Reference paper on the positional securing of PV flat roof systems against shifting due to thermal expansion (“Temperature creep”)

Reference paper

Initial situation/motivation

PV flat-roof systems are a major market segment of photovoltaics and provide significant potential for the expansion of PV in Germany. Commercial and industrial buildings in particular offer huge surfaces and can currently benefit from self-consumption.

The vast majority of PV systems on flat roofs are tilted systems with ballast. Advantages:

- Yield optimisation
- self-cleaning effects
- no penetration of the roof sealing
- Possibility of aerodynamically low-ballast securing against wind suction and wind pressure

Typically, low ballast installations are aerodynamically optimised systems where the required amount of ballast against wind suction and wind pressure is determined based on the results of wind tunnel tests. Effects resulting from temperature, however, such as shifting of the PV system on the roof cladding - also referred to as temperature movement or caterpillar effect - are not taken into account.

For the installation, however, they have to be taken into account, as it is known meanwhile that even with a very flat roof pitch (e.g. 1°)[1] repeated temperature changes can lead to shifting effects of the mounting structure on the roof sealing. This effect is independent of the wind load and the ballast weight! Thus, temperature effects such as shifting due to temperature must also be considered in the positional securing.

Scope of application
This reference paper is supposed to provide recommendations on how adequate positional securing against temperature creep on flat roofs with sealing can be achieved. The universally applicable formulas for constraining and downslope forces also provide the planning experts with assistance for the respective individual solutions.

How does the temperature creep occur?

Both short-term temperature variations during the day and seasonal temperature differences, as well as exposure to direct sunlight, cause thermal deformations and constraining forces that must be borne by the mounting structure and the bearings. In the relevant roofing rules (flat roof guideline) and waterproofing standards (DIN 18531), a temperature range of -20 °C < T < 80 °C is defined for roof applications, which corresponds to a maximum temperature deviation of 100 Kelvin between the coldest and the warmest situation. With temperature variations, the profiles of the PV mounting structure regularly lengthen and shorten due to thermal expansion (day/night, seasonal), slipping only a few millimetres – however repeatedly – on the roof sealing. Even with the lowest roof pitches, downslope forces are effective so that the PV system moves down by a tiny amount (tenths of a millimetre) when it slips. In the course of time, this can lead to a continuous displacement. Displacements of ballasted systems on the roof due to temperature are not a one-off occurrence, but continuous processes happening with every heating and cooling cycle. This slow shifting process is also vividly described as the "caterpillar effect".

[1] Sealed roofs are often flatly inclined for drainage at up to 5 % or 3°.

[2] The maximum temperature depends in particular on the colour and may differ from these specifications.

Possible effects of shifting due to temperature

Therefore, when maintaining ballasted solar systems, it is frequently discovered that the solar system has shifted on the roof. The shifting either takes place between the supporting structure frame and the surface protection mat or between the protection mat and the roof sealing.

The supporting structure of the PV system can collide with other components on the roof or get hooked. Damage can occur to the roof sealing or other components such as parapets, rooflight domes, ventilation pipes, lightning protection systems, cable routing etc. At worst, if there are no "obstacles" and no inspection or maintenance is done, the PV system can move up to above the edge of the roof over the years.

In addition to mechanical damage, e.g. to the roof sealing, shifting of PV system can also cause damage to electrical components, such as cable damage, and associated risks from bare cables (electric shock, risk of electric arc).

Without mechanical fastening, a displacement of the rooftop system cannot be ruled out in most cases. The static friction coefficient (e.g. between roof sealing and building protection mat) has almost no influence on the temperature creep.

Securing the PV system against shifting is therefore mandatory, not only to protect the roof sealing, but also for reasons of electrical safety and fire protection.

Possible Solutions

In order to protect the roof sealing, a protection and sliding layer between the mounting system and the roof sealing is mandatory. A thicker protective layer has a clearly positive effect with regard to temperature creep, as thermal expansions can be compensated better and a possible build-up of forces between the mounting frame, protective layer and roof sealing ("constraint forces") can thus possibly be avoided. Attention must be paid in any case to prevent a slipping of the substructure on the protection mats, for example by connecting the protection/separation layers to the bottom rail (i. e. gluing, clamping or other mechanical fastening). Of course, care must also be taken for a compatibility of materials of the respective protective layers and roof sealings. Due to the variety of potential materials this may need to be clarified individually. In the following, three solution approaches for the prevention of temperature creep are pointed out.

Bild 1: Wirkung der Ausdehnungskräfte →

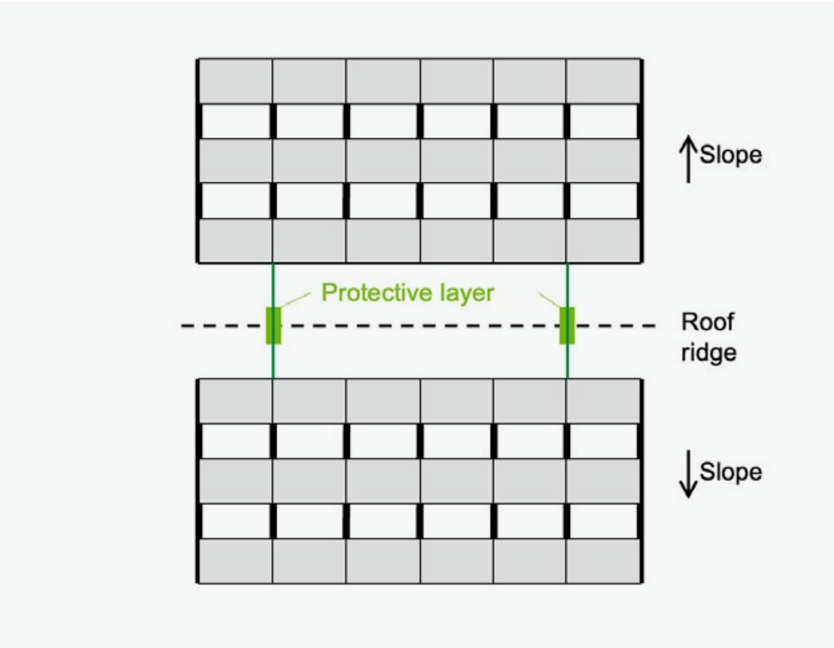

Fig. 1: Coupling of two fields with different roof pitches ↑

Approach 1:

Coupling of the fields

For draining reasons, a roof pitch on the flat roof is mandatory (minimum 2 % or 1° roof pitch ([7], [8]). Often partial roof surfaces incline in different directions.
In the case of PV system components being installed on surfaces with different inclinations, coupling the system components, e.g. with steel wire, can replace the positional securing. In this case, it has to be considered that fields of approximately equal mass and equal, but opposite, inclination can be coupled with each other (force equilibrium).

Note on safe execution

The coupling must be carried out in such a way that damage to the ridge is prevented, e.g. using a load-distributing surface protection mat.

Approach 2:

Division into small fields

The temperature creep effect depends on the size of a connected module field, on the characteristics of the roof surface (roof sealing membrane) and on the interlayer underneath the mounting system. The decisive factor for the temperature deformation is the distance between the movement joints.

A division into smaller fields can be achieved by additional movement joints (e.g. every 5 - 8 meters) and thus the creep effect can be reduced. In practice, however, the usual range is 15 to 20 meters with movement joints of 5 to 10 cm.

By coupling the different module fields or the individual modules with each other by using connection elements, the additional ballast can be reduced accordingly depending on the load bearing capacity of the connection.

It must however be stressed that the division into small fields results in an increased required ballast and thus in an increased roof area load. This may cause the permissible load reserve of the roof to be exceeded. In this case, this option is not applicable.
This option also requires additional material (base rail) and it must be ensured that the load does not damage the roof sealing or maybe the insulation.

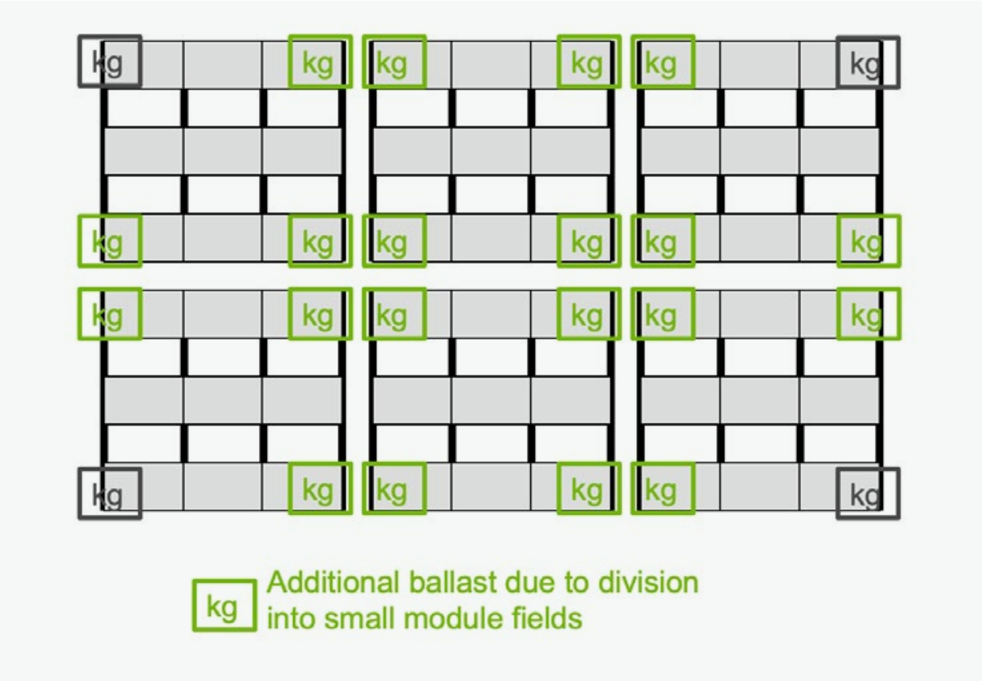

Fig. 2: Splitting of one large module field into three smaller module fields ←

Approach 3:

Fastening on fixed points on the building

Approach 3a: Fastening to additional fixing points

Fastening the supporting structure to additional load attaching points is an additional way to secure the PV system against temperature creep.

Attention!
Existing load attachment points (securants) may not be used.

Additional anchoring points must be included, which need to be installed by the roofer.

Attention!
Most commercially available load anchorage points for fall protection are also not suited for positional securing, as they are supposed to deform elastically and plastically under horizontal load in their intended use as fall protection.

Attention!
For the dimensioning of the fixing points a structural engineer must be consulted.

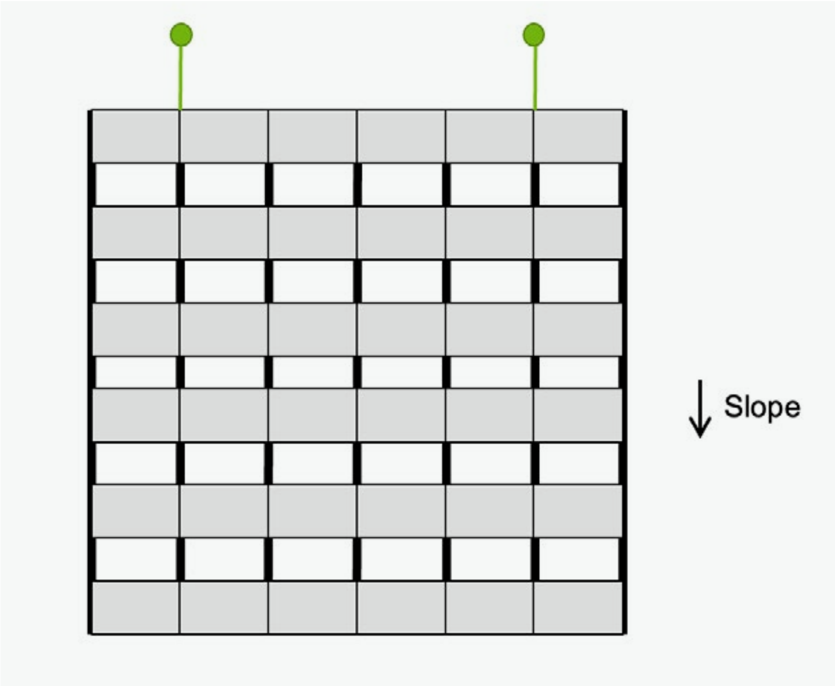

Fig. 3: Fastening to additional fixing points ↑

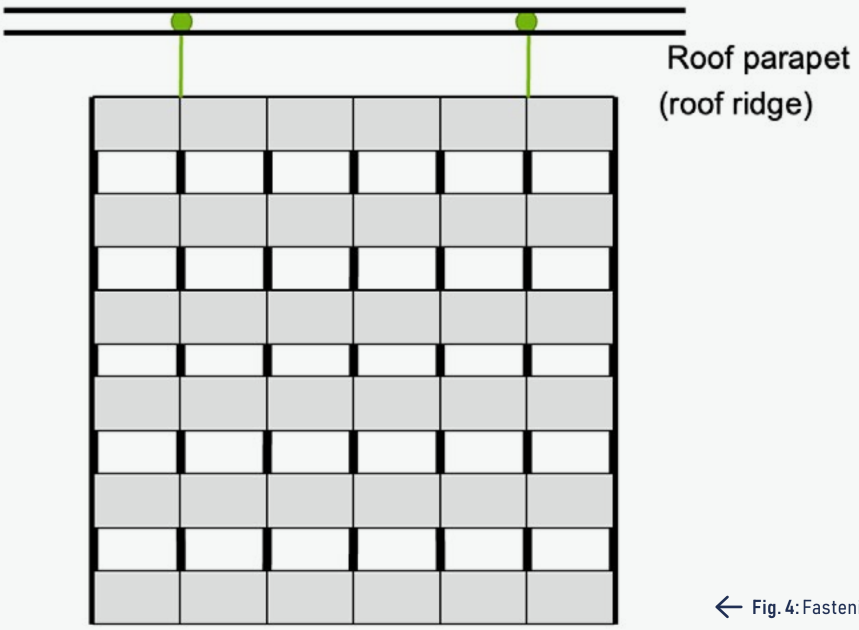

Fig. 4: Fastening to the roof parapet

Approach 3b: Fastening to the roof parapet

A further option for a mechanical system protection is the fastening to the substructure of the roof parapet (not to the sheet metal cover). In this context, it should be noted that there are many different types of roof parapets, e.g. made of reinforced concrete, wooden planks or steel profiles.

Attention!
If this option is intended, the load transmission as well as the horizontal load bearing capacity of the roof parapet is to be verified by a structural engineer.

Ideally, suitable anchorage points for a positional securing of the PV system are already provided for in the planning of new buildings, including any necessary sealing of these anchorage points.

Note
Intra-system structural effects on the PV mounting system must be taken into account.

Approach 3c: Bracing against the roof parapet

It is also possible to brace the supporting structure over a large area against the roof parapet. This requires that loads can be safely transmitted to the supporting structure of the building.

The advantage of this solution is that no penetration of the elevated roof sealing or the sheet metal at the roof parapet is necessary. However, a protective layer must be provided on the contact surface to prevent damage (NO sharp edges!). Also, any drainage on the edges of the roof may not be disrupted.

The advantage of this option is that a continuous load transmission into the roof parapet causes lower load concentrations than solution 3b. Also in this case, a structural engineer should be consulted.

Manufacturer-specific solutions
It should be noted that manufacturer-specific solutions exist that completely avoid or compensate for the creeping effect.

Determination of the occurring horizontal loads

The calculations described in the following are only to be applied for fixed systems.
- Solutions 3 -.

A) Downhill-slope force

In the event that the fastening of the PV system is very elastic and no constraining forces build up, the retention forces are determined as if no friction existed between the roof sealing and the rails.

The retention forces thus equate to the downhill-slope force and are determined for the dead weight of the PV installation as follows.

Total weight G_{ges} (kN):
G_{ges} (kN) = Module weight m_{Module} + Weight Mounting system $m_{Mounting\ system}$ + Ballast $m_{Ballast}$

The area of the PV system that acts on the fixed point (effective load influence zone) must be taken into account here.

$H_{a.k}$ (kN) = G_k (kN) × sin α

with
$H_{a.k}$ = downhill-slope force (index k stands for the so-called characteristic value)
α = Roof tilt angle in degrees

For the verification of the attachment with rated values (index d), a safety factor Q of serviceability (SLS) should be added to the downhill-slope force:

$H_{a.d} = g_Q \times H_{a.k}$ (kN)

with
γ_Q = partial safety factor for unfavourable variable loads = 1,0 (DIN EN 1990, annex A)
For the verification of the fixed point, a material safety factor γ_M should be included.

Exemplary calculation for A):
Module array with 9 module rows of 10 modules each, with roof tilt angle: 3°
The installation of diagonal bracings is necessary if the stiffness of the entire PV system is not sufficient to transmit the downhill-slope force from the separate modules to the fixed points.

Calculation of the total weight force:

ballast weight:

$m_{Ballast}$ = 183 stones × 10 kg = 1,830 kg

module dead weight with example module weighing 18.2 kg

m_{Module} = 90 modules × 18.2 kg/module = 1,638 kg

mounting system weight: dead weight 5 kg/module

$m_{mountingsystem}$ = 90 modules × 5 kg/module = 450 kg

Total weight of the module field

m_{ges} = 1,830 kg + 1,638 kg + 450 kg = 3,918 kg

Conversion to weight force:

G_{ges} = 3,918 kg × 9.81 m/s^2 = 38,400 N

G_{ges} = 38.4 kN

Calculation of the downhill-slope force

Characteristic downhill-slope force for roof pitch 3°:

$H_{a,k,ges}$ = 38.4 kN × sin (3°) = 2.01 kN

The load is distributed evenly between the 2 **fixed points**:

$H_{a,k,Fixedpoint}$ = 2.01 kN/2 = 1.01 kN

The partial safety factors determine the rated value of the horizontal force acting on one of the **fixed points**:

$H_{a,d,Fixedpoint}$ = 1.0 × 1.01 kN = 1.01 kN

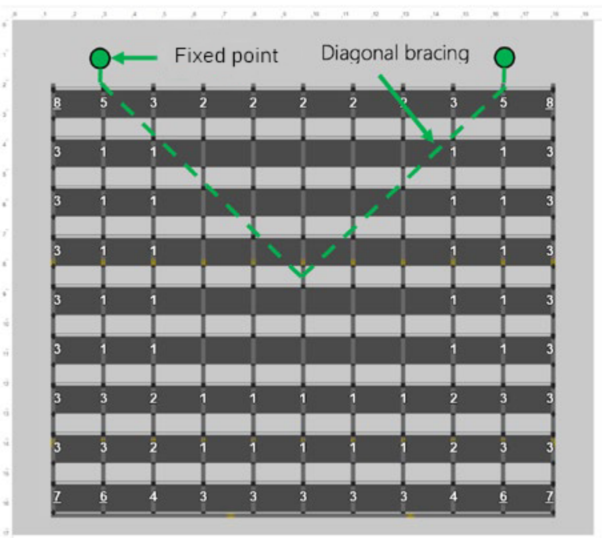

Fig. 5: Ballasting plan with specification of the ballasting in number of stones (à 10kg)

←

B) Force of constraint (static friction)

In the event that the fixation for positional securing does not yield when the PV system is contracted due to temperature, static frictional force can build up in the most unfavourable case:

Force of constraint:

$H_{Z,k}(kN) = \mu \times G_k (kN) \times \cos \alpha$
μ = static friction coefficient [-]

The static friction coefficient can be determined in in-situ tests together with the kinetic friction coefficient (cf. BSW reference paper [9]). The maximum occurring force becomes decisive before the system starts to slide.

Exemplary calculation for B)
For the above exemplary calculation, the constraining force H_Z is determined assuming a static friction coefficient on site of $\mu = 0.8$:

$H_{Z,k,ges} = 0.8 \times 38.4\ kN \times \cos(3°) = 24.5\ kN$
$H_{Z,k,Fixedpoint} = 24.5\ kN/2 = 12.3\ kN$
$H_{Z,d,Fixedpoint} = 1.0 \times 12.3\ KN = 12.3\ kN$

The load from the constraint force is rather high and not so easy to be transmitted into the building. It is therefore advisable to take additional measures (installation of elastic spring elements or similar) to prevent the buildup of a constraining force.

Standards, guidelines and reference documents

- [1] DIN EN 1990 Eurocode: Grundlagen der Tragwerksplanung
- [2] DIN EN 1991-1 Einwirkungen auf Tragwerke – Teil 1-1: Allgemeine Einwirkungen auf Tragwerke
- [3] DIN EN 1992 Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken
- [4] DIN EN 1993 Bemessung und Konstruktion von Stahlbauten
- [5] DIN EN 1995 Bemessung und Konstruktion von Holzbauten
- [6] DIN EN 1999 Bemessung und Konstruktion von Aluminiumtragwerken
- [7] DIN 18531 (2017) Abdichtung von Dächern sowie von Balkonen, Loggien und Laubengängen – Teil 1: Nicht genutzte und genutzte Dächer – Anforderungen, Planungs- und Ausführungsgrundsätze.
- [8] Deutsches Dachdeckerhandwerk – Regeln für Abdichtungen (Flachdachrichtlinie des ZDVH)
- [9] Hinweispapier BSW-Solar: Empfehlung für anzusetzenden Haftreibungskoeffizienten bei ballastierten Solaranlagen

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