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MOUNTING OF PHOTOVOLTAIC PANELS SUPPORTING STRUCTURE ON TRANSVERSE FRAMES OF A STEEL HALL

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ABSTRACT: An innovative method of assembling photovoltaic panels supporting structure on flat roofs of large-area hall buildings, an alternative to the conventional non-invasive approach stabilised only by balast, is presented here against the background of theoretical considerations concerning this issue. In the proposed solution, columns supporting the combined truss–beam grillage of the structure remain structurally integrated with the bearing transverse frames of hall structure, which constitute their support. Thus, this erection process is of an invasive character, with bearing elements piercing through the existing roof covering. However, it assures a clear load transfer path and appropriate compensation of thermally induced strains at sufficient rigidity and geometric stability, required by the panel service regimen. The solution presented here originated in the legal requirement to ensure sufficiently wide fire passages on the roof of an unequivocally defined number and at specified maximum spacing. Under such conditions, these are to be treated as an unavoidable compromise and not an optimum setting.

KEYWORDS: photovoltaic panels, truss–beam grillage, steel hall, invasive mounting system, stress compensation

Introduction

Construction of high-power stand-alone photovoltaic farms usually results in a need for a large area of land. Therefore, if at all possible, it is preferred to mount such panels on the roofs of existing structures in the highly developed areas (Strzalka et al., 2012; Nordberg et al., 2021). Roofs with a high slope appropriately oriented towards the sun may be used for that purpose. However, flat roofs of large area shopping malls are often used for that as well (Bayod-Rújula et al., 2011). When applying such solutions, the selection of the photovoltaic panels' supporting structure is often determined by the existing structural system. This system, designed a priori, without taking into account the additional loads generated by the photovoltaic farm added after years of service, may prove to be unsuitable for such purpose, and may require additional strengthening or stiffening. Thus, a computational verification, taking into account the new circumstances, may be required.

When the supporting structure of a photovoltaic energy system is located on a flat roof, one has to take into account not only the need to assure sufficient rigidity and fastening but also the need to orient the constituting panels at a proper angle towards the falling sunlight. Therefore, two alternative mounting systems are applied the most often (Piliński, 2016; Selecki & Olesz, 2021), that is:

- a non-invasive system – independent of the existing building bearing structure, stabilized only by freely distributed ballast pads (Figure 1), continuity of the existing roof covering is preserved here,
- an invasive system – structurally anchored to the existing building bearing structure, with structural elements piercing the existing roof covering.

Figure 1. Panels of the photovoltaic system mounted on the large area flat roof with a non-invasive ballast system, without structural connection to the existing building bearing structure

Source: Cracow University of Technology.

The main disadvantage of a non-invasive system is the difficulty of application on roofs with covering made of soft materials such as mineral wool, styrofoam or an external membrane layer (Bajno & Grzybowska, 2023).

Both dimensions and distribution of separate photovoltaic system segments over a roof are restricted by the requirements of fire protection (Jaskółowski & Wiatr, 2016; Barasiński et al., 2018;

Ju et al., 2019; Urbańczyk et al., 2020; Aram et al., 2021; Cancelliere et al., 2021; Sulik & Papis, 2021; Papis, 2024). These are listed in many recommendations, in particular in (Prume & Viehweg, 2018; VDE-AR-E 2100-712, 2018; Fire Protection Association, 2023). The structure has to be subdivided into units having the dimensions *L x L* not larger than 40 m by 40 m each, at the same time preserving the unobstructed passages between these units at least *a* = 5 m wide, and a minimum of 1 m distance between the units and roof edge (Żukowski & Radzajewska, 2016) (Figure 2).

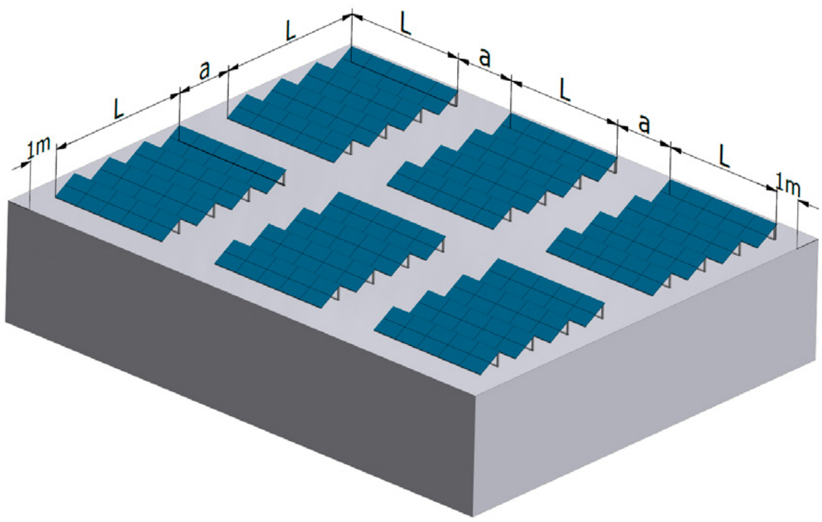

Figure 2. Dimensions of photovoltaic system units acceptable from the fire protection standpoint

The efficiency of the photovoltaic installation depends on its orientation towards the geographical directions

Poland is characterised by beneficial, though regionally variable, sunlight conditions, which have to be taken into account when new photovoltaic installations are designed and erected (Żukowski & Radzajewska, 2015). In general, it is assumed that the south of Poland is sunnier than the north (Figure 3).

The efficiency of photovoltaic installation depends on the angle between the panels and the roof surface and orientation towards the geographical directions (Rowlands et al., 2011; Pepłowska & Olczak, 2018). Photovoltaic panels reach their highest efficiency when the sunrays strike their surface at the right angle.

Thus the power that is potentially available at a given flat roof may not be determined as a simple product of the roof area and forecast irradiation level, but depends mostly on the so called conversion coefficient, which takes into account not only the location of particular installation but also the slope of constituting panels and the distances between the rows of such panels (Martinez-Rubio et al., 2015). Usually, this factor varies between 0.26 and 1.0, while the maximum value is reached at zero slope and zero distance between the rows of these panels, this usually being impossible in practice due to the service requirements and fire protection.

North – South (N-S) orientation of panels is particularly advantageous for all of the panels, also an East – West (E-W) orientation may be applied, at half of the panels oriented towards East while the remaining panels oriented towards West (Fig. 4).

The S-N orientation of the panels is often described as the so called "golden standard" (Szymański, 2017). The so oriented installation will develop the highest power mid-day, but at significantly lower power in the wee hours of morning and evening. This orientation allows to utilize the potential of the photovoltaic farm in full, but at the expense of uneven power generation level during the whole daylight time. This may result in the need to use energy delivered by external power grid during the hours of lower insolation, while releasing to the grid the excess energy generated during the period of highest insolation (Rad et al., 2023).

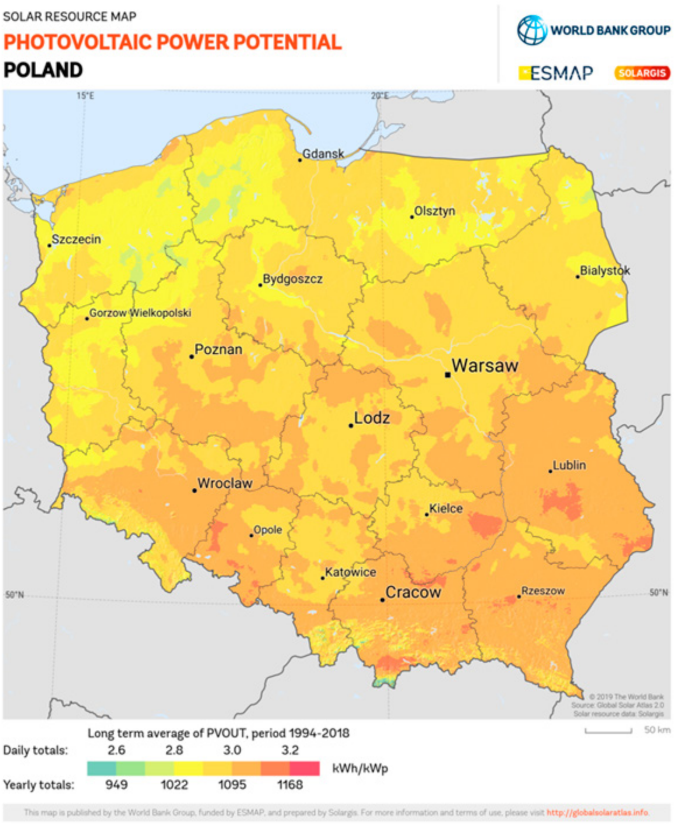

Figure 3.
Photovoltaic power generation potential in Poland
Source: Global Solar Atlas 2.0. (2025).

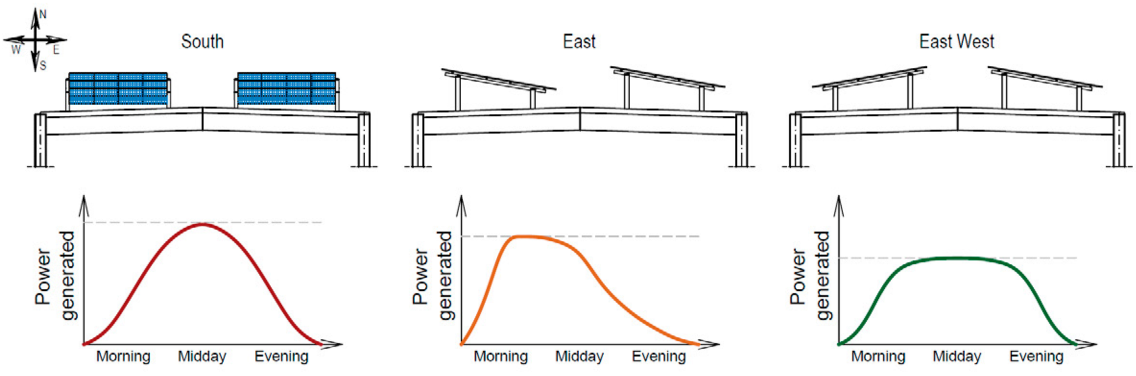

Figure 4. Effectiveness of photovoltaic installation structurally joined to the bearing structure of a hall building at different orientations of constituting panels

Photovoltaic panels oriented in the E-W direction usually generate about 65-80% of the energy, which could be potentially available at the orientation in S-N direction (Khatib & Deria, 2022; Carrera et al., 2023). In such a configuration, usually a part of the units is mounted on the eastern and the other part on the western slope of the roof. Under such circumstances, the eastward panels begin energy generation early in the morning, but their efficiency falls before noon. At this time the westward panels begin to generate energy and this activity persists until evening. In order to optimize the efficiency of the photovoltaic farm in such configuration, it should be subdivided into two independent subsystems (Hartner et al., 2015). This offers an advantage of a flatter power generation curve during the day. Thus one avoids overloading the power grid, and this may result in longer trouble free operation of the system (Figure 4).

Under Polish conditions, photovoltaic farms are customarily oriented towards south. This allows for the most effective use of insolation and assures the highest energy output in both daily and yearly cycles (Olczak et al., 2017).

The risk of mutual panel overshadowing should be taken into account when designing the supporting structure of a photovoltaic installation (Appelbaum & Bany, 1979; Boehm et al., 2008). When

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the installation is mounted on the roof of a hall located in a suburban area, usually the risk of overshadowing by neighboring high trees or high rise buildings may be disregarded. But care should be taken to avoid the mutual overshadowing by adjacent photovoltaic panels. For photovoltaic installations mounted on flat roofs the distance assuring unrestricted visibility of the sun may be determined by the following formula:

$$D = \frac{S \sin\left[180^o - (\alpha + \beta)\right]}{\sin \alpha} \tag{1}$$

where:
S – width of one installation segment measured on the panels surface,
α – an insolation angle during winter solstice, measured with respect to the panel level,
β – the angle between horizontal and surfaces of the panels,
D – minimum legal distance between the lowest edges of adjacent sectors (Figure 5).

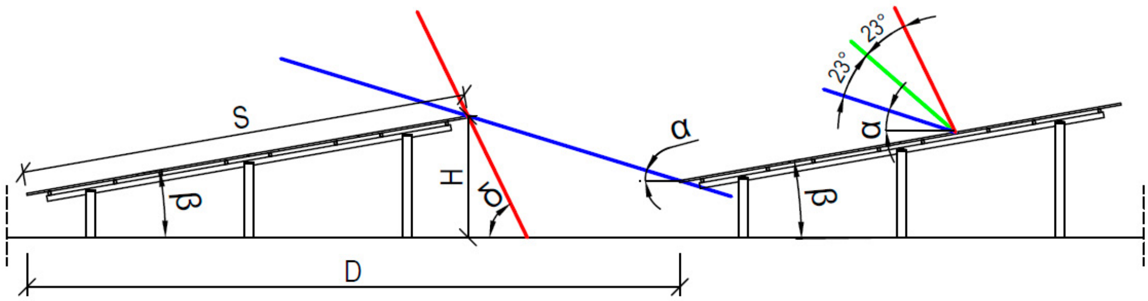

Figure 5. Minimum distances between individual sectors of a photovoltaic installation acceptable due to the potential mutual overshadowing effect (δ – an insolation angle during summer solstice)

Characteristics of the proposed supporting structure, its components and bearing systems

When selecting a mounting system for a photovoltaic system located on a flat roof, besides assuring necessary stability and secure attachment, one should take into account the capability of setting the constituting panels at an appropriate angle with respect to the incident sun rays.

An innovative mounting system for the supporting structure of photovoltaic panels, integrated with the transverse bearing frames of a steel hall structure, constituting its support, is presented here (Figure 6). The Authors recommend application of such a system in the engineering practice wherever an opportunity arises to do so. This system assures a clear load transfer path, including compensation of thermally generated strains at the same time providing sufficient rigidity and geometric invariance, required by the panel service conditions (Kołat et al., 2024; Kołat et al., 2025).

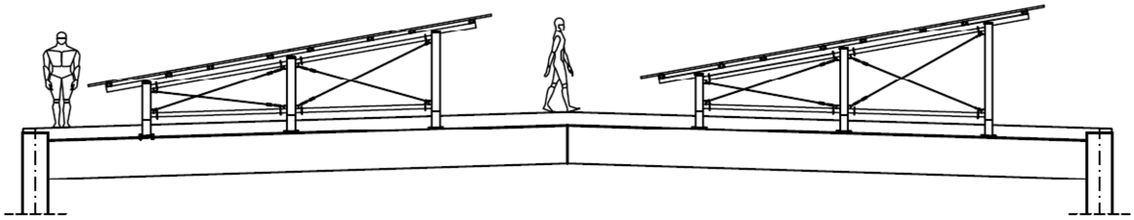

Figure 6. Segments of a photovoltaic system mounted directly on the transverse frames of a steel hall

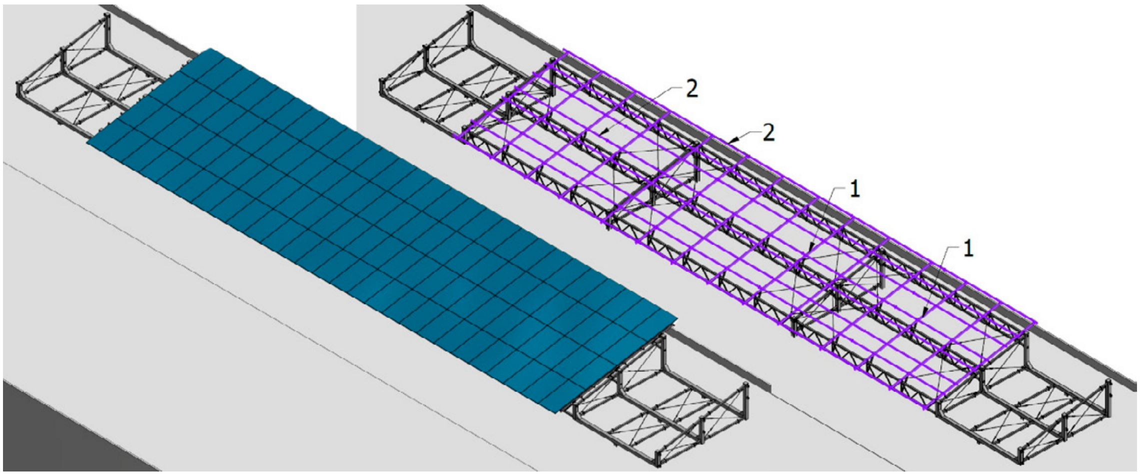

Figure 7. Single component of the photovoltaic system described here, flanked on both sides by technical and service gangways. On the left – general view with mounted panels. On the right – view of the bearing structure with panels removed. Plane trusses distributing the loads to the P type columns in the longitudinal direction are visible here. Denotations applied: 1 – main, transverse bearing beams, 2 – longitudinal secondary beams

Technical design of the presented bearing structure has been numerically verified in detail against the safety of the prospective service under authoritative combinations of actions affecting it and rational, prescribed by the relevant standards, representative values of these actions as well as for their most adverse locations, within the scope of a diploma thesis prepared by the first author of this paper (Kołat, 2025). Complete presentation of the numerical procedures applied in practice and detailed discussion of the obtained results has been intentionally excluded from this elaboration due to its volume and complexity, as it does not constitute the main purpose of this work in the Authors' intent. Description of the recommended technical solutions and construction details, in particular those considered innovative with respect to the traditionally applied typical solutions constituted our objective during preparation of this paper.

The following technical solutions have been selected for detailed presentation:

- the supporting structure of the photovoltaic system is made as a sufficiently braced truss-beam spatial grillage (Figure 7), with two types of columns applied to support these trusses, that is straight columns (denoted subsequently as P), and U-shaped composite columns (denoted subsequently as U),
- all the bearing columns pass through the roof covering and are joined with the bearing transverse frame girders of the hall structure via articulated joints,
- plane trusses spanned between columns of the photovoltaic system take all the climate and service loads coming from individual panels and transfer these onto the supports,
- a light grillage, made of small size hot-rolled steel sections or cold-formed thin-walled steel sections, is spanned over these trusses and used to mount the components of technical equipment such as cable routes, supports, lightning protection system, etc.,
- following the requirements of fire protection, the technical-service gangways used to service the island have been routed over horizontal cantilevers of the U-shaped columns.

Orientation of the structure in question is therefore forced by the orientation of the load-bearing structure of the existing hall. A change in the orientation of individual photovoltaic installation panels is possible in such case in a very limited scope, restricted not only by the structure of the building itself, but most of all by the details of the roof support. An alternative application of the non-invasive ballasted photovoltaic system mounting method allows for significantly higher flexibility in the orientation of the island, however, it does not eliminate any of the disadvantages discussed at the beginning of this paper.

The straight column (P-type) is designed as a cold-formed, closed steel section of the RHS type (a square or rectangular hollow section), terminated with properly-shaped collar footing, fitted with bolt holes to bolt it directly to the main girder of the steel hall structure. The column should be capped at the top to prevent rainwater ingress. Cantilevers made of steel plate and welded to the sides of the

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column are used to mount the longitudinal grillage trusses. These trusses are joined to the column by bolts, as lapped joints. Whole column is technologically prepared for hot dip galvanization, executed a priori, before mounting.

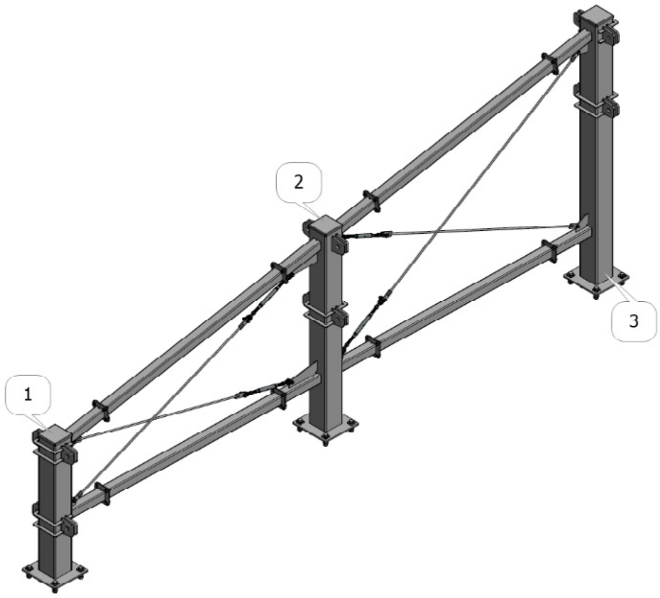

Figure 8.
P-type columns, capped at the top and joined at two levels by main transverse bearing beams: 1 – front column, 2 – middle column, 3 – back column. Bracing of the transverse system is visible

Source: Kołat et al. (2025).

Straight columns differ in height (the front one is the shortest, while the back one is the highest), thus ensuring proper tilt of the photovoltaic panel system (Figure 8). These columns are joined at two levels in the direction perpendicular to the longitudinal axis of a single photovoltaic segment by main beams. The top beam is routed at an angle to the horizontal to directly support the panels resting on it (Figure 8).

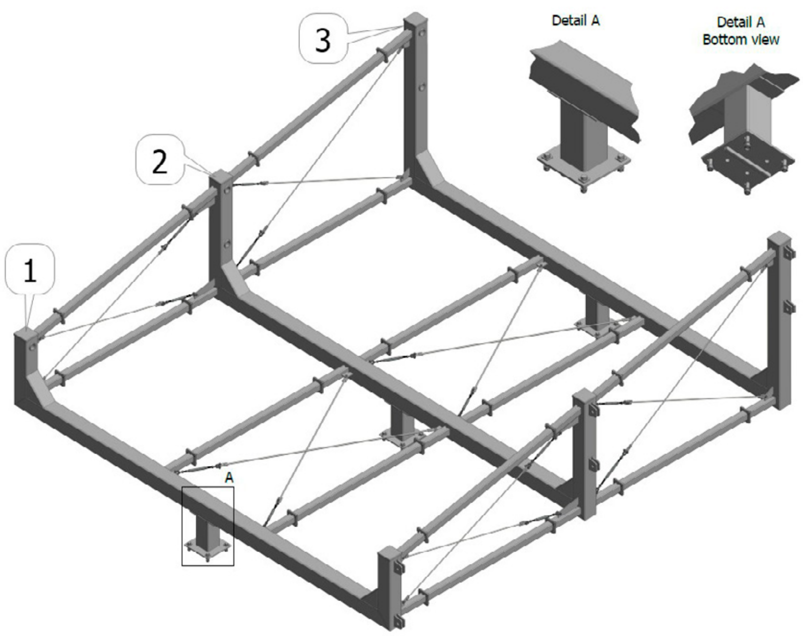

Figure 9. U-type column constituting a support for the technical and service gangway: 1 – front column, 2 – middle column, 3 – back column. The recommended bracing system is shown as well

The U-shaped columns (Figure 9) are made of a cold-formed, closed steel section identical to the one used to make the P-shaped columns. The collar footing used to join the column to the main girder of the hall has been shaped here in a way similar to the P-type column. This footing is located at the axis of the whole system, and thus it resists the loads applied by the pair of columns located at the ends of the horizontal beam forming the whole cantilever system (Fig. 9). Individual columns are fitted with supports made of steel plate and used to mount the main (distance) beams and bracing bars. Proper care should be taken to ensure sufficient rigidity of the joint between the vertical supporting part of the column and the horizontal beam. Potential significant flexibility of this joint could result in excessive displacements exhibited under load by transverse vertical systems at the sides of the column, and this in turn would generate a risk of failure in top and bottom chord mounts of neighboring trusses forming longitudinal grillage of the island.

The trusses of the bearing grillage (Figure 10) are flat systems, set vertically in the direction parallel to the longitudinal axis of a single island segment. The chords of these trusses are made of cold-formed closed square or rectangular steel hollow sections (RHS). Analogous sections of smaller size have been applied as columns and crossbars. The truss is mounted to both the P-type and U-type columns by bolted pin joints. Additional supports used to join the truss with main beams of the grillage supporting the photovoltaic panels are formed at the top of the top chord.

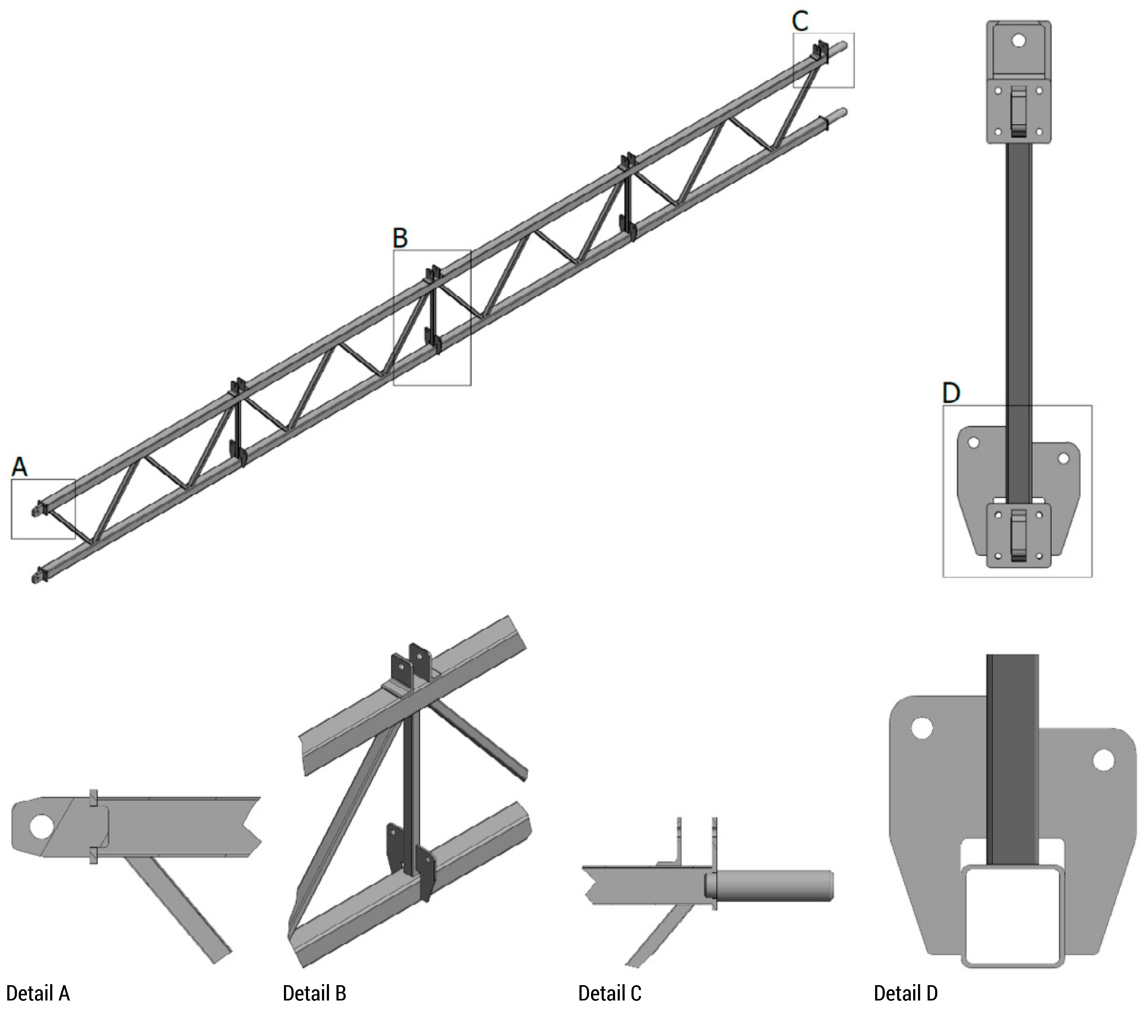

Figure 10. Structural scheme of a longitudinal plane truss in bearing grillage. The location of details A, B, C and D shown magnified at the bottom is indicated

Source: Kołat et al. (2025).

The main, transverse beams of the grillage directly supporting photovoltaic panels (Figure 11), denoted as 1 on Figure 7, are made of cold-formed closed steel section of the RHS type with strengthening pieces of steel plate welded at the mounting points to the truss depicted on Fig. 10. Brackets made of hot-rolled steel angle have been welded to the top surfaces of these beams at the mounting points of the secondary beams (denoted as 2 on Figure 7). Special grips have been formed at the bottom surfaces of these beams to mount the struts joining beam grillage with the bottom chord of the bearing trusses.

The secondary longitudinal beams of the grillage supporting photovoltaic panels (Figure 12), on Figure 7 denoted as 2, are made of cold formed RHS section as well. These are capped at both ends by collar plates with bolt holes for bolted end-plate joint. Oblong holes to mount these beams to the main beams are made in their side walls. Straight through holes are made in the top walls of these beams to mount the fasteners for photovoltaic panels.

The transverse systems of the single photovoltaic installation segment supporting structure, depicted on Fig. 8, are fitted in their planes with struts protecting their components against potential lateral-torsional buckling (Figure 13).

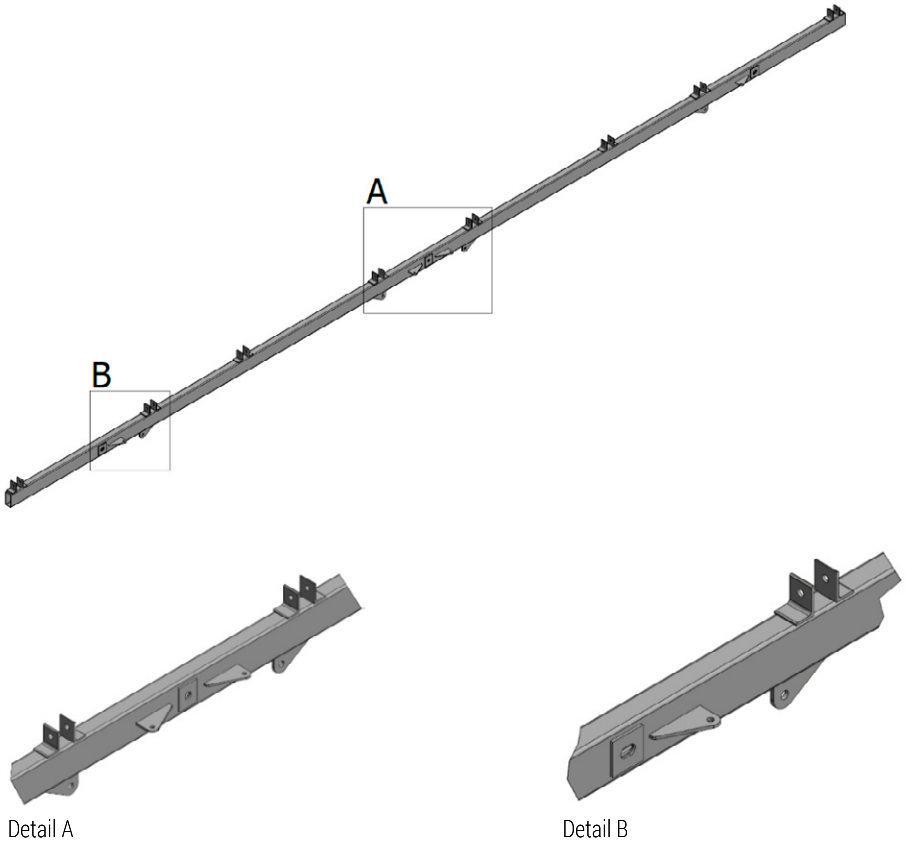

Figure 11. Main bearing beam (transverse) of the beam grillage constituting a direct support of the photovoltaic panels. Denoted as 1 on Fig. 7

Source: Kołat et al. (2025).

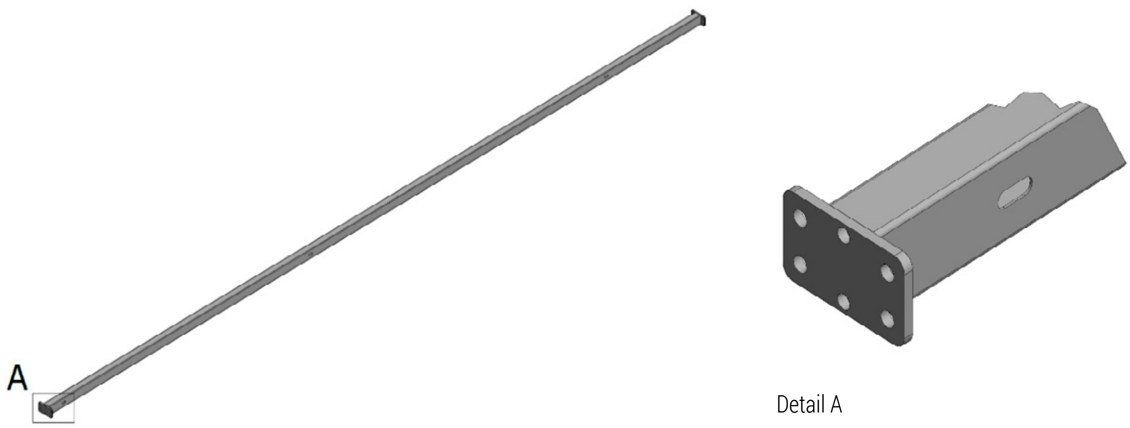

Figure 12. Secondary bearing beam (longitudinal) of the beam grillage, constituting a direct support for photovoltaic panels. Denoted as 2 on Fig. 7

Source: Kołat et al. (2025).

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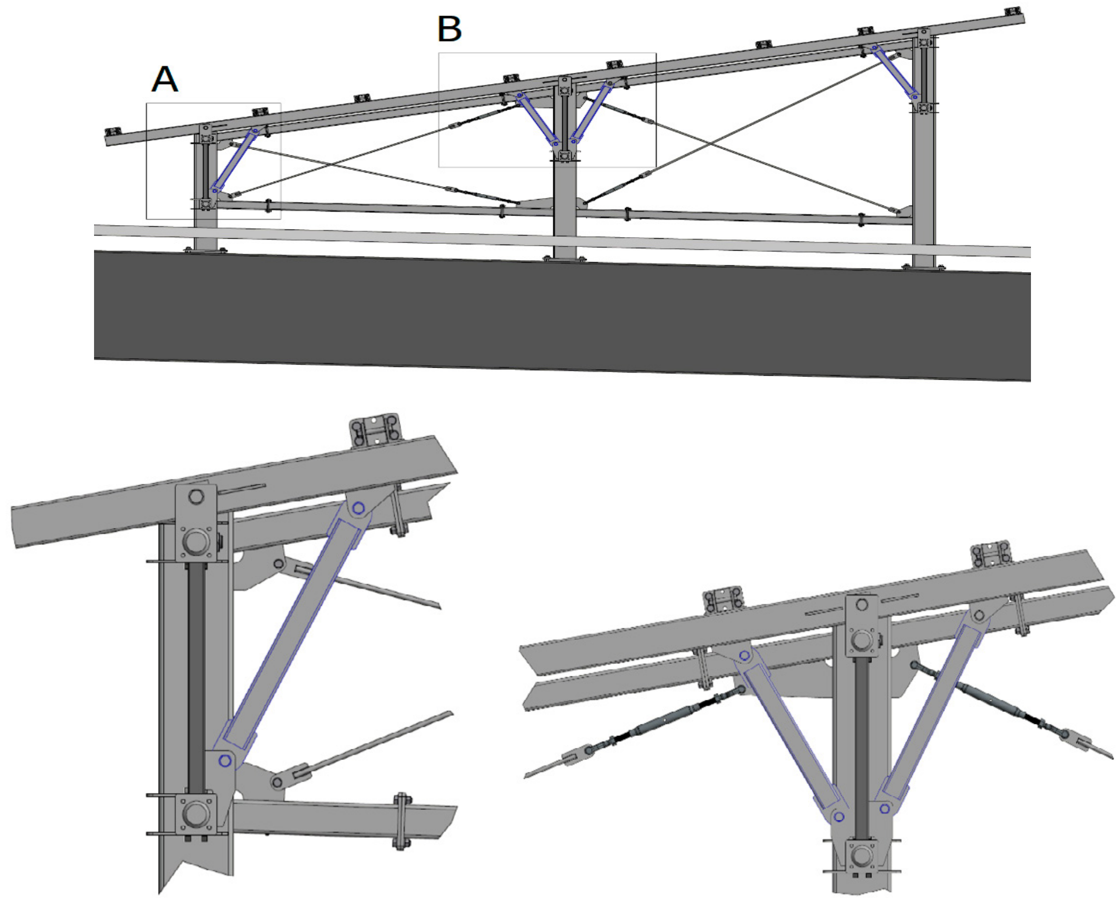

Detail A

Detail B

Figure 13. Location and formation of struts protecting the components of the transverse supporting system (main beams, P-type columns) against potential lateral-torsional buckling

Source: Kołat et al. (2025).

Articulated support of the columns of a single photovoltaic installation segment supporting structure on the transverse steel hall bearing frame girders

In the structural solution recommended by the Authors all the columns of the single photovoltaic installation segment supporting structure are joined to the transverse steel hall bearing girders corresponding in location by articulated joints. In order to minimize the influence of eccentric (not axial) local bending in the webs of these girders, usually made of I-beams with relatively slender webs, centering plates have been applied to form the joints of this type (Figure 14).

The designed joint should be flexible, this in turn results in the recommendation for application of a sufficiently thin end-plate in the T-stub formed at the end of the column. This would enforce the joint destruction model with plastic deformation of the said plate, however it may also be associated with possible bending of bolts generated by the lever effect.

Structural bond between the structural supporting segments of the photovoltaic system and the bearing structure of the steel hall is obtained in the mounting scheme described above through local penetration of the existing roof cover (Figures 13, 14). Therefore special care should be taken to assure water-tightness of such areas. An example of the hazardous zone treatment, which may be applied to the area in question is shown on Figure 15.

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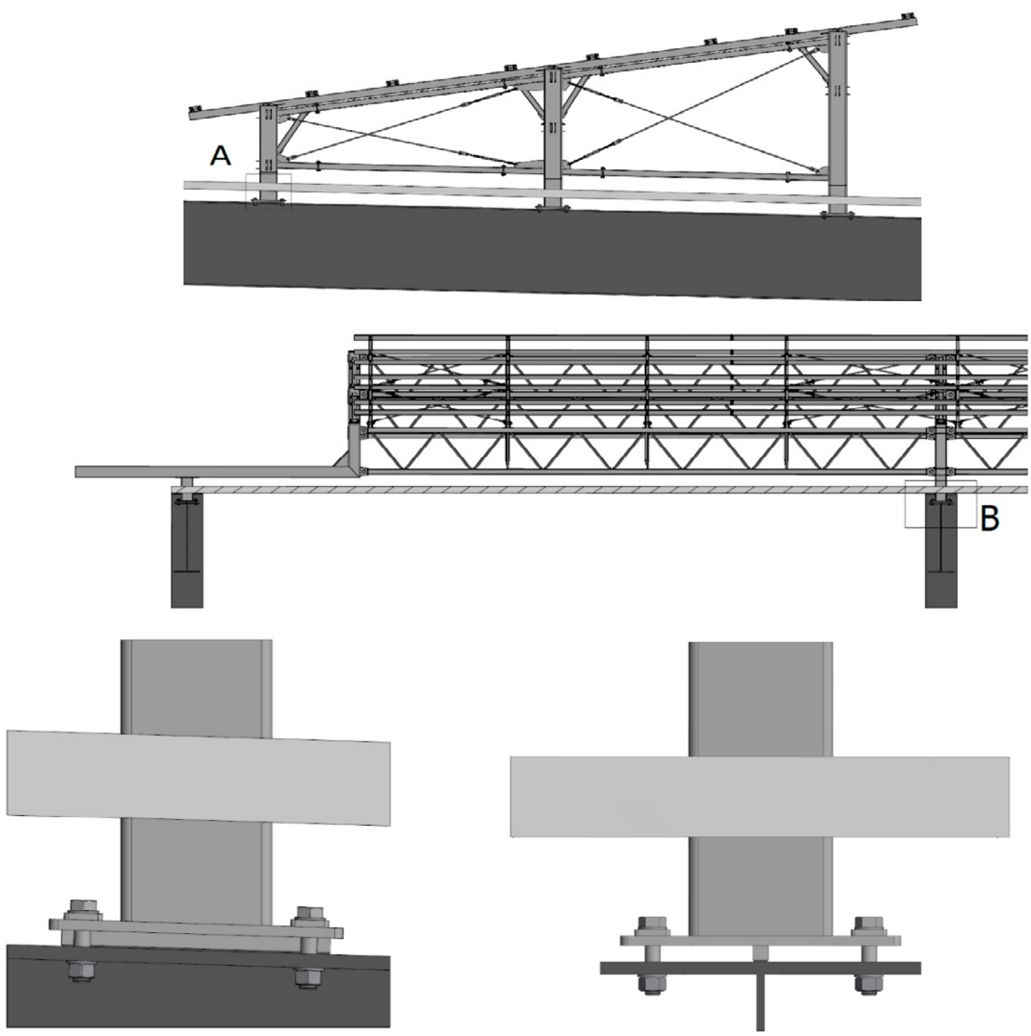

Figure 14. Details of the articulated joint between the column of the single photovoltaic installation segment supporting structure with the corresponding girder of the transverse steel hall bearing frame

Source: Kołat et al. (2025).

Compensation of thermally induced strains

Due to the very limited deformability of the material used to make photovoltaic panels, geometrical stability of basic elements and structural systems used to form the supporting structure for these panels should be ensured. This is particularly important when dealing with components directly in contact with the panels. Thus, a sufficiently reliable bracing of these systems should be ensured in many planes, with capacity for regulation and fine-tuning the tensioning forces (Figures 13, 14). Potential shape deformations, generated by the changes in local climate (of the summer – winter or day – night type) and thus difficult to avoid under these circumstances may result in the brittle destruction of the panels, and as such not preceded by any signs of the imminent danger.

Figure 15. Roof covering treatment ensuring water-tightness of such covering in the area penetrated by the supporting column of a single photovoltaic system segment

The segments of the photovoltaic system supporting structure, structurally joined to the transverse frames of the existing steel hall bearing structure, take over and to an extent amplify the stresses induced at the level of hall eaves by partial restriction of strains resulting from thermal expansion of steel. When the hall is relatively long, the longitudinal forces induced by these stresses, accompanied by internal forces of other origins, may reach a destructive magnitude. Thus, the structural solutions applied in the construction of photovoltaic system segments located directly above the expansion joints in the main structure of the hall are particularly important. These must allow for sufficient compensation of such stresses. Details of the solution recommended by the Authors in such case are depicted in detail on Fig. 16. This compensator is located at the joint between the U-type column and the flat truss grillage of a single photovoltaic panel, under the assumption, that the U-type column is located directly above the expansion joint in the hall. Of course, a mirror example of this compensating device is installed at the other side of the column. Thus the thermally induced displacements may be easily compensated for by relative movement of the two circular bars mounted at the end of the truss along the axes of its chords with respect to the appropriately sized openings located along the same axes and formed by pieces of a properly sized circular pipe welded into the vertical branch of the U-type column.

Concluding remarks

Integration of the individual photovoltaic system segments supporting structures with transverse frames of an a priori existing steel hall bearing structure undoubtedly ensures the desired stability of the whole system, at the same time yielding a clear external load transfer path, of course provided that this bearing structure has been correctly computationally verified against such additional loads. This may result in the need to strengthen or additionally stiffen the structure existing a priori. It seems that, wherever technically possible, such a mounting system of large area photovoltaic panels could constitute a viable alternative to the traditional supporting systems, in particular the ballasted ones. In spite of the fact that it is of an invasive character as it interferes with an existing roof covering, if the work is conducted with due diligence, it should not present any technological or execution difficulties during assembly. Practical application of this method allows for compliance with all kinds of restrictions resulting from building law, especially those concerning fire protection.

Application of the photovoltaic system supporting structure fastening method on the bearing frames of a steel hall, as recommended by the Authors, will prove to be sufficiently reliable only if adequate attention is paid to the construction detail. The grillage supporting photovoltaic panels will have, in this solution, to absorb all the imperfections existing in the structural frame system, in particular, these having the nature of possible geometric deviations from perfect alignment. As this system is located directly above the transverse frames of a hall and in addition structurally connected to these, the influence of imperfections of this type will be significantly magnified and reinforced. Thus, ensuring an effective compensation method for thermal stresses developing in the grillage structure is of key importance. Nonetheless, sufficiently efficient bracing of individual elements and subsystems present in the structure of each island segment is important in the opinion of the Authors to ensure their geometric invariance. This should minimize the risk of panel brittle fracture and thus ensure sufficiently safe conditions of service.

The structural system proposed by the Authors has weak spots at the locations where individual segments of the system are joined together over the expansion joints in the structure of a long steel hall. At those locations, especially at a nonsymmetrical load, a risk may occur of the longitudinal beams of the photovoltaic system grillage separating from the compensator sockets built into the vertical parts of the U-shaped columns located between these segments to allow these beams a freedom of horizontal movement to compensate for the thermal expansion of steel. Thus, assembly of this part of the photovoltaic island requires particular diligence, including but not limited to the assumption and subsequent unconditional enforcement of sufficiently rigorous design requirements. However, it has to be noted here, that numerical analyses of various types conducted by the first author of this paper on a 3D computational model, under the assumption of the most adverse design scenarios and appropriately realistic representative values of the loads, did not yield intolerable displacements and deformations.

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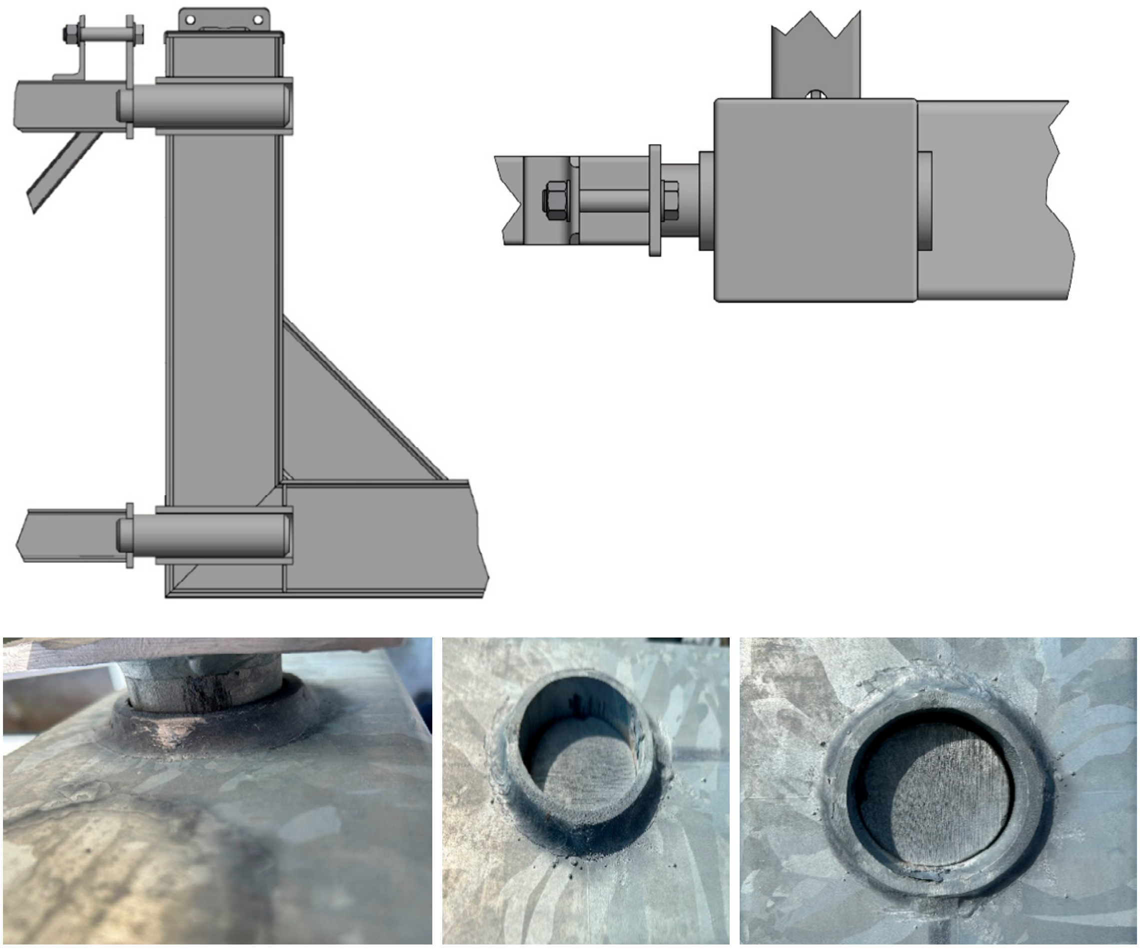

Figure 16. Compensation of thermal deformations at the joint between the U-type column and the truss grillage of a single photovoltaic system segment by relative movement of a circular bar and a circular pipe. At the bottom row – the details of this solution applied in practice: at the left – view from the inside of the compensating device, remaining views – from the outside

Source: Kołat et al. (2025).

Application of the U-shaped columns, of not very favorable static scheme, in the proposed solution was forced by the legal requirement of preserving sufficiently wide fire passages on the roof of the hall. The number and maximum allowed spacing of these passages are precisely prescribed by law. Thus these columns should be treated as an unavoidable compromise and not an optimum solution.

The Authors do not address the issue of the adequacy of standard climate load models especially those generated by the wind action or snowfall on the authoritative design of photovoltaic panels related to the critical design scenarios (Kawa & Studziński, 2024). Detailed discussion of these problems would require a separate, and undoubtedly voluminous presentation.

The contribution of the authors

Conceptualization, K.K., M.M. and P.Z.; literature review, K.K. and P.Z.; methodology, K.K., M.M. and P.Z.; formal analysis, K.K., M.M., M.P. and P.Z.; writing, K.K., M.M. and M.P.; conclusions and discussion, K.K., M.M., M.P. and P.Z.

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MOCOWANIE KONSTRUKCJI WSPORCZEJ POD PANELE FOTOWOLTAICZNE NA RAMACH POPRZECZNYCH HALI STALOWEJ

STRESZCZENIE: Na tle rozważań teoretycznych dotyczących szeroko pojętej problematyki instalowania paneli fotowoltaicznych na płaskich dachach wielkopowierzchniowych budynków halowych zaprezentowano innowacyjny sposób montażu tego rodzaju konstrukcji, alternatywny względem konwencjonalnego podejścia nieinwazyjnego, stabilizowanego jedynie balastowo. W proponowanym rozwiązaniu słupy podpierające kratownicowo – belkowy ruszt konstrukcji pozostają strukturalnie zintegrowane z ramami poprzecznymi układu nośnego hali stalowej, stanowiącymi ich oparcie. Montaż ten ma zatem charakter inwazyjny, z elementami nośnymi przebijającymi na wskroś istniejące pokrycie dachu. Zapewnia jednak czytelność przenoszenia przyłożonych obciążeń, a także odpowiednią kompensację generowanych termicznie odkształceń, a przy tym daje odpowiednią sztywność i geometryczną niezmienność, co jest wymagane przez warunki użytkowania paneli. Zaprezentowane rozwiązanie zostało wymuszone wymogiem prawnym zachowania na dachach hal odpowiednio szerokich przejść pożarowych, o jednoznacznie definiowanej ich liczbie i maksymalnym rozstawie. W tej sytuacji trzeba je traktować raczej jako niezbędny kompromis, nie zaś jako ukształtowanie optymalne.

SŁOWA KLUCZOWE: panele fotowoltaiczne, ruszt kratowo-belkowy, hala stalowa, inwazyjny system mocowania, kompensacja naprężeń

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