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ANALYTICAL STUDY OF THE MOVEMENT OF RETRACTABLE ROOFS IN SPORTS FACILITIES

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ABSTRACT

Although modern retractable roof systems have been used worldwide since the 1930s in one form or another, they only became commonly used in stadium design at the beginning of the new millennium.The study aimed to analyze ten case studies, each representing the types of motion in retractable roof structures implemented in sports facilities from the 1960s until 2022. The types of motion and their directions were analyzed in relation to the types of retractable roof structures according to Frei Otto's classification. The study also attempted to classify them as deployable structures based on the modern classification of deployable structures, seeking new structures that achieve higher motion efficiency, better storage, and lighter weight. The results of the study showed that the types of motion in retractable roof structures implemented in sports facilities included sliding motion, rotational motion, and combined motion in rigid structures. As for membrane structures, retractable roof structures were implemented with sliding motion, folding, and assembly. Compared to deployable structures, the study found that folding motion can be achieved in rigid structures for use as retractable roof structures in sports facilities through panel-based structures, particularly rigid panels inspired by bio-origami. This achieves a foldable roof with geometric rigidity, higher storage efficiency, and lighter weight

KEYWORDS: : Retractable roofs, Deployable structures, Sports stadium design, Bio-Origami Kinetic structures, Types of motion

دراسة تحليلية لحركة الأسقف القابلة للسحب في المنشآت الرياضية

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الملخص:

على الرغم من أن أنظمة الأسقف القابلة للسحب الحديثة قد استُخدمت في جميع أنحاء العالم منذ ثلاثينيات القرن الماضي بشكل أو بآخر، إلا أنها لم تُستخدم بشكل شائع في تصميم الملاعب إلا في بداية الألفية الجديدة. هدفت الدراسة إلى تحليل عشر دراسات حالة، تمثل كل منها أنواع الحركة في هياكل الأسقف القابلة للسحب التي تم تنفيذها في المنشآت الرياضية من الستينيات حتى عام ٢٠٢٢م. تم تحليل أنواع الحركة واتجاهاتها فيما يتعلق بأنواع هياكل الأسقف القابلة للسحب وفقًا لتصنيف فراي أوتو. حاولت الدراسة أيضًا تصنيفها كهياكل قابلة للنشر بناءً على التصنيف الحديث للهياكل القابلة للنشر، بحثًا عن هياكل جديدة تحقق كفاءة حركة أعلى وتخزينًا أفضل ووزنًا أخف. أظهرت نتائج الدراسة أن أنواع الحركة في هياكل الأسقف القابلة للسحب التي تم تنفيذها في المنشآت الرياضية شملت الحركة الانزلاقية والحركة الدورانية والحركة المركبة في الهياكل الصلبة. أما بالنسبة للهياكل الغشائية، فقد تم تنفيذ هياكل الأسقف القابلة للسحب مع الحركة الانزلاقية والطي والتجميع. بالمقارنة مع الهياكل القابلة للانتشار، وجدت الدراسة أنه يمكن تحقيق حركة الطي في الهياكل الصلبة المستخدمة كأسقف قابلة للسحب في المنشآت الرياضية من خلال هياكل قائمة على الألواح، وخاصةً الألواح الصلبة المستوحاة من فن الأوريجامي. وهذا يحقق سقفًا قابلًا للطي يتميز بصلابة هندسية وكفاءة تخزين أعلى ووزن أخف.

الكلمات المفتاحية: أسقف قابلة للسحب، هياكل قابلة للنشر،أسقف ملاعب رياضية، هياكل الأوريجامي الحركية المستوحاة من الكائنات الحية ، أنواع الحركة واتجاهتها.

1. INTRODUCTION

For thousands of years, the study of architecture relied on the fixed mass in terms of its strength, function, and beauty—these are the three inherited considerations of architectural art since the first century BC: "durability, utility, and beauty." However, architecture has always included moving parts to meet many necessary requirements. The structures and movable parts in architecture date back to early human civilizations, such as yurts, which include transformable components and parts that can be opened and closed. This continued with ancient Egyptians, who used certain movements in some components of movable elements inside buildings, like the scissor movement in folding chairs. The Romans also used folding roofs in Greek theaters, in addition to ancient Mongolian societies that used portable tents.

One of the most prominent designers who activated the considerations of movement in design at the beginning of the Renaissance was Leonardo da Vinci. He studied methods of designing transformable buildings such as movable bridges and sun umbrellas, applied the principles of bird wing folding in flying devices, and also developed a movable roof.

This research will focus on the movements of retractable stadium roofs. The types of roofs in sports stadiums vary in terms of movement and storage, ranging from fixed roofs to roofs that are fully or partially retractable, and can be stored fully or partially. We will analyze the movement according to the type of structure of the retractable roof, and we will also analyze it based on the classification of deployable structures, with the aim of identifying the deployable structures applied in retractable roofs in stadiums.

2. RETRACTABLE ROOFS

2.1. Definition of Retractable Roofs

Retractable roof structures are a type of roof structure that can be moved or folded either fully or partially in a short period, allowing the building to be used with an open or closed roof. It is a permanent structure capable of undergoing geometric transformation or folding between two distinct configurations, commonly referred to as open and closed configurations. This ability to transform geometrically is what distinguishes retractable roofs from traditional fixed roofs. The process of transitioning from the open to the closed configuration is referred to as closing or retracting, while the reverse process is referred to as opening or extending [1,2].

2.2. The Beginning of Retractable Roofs in Sports Stadiums

The Colosseum was the first stadium to be covered with a retractable roof. The Colosseum could be covered with a fabric roof by deploying a canvas awning over the open top. This awning, made of sails and called the "velarium," protected spectators from weather and sun heat. The sails weighed approximately 24 tons and required the effort of two ship crews to set up. Columns protruding from the top of the stadium raised and secured the sails in place. It is also believed that ropes from the sails extended down to ground-level posts [3]. In the nineteenth century, the first large retractable roof that covered the entire stadium was the Civic Arena USA in 1961, after the Colosseum, which only covered the spectator area [3].

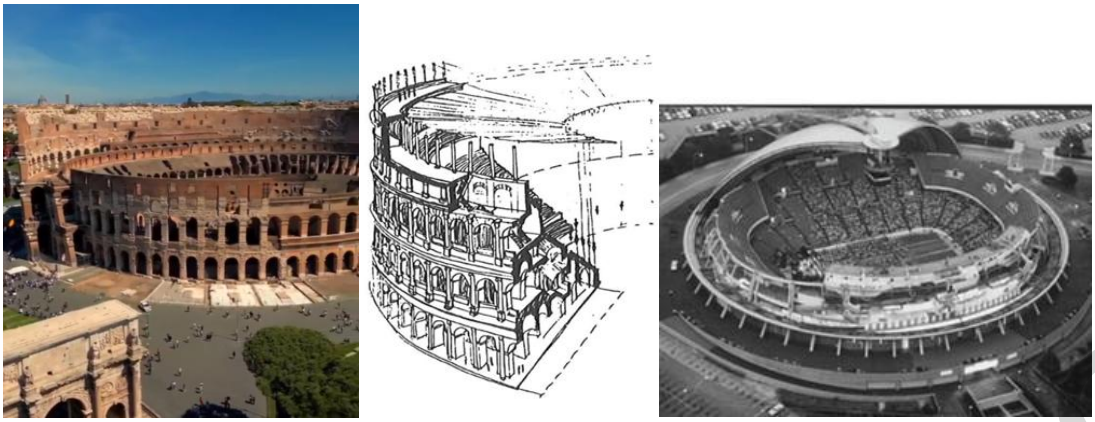


Fig. 1: Illustrates the retractable roof of Colosseum & the first retractable roof In the nineteenth century Civic Arena USA; source: [3,4]

2.3. Frei Otto and Burkhardt's Classification of Retractable Roofs

Retractable roofs are a subset of the broader concept of movable structures. Several individual classifications have been proposed for retractable roof structures. For example, Frei Otto and Berthold Burkhardt classified retractable roofs in their 1972 publication. This classification includes three main categories: "Rigid Frame Structures" (which include rigid panels and rigid bars element structures) and "Membrane structures", further divided into fixed-support and movable-support structures), "Types of movement" (such as sliding, folding, and rotating), and "directions of movement" (including parallel, central, circular, and peripheral directions)[1].

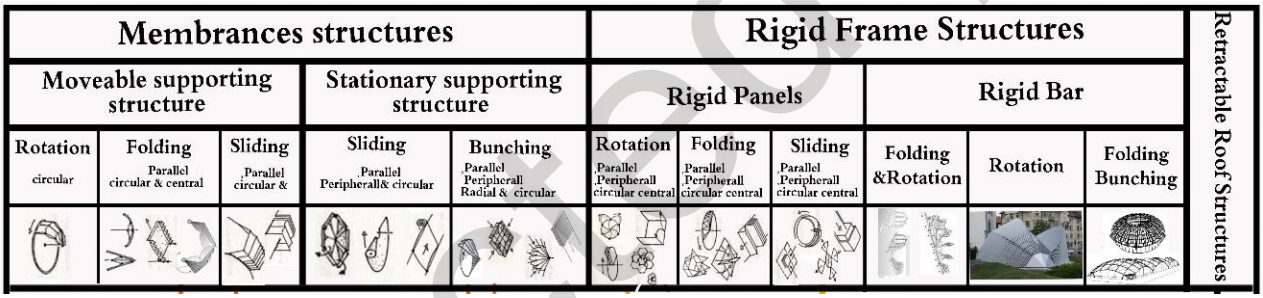


Fig. 2: Illustrates Frei Otto and Burkhardt's Classification of Retractable Roofs; source: Author based on [1]

3. DEPLOYABLE STRUCTURES

3.1. Definition of Deployable Structures

Deployable structures are a broad category of structures capable of transforming themselves from small, closed, or stored configurations into much larger, open, or expanded configurations [5] . Retractable roof structures are considered part of deployable structures in the functional classification of deployable structures according to Félix Escrig's classification [6] .

3.2. Topology of Deployable Structures According to Rivas Adrover's Classification

Deployable structures are classified based on "generative techniques" of movement into two approaches: the first is inspired by natural biological structures, divided into movable structures in plants (such as flexible motion concepts in adaptive shading systems—folding leaf movements) and movable structures in animals (such as wing folding in beetles). The second approach is origami techniques, which include (origami trusses, rigid origami, air-inflated origami, curved rigid composite origami, and rigid origami bags) [7].

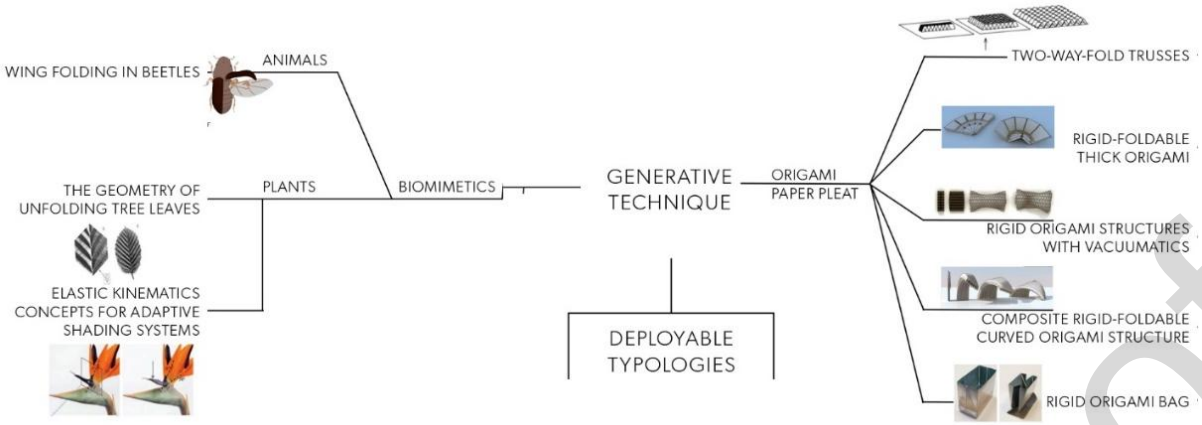


Fig. 3: Illustrates the topology of deployable structures in terms of motion techniques; source: Author based on [7]

3.3. Modern Classification of Deployable Structures

The modern classification of deployable structures in 2021, introduced by a group of researchers—Amela Šljivić and others—was developed based on the primary application and the elements used in forming the structure. This proposed classification includes (rigid bar, Plate Element, Spatial Elements, Compained Elements) [8].

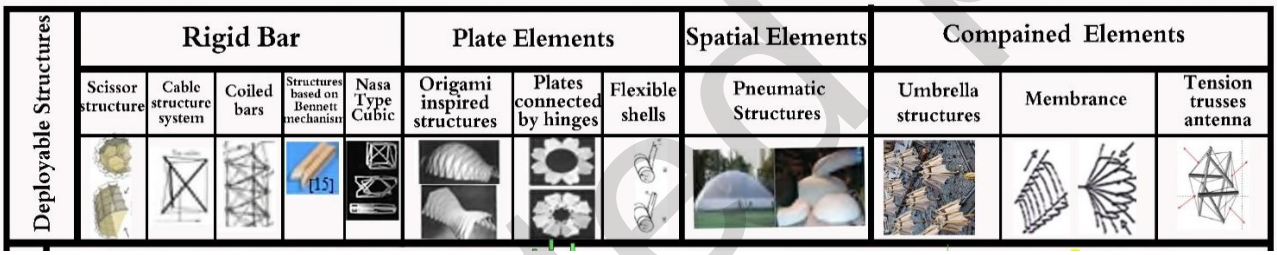


Fig. 4: Illustrates Modern Classification of Deployable Structures; source: Author based on [8]

4. ANALYTICAL STUDY

The analytical study is based on the kinematic classification of retractable structures for a group of sports facilities. By examining the movement of roofs in sports facilities constructed from 1961 to 2022, a total of 47 sports facilities with retractable roofs were identified. From these, 10 case studies were selected, representing all types of movement (central sliding, circular sliding, parallel sliding, peripheral rotation, folding, central and radial assembly, and combined sliding and rotation movements) observed in retractable roofs of sports facilities.

4.1. Types of retractable roof motion in case studies

4.2. Case Study 1: Mercedes Benz Stadium- 2017

The Mercedes Benz Stadium consists of eight movable units, each weighing approximately 500 tons. These units, referred to as "petals," move in straight lines during opening and closing. Each unit moves on two tracks: the inner track supports the wheels from below, and the outer track supports the wheels from above, resembling railway units. The units are connected to the fixed part of the roof and move independently using 12 electric motors. The opening and closing motion resemble the movement of a camera aperture, moving in a straight line despite appearing curved [8]. So, it moves with Central Sliding Motion.

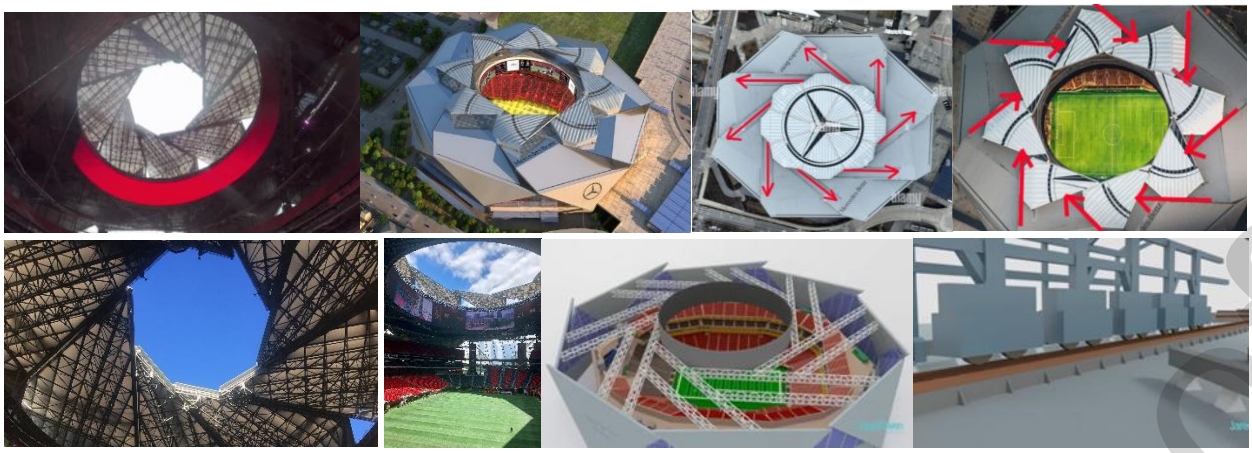


Fig. 5: Illustrates the motion of retractable roof of Mercedes Benz Stadium source: [9]

4.3. Case Study 2: GelreDome – Arnhem- 1998

The roof of the GelreDome Stadium consists of two solid structural blocks that slide in parallel, allowing the stadium to be multi-functional and suitable for various activities [10]. So, it moves with Parallel Sliding Motion.

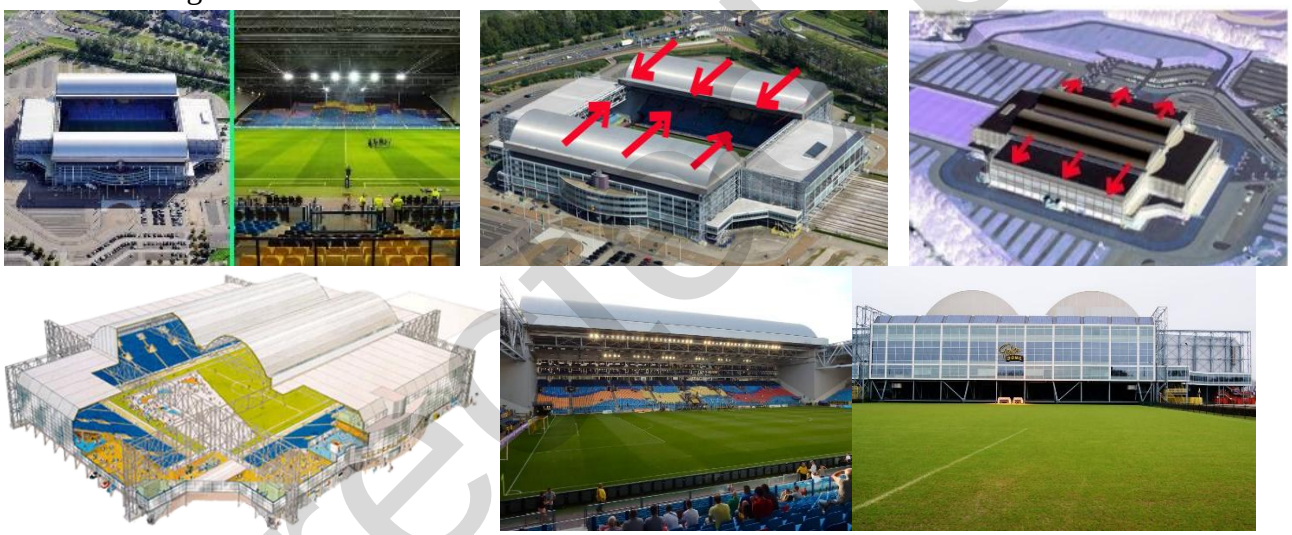


Fig. 6: Illustrates the motion of retractable roof of Gelre-Dome Stadium; source: [10]

4.4. Case Study 3: Santiago Bernabéu Stadium -2022

On the other hand, the roof of the Santiago Bernabéu Stadium is composed of a fixed part and a movable part. The movable part consists of a membrane structure supported by a movable frame that slides in parallel [11]. So, it moves with parallel Sliding Motion.

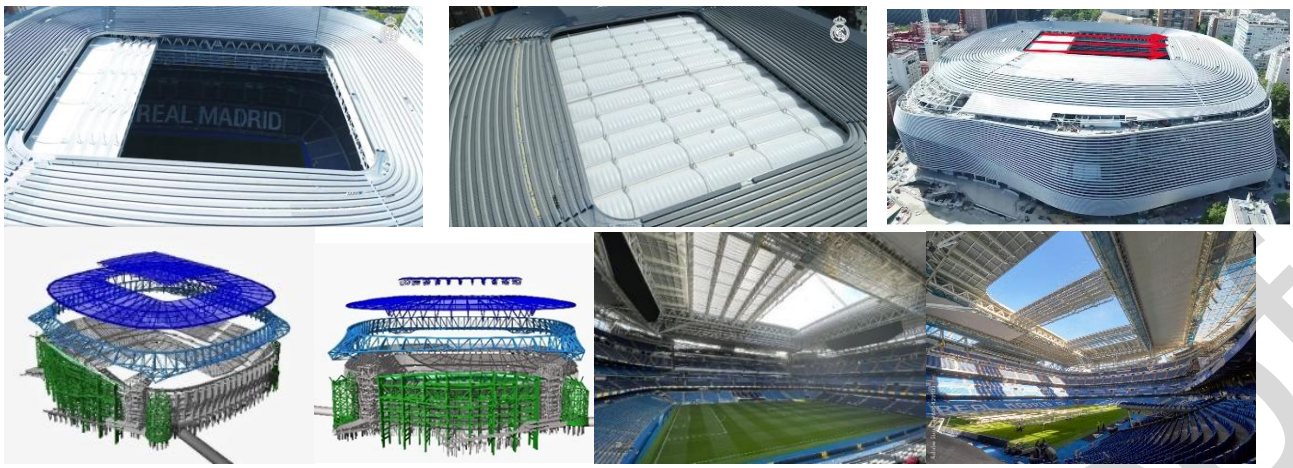


Fig. 7: Illustrates the motion of retractable roof of Santiago Bernabéu Stadium; source: [11]

4.5. Case Study 4: Noevir Stadium, Kobe- 2001

The roof of Noevir Stadium consists of four solid structural blocks that slide along a circular curve on two movement tracks, transforming the roof from an open to a closed configuration [12]. So, it moves with Circular Sliding Motion.

Fig. 8: Illustrates the motion of retractable roof of Noevir Stadium; source: [12]

4.6. Case Study 5: State Farm Stadium, Phoenix -2006

On the other hand, the State Farm Stadium features two solid structural blocks that slide circularly along a curved track to open and close the stadium roof [13] So, it moves with circular sliding motion.

Fig. 9: Illustrates the motion of retractable roof of State Farm Stadium; source: [13]

4.7. Case Study 6: Qizhong Forest Sports City Tennis Stadium-2005

The roof consists of eight solid panels that move circularly along the perimeter of a steel ring to open and close the roof, resembling the blooming and closing of flower petals [14] So, it moves with Peripheral Rotational Motion.

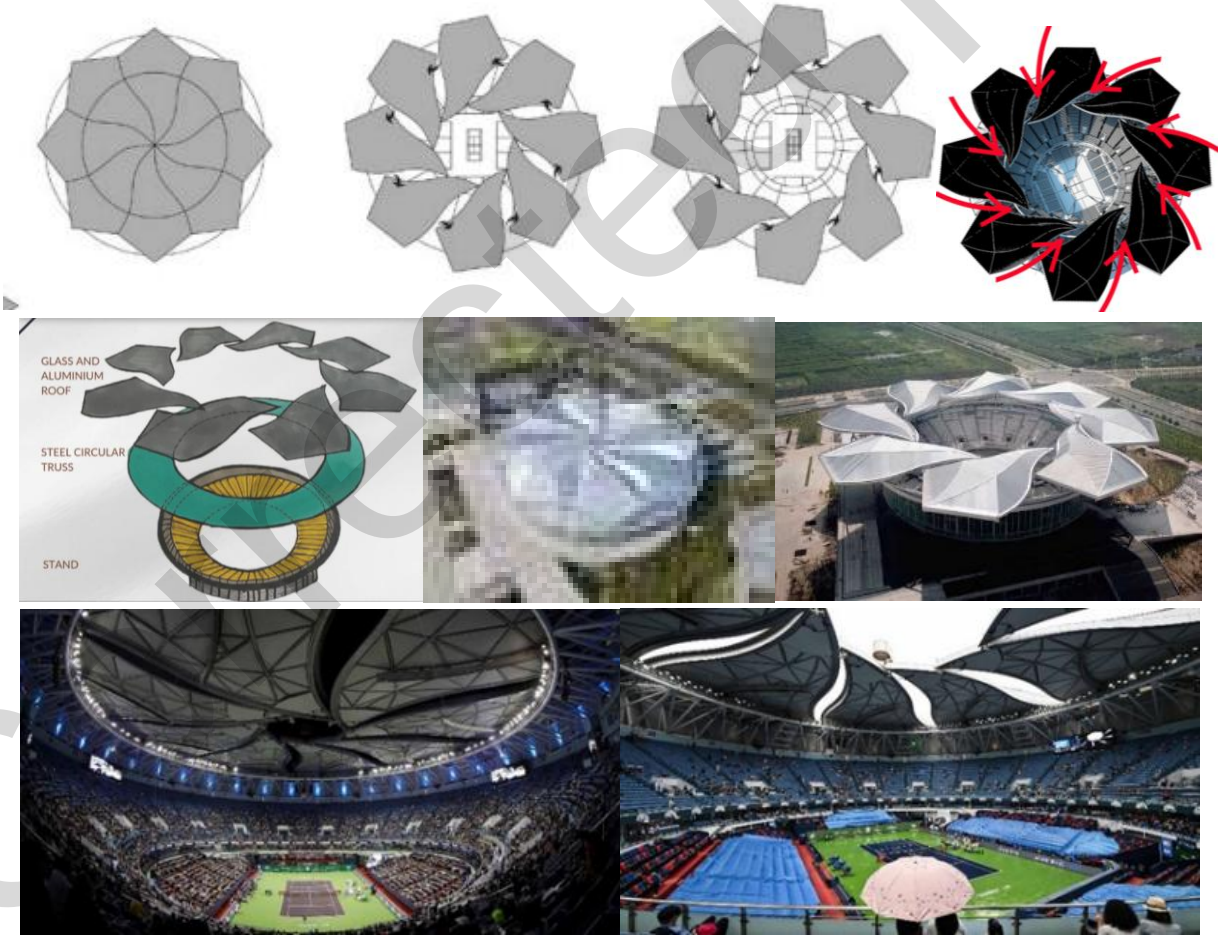


Fig. 10: Illustrates the motion of retractable roof of Qizhong Forest Sports City Stadium; source: [14]

4.8. Case Study 7: Al Bayt Stadium, Qatar-2020

The roof of Al Bayt Stadium in Qatar consists of a membrane structure supported by a movable frame. It moves with a parallel folding and assembly motion in three stages, powered by 64 motors [15]. So, it moves with parallel folding and assembly motion.

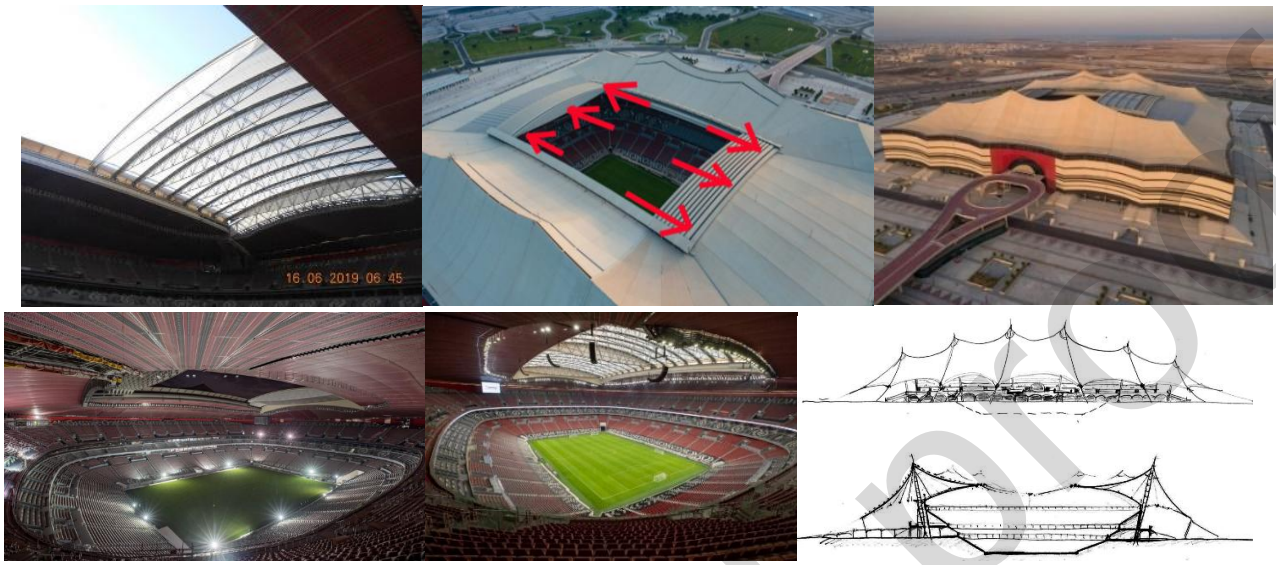


Fig. 11: Illustrates the motion of retractable roof of Al Bayt Stadium; source: [15]

4.9. Case Study 8: Warsaw National Stadium 2011

The roof of the Warsaw National Stadium consists of a membrane structure supported by a fixed frame. The membrane folds centrally toward the center when opening the stadium, converting it into an open configuration [12]. So, it moves with Central Folding Motion.

Fig. 12: Illustrates the motion of retractable roof of Warsaw National Stadium; source: [12]

4.10. Case Study 9: Al Janoub Stadium-2019

Meanwhile, the Al JANOUB Stadium features a membrane structure supported by a fixed frame, with the membrane moving toward two radial centers distributed on either side of the stadium roof [16]. So, it moves with Radial Folding Motion.

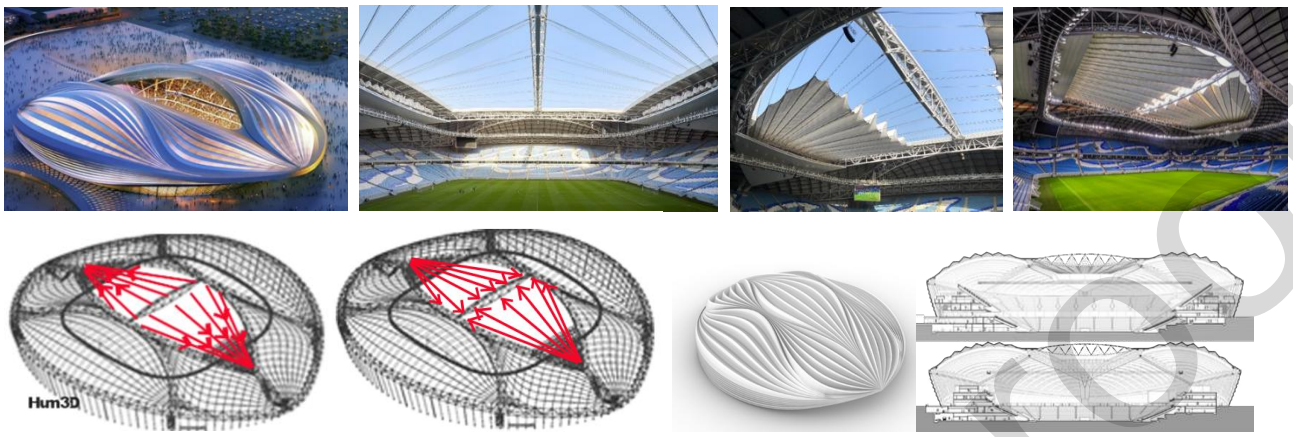


Fig. 13: Illustrates the motion of retractable roof of Al Janoub Stadium; source: [16]

4.11. Case Study 10: Rogers Centre (Skydome), Toronto-2002

The fully retractable roof is divided into three movable solid panels and one fixed panel. Two panels move with a sliding motion, while the third rotates peripherally to transform the stadium into a covered configuration [13]. So, it moves with Combined Motion (Sliding and Rotation).

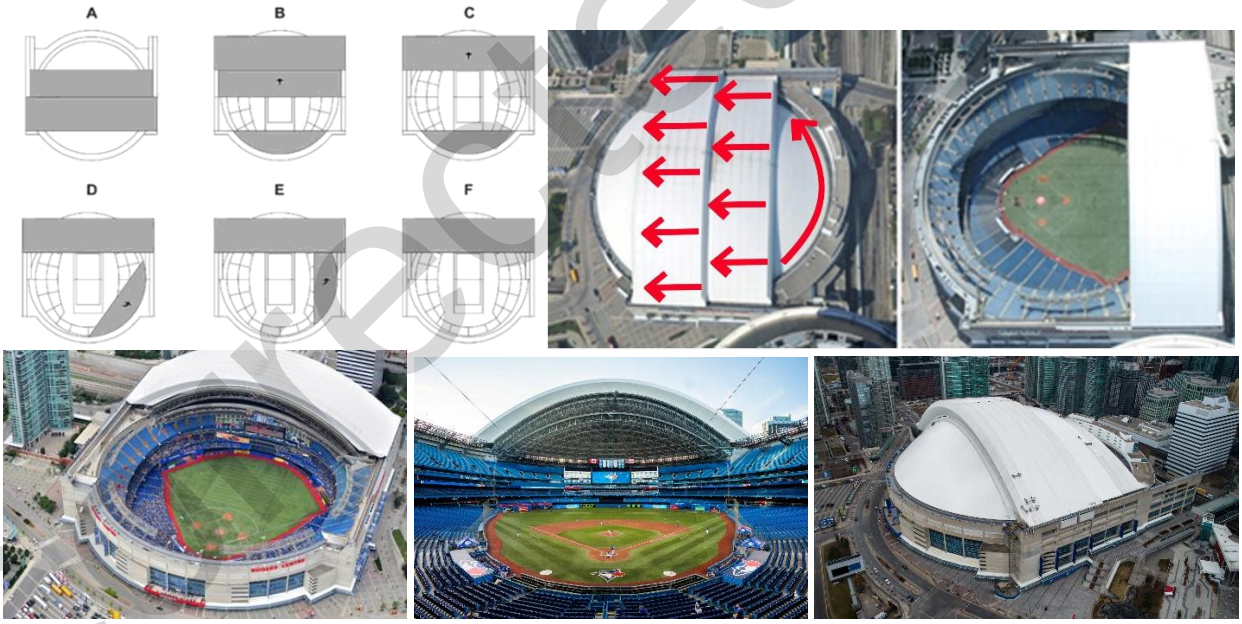


Fig. 14: Illustrates the motion of retractable roof of Rogers Centre (Skydome), Stadium; source: [13]

Below is a table summarizing the case studies, analyzing them in terms of the type of motion, direction, type of retractable roof structure, location, and construction date.
After that, we will conduct a comparative analysis of the case studies according to Frei Otto's classification of retractable roofs and according to the modern classification of deployable structures.

Table (1): Analysis of the case studies according to the type of motion, its directions, and movement paths; source: the researcher.

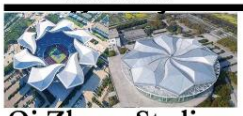
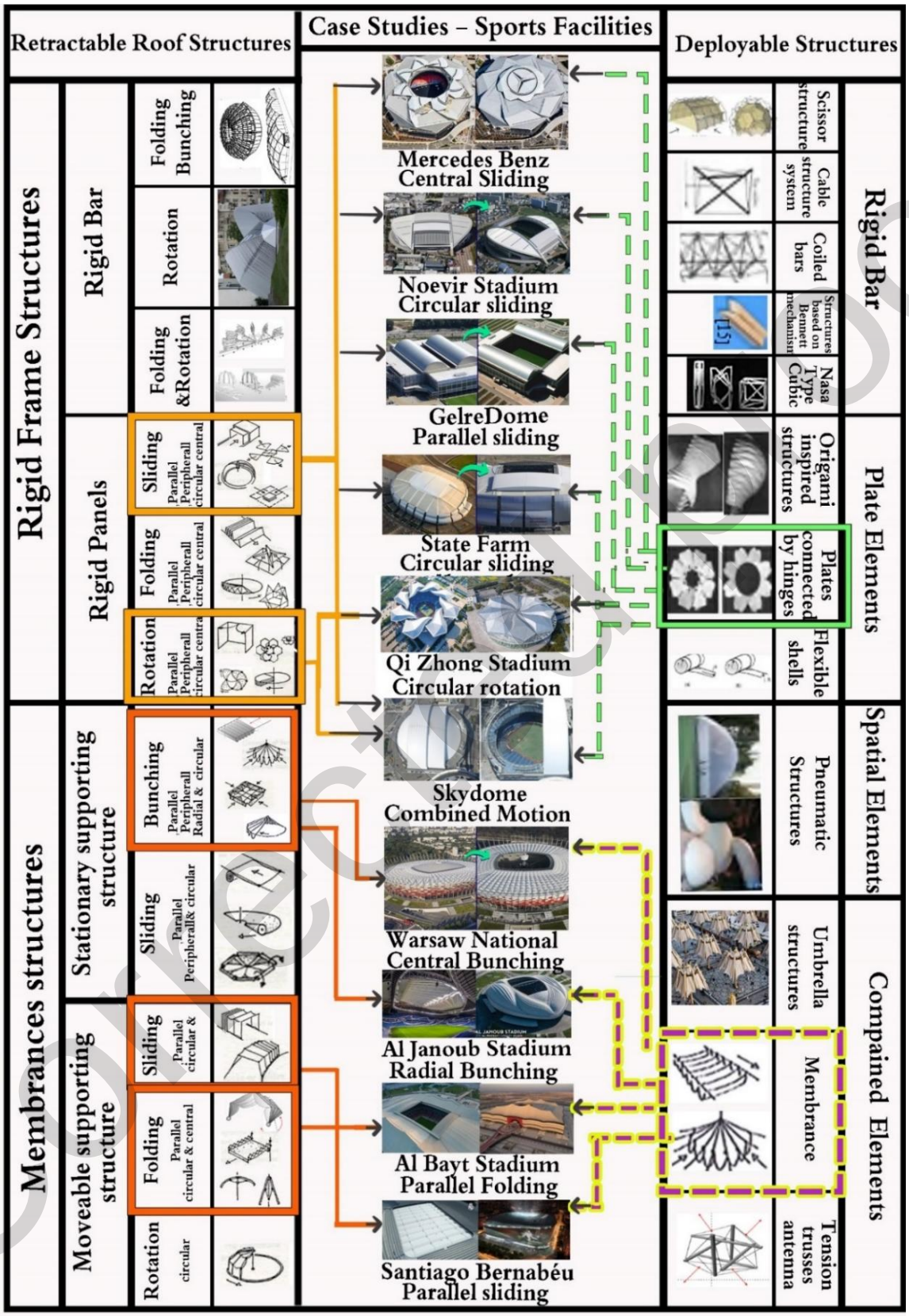
Sports Facility	Location	Date	Retractable Roof Structure	Tracks	Movement Type
 Mercedes Benz Stadium	USA	2017	Rigid Frame Structures Rigid Panels	8	Central–Sliding
 Noevir Stadium	Japan	2001	Rigid Frame Structures Rigid Panels	2	Circular–Sliding
 GelreDome Stadium	Holland	1998	Rigid Frame Structures Rigid Panels	2	Parallel–Sliding
 State Farm Stadium	USA	2006	Rigid Frame Structures Rigid Panels	2	Circular–Sliding
 Qi Zhong Stadium	China	2005	Rigid Frame Structures Rigid Panels	2	Circular rotation
 Skydome Stadium	Canada	2005	Rigid Frame Structures Rigid Panels	3	Combined Movement Rotation –Sliding
 Warsaw National Stadium	Poland	2011	Membrances structures Stationary supporting struc	1	Central–Bunching
 Al Janoub Stadium	Qatar	2019	Membrances structures Stationary supporting struc	2	Radial–Bunching
 Al Bayt Stadium	Qatar	2020	Membrances structures Moveable supporting struc	2	Parallel Folding
 Santiago Bernabéu Stadium	Spain	2022	Membrances structures Moveable supporting struc	2	Parallel–Sliding

Table (2): Analysis of the case studies according to the retractable roof structures, deployable structures and movement types in stadiums, source: the researcher.



5. DATA REPRESENTATIONS

5.1. Analysis of Structures Used in Retractable Roofs for Sports Facilities

The study recorded that the implementation of retractable roof structures consisted of rigid frame structures at 60% and membrane structures at 40%. This is because the use of rigid frame structures makes it possible to cover large areas without the need for intermediate structural elements, while membrane structures offer greater flexibility and lightness, allowing for more innovative and manageable designs.

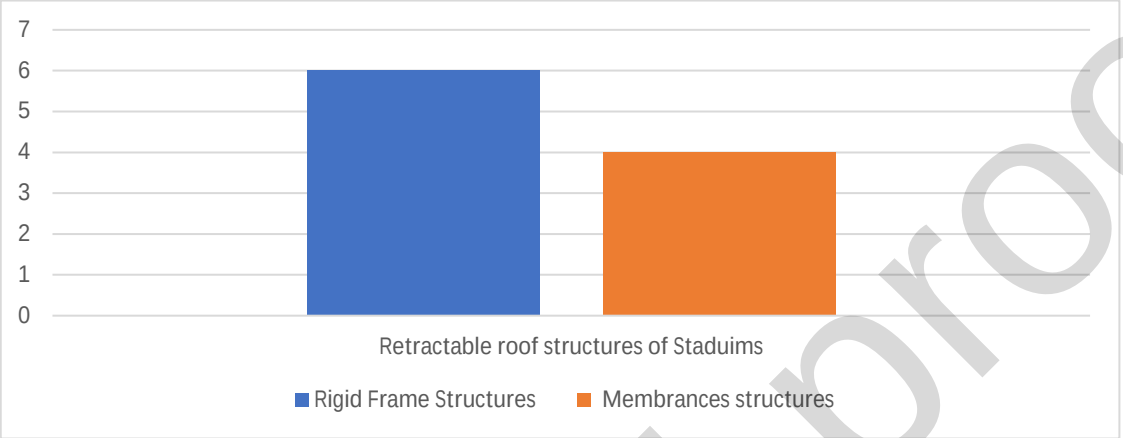


Fig. 15: Types of retractable roof structures, source: the researcher.

Additionally, the implementation of retractable roofs using rigid structures provides a safer environment under various weather conditions. Finally, although membrane structures are less costly than rigid structures, the rigid structures that have been implemented are rarely replaced with fixed roofs, unlike some examples of membrane structures used in sports facilities.

5.2. Analysis Of Motion in Rigid Structures Used in the Case Studies

The implementation of rigid structures recorded 100% rigid panels and 0% rigid bars in the retractable roofs of the case studies under consideration. This is because the use of rigid panels in movable roof structures provides a stable and robust surface that can be relied upon, offering better resistance to weather conditions compared to rigid bars. This makes rigid panels more suitable for retractable roof applications in stadiums. Rigid panels can be used in large-scale designs and better meet durability requirements.

Furthermore, sliding motion was recorded in 80% of rigid roof structures, rotational motion in 10%, and combined sliding and rotational motion in 10%. Folding motion in rigid structures was recorded at 0%, indicating the absence of folding motion in these roofs. The higher prevalence of sliding motion is due to its simplicity, as it can be considered a straightforward and uncomplicated movement. Additionally, the direction of movement for retractable parts is mostly circular and parallel sliding, which is related to the type and shape of the structure.

Representation of Data for Rigid Structures in Retractable Roofs of Sports Facilities According to the Following Chart:

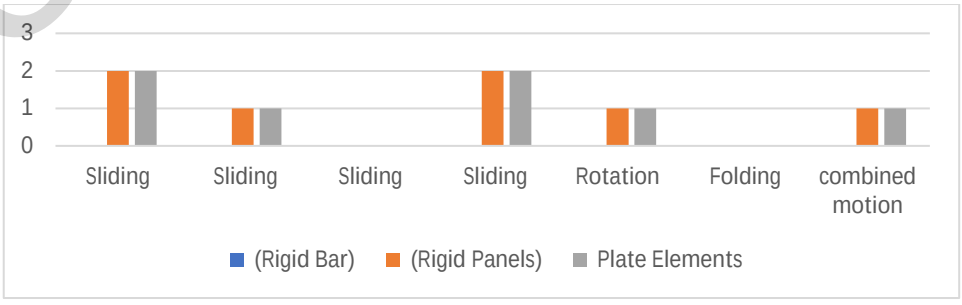


Fig. 16: Types of motions in rigid frame retractable roof structures, source: the researcher.

5.3. Analysis Of Motion in Membrane Structures Used in The Case Studies

The research study recorded the use of retractable roof structures of the membrane type, divided into fixed-supportive membrane structures at 50% and movable-supportive membrane structures at 50% of the total sports facilities that utilized membrane structures in retractable roofs. Sliding motion in the parallel direction was recorded in 50% of movable-support membrane structures, reflecting the simplicity and suitability of this type of motion for these less complex structures compared to others.

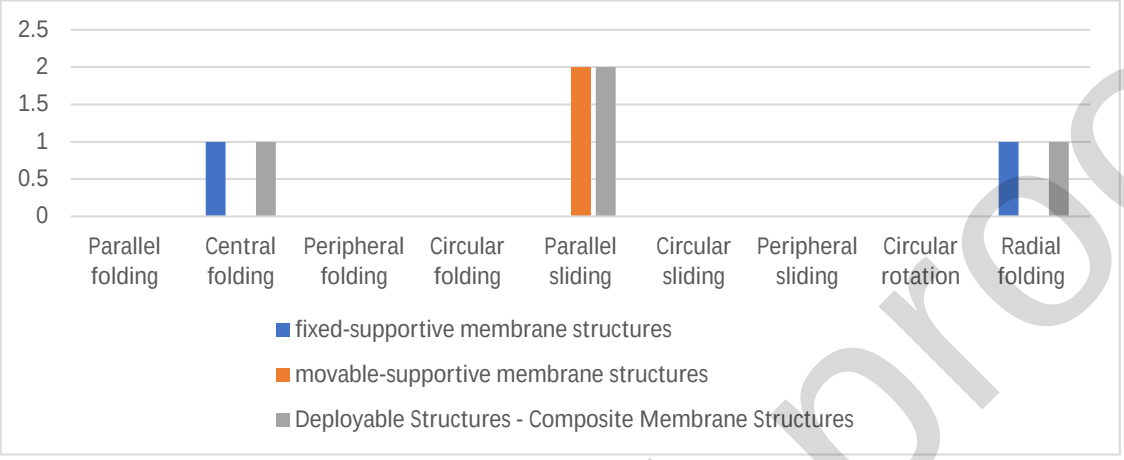


Fig. 17: Types of motions in membrane retractable roof structures, source: the researcher.

The study recorded the implementation of fixed-support membrane structures with membrane motion involving central and radial folding and assembly in 50% of membrane structures used in retractable roofs for sports facilities. This confirms that the type and direction of motion are influenced by the shape and type of structure used.

The use of both types of membrane structures reflects the diversity and flexibility of this type of structure, with motion types including parallel sliding and central folding and assembly, offering higher storage capacity for the folded roof.

5.4. Application of Deployable Structures in Retractable Roofs for Sports Facilities

It is noted that deployable structures have been applied in retractable roofs using membrane structures, which fall under composite structures, and articulated panel structures, which belong to panel element structures, according to the modern classification of deployable structures (2021). However, the use of origami-inspired structures, which are part of articulated panel structures, has not been recorded for retractable roofs in sports facilities.

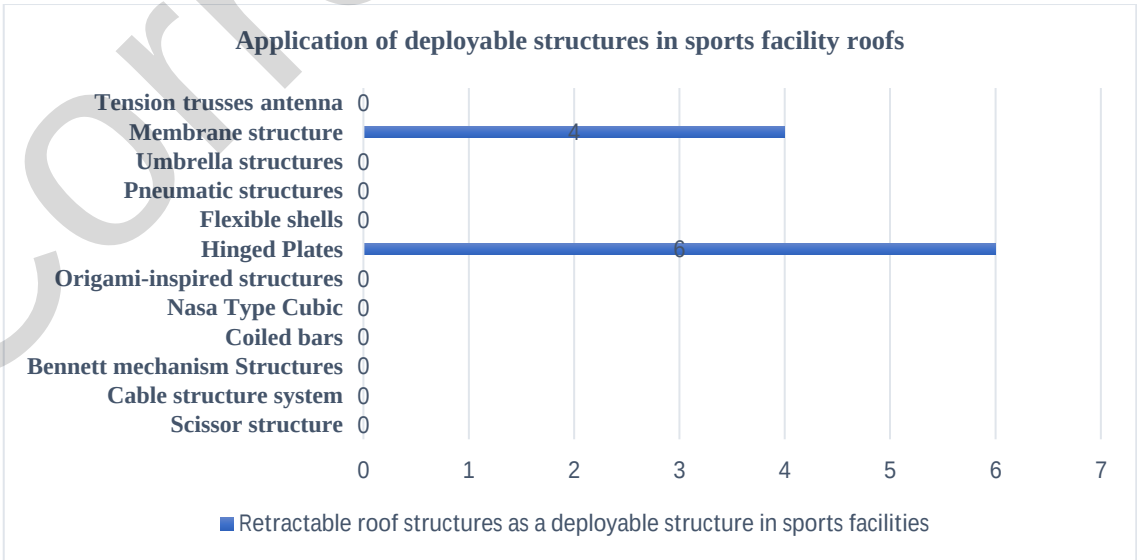


Fig. 18: Types of deployable structures applied in retractable roof structures in sports facilities. Source: The researcher.

6. RESULTS

6.1. Results of the Analytical Study

The results of the analytical study yielded findings related to the implementation of retractable roof structures in sports facilities, as well as results concerning the application of deployable structures in sports facilities, as follows:

- The research study confirmed, based on the case studies, that the motion of retractable parts depends on the shape and type of the structure. Additionally, the implementation of retractable roof structures reflects the economic, technological, and architectural progress of the countries where they were constructed.
- Rigid structures enabled the covering of large areas without the need for intermediate structural elements, while membrane structures provided greater flexibility and lightness, allowing for more innovative and manageable designs.
- The use of rigid structures in retractable roofs offers a safer environment under various weather conditions.
- Rigid panels were more prevalent than rigid bars in rigid structures, as they are more suitable for retractable roof applications in stadiums. Rigid panels can be used in large-scale designs and better meet durability requirements.

6.2. Results of the Comparison with Deployable Structures

Regarding the results of applying deployable structures in sports facilities, it was found that only panel elements of the articulated type and membrane structures were used. This indicates that the use of bio-origami-(Origami inspired biologically) inspired panel elements represents an innovation. Additionally, it suggests the potential for incorporating folding motion in rigid-element structures for retractable roofs, achieving high storage efficiency with a lighter rigid structure.

CONCLUSION

The analytical study concluded that the motion of retractable roof components is intrinsically linked to the structure's shape and type, reflecting the economic, technological, and architectural advancement of their respective countries. Rigid structures effectively cover large spans without intermediate support, providing safety under various weather conditions, while membrane structures offer greater flexibility and lighter, more innovative designs. Rigid panels are favored over bars in retractable roofs for their durability and suitability in large-scale stadium applications. The study also highlighted that deployable structures in sports facilities utilize articulated panel elements and membrane systems, with bio-origami-inspired panels representing a significant innovation. This suggests promising potential for integrating folding motions within rigid-element retractable roofs to enhance storage efficiency and reduce weight.

RECOMMENDATIONS

It is recommended to use deployable structures of the bio-origami-inspired panel type in retractable roof structures in general, and in sports facilities in particular, after ensuring their ability to bear loads and resist collapse during opening and closing operations.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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