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PULL-TROUGH RESISTANCE OF TENSILE-LOADED SCREW-FASTENINGS OF THIN-WALLED SHEETING AND SANDWICH PANELS

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Abstract. *Fixings of different thin-walled building components differ in load-bearing behaviour and load-bearing capacity, even if identical screw fasteners are used. This is most pronounced for fixings under tensile loading. In this case, the differences are caused by the differences in geometry and material properties of the thin-walled building components, leading to differences in local deformation behaviour and therefore local stressing. We discuss the influence of parameters such as geometry and material on load-bearing behaviour and pull-trough resistance of fixings with screw fasteners. A comparison between the different thin-walled building components is made, also focusing on the difference between sheeting made of steel and made of aluminium. The conclusions of this discussion have to be taken into account when designing test set-ups for the determination of the characteristic resistance values of such connections. A short review of the new ECCS-Recommendations dealing with testing of fixings is done.*

For thin-walled trapezoidal sheeting and corrugated sheeting design equations can be obtained by evaluating a huge number of test results. These equations are presented and compared with theequations in design codes. For sandwich panels, a equation allowing analysing the influence of material and geometrical parameters on the load-bearing resistance is presented.

1 INTRODUCTION

Trapezoidal and corrugated sheeting as well as linear trays and sandwich panels are typical building components of lightweight building construction. It usually involves building components made of steel sheet with a thickness of 0.40 mm to 1.50 mm. Sandwich panels as composite systems have an insulation core made of polyurethane foam, polystyrene foam or of mineral wool. Except for linear trays, they are also often made of aluminium with plate thicknesses of 0.40 mm to 1.00 mm.

For fixing of these building components mostly thread-forming screws are applied, for one thing self-tapping screws, where pre-drilling is necessary when applying them, for another thing self-drilling screws allowing for drilling and thread forming in one operation. The screws mostly consist of stainless steel. In applications were they are not exposed to weather also zinc-plated non-alloy steel are used. Since the above mentioned building components mostly involve external wall or roofs exposed to weather, washers with a scorched EPDM sealing (so-called sealing washers) or sealing EPDM rings are necessary. The metallic part of the sealing washers also consist of stainless steel, they rarely consist of aluminium.

In principle, the same fasteners are applied for all building components. As a rule, the fastener itself is not decisive for the load-bearing capacity of the connection, but pull-through of the washer and the head through the component to be attached, i.e. the geometry and the mechanical properties of the building components are decisive for the load-bearing capacity. Therefore, in the following, we will look at the dependency in load-bearing capacity of connections subjected to tensile loading for different building components and the resulting consequences for the determination of the load-bearing capacity values.

2 LOAD-BEARING BEHAVIOUR

2.1 Trapezoidal and corrugated sheeting

Based on the high stiffness and strength of the sheet made of steel, tensile loading of the connection only results in a local stress in the trough adjacent to the substructure. The webs being connected to the trough hardly deform. In case of a too high stressing, bending of the flange occurs, running in the longitudinal direction of the profile. Failure also appears through a crack in longitudinal direction. The only influencing parameters on the load-bearing capacity determined through the profile are therefore tensile strength, plate thickness as well as flange width or rather the position of the fastening location in the flange.

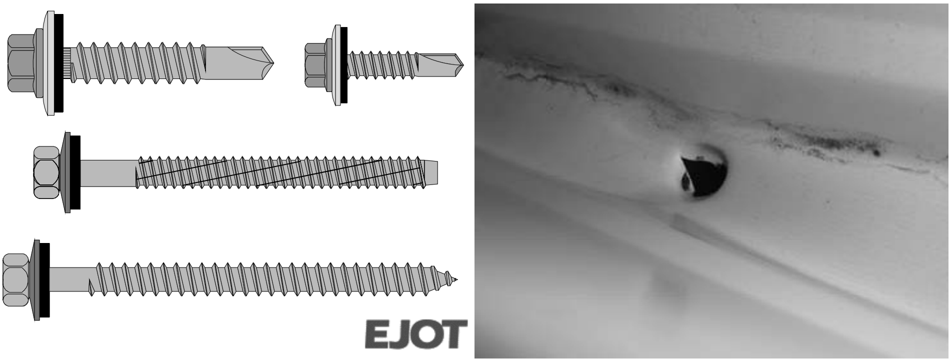


Figure 1: Examples of screw fasteners and failure mode for fixings of steel sheeting.

For trapezoidal and corrugated profiles made of aluminium fixed in the trough an additional strong influence of the profile geometry turns out. This influence is manifested for example through a failure mode depending on the profile geometry. As a rule, failure occurs as pull-trough with four radial cracks (Figure 2a) starting from the borehole under 90°. In case of wide chords, however, they can move around rectangular to the tension direction up to the web (Figure 2b). In case of a very small width of the adjacent chord in proportion to the washer diameter, the cracks under 45° run to the tension direction and then they can continue to run along the line chord to web (Figure 2c). For corrugated sheeting it is to be considered that the load-bearing capacity must not compulsorily increase with the washer diameter, since the local stress of the corrugated sheeting can reduce the load-bearing capacity through the edges of the washer being rigid in contrast. In [1] a detailed look is taken on the failure modes and influencing parameters for trapezoidal and corrugated sheeting made of aluminium that are fastened in the trough.

The crest-fixing of trapezoidal or corrugated sheets is mostly done with saddle washers. Without these saddle washers, the sheet of the flange not supported by a substructure would strongly deform under the point load. The saddle washer induces the forces of the screw, at least in parts, directly into the stiffer webs. Therefore, the stiffness of the saddle washer in this direction has a wide influence, for which reason the saddle washers are mostly stiffened with transverse ribs. Thus, the stressing conditions are lying between that of a rigid support comparable to that for the transversal load at a support and a point load introduced into the flange like a fixing without saddle washer [2]. Therefore, the failure of the connection is a combined failure from crippling of the webs and cracks in transverse direction starting from the borehole (Figure 2d). For this reason, design approaches such as those presented in [3] assume a dependence on the yield strength instead of the tensile strength.

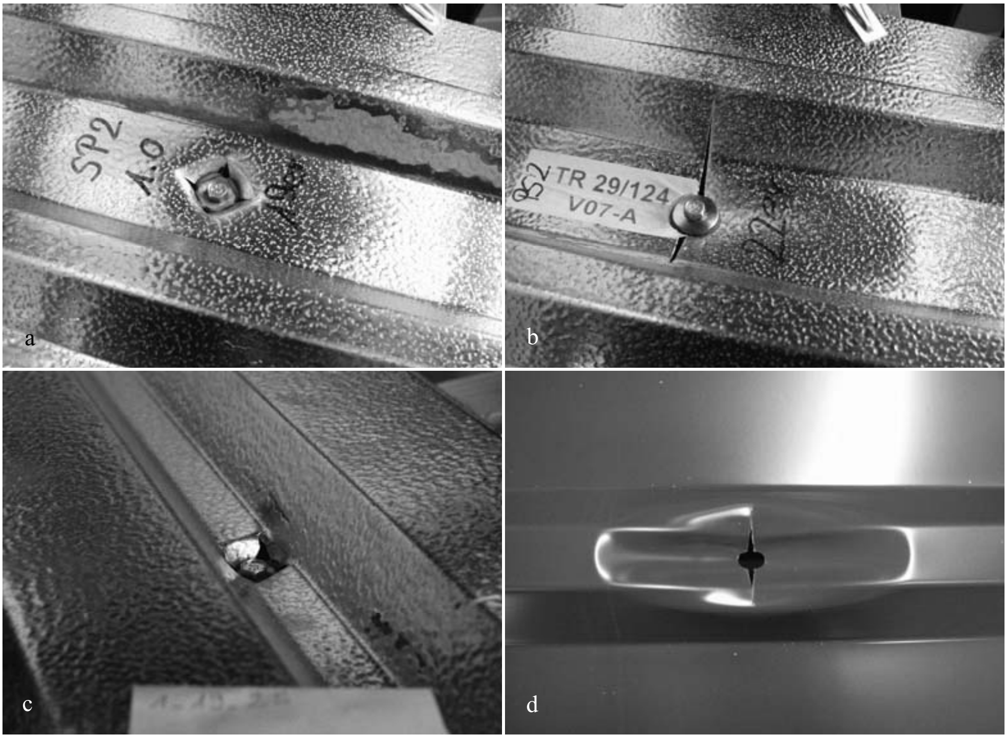


Figure 2: Failure modes of fixings of aluminium trapezoidal sheeting.

2.2 Sandwich panels

For sandwich panels, the load-bearing behaviour and the load-bearing capacity are influenced by the core supporting the often flat or only slightly profiled faces. Depending on the ratio of bending stiffness of the face and elastic modulus of the core, the stresses occurring in the faces vary. Nevertheless, failure of fixings of sandwich panels is a rather local failure and its form of appearance is always quite the same (Figure 3), as far as no hidden fixings are used. Failure will finally occur by cracking of the face, therefore an increasing elastic modulus and compression strength of the core increases the load-bearing capacity.

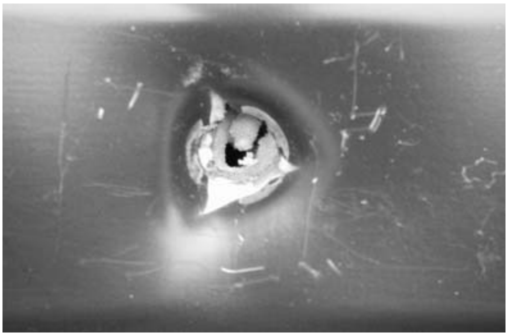


Figure 3: Failure mode for fixings of sandwich panels.

3 DETERMINATION OF THE LOAD-BEARING CAPACITY THROUGH TESTS

3.1 Trapezoidal and corrugated sheeting

The determination of the load-bearing capacity of fixings of steel sheeting through tests can be done on the basis of [5] for example. Since the profile geometry for the profiled steel sheets treated in [5] has no or negligible influence, the load-bearing capacity can be determined on a standardised V-shaped specimen (Figure 4) retracing to [6].

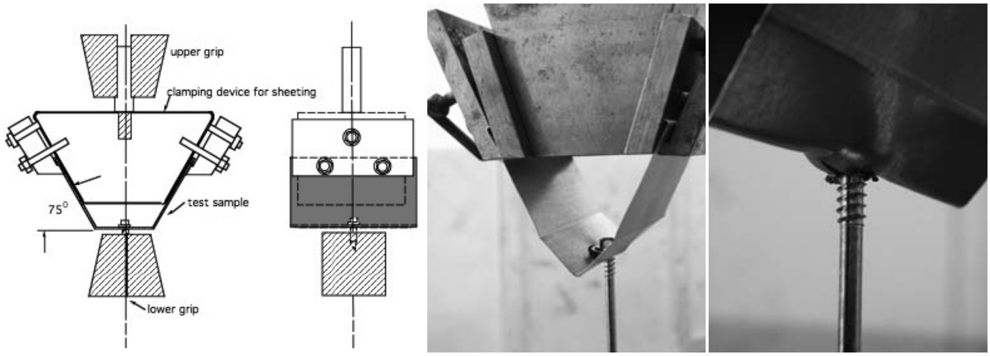
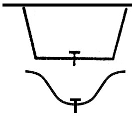
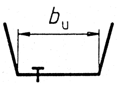
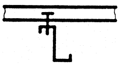
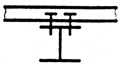
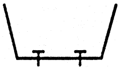
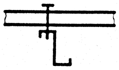
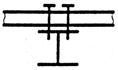


Figure 4: Test set-up according to [5] and failure mode for fixings of steel sheeting.

Wind loads result in a repeated loading of the connection, reducing the resistance of the connection. The first edition of the ECCS Recommendations [5] suggested a reduction factor of $\alpha_{cycl} = 0.5$ which can also be found in EN 1993-1-3. Since this value has initially been determined in [6] to $\alpha_{cycl} = 2/3$ and a reduction factor of $\alpha_{cycl} = 2/3$ is also applied in European Technical Approvals, this has been corrected in the new second edition of the ECCS Recommendations to $\alpha_{cycl} = 2/3$. In addition, reduction factor are available for special cases of application. The factors α_E listed in Table 1 are taken from EN 1999-1-4 for aluminium sheeting, but they are basically the same for steel sheeting.

Table 1: Reduction factor α_E for special cases of application.

						
1.0	$b_u \leq 150$: 0.9 $b_u > 150$: 0.7	0.7	0.9	0.7 0.7	1.0	0.9

Alternatively, a test with a sheeting is presented that can also be used for the determination of the pull-through bearing capacity of the fasteners regarding profiled aluminium sheets, since the influence of the profile geometry is taken into account.

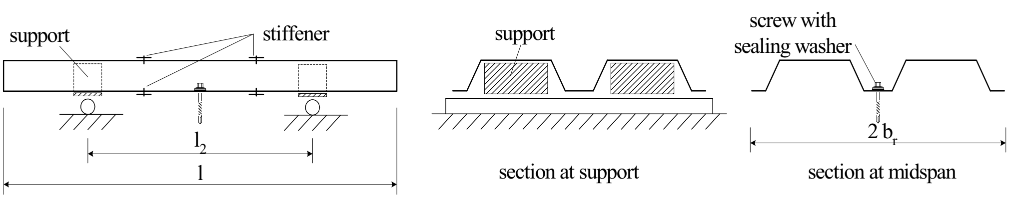


Figure 5: Test set-up for fixings of steel and aluminium sheeting.

The Recommendations [5] do not give a special test set-up for crest-fixings. Several proposals for test set-ups can be found in different (predominantly national) standards. Resistance values obtained for trough fixing should not be used for crest-fixing, because of the lower resistance of this connection due to web-crippling effects.

3.2 Sandwich panels

The determination of the load-bearing capacity through tests can be effected on the basis of [7] for example. The tests are performed with a specimen made form a panel and the test-setup complies with the one shown in figure 5. A special remark is given that as there is also an effect of thickness of the panels core material. Also, the reduction factor α_{cycl} should be determined trough tests with repeated loading.

4 DETERMINATION OF THE LOAD-BEARING CAPACITY BY CALCULATION

4.1 Trapezoidal and corrugated sheeting

The pull-through resistance of fixings of steel sheeting can be calculated according to EN 1993-1-3 with

$$R_k = t \cdot d_w \cdot f_u \tag{1}$$

Thereby t is the sheet thickness, f_u is the tensile strength and d_w is the diameter of the washer or the head of the fastener. This value must be reduced by multiplication with α_{cycl} if the connection is subjected to tensile forces due to wind loading and with α_E for special cases of application.

On the basis of this approach – other approaches resulted in only slightly better correlations with increasing complexity – tests with V-shaped specimens according to [5] have been recalculated and evaluated statistically. Considering the variances of the input parameters with $V_{Rm} = 0{,}076$, $V_t = 0{,}0195$ and $V_{dw} = 0{,}00008$, the characteristic value of the load-bearing capacity resulted in

$$R_k = 1.12 \cdot t \cdot d_w \cdot f_u \tag{2}$$

a value being slightly above that of EN 1993-1-3. The above mentioned tests have all been performed with sealing washers. Thus, the increased load-bearing capacity compared to that in EN 1993-1-3 can be ascribed to the influence of the EPDM of the sealing washer that weakens local stress peaks.

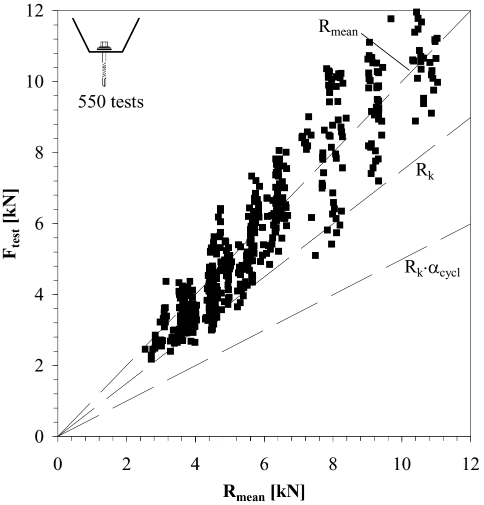


Figure 6: Comparison of calculated load-bearing capacity with test results.

The parameter range of equation (2) includes:

- thread forming tapping screws with hexagon head, width across flat 8 and collar diameter 10.5 mm, hexagon head, width across flat 3/8" (9.5 mm) or comparable head diameter.
- sealing washers made of stainless steel with vulcanised EPDM sealing, 11 mm $\leq d_w \leq$ 22 mm.
- sheet thicknesses of 0.40 mm to 1.50 mm and tensile strength of R_m = 360 N/mm² to 450 N/mm².

For aluminium sheeting, the pull-through resistance can be calculated with

$$R_k = 6.1 \cdot t \cdot \sqrt{\frac{d_w}{22}} \cdot f_u \tag{3}$$

according to EN 1999-1-4. This value has to be multiplied with the reduction factors α_E for special applications (Table 1), α_M for the metallic material of the sealing washer (α_M = 1 for stainless steel and α_M = 0,8 for aluminium) and α_L to take the effects of flexural tensile stresses at support fastenings into account (see EN 1999-1-4 for details). For unknown reason the factor α_{cycl} is already included in (3).

Since, however, the influence of the profile geometry is not registered, in this case an equation is involved providing results that are on the safe side. An alternative design proposal for aluminium trapezoidal profiles with fixing in the trough has been presented in [1]. In the meantime, this proposal could be extended with regard to the field of application based on further test results being available, especially on trapezoidal profiles with a very small thickness. As a result, minimal modifications ensued in the pre-factors. The characteristic value of the resistance of fixings of trapezoidal sheeting is:

$$R_k = t \cdot R_m \cdot \left(0.394 \cdot d_w + 7.42 \cdot t \cdot \frac{d_w}{b_u} \right) \tag{4}$$

The characteristic value of the resistance of fixings of corrugated sheeting is

$$R_k = t \cdot R_m \cdot \left(1.263 \cdot d_w + 10.00 \cdot t \cdot \frac{h}{b_r} - 11.67 \cdot t \cdot \frac{d_w}{r} \right) \tag{5}$$

To theses values the same reduction factors as for equation (3) apply. In addition to these, they have to be multiplied with α_{cycl} and with the factor α_O = 0,82 for stucco embossed sheets. Figure 7 shows the comparison between test results and calculated values.

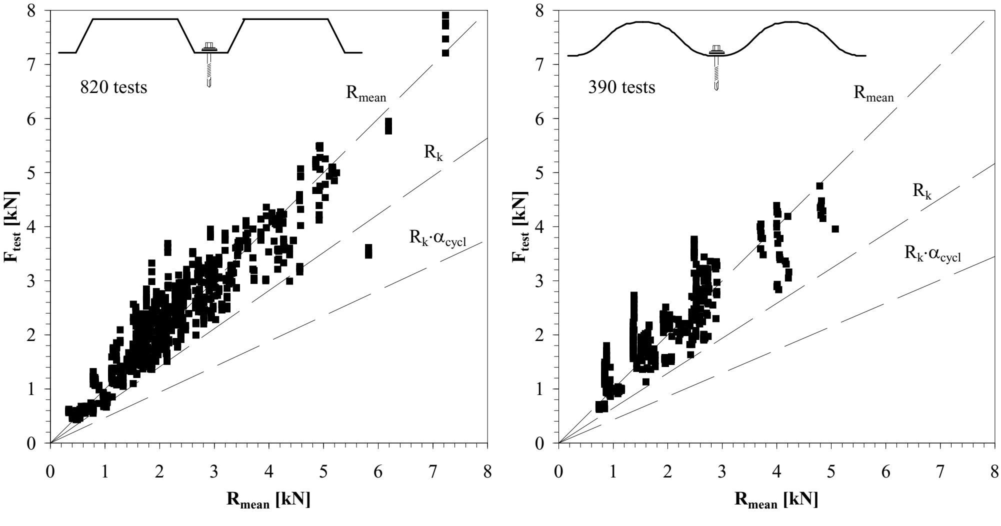


Figure 7: Comparison of load-bearing capacity with test results.

For the equations (4) and (5), the following parameter range applies:

- thread forming tapping screws with hexagon head, width across flat 8 mm and collar diameter 10.5 mm, hexagon head, width across flat 3/8‘‘ (9.5 mm) or comparable head diameter. For a larger head diameter, the results are on the safe side.
- sealing washers made of stainless steel or aluminium with vulcanised EPDM sealing, 10 mm $\leq d_w \leq$ 29 mm (corrugated profiles: 10 mm $\leq d_w \leq$ 16 mm)
- trapezoidal sheets with heights of 20 mm $\leq h \leq$ 80 mm and widths of the connected trough of 20 mm $\leq b_u \leq$ 180 mm
- corrugated sheets with heights of 17 mm $\leq h \leq$ 55 mm, rib widths 75 mm $\leq b_r \leq$ 180 mm and radii of 24 mm $\leq r \leq$ 50 mm
- sheet thicknesses of 0.35 mm (corrugated profiles: 0.50 mm) to 1.50 mm and tensile strengths up to R_m = 300 N/mm².
- geometrical parameters according to Figure 8.

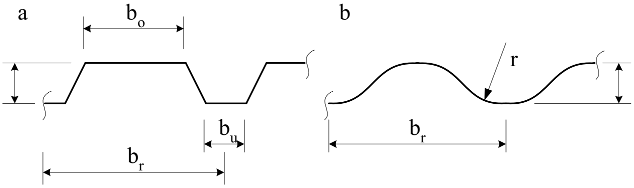


Figure 8: Geometrical parameters for equations (4) and (5).

All approaches listed here basically refer to fixing in the trough. It can be revert to [3] or to test results for crest fixing.

4.2 Sandwich panels

Based on the complex interaction of geometrical and mechanical properties of the faces with the (normally anisotropic) mechanical properties of the core material, the load-bearing capacity can be only insufficiently concentrated in a simple design equation. In [4], the simple approach

$$R_k = 2.21 \cdot \sqrt{E_{Cc} \cdot f_{Cc}} \cdot d_w^2 + 0.65 \cdot t \cdot f_u \cdot d_w \qquad (6)$$

is presented, which has been previously derived from calibrated numerical calculations on test results on quasi-flat wall panels with a core of polyurethane foam. This approach should rather serve for assessing the relative influence of individual parameters on the load-bearing capacity. A comparison of equations (1) or (2) with (6) shows best the differences in load-bearing behaviour and capacity between trapezoidal sheeting and sandwich panels: The constant factor in (6) to scale the share of the face in the load-bearing capacity is approximately half as much as the constant factor in equations (1) or (2). So using test results obtained with V-shaped specimens for the design of fixings of sandwich panels tends to be unconservative, although this was sometimes done in the past. Fortunately there is also an amount of load-bearing capacity associated with the core material and the reduction factor α_{cycl} for fixings of sandwich panels is approximately $\alpha_{cycl} \approx 1{,}0$, both balancing the differences in the constant factor.

Figure 9 shows the relative share of the face in the load-bearing capacity of the connection in dependence on the compressive modulus E_{Cc} of the core layer for two compressive strengths f_{Cc} of the core layer, and different sheet thicknesses t of the faces adjacent to the sealing washer. Both compressive strengths 0.1 N/mm² and 0.2 N/mm² represent the lower limit and upper limit of common applications. The tensile strength R_m = 360 N/mm² has been applied for the evaluation, the value of d_w = 19 mm usual for sandwich panels has been applied for the washer diameter. As expected the influence of the face (and the material properties of the face) on the pull-trough resistance declines with increasing stiffness of the core material. Practically, it should be reverted to results from tests according to [7] for the design, which is mostly inevitable due to the strongly varying parameters of geometry and the mechanical properties.

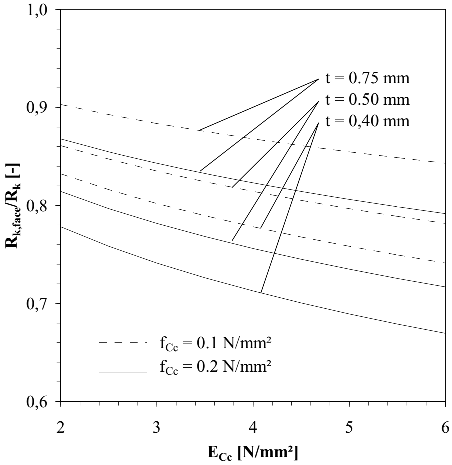


Figure 9: Fraction of load-bearing resistance given by the face in dependence on material properties of the core and faces.

5 CONCLUSION

For the connection and fastening of building components such as trapezoidal and corrugated sheeting as well as linear trays and sandwich panels mostly thread-forming screws are applied. Despite principially identical screw fasteners are used, the fixings of these different building components differ in load-bearing behaviour and load-bearing capacity. The effect of these difference was discussed with regard to testing and design of the connections. The test set-up has to be designed accordingly. We recommend to use a test set-up according to Figure 5 for tests with aluminium trapezoidal sheeting or sandwich panels. For steel trapezoidal sheeting a V-shaped specimen is sufficient.

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