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Expert statement: Perforating fastening of solar plants with hanger bolts respectively steel screws.

For the application case of a mounting of solar plants on roofs with light-metal coverings, there are generally two alternative types of fastening. The term "light-metal covering" stands for trapezoidal sheet metal and corrugated metal made of steel or aluminium, sandwich elements and standing seam roofs. In these cases, the fastening can be effected using pervasive fasteners to the substructure for the transfer of loads. With these types of roof types, a fastening to the covering shell using trapezoidal clamps or standing seam clamps is also possible. In both cases, a verification of usability by means of a general technical approval or an individual approval issued by the supreme national building authority of the country where the project is realized is required.

The perforating fastening to the substructure is effected depending on the type of the load-bearing roof structure made of wood, steel or ferro-concrete with specific fasteners. These are usually hanger bolts for load-bearing systems made of wood, self-drilling steel screws for steel systems and concrete screws or threaded rods with fastening anchors for concrete structures.

According to the type of roof covering, supported and unsupported connections are to be differentiated. The supported connection represents a constellation where the bended screw can rest due to downhill-slope forces resulting from dead load and snow. In all other cases, like for example corrugated fibre-cement or a screw joint in the bottom flange, it is an unsupported connection.

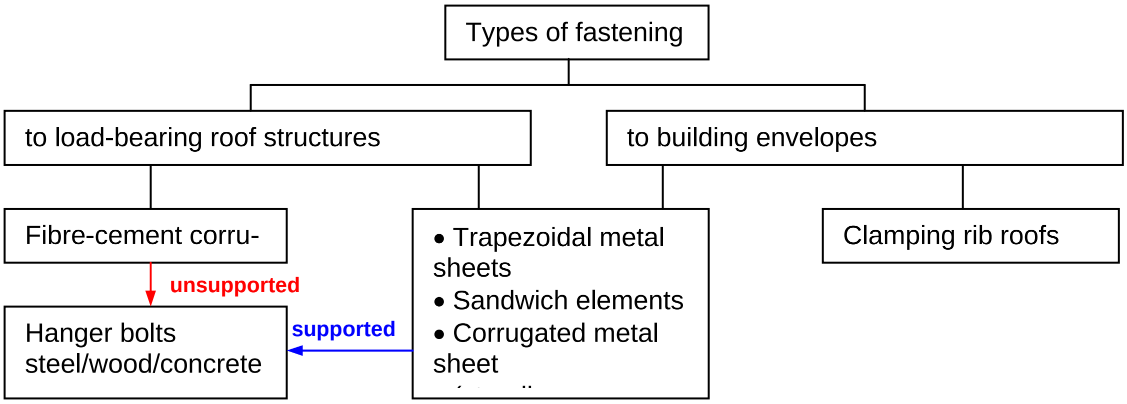

Fig 1 Classification of the types of fastening

The subject of this expert statement is the explanation of the general load carrying action and the required arithmetic verifications for fastening systems with hanger bolts. In most application cases, the profiles (module-bearing profiles or base beams with cross rails) are not fastened centrically above the screw, but manufacturer-specific adaptations are used that allow an adjustment of the rack on the roof. The adaptation can be a flat plate, possibly with slotted hole, an angle or also an innovative clamping system. Figure 2 shows the basic cases of application. Mounting on a flat roof covering or with fibre cement tiles is part of the category of the unsupported hanger bolts, the application in trapezoidal or corrugated metal sheet is part of the category of supported connections as far as a form fit under slight bending deformation is possible.

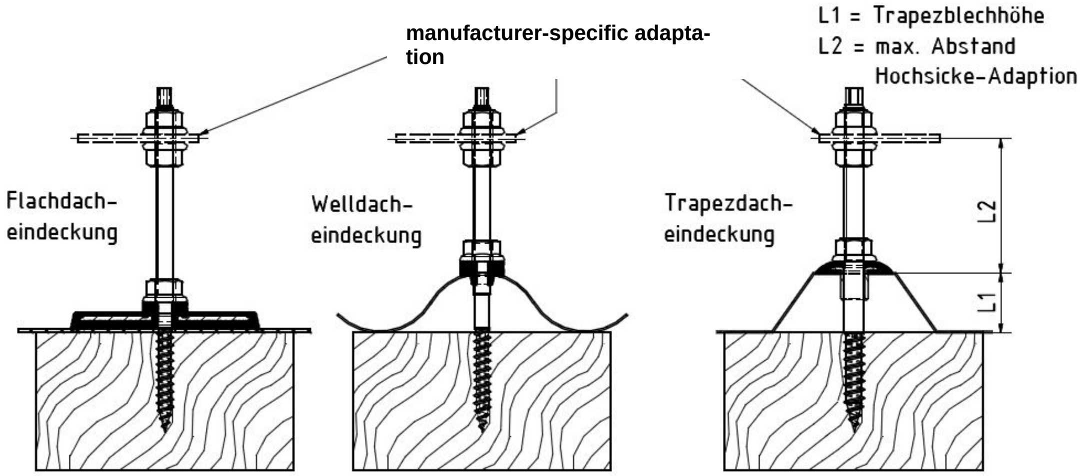

Figure 2 Design variant with hanger bolts

Numerous manufacturers on the market have a general technical approval for the hanger bolts they offer that covers the hanger bolt itself but not the possible eccentricity induced by lateral connection elements. Dashed signatures like in figure 2 can give the misleading impression that all imaginable connection eccentricities are covered by the accordant formula mechanisms of a technical approval.

In figure 3, the resulting load $P_{E,d}$ is shown that is made up of the dead load of the solar plant and wind suction loads and in the case of pressure loads are made up of the dead weight, snow loads and pressing wind loads. The load application angle of the resulting force depends on the roof inclination and the ratio of the wind load to the self-weight and snow loads and is the subject of a structural calculation.

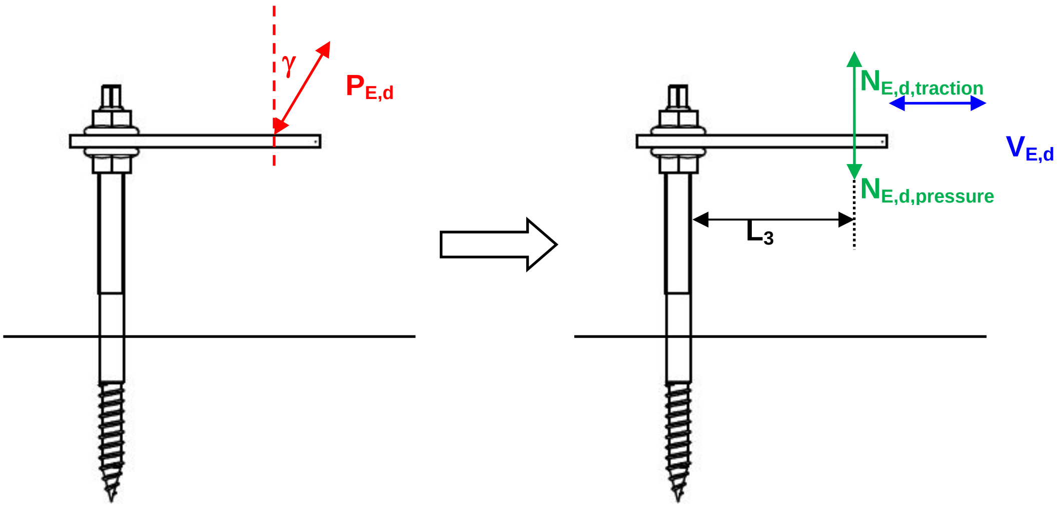

Figure 3 Impact on hanger bolts with one-sided fastening and subdivision in force components.

For reasons of arithmetic convenience, the resulting load for the structural verification of the forces parallel to the screw axis $N_{E,d}$ and forces vertically to the screw axis at the height of the connection $V_{E,d}$ are subdivided. The latter result from downhill slope forces from self-weight and snow and form a critical constellation especially in regions with heavy snow loads, as bending moments in the hanger bolt arise for which the hanger bolt has not been designed in the first place.

Thus, the structural verification of the screw cannot be limited to an observation of transmissible traction and pressure forces. In fact, a whole series of verifications is to be carried out that deal with the most different kinds of failure. Fig. 4 shows the different verification steps.

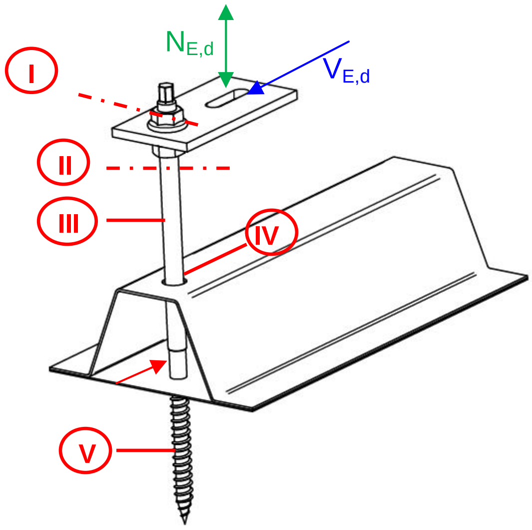

Figure 4 Verifications and verification sections for the structural verification of hanger bolts.

In the verification sections, the following arithmetic verifications are to be created.

I Verification of the lateral fastening (net section) regarding bending and normal force
II Verification of the the screw section regarding bending with longitudinal force
III Verification of the metric thread range regarding stability (buckling)
IV Verification of the bearing stress capacity (only with supported connections)
V Load-bearing capacity of the screw including edge distances (EN 1995-Eurocode 5)

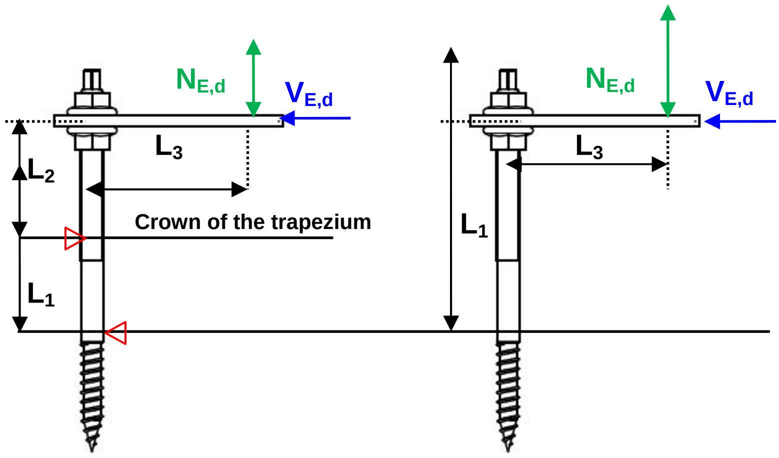

Figure 5 Geometric parameters supported/unsupported

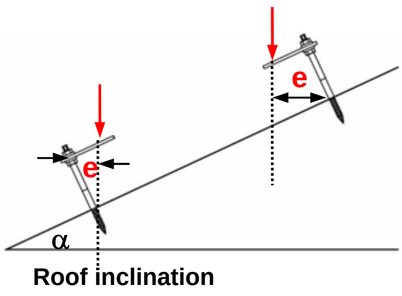

Figure 6 Impact of lateral adaptation

With hanger bolts with unilateral fastening, only the alignment of the fastening can have a positive influence on the stress acting on the hanger bolt. With an alignment of the adaptation to the ridge, the eccentricity of the resulting force from the connection point to the screw-in point into the wood decreases, or in other words, the downhill-slope force reduces the pressure load (figure 6). Thus, the verification section II directly beneath the adaptation should be decisive for the structural verification of the screw. If there is only little eccentricity, the flexural buckling verification of the metric thread is decisive in most cases. In a constellation with an adaptation alignment towards the eaves, the downhill-slope forces lead to an increase of the bending in the screw (figure 6). Thus, with lateral fastening, a considerably reduced bending load-bearing capacity of the overall hanger bolt system is to be reckoned with. Regarding stress resistance, the alignment of the adaptation to the ridge will be approximately in the middle of the constellations described before.

In the following, the structural verifications of the hanger bolt system with lateral fastening are shown exemplarily and explained. Der **Verification section I** covers the adaptation. In ideal cases, the verification of the adaptation is regulated in a general approval for use by the construction supervising authority. Otherwise, the verification is to be provided by calculation as far as there are accordant regulations. In figure 7, a popular design of an adaptation is displayed that has a drilling at the connection to the drilling screw. For reasons of adjustability, a slotted hole is intended for the fastening of the mounting rail. The stress analysis is decisive for this fastening element. The net section after deduction of the hole drillings is decisive for the verification:

Effective width: $b_{eff} = b - \varnothing_{hole}$ (1)

Effective cross section area: $A_{eff} = b_{eff} \cdot t$ (2)

Effective section modulus: $W_{eff} = A_{eff} \cdot t/6$ (3)

Stress analysis: $\sigma_x = V_{Ed} / A_{eff} \pm k \cdot N_{E,d} \cdot L_3 / W_{eff} \leq f_{0.2}$ (4)

The factor k stands for the clamping level and also takes into account to what extent there is an impediment to twisting of the adaptation caused by the rack respectively the module frame. The strains on the adaptation are lowest with a clamping level of 50% ($k = 0.5$), as the bending moments build up evenly on both ends. In this case, it is to be checked if the mounting rail respectively the module frame can take the accordant bending and torsion impacts. On the safe side, $k = 1.0$ can be chosen. When an intentional setting of the mounting is carried out, L_3 may be assessed according to the actual mounting position. Apart from that, the most unfavourable constellation at the end of the slotted hole is to be assumed for L_3 It must be said that slotted holes are not covered by the rules and standards of steel and aluminium engineering. Thus, a general technical approval is required for the verification of the transmissible forces in the direction of the slotted hole.

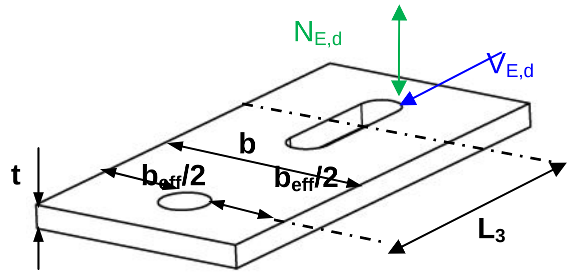

Figure 7 Geometric parameters of an adaptation (example)

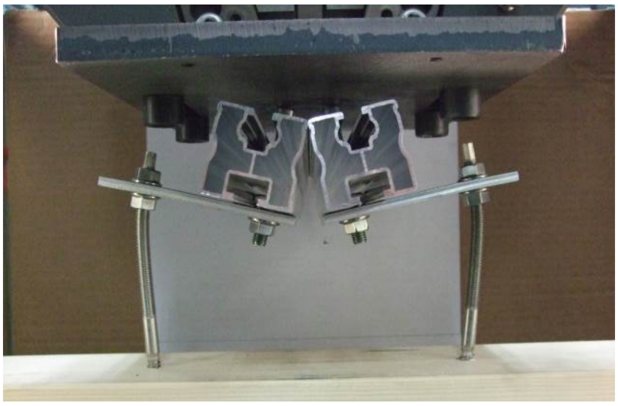

Figure 8 Deformations in the course of the tests

The verification at the upper section of the threaded part of the hanger bolt is carried out in a similar way (**verification section II**). Using the example of a bending test, figure 8 shows that the bending at the section can be the decisive failure criterion.

Stress analysis: $N_{Ed} / N_{pl,d} \pm k \cdot N_{E,d} \cdot L_3 / M_{pl,d} \leq 1.0$ (5)

with
$N_{pl,d}$ plastic limit normal force of the hanger bolt (metric)
$M_{pl,d}$ plastic limit momentum of the hanger bolt (metric)
k clamping level $0 \leq k \leq 1,0$

$N_{pl,d}$ and $M_{pl,d}$ are stress capacity values that are usually determined by tests. These values can be looked up in the general approval for use by the construction supervising authority for the hanger bolt.

However, the structural verification of the stability of the hanger bolt is more complex **(Verification section III)**. Figure 9 illustrates this correlation. If a plastic ruler is put under pressure, little pressure forces are sufficient to make it bend sidewards. However, the same ruler could take considerably higher tensile forces. Here, we must differentiate between supported and unsupported mounting. Failure of structural stability by evasion to the side depends largely on the length of the object under pressure. As a supported hanger bolt in the corrugation top is secured against lateral evasion, it only buckles when a considerably higher load level is reached. These effects are to be considered when carrying out the structural verification.

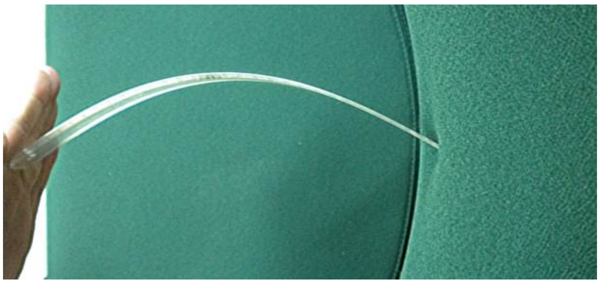

Figure 9 Buckling of a ruler

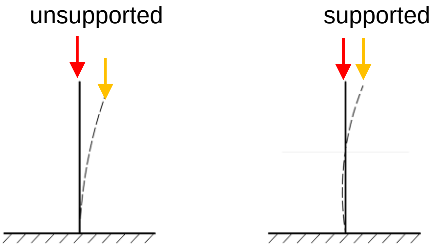

Figure 10 Buckling of rods

The so-called verification of flexural buckling requires the determination of the flexural buckling length coefficient β_1 as an input value. This value can be looked up both for supported and unsupported hanger bolts in table 1. The effective screw length L_i is also specified. With supported hanger bolts, only the distance between the trapezoidal crown of the covering shell and the center of gravity of the adaptation L_2 is to be assumed. However, the distance between the upper edge of the wooden beam and the center of gravity of the adaptation (figure 2) is to be assumed.

Table 1 Buckling length coefficients and effective screw length

	β_1	L_i
unsupported	2.55	$L_1 + L_2$
supported	$0.7 + 1.85 \cdot L_2 / L_1$	L_2

The structural verification of flexural buckling is to be carried out using the following equation.

$$\frac{N_{E,d,Druck}}{N_{pl,i}} + \frac{\alpha \cdot M_{E,d,Druck}}{M_{y,Rd,i}} + \frac{\alpha \cdot N_{E,d,Druck} \cdot L_i}{20 \cdot M_{y,Rd,i}} \leq 1 \qquad (6)$$

with

$N_{E,d,pressure}$ Rated value of the acting pressure force

$M_{E,d,pressure}$ Rated value of the bending moment

$$M_{E,d,Druck} = \sqrt{\left(V_{E,d} \cdot L_i - N_{E,d,Druck} \cdot L_3 \cdot \sin\delta\right)^2 + \left(N_{E,d,Druck} \cdot L_3 \cdot \cos\delta\right)^2} \qquad (7)$$

$N_{pl,i}$ Rated value of the plastic normal force (approval)

$M_{y,Rd,i}$ Rated value of the yield moment (approval)

δ Alignment of the adaptation (eaves -90°/gable 0°/ridge +90°)

The rated values of the plastic limit normal force and the yield moment are product-specific and can be looked up in the accordant general approval for use by the construction supervising authority. Table 2 exemplarily includes a range of rated resistance values.

Table 2 Rated value of the plastic normal force $N_{pl,i}$ and the yield moment $M_{y,Rd,i}$

	∅	M10	M12	∅	M10	M12
unsupported	$N_{pl,L1}$	10-15 kN	20-25 kN	$M_{y,Rd}$	36-41 Nm	72-80 Nm
supported	$N_{pl,L2}$	20-25 kN	33-38 kN	$M_{y,Rd}$	55-57 Nm	90-92 Nm

$$\alpha = \frac{1}{1 - \frac{N_{d,Druck}}{N_{Ki,d}}} \qquad (8) \qquad \text{with} \qquad N_{ki,d} = \frac{\pi^2 \cdot E \cdot d^4}{64 \cdot (\beta_1 \cdot L)^2 \cdot 1{,}1} \qquad (9)$$

α Enlargement factor

$N_{ki.d}$ ideal buckling load of the hanger bolt

E Modulus of elasticity 190,000 N/mm²

d Average value of the external diameter and the core diameter (M10 = 8.6 mm; M12 = 10.6 mm)

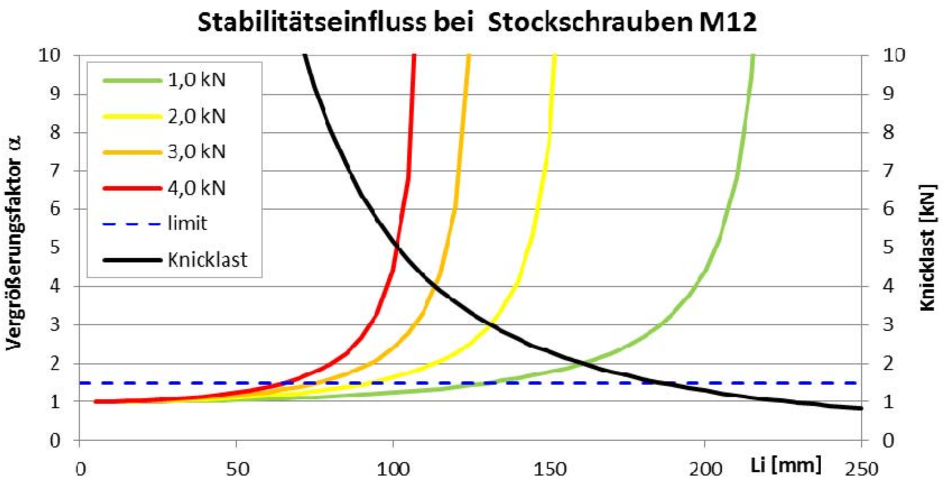

Figure 11 Graphic evaluation of the influence of the stability of the hanger bolts

For reasons of illustration, the correlations described using formulas are graphically displayed in figure 11. The black curve shows clearly that the buckling load is reduced overproportionally with increasing screw length.

At the same time, the enlargement factor α, that is to be applied to the bending moment due to downhill slope forces in equation 6 (2. term) and also to the undesired slanted position (3. term) due to mounting imperfections increases progressively. Assuming that the enlargement factor α = 1.5 represents an approximate limit of applicability, the possible effective length of the hanger bolts L_i = 65 mm with a pressure load $N_{E,d}$ = 4.0 kN and L_i = 130 mm with a pressure load $N_{E,d}$ = 1.0 kN. All in all, the evaluation shows that hanger bolts only have a very limited range of application in alpine regions with heavy snow loads. The structural verification of the bending tensile strength is to be carried out using the following equation.

$$\frac{N_{E,d,Zug}}{N_{pl,i}} + \frac{M_{E,d,Zug}}{M_{y,Rd,i}} \leq 1 \tag{10}$$

with

$N_{E,d,traction}$ Rated value of the traction force per screw

$M_{E,d,traction}$ Rated value of the bending moment per screw

$$M_{E,d,Zug} = \sqrt{\left(V_{d,S} \cdot L_i - N_{d,S,Zug} \cdot L_3 \cdot \sin\delta\right)^2 + \left(N_{d,S,Zug} \cdot L_3 \cdot \cos\delta\right)^2} \tag{11}$$

Only in the case of a supported connection with horizontal forces being transferred punctually into the crown of the trapezoidal sheet metal, **(verification section IV)**, the verification of the bearing stress capacity of the trapezoidal sheet metal is to be carried out.

$$\frac{M_{E,d,Druck}}{0{,}63 \cdot F_{b,R,k} \cdot L_1} \leq 1 \tag{12}$$

The required characteristic values for the structural verification of the bearing stress capacity depend largely depend on the sheet metal thickness, the strength of the sheet metal and the geometry and the stiffness of the insulation, as the latter obstructs a lateral evasion of the sheet metal. In table 3, the values for the hanger bolts M10 by the manufacturer Schletter are specified. These values must not be used for the structural verification of any other hanger bolts.

Table 3 Characteristic values of the bearing stress capacity Fb,R,k for profiled metal sheets made of steel

		Sheet metal thickness $t_{II,N}$ [mm]						
Steel sheets		0.40	0.50	0.55	0.63	0.75	0.88	≥ 1.00
M 10	$F_{b,R,k}$ [kN]	1.60	2.30	2.70	3.30	4.30	5.70	7.00

The verification of the load-bearing capacity of the hanger bolt against being pulled out of the wood by uplifting forces **(Verification section V)** and against pressing loads are to be carried out using the following formula. This formula is specified in the European standard for wood engineering (Eurocode 5).

$$\frac{1{,}33 \cdot N_{E,d}}{k_{mod} \cdot F_{ax,Rk}} \leq 1 \tag{13}$$

with:

$$F_{ax,Rk} = 0.52 \cdot d^{0.5} \cdot l_{ef}^{0.9} \cdot \rho_k^{0.8} \tag{14}$$

d	External diameter of the thread (M10 = 10 mm; M12 = 12 mm)
l_{ef}	Effective screwing depth of the wood thread
ρ_k	Characteristic bulk density; $\rho_k = 350$ kg/m³ for property class C24
k_{mod}	Modification factor according to EN 1995 (Eurocode 5)

In summary, it can be stated that the structural verification of a hanger bolt for the fastening of solar plants to roofs with wooden structures does not consist of one individual verification step, but requires several individual verifications with the most unfavourable of them being decisive. Apart from that, it is compulsory that the verification of structural safety is comprehensible to experts for example to inspection engineers/civil engineers. A simple specification of utilization ratios does not meet this requirement.

Due to the high repetition factor and the cost factor, by now, structural verifications of solar plants are usually created using software solutions by different software producers. Usually, the manufacturer of the component that is to be structurally verified provides the input for the software. According to the experience of the author, the programmers of such software usually have no knowledge of structural engineering whatsoever. Thus, in many cases data from a data bank are used for the determination of the traction and pressure forces without carrying out specific calculations. This is the most likely option, if required input parameters like the geometry of the sheet metal and the strength of the sheet metal are not queried.

In cases of damage, it is often difficult to determine the ones responsible, as the software producers usually have a caveat emptor. Installers/fitters can protect themselves from liability claims by obtaining a testable structural analysis with stamp and signature of a structural engineer.

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