained typical failure modes.

3.5 Bending, shear and transverse force interaction

The reductions in the bending moment and shear buckling resistances due to the accompanying transverse force have never been studied in the past according to the authors' knowledge. Therefore, research program, including experimental and numerical investigations was performed by the authors [34,35,36] between 2015-2017. Eleven test specimens were tested under different loading conditions resulting in different bending-shear-transverse force utilization ratios. Based on the experimental results numerical model is developed and imperfection sensitivity analysis is performed. Based on the numerical results it was revealed that the necessary imperfection magnitude and shape should be selected according to the dominant failure mode. Figures 7a and 7b show a typical web buckling failure mode under dominant transverse force. Using the validated numerical model an extended parametric study is conducted. On the basis of the results an interaction equation is proposed by the authors in form of Equation 4. The results show that the bending and shear interaction can be neglected in the presence of transverse force, however, the transverse force results in significant reduction on the bending moment and shear buckling resistances. The interaction surface together with the numerical simulation results are presented in Figure 8c.

$$\max\left\{\left(\frac{M}{M_R}\right)+\left(\frac{F}{F_R}\right)^{2.9};\left(\frac{V-0.5\cdot F}{V_R}\right)^{1.2}+\left(\frac{F}{F_R}\right)^{1.2}\right\}\leq 1.0 \tag{4}$$

where M_R, V_R and F_R are the bending, shear buckling and patch loading resistances, and M, V and F are the corresponding internal forces within the cross-section to be checked. Further details can be found in [34,35,36].

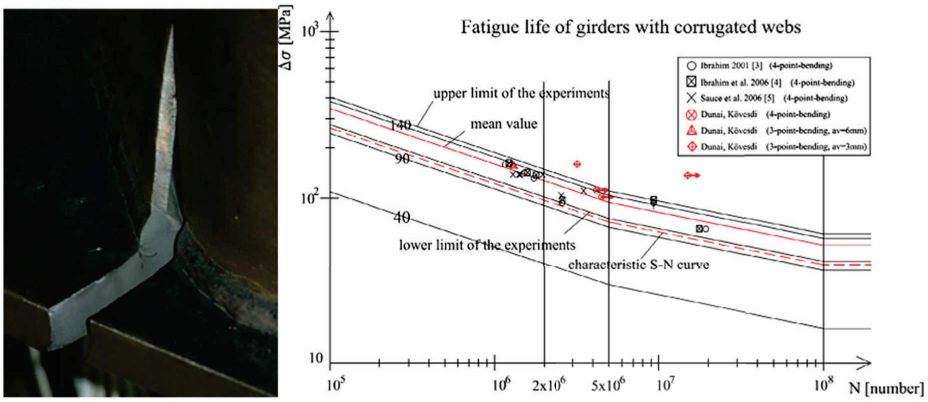


a) FE analysis b) test results c) FE results with the proposal

Figure 7: Investigation of the bending-shear-patch loading interaction.

3.6 Fatigue behavior

Experimental investigation was executed on the fatigue behavior of trapezoidally corrugated web girders by Kövesdi and Dunai [37] in 2014. Six specimens having the same corrugation profile were tested. Two specimens were loaded by four-point-bending and four specimens by three-point-bending arrangements. The weld size at the web-to-flange joint was 3 and 6 mm and the bend radius employed between the web folds was 60 mm. Three specimens failed due to fatigue cracks as shown in Figure 8a. Based on the test results it was pointed out that smaller weld size results in longer fatigue life time, therefore the application of the minimum weld size is recommended for the design. Based on the nominal stresses the fatigue detail category 90 was proposed according to the EN1993-1-9 [3] considering the previous experimental results from the literature, which are collected and presented in Figure 8b.



a) fracture at the S-point b) fatigue detail category

Figure 8: Fatigue life investigation.

The results emphasized that the highest measured stress concentration reached 125% compared to the measured nominal stress in the undisturbed zone of the flange in case of four-point-bending and 116% in the case of three-point-bending. Furthermore, it was observed that the combined bending and shear force has a significant influence on the fatigue behavior of corrugated web girders and the M-V interaction can significantly reduce the fatigue life time of the corrugated web girder, which should be considered in the design.

3.7 On-going research activities

Current research focus of the authors is on the lateral torsional buckling resistance of steel trapezoidally corrugated web girders. An extensive experimental and numerical research program is under design, execution and development with the final purpose of providing conventional semi-empirical design procedures and suggestions for the modelling issues.

In addition, steel-concrete composite girders with trapezoidally corrugated web girders are also investigated by the authors using experimental and advanced numerical studies. The focus of the research is extended to the investigation of the structural behavior and load carrying capacity of embedded shear connectors [38], which are investigated by full scale test specimens.

4 Conclusion

In the last 15 year numerous improvement proposals were developed for trapezoidally corrugated web girders at the Department of Structural Engineering, Budapest University of Technology and Economics, Hungary. The improvements cover the stress distribution, patch loading resistance, bending moment resistance, interaction phenomena under combined bending, shear and transverse force and the fatigue behavior of corrugated web girders. The current paper summarizes the key issues on the improved design proposals. Detailed description and further details on the executed research programs can be found in the cited references. In addition, ongoing research activities of the authors are focusing on the lateral torsional buckling resistance and on the steel-concrete composite girders using embedded shear connectors. The developed methods were applied in the design of two extradosed bridges on the Tisza and Danube bridges in Hungary.

5 References

[1] NACA Technical note 3801. “Experimental investigation of the strength of multiweb beams with corrugated webs”, Washington, 1956.

[2] EN 1993-1-5:2005, Eurocode 3: Design of steel structures, Part 1-5: Plated structural elements.

[3] EN 1993-1-9:2003, Eurocode 3: Design of steel structures, Part 1-9: Fatigue.

[4] EN 1994-1-1:2004, Eurocode 4: Design of composite steel and concrete structures, Part 1-1: General rules and rules for buildings.

[5] Lindner, J.: Zur Bemessung von Trapezstegtragern, Stahlbau, 61, 311-318, 1992.

[6] Aschinger, R., Lindner, J.: Zu Besonderheiten bei Trapezstegtragern, Stahlbau, 66, 136-142, 1997.

[7] Abbas, H.H., Sauce R., Driver R.G.: Behaviour of corrugated web I-girders under in-plane loads, Journal of Engineering Mechanics, ASCE, 132, 806-814, 2006.

[8] Abbas, H.H., Sauce, R., Driver, R.G.: Analysis of flange transverse bending of corrugated web I-girders under in-plane loads, Journal of Structural Engineering, ASCE, 133, 347-355, 2007.

[9] Abbas, H.H., Sauce, R., Drive,r R.G.: Simplified analysis of flange transverse bending of corrugated web I-girders under in-plane moment and shear, Engineering Structures, 29, 2816-2824, 2007.

[10] Baláž, I., Koleková, Y.: Influence of transverse bending moment in the flange of corrugated I-girders, Procedia Engineering, 40, 26–31, 2012.

[11] Leiva-Aravena, L., Edlund B.: Buckling of trapezoidally corrugated webs, ECCS Colloquium on Stability of Plates and Shells, Belgium, Ghent University, 107–116, 1987.

[12] Kähönen, A.: Zur Einleitung von Einzellasten in I-Träger mit trapezförmig profilierten Stegen, Stahlbau, 57(8), 250-252, 1988.

[13] Roberts, T.M., Rockey, K.C.: A mechanism solution for predicting the collapse loads of slender plate girders when subjected to in-plate patch loading, Proc Inst Civil Eng, 67(2), 155-175, 1979.

[14] Elgaaly, M., Seshadri, A.: Girders with corrugated webs under partial compressive edge loading, Journal of Structural Engineering, ASCE, 123(6), 783-791, 1997.

[15] Luo, R., Edlund B.: Ultimate strength of girders with trapezoidally corrugated webs under patch loading, Thin-Walled Structures, 123(6), 135-56, 1996.

[16] Johnson, R.P., Cafolla, J.: Local flange buckling in plate girders with corrugated webs, Proceedings of the Institution of Civil Engineers, Structures and Buildings, 122, 148–156, 1997.

[17] Watanabe, K., Masahiro, K.: In-plane bending capacity of steel girders with corrugated web plates, Journal of Structural Engineering, JSCE, 62, 323-336, 2006.

[18] Li, G.Q., Jiang, J., Zhu Q.: Local buckling of compression flanges of H-beams with corrugated webs, Journal of Constructional Steel Research, 112, 69-79, 2015.

[19] DASt-Richtlinie 015: Trager mit schlanken Stegen. Stahlbau-Verlagsgesellshaft, Köln, 1990.

[20] Elgaaly, M., Seshadri, A., Hamilton, R.W.: Bending strength of steel beams with corrugated webs, Journal of Structural Engineering, ASCE, 123(6), 772-782, 1997.

[21] Elgaaly, M., Seshadri, A.: Girders with corrugated webs under partial compressive edge loading, Journal of Structural Engineering, ASCE, 123(6), 783-791, 1997.

[22] Ibrahim, S.A.: Fatigue analysis and instability problems of plate girders with corrugated webs, PhD Dissertation, Drexel University, Philadelphia, USA, 2001.

[23] Sauce, R., Abbas, H.H., Driver, R.G., Anami, K., Fisher, J.: Fatigue life of girders with trapezoidal corrugated webs, Journal of Structural Engineering, ASCE, 137(7), 1070-1078, 2006.

[24] Ibrahim, S., Dakhakhni, W., Elgaaly, M.: Behaviour of bridge girders with corrugated webs under monotonic and cycling loading, Engineering Structures, 28, 1941-1955, 2006.

[25] Wang, Z.Y., Wang, Q.: Fatigue assessment of welds joining corrugated steel webs to flange plates, Engineering Structures, 73, 1-12, 2014.

[26] Kövesdi, B., Jáger, B., Dunai, L.: Stress distribution in the flanges of girders with corrugated webs, Journal of Constructional Steel Research, 79(12), 204-215, 2012.

[27] Kövesdi, B., Jáger, B., Dunai, L.: Bending and shear interaction behaviour of girders with trapezoidally corrugated webs, Journal of Constructional Steel Research, 121, 383-397, 2016.

[28] Kövesdi, B., Braun, B., Kuhlmann, U., Dunai, L.: Enhanced design method for the patch loading resistance of girders with corrugated webs, Proceeding of the 5th European conference on steel and composite structures, Eurosteel 2008, Graz, Austria, B, 1155–1160, 2008.

[29] Kövesdi, B., Braun, B., Kuhlmann, U., Dunai, L.: Patch loading resistance of girders with corrugated webs, Journal of Constructional Steel Research, 66, 1445-1454, 2010.

[30] Kövesdi, B., Dunai, L.: Determination of the patch loading resistance of girders with corrugated webs using nonlinear finite element analysis, Computers and Structures, 89, 2010-2019, 2011.

[31] Jáger, B., Dunai, L., Kövesdi, B.: Flange buckling behavior of girders with corrugated web Part I: Experimental study, Thin-Walled Structures, 118, 181-195, 2017.

[32] Jáger, B., Dunai, L., Kövesdi, B.: Flanges buckling behavior of girders with corrugated web Part II: Numerical study and design method development, Thin-Walled Structures, 118, 238-252, 2017.

[33] Jáger, B., Dunai, L.: Flange buckling behavior of trapezoidally corrugated web girders subjected to bending and shear interaction, Proceedings of the Annual Stability Conference, Baltimore, MD, USA, p. 13, 2018.

[34] Jáger, B., Dunai, L., Kövesdi, B.: Girders with trapezoidally corrugated web subjected by combination of bending, shear and patch loading, Thin-Walled Structures, 96, 227-239, 2015.

[35] Jáger, B., Dunai, L., Kövesdi, B.: Experimental based numerical modelling of girders with trapezoidally corrugated web subjected to combined loading, Proceedings of the 7th International Conference on Coupled Instabilities in Metal Structures, CIMS2016, Baltimore, Maryland, USA, p. 14, 2016.

[36] Jáger, B., Dunai, L., Kövesdi, B.: Experimental investigation of the M-V-F interaction behavior of girders with trapezoidally corrugated web, Engineering Structures, 133, 49-58, 2017.

[37] Kövesdi, B., Dunai, L.: Fatigue life of girders with trapezoidally corrugated webs: An experimental study, International Journal of Fatigue, 64, 22-32, 2014.

[38] Jáger, B., Németh, G., Kovács, N., Kövesdi, B., Kachichian, M.: Push-out tests on embedded shear connections for hybrid girders with trapezoidal web, Proceedings of the 12th International Conference on Advances in Steel-Concrete Composite Structures, ASCCS 2018, Universitat Politècnica de València, València, Spain, June 27-29, 2018.