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CLASS II MECHANISMS IN THE CONSTRUCTION OF RETRACTABLE ROOFS

MECHANIZMY KLASY II W BUDOWIE RUCHOMYCH PRZEKRYĆ DACHOWYCH

Abstract

This work presents retractable roofs of new designs based on class II mechanisms. Firstly, roofs that are currently in existence were analysed in terms of the mechanisms involved in their construction. Then, the possibility of constructing a roof based on the variety of quadruples in which all links are joined with roof panels was investigated. The boundary conditions that have to be fulfilled by such a construction were specified. Ultimately, research models were constructed with the use of construction solutions similar to those applied in buildings currently in existence.

Keywords: membrane roof, retractable roof, mechanisms class II

Streszczenie

W artykule przedstawiono propozycję nowych rozwiązań ruchomych dachów w oparciu o mechanizmy klasy II. W pierwszej kolejności przeanalizowano istniejące zadaszania pod kątem występujących w ich budowie mechanizmów. W kolejnym etapie sprawdzono możliwość skonstruowania zadaszania opartego na różnego rodzaju czworobokach, których wszystkie człony połączone są z panelami dachowymi. Określono warunki brzegowe, które musi spełniać tego typu konstrukcja. Ostatecznie zbudowano modele badawcze, stosując rozwiązania konstrukcyjne analogiczne do rozwiązań używanych w istniejących obiektach.

Słowa kluczowe: dachy membranowe, ruchome dachy, mechanizmy klasy II

1. Introduction

One of the biggest challenges that 21st century designers are faced with is mobile architecture, sometimes also described as the architecture in motion, kinetic or dynamic architecture. Moving walls and ceilings, roofs that can retract horizontally (in and out) and vertically (up and down), rotating facades and segments of a construction are examples of this type of architecture. The element of building construction that recently has undergone the most rapid development is the retractable roof. New possibilities in terms of materials and manufacturing technologies bring about the construction of retractable roofs that are increasingly larger in size and retract much faster. The changing shape of the retractable cover of a construction constitutes a key factor in its visual and esthetic perception. It is also expected to be in harmony with the surroundings and enhance the attractiveness of the entire building.

Retractable roofs with their construction based on class II mechanisms were singled out for the analysis. It included retractable roofs on constructions such as the Reliant Stadium in Houston (USA), Marlins Park Stadium in Florida (USA) and Wimbledon Centre Court (UK).

The analysis of building structures with retractable roofs inspired a quest for new solutions regarding the structure of mechanisms. With reference to already existing solutions, the class II mechanisms were subject to thorough examination. Preliminary analysis provided all possible solutions containing rotary and prismatic kinematic pairs for two assembly options. The research covered constructions with roof panels directly connected with the mechanism coupler or mounted on the coupler plane. This preliminary analysis resulted in determining the boundary conditions following a number of conditions restricting the area of research. The results obtained from the analysis constitute the main topic discussed in this paper.

2. Second class mechanisms in the construction of roofs for sports stadiums

At the first stage, the retractable roofs were analysed in terms of the movement that they performed. Two methods of movement were specified i.e. rotary and translation/forward movement (Fig. 1). In general, roof panels are directly attached to drives, of which movement is imposed by the shape of railings. If it is circular, the independent variable appearing in translation equations is an angle, whereas in the case of line-shaped railings, it is a line quality.

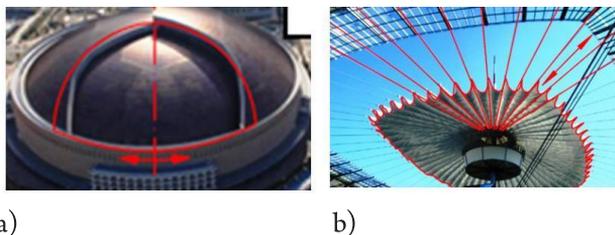


Fig. 1. Retractable roofs with a four-bar linkage: a) Reliant Stadium in Houston, USA (source: <http://www.uni-systems.com/en/projects/featured-projects/reliant-stadium>, access: 29.12.2015), b) Marlins Park in Florida, USA (source: www.uni-systems.com, access: 29.12.2015)

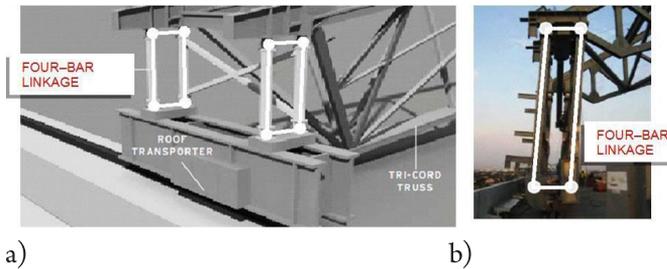


Fig. 2. Roofs with movement: a) rotary along railings – Fukuoka Dome stadium, Japan (source: https://upload.wikimedia.org/wikipedia/commons/8/84/Fukuoka_Seaside_Momochi_Aerial_Shoot.jpg, access: 29.12.2015), b) translating along lines – PGE National Stadium in Warsaw (source: https://en.wikipedia.org/wiki/National_Stadium,_Warsaw#/media/File:POL_Stadion_Narodowy_Warszawa_09.jpg, access: 29.12.2015)

The roofs of the Reliant Stadium in Houston (USA) and Marlins Park in Florida (USA) are constructed with the use of two four-bar-linkages that can accommodate the impact of sudden gusts of wind (Fig. 2). Hence, each panel is able to perform movement that is transversal to the direction in which the roof is progressing. The range of movement of the Reliant Stadium roof panels is 21.5 inches with respect to the base.

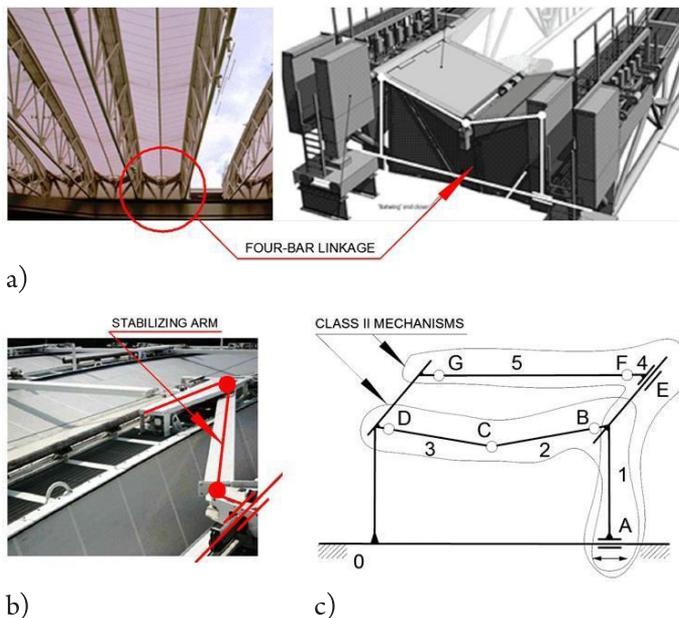


Fig. 3. The roof of Wimbledon Centre Court (UK) with 2nd class mechanisms: a) four-bar linkage connected to the roof panels (source: https://commons.wikimedia.org/wiki/File:Flickr_-_Carine06_-_The_roof_is_closing.jpg, access: 29.12.2015), b) the mechanism determining the maximum distance between the panels (source: http://www.moog.com/literature/ICD/Moog-Wimbledon_Roof_Electromechanical_Actuators-article-en.pdf, access: 29.12.2015), c) diagram of the mechanisms (by A. Pawlak-Jakubowska)

Two class II mechanisms were specified in the roof of the Wimbledon Centre Court (UK). The roof panels covered with technical materials are attached to one of the mechanisms (Fig. 3). The other mechanism maintains constant distances between trusses with membranes. One link of this mechanism is called a stabilizing arm with its length defining the maximum distance between girders (Fig. 3b).

Located between two drives, the two roof panels (links 2 and 3 in Fig. 3c) are interconnected to each other and to the lattices in a rotary manner (kinematic pairs B, C, D). The movement of the roof panels is triggered by the motion of the first drive (link 1 in Fig. 3c) while the other drive is blocked. This first drive is a driving device for both the roof panels and the mechanism determining the maximum opening of the roof segment (links 4 and 5). The stabilising arm 5 is connected with the lattice girder and link 4 (kinematic pairs F and G) in a rotary manner. Link 4 performs a translation along the lattice girder (kinematic pair E). Fig. 4 presents the translatory movement of the roof links located between two drives. The movement of the driving device 1 causes links 2 and 3 to move the roof to the position, which ensures the minimum gradient required for water drainage.

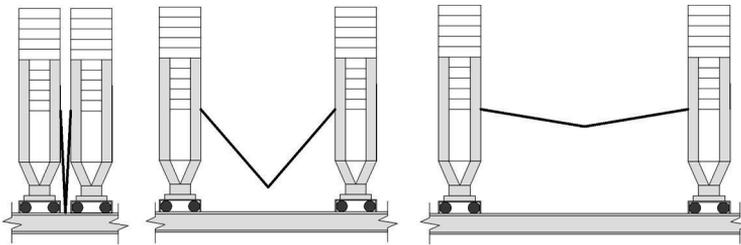


Fig. 4. Roof panels located between two driven trucks in Wimbledon Centre Court: a) open , b) movement, c) retracted roof (all by A. Pawlak-Jakubowska)

The analysis of construction solutions used in the retractable roofs such as Reliant Stadium in Houston (USA), Marlins Park in Florida (USA) and Wimbledon Centre Court (UK) inspired a search for new roof forms regarding the structure of mechanisms.

3. Construction of research roof models based on class II mechanisms

In order to specify the possible designs for retractable membrane roofs that are linked with class II mechanisms, a number of conditions have been considered, which have to be fulfilled by such mechanisms. Correct functioning of the mechanisms depends on the length of the moving links and the range of movement of the driving link. The ratio of the lengths of individual links decides on the category the mechanism belongs to. There are three categories, namely: double-crank, crank-rocker, drag-link and double-rocker mechanisms¹.

¹ This division is connected with Grashof condition [4, p. 40-49], [5, p. 46-53].

In order to specify the movement performed by the roof joined with the mechanism, all its theoretical solutions that contained translation and rotary kinematic pairs have been considered [6, p. 95-101]. The extreme (turning) as well as idle positions were determined. In addition, the issue of the roof - coupler joining point was covered in the research, as in the following two cases:

- ▶ a roof panel directly joined with the coupler – then its movement defines the trajectory of the roof movement.
- ▶ The connecting point of the roof panel is located on the so-called coupler plane – then the roof trajectory depends on where the point is on the coupler plane.

Having done the analysis and considered that a vast area of research needs to be covered, the discussion on the issue of the roof connection with the use of a coupler plane was omitted.

Hence, very detailed research has been carried out on roof panels directly joined to the links of the mechanism. Exploiting a wide range of possibilities of parametric modelling in AutoCAD, the translation of the mechanism links was determined. The obtained data was used to define viable solutions that fulfil the following imposed boundary conditions:

- 1) The inclination angles of panels such as, for example, roof slopes should take values between 10° and 85° . This assumption brings about proper water drainage and simultaneously sorts out the issue of roofing over an enclosed area, such as a courtyard. Criteria adopted regarding the inclination of panels (links) enable a collision-free movement of the roof.
- 2) All panels connected to links of the mechanism must function as roof slopes. Hence, if, during a movement, one panel covers the other from the top (Fig. 5a), such a position is eliminated from the movement range. This condition restricted the movement range of individual links.
- 3) The solutions requiring the installation of a circular gutter were eliminated. They are cases in which the adjacent links form a V-shaped basket while moving, thus making rainwater gather between the panels (links). The task of draining water while the panels move horizontally is relatively straightforward, whereas doing it while the panels move along an arch (Fig. 5b) becomes a bit of a challenge, among others, in terms of installing an arch-shaped gutter.
- 4) Translation kinematic pairs are located exclusively at the base. This condition results from the analysis of constructions with retractable roofs in which the prismatic kinematic pairs often connect the roof with the lower link of the construction.

The obtained results were analysed in terms of the adopted boundary conditions, whereby several mechanisms were selected for further analysis. A variety of possibilities for covering an area with the use of roofings that harnesses two mechanisms of class II were taken into consideration. Symmetrical and non-symmetrical mechanism connections were examined considering the same and different types of mechanisms. Consequently, the roofs constructed on the basis of a symmetrical connection of two identical mechanisms were selected for a detailed analysis due to their viable and technologically less challenging construction (two driving devices of the same type, the links in the joined mechanisms of identical lengths and



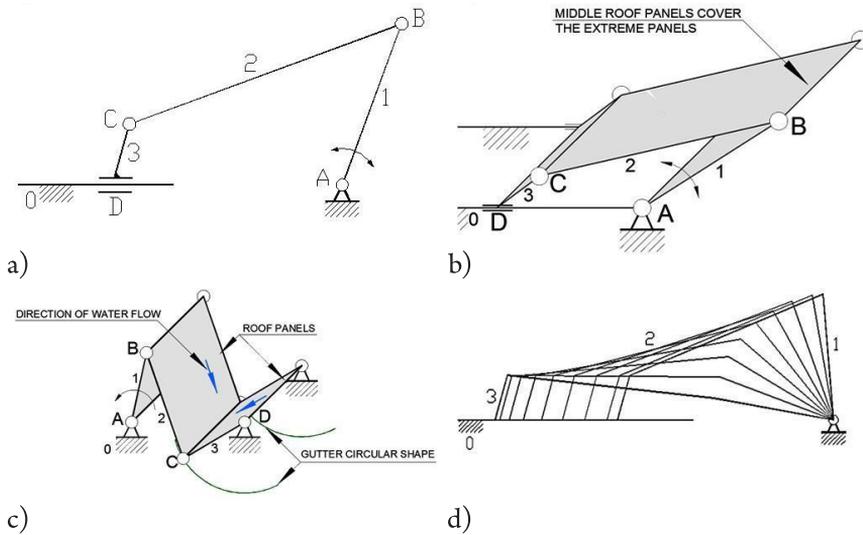


Fig. 5. Class II mechanisms with a rotary driving link: a) mechanism diagram (by K. Romaniak), b) roof panel 2 covers panel 1 from the top (by A. Pawlak-Jakubowska), c) an arch-shaped gutter (by A. Pawlak-Jakubowska), d) restricted movement range (by A. Pawlak-Jakubowska)

the gutters can be installed at the same level). A mixed combination of class II mechanisms imposes the use of different drives (rotary and translatory), panels of different dimensions and, in some cases, the gutters must be installed at different levels.

A detailed analysis has been carried out for four models constructed on the basis of two class II mechanisms that were joined together. The research method was illustrated on the example of the mechanisms with a rotary drives, three rotary kinematic pairs and one prismatic kinematic pair (Fig. 5a). In the two symmetrically joined mechanisms, the drives are located on the outer edges of the roof and the prismatic kinematic pairs can be found in the central link of the construction (Fig. 6a). Thus, the roof retracts starting from the outer edges towards the centre of the covered area. Symmetrically located roof panels can perform a synchronised movement or each link of the roof can move independently. The percentage rate of the covered area was assessed following a dimensionless analysis, which mainly aimed at establishing proportional relationships between the lengths of individual links. The following letter symbols have been adopted: a, b, c – lengths of the moving links, d – the length of the base (Fig. 6b).

A constant angle between the base and link 3 (a shape angle) has been noted as κ .

A detailed analysis exploited the possibilities of parametric modelling available through the AutoCAD software. For model number 1 the following assumptions were adopted:

- ▶ constant length of a driven link (coupler) b ,
- ▶ the lengths of links 1 and 2 proportional to b :
- ▶ $a = (i + 0.1)b, c = (i + 0.1)b$, where $i = 0, 0.1, \dots, 0.9$,
- ▶ different values of a shape angle κ ($85^\circ, 60^\circ, 45^\circ, 30^\circ, 15^\circ$),
- ▶ movement range of link 1 ($10^\circ - 85^\circ$).

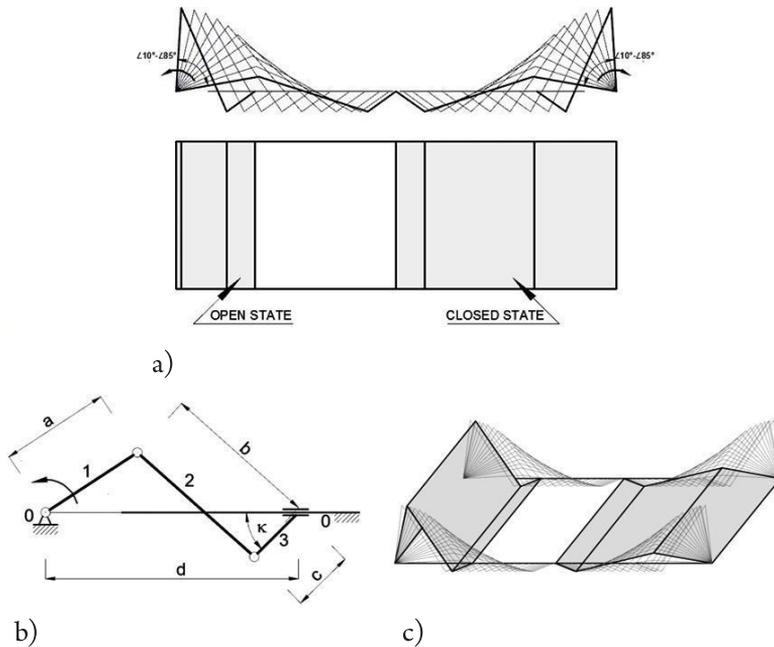


Fig. 6. Model with a rotary driving link: a) open and retracted roof respectively, b) notation of the lengths of individual links of mechanism, c) roof axonometry (all by A. Pawlak-Jakubowska)

As a result of the carried out research, the percentage values of the open area (noted as O in Table 1) and the d values were assessed. The adopted assumption was that the satisfying result would be the opening of 70% or more of the covered area. In addition, it was significant to obtain as large as possible span d , which defines the area of covered space. It was agreed that a satisfactory result would be a value greater than $1.8b$. Table 1 presents a fragment of the results obtained; in bold the data fulfilling adopted criteria. Empty spaces mean that driving link 1 does not reach values within the full range of movement (10° - 85°).

Table 1. Percentage values of the open roof space and d lengths in relation to selected lengths a and c proportional to a given b and adopted values of angle κ

		Angle $\kappa = 85^\circ$		Angle $\kappa = 60^\circ$		Angle $\kappa = 45^\circ$		Angle $\kappa = 30^\circ$		Angle $\kappa = 15^\circ$	
		O [%]	d	O [%]	d	O [%]	d	O [%]	d	O [%]	d
$a=0,7b$	$c=0$	56	$1,68b$	56	$1,68b$	56	$1,68b$	56	$1,68b$	56	$1,68b$
	$c=0,1b$	60	$1,67b$	58	$1,71b$	56	$1,74b$	54	$1,76b$	53	$1,77b$
	$c=0,2b$	69	$1,65b$	63	$1,74b$	59	$1,79b$	55	$1,83b$	51	$1,86b$
	$c=0,3b$	90	$1,63b$	72	$1,76b$	63	$1,84b$	56	$1,91b$	50	$1,95b$
	$c=0,4b$	–	–	–	–	72	$1,88b$	58	$1,98b$	50	$2,05b$
	$c=0,5b$	–	–	–	–	–	–	61	$2,05b$	49	$2,14b$

		Angle $\kappa = 85^\circ$		Angle $\kappa = 60^\circ$		Angle $\kappa = 45^\circ$		Angle $\kappa = 30^\circ$		Angle $\kappa = 15^\circ$	
		O [%]	d								
$a=0,8b$	$c=0$	63	1,78b								
	$c=0,1b$	71	1,76b	68	1,8b	66	1,83b	63	1,85b	61	1,87b
	$c=0,2b$	90	1,74b	78	1,83b	71	1,88b	65	1,93b	60	1,96b
	$c=0,3b$	–	–	–	–	–	–	68	2b	59	2,05b
	$c=0,4b$	–	–	–	–	–	–	77	2,07b	59	2,14b
	$c=0,5b$	–	–	–	–	–	–	–	–	59	2,23b
$a=0,9b$	$c=0$	73	1,87b								
	$c=0,1b$	91	1,86b	84	1,9b	80	1,93b	75	1,95b	72	1,96b
	$c=0,2b$	–	–	–	–	–	–	84	2,02b	72	2,05b
	$c=0,3b$	–	–	–	–	–	–	–	–	73	2,14b

Table 2 presents selected examples of roofs constructed with the use of data highlighted in bold in Table 1. For consecutive values of angle κ , the diagrams of mechanisms constituting the base of a roof construction were presented with given lengths of individual links determined proportionally to the b length. Horizontal projection of the roof illustrates the open space percentage, whereas a vertical projection shows translations of individual roof panels.

Table 2. Examples of roofs fulfilling boundary conditions

No.	Angle κ	Values of a, b, c and d specified for one mechanism	Horizontal and vertical roof projections
1	85°		
2	60°		

No.	Angle κ	Values of a , b , c and d specified for one mechanism	Horizontal and vertical roof projections
3	45°		
4	30°		

For the model where $a = 0,8b$, $c = 0,2b$ and angle $\kappa = 60^\circ$, as much as 78% of the roof open space can be obtained (Fig. 7). When specified, the translations of individual panels determine a working space of the whole roof. By analogy, a similar analysis was carried out for the remaining solutions presented in Table 2.

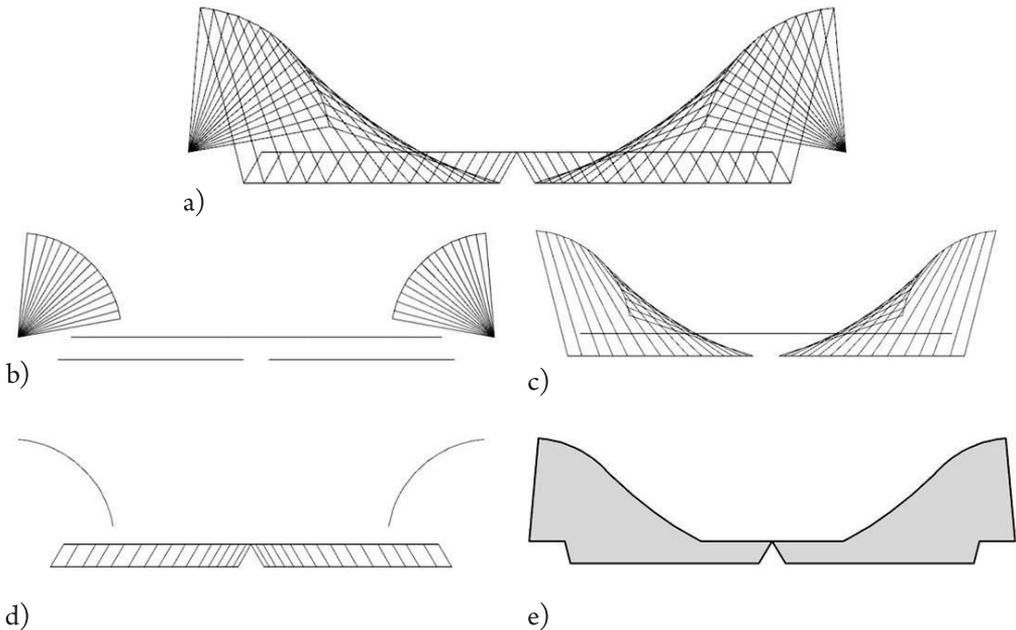


Fig. 7. Movements of: a) links 1,2 and 3, b) driving link 1, c) link 2, d) link 3, e) roof working space (all by A. Pawlak-Jakubowska)

To drain water from the panels of a model with a rotary driving link, the installation of gutters and downpipes is required. From the driving panels, the rainwater runs down to a gutter located at the base level and then into a downpipe (Fig. 8). As the angle between panels 2 and 3 is variable, a flexible gutter can be installed, which will take the water to a gutter that is linked to a downpipe. This type of gutter system makes it possible for water drainage to occur in every position of the roof, open or closed, and even when the roof stops at any moment of its movement.

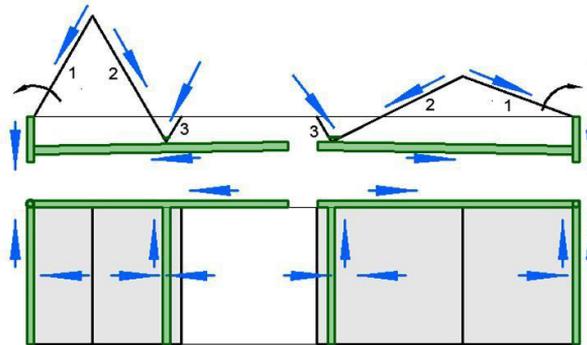


Fig. 8. Water drainage from the roof (by A. Pawlak-Jakubowska)

Finally, the last stage of the research focused on digital models made with the use of the Autodesk Inventor Professional 2016 software. This particular software provides tools for making a model and then performing kinematic simulation.

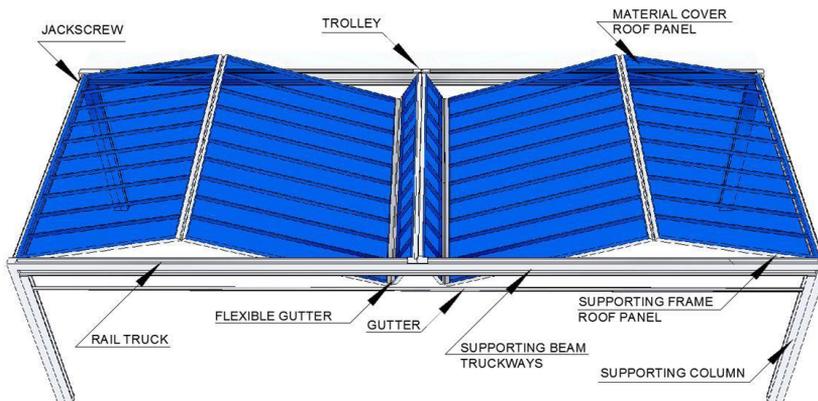


Fig. 9. Components of the research model (by A. Pawlak-Jakubowska)

Exploiting information regarding retractable roof construction technologies [2], the solutions for the construction of individual elements of research models were proposed (Fig. 9).

4. Conclusions

The quest for new designs of retractable roofs went through several stages. Firstly, all theoretically possible solutions for class II mechanisms with rotary and translation kinematic pairs were determined. The set of solutions was subject to numerous selections that considered a variety of conditions. Thus, boundary conditions were specified, which should be fulfilled by roofs joined with selected mechanisms. Finally, several solutions were selected and used to build research models. A research model is a set of roofs built on the basis of one mechanism of a specific structure. For each such a model, a detailed investigation was carried out in terms of its kinematics, for example, its movement range and working area, as well as the water drainage method. The solutions, which fulfilled adopted assumptions i.e. the percentage of the open space over 70%, were selected. Ultimately, construction solutions for individual elements of the models were proposed. The solutions were modelled on real roofs currently in existence.

The research carried out and the results obtained indicate the possibility of determining new designs of retractable roofs based on structural and kinematic research of mechanisms. In currently existing retractable roofs built on the basis of class II mechanisms, two panels are joined with the driving links of mechanism at most. In the solutions proposed in this work, a driving link is also joined with roof panels and functions as a roof segment.

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