AN EVALUATION OF TRANSFORMABLE SPATIAL FRAME (PLATE) ARCHITECTURAL STRUCTURE

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Abstract—Transformable architecture is a suitable strategy for buildings that need to be reconfigured, either by being folded to a compact form for ease of erection and transportation or by changing their geometry and shape, in order to be able to respond to altering functional and aesthetic requirements. The design of this type of building involves general architectural design criteria in terms of form, function and aesthetics, but must also incorporate the special methods needed to make portable, adaptable, lightweight and reusable strategies. In this paper, the major types of transformable spatial frame structures are classified and examined in terms of structural principles and transformation mechanism, in order to explore their potential applications in the field of flexible, adaptable and kinetic intelligent architecture. This research evaluates this type of structures in terms of design, Construction, Maintenance and application and will summarise their main design consideration that should be considered by designers from early stage of design through construction and maintenance.

Keywords—Transformable, Spatial Frame structures, Deployable, Movement, Adaptability

I. INTRODUCTION

A transformable structure consisting of a two-dimensional or three-dimensional rigid plate supported by a secondary structure, which is moved by means of a mechanical driving system without changing its shape during motion, is described as a transformable frame structure. A transformable frame structure is usually divided into several parts that are independently supported by a secondary structure. All separate retractable frames are overlapped or connected in the fully closed state where they should be properly integrated, in order to achieve sufficient stability and rigidity to withstand external loads. These structures are usually applied in retractable roofs, a design selection that has developed very rapidly during recent years. Unlike the other type of transformable architectural structure, in which the transformation is performed by the retraction or expansion of the transforming components, all the structural and architectural elements remain intact (in most cases) during movement. One of the crucial challenges to consider in the design of these structures is to find a proper method to fill in the gap between the moveable panels. The solution should not interfere with the movement of individual panel, however, it must prevent leakage of rain, snow and wind. This issue is not only structurally important but it also can affect the quality and performance of the architecture [1]. One of the main differences between transformable spatial frame structures and other types of transformable structures lies in the way in which the transformation happens. In most types of transformable structures, structural components expanded or retract during the transformation process, while in frame structure transformation is based on the movement of plates on defined driving tracks. Due to this characteristic, these structures have less impact on the redefinition of architectural spaces as they can only convert a fully closed space into a partially or fully open space, while in many other types structural and
architectural elements can also be deformed during operation. Each moveable part may include a structural frame, a covering material such as a steel plate or membrane, and a driving system that allows the movement to take place on a driving track. As structural elements do not deform during transformation, the issues that determine the architectural characteristics and structural and operational efficiency of this type of structure relate to their transformation configurations, including the transformation patterns, the shape of moveable plates and the relationship between the skeletal frame and the moveable parts together with issues concerning their operation, such as mechanical systems, monitoring devices, the driving track etc. Therefore, this chapter will classify the possible transformation configurations of transformable spatial frame structures and evaluate their potential in the redefinition of architectural spaces [2].

II. TRANSFORMATION CONFIGURATIONS OF SPATIAL FRAME STRUCTURES

Transformation configurations of spatial frame structures play a crucial role in responding to architectural, functional and aesthetic requirements. The selected method of configuration should take into consideration various factors including environmental conditions, function and purpose of the structure, aesthetic considerations and issues relating to the operation and management of the structure. The method of retraction pattern should properly relate to the position of the roof in an open, closed and semi-open configuration, to not only ensure that it meets the required conditions and does not interfere with the function of the space, but also that it achieves an aesthetically pleasant architectural image. Another issue concerning the design of the retractable panel is the selection of the frame structure that supports the roof covering. It should be devised in such a way as to ensure it creates a vibrant, dynamic internal space when the roof is in a closed position. The following diagram illustrates the possible methods of opening and closing of the transformable spatial plate structures. In order to obtain a clear understanding of transformation patterns and their role in the reconfiguration of architecture, the major architectural examples that implement transformable plate structures will be explained and evaluated (Figure 1).

![Movement Pattern of spatial Frame Structures](Figure 1)

A. Linear Movement

In this type of transformation pattern, spatial plates are moved horizontally on linear tracks. Depending on the design requirements panels can be stored somewhere outside the building so that a fully open space is achieved, or they may move or overlap somewhere within the functional space and define a semi-open space. This mechanism is one of the simplest methods of retracting frame structures that may use parallel linear tracks on both ends of the retractable frames. This method is usually applied to a rectilinear plan shape or may be combined with other transformation mechanisms in various plan configurations. Each retractable panel includes a moveable structural frame and covering materials including a steel plate or membrane moving along or overlapping with the linear driving tracks. For example the retractable roof over the Ariake Coliseum completed in 1993 and designed by Kenchiku Mode Kenkyuujo Co. Ltd includes two retractable panels that move horizontally on ground-running tracks. Each panel is an arch-type plane truss girder covered by metallic sheets [2]. This roof operates independently to the main structure of the coliseum toward the central space to create a fully closed space. The retractable roof was added to the pre-existing outdoor facility where the Japan Tennis Tournament was held. The simplicity of its mechanism is operated and supported independently, preventing deterioration of the existing structure and its design. This roof can be used in a fully open, semi-open or
fully closed configuration with the maximum degree of openness being 68% (Figure 2).

*Figure 2: Retraction process of Ariake Coliseum Roof, pictures from (Ishii, 2000)*

The retraction process takes 17.5 minutes with a speed of 3m/min. To prevent damage to the retractable panels, the opening and closing is performed with a maximum wind velocity of 20m/s [1]. Similar to most retractable roofs, this structure was designed to extend the performance of the building for use by both outdoor and indoor activities. As the roof cannot create a 100% degree of openness due to space limitation, the edges of the retractable panels are inclined so that the shadow of the roof does not affect the tennis players. Retractable panels are supported by steel frame structures consisting of inverse quadrangular pyramids. Each section of the roof is moved along the supporting structure by means of a series of driving bogies on reinforced concrete roadbeds set on the ground (Figure 3).

*Figure 3: Details of Driving and operation system, Ariake Coliseum Roof*

One of the most recent examples of retractable frame structures implementing a linear movement pattern is the roof over the Reliant Stadium in Texas, USA. This retractable roof uses a similar driving system to that of Ariake’s roof. It consists of two retractable panels; each is supported by five deep trusses which move along a conventional rail assembly using forty wheels and eighty motors. The roof can open or close in 10 minutes. The main difference in the Reliant stadium, is that in order to keep the weight down and allow the natural grass playing field to be maintained, Nirdais fabric (a type of Teflon-coated fiberglass with 25% translucency) was used as the finishing material over the steel truss framework [3] (Figure 4). The application of the fabric, which is pre-stressed by means of cables over the tri-chord trusses, provides ambient sunlight, even when the roof is in a closed state.

*Figure 4: Reliant stadium retractable roof, pictures from (http://www.worldstadium.com)*

The retractable roof over the Wembley Stadium also includes a retractable roof applying a linear transformation mechanism. The new 90,000-seated Wembley Stadium project has been one of the most controversial projects in London in recent years [4]. The stadium, which is the national arena for English football, can accommodate Cup Finals together with other social events such as music shows. It is the largest covered football stadium in the world. State-of-the-art technology has been implemented for the design and construction of this stadium. One of the key features of the stadium is its partially retractable roof. The centre of the stadium is covered by a retractable roof consisting of retractable panels which retract to the south and are supported by a spectacular arch of 315m span which is the longest single span structure in the world. A series of built-in steel trusses and driving tracks guide the roof during the retraction process (Figure 5). The retractable roof not only develops the function of the building from a covered football stadium to a multi-functional building, it also allows as much daylight and ventilation to reach the pitch level as possible. The roof can be retracted in 15 minutes. The arch plays three main roles in this stadium; iconic,
structural and architectural. Firstly, it acts as a landmark for London which is visible from 13 miles away [5]. Secondly it supports the majority of the roof. Finally, it allowed the architect to eliminate the need for columns within the interior so that every seat has a full, unobstructed view of the pitch. The arch also provides a beacon for the stadium illuminating the north-west London sky on match days. Each segment of the retractable roof has the potential to be retracted separately, so it brings more control and architectural flexibility. It can be argued that this stadium with the integration of tensile, compressive and transformation principles and its consideration of the architectural and environmental requirements is one of the most successful structures in the world built in recent times.

The Civic Arena (Mellon Arena) in Pittsburg, Pennsylvania includes retractable curved walls that operate on circular tracks. This retractable structure consists of eight curved steel panels, which are radially placed and are supported by a huge cantilever arch placed outside of the building. The roof is retracted in less than 3 minutes subject to favorable environmental conditions. The roof has been in operation for more than three decades having been built in 1961. However after renovation in 1995 and the installation of a new scoreboard, the roof is now never opened. The importance of this retractable roof was in the revolutionary architectural design. However, its shortcoming was the leakage of rainwater from the gap between the retractable panels, poor acoustics, and the limitations concerning extending its function for other events. These problems were important lessons for the design of subsequent retractable roof structures (Figure 6).

Figure 5: Retractable roof over Wembley Stadium, B) Roof in open state, C) Steel trusses, pictures from [6]

B-Circular and rotational movement

Transformable plate structures utilizing this retraction mechanism, are open and closed on either horizontal or vertical circular tracks, or are operated around specified pivotal axes. Retractable panels are usually moved or overlapped around the perimeter of their supporting structures and define a retractable roof or they may define an entire transformable building and operate on driving circular tracks on the ground. The degree of openness of this type of structure is usually less that 100% unless the stored roof is moved outside of the perimeter of the building by means of an additional driving system. One of the main properties of this type of structure is that it is possible to stabilize the retractable panels during the sequential stages of the transformation. In this case, retractable panels are moved in separate driving paths and can be operated individually.

Figure 6: The retractable roof with circular transformation over Civic Arena, pictures from (http://www.recentpast.org)

The Ohita stadium is another example of a retractable frame structure implementing a vertical circular transformation mechanism. This building completed in Japan in 2001 for the 2002 World Cup, has a capacity of 40,000 people and was designed in such a way as to serve as a multi-functional venue for various applications ranging from sports events such as soccer games, track and field to cultural events such as music concerts [3]. The roof of the building consists of two spherical layers, including a lower layer, which has three-dimensional single layer arched-framed trusses made of titanium material and a fixed shell, and the upper layer, consisting of two spherical moveable membranes of fibreglass fabric with 25% translucency.
The upper membrane slides over the lower fixed shells in such a way that it resembles huge eyelids (Figure 7). The retractable membranes operate between arches along the curve surface of the dome by means of a cable traction system in 20 minutes. The arches create a visual problem when the roof is open but this method was adopted because of its economic efficiency. The roof is designed to only resist wind velocities of up to 20 m/s. One of the major considerations in design of the building in Japan is to ensure its stability and safety in typhoon wind conditions. This issue usually requires special structural and architectural arrangements so that it increases costs in terms of both the design and construction. In the case of the Ohita dome, the transformation of the roof was considered as a good point in decreasing the cost of the building. The roof is retracted during typhoons (severe weather conditions) so that it overlaps the fixed roof in order to reduce wind loads and minimize the area exposed to the wind. In order to reduce the bending moment caused by the wind, a locking system between the fixed and moveable part is activated. This roof is one of the lowest cost retractable roofs of the world.

C-Combined movement
A transformable frame structure may include moveable sections with different shapes and configurations. On the basis of the architectural requirements or restriction imposed by the plan of a building, retractable panels may move in different geometric driving tracks, ranging from plane and parallel paths to regular and irregular curved routes. This type of transformation mechanism is called a combined movement. Retractable panels may move and be stored somewhere on the perimeter of the building so that they create partially open spaces, or they may be stored in a position outside the perimeter.

The Skydome in Toronto is an early important example of a retractable roof structure utilizing a combined movement. The Sky Dome was completed in 1989, and was the first building incorporating the rigid retractable panels. This stimulated further research and investigation into retractable roof structures. The retractable roof consists of two parabolic arches in the form of a barrel vault in the middle with two panels at each end in the form of a quarter dome. During the retraction, both the middle panel and the dome-shaped panel D operate in a telescopic manner along a combination of linear and circular tracks. Panels B and C retract along the linear paths while panel B rotates 180° until it resets underneath panel B (Figure 8). The gap between the panels is 1.0 m and the panel depth is 4 [7]. The segments of the roof consist of stiff structures of hollow, tubular steel members and in addition include acoustic and thermal insulation, vapour retarder and PVC membranes. The roof is secured by means of half a million fasteners and stiff membranes, to be enable it to resist high speed winds and hurricanes. It can also withstand the accumulative loads of five years of snowfall. The total retraction time is about 20 minutes, with a running speed of 10m/min, exposing 91% of the stadiums seating to the open sky.

The deployable roof covers an area of approximately 32500 m² and has proved its efficiency by its frequent operation of 100 times per year. The safety considerations in its design and construction were established so that it can be operated even when the building is filled to capacity [1]. The roof has an expected lifespan of 100 years. One of the key features of the building is that it can be adapted to

Figure 7: Perspective views of ohita dome stadium with roof in fully open position, pictures from (www.worldstadium.com)

Figure 8: The retraction process of Toronto Skydome, Pictures from (http://www.columbia.edu)
accommodate various events ranging from small-scale to large-scale, by the utilization of the moveable spectator seating (Figure 9). The design of the Toronto Sky Dome was selected in a design competition (Figure 10).

Figure 9: Aerial views of the Skydome, A) Roof in fully open state, B) Roof in partially open state, pictures from (http://mysite.verizon.net)

Figure 10: Skydome retractable roof, A) internal view of the roof, B) Aerial view

D-Pivotal Movement

In this type of transformation, moveable sections are transformed horizontally or vertically under a central pivot. Retractable plates are usually supported and operated by a central structure from one end and are hung from the other end. Moveable sections may operate individually, or simultaneously, by means of a driving system. The main characteristic of a pivotal mechanism is that it enables transformable structures to achieve various spatial configurations. The integration of the structural and architectural features and the ability to create a vibrant environment by the controlled change of the spatial position of the transformable plate, is also of great importance.

The kinetic roof of the Venezuelan Pavilion at the EXPO 2000 in Hanover, Germany is an impressive example of transformable frame architecture, which fulfils both functional and artistic expectations [8]. The roof includes 16 petal-shaped moveable sections in a spirally shaped arrangement and is covered by a cupola (Figure 11). Each petal consists of a curved triangulated steel truss covered by a fabric membrane, pre-tensioned by means of tensile cables in order to achieve structural stability against external forces. The retractable wings radiate outward from the centre in overlapping layers. This monumental roof, which designed to symbolise the landscape of Venezuela, covers a cylindrical-shaped building. It opens and closes like a flower and incorporates the colours of the Venezuelan national flower [9].

Figure 11: The deployment process of the roof over the Venezuelan Pavilion, pictures from (http://www.sl-rasch.de/)

All 16 steel trusses are hinged to the central mast of the pavilion and each is operated by means of an automatically controlled hydraulic piston (Figure 12). In its closed position the foldable roof provides protection from rain and wind, while in its open state it provides shade for a naturally ventilated and lightened exhibition pavilion. The building is naturally lit. The roof is fully deployed in less than 2 minutes and covers a 40m diameter space. In the design, the unity between the structural and enclosure components offers a close interaction with and response to changing weather conditions, but also highlights the symbolic potential of transformable frame architecture.

Figure 12: The arrangement of retractable wings around the central mast, B) Details of hydraulic pistons, pictures from (http://www.sl-rasch.de/)
The Qizhong Tennis Stadium’s roof is a recent example of a transformable spatial plate structure utilizing a pivotal mechanism. The stadium was completed in August 2005 using a new technological design strategy that makes it different from most of the transformable plate structures currently in use around the world [2]. The retractable roof system that covers the central space of the stadium includes eight petal-shaped sections and each rotates around a fixed shaft by means of three concentric driving tracks. Each wing of the roof consists of a steel pipe roof truss covered by a steel plate (Figure 13). The retractable roof is supported by a fixed spatial steel ring-truss of 123m diameter. The idea of this transformable roof stems from Shanghai’s city flower (Magnolia) (Figure 13). Its opening and closing resembles the blooming of a Magnolia Flower. The building illustrates the current development in transformable plate structure design that goes beyond converting an indoor space to an outdoor one. It is an example of the potential of spatial frame structures to integrate technology, science and art.

As a way of summarising the main points arising in this paper the following table (see figure 14) identifies the key issues relating to transformable spatial frame structures.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Evaluation of Transformable Spatial Frame Structures</th>
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<tbody>
<tr>
<td><strong>Design</strong></td>
<td>Flexible modular design is possible. Several individual modules can be assembled to create a large movable structure. One of the main advantages of this type of structure is that each unit can be moved separately by means of a separate operating system.</td>
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<tr>
<td>Expansion and flexibility</td>
<td>As each section of a spatial plate structure keeps its shape and geometry and is not transformed during motion, this type of structure can not be converted to a compact configuration in comparison with many types of transformable structures. However the application of flexible materials such as tensile fabric or pneumatic membrane can help the creation of more compact spatial plate structures in the fully open configuration. It is argued that by changing the level of the pre-tension state, it may be possible to have spatial frame structures with reconfigurable geometry.</td>
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<tr>
<td>Compactability and transportability</td>
<td>They have a high degree of structural stability due to the fact that their skeletal system does not transform during the motion process. Therefore, they are not subject to changing load conditions derived from the movement of structural components as other structures are affected. However environmental loads may affect their operation. The selection of sealing system (if it is not consider properly) may affect structural stability and operation.</td>
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<tr>
<td>Structural stability and deformability</td>
<td>Depending on the proposed operating systems and driving mechanisms, architectural spaces may be obstructed either by static supporting structures or movable components. In application for retractable roof structures, depending on the selected movement mechanism, extra spaces may require outside the main structure to enable the roof to be rested in cases where the building is required to be converted to a fully open space to meet a particular purpose. The use of lightweight material and combined movement mechanism that allow the movable sections to come to a compact configuration are proposed as a strategy to reduce architectural obstruction.</td>
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<td>Architectural obstruction</td>
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**II. EVALUATION OF TRANSFORMABLE SPATIAL FRAME STRUCTURES**
Highly reliable structures. Suitable alternative for large-scale transformable roof structures. However, due to the huge size and high weight of their individual sections, special arrangements should be made to ensure the safety of workers and occupants during the construction and maintenance process. Operating systems should also be designed properly to be able to withstand both internal loads and external forces and guarantee smooth operation.

Special lifting equipment is required for the deployment and construction (related to weight and size of the constituent units). Depending on the type of covering components, special equipment may be needed, for example compressors for pneumatic membranes.

Modular units are manufactured and shipped to the destination. Individual units may be manufactured in several sections and assembled on site. Attention should be paid during the installation process to make sure gaps between different sections are properly sealed when the structure is meant to be fully enclosed as an architectural space.

They can have a high degree of life-expectancy depending on the choices of structural and covering materials. However, depending on the frequency of movement and the weight of movable structures, their operating systems can subject to high degree of wear and tear. To minimize this, special attention should be paid during the design process to properly calculate and analyse all possible forces that may affect the operating system.

Regular inspection is necessary to make sure that the structure is in full working order. The gaps between the movable units should be checked to ensure that it seals when the structure is in the fully closed configuration. The moving paths should be inspected regularly to make sure that they are free of any obstruction.

The maintenance and replacement costs can increase dramatically if the structure fails to operate before the expected period that has been arranged for the planned maintenance programme. Any design mistakes can increase the whole-life-cycle costing of the building and endanger its safety.

Good alternatives for retractable roofs, movable curtains and walls. This type of structure has the potential to be applied to architecture that requires to be transformed in a variety of configurations other than just transforming from a fully open to fully closed state. The application of separately controlled spatial frame modules can extend their applications.

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the design of transformable patterns it is necessary to pay special attention to the effect of the movable panels on the space occupied, in terms of changes of the environmental conditions and the impact of transformation patterns on the quality of the architectural space. As transformable retractable frame structures may occupy more space during the retraction process, it is necessary to evaluate the impact of the transformation mechanism on the adjacent buildings to avoid disrupting the surrounding environment. From a maintenance point of view, the selection of the transformation pattern should be devised in such a way as to ensure that the gaps in transformable modules during and after deployment, do not damage the internal or internal appearance due to the leakage of rainwater or airflow.

IV. REFERENCES


