An Architectural Evaluation of Transformable Roof Structures

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Introduction

The term 'transformable architecture' as used in this paper describes a distinct class of structures that can change their geometry and shape when required. They have the great advantage of speed and ease of erection and dismantling compared to conventional building forms. Buildings that incorporate these structures can not only benefit from the advantages gained by deployability but also from the unique quality and flexibility of the spaces created.

This paper mainly deals with transformable roof structures, which have begun to dominate other structural types for multi-functional and large-scale buildings in recent years. Considerable literature regarding the history, structural concepts, analysis, and calculation of transformable structures exists, but there is little on their architectural application and evaluation. An important factor for architects in the early design stage is to choose the structure that most closely responds to the requirements of their proposal. Architects need to know what type of transformable structural principles can meet their design requirements and most precisely integrate with their architectural ambitions. This is a significant design challenge, especially when a flexible, adaptable and multi-functional space is expected. Better information on this aspect of transformable structural design could result in a more informed choice of system.

This paper reviews recent developments in the area of transformable roofs and explores their architectural potential. It examines some significant examples of transformable structures in order to study their architectural characteristics and the opportunities that they bring to the design of adaptable architecture. The objective of this research is to create a holistic understanding of the major types of transformation systems and their potential architectural applications.

Transformable Roof Structure Systems

Transformable roofs use a type of structure that is attached to a fixed or mobile building, which includes moveable or transformable parts to convert completely, or partially, an indoor into an outdoor space. Transformable roofs allow the redefinition of the enclosure of buildings in order to respond to architectural or structural requirements, or to adapt to disparate environmental situations. The design of transformable roof structures requires special techniques and considerations including construction techniques, materials, structural performance, which make their design more difficult and complex in comparison with conventional static architecture. In recent years major advancements in these areas have made it possible to design more lightweight optimised transformable roofs. Tensile, tensegrity, pneumatic and spatial hinged bars and plates systems have been applied to transformable roof structures using sliding, rotating, linear, scissor and non-configurable mechanisms to allow for the various degree of coverage and exposure of space. This paper examines the principal examples of transformable tensile, tensegrity and spatial bar roof structures so that their degree of success can be evaluated in architectural terms.

There are two major categories of transformable structures: self-supported and non-self-supported structures. The latter category includes structures, which require additional elements, or a secondary supporting structure to ensure their stability and rigidity in the deployed configuration, while the former includes structures that are self-supported in open configurations. Both these types can be used either as a whole building or to be attached to permanent or temporary architecture. Tensegrity and tensile principles are inherently capable of being self-supported structures due to the integration of tensile materials in their designs. Spatial bar systems usually have a finite mechanism though they can also use a mechanical arrangement to lock the structure in a variety of states.

Transformable tensile structures
The application of tensile and tensegrity principles in transformable structures can result in structures which are self-supported in the fully deployed state, which nevertheless can be readily folded when necessary. Fabric tensile membrane structures rely on pre-stress for stability and adequate stiffness. Due to their lightness, high level of compactability, and ease of transportation, the popularity of these structures in temporary and mobile applications has hugely increased in recent years. The success of this type of structure in more ambitious transformable applications depends on the advancement of tensile materials, construction techniques and mechanisms used during their folding process.

Olympic Stadium, Montreal: The retractable roof over the 1987 Olympic Stadium by Roger Taillibert (Fig. 1) covered an elliptical area of c.19,000m² [Ishii 1999] and is an important early example of transformable architectural design [Asefi & Kronenburg 2005]. The membrane was tensioned and controlled by cables from a tower and was connected to the building's concrete roof at its periphery. Although the membrane gains its stability and rigidity by pre-tensioning forces, it is sustained by the supporting concrete structure when fully deployed. The PVC retractable membrane roof remained in operation for ten years before being replaced by a fixed Teflon-coated Fibreglass structure.

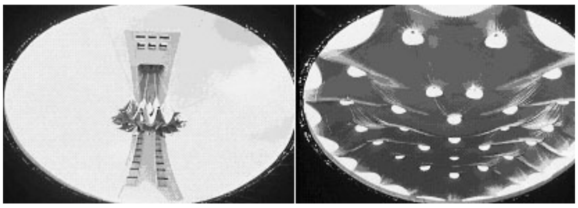


Figure 1. Olympic Stadium, Montreal.


Figure 2. Allianz Arena in Munich

Allianz Arena Suspended Ceiling, Munich: The most recent important example of a transformable tensile roof structure is the suspended ceiling for the new stadium by Herzog de Meuron, the Allianz Arena, host to the opening match of the World Cup in 2006 (Fig. 2). Its suspended retractable ceiling permits natural light to enter the building. Radially placed retractable membranes are supported by steel beams constructed under the transparent air-inflated roof of the stadium and are retracted by cables. The retractable membrane in this remarkable stadium allows the turf pitch to grow but also to control the building's visual and climactic environment.

Transformable Tensegrity Roofs
Tensegrity structural strategies utilise both tensile and compressive elements to reduce the overall weight of the roof and they can also be folded into a very small bundle making them a good alternative for transportable buildings. Analytical studies have proven that with a small change in energy, tensegrity structures can change their shape substantially increasing their potential for application in flexible and adaptable architecture [Skelton *et al* 2001].

The typical definition of a tensegrity structure is a system in a stable self-equilibrium state comprising a discontinuous set of compressed components inside a continuum of tensioned components.

However, the majority of tensegrity ‘type’ structures that are currently in use for large-scale buildings are supported by secondary structures, and although many of them employ discontinuous compression components and continuous tension components, they are not self-stabilised. During recent years much research has been carried out regarding the possible application of tensegrity structures in architecture but there are still only a few buildings in existence. It can be argued that one of the most complicated issues in the design of transformable tensegrity structures is the creation of a suitable transformation mechanism to control the process of folding and deployment. This challenge can be resolved more easily in temporary small-scale buildings - in large-scale repeated transformation roofs it is still under investigation, however, examples of fixed and immobile strut-cable roofs may provide clues to future development in this area.

Phoenix Central Library: The tensegrity roof over architect Will Bruder’s Phoenix Central Library, Arizona, USA is an impressive example of the application of a cable-truss system in architecture. The roof covers the 11.6m high vloume of the main reading room (Fig. 3). It is supported on tensile cables anchored into the steel caps bolted to the tapered columns, and are braced by steel struts. Twenty-two circular skylights and a strip of glazing set into the roof perimeter give it the sense of a floating structure. The tensegrity roof is an important feature of the reading room that integrates structural, architectural and monumental functions. Although the roof is not transformable its impressive features suggest that tensegrity principles could be an exciting alternative for long-span transformable spaces in which massive structural elements can be avoided.

Figure 3. Phoenix Central Library.

Georgia Dome

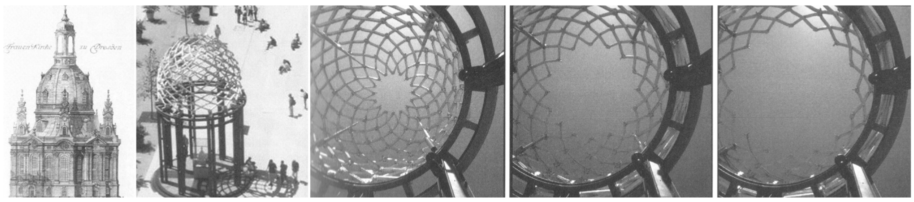
Georgia Dome, Atlanta: The Georgia Dome (Fig. 4) is a milestone in the development of tensegrity structures. The cable-dome structure is supported by an outer concrete ring placed on fifty-two columns at twenty-six attachment points. The Teflon-coated fabric membrane roof includes an upper triangulated network of cables, which is connected to three tension hoops located 20.7m, 47m and 76m from the outer beam by means of compression posts [Ishii 1999]. The flying posts are tied together by cable hoops and are held back by diagonal cables.

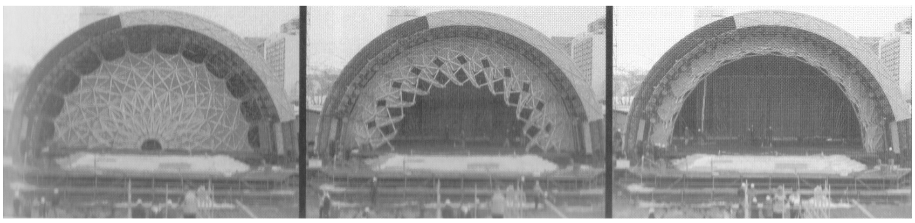
Figure 4. Georgia Dome, Atlanta.

The Georgia Dome is the largest dome in the world and consequently indicates the great potential of tensegrity structures for large multi-purpose buildings. The integration of the structural elements, the translucent membrane covering, monumental features of the building (especially at night), and most importantly, convertibility of the building from a football stadium to other uses is a turning point in the development of tensegrity principles for architectural applications. Another important feature of this building was its short design and construction period of just thirty months principally resulting from prefabrication of the structural elements.

Spatial bar structures
Pantographic and scissor principles are one of the earliest structural systems applied for transformable architecture. The *Yurta* transportable nomad dwelling is an exemplar of the flexible benefits of scissor mechanism design [Kronenburg 2003]. These lattice expandable structures consist of bars linked together by scissor hinges allowing them to be folded into a compact bundle. Although many impressive architectural applications for these mechanisms have been proposed (Calatrava, Hoberman and Escrig are the most important experts in this area), due to the mechanical complexity of their systems during the folding and deployment process few have been constructed at full-scale.

Iris Dome: A remarkable example of a transformable roof employing scissor-like mechanism is Chuck Hoberman's Iris Dome. In 1998, he was invited to construct an architectural scale example at the Expo 2000 in Hanover, Germany, symbolizing the destruction and rebuilding of the Frauenkirche Cathedral [Hoberman 2005] (Fig. 5). The dome utilised a set of pantographs connected together around a hemisphere, powered by means of four computer-controlled hydraulic pistons situated on its perimeter. Hoberman employed these same structural principles in two-dimensional form for the Mechanical Curtain, an award stage at the Winter Olympic Games, USA in 2002 (Fig. 6). The curtain used a moveable semi-circular screen based within a fixed arch. This transforming screen had four different shaped panels that were radially arranged and layered over each other. This structure is perhaps the most innovative full-scale application of scissor-like elements for transformable structures yet to be constructed.





Figures 5 and 6. Iris Dome and Mechanical Curtain.

Architectural Evaluation of Transformable Roofs
In evaluating transformable architecture it is important to judge to what extent different structural principles can be used to meet design expectations. It is necessary to find evaluation criteria that not only considers the general requirements of architecture such as form, function and respect for human scale but also deals with specific requirements that inherently result from the structure's transformability, such as multi-functionality and adaptability in disparate environmental conditions. There are four main issues that transformable architecture, and in particular transformable roof structures, should respond to in order to be as effective as possible. These are: adaptability and response to change; aesthetic issues; operational conditions; maintenance and management.

Transformable roof structures should be adaptable not only to local environmental changes but also to user requirements as functions change. Consideration of the different types of transformable structures introduced here reveals that their success in this regard is directly related to the degree of integration of structural elements, covering material, transformation mechanisms and the flexibility of operation. It can be argued that the compatibility of these four factors determines the effectiveness and success of transformable roof strategies, and also extends their application from simple closed to open states, to a variety of other desired configurations achieved during the deployment process.

Transformable tensile roofs can respond to change due to two principal features in their design: the use of lightweight, flexible materials and the integration between structural and architectural components. They may also require additional tensile cables to ensure their pre-tension in deployed configuration. These cables guarantee the stability of the membrane structure especially when it is subject to external loads, but they also cause visual obstruction that may affect the performance of the building.

Tensegrity roofs can be considered to have realistic potential for transformable roof structures due to the lightness and the flexibility of the structural components, and their self-equilibrium geometry in the deployed state. Flying struts, in combination with light, flexible cables are an elegant structural combination for buildings that demand the sense of lightness with long unobstructed spans. However, despite their great potential, the complexity of their deployment mechanisms has proved problematic. Although the discontinuity of the compressive members makes a wide span structure capable of stowage in a compact volume, it also makes it difficult to create a mechanism that will repeatedly retract and deploy at large scale.

Transformable spatial bar structures in their simplest form consists of several modules of two bars connected to each other through a hole equally placed in both bars. Different arrangements of the modules result in a large range of structural possibilities including flat foldable space grids, domes and spherical and cylindrical structures. The development of angulated scissor-element modules has extended the application of this type of structure into more complex shapes. This type of structure deploys easily and quickly though great care must be taken in detailed design and manufacture. These structures have a finite mechanism and a very high degree of flexibility and their movements must be limited by use of additional tensile cables or locking systems, which also make it possible to use transformable spatial bar structures in various desired states achieved during the deployment process.

Conclusion

This paper has introduced the discrete types of roof structure that are capable of transformation. It is evident that the evaluation of these structures is difficult due to the complexity of their designs and functions. However, their architectural applications and features respond to the continuously increasing demand for adaptability to changing user requirements. Transformation capabilities provide the benefits of adaptability and multi-functionality, but do not impede the monumental and visual aspects of design synonymous with expanding architectural ambition. Close collaboration between architects, structural and mechanical engineers, and specialist designers in research, practice and education is important to develop further the potential of this increasingly necessary form of architectural design.

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