SHEAR BEHAVIOUR OF TRAPEZOIDAL SHEETING WITHOUT SHEAR PANEL CONSTRUCTION

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Abstract. *The stiffening effect of trapezoidal sheeting had been used for a long period of time. If according to the present state of standardization the shear stiffness S is considered the construction of a shear panel is necessary. Therefore all four edges of the trapezoidal sheeting must be connected to the substructure. That might cause difficulties in construction especially in industrial buildings where main beams and secondary beams are often not present at the same height level. This paper deals with the problem that the trapezoidal sheeting is connected only at two edges with their substructure, e.g. I-beams. Full scale tests were carried out on the basis of which a finite element model was developed. Extensive parameter studies using this model delivered parameters for a simplified strut model leading to the stiffening effect of a special shear stiffness S. This stiffness S may be incorporated in a calculation to show sufficient safety against lateral torsional buckling.*

1 INTRODUCTION

I-beams may be subjected to lateral torsional buckling where lateral deflections and twisting occur, figure 1. But unsupported beams as usually assumed in codes are very rare in practice. Therefore the unfavourable effect of this stability problem can be minimized by taking into account the positive effects of constructional details. In roof or wall structures trapezoidal steel sheeting often occurs and can be used as stiffening structural element. Hereby the stiffening is given by two effects : the rotational spring stiffness c_ϑ and the shear stiffness S [1] - [3]. But if the shear stiffness S is taken into account as stiffening action the construction of a shear panel is necessary according to the present state of standardization. Therefore all four edges of the trapezoidal sheeting must be connected to the substructure. In the following a solution is presented in case the trapezoidal sheeting is connected only at two edges with their substructure.

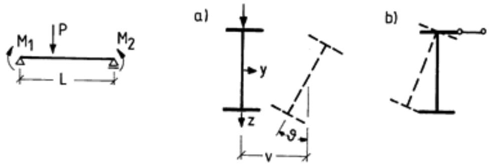

Figure 1: Lateral torsional buckling of beams: a) laterally unsupported, b) laterally supported

Twelve full scale tests were carried out on two types of trapezoidal steel sheetings using different kinds of fasteners. Based on the measurements and results a finite element model was developed and calibrated on the test result. The calculations show excellent agreement with the experimental results, allowing the use of this FE model for extensive parameter studies. In order to cover a broad spectrum of possible systems in practice the following parameters were varied : type of trapezoidal sheeting, sheet thickness, profile length, length and bending stiffness of the beam to be stiffened, stiffness of the fasteners at the connection to the beam and the connections between the sheetings itself.

2 BASIS CONSIDERATIONS

2.1 Shear stiffness under the assumption of a shear panel

Analytical solutions were presented e.g. by *Schardt and Strehl* [4] and *Davies, Bryan, Lawson, Baehre* leading to the European recommendations [5]. The first method is especially used in Germany and takes into account bending within the cross section, torsion of the panels, stressing by shear and warping of the end sections. Internationally more important is method [5] because the influence of the fasteners are also accounted for. In [6] the different methods were compared. The solution of *Strehl* [4], [11] is later used as reference solution because for a great number of trapezoidal profiles the shear stiffness S can numerically calculated in a simple way.

2.2 Connectors

Different types of connectors may be used in practical applications. Each of them have a special nonlinear load-deflection behaviour as shown in figure 2. Fore simplification the straight lines proposed by ECCS may be used. It must be kept in mind that the curves depend also on the thickness of the sheeting as well as on the type of trapezoidal profiles investigated.

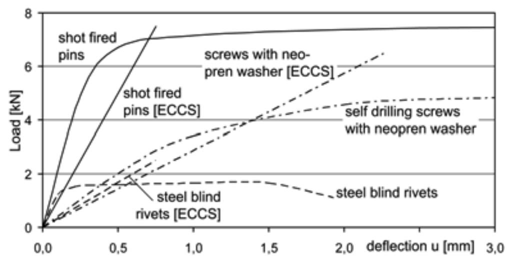

Figure 2: Example for load-deflection curves for different kinds of fasteners, a thickness of sheeting t_N = 0.75 mm and a profile 39/183 mm [8]

3 TEST RESULTS

3.1 General

Full scale tests were carried out in order to achieve information about the load carrying behaviour of trapezoidal steel sheets fastened at two edges. The investigated roof construction consists of different elements. Therefore many combinations of these elements are possible. Within the tests the following components were used .

- trapezoidal sheeting Arcelor HSA 39/183, t_N = 0.75 mm and UB 85/280, t_N = 0.75 mm
- sheet/member fasteners : shot fired pins Hilti ENP 19L15, self drilling screws EJOT-JT2-8-5,5-V16, seam fasteners : steel blind rivets EJOT 4,8

In order to get sufficient interpretation of the test it is also neccessary to make tests on components such as

- tension tests on samples cut from the trapezoidal sheeting which show a linear elastic – ideal plastic behaviour, leading to a characteristic strength of $f_{y,k}$ = 390 N/mm^2 and a Youngs modulus of E = 195000 N/mm^2
- shear tests on the fasteners mentioned before following mainly the test set up according to [5]. In all cases the stiffness is higher as proposed by ECCS and the deflection capacity is higher than 0.5 mm, see figure 2.

3.2 Full scale tests

The tests should show the stiffening effect of trapezoidal sheeting connected to beams at two edges only. In real constructions the beams may be open sections like IPE which tend to fail by lateral torsional buckling. In this failure state lateral forces occur which are distributed approximately parabolic or sinusoidal. Therefore a frame was constructed, see figure 3 b), where the sheeting is connected to two main beams consisting of a cross section U180 with an additional plate t = 3 mm leading to a hollow section, see figure 3. Both main beams are connected horizontally to each other. The parabolic distribution of the lateral forces are simulated by three lateral point loads, where also the deformations are measured.

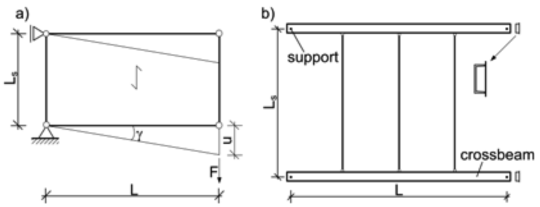

Figure 3: Test setup, a) : shear panel construction, stressed by shear, at 4 edges connected to substructure, b) beam construction, stressed by transverse forces, at 2 edges connected to substructure

This test setup differs from that which is usually used if the shear deformation γ of a four sided hinged frame is determined which becomes deformed to a parallelogram, see figure 3 a), [7]. This is the basis for determining the shear stiffness S of a shear panel.

12 tests were carried out, details see [8]. Load-deflection curves were measured, both without and with trapezoidal sheets. Because the trapezoidal sheets were used more than once different stick out beyond the support lines were accounted for.

4 DESCRIPTION AND VERIFICATION OF A FINIT ELEMENT MODEL

The FE model should take into account all important parameters for this problem, which are: dimension of the whole construction, geometry (height, thickness,..) of trapezoidal sheeting, material, number of panels and number of joints, seam fasteners and their distance, type and number of member fasteners, dimension and material of the beams, support and loading conditions.

The program system Ansys 10.0 [9] taking into account different types of elements (SHELL93, SHELL43, COMBIN39) is used. In order to verify the FE model different methods were used :

a) recalculations of tests :

- the 12 tests described in chapter 3.2 where the trapezoidal sheet was supported at two edges only,
- 2 shear penal tests of *Dürr* [7], one with supports at two edges, one with supports at four edges,
- 6 shear penal tests of *Walter* [10] using different types of fasteners.

In all these cases excellent or at least good agreement with the experimental load-deflection curves are recognized.
b) comparison of theoretical values :
- analytical values for the shear stiffness S using the method of *Strehl* [4], [11] for an ideal shear panel. 5 different profiles (39/183, 85/280, 135/310, 160/250 and 200/420) and 3 thicknesses (0.75, 1.0, 1.25 mm) were investigated. The relation between the results of the FE model and the value due to [11] of the 15 cases show a mean value of 0.986 with a maximum of 1.019 and are therefore extremely sufficient.

In general it is shown that the proposed FE model show excellent agreement with the values compared, allowing the use of this FE model for extensive parameter studies.

5 PARAMETRIC STUDIES

Two different types of loading are taken into account: shear panel loading and sinusoidal transverse lateral loading. in both cases the results are called S_S respectively S_E. In order to cover a broad spectrum of possible systems in practice the following parameters were varied: type of trapezoidal sheeting, sheet thickness, profile length, length and lateral bending stiffness I_z of the beam to be stiffened, different stiffnesses of the seam fasteners and the member fasteners. Especially the two interesting support conditions: two edges supported and four edges supported are investigated. The results show that all these parameters influence the outcomes and must be taken into account in order to get sufficient results.

As a next step only those cases were investigated where sinusoidal transverse lateral loading can be observed and the trapezoidal sheet is supported at two edges with a stick out of 5 cm above the support lines leading to the shear stiffness S_E. Again it can be seen that an analytical function to cover the results is not possible.

6 MECHANICAL MODEL

6.1 General

The mechanical model consists of two steps: in the first step a simplified strut model is used, see figure 4 a), in order to determine the stiffness S^*, see eq. (1). There is a bedding between the equivalent beam having the stiffness S^* and the cross beam having the stiffness $2 \cdot I_z$. In the second step this strut model is modified in such a way that another equivalent beam having the stiffness S_{beam} is connected rigidly with the cross beam having the stiffness $2 \cdot I_z$, see figure 4 b).

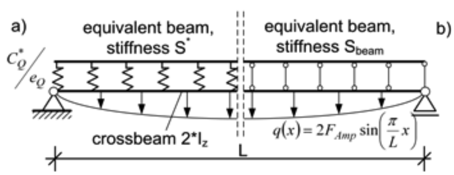

Figure 4: strut models, a) for calculation of S^*, b) for determination of S_{beam}

The equivalent beam stiffness S^* is calculated by eq.(1) with C_{tot} as the total stiffness.

$$S^* = LC_{tot} \tag{1}$$

where

$$\frac{1}{C_{tot}} = \frac{1}{C_{sheet}} + \frac{1}{C_{cross}} + \frac{1}{C_{con}} \tag{2}$$

For a qualified solution the assumption about the stiffnesses C_{sheet} and C_{cross} is decisive because they very much depend on the type of the trapezoidal sheeting. Therefore two different solutions are proposed given in chapters 6.2 and 6.3

If the stiffness S^* due to eq. (1) is known a second step is necessary in order determine the stiffness S_{beam} of the equivalent beam. This is done by investigating the system of figure 4 a) taking into account the sinusoidal lateral force q(x) which leads to a lateral deflection u_m at midspan. From the system of figure 4 b) one gets eq. (3).

$$S_{beam} = 2\left(\frac{L}{\pi}\right)^2 \left(\frac{F_{Amp}}{u_m} - EI_z\left(\frac{\pi}{L}\right)^4\right) \tag{3}$$

6.2 Special solution for selected types of trapezoidal sheeting

The stiffness of the seam fasteners of the connection of two sheets side by side:

$$C_{con} = \frac{c_S L_s + 2C_Q^*}{n_T - 1} \tag{4}$$

with n_T = number of sheets and L_s = length of the sheeting.

Stiffness of the member fasteners:

$$C_{cross} = \frac{L_s^2}{2L\dfrac{e_Q}{C_Q^*}} \tag{5}$$

The modified stiffness C_Q^* of the member fasteners connected to the cross beams:

$$C_Q^* = \left(mC_Q + n\right)C_Q \tag{6}$$

where the values of m and n depend on the special type of trapezoidal sheeting, they should be taken from table 1.

Table 1: coefficients m, n, a, b and c for use in eqs.(6) and (8)

profile	thickness t_N [mm]	m [cm/kN]	n [-]	a [kN/m²]	b [kN/m]	c [kN]
HSA 39/183	0.88	-0.0043	1.07	1548	4587	-5032
HSA 39/183	1	-0.0045	1.10	1917	7301	-7857
HSA 39/183	1.25	-0.0040	1.12	2562	15674	-16313
UB 85/280	0.88	-0.0049	1.27	825	2204	-3450
UB 85/280	1	-0.0048	1.27	1074	3497	-5232
UB 85/280	1.25	-0.0045	1.30	1611	7692	-10805
EKO 160/250	0.88	-0.0054	1.26	245	456	-1098
EKO 160/250	1	-0.0054	1.30	332	726	-1616
EKO 160/250	1.25	-0.0048	1.32	548	1630	-3247

The stiffness C_{sheet} of the trapezoidal sheeting:

$$C_{sheet} = \frac{S_{S4s}}{L} \tag{7}$$

This value S_{S4s} is the value for a shear panel which is supported at all four edges but takes into account a stick over above the support lines of e = 5 cm, which always appears in construction, see figure 5.

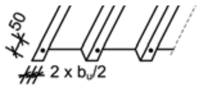

Figure 5: sketch concerning the stick over above support line

The usual methods following chapter 2.1 of calculating the shear stiffness $S = S_{S4s}$ does not consider the stick over. Therefore this value must be calculated separately. Unfortunately it depends significantly on the type of profile and can not be generalized. For 7 profiles (35/207, 39/183, 85/280, 106/250, 135/310, 150/280 and 160/250) and 4 thicknesses (0.75, 0.88, 1.0, 1.25 mm) often used in practice and partly mentioned in chapter 4 the necessary parameters a, b, c in order to calculate S_{S4s} due to eq. (8) are known [8], due to the lack of place only some are given in table 1.

$$S_{S4s} = aL_s^{\ 2} + bL_s + c \tag{8}$$

The admissibility of this simplified strut model was verified by the parameter studies of approximately 6800 analyses for the profiles and thicknesses mentioned before. The relation $\beta = S_E/S_{beam}$ varies from 0.90 to 1.20 with a mean value of m = 1.001 and a standard deviation of s = 0.056 leading to a lower statistical value of $ß_s = 0.91$. For practical use a value of ß = 0.9 is chosen and therefore the shear stiffness S can be calculated by eq. (9).

$$S = 0.9\, S_{beam} \tag{9}$$

6.3 General solution valid for all types of trapezoidal sheeting

Because the method used in chapter 6.2 needs special parameters, see eqs. (6) and (8), and is therefore restricted to the profiles mentioned there. A general method is necessary for all other types of profiles of trapezoidal sheeting.

The stiffness of the seam fasteners of the connection of two sheets:

$$C_{con} = \frac{c_S L_s + 2C_Q}{n_T - 1} \tag{4a}$$

with n_T = number of sheets and L_s = length of the sheeting

The stiffness C_{cross} is calculated due to eq. (5a) which is similar to eq. (5).

$$C_{cross} = \frac{L_s^{\ 2}}{2L\dfrac{e_Q}{C_Q}} \tag{5a}$$

The stiffness C_{sheet} of the trapezoidal sheeting is now calculated due to eq. (7a)

$$C_{sheet} = \frac{S_{Strehl}}{L} \tag{7a}$$

where S_{Strehl} is the theoretical shear stiffness mentioned in chapter 2.1: shear panel supported at four edges, without a stick over above the support lines. This value is known for a great number of trapezoidal sheeting profiles or can easily be calculated following [11].

Again the admissibility of this simplified strut model was verified by the parameter studies of approximately 6800 analyses already mentioned in chapter 6.2. The relation $\beta = S_E/S_{beam}$ varies from 0.78 to 1.45 with a mean value of m = 1.15 and a standard deviation of s = 0.12 leading to a lower statistical value of $ß_s = 0.95$. But if the profile 35/207 is taken into account only the statistical value becomes $ß_s = 0.82$. Therefore for practical use and simplified application a value of $ß = 0.8$ is proposed in general and the shear stiffness S should be calculated by eq. (9a).

$$S = 0.8\, S_{beam} \tag{9a}$$

7 EXAMPLE

7.1 Analysis of the shear stiffness S

The system shown in figure 6 is investigated.
member fasteners :
screws with neoprene washer in each trough : $C_Q = 66.7$ kN/cm, $(1/C_Q) = 0.15$ mm/kN
seam fasteners :
screws in a distance of 30 cm, stiffness 0.25 mm/kN, $c_S = 1/(0.025 \cdot 30) = 1.33$ kN/cm^2
Lateral transversal load with an amplitude of $F_{amp} = 1$ kN/cm : $q(x) = 2 \sin(\pi x/L)$ kN/cm

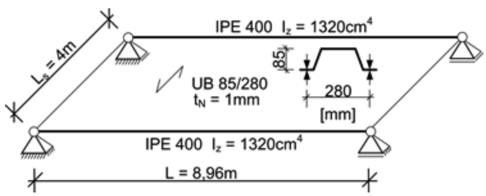

Figure 6: example

Special solution corresponding to chapter 6.2 :

eq.(6):	$C_Q^* = 66.7\,(-0.0048 \cdot 66.7 + 1.27)$	= 63.4 kN/cm
which leads to the bedding	$C_Q^* / e_Q = 63.4/28$	= 2.264 kN/cm^2
eq.(8):	$S_{S4s} = 1074 \cdot 4^2 + 3497 \cdot 4 - 5232$	= 25940 kN
eq.(7):	$C_{sheet} = 25940 / 896$	= 29.0 kN/cm
eq.(4):	$C_{con} = (1.33 \cdot 400 + 2 \cdot 63.4) / (8-1)$	= 94.3 kN/cm
eq.(5):	$C_{cross} = 400^2 \cdot 63.4 / (2 \cdot 896 \cdot 28)$	= 202 kN/cm
eq.(2):	$C_{tot} = 1/(1/29.0 + 1/94.3 + 1/202)$	= 20.0 kN/cm
eq.(1):	$S^* = 20.0 \cdot 896$	= 17900 kN

The analysis of the system of figure 4a) leads to $u_m = 12.23$ cm and from eq.(3)

S_{beam} =	$2(896/\pi)^2 \{ 1/12.23 - 21000 \cdot 1320(\pi/896)^4 \}$	= 12620 kN
eq.(9):	$S = 0.9 \cdot 12620$	= 11400 kN

General solution corresponding to chapter 6.3 :

The analysis is similar to the one shown before, but using:
bedding $C_Q / e_Q = 66.7/28 = 2.382$ kN/cm^2, shear stiffness $S_{Strehl} = 17440$ kN
$C_{sheet} = 19.5$ kN/cm, $C_{con} = 95.1$ kN/cm, $C_{cross} = 213$ kN/cm, $C_{tot} = 15.0$ kN/cm,
$S^* = 13440$ kN, $u_m = 14.39$ cm, $S_{bam} = 10620$ kN, $S = 8500$ kN

7.2 Effect of the shear stiffness S on the lateral torsional buckling load

The determined values for the shear stiffness S are used to calculate the lateral torsional buckling load according to EN 1993-1-1, chapter 6.3.2.3 [1]. It is assumed that the beams IPE 400 S235 are subjected to a vertical load q acting on the upper chord. Using the values S from chapter 7.1 the elastic critical moments M_{cr} are determined [12] neglecting the rotational spring stiffness c_ϑ.

- S = 0 : $M_{cr} = 117$ kNm, $\bar{\lambda}_{LT} = 1.624$, $\chi_{LT,mod} = 0.3420$, $q_u = 10.5$ kN/m

- $S = 0.5 \cdot 8500 = 4250$ kN : $M_{cr} = 1115$ kNm, $\bar{\lambda}_{LT} = 0.525$, $\chi_{LT,mod} = 0.9540$, $q_u = 29.2$ kN/m
- $S = 0.5 \cdot 11400 = 5700$ kN : $M_{cr} = 1400$ kNm, $\bar{\lambda}_{LT} = 0.468$, $\chi_{LT,mod} = 0.9850$, $q_u = 30.1$ kN/m

It can be seen, that generally the value S has a very great influence on M_{cr}, but the difference between the two methods of 6.2 and 6.3 results only in 3 % of the ultimate load q_u.

8 CONCLUSION

I-beams are prone to fail by lateral torsional buckling. Adjacent members like trapezoidal steel sheeting have positive effects on the stabilization of the beams especially by their shear stiffness S. When considering S usually a shear panel must be present, and all 4 edges of the sheet must be connected to the substructure. This may cause difficulties in practical applications. In this paper a simplified calculation method is proposed to calculate a modified shear stiffness S assuming that only two edges are connected to the substructure. It also must be recognized that the sheet is not stressed by shear forces but by lateral transverse forces occuring when lateral torsional buckling takes place. The application is shown in an example, where the great effect of S can be recognized.

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