TYPOLOGY OF RETRACTABLE ROOF STRUCTURES IN STADIUMS AND SPORTS HALLS

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www.iu-cg.org

Znanstvena revija, št. 3 / leto 2015
Univerza v Ljubljani
Fakulteta za arhitekturo in
Fakulteta za gradbeništvo in geodezijo
Ljubljana, 2015

Scientific journal, no. 3 / Year 2015
University of Ljubljana
Faculty of Architecture and
Faculty of Civil and Geodetic Engineering
Ljubljana, 2015

Naslov revije:

IGRA USTVARJALNOSTI
teorija in praksa urejanja prostora

Title of the Journal:

THE CREATIVITY GAME
Theory and Practice of Spatial Planning

Urednici: Alenka Fikfak, Alma Zavodnik Lamovšek

Editors: Alenka Fikfak, Alma Zavodnik Lamovšek

Uredniki tematskega dela: Cristian Suau, Saja Kosanović, Carmelo Zappulla

Thematic section editors: Cristian Suau, Saja Kosanović, Carmelo Zappulla

Oblikovanje in naslovnica: Gašper Mrak
Lektoriranje: Mojca Vilfan
Prevod: Mojca Vilfan
Klasifikacija: (UDK) Renata Stella Čop, (DOI) Teja Koler Povh

Design and Title page: Gašper Mrak
Slovene text proofread by: Mojca Vilfan
Translation: Mojca Vilfan
Classification: (UDK) Renata Stella Čop, (DOI) Teja Koler Povh

Založila in izdala: Univerza v Ljubljani,
Fakulteta za arhitekturo in
Fakulteta za gradbeništvo in geodezijo

Published by: University of Ljubljana,
Faculty of Architecture and
Faculty of Civil and Geodetic Engineering

Spletna stran revije:
http://www.iu-cg.org/

Journal's Web Page:
http://www.iu-cg.org/

Spletna stran številke
http://www.iu-cg.org/paper/2015/iu03.html

Currrent Issue LInk
http://www.iu-cg.org/paper/2015/cg03.html

ISSN 2350-3637

ISSN 2350-3637

Univerza v Ljubljani
Fakulteta za arhitekturo

Univerza v Ljubljani
Fakulteta za gradbeništvo in geodezijo

Andrej Mahovič: TIPOLOGIJA PREMIČNIH STREŠNIH KONSTRUKCIJ STADIONOV IN ŠPORTNIH DVORAN

TYPOLOGY OF RETRACTABLE ROOF STRUCTURES IN STADIUMS AND SPORTS HALLS

DOI: 10.15292/IU-CG.2015.03.090-099 ▮ UDK: 624.94:725.84 ▮ 1.02 Pregledni znanstveni članek / Professional Article ▮ SUBMITTED: June 2015 / REVISED: September 2015 / PUBLISHED: October 2015

IZVLEČEK

Premične strešne konstrukcije so eden izmed štirih osnovnih sistemov (poleg prireditvene površine, tribun in ovoja) stadiona in športne dvorane. Streha varuje uporabnike stavbe pred različnimi vremenskimi vplivi in ustvarja optimalne pogoje za izvajanje različnih dejavnosti. Stadioni in športne dvorane s premično strešno konstrukcijo povečujejo število dejavnosti, ki se lahko v stavbi izvajajo, izboljšujejo kakovost izvajanja in spremljanja različnih dogodkov ter vplivajo na občutenje in doživetje ljudi ob uporabi ali opazovanju takšne stavbe. Premična strešna konstrukcija omogoča naravno osvetlitev in prezračevanje prireditvenega prostora, omogoča ustvarjanje optimalnih pogojev za rast trave na prireditveni površini, zmanjšuje stroške uporabe in vzdrževanja stavbe. Različne tipologije premika strešnih konstrukcij (frekvenca odpiranja in zapiranja, zasnova konstrukcije, načini premika) so kategorizirane glede na njihovo arhitekturno in konstrukcijsko zasnovo. Uporaba različnih premičnih sistemov streh v svetu je pokazatelj njihove učinkovitosti in smotrnosti ter izhodišče za uporabo premika tudi pri drugih osnovnih sistemih stadionov in športnih dvoran. Raziskovanje in načrtovanje lastnosti premičnih strešnih konstrukcij vodi v zasnovo novih premičnih sistemov, ki lahko z uporabo načela premika spremenijo namen premičnih elementov ali prevzemajo lastnosti drugih osnovnih sistemov.

KLJUČNE BESEDE

stadion, športna dvorana, premična strešna konstrukcija, tipologija premičnih streh

ABSTRACT

Retractable roof structures are one of the four fundamental systems (in addition to the playing area, stands and facade) in a stadium and sports hall. The roof protects users against various weather conditions and creates optimum circumstances for carrying out different activities. Stadiums and sports halls with retractable roof structures can host a greater variety of activities, improve the quality of their implementation and the quality of visitors' experience, and affect the perception and experience of people using or observing such buildings. A retractable roof structure allows for natural lighting and ventilation of the venue, gives optimal conditions for grass growth on the playing field, and reduces costs of use and maintenance of the building. Different typologies of movement of roof structures (frequency of opening and closing, design of the structure, and methods of movement) are categorised in terms of their architectural and structural design. Application of different retractable roof systems worldwide is indicator of their effectiveness and efficiency, and is basis for use of movement also in other fundamental systems of stadiums and sports halls. Research and identification of characteristics of retractable roof structures lead to the design of new moving systems that can with the application of the moving principle change the purpose of movable elements or assume the characteristics of other fundamental systems.

KEY-WORDS

stadium, sports hall, retractable roof structure, typology of retractable roofs

1. INTRODUCTION

Origins of the development of retractable roof structures can be traced back to ancient times when Romans covered their buildings intended for mass events (amphitheatre, theatre, and circus) with foldable awnings. They used simple retractable systems (wooden beams, ropes, canvas) for unfolding the roof above stands and thereby protecting users from a variety of weather conditions.

Today, retractable roof structures are used in stadiums and sports halls to allow the implementation of various activities inside the building regardless of weather conditions, to allow a multipurpose use of the playing area, to provide natural conditions for grass growth in the pitch inside the building, to enable natural lighting and ventilation of the venue, and to provoke different perceptions and experiences of people using or observing such buildings.

Structural design and technology of movement in modern retractable roof structures are based on the application of structural systems of movement and their components, which were initially used in the movement of ships during their construction in shipyards, as well as in the transhipment of containers in ports, and in oil drilling rigs, the common characteristics of which were heavy weight and large dimensions of the movable elements.

The increasing number of planned and built stadiums and sports halls with retractable roof structures has led to the definition of fundamental principles and rules for their design. Rotation, sliding, folding, lifting and lowering of the roof of a stadium and sports hall have given new possibilities for use of the building. Rigid roof structures and roof membranes, weighting a few hundreds of tones, are moved or folded within minutes through various mechanisms, transforming the building from a closed into an open roof and vice versa.

Movement of the roof structure significantly influences the structure of space inside the building, the architectural and structural design and expression of the building, user safety, and other engineering properties of the building. Introduction of retractable roof structures in stadiums and sports halls undermines the specific attributes of each building type, making them become similar in terms of design and size.

Development and application of retractable roof structures define the basic intent and purpose of movement. Characteristics of the retractable building type define the basis for application, which could lead to the upgrading of the basic purpose of movement. In doing so, we are interested in: the typology of retractable roof structures of stadiums and sports halls in relation to frequency of movement, conceptual design of movable element and type of movement; possible combinations of different types of movement to achieve multipurpose use of a retractable roof structure; types of movement of other fundamental systems of stadiums and sports halls.

By using different types of movement, retractable roof structure may take on the characteristics and functions of other fundamental systems (playing area, stands, and facade) of a stadium and sports hall.

2. DEFINITION OF RETRACTABLE ROOF STRUCTURES

Retractable roof structures in stadiums and sports halls can be defined as follows: "Retractable roof structures are a type of roof structure, which can be completely or partly moved or folded in a short period of time so that the building can be used with an open or closed roof" (Ishii, K., 2000).

The process of opening and closing of the roof structure can be executed when the building is not in use or simultaneously with an activity taking place. In either case, safety of all building users is of paramount concern.

2.1 Typology of retractable roof structures based on frequency of opening and closing

One of the important factors to take into account when designing retractable roof structures of stadiums and sports halls is the frequency of opening and closing of the roof structure. During the design of the building, the anticipated frequency of opening and closing determines the design of the structure, type of movement, size of movable roof elements, and type of moving system.

Design, construction, use and maintenance have influenced the formation of different types of retractable roof structures that vary in the frequency or repetition of opening and closing. Types of retractable roof structures based on frequency are:

Retractable roof structures that are opened or closed twice a year, that is in summer and winter period (frequency depending on the season) (Figure 1). Design of this type of retractable roof structure is used in buildings that are closed during the transition from summer to winter and vice versa.

Frequency depending on the season

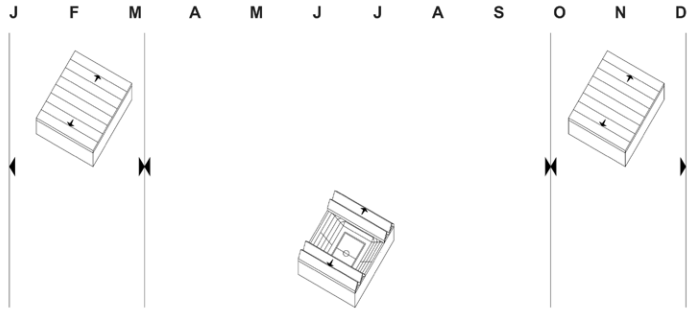


Figure 1: Demonstration of roof structure movement depending on the season (annual opening and closing).

Example: Swimming Pool Boulevard Carnot, Paris, France (1967); roof structure design: membrane; movement frequency: twice a year; type of movement: folding (Figure 2).

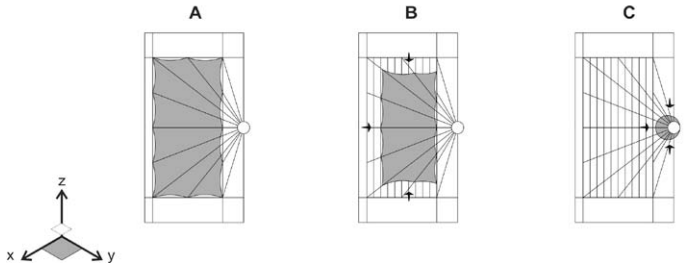


Figure 2: Demonstration of opening and closing of roof structure by seasonal frequency (A - closed, B - half-open, C - open) in Swimming Pool Boulevard Carnot.

Retractable roof structures that are primarily closed and are opened occasionally or when there are special requirements (frequency closed - open) (Figure 3). This type of retractable roof structure design is mainly used in smaller buildings (sports halls) intended for indoor events, where the open roof is used only occasionally (e.g. favourable weather conditions that do not affect the implementation of activities). This opening method is also used for the relief of the roof structure in the event of large quantities of snow, which slide off the roof during its movement. If the building's playing area is made of natural grass, the open roof is used to provide optimal conditions for grass growth.

Frequency closed - open

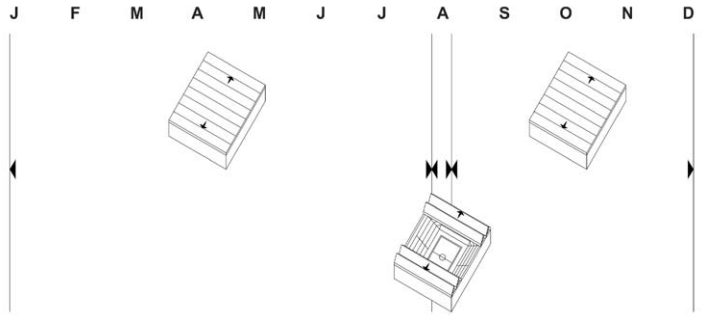


Figure 3: Demonstration of roof structure movement in buildings with primarily closed roofs that are opened only in special cases (annual opening and closing).

Example: Ball Dome sports hall, Fuchumachi Hayahoshi, Japan (1991); roof structure design: rigid; movement frequency: in case of favourable weather conditions; type of movement: sliding, rotation (Figure 4).

Retractable roof structures that are primarily open and are closed if necessary (frequency open - closed) (Figure 5). This type is used for larger buildings (stadiums) that host open-air events and use the retractable roof structure only a few times a year in case of adverse weather conditions. The roof is closed in case of rain, wind, heat or cold.

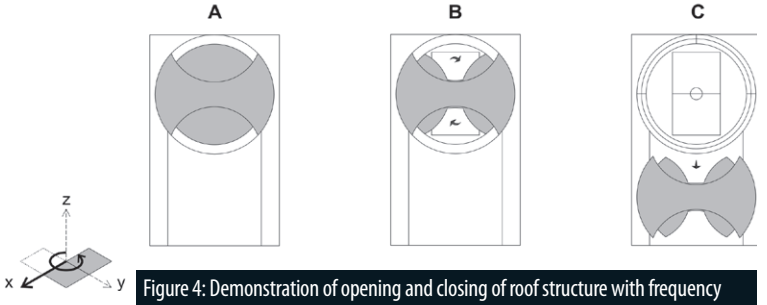


Figure 4: Demonstration of opening and closing of roof structure with frequency closed - open (A - closed, B - half-open, C - open) in Ball Dome Sports Hall.

Frequency open - closed

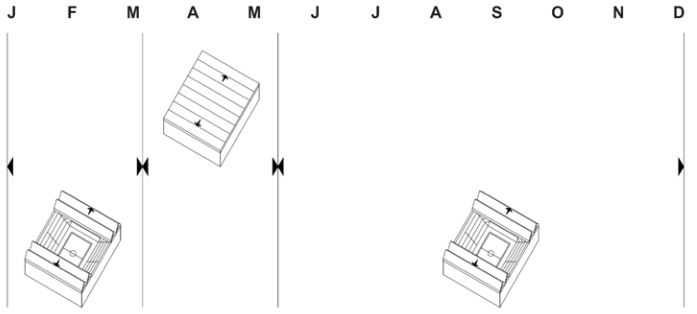


Figure 5: Demonstration of roof structure movement in buildings with primarily open roofs that are closed in special cases (annual opening and closing).

Example: Tennis stadium Waldstadion, Frankfurt, Germany (2005); roof structure design: membrane; movement frequency: depending on weather conditions; type of movement: folding (Figure 6).

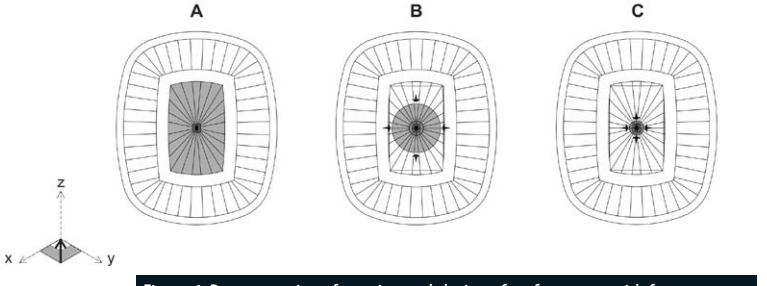


Figure 6: Demonstration of opening and closing of roof structure with frequency open - closed (A - closed, B -half-open, C - open) in Tennis stadium Waldstadion.

Retractable roof structures that are regularly opened and closed (frequency of repetition) (Figure 7). The roof is opened and closed monthly, weekly, daily or several times a day, even with activities taking place. Thus, building users can observe how the roof structure or parts of the structure

are closing and opening. Roof structure movement is creating different atmospheres and different conditions for carrying out various activities. The possibility of constant opening and closing allows the building to adapt to changing weather conditions.

Frequency of repetition

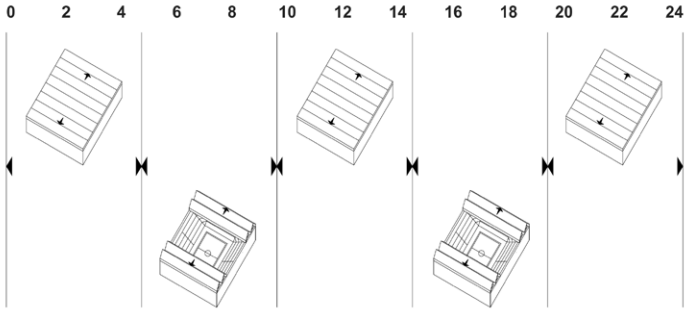


Figure 7: Demonstration of roof structure movement in buildings with regularly opening and closing roofs (daily opening and closing).

Example: Tennis stadium Qizhong Forest Sports City Arena, Shanghai, China (2003); roof structure design: rigid; movement frequency: constantly, also during events; type of movement: sliding (Figure 8).

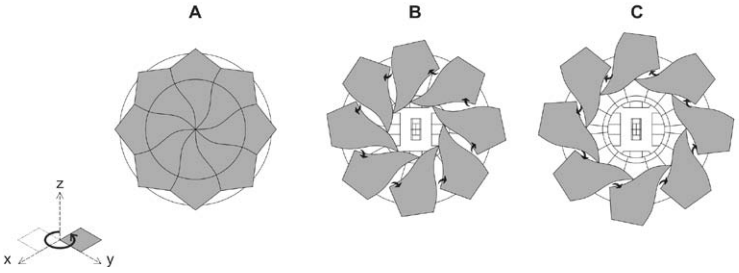


Figure 8: Tennis stadium Qizhong Forest Sports City Arena; demonstration of opening and closing of roof structure with frequency of repetition (A - closed, B - half-open, C - open).

2.2 Typology of retractable roof structures based on structural design

Stadiums and sports halls with retractable roof structures have different structural designs of movable and fixed roof elements. Structures are made of different materials, which vary according to the size of the movable element (range), weight of the movable element, frequency of opening and closing of the movable structure, duration of the move, type of movement of the roof structure, and additional load (high winds, high snow).

Based on the structural design of their movable and fixed elements, retractable roofs in stadium and sports halls can be divided into three types:

- retractable roof structures composed of rigid elements (Figure 9, A);
- retractable roof structures composed of membranes (Figure 9, B);
- retractable roof structures as combination of different elements (rigid elements and membranes) (Figure 9, c).

Structure design of retractable roof elements

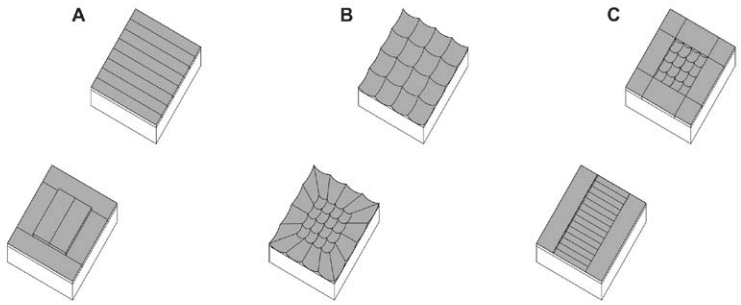


Figure 9: A. Retractable roof structures composed of rigid elements; B. Retractable roof structures composed of membranes; C. Retractable roof structures composed of a combination of rigid elements and membranes.

Retractable roof structures composed of rigid elements. The entire roof or individual smaller parts of the retractable roof are composed of rigid elements that are moving in various ways. Example: Wembley Football Stadium, London, UK (2007); structure design of fixed and movable roof elements: rigid; type of movement: sliding (Figure 10).

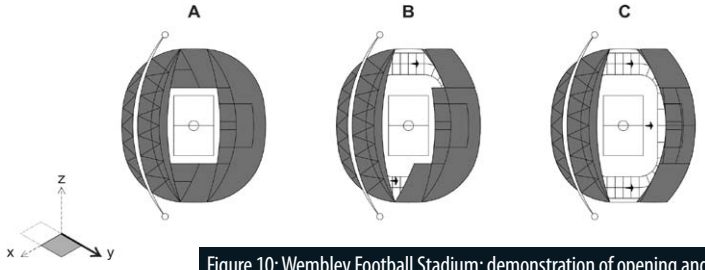


Figure 10: Wembley Football Stadium; demonstration of opening and closing a rigid roof structure (A - closed, B - half-open, C - open).

Retractable roof structures composed of membranes. The entire roof or individual smaller parts of the retractable roof are membranes that are moving in various ways. Example: Tennis Stadium Rothenbaum, Hamburg, Germany (1997); structure design of fixed and movable roof elements: membrane; type of movement: folding (Figure 11).

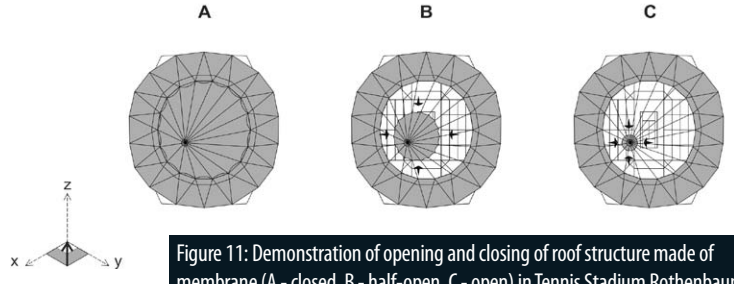


Figure 11: Demonstration of opening and closing of roof structure made of membrane (A - closed, B - half-open, C - open) in Tennis Stadium Rothenbaum.

Retractable roof structures as combination of different structure designs. Entire roof or individual smaller parts of the retractable roof are composed of different elements that are moving in various ways. Example: The Big "O" Olympic Stadium, Montreal, Canada (1976); structure design of fixed and movable roof elements: rigid, membrane; type of movement: folding (Figure 12).

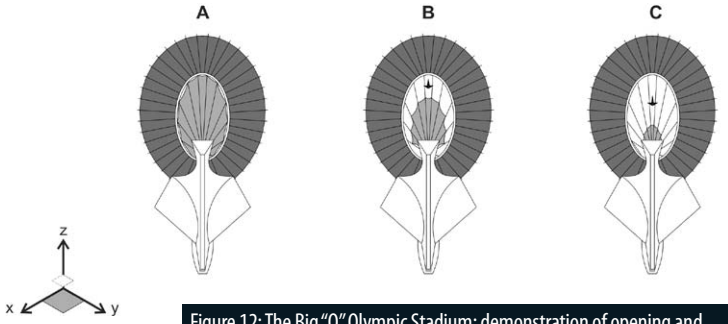


Figure 12: The Big "O" Olympic Stadium; demonstration of opening and closing of roof structure composed of different elements (rigid, membrane) (A - closed, B - half-open, C - open).

2.3 Typology of retractable roof structures based on type of movement

The selection of a retractable roof structure with a specific type of movement during design and realisation of stadiums and sports halls depends on the following: purpose of the retractable roof structure; duration of roof structure movement; frequency (repetition) of open and/or closed roof structure; building size and size of movable elements.

Based on the type of movement, different types of retractable roof structures can be identified:

- roof structures with sliding system;
- roof structures with lifting system;
- roof structures with rotating system;
- roof structures with folding system;
- roof structures with expendable system;
- roof structures with combined system.

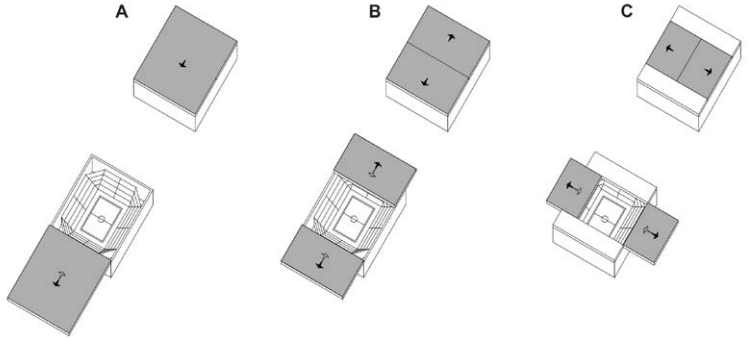
Roof structures with sliding system

Definition of the sliding system: A roof structure with sliding system is moved by sliding in the horizontal direction (Figure 13).

Design of roof structures with sliding system

Examples: Ariake Colosseum Hall, also known as Ariake Tennis Forest Park, Japan (1987), represents a building with a rigid retractable roof structure. The entire roof structure is composed of two elements and moves by sliding in the longitudinal direction, transforming the building's structure from closed to open roof and vice versa. The roof is composed of steel truss

Figure 13: A. Sliding of the entire roof structure; B. Sliding of individual parts of the roof structure (movement in the longitudinal direction of the building); C. Sliding of smaller parts of the roof structure (movement in the transverse direction of the building).



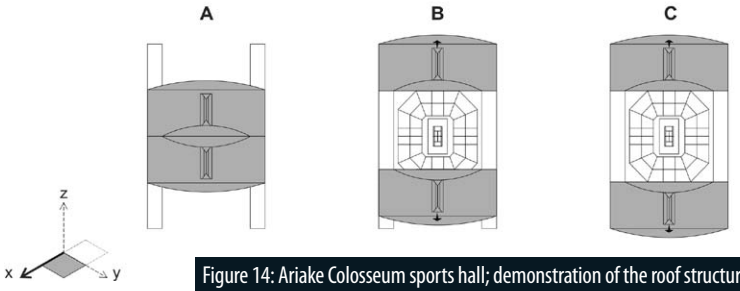


Figure 14: Ariake Colosseum sports hall; demonstration of the roof structure sliding in the longitudinal direction (A - closed, B - half-open, C - open).

and the load bearing steel pillars, and moves (slides) on rails by means of electric motors. By retracting the roof the entire floor area of the building opens (Figure 14).

Another example of the horizontal movement of a rigid roof structure is Amsterdam Arena, Netherlands (1996). The roof of the covered stadium is composed of one fixed and two movable elements, which are moved horizontally in the transverse direction of the building. Steel lattice of the movable roof structure slides along two main transverse beams by means of wheels and electric motors. With movement of the roof elements the entire playing field opens up, while stands remain under the fixed part of the roof (Figure 15).

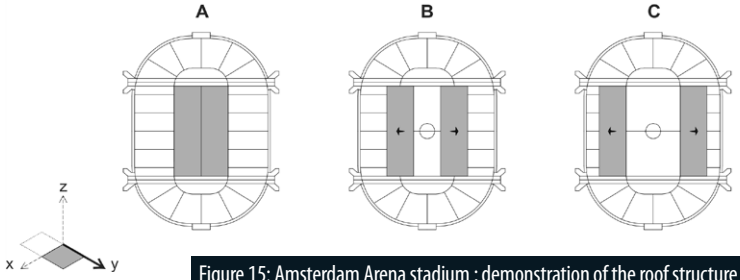
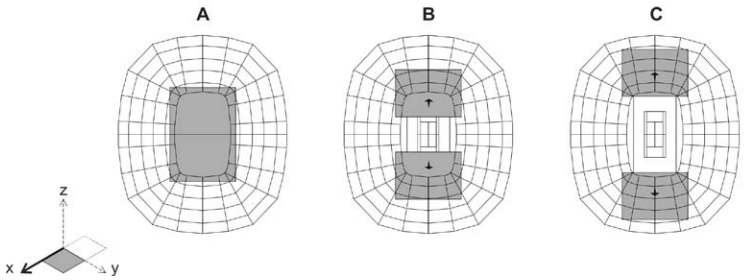


Figure 15: Amsterdam Arena stadium ; demonstration of the roof structure sliding in the transverse direction (A - closed, B - half-open, C - open).

The third example illustrates the sliding system in a membrane roof. Gerry Weber Tennis Stadium, Germany (1994) is realised with a fixed and movable roof structure (Picture 14). The movable element is made of two parts which cover up the playing area. The lightweight construction slides along cradles by means of a winding system placed beneath the level of the fixed roof, changing the building's structure from closed to open roof and vice versa. The roof structure is characterised by lightness, simple control, and transparency that allows light coming into the building even with a closed roof (Figure 16).

Figure 16: Gerry Weber Tennis Stadium; demonstration of roof structure with sliding system (A - closed, B - half-open, C - open).



Roof structures with lifting system

Definition of lifting system: Roof structure with lifting system is lifted and lowered to a desired height (Figure 17).

Design of roof structures with lifting system

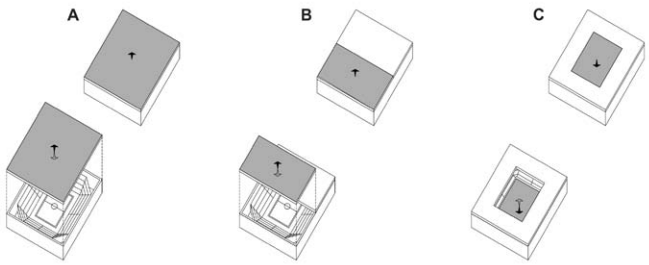


Figure 17: A. Lifting system opening entire roof structure; B. Lifting system opening individual roof parts (roof structure lifting); C. Lifting system opening individual roof parts (roof structure lowering).

Roof structures with rotating system

Definition of rotating system: Roof structures with rotating system are rotated around the axis (Figure 18).

Examples: Civic Arena, USA (1961) is the first sports hall with a rigid retractable roof structure. The retractable roof structure of stainless steel was fully opened and closed by rotation around the vertical axis. It consisted of the main supporting arch and eight movable elements, of which six separate roof elements were circularly rotated and stacked. The elements were rotated by means of a moving mechanism consisting of rails, wheels, and electric motors. The building partially collapsed on its own and was completely demolished in 2012 (Figure 19).

Design of roof structures with rotating system

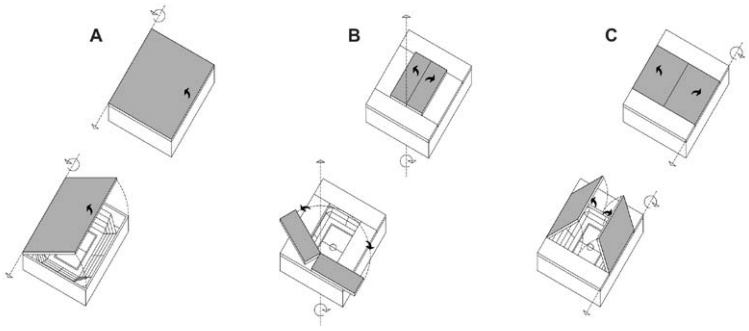


Figure 18: A. Rotation of the entire roof structure; B. Rotation of individual roof parts (rotation around the vertical axis); C. Rotation of individual smaller roof parts (rotation around the horizontal axis).

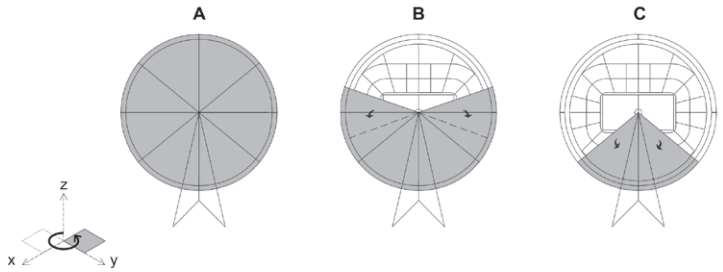


Figure 19: Civic Arena sports hall; demonstration of the roof structure rotation around the vertical axis (A - closed, B - half-open, C - open).

The multipurpose sports hall La Caja Mágica, Spain (2009) with a rigid steel roof structure has a combination of rotating and sliding systems. The building's roof is opened and closed with only one type of moving system or combination of both. Roof rotation around the horizontal axis is enabled by telescopic columns for each of the movable elements that change the roof pitch (Figure 20).

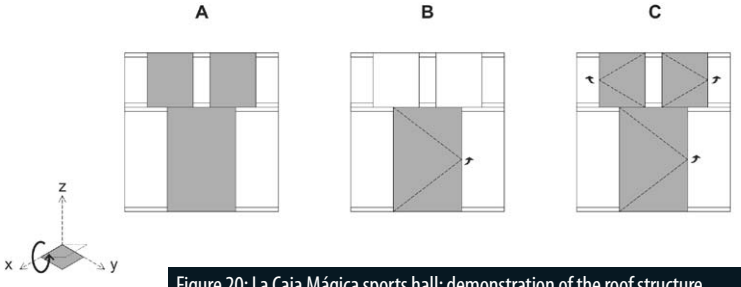


Figure 20: La Caja Mágica sports hall; demonstration of the roof structure rotation around the horizontal axis (A - closed, B - half-open, C - open).

Roof structures with folding system

Definition of folding system: A folding system enables elements of roof structures to be folded (Figure 21).

Design of roof structures with folding system

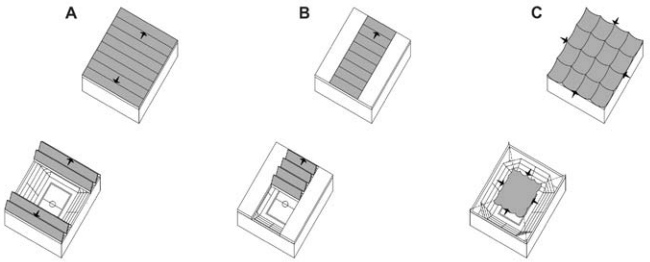


Figure 21: A. Folding of the entire roof structure B. Folding of individual roof parts (folding in the longitudinal direction of the building); C. Folding of individual smaller roof parts (folding into the centre of the building).

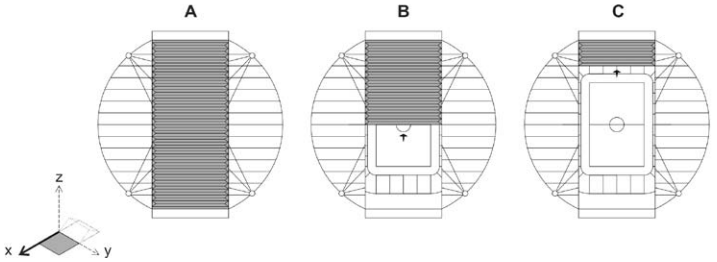


Figure 22: Toyota Stadium; demonstration of roof structure with folding system (A - closed, B - half-open, C - open).

Examples: Toyota Stadium, Japan (2001) illustrates a retractable roof structure composed of membranes that can be folded at the shorter side of the building. The roof is composed of fixed and movable elements. The fixed part of the roof covers stands along the longitudinal side of the playing area, while the movable elements cover stands at the transverse side of the playing area (Figure 22).

Waldstadion, Germany (1925) is a football stadium that was renovated in 2005. It has one of the largest retractable roof structures in the world. Stands are covered by a fixed roof structure, while an almost rectangular foldable membrane hovers over the playing field. Cradles of the foldable membrane are made of steel ropes that run from the centre and connect the support frame to form the roof. The roof membrane is folded into the centre of the stadium.

Roof structures with expandable system

Definition of expandable system: An expandable system is used to expand and contract the roof structure.

Example: Iris Dome was designed by inventor Chuck Hoberman. The design was first publicly exhibited in the Museum of Modern Art (MoMA) in New York in 1991 and introduced a new type of retractable roof that closes and opens like the iris of the eye. The retractable roof structure is composed of rigid panels or membranes attached to frames; they glide over one another to form a continuous surface in the form of a complete dome when fully extended (Figure 23).

Roof structures with expandable system

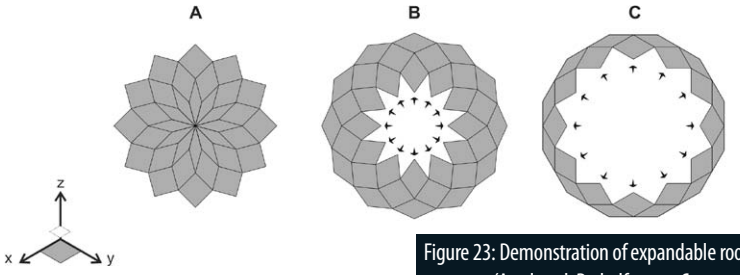


Figure 23: Demonstration of expandable roof structure (A - closed, B - half-open, C - open).

Roof structures with combined systems

Definition of combined systems: The roof structure is retracted by utilizing a combination of different systems (Figure 24).

Design of roof structures with combined systems

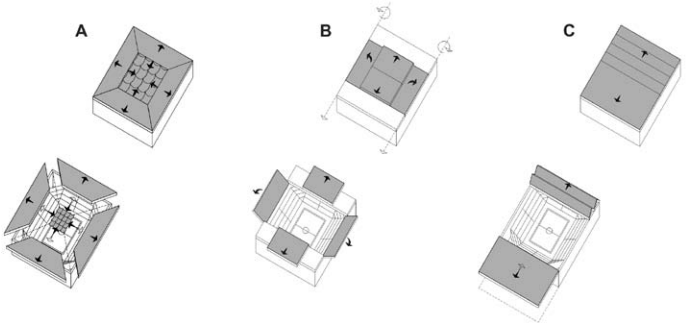
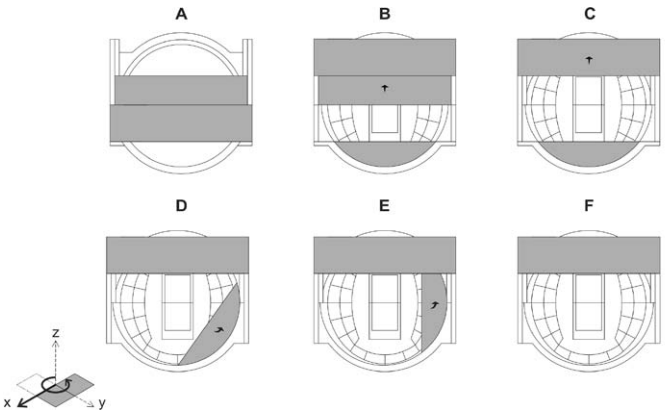


Figure 24: A. Retraction of entire roof structure with rigid elements and membrane (sliding system, folding system) B. Retraction of individual rigid roof parts (sliding system, rotating system); C. Retraction of entire rigid roof structure (sliding system, folding system).

Example: Toronto "Skydome", Canada is a multipurpose stadium, built in 1989. The geometry and design of the rigid retractable roof structure are very complicated and are result of a design that enables independent movement of elements (rotation, sliding). Movement is enabled by a mechanism of rails, wheels and electric motors that stacks four autonomous parts of the roof structure on the side of the building, opening up 90% of the floor area (Figure 25).

Figure 25: SkyDome stadium; demonstration of a combination of sliding and rotating of the roof structure (rotation around the vertical axis) (A - closed, B - partially open; 30%, C - half-open; 50%, D - partially open; 70%, E – open; 90%).



2.4 Architectural design of retractable roof structures

The architectural design of stadiums and sports halls with retractable roof structures follows compositional starting points adjusted to movement and a different functional design of the building as the building's structure changes from closed to open roof with opening and closing of the roof. Retractable roof structures increase the variety of possible activities taking place inside the building. All this affects the functional design and layout of the building as well as the size and number of supporting facilities. In case of multipurpose use of space it is necessary to adapt the design of the building (floor plans, sections) to requirements of different activities (size of event space, number of visitors, and type, number and size of supporting facilities).

Buildings with retractable roof structures have special properties, requirements and conditions that need to be taken into account and put attention to during planning (Schumacher, M., Schaeffer, O., Vogt, M., 2010; Ishii, K., 2000):

- the impact of movement on building users (feeling, experience);
- issue of safety during opening and closing of the roof structure;
- the speed of opening and closing of the roof structure;
- degree of openness of the building during movement of the roof structure (fully or partially open);
- multipurpose use of space in various positions of the retractable roof structure;
- impact of shade created by retractable roof structure;
- impact of wind when the retractable roof structure is open;
- characteristics of the space formed by closed or open retractable roof structure;
- type of building (open building, which a retractable roof structure changes to closed or closed building, which a retractable roof structure changes to open);
- installations design of movable elements;
- fire safety plan during the process of opening and closing of the roof;
- economic efficiency or viability of a retractable roof structure;
- influence of retractable roof structure on building management;
- cost increase arising from the movement of the roof structure.

In architectural design, movement of a roof structure may also appear as an act that allows the fundamental movable system to assume a new feature. With a specific moving system or a combination of them the following can be achieved:

- movable roof element transforms into stands (increased building's capacity) (Figure 26, A);
- movable roof element transforms into a roof outside the building (increased number of activities that can take place inside or outside the building) (Figure 26, B);
- movable roof element transforms into playing area (more playing areas inside the building) (Figure 26, C);
- retractable roof structure creates new space (more event spaces inside the building) (Figure 26, D);
- retractable roof structure transforms the building from stadium to hall (merging two building types into one) (Figure 26, E);
- retractable roof structure changes the building size (building adapts to the number of activities or visitors) (Figure 26, F).

Multipurpose use of retractable roof structures achieved with different moving systems

2.5 Constructural design of retractable roof structures

Use of retractable roof structures, research of structure features and technology solutions for the design of retractable systems allow us to take advantage of the moving elements to enhance the building's efficiency and adaptability to different needs of users, which is an architectural and engineering challenge.

Retractable roof structures are elements that bridge large spans, are heavy, have larger dimensions, and their movement takes place at high altitude. The increasing frequency of opening and closing of a roof structure also increases the interval of forces acting on the structure and deterioration of material due to continuous friction. During movement, both static and dynamic forces are most heavily acting on the moving mechanism and the roof's supporting structure. Weight of a retractable structure (the movable element) is composed of a top layer of the roof (outside layer), a load-bearing structure of the movable element, an inner layer of the roof (ceiling), and different elements of the installation and moving system. Further forces represent various additional loads such as snow, wind and other natural phenomena. Roof constructions can be made from various materials, such as steel, wood, concrete, high-quality steel, cables, braided cables, and recently carbon fibres and tapes, special membranes, or a combination of different materials. Retractable roof structures are moved using various moving mechanisms and leads that have been taken mainly from the industry

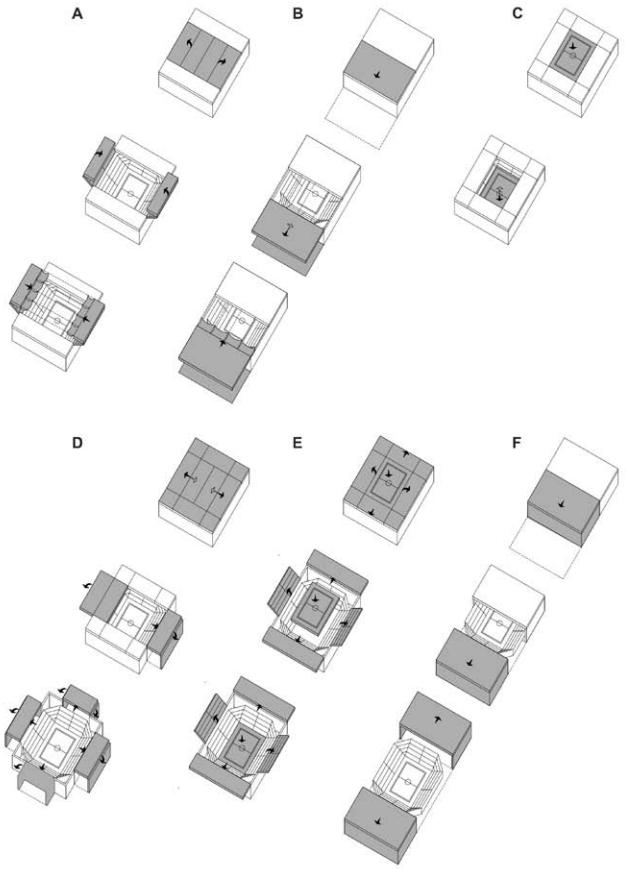


Figure 26: A. Movable roof element as stand (stand capacity change; open part of the building is covered by a folding membrane); B. Movable roof element as roof of the outdoor event space (different event spaces; open part of the building is covered by a folding membrane); C. Movable roof element as additional vertically movable playing area (different playing areas). D. Movable roof element as new space (different event spaces; movable roof parts create new volumes); E. Movable roof element as stand, event space (stand capacity change) F. Movable roof element as increase of event space (implementation of different activities).

(shipyards, oil platforms, ports). Thus, different wheels and electric motors, push systems, hydraulic lifts or winding cables are used that move the roof structure along cradles (rails) or surface (fixed part of the roof structure, secondary beams). The surface on which the retractable roof structure moves or rests has its specific constructional features, which are characterized by a large load weight, large point loads and load forces when moving and stopping. In all listed characteristics and requirements that determine the type and construction of the retractable roof structure the safety of building users and passers-by is of paramount importance.

2.6 Movement of fundamental systems of stadiums and sports halls

Adaptability of stadiums and sports halls has been characteristic for both building types since the beginning of their development (Nixdorf, S., 2009). The development of retractable roof structures has proceeded in parallel with the development of other mobile systems of a building (playing area, stands, and facade) because these methods and systems of movement are alike. The stadium and sports hall are becoming building types, in which most fundamental systems are moving to achieve flexibility in the implementation of various activities. Thus, various methods of movement of their fundamental systems have developed (Figure 27):

- movement of playing field within or outside the building (Figure 27, A): sliding system, lifting system, rotating system, combination of different systems. Movement of playing field allows the implementation of various activities inside the building and relocation of the playing area to the exterior of the building, where there are more suitable conditions for natural grass growth covering the pitch. Examples: University Sports Hall, Ljubljana, Slovenia (1997); moving system: lifting and lowering of playing area inside the building. Sapporo Dome, Sapporo, Japan (2001); moving system: sliding and rotating of playing area inside and outside the building. Cardinals Stadium, Glendale, Arizona, USA (2006); moving system: sliding of playing area outside the building.
- movement of stands within or outside the building (Figure 27, C): sliding system, lifting system, rotating system, folding or telescopic system, combination of different systems. Movement of stands allows adjustment of building's capacity (number of visitors), changes the shape of the auditorium in relation to the visitors' focus (longitudinal or central focus), and relocation of stands to the exterior of the building. Examples: Grand Stade, Saint-Denis, Paris, France (1994); moving system: sliding of stands. Crystal Ballpark, Seoul, Korea (1997); moving system: rotation of stands. Reyno de Nevarra Arena, Nevarra, Spain (2012); moving system: folding, lifting and lowering of stands.
- movement of facade (Figure 27, D): sliding system, lifting system, rotating system, folding system, combination of different systems. Facade movement has come about primarily as result of the need to facilitate movement of building's other fundamental systems. Examples: AT&T Stadium, Texas, USA (2009), moving system: sliding of facade. Olympic Basketball Arena, London, UK (2011); moving system: folding of facade.

An increasing number of stadiums and sports halls use at least one movable fundamental system; efficiency of movement is evident in the design of buildings with a combination of movable fundamental systems, since such buildings can adapt to almost any activity (sports, cultural, trade fair, and congress). The effectiveness or efficiency of the use of movable fundamental systems is achieved by taking the movement into account in the planning phase of the building's construction as in this way it is feasible to anticipate the possibility of multipurpose use of the building.

3. CONCLUSION

Typology of retractable roof structures provides basic guidelines for the design of stadiums and sports halls whose fundamental objective is flexibility to achieve high quality of the greatest possible number of different events and performances throughout the year. The frequency of movement, structural design, and types of movement have so far followed only the

Movable fundamental systems

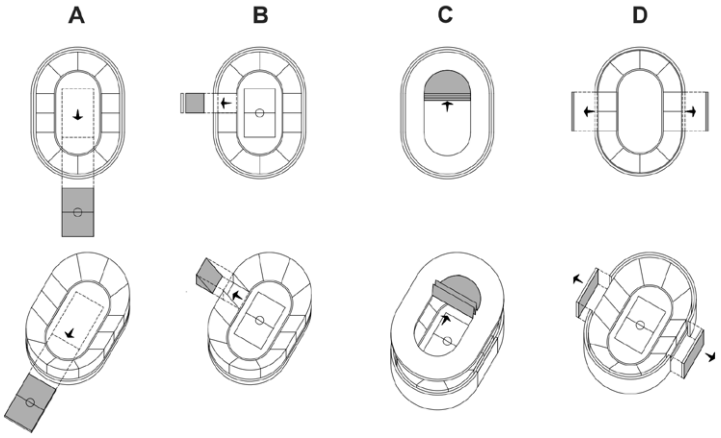


Figure 27: A. Movable playing areas; B. Movable stands; C. Movable roofs, D. Movable facade.

mentioned objective. Using movement in terms of changing the core functions of the fundamental system, a new meaning is added to the movable element. The purpose of retractable roof structures is not only to protect users from weather, increase the number of activities inside the building or provide ideal conditions for grass growth on the pith, but also to change the capacity of stands, increase the number of event spaces, achieve several different kinds of playing areas, and increase or decreases the event space size. All described acts are achieved through various methods and systems of movement and by a predetermined function (one or more) the fundamental system will assume. Planning of such a type of building requires a predetermined plan for transformation of a building or changing the characteristics of individual fundamental systems. Combining different types of movement and various functions of the moving system allows a range of different new forms of buildings that can adapt to daily changes, thereby allowing multiple use of space that provides high quality or equal conditions for all users. A building designed in this way enables high-quality and efficient management of the building and allows implementation of a maximum number of activities, which justifies the economical aspect of construction, use and maintenance of such building.

LITERATURE

About.com (2015). Mellon Arena, 66 Mario Lemieux Place, Pittsburgh, PA. About.com, Pittsburgh. Accessed online on 18 September 2014: http://pittsburgh.about.com/od/penguins/l/blmellonarena.htm.

ArchDaily (2015). "Olympic Tennis Centre / Dominique Perrault Architecture" 18 May 2012. ArchDaily. Accessed online on 16 September 2015: http://www.archdaily.com/235544/olympic-tennis-centre-dominique-perrault-architecture.

Barton, L. (2014). Retractable Stadium Roofs & Flooring. Accessed online on 18 September 2014: http://enr.construction.com/features/buildings/2008/archives/docs/Retractable_Stadium_Roofs_and_Flooring.pdf.

Bielinski Kierkuć, J. (2012). Stadia: Sport and Vision in Architecture. The Modern Stadium: Antiquity: Greek tradition and roman innovation. Panem et Circenses: Rome, Games and Empire, pgs. 18– 47. Sir John Soane's Museum, London.

Connolly, P., Dodge, H. (1998). The Ancient City: Life in Classical Athens & Rome. Oxford University Press, Oxford.

Detail 2015. Multi-purpose Venue: Grand Stade de Lille Métropole. Detail, English Edition 2/2015. Detail-online. Accessed online on 21 April 2015: http://www.detail-online.com/architecture/topics/multi-purpose-venue-grand-stade-de-lille-metropole-022422.html.

Drew. P. (2008). New Tent Architecture. Thames & Hudson, London.

Futagawa, Y. (2007). GA: Contemporary Architecture 09, SPORTS, A.D.A. EDITA, Tokyo.

Gannon, T. (2008). Eisenman Arhitects: University of Phoenix Stadium for the Arizona Cardinals. Princeton Architectural Press, New York.

Hoberman Associates (1994). Iris Dome at the MoMA. Accessed online on 22 September 2014: http://www.hoberman.com/portfolio/irisdome-moma.php?projectname=Iris+Dome+at+The+MoMA.

Ishii, K. (2000). Structural Design of Retractable Roof Structures. IASS, WIT Press, Boston.

Janberg, N. (2015). International Database for Civil and Structural Engineering, Structure. Sant Jordi Sports Palace. Accessed online on 5 September 2015: http://structurae.net/structures/sant-jordi-sports-palace.

John, G., Sheard, R., Vickery, B. (2013). Stadia: A design and development guide, Fifth edition. Architectural Press, Elsevier Limited, Oxford.

Jordana, S. (2011). "Floating OffShore Stadium / stadiumconcept". 25 May 2011. ArchDaily. Accessed online on 3 May 2015: http://www.archdaily.com/?p=138162.

Jensen, F.V. (2001). Cover elements for retractable roof structures. University of Cambridge, Department of Engineering. Accessed online on 18 October 2015: http://www-civ.eng.cam.ac.uk/dsl/publications/fvjfirstyear.pdf.

Kitazawa, A. (2006). Jean Nouvel, 1987–2006. Architecture and Urbanism, April 2006 Special Issue 06:04. A+U Publishing.

Kassabian, P. E., You, Z., Pellegrino,S. (1999). Retractable roof structures. Accessed online on 10 October 2015: http://www.pellegrino.caltech.edu/PUBLICATIONS/Retractable%20roof%20structures_1999.pdf.

Kronenburg, R. (2007). Flexible: Architecture that Responds to Change. Laurence King, London.

Leskovec, B., (1998). Nekateri vidiki pri zasnovi športnih dvoran, Gradbeni vestnik, 1-2, 1998, pgs. 9–18.

Maffei, A. (2002). Toyo Ito: Works, Projects, Writings. Electa Architecture, Milan.

Mais, D. (2015). UNLV Now! Events Centre, Maisstudio. Accessed online on 21 April: http://www.meisstudio.com/unlv-now.

Masubuchi, M. (2013). CONCEPTUAL AND STRUCTURAL DESIGN OF ADAPTIVE MEMBRANE STRUCTURES WITH SPOKED WHEEL PRINCIPLE – FOLDING TO THE PERIMETER. Accessed online on 14 October 2015: https://opus4.kobv.de/opus4-tuberlin/files/3664/masubuchi_motoi.pdf.

McConnell, C. (2015). Home Sweet Dome. Pittsburgh Magazine. Accessed online on 27 April 2015: http://www.pittsburghmagazine.com/core/pagetools.php?pageid=12409&url=%2FPittsburgh-Magazine%2FJuly-2010%2FHome-Sweet-Dome%2F&mode=print.

Morgan (2015). Kinetic Structures Capabilities, OPERABLE ROOF SYSTEMS, Rogers Centre (formerly Toronto Skydome). Morgan, kinetic Structures. Accessed online on 27 April 2015: http://www.morganengineering.com/k_capabilities.php.

Nixdorf, S. (2008). Stadium Atlas: Technical Recommendations for Grandstands in Modern Stadia. Ernest & Sohn, Berlin.

Pittsburgh Hockey.net (2014). The Civic Arena (Mellon Arena) History 1961 – Present. Accessed online on 18 September 2014: http://pittsburghhockey.net/old-site/Common/CivicArena/CivicArena.html.

Smith, K. (2002). Current Technologies and Trends of Retractable Roofs. Accessed online on 22 September 2014: http://dspace.mit.edu/bitstream/handle/1721.1/85746/52849249-MIT.pdf?sequence=2.

Sheard, R. (2001). Sport Architecture. Spon Press, London.

Schumacher, M., Schaeffer, O., Vogt, M. (2010). Move: Architecture in Motion – Dynamic Components and Elements. Birkhäuser, Basel.

Yoshida, N. (2006). Jean Nouvel 1987–2006. Architecture and Urbanism, April 2006, Special Issue, Tokyo.