Current Technologies and Trends of Retractable Roofs

by

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Abstract

In recent years, retractable roofs have become a popular feature in sport stadiums. However, they have been used throughout time because they allow a building to become more flexible in its use. This thesis reviews the current technologies of retractable roofs and discusses possible innovations for the future.

Most retractable roofs use either a 2-D rigid panel system or a 2-D membrane and 1-D cable system. These structures can be seen throughout the world. Designing retractable/deployable systems involves evaluating the structural features and opening and closing features to determine what is appropriate for a particular building. Common issues for designing these structures are summarized.

Current retractable roof research is commonly incorporated within the field of deployable structures. The word deployment means the act of unfolding or opening while retraction is the opposite (Pellegrino 2001). Pantograph structures along with other bi-stable structures are being researched to find new configurations that could be used for civil applications. Small-scale models have been produced but large-scale models still need to be developed to help progress the research.

The paper will conclude with the case studies of two roofs, one being Toronto’s Sky Dome and the other being the Gerry Weber Tennis Center.
# Table of Contents

1. Introduction ............................................................................................................. 5

2. Background ............................................................................................................. 6

3. Types ........................................................................................................................ 9  
   Structural System .................................................................................................. 9  
   Retracting and Deploying Methods ....................................................................... 10  
   Current Constraints .............................................................................................. 12

4. Architectural Design ............................................................................................. 13  
   Economic Efficiency .............................................................................................. 13  
   Condition of Building (Open or Closed State) .................................................... 15  
   Common Malfunctions ......................................................................................... 15  
   Safety considerations ............................................................................................ 17

5. Structural Design .................................................................................................. 18  
   Framing Systems .................................................................................................. 19  
   2-D Panel Structures ............................................................................................ 20  
   Membrane Structures ........................................................................................... 21  
   Pantograph (Scissor Like Elements) Structure .................................................... 23  
   Loads ..................................................................................................................... 27  
   Safety .................................................................................................................... 29  
   Management, Maintenance, and Monitoring ....................................................... 29

6. Current Research .................................................................................................. 31  
   Folding Mechanisms ............................................................................................ 31  
   Hoberman Associates ............................................................................................ 34  
   Pantographs/Scissor-like-Elements ...................................................................... 36  
   Flexible Shells ....................................................................................................... 37

7. Examples ................................................................................................................ 39  
   Toronto Sky Dome ................................................................................................ 39  
   Gerry Weber Tennis Center .................................................................................. 41

8. Conclusion .............................................................................................................. 42
Table of Figures

Figure 1: Leonardo de Vinci’s deployable structures (Courtesy of Gantes). .................. 6
Figure 2: Pinero and his movable, deployable roof (Courtesy of
http://people.sd.pollyu.edu.hk). .................................................................................. 7
Figure 3: Various open and closing systems (Courtesy of Ishii). ................................. 11
Figure 4: Proposed methodology for designing deployable structures (Courtesy of
Gantes). ...................................................................................................................... 19
Figure 5: The Ocean Dome, located in Saitana, Japan .................................................. 20
Figure 6: The Oita Stadium (Japan), also known as the “Big Eye,” ................................. 21
Figure 7: Pantograph concept (Courtesy of Gantes). ..................................................... 23
Figure 8: Swimming pool roof in Seville, Spain (Courtesy of Gantes) ......................... 24
Figure 9: A spherical lamella grids and two-way cylindrical girds (Courtesy of Gantes).. 25
Figure 10: Geometric designs of various pantographs (Courtesy of Gantes). .................. 26
Figure 11: Biological deployable structures (Courtesy of Kresling). ............................. 32
Figure 12: Foldable rigid connections (Courtesy of Ebara and Kawaguchi). .................. 33
Figure 13: Angulated scissor elements (Courtesy of Al Khayer and Lalvani). ............... 34
Figure 14: The Iris Dome. (Courtesy of Hoberman Associates) ................................. 35
Figure 15: A geodesic dome with membrane material attached. (Courtesy of Hoberman
Associates). .................................................................................................................. 35
Figure 16: Doubly-faceted curved deployable strutures (Courtesy of Al Khayer and
Lalvani). ...................................................................................................................... 36
Figure 17: Double layer spatial deployable structures ................................................. 37
Figure 18: A bi-stable flexible shell structure. (Courtesy of Pellegrino, 2001)............. 38
Figure 19: Toronto’s Sky Dome Closed. (Courtesy of web.media.mit.edu). ................. 40
Figure 20: Toronto’s Sky Dome Open. (Courtesy of www.pbs.org) ............................ 40
Figure 21: Gerry Weber Tennis Center (Courtesy of www.structurae.de) .................... 41
1. Introduction

In recent years, retractable roofs have become a popular feature in sport stadiums. Retractable roofs increase the versatility of the stadium, making it pleasant to watch a game in the sunshine or undercover while raining. According to Ishii in *Structural Design of Retractable Roof Structures*, “A retractable roof structure is a type of structure in which a part of or the entire roof structure can be moved or retracted within a short period of time so that the building can be used either in an open state or in a closed state of the roof.”

Current retractable roof research is commonly incorporated within the field of deployable structures. The word deployment means the act of unfolding or opening while retraction is the opposite (Pellegrino 2001). Deployable structures are thought of as, “a special case within the broader class of adaptive structures (Gantes, 2000).” They are structures that can be closed in a compact form and then transformed to their full load-carrying configuration. Deployable structures are more commonly used in the aerospace industry but civil applications are being researched and new applications are being developed.

This thesis will review the current technologies of retractable roofs and discuss possible innovations for the future. A brief background will introduce the use of retractable roofs to their current state. Different types of retractable roofs and their applications will then be examined. Design procedures and common issues encountered in design will be analyzed. The paper will conclude with the case studies of two roofs, one being Toronto’s Sky Dome and the other being the Gerry Weber Tennis Center.
2. Background

Deployable/ retractable structures can be traced back to ancient times. Tepees from Native Americans and Berber tents from the African deserts were used early on because of their rapid assembly and disassembly and their ability to be reused (Gantes, 2000). The Roman Coliseum was likely the first stadium to have a retractable roof. Remnants of the columns used for the retractable roof can still be seen today (Ishii, 2000). In medieval times, many inventors including Francesco de Giorgio and Leonardo de Vinci played with the concepts of movable and rapidly erected structures (Gantes, 2000).

![Image of Leonardo de Vinci's deployable structures](image)

*Figure 1: Leonardo de Vinci's deployable structures (Courtesy of Gantes).*

By the 1930’s small retractable roofs had been constructed using crane technologies (Ishii, 2000). Most countries have standards and specifications for these types of roofs (Ishii). In the 1950’s in Germany, Professor F. Otto started “research on retractable roofs constructed of membrane structures and obtained a good number of results (Ishii).” Because of this, membrane retractable roof structures became popular, especially in Europe. One design researched by Professor F. Otto was eventually implemented on a
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Figure 1: Leonardo de Vinci’s deployable structures (Courtesy of Gantes).

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connections and deployment mechanisms (Gantes, 2000).” However, the flexibility of these structures is seen as a benefit to many owners and drives the need for new technology in deployable/ retractable structures.

The flexibility that retractable/deployable roofs provide has been acknowledged throughout time. Movable structures allow a building to become more flexible in its current and future functions. This flexibility is also a desired feature in sustainable building, a current trend in building. Their ability to allow for natural ventilation when convenient and provide insulation when needed is an ideal situation for energy efficient buildings. The flexibility that deployable/ retractable roofs provide has helped advance the development of current technologies and drives the need for innovative designs for the future.
3. Types

Currently, retractable roofs are mainly used for recreational and industrial buildings. Although there are only two main types of buildings that use retractable technology, there have been many different types of roofs developed. When deciding what roof is most appropriate for a particular building in the preliminary design, the following issues should be addressed: structural system, degree of openness, retracting and deploying mechanism, and constraints and common malfunctions of particular roofs (Ishii, 2000).

**Structural System**

Retractable/deployable roofs can use a number of different structural systems. One structural system is composed of 1-D stiff bars, connected “to each other in arrangements of pantographs (also known as scissor like elements) (Gantes, 2000).” Another structural system is stiff 2-D panels (Gantes). A third system is, “Tension structures, consisting of flexible 1-D cables or 2-D membranes or combination of both, either pre-stressed or pneumatic (Gantes).” Lastly the system could be composed of, “tensegrity structures consisting of combinations of stiff rods and flexible cables (Gantes).”

Two of the four primary retractable roof systems are currently being used more often. The first being the stiff 2-D panel system. This system consists of a panel type of structure that uses a frame, typically steel, with a material such as glass, plastic, or metal stretched onto it (Ishii, 2000). Most large-scale retractable roofs use this system. The other system used is the flexible 1-D cables and 2-D membranes. This system commonly
uses membrane materials and opens and closes by folding or rolling the material. Crane structures, “the most frequently used in actual buildings with a retractable roof”, are considered to fall into this category (Ishii, 2000). In the design section of this paper these two systems will be examined at more closely because they are used most commonly. Pantograph structures, which are stiff 1-D bars systems, will also be examined because attempts are currently being made to apply this technology to retractable deployable roofs.

Each different retractable/deployable system has different architectural properties. The system chosen for a particular building is determined by the “intended purpose, applications, environmental conditions, site conditions, and condition for control and management, etc. (Ishii, 2000).” The properties of the above systems will be discussed further in the design section.

Retracting and Deploying Methods

Just as there are many structural systems for retractable roofs there are many mechanisms for retracting and deploying the roofs. The mechanisms can be classified in the following categories: sliding systems, pivoted moving systems, folding/rolling systems, expandable systems, or combined systems (Ishii, 2000). A summary of these mechanisms can be seen in Figure 3.
Parallel movement - Overlapping system  
Circularly movement - Overlapping system  
Up and down movement - Overlapping system  
Parallel movement  
Parallel movement - Folding system  
Circular movement - Folding system  
Up and down system - Folding system  
Pivoted system

Figure 3: Various open and closing systems (Courtesy of Ishii).

Sliding systems can be used for either a frame or membrane structural system. The roof can be opened by moving/overlapping the elements in either a horizontal or vertical direction while moving in either a circular or linear (parallel) motion. The pivoted moving system opens the roof by using “rotatable roof panels on their axis (Ishii, 2000).”

The folding or rolling system is primarily used for membrane structures. This mechanism opens the roof by folding or rolling the membrane material. Expandable systems are primarily used to open and close truss frames. The deployment and retraction could also involve any combination of the above systems. (Ishii, 2000)

The above opening and closing methods all need a driving mechanism to enable the deployment/retraction motion. There are four driving methods commonly used. The first method uses a tractor that has a built in motor and has wheels that travel along a cable or track. This can be called the “self-running wheel method (Ishii, 2000).” The second method also uses wheels along tracks but is pulled by cables and it is called the “cable
traction method (Ishii, 2000).” The third method uses gears that run along rails. The gears have teeth that inter-lock and this can be called the, “rack and pinion method” or the “rack and gear method (Ishii, 2000).” The fourth method is called the “jack method (Ishii, 2000).” This method uses a jack to drive the deployment and retraction (Ishii, 2000). The first three methods could be employed in most of the above opening and closing systems; the jack method is more limited in its applications.

**Current Constraints**

Retractable/deployable roofs have become a popular trend in stadiums and industrial buildings. However, there are still many constraints that limit retractable technology to these particular buildings. A common constraint is the geometry of the roof. Some shapes do not allow for an existing retractable roof system to be used at all. Another, more important, constraint for retractable/deployable roofs is their high design. The extra design, construction, and maintenance costs are not practical for most applications. Hopefully, new innovations will decrease the costs and limit geometry constraints of retractable roofs.
4. Architectural Design

Architectural design considerations are important in helping to determine the proper system for a retractable/deployable roof. The design process has not been standardized. However, a number of standards have been proposed. The following considerations were determined from summarizing a number of proposed architectural standards (Ishii, 2000).

The design should entail the evaluation of the following considerations:

- Economic efficiency of the retractable roof system
- Capability of retraction and deployment feature
- Condition of building in either mode
- Common malfunctions
- Safety considerations

The following sections briefly discuss these topics as a means of introducing the architectural design.

**Economic Efficiency**

Retractable/deployable roof systems incur a large cost compared to static roof systems. Stadiums and industrial buildings are typically the only types of facilities that can profit from the retractable/deployable systems. The revenue made from the flexibility of the building can offset the extra design, construction, and maintenance costs. If retractable/deployable roofs became more standardized, requiring less design, construction, and maintenance costs, they could become more widely used.
**Capability of the Retraction/Deployment Feature**

One of the first considerations to help determine the proper structural system for a retractable roof is determining the frequency in which the roof is opened and closed, the degree of openness, and the time it takes to open and close the roof. Roofs usually have one of the following three frequencies. The roof is primarily open and closed occasionally for bad weather, it will primarily be closed and opened occasionally for good weather, or it will open and close frequently (Ishii, 2000). The three situations require unique design considerations. The most important of these is the position of the roof, which determines proper load cases that should be applied to the structure.

The degree of openness applies to the percentage of the roof surface that can be retracted or deployed. This value is usually quantified by calculating the percentage of the area of the roof that can be opened. Values for sports stadiums range from approximately 60% to as much as 90+% (Ishii, 2000). The structural system can determine how much the roof can be opened or closed. Stiff 2-D panels can have the lowest percentage of open area. This is mainly due to the fact that the panels have to be stored above the structure. They could also have a high percentage of open area if the site of the building has area beyond the building to store the panels.

The time that is required for the roof to open or close is usually determined by the functionality of the structure. Opening or closing a roof ranges from 2.5 minutes to approximately 30 minutes (Ishii, 2000). Opening or closing times average 10-15 minutes.
because faster movement in the system increases the power consumption and could also cause safety issues (Ishii, 2000).

**Condition of Building (Open or Closed State)**

The condition of the building in both the open and closed state is also an important consideration in designing retractable/deployable roofs. The major issue is knowing the environmental state of both modes. Flexibility is achieved by ensuring that the area under the deployed or retracted roof is useable for the proposed functions (Ishii, 2000). The environment of the area in either state should not affect the occupants; the main issues being wind and shadow when the roof is retracted. Airflow around the roof in its open position could potentially cause high wind speeds in the exposed areas or fields. The shadow of the retracted roof could also distract the occupants in the area. (Ishii, 2000)

**Common Malfunctions**

Failures of retractable/deployable roofs can occur in either the deploying/retracting system or the normal roof system (for example, water leakage). Although failures of the normal roof structure are not unique to retractable roof structures, they can sometimes restrict the use of the building, making it necessary to replace the structure. A malfunction in one small part of the deploying/retracting system can lead to failure in opening and closing the structure, also making it necessary to replace the structure. Any
failure of a retractable roof can result in a costly solution. Below is a summary of potential malfunctions in retractable roofs (Ishii, 2000).

Table 1: Common Malfunctions of Retractable Roof Systems (Ishii, 2000).

<table>
<thead>
<tr>
<th>Part</th>
<th>Potential Malfunctions and Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running Unit</td>
<td>• Falling from rail or cable, floating, brake trouble, insufficient locking device, failure in speed control, swinging, obstacles, fatigue of mechanical unit, wearing, etc.</td>
</tr>
<tr>
<td></td>
<td>• Overrunning or collision due to operating failure.</td>
</tr>
<tr>
<td></td>
<td>• Power failure, electric leakage, disconnection, etc.</td>
</tr>
<tr>
<td></td>
<td>• Failure of synchronization control, zigzag running, falling object due to swinging.</td>
</tr>
<tr>
<td></td>
<td>• Trouble of suspension rope, cut-off of rope, etc.</td>
</tr>
<tr>
<td></td>
<td>• Improper running due to unequal settlement.</td>
</tr>
<tr>
<td></td>
<td>• Loosening and falling of bolts due to vibration during running.</td>
</tr>
<tr>
<td>Control</td>
<td>• Synchronization control: Difference in length of running between left and right.</td>
</tr>
<tr>
<td></td>
<td>• Skew control: Left and right deviation.</td>
</tr>
<tr>
<td>Roof Surface</td>
<td>• Flapping of the roof membrane due to wind during extension or retraction.</td>
</tr>
<tr>
<td></td>
<td>• Contact with solid substances.</td>
</tr>
<tr>
<td></td>
<td>• Derailment of a trolley.</td>
</tr>
<tr>
<td></td>
<td>• Damage to membranes and cables due to repeated folding.</td>
</tr>
<tr>
<td></td>
<td>• Stress concentration on the membrane due to incorrect synchronous control.</td>
</tr>
<tr>
<td></td>
<td>• Morphological change in the membrane due to creep.</td>
</tr>
<tr>
<td></td>
<td>• Insufficient re-pre-tensioning of membranes and cables.</td>
</tr>
</tbody>
</table>
Safety considerations

Malfunctions can lead to safety issues for the retractable/deployable system. The architectural design should consider common malfunctions to help prevent safety comprises from occurring later in the design process. A complete safety analysis should be done at the end of the structural design to establish a proper maintenance and monitoring program.
5. Structural Design

The structural design of a retractable/deployable roof is anything but typical. The major difference compared to a normal roof structure is the challenge of producing a structural effect over the entire roof surface (Ishii, 2000). The pieces or parts of the roof need to be designed so they can move separately but also act as one unit to produce the shelter that is needed. The behavior of the roof structure also varies with each configuration all of which need to be considered in order to effectively design the roof. The dynamic behavior needs to be managed to provide an efficient load transferring system and achieve proper timing. Lastly this all needs to be done while considering the safety of the structure. Gantes suggested the flow chart in Figure 4 as a proposed methodology to design retractable roofs.

The following section examines various components of designing structural systems for retractable/deployable roofs. The design process for each of the structural systems introduced earlier (2-D panel, membrane, and pantograph roofs) will be discussed. The loads that are applicable for designing retractable/deployable roofs will also be reviewed. A review of the safety and maintenance, management, and monitoring considerations and procedures will conclude the section.
Figure 4: Proposed methodology for designing deployable structures (Courtesy of Gantes).

Framing Systems

The framing systems of retractable/deployable roofs vary greatly according to the type of retractable roof used. Membrane structures use very few framing members, 2-D panels use a variety of framing systems (similar to static roofs), and pantograph roofs are frame intensive roofs. The three systems will be examined separately for this reason.
2-D Panel Structures

As mentioned previously, stadium and industrial buildings commonly use 2-D panels as the structural system for their retractable roof. Panel systems are commonly used for large roof areas, typically in the range of 5,000 m² to as much as 50,000 m² (Bank One Ballpark) (Ishii, 2000). Most 2-D panel roofs are composed of steel frames with a covering material and typically use an overlapping system as the retraction method (Ishii, 2000). Below are figures demonstrating a 2-D panel roof.

Figure 5: The Ocean Dome, located in Saitana, Japan.
(Courtesy of www.mhi.co.jp and www.jnto.go.jp)

Generally, roofs for stadiums and industrial buildings have some curvature, either arch like or dome shaped. Since the 2-D stiff panels are not continuous along the entire roof it is difficult to achieve a shell effect (Ishii, 2000). The individual panels need to be analyzed as independent structures for the closed state, open state, and dynamic state. The members must be rigid enough to transfer the required loading. Proper clearance between panels needs to be achieved to ensure that differential deformation from either long-term or short-term loading can occur without damage. However, sufficient seals between panels should be made to insure a leak proof roof. (Ishii, 2000)
2-D panel roofs have become very popular because of the flexibility they incur and the minimal analysis needed to design the structure. The disadvantages of panel roofs are that they are extremely bulky and space consuming. There is little flexibility in the structural designs and retracting methods.

Membrane Structures

Membrane structures that are retractable have been in use longer than any other system. They are lightweight and foldable which allows the retracted roof to be compact and easily stored (Ishii, 2000). Membrane structures, unlike stiff 2-D panels, can take advantage of a number of retraction/extension methods. The frame that membrane structures use can either consist of stiff or tensioned elements. Membrane structures can also use a differential pressure system to support the membrane material. Below is an example of a membrane structures. (Ishii, 2000)

Figure 6: The Oita Stadium (Japan), also known as the “Big Eye,”
(Courtesy of www. Takenaka.co.jp) .
Membrane structures can be used for a wider range of buildings; however they are typically smaller spaces than those for which 2-D stiff panels are used. The structures are commonly used for theaters, pavilions, and recreational buildings (pools, ice rinks, and tennis courts) (Ishii, 2000).

One of the main considerations for designing membrane structures is achieving appropriate tension in the membrane. The tension in the membrane should remain sufficient throughout its lifetime to be able to effectively transfer loads to the support system. The tension should be uniform along the membrane material. If there is an imbalance the material will gradually find equilibrium and will commonly result in creep issues. If a tear occurs in the membrane the structure of the roof should be able to remain stable and it should not incur serious structural damage to the entire roof. The membrane should have an effective boundary structure; one that is able to withstand the forces applied by the roof membrane. (Ishii, 2000)

The membrane surface should also be curved so it does not collect rainwater and snow. The form should not deform extensively when wind, rain, or snow loads are applied. Special consideration needs to be made so that the deformed membrane does not touch any other part of the roof. Without a proper design wind forces could also cause dangerous vibrations in the membrane material. The maximum uplift forces from wind loads should not reverse the curvature in the roof (Ishii, 2000).
The deployed configuration of the membrane roof should have sufficient locking capabilities with the supporting structure. The moving parts of the roof should also be securely connected to their tracks to ensure that large movement or slipping does not occur when large loads are applied. Similarly when the roof is in the retracted position it should be able to be safely stored (Ishii, 2000).

**Pantograph (Scissor Like Elements) Structure**

Pantograph means a framework that uses rods that have three nodes, one at each end and one in the middle (Gantes, 2000). The nodes are connected to other nodes with hinges to other rods of equal length. This configuration allows movement in the direction perpendicular to the plan of the pantograph. The diagram below shows the pantograph concept (Gantes, 2000).

![Pantograph Diagram](image)

**Figure 7: Pantograph concept (Courtesy of Gantes).**

Pantograph structures historically are more applicable for space structures. However, there is continuing effort from a number of enthusiasts to configure an applicable form of these structures for earth applications. There have been a few instances in which
pantographs have been used for earth structures. A swimming pool roof in Seville, Spain offers an example of pantograph structures and can be seen in Figure 8.

![Swimming pool roof in Seville, Spain](image)

**Figure 8: Swimming pool roof in Seville, Spain (Courtesy of Gantes).**

The first pantograph structure was designed and patented by Emilio Perez Pinero in 1961 (Gantes, 2000). Since Pinero’s patent in 1961 many others have been filed with various changes from his original design intended to improve on the behavior of the pantographs. Many of the later designs use different lengths of bars to try to achieve a stress free state in both the deployed and retracted configuration. The research led to defining a number of shapes that all use slightly different geometric configurations. Some of the suggested configurations are uniform rhomboid patterns, rhomboid patterns with a center, quadrangular patterns of meridians, two-way cylindrical grids, three-way cylindrical grids, two-way spherical grids, three-way spherical grids, geodesic grids, and finally spherical lamella grids. Examples of a few of the configurations can be seen Figure 9 (Gantes, 2000).
The ability of most of these structures to be stress free in both the deployed and retracted state indicates that they must have gone through some “snap through” type of deployment. Snap through means that a structure moves from a stable state by buckling to another stable state (Gantes, 2000). A geometric design approach for these types of structures has been developed by Gantes throughout his career. His basic requirement is that “the sums of the lengths between pivot and end node of the bars of SLEs (scissor like elements) that are connected to each other are equal. (Gantes, 2000).” This can be mathematically shown with the following equation:

\[ a+b = c+d \]
From this basic requirement and taking into account “symmetry or other special conditions,” most pantograph configurations can be designed (Gantes, 2000).

In addition to than the two examples shown previously, there are proposed designs for other types of roof structures. The proposed examples have all been built on a small scale and can be seen in Figure 10.

Figure 10: Geometric designs of various pantographs (Courtesy of Gantes).
The main objectives of the small scale experiments “were to verify the geometric design formulations, to provide a basis for comparison for the numerical analysis results, and to identify critical engineering issues related to the manufacturing, deployment and dismantling of deployable structures (Gantes, 2000).” Large-scale models have also been developed but finding appropriate materials and connection mechanisms has proven to be difficult.

**Loads**

Like all structures, loads need to be considered when designing the structural system. The typical loads that need to be analyzed are live, dead, wind, earthquake, and snow. Designing retractable/deployable roofs also involves considering a number of loads that are specific to moving structures. Some of the loads that need to be considered are temperature, horizontal load, impact forces during opening and closing, inertia force, brake force and impact load to buffer (Ishii, 2000). Most importantly, clearly defining the position of the roof in its typical position will allow for accurate load calculations.

For both snow and wind loads it is necessary to define the position of the roof, being either typically in the open state, the closed state, or the semi-open locked state. It is also important to define the conditions of the roof in its moving state. For heavy snow loads it is dangerous to move the roof (Ishii, 2000). If the roof remains open during heavy snow loads, the roof will be more economical because it does not have to be able to handle the heavy loads (Ishii, 2000). However, leaving the roof closed allows it to be analyzed as a normal roof for snow loads. The individual panels also need to be analyzed to ensure
sufficient clearance between them during heavy snow loads. It is also important to consider snow and ice on the rails of the moving roof and, for cable structures, the freezing of the cables (Ishii, 2000).

Wind loading is one of the most important loads for retractable/deployable roofs (Ishii, 2000). It is essential to know what state the roof will be in for severe winds. Designing the roof for severe winds for all its states (open, closed, semi-open) would be costly and would increase the size of the structural elements. For these reasons the driving mechanism should have enough power to open and close the roof to its desired position during high wind conditions (Ishii, 2000). If the shape of the open condition is “disadvantageous against wind loads” or the “interior should not be subjected to wind or rain” the roof should be designed closed for severe winds (Ishii, 2000). If the “closed state (is) disadvantageous for resisting strong wind” or it is economical, the roof should be designed open for severe winds (Ishii, 2000).

Earthquake loading should be considered for open and closed configurations equally (Ishii, 2000). The probability of an earthquake occurring when the roof is moving is very slim. However, a real-time monitoring system should be in place to detect seismic activity. If any movement is detected the roof should stop immediately. The major considerations for earthquake loading are ensuring that the roof does not derail, collide, or violently swing. Individual panels also need to be analyzed to ensure there is sufficient clearance between panels so no collision occurs during an earthquake (Ishii, 2000).
Safety

The safety of the retractable/deployable roof is also a major consideration in the design process. Designers should design for "sufficient countermeasures against accidents and failures (Ishii, 2000)." They should ensure that the system could be constructed in a safe manner. The system should be designed so if a mechanism fails the rest of the system can operate safely. If the driving mechanism fails there should be a back up system to be able to position the roof in its appropriate configuration. Lastly, maintenance, management, and monitoring systems should be implemented to ensure that the system is regulated properly (Ishii, 2000).

Management, Maintenance, and Monitoring

Once the retractable/deployable system has been designed and constructed, a proper management plan needs to be established. Managing a retractable/deployable roof entails maintaining smooth and reliable operation (Ishii, 2000). For reliable operation there are two components that need to be examined, procedures of operation and maintenance of the structure. Strict procedures should be established that give specific instruction for all cases of opening and closing of the roof. These cases include everything from normal opening and closing to emergency cases such as after an earthquake, accident, or power failure (Ishii, 2000). The second component for reliable operation is to insure that the structure is well maintained. There should be scheduled inspections for checking all the parts of the retractable/deployable roof. The roof should be designed so it is easily
accessible for maintenance work. There should be continual repairing of members that may look as though they are about to fail. Also, there needs to be close attention to the maintenance of tracks of the retractable/deployable roof. Long-term settlement of the permanent structure could lead to differential settlement of the tracks. If not taken care of, the roof could derail. There should also be alarm systems and a real-time monitoring system installed to notify if any malfunction occurs.
6. Current Research

Most of the current research and innovations in deployable/retractable roofs is coming from either, Cambridge’s Deployable Technology Center led by Professor S. Pellegrino, Greece lead by Professor C. J. Gantes, or from a number of professors in Seville, Spain. One conference lead by Pellegrino in Cambridge, UK was held in 1998 called the, “Symposium on Deployable Structures: Theory and Applications.” The topics that were discussed in this conference covered a variety of applications for deployable/retractable structures in general. For deployable/retractable roofs specifically the research focused around four major topics. They were:

- New folding mechanisms
- Hoberman Associates
- New configurations for pantographs/scissor-like-elements
- Flexible shells

The following sections briefly discuss the concepts and techniques introduced in the recent papers.

Folding Mechanisms

Folding mechanisms have always been a major constraint for deployable/retractable roofs. In many cases, the weakest link in a deployable structure is the folding component. For this reason new methods are being researched. Some of topics being examined are: biological structures and their folding patterns, rigid connections to
develop deployable moment frames (versus pinned, space frame structures), and developing structures that do not depend on the "joints" for load paths.

Biological structures use many folding and deploying/retracting mechanisms to change shape. Some of the most interesting natural models of this are beetle wings, folding leaves, pinecones, and worms (Calladine, 2000, Brackenbury, 2000). Each of these things can be found in nature exhibits a folding/compacting ability. The diagrams in Figure 11 demonstrate how they work.

Figure 11: Biological deployable structures (Courtesy of Kresling).
Calladine, who wrote an essay called, “Deployable Structures: What Can We Learn from Biological Structures?” feels that these mechanisms could give insight on how new folding mechanism can be developed for the field of deployable/retractable structures.

Most current frame designs for deployable/retractable roof are space frames. Space frames use pinned connections. However, when these structures are subjected to gravity, wind, and earthquake loads, moment connections would improve the frame’s rigidity (Ebara and Kawaguchi, 2000). For this reason, a “foldable rigid connection” was developed by Ebara and Kawaguchi in Japan. They found that three connection configurations could possibly be useful in structural applications. The configurations are shown in Figure 12.

Figure 12: Foldable rigid connections (Courtesy of Ebara and Kawaguchi).
**Hoberman Associates**

Chuck Hoberman, of Hoberman Associates, has been designing toys for many years and has extended his toy design concepts for structural applications. The Iris Dome is a retractable roof based on a concept developed for toys. The concept is also closely related to the concept of pantographs. However the main difference in Hoberman’s design verses typical pantographs is that he has angulated the scissor members (Al Khayer and Lalvani, 2000). A diagram of the differences can be seen in Figure 13.

![Diagram of Differences](image)

**Figure 13:** Angulated scissor elements (Courtesy of Al Khayer and Lalvani).

The Iris dome below is composed of “layers of angulated elements and each layer forms a complete ring lying on a conical surface (Pellegrino, 2001). The Iris Dome was first put on exhibit at the Museum of Modern Art in New York City in 1991. There was also a scale model of the Iris Dome developed for the Expo 2000 in Hanover, Germany. The dome has a diameter of 6 meters and a height of 4.2 meters. Images of these models can be seen below.
Recently, Hoberman Associates has developed a membrane for their scissor-like-structures. The membrane is configured to fold in the same way after each retraction. The membrane covering may eventually allow the Iris Dome to be used for an actual building.
**Pantographs/Scissor-like-Elements**

New configurations of pantograph or scissor-like-elements continue to be researched. Promising configurations have been studied by architects at the School of Architecture at Pratt Institute in Brooklyn, New York. The structures are modeled from previously developed pantograph configurations like C. Hoberman’s angulated scissors. The scissors are configured to produce doubly-faceted curved surfaces; they are termed "polygonal hyperboloids." A few of the geometric configurations are shown below in Figure 16.

![Figure 16: Doubly-faceted curved deployable structures (Courtesy of Al Khayer and Lalvani).](image)

These configurations are not particularly applicable to roof structures. However, they are innovative and warrant consideration. R. Garcia Dieguez and J. C. Gomez de Cozar, Universidad de Seville, discuss other pantograph structures that are more applicable for roof structures. The system they have developed is "composed of layers of rhombic and scissor-like meshes with variable angles." Although similar to systems discussed earlier in the pantograph section, this system distinguishes itself by having two layers. The two
layers allow for a roof and ceiling system and they also add bending stiffness to the structure. Examples of these structures can be seen in Figure 17.

![Double layer spatial deployable structures](image)

**Figure 17: Double layer spatial deployable structures**
(Courtesy of Garcia Deiguez and Gomez de Cozar).

**Flexible Shells**

Flexible shells are considered to be bi-stable composite or steel tubes (Pellegrino 2001). These tubes have two stable positions, the collapsed position and the stretched “STEM” position. These structures use a “thin-walled cylindrical shell whose cross-section forms an arc of a circle” while in the STEM position and is “flattened and rolled up in a small
container” while in the collapsed position (Pellegrino, 2001). However, this tube does not have any applications for civil or even large-scale projects. But the concept is still new and could possibly lead to applications in the future. Below are pictures of these structures.

![Figure 18: A bi-stable flexible shell structure. (Courtesy of Pellegrino, 2001)](image)

There continues to be research in many of the areas of retractable/deployable roof technology. One method that could advance the development of the proposed configurations for real applications is making large-scale models of them. Many of the proposed ideas have been tested on small scales, but modeling materials properly can be a challenge. For example, scaling down the thickness of thin membranes to match the scale of the rest of the model is sometimes impossible. It is also hard to test the mechanisms on retractable/deployable roofs on small scales.
7. Examples

To demonstrate the ideas presented above, two retractable/deployable roofs will surveyed. Two of the three structural systems that were discussed, rigid 2-D panels and membrane systems, will be represented by one of the following examples. The two roofs will be:

- Toronto Sky Dome (rigid 2-D panels)
- Gerry Weber Tennis Center (membrane)

Each of these structural systems will be examined as well as their architectural features.

Toronto Sky Dome

The Toronto Sky Dome is in Toronto, Canada. The stadium is used for baseball and has the capacity for as many as 54,000 fans. The roof opens in 20 minutes and the stadium is 91% exposed. The roof structure (32,374 m² in area) is composed of four steel-framed dome shaped shells, which rest on a reinforced concrete base (Ishii, 2000). Three of the four panels move, “opening by a unique geometric motion which leads to a compact telescoping placement of the roof when fully opened (Ishii, 2000).” The roof was designed and coordinated by a number of geometric points that were developed by “defining the roof centerline shape in the two principle directions by mathematical formulae (Ishii, 2000).” The structural system was also developed to have a number of load paths, so one structural element would not cause a failure in the whole system (Ishii, 2000). In its first two years of usage the roof opened and closed over 200 hundred times safely (Ishii, 2000). Below are pictures of the Toronto Sky Dome.
Architects: Rob Robbie (RAN Consortium)

Engineer: C. M. Allen (RAN Consortium)

Site: Toronto, Canada

Opened: 1989

Figure 19: Toronto’s Sky Dome Closed. (Courtesy of web.media.mit.edu).

Figure 20: Toronto’s Sky Dome Open. (Courtesy of www.pbs.org).
**Gerry Weber Tennis Center**

The Gerry Weber Tennis Center is located in Westfalen, Germany. It was built in 1994. This structure has a membrane roof that uses a cable truss-suspended frame. The roof is composed of a permanent membrane and retractable membrane component. The permanent area is 6,200 m² and the retractable area is 1,400 m². The retractable membrane material is made out of ETFE foil and the permanent membrane material is made of PVC-coated polyester fabric. The roof is opened and closed by a spoke wheel system. The membrane is stabilized by a differential air pressure system. Below is a picture of the Gerry Weber Tennis Center.

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Architects: Schlaich, Bergermann and Partners

Engineer: Schlaich, Bergermann and Partners

Site: Westfalen, Germany

Opened: 1994

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Figure 21: Gerry Weber Tennis Center (Courtesy of www.structurae.de)
8. Conclusion

Retractable/deployable roofs have been used throughout time because it allows a building to become more flexible in its use. Most retractable roofs use either a 2-D rigid panel system or a 2-D membrane and 1-D cable system. These structures can be seen throughout the world. In the sixties membrane roofs became popular especially in Europe and more recently 2-D panels have become popular mainly in the U.S. and Japan.

Designing retractable/deployable systems involves evaluating the architectural features of structural systems and opening and closing systems to determine what is appropriate for a particular building. The structural design process involves designing the framing system and evaluating normal and retractable specific loads. It is also very important to ensure that the structure is safe and has appropriate management, maintenance, and monitoring procedures.

Current research is focused primarily on snap-through structures, either in the form of pantographs or flexible shells. Pantograph structures are being researched to find new configurations that could be used for civil applications. Small-scale models have been produced but large-scale models still need to be developed to help progress the research. Hopefully the innovations will lead to practical configurations that are economical for civil structures.
References


Southampton, UK.


