Investigation of the Shear Stiffness of Profiled Steel Sheeting Diaphragms

M. Duerr

H. Saal

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Investigation of the shear stiffness of profiled steel sheeting diaphragms with only two edges fastened

Duerr, M.[1] and Saal, H.[2]

Abstract

The shear stiffness of profiled steel sheeting diaphragms can be used to stabilize members and structures as well. The available design rules accounting for this effect suppose that all four edges of the shear diaphragm are fastened. As the shear connectors, which are used to fasten the sheeting to the parallel members, cause additional work, costs and effort, the diaphragm is - according to its uniaxial load bearing behaviour for transverse loading – often fastened only at the two edges, which are normal to the span of the profiles.

The effect of free edges parallel to the span is investigated numerically and verified experimentally for the diaphragm under shear loading. This nonlinear investigation includes the flexibility of the fasteners which connect the sheeting to the supporting structure. The result of the investigations is a formula for calculating the shear stiffness of profiled steel sheeting diaphragms with only two edges fastened.

1. Introduction

The ultimate load of slender beams can be increased by using the diaphragm effect of covering trapezoidal sheeting attached to the compression flange. The profile is fixed in the lateral direction at the location where the sheeting is attached when the shear stiffness S of the sheeting meets the following requirement according to [1]:

$$S \geq \left(EI_{\omega} \frac{\pi^2}{l^2} + GI_T + EI_z \frac{\pi}{l^2} 0.25h^2 \right) \cdot \frac{70}{h^2} \qquad (1)$$

[1] Scientific Assistant, Versuchsanstalt für Stahl, Holz und Steine, Universität Karlsruhe (TH), D-76128 Karlsruhe, Germany
[2] Full Professor, idem.

A restriction is given by [2], which allows the application of (1) only if all four edges of the diaphragm are fastened. Actually often only the two edges, which are normal to the span of the profiles, are fastened. This is because fastening along the longitudinal edges requires high constructive effort or increased use of material, e.g. by using special shear connectors. The effect of free longitudinal edges was investigated numerically and experimentally such that the shear stiffness and strength of trapezoidal sheeting with this type of fastening can also be taken into account for increasing the lateral torsional buckling load.

2. Testing of diaphragms

The experiments with the trapezoidal sheeting diaphragms were performed with the shear frame shown in figure 1.

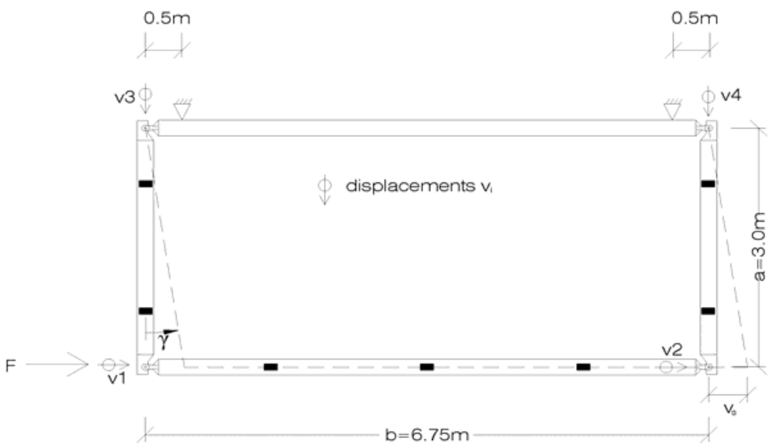

Figure 1: shear frame in horizontal projection

The displacements of the frame were measured with two displacement transducers v_1 and v_2 parallel to the direction of the applied load and at the two supports of the frame with two transducers v_3 and v_4 normal to this direction. The displacement due to shear is

$$v_s = \frac{v_1 + v_2}{2} - \frac{a}{b}(v_3 - v_4) \tag{2}$$

With the shear displacement v_s the shear stiffness S is obtained from

$$S = \frac{\Delta T}{\Delta \gamma} = \frac{\Delta F \cdot a}{b \cdot \Delta v_s} \tag{3}$$

with

$$\Delta T = \frac{\Delta F}{b} \quad \text{increment of shear flow T} \quad (4)$$

$$\Delta \gamma = \frac{\Delta v_s}{a} \quad \text{increment of diaphragm angle} \quad (5)$$

The experiments were performed with profiles LS 5/35/1035 with t_N=1.0mm and steel grade S320GD+Z as shown in figure 2.

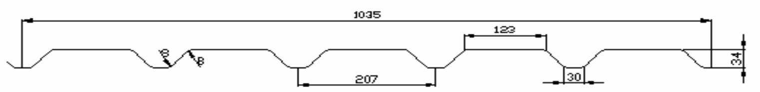

Figure 2: nominal dimensions of trapezoidal sheet LS 5/35/1035

The span of the profiles was parallel to the short span of the frame. They were connected in every trough to the frame with self-drilling screws with tapping screw thread type EJOT JT2-12-5.5x35 V16. This type of screws was also used at the longitudinal edge with spacing of e_R=150mm if the four edges of the diaphragm were fastened. Self-drilling screws with tapping screw thread type EJOT JT2-4.8x19 were used as seem fasteners with spacing e_L=150mm.
Some of the fasteners were tested separately in small scale tests according to [3] to determine their flexibility when subjected to a shear force.
Table 1 provides additional description and results of the diaphragm tests which were performed in the laboratories of the Versuchsanstalt für Stahl, Holz und Steine.

	diaphragm test 1	diaphragm test 2
type of fastening	four sides fastened	two sides fastened
dimensions a – length of diaphragm b – width of diaphragm	 3000mm 6831mm	 3000mm 6624mm
characteristic loads	85kN: plastic deformations 100kN: obvious profile distortion 166kN: failure of fastener	55kN: plastic deformations 70kN: obvious profile distortion 105kN:buckling of rib at longitudinal edge 121kN: failure of fastener
shear stiffness S	7350kN/m	6185kN/m

Table 1: description and results of diaphragm tests

3. Numerical Analysis

Numerical analyses were performed with the Finite Element program ANSYS to investigate the shear stiffness of diaphragms with only two edges fastened. The FE-model of the trapezoidal sheeting under shear loading is shown in figure 3.

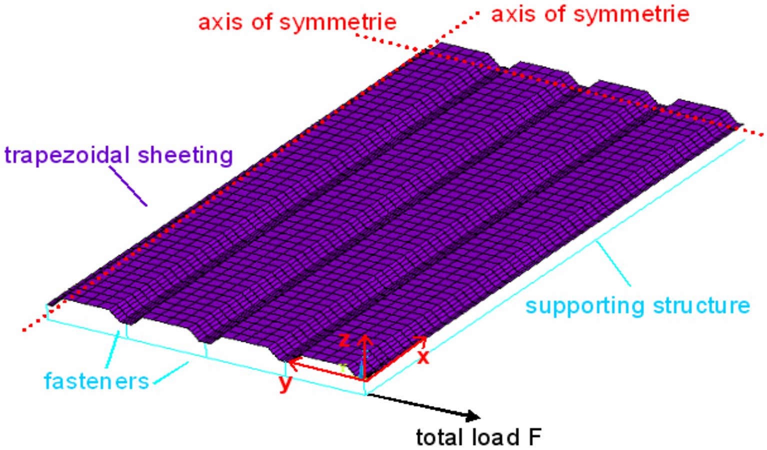

Figure 3: FE-model of trapezoidal sheeting and supporting structure

The fasteners were modeled by nonlinear springs with an implemented and approximated load-deformation-behavior according to figure 4. This graph resulted from the small scale tests according to [3].

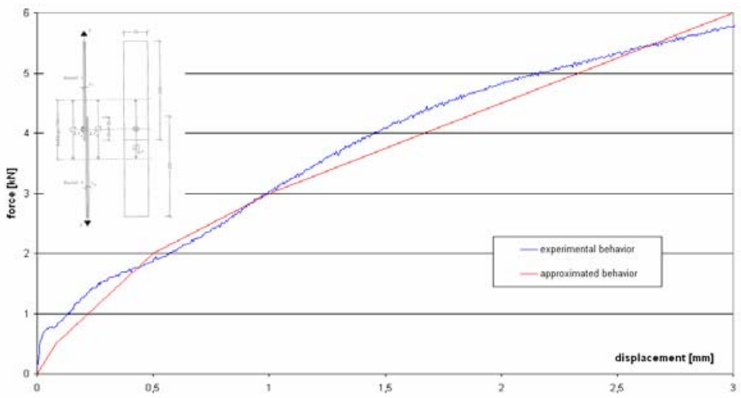

Figure 4: approximated load-deformation-graph for fasteners

For verification of the FE-model profiles with different cross-sections and different thickness were numerically analyzed for four-sided fastening. The results of this analysis were compared to [4] which is based on [5]. As [5] is based on the theory of elasticity for this comparison neither for the spring elements nor for the supporting structure any flexibilities were allowed.

Table 2 compares the shear stiffness obtained from the numerical analysis with the stiffness according to [4].

profile	width of diaphragm b [m]	thickness [mm]	shear stiffness S [kN/m]		difference [%]
			FEM	[4]	
35/207	3.0	0.75	4215	4366	4
		1.00	8621	8831	2
		1.25	15540	14926	4
105/345	6.0	0.75	807	794	2
		1.00	1727	1669	3
		1.25	3039	2941	3
135/310	6.0	0.75	1053	1103	5
		1.00	2198	2306	5
		1.25	3829	4036	5

Table 2: comparison of FE-calculated shear stiffness S with [4]

The small differences shown in table 2 for the results obtained by the two methods demonstrate that the FE-model is suitable for numerical analyses of shear diaphragms.

In order to verify the FE-model with the performed tests it was extended to include the nonlinear load-deformation-relation of the fasteners shown in figure 4, the mechanical properties of the trapezoidal sheeting and the stiffness of the supporting structure. The comparison of experimental and numerical shear displacement v_s for a diaphragm with fastening along four edges is shown in figure 5.

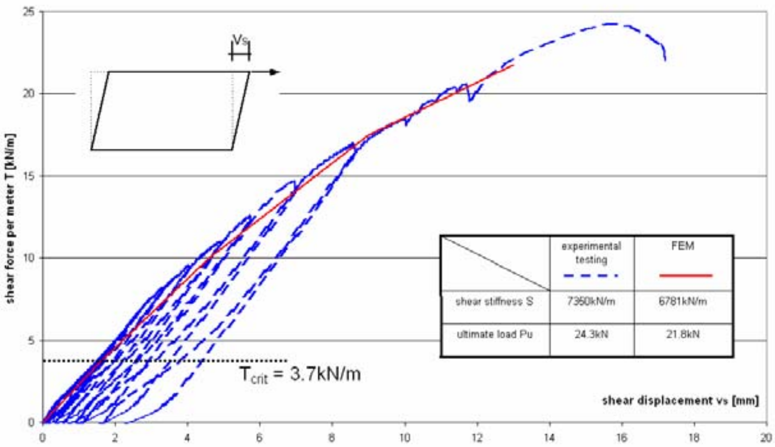

Figure 5: Load-deformation-relations obtained from the test and from the FE-analysis for the diaphragm with fastening along four edges

The experimental shear stiffness evaluated for T_{crit}=3.7kN/m according to [4] deviates from the FEM-based value at the same load level by 8%. The difference of the experimental and the FEM-based value of the ultimate load is 11%. Both the experimental and FEM-based ultimate load was limited by the maximum forces of the fasteners located in the corners of the diaphragm.

The test with only two edges of the diaphragm fastened was investigated with the same FE-model with the only difference that the fastening at the longitudinal edges was removed. The comparison of experimental and numerical shear displacement v_s for a diaphragm with fastening along two edges is shown in figure 6.

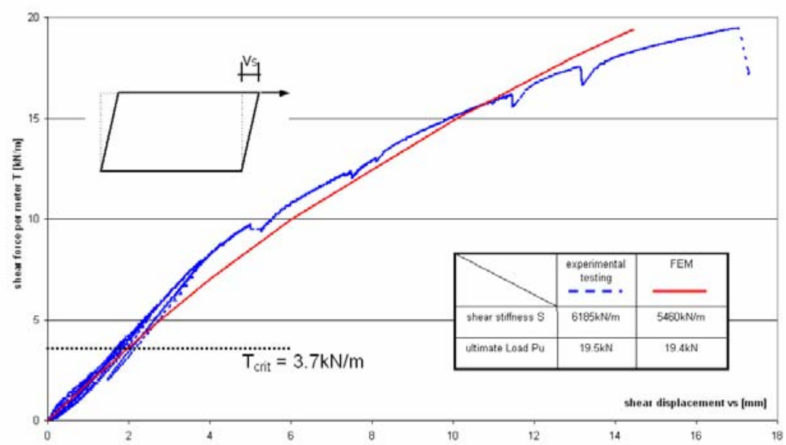

Figure 6: Load-deformation-relation resulting from experimental testing and FEM for fastening along two edges

In this case the experimental shear stiffness evaluated for T_{crit}=3.7kN/m according to [4] deviates from the FEM-based value at the same load level by 13%. The difference of the experimental and the FEM-based value of the ultimate load is 1%. Both the experimental and FEM-based ultimate load was limited by the maximum forces of the fasteners located in the corners of the diaphragm.
Figure 5 and figure 6 show the overall close agreement of numerical and experimental results for the load-displacement-curve.

4. Parametric study with the verified Finite-Element-model

With the verified FE-model a parametric study was performed for six different types of trapezoidal sheeting with profile height ranging from 30mm to 153mm. The study included the profile LS 5/35/1035 with its effective geometry and material properties. The characteristic values of the other investigated profiles types are listed in table 3.

type of profile	30/221	40/183	59/225	105/345	153/280
thickness t_K [mm]	0.96	0.96	0.96	0.96	0.96
profile height [mm]	30	40	59	105	153
width top flange [mm]	120	119	140	210	119
width bottom flange [mm]	40	40	35	40	40
pitch of corrugations [mm]	221	183	225	345	280
length of diaphragm [mm]	3000	3000	3000	5000	5000
T_{crit} according to [4] [kN/m]	4.1	3.7	3.0	1.8	2.5
S according to [4] [kN/m]	11389	5640	2940	1378	1898

Table 3: characteristic values of investigated profile types

Diaphragms with different a/b-ratios were numerically investigated with four sides fastened and with two sides fastened. This investigation reflected the nonlinear behavior of the fasteners as shown in figure 4 and bi-linear material properties with E=210000N/mm² and fy=320N/mm² for the trapezoidal profiles. Figure 7 shows the shear stiffness S for diaphragms fastened along four edges with a/b-ratios ranging from 0.25 to 1.75.

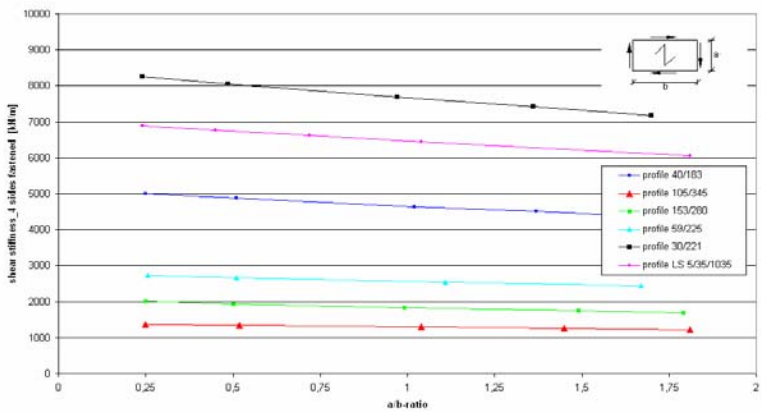

Figure 7: variation of shear stiffness with different a/b-ratios for diaphragms with fastening along four edges

Figure 7 shows that the shear stiffness decreases with increasing a/b-ratio. This influence, which amounts for the profile 30/221 to 12%, is due to the flexibility of the fasteners and the interaction of longitudinal and transverse forces in the corners of the diaphragm. The numerical analysis shows that with rigid fasteners the shear stiffness is independent of the a/b- ratio. Removing the fastening along the longitudinal edges increased the influence of the ratio a/b on the shear stiffness S significantly as figure 8 shows.

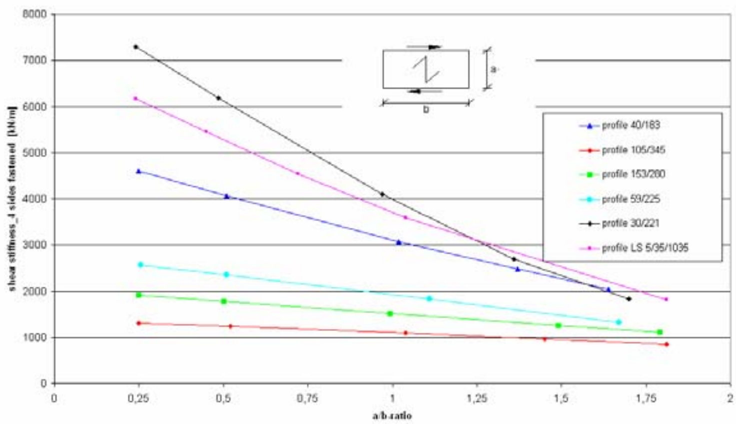

Figure 8: variation of shear stiffness with different a/b-ratios for diaphragms with fastening along two edges

The obvious loss in shear stiffness with increasing a/b-ratio for diaphragms with fastening along two edges is explained by figure 9, which shows the distribution of the forces of the fasteners along the edge.

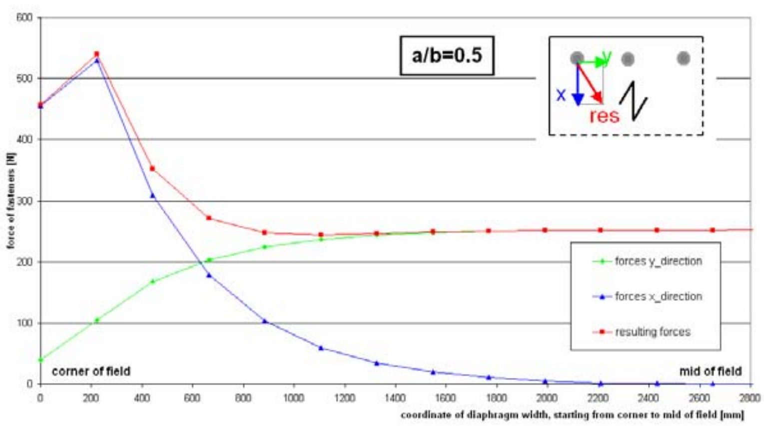

Figure 9: forces of the fasteners along edge for a/b=0.5

It is obvious that the fasteners close to the corners of the diaphragm are mainly exposed to forces F_x resulting from the free longitudinal edge. As the number of fasteners decreases with smaller width b of the diaphragm the forces F_x per fastener will increase significantly and cause larger deformations. This is proven by figure 10 which shows the changes connected with an increase of a/b form 0.5 to 1.0. Figure 10 also shows, that with this increase the force of the fastener increases more for profiles with small profile height than for higher ones.

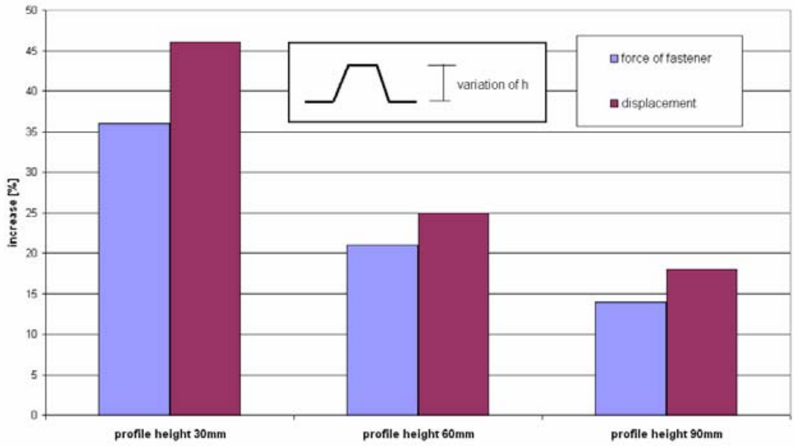

Figure 10: increase of maximum forces of edge fasteners and displacements with a/b increasing from 0.5 to 1.0

Figure 9 and 10 demonstrate the non-uniform distribution of the shear forces for diaphragms with only two edges fastened. This deviates from the uniform distribution supposed in [5] for a diaphragm fastened along four edges. The shear forces are concentrated in the corners of the diaphragm with fastening only along two edges.

5. Evaluation of numerical results and approximated calculation

Figure 11 shows the ratio of the two-sided shear stiffness (see figure 8) to four-sided shear stiffness (see figure 7) for the investigated profile types subject to the a/b- ratio of the diaphragm.

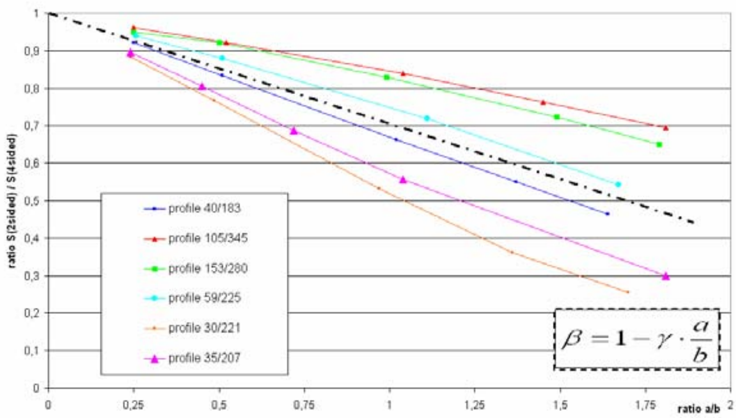

Figure 11: ratio of shear stiffness with fastening along two edges to that with fastening along four edges for different profiles and a/b-ratios

For a diaphragm with free edges parallel to the span and with b→∞ it is obvious that the shear stiffness S is the same as for a diaphragm fastened along four edges. This is explained by the decreasing influence of the free longitudinal edge with increasing width of the diaphragm. The loss of stiffness is mainly controlled by the shear stiffness of the diaphragm with fastening along four edges.
The graphs of figure 11 can be approximated by using straight lines with

$$\beta = 1 - \gamma \cdot \frac{a}{b} \qquad (6)$$

Figure 12 shows the factor γ, which is easily taken from figure 11 depending on the shear stiffness of the diaphragm with fastening along four edges.

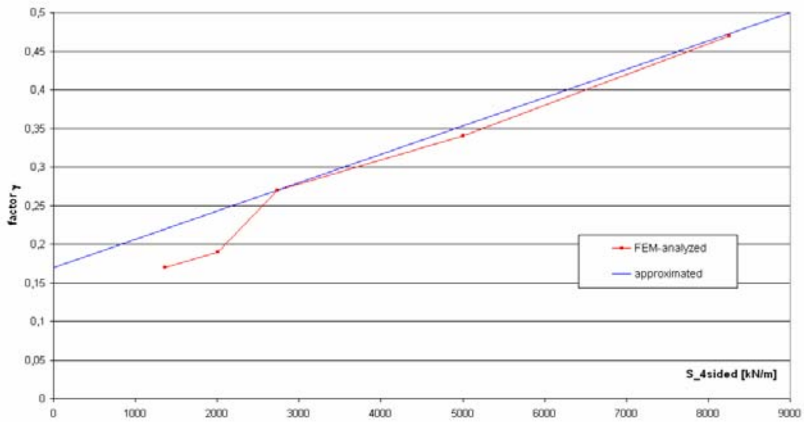

Figure 12: variation of factor γ with shear stiffness of diaphragm with fastening along four edges

Thus the shear stiffness $S_{2\text{-sided}}$ of diaphragms with two sides fastened can be calculated depending on the shear stiffness $S_{4\text{-sided}}$ by means of factor γ according to figure 12 or approximated by

$$\gamma = 0.17 + 0.33 \cdot \left(\frac{S_{4-sided}}{9000} \right) \qquad (7)$$

to

$$S_{2-sided} = (1 - \gamma \cdot \frac{a}{b}) \cdot S_{4sided} \qquad (8)$$

Equation (8) applies for trapezoidal sheeting according to [4] with profile heights ranging from 35mm to 175mm and a/b-ratios of the diaphragm less than 1.75 if fasteners are at least as stiff as described by figure 4.

6. Conclusions

The shear stiffness of diaphragms fastened only along two edges can easily be derived from that of diaphragms fastened along all four edges by the application of a knock-down-factor. This factor depends on the a/b-ratio and the shear stiffness of the diaphragm with all four edges fastened.
This results from numerical investigations which were verified both by comparison with [3] and with experimental results.
The equation which is given to calculate the shear stiffness for diaphragms with only two edges fastened applies for trapezoidal sheeting according to [4] with profile heights ranging from 35mm to 175mm and a/b-ratios of the diaphragm less than 1.75 if the fasteners are at least as stiff as described by figure 4. The knock-down-factor applies for the stiffness under the design load according to [4]. The load-displacement behavior of the diaphragms which was numerically found and experimentally confirmed is linear up to this load-level for both types of fastenings. The ultimate loads of the diaphragms are much higher than these design loads.

7. References

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