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TRAPEZOIDAL SHEETING MADE OF STAINLESS STEEL – TWO AMENDMENTS TO COMPLETE THE DESIGN CODES

Thomas Misiek*, Helmut Krüger*, Karsten Kathage and Thomas Ummenhofer***

* Versuchsanstalt für Stahl, Holz und Steine, Karlsruhe Institute of Technology
e-mails: thomas.misiek@kit.edu, helmut.krueger@va.uka.de, thomas.ummenhofer@kit.edu

** Deutsches Institut für Bautechnik
e-mail: kka@dibt.de

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Abstract. *Trapezoidal sheeting made of stainless steel can be used for applications with high requirements on visual appearance or corrosion resistance. The calculation of the load-bearing capacity of thin-walled structures including trapezoidal sheeting normally follows the procedures of EN 1993-1-3 and similar codes. EN 1993-1-4 complements this standard concerning thin-walled structures made of stainless steel. This standard relies on many publications on thin-walled structures made of stainless steel. But unfortunately these publications almost all focus on thin-walled beams and columns and therefore some topics that are specific to trapezoidal sheeting are not recognized.*

The results of the presented research results on the load-bearing behaviour of thin-walled trapezoidal sheeting made of stainless steel are closing this gap: With the proposed additions to the existing design formulae, the complete calculation of the load-bearing capacity of trapezoidal sheeting made of stainless steel is possible.

1 INTRODUCTION

For high demands on the optical appearance and on the corrosion resistance, trapezoidal profiles are made of stainless steel. Bases for a mathematical determination of the load-bearing capacity, however, have not been available up to now. Together with EN 1993-1-3, EN 1993-1-4 shall facilitate the mathematical determination of the load-bearing capacity of trapezoidal sheeting made of stainless steels. Since EN 1993-1-4 has not been established for thin-walled components, especially for trapezoidal sheeting, typical problems were not treated. Therefore, the aim of the investigations was to examine the applicability of the rules of EN 1993-1-3 in connection with EN 1993-1-5 for the design of trapezoidal sheeting. At the same time, these regulations could be tested for completeness and to close possible gaps. As an example, the lacking buckling curves for stiffeners of flat cross-section parts such as flanges and webs should be mentioned. An influence of the non-linear stress-strain relationship of stainless steel on the buckling curve can be assumed since there are significant differences between the buckling curves for trapezoidal sheeting made of non-alloy structural steel and made of aluminium, which also shows a non-linear stress-strain relationship. A further example are the regulations for the verification of the maximum supporting forces (web crippling).

2 CONSTITUTIVE EQUATIONS

In EN 1993-1-4, the formulation according to [1] is recommended for the description of the non-linear material law.

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E} + 0.002 \cdot \left(\dfrac{\sigma}{f_y} \right)^n & \text{for } \sigma \le f_y \\ 0.002 + \dfrac{f_y}{E} + \dfrac{\sigma - f_y}{E_y} + \varepsilon_u \cdot \left(\dfrac{\sigma - f_y}{f_u - f_y} \right)^m & \sigma > f_y \end{cases} \tag{1}$$

$$E_y = \frac{E}{1 + 0.002 \cdot n \cdot E / f_y} \tag{2}$$

$$\varepsilon_u = 1 - \frac{f_y}{f_u} \tag{3}$$

$$m = 1 + 3.5 \cdot \frac{f_y}{f_u} \tag{4}$$

This material law was also applied in the scope of the investigations presented below. The parameters f_y and n were determined from tension-compression tests using a test setup according to [2]. The determination of the parameters from the test was done through variation to fit the test results (Figure 1).

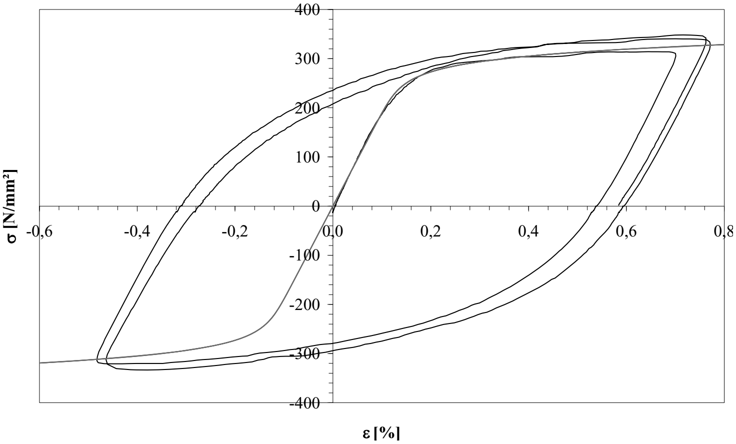

Figure 1: Stress-strain-curve.

The material (stainless steel sheet 1.4301 with thicknesses between 0.50 mm and 0.80 mm) used in the further tests showed yield strengths of f_y = 280 MPa to 300 MPa and exponents of n = 11 to 13. The parameter f_u was determined by standard tensile tests and varies from 650 MPa to 690 MPa.

3 PLANE CROSS-SECTION PARTS WITH INTERMEDIATE STIFFENERS

3.1 Mechanical model

The determination of the load-bearing capacity of plane cross-section parts with intermediate stiffeners is performed by the determination of the effective width of partial areas adjacent to the stiffener, and the subsequent determination of the compressive load-bearing capacity of the compression member formed through stiffening. The geometry of the compression member is composed of the stiffener itself and the adjacent effective areas (Figure 2).

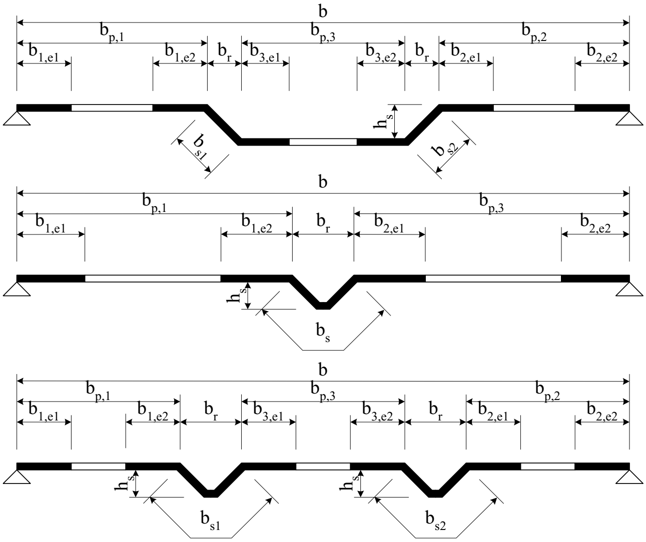

Figure 2: Flange cross-sections with stiffeners.

The compression member can be regarded as a column on elastic foundation (Figure 3). Due to the connection with the neighbouring plane cross-section parts, the spring stiffness results from the static system in transverse direction, i.e. from the bearing on the adjacent webs for the flange of a trapezoidal sheeting. The compressive load capacity is limited by buckling of this elastically supported compression member.

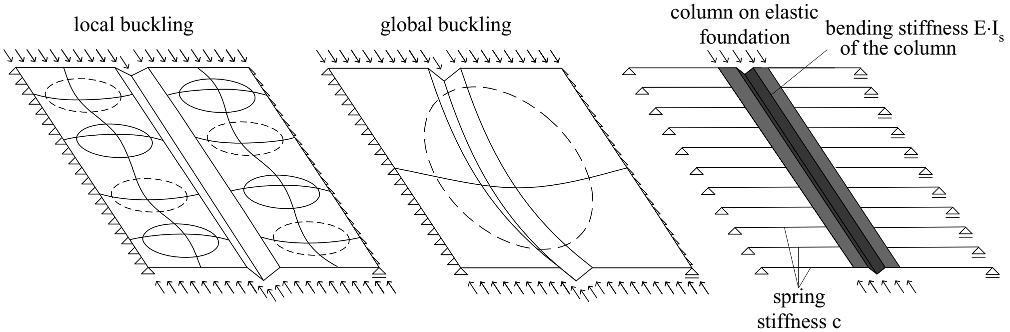

Figure 3: Column on elastic foundation.

3.2 Design according to EN 1993-1-3 and its backgrounds

The buckling curve given in EN 1993-1-3 for the determination of the load-bearing capacity of stiffeners has been introduced by Höglund in [3] for the first time. Interestingly this curve does not base on the Ayrton-Perry equation often used in other respects. The formulation is

$$\chi_d = \begin{cases} 1.0 & \bar{\lambda}_d \leq 0.65 \\ 1.47 - 0.723 \cdot \bar{\lambda}_d \quad \text{for} & 0.65 \leq \bar{\lambda}_d \leq 1.38 \\ 0.66 / \bar{\lambda}_d & 1.38 \leq \bar{\lambda}_d \end{cases} \tag{5}$$

Although in [3] no indications for the determination of the buckling curves are included, it can be assumed that they have been determined by recalculation of bending tests on trapezoidal sheeting. Assumptions regarding the effective width in the web and in the plane cross-section parts of the flanges adjacent to the stiffeners are partly necessary. An assumption has also to be made for the actual stress in the area of the stiffener. The determination of the effective width of a plane cross-section part is effected by the supposition that the yield strength is reached at the edges of the plane cross-section part. If this plane cross-section part is adjacent to a stiffener that buckles before reaching the yield strength, this assumption for determining the effective width is on the safe side (Figure 4). The effective width, which exists when reaching the load-bearing capacity of the stiffener, is bigger than primarily assumed, but in fact the existing stress is smaller. Regarding the above component tests, for the recalculation of the load-bearing capacity of the stiffener a stress of the value $\sigma = f_y$ on the stiffener can be assumed.

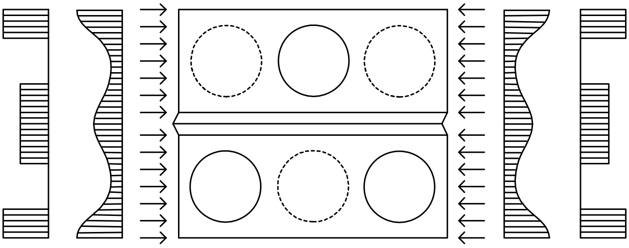

Figure 4: Stress distribution.

Within the scope of design, the smaller existing stress can be considered in a further calculation step by determining the effective width with the yield strength reduced by the factor χ_d according to equation (5). Then, new cross-section values for determining the load-bearing capacity of the stiffener are received. Neither in [3] nor in the national standards being based upon, for example StbK-N5 (Sweden) or DIN 18807 (Germany), an iteration is provided. Therefore, for the determination of the buckling curve presented in the following, it has been assumed that no iteration will be performed. Within the scope of the recalculation of the results from tests and FE analyses no iteration was performed.

3.2 Determination of the buckling curve

The determination of the buckling curve was effected using the Finite Element Method. The FE-model was built-up from 4-node structural shells using the software package ANSYS. Both local and global imperfections were applied, using the geometry of the corresponding eigenmodes. For calibrating the models applied, the buckling curve for components of non-alloy steel given in EN 1993-1-3 was recalculated at first. In addition, the results from buckling tests on plane cross-section parts with stiffeners were recalculated (Figure 5).

Figure 5: Tests with stiffened plates: local and global buckling.

The application of a geometrical imperfection of $l_b/400$ for global buckling given in EN 1995-1-5 and the usual local imperfection [4] of $w_0/t = 0.1$ resulted in a good correlation between calculated results and comparative test data. In the investigated slenderness range, the last mentioned value slightly deviates from the indications given in EN 1993-1-5. For the stress-strain relationship according to equations (1) to (4), the parameters $f_y = 230$ MPa, $n = 5$ and $f_u = 540$ MPa were used. The reduction factor χ_d was determined from the load-bearing capacities calculated for the two plane cross-section parts and the stiffener. For the evaluation, the effective widths were calculated according to [5], since comparative calculations on unstiffened plates showed a good agreement between Finite Element results and [5]. The values are presented in Figure 6.

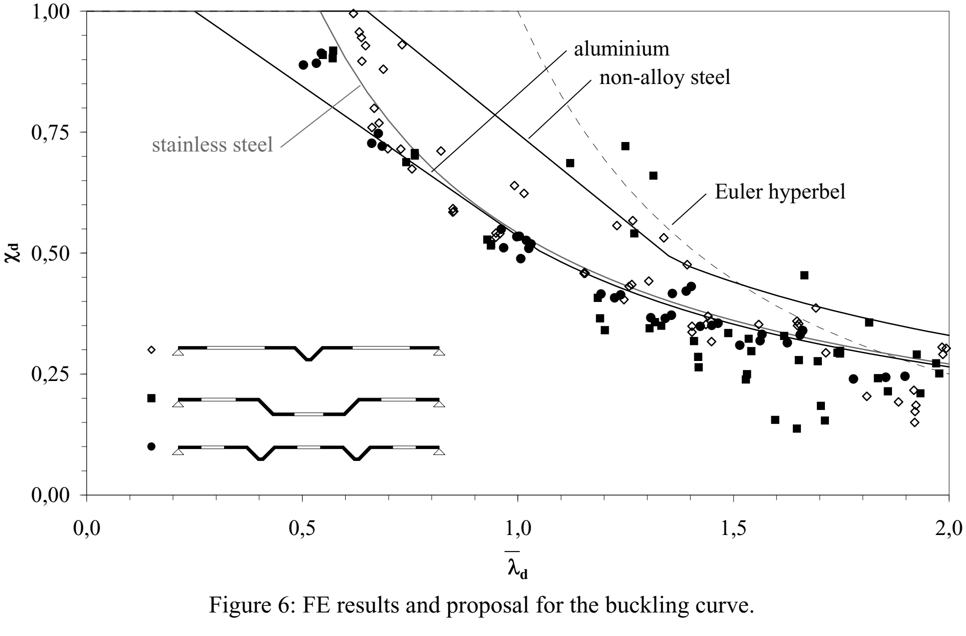

Figure 6: FE results and proposal for the buckling curve.

The higher scatter in the results for higher slenderness results from differences in behaviour: Some geometries show a post-critical behaviour which is typical for plates and some behave more like columns. The evaluation was done using a lower boundary curve. Maintaining the fundamental formulation according to Höglund, the proposed equation for the buckling curve is

$$\chi_d = \begin{cases} 1.0 & \text{for } \bar{\lambda}_d \leq 0.542 \\ 0.542 / \bar{\lambda}_d & 0.542 \leq \bar{\lambda}_d \end{cases} \tag{6}$$

Compared to Höglund, the linear part is missing. The proposal for the buckling curve has been included in Figure 6 which also shows the curves for non-alloy steel and aluminium. For the typicl application range, the created curve is quite similar to the one used for aluminium.

4 WEB CRIPPLING

4.1 Design according to EN 1993-1-3 and testing procedures

The load-bearing capacity of a trapezoidal sheeting for web crippling (Figure 7) at the intermediate support is determined by using

$$R_{w,Rk} = 0.15 \cdot t^2 \cdot \sqrt{f_y \cdot E} \cdot \left(1 - 0.1 \cdot \sqrt{r/t}\right) \cdot \left(0.5 + \sqrt{0.02 \cdot l_a/t}\right) \cdot \left(2.4 + (\phi/90)^2\right) \tag{7}$$

For determining the load-bearing capacity at the end support, the constant factor must be set to 0.075 and calculated with $l_a = 10$ mm for considering the rotation of the end tangent. Within the scope of verification the interaction with the hogging moment has to be considered, since already small bending moments result in a significant reduction of the transmissible reaction force at the intermediate support.

Figure 7: Web crippling failure at intermediate support.

4.2 Verification for the design of trapezoidal sheeting made of stainless steel

Equation (7) is based on test results and was checked for its applicability concerning the safety level within the scope of the investigations documented in [6] (trapezoidal sheeting made of non-alloy steel) and [7] (trapezoidal sheeting made of aluminium). For this purpose a test setup was selected that directly transfers the forces into a second support of the width l_a (direct carriage). If so, no additional bending moments occur.

A verification of equation (7) for the design of trapezoidal sheeting made of stainless steel is missing and has to be done. To facilitate a direct comparability with the results of [6] and [7], the tests were also performed with direct carriage, despite both EN 1993-1-3 and EN 1999-1-4 require for this loading situation a reduction of the constant factor in equation (7) to the half.

Figure 8 shows a comparison between the test results as well as between results from Finite Element analyses and equation (7).

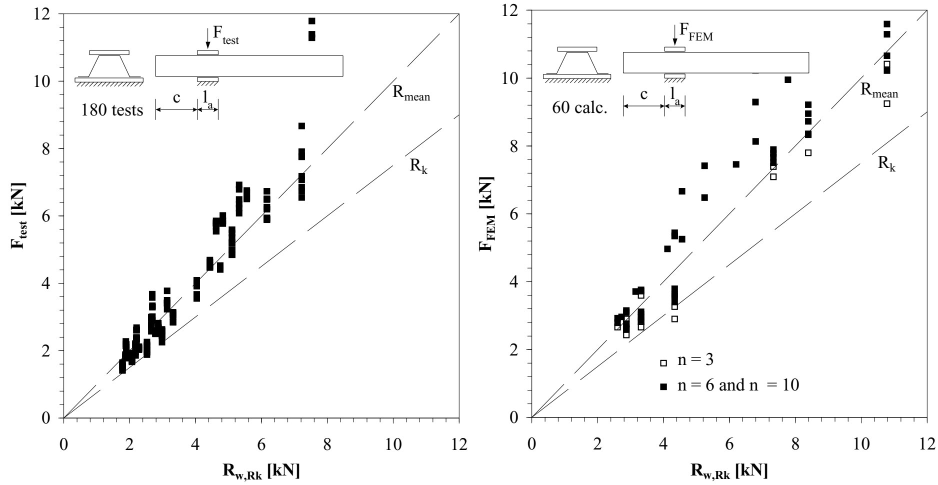

Figure 8: Comparisons of test and numerical results with equation (7).

For both, the test results and the calculations are below the characteristic values according to equation (7). This is especially the case for the geometries of the main application range. Variations between equation (7) and the results especially appear for small plate thicknesses t, big web heights s_w and small exponents n. For the support width l_a, no clear correlation could be found. A statistical evaluation according to [6] has shown, that, compared to trapezoidal sheeting made of non-alloy steel or aluminium, the safety level is lower. To obtain the same safety level, the load-bearing capacity calculated according to equation (7) should be multiplied with 0.75.

4.3 Re-calculation of test setups

Additional comparative calculations have been performed assuming sheeting made of non-alloy steel and stainless steel. In this case, the usual setup for an intermediate support was used which is a three-point bending test for which an interaction with the bending moments exists. Therefore a direct verification of equation (7) by the results of this test or calculation is not possible with: An extrapolation towards M = 0 ought to be done, which results in unreliability upon checking, causing unreliability in the verification. Therefore the results of this recalculation were not compared with equation (7) but with the capacities obtained for a trapezoidal sheeting made of non-alloy steel for which the safety level of equation (7) has been already verified.

The results are shown in Figure 9. It shows only small differences between the sheeting made of different materials. The non-linear material behaviour does not seriously affect the load-bearing capacity.

The investigations on web-crippling of trapezoidal sheeting made of stainless steel can therefore be summarized as follows: The level of safety when using equation (7) for the calculation of the web crippling capacity of trapezoidal sheeting made of stainless steel might be smaller than for sheeting made of non-alloy steel or aluminium. But this level of safety is still high enough to permit the use of equation (7).

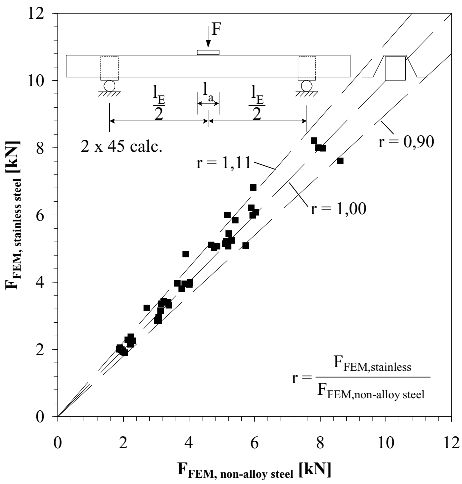

Figure 9: Comparisons of web-crippling resistance for stainless steel and non-alloy steels.

5 SUMMARY

In conjunction with EN 1993-1-3, EN 1993-1-4 shall facilitate the determination of the load-bearing capacity of trapezoidal sheeting made of stainless steels. Since EN 1993-1-4, however, is not specifically prepared for trapezoidal sheeting, typical problems concerning thin-walled components are not treated, especially for trapezoidal sheeting. Therefore, the aim of the presented investigations was to check the applicability of the regulations given in EN 1993-1-3 in conjunction with EN 1993-1-5 for the design of trapezoidal sheeting.

The performed investigations show that the applicability is given. For the calculation of the buckling load of the stiffeners it is recommended, however, to use a different buckling curve. A proposal is given by equation (6) within this paper.

REFERENCES

[1] Rasmussen, K., *Full-range stress-strain curves for stainless steel alloys*, Department of Civil Engineering, University of Sydney, Australia, 2001.

[2] Gehring, A. and Saal, H., „Kennwertermittlung für die Simulation des Walzprofilierens von Dünnblech“, *Tagung Werkstoffprüfung 2006 - Fortschritte der Kennwertermittlung für Forschung und Praxis*, M. Borsutzki and S. Geisler (eds.), Stahlinstitut VDEh, Düsseldorf, 109-114, 2006.

[3] Höglund, T., *Design of trapezoidal sheeting provided with stiffeners in the flanges and webs*, Swedish Council for Building Research, Stockholm, Sweden, 1980.

[4] Huck, G., *Das Konzept der wirksamen Breite bei Bauteilen aus elastoplastischem Material*, Berichte der Versuchsanstalt für Stahl, Holz und Steine der Universität Fridericiana in Karlsruhe, 4. Folge Heft 27, Karlsruhe, Germany, 1993.

[5] Bezkorovainy, P., Burns, T., Rasmussen, K.; *Strength curves for metal plates in compression*, Department of Civil Engineering, University of Sydney, Australia, 2001.

[6] Shin, T.S., *Untersuchung der Tragfähigkeit von Stahltrapezprofilen unter einer örtlich konzentrierten momentenfreien Lasteinleitung*, Wissenschaft & Technik Verlag, Berlin, Germany, 1995.

[7] Baehre, R. Holz, R., Huck G, Ladwein Th., *Vergleich empirischer und berechneter Tragfähigkeiten von Aluminiumtrapezprofilen,* Fraunhofer IRB Verlag, Stuttgart, Germany, 1990.