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"Classification of Structural Systems; Retractable Roofs for Stadia",
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CLASSIFICATION OF STRUCTURAL SYSTEMS FOR RETRACTABLE ROOFS FOR STADIA

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1. Introduction.

The covered stadiums definitely are preferable compared to the open stadiums. Enclosing a stadium increases not only the number of event days but the revenue. It also creates opportunities for new kinds of events(2). The message is :"sports are big business and the business is entertainment. Part of the entertainment is the stadium itself"(1). A stadium also that is protected from the weather conditions can provide the spectators better and more comfortable seats along with an environmentally controlled space. So the spectators will not freeze or get wet to see a game.

The retractable roofs have even more advantages because they combine both the merits of closed and open stadiums. In a nice day the closed stadium is not particularly nice. So the roof can be retracted and the stadium can be used as an open one.

In this study we are looking into the design of retractable roofs for stadiums of the size of 50,000 to 60,000 seats. We will not address roofs or systems that are applicable for smaller scale facilities such as swimming pools or small tennis courts. The major concern when designing these facilities is the structural system of the roof and this is where we will expand on. We will present various solutions for retractable roofs for stadiums and an evaluation of the structural performance with the advantages and disadvantages of each one.

2. Structural Systems

Retractable roofs fall into two major categories. Rigid roofs that use mainly steel trusses or arches and the lightweight roofs that are made of cables or light frames and structural fabric (tensile structures).

The rigid roofs as their name suggests are composed from rigid segments. Depending on the variation all segments may be movable or only some of them may be movable. The segments usually telescope into or over each other to create the open stadium. Each segment though does not fold in a mechanical way but just moves rigidly to its open stadium position.

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The lightweight structures are composed of a cable net or light frames and structural fabric which is supported to them. When cables are used, secondary cables are used to retract the fabric to create the open stadium. In the case of light frames they slide along tracks to uncover the stadium.

A classification of the structural system for retractable roofs is shown in table 1. Conceptual sketches for each system are shown in figure 1.

2.1 Rigid Retractable Roofs.

Three are the possible solutions to the problem of rigid retractable roofs:

1. Translational systems with the roof segments gliding in one or two directions on linear (parallel) tracks while telescoping over or into each other.

2. Rotational systems with the roof segments following a circular track and stacking on top of each other.

3. Combination of the previous two. Some linear segments and some circular ones.

All systems can use trusses and/or arches to compose the overall structure. Since the major load for these structures is the dead load, parabolic arches that follow the line of thrust are considered the best since they carry the load in compression. The arch will bent under unbalanced loads such as wind, snow or earthquake. The major drawback is that the arches apply a powerful horizontal thrust on the supports. Not only that but the reactions at the supports change direction as the wind loads change. So the stands (spectator seats) that usually provide the support for the arches have to be braced so as not to allow any horizontal displacement.

Trusses are structurally less efficient than the arches, so, under a given load the depth and weight of their structural members are considerably greater and they will be exposed to greater forces. On the other hand they have the advantage of exerting only vertical forces on the supports and as a result there is no need to brace the stands.

In the following pages we will explain each system bringing examples and analyzing the advantages and disadvantages of each one.

2.1.1 Translational Systems.

A system is classified as translational if the moving rigid segments of the roof glide on one or more linear tracks per each side.

The roof is separated into rigid segments composed of trusses or arches. The segments span the short dimension of the stadium and can roll (glide) along tracks parallel to the long side of the stadium. The segments can telescope into each other or just park next to each other. It's obvious that the latter uses more space than the former. The segments can also be designed to move in one or two directions. That means that the segments either gather all together at one end of the stadium or gather at both ends of the stadium having each segment roll towards the nearest end. The two directional system needs less space and smaller overall height can be achieved, contrary to the one directional system that needs more parking space and higher structure.

When trusses are used they usually have large depths (22m (73ft) for the Domed Stadium of Toronto). This gives a less attractive solution than that using arches. For the same stadium the arches could be kept in the range of 4.5m (15ft) which is considerably smaller. On the other hand though the overall height of the roof is smaller for the case of trusses in some cases as much as 15m (50ft).

The translational systems permit to the designer to design a structure that will be 100% open without any considerable difficulties. In this case, cantilevers or another structure must be provided to hold the segments in their open position, or additional space off the stadium must be used for inclined linear tracks.

The design of a translational solutions for the Toronto Stadium (by M.S. Yolles & Partners Ltd.) is shown in figure 2 (scheme 1). The major advantages of the first system is that it is simple and that it uses only one track per each side for the whole roof. The overall height of the roof is only 50m (166ft). Because of the use of trusses the supporting structure is subjected only to vertical forces so expensive bracing can be avoided. Some of the disadvantages of the system is the deep trusses, 22m (73ft), that carry the roof in both the closed and open position. Also the big cantilevers that are needed to support the tracks for the parking of the roof in the open position, overhang out of the property line. The segments move only in one direction this way requiring longer cantilevers.

The already approved Phoenix stadium designed by Horst Berger Partners and shown in figure 3 (scheme 2) uses also a translational system. This system uses also one track per side, is clearly translational and the segments move in two directions to uncover the stadium. An innovative scheme of the design is the fact that the tracks are held in their position by cables which in their turn are supported on a truss along each of the longer sides of the stadium. Each track has two cables pulling it towards the sides of the stadium and a third cable links the two tracks together and pulls them closer to each other. All the permanent segments of the roof support at least one of their side on the track girders. Some engineers though expressed their concern with regard the deflections of system and the fact that the tracks are just hanging in the air. The structure is covered by a fabric and has a very small weight compared with other schemes. The weight of the roof is very small due to the use of the fabric and this is a major advantage of the system.

Although the system is considered innovative it does not provide the advantages other systems provide. The roof uncovers only 50% of the the field is actually uncovered and the seats remain covered with the translucent fabric used. The vertical deflections of the system are expected to be high and also the system is expected to be susceptible to vibrations. The system cannot be designed to avoid progressive collapse so the developer must be willing to accept higher risks for the structure.

Another example of the translational system has been proposed by the Iffland Kavanagh and Waterbury. The system is applicable for circular stadiums and is shown in figure 5. The roof is a dome, the segments of which slide on single tracks to uncover the center part of the stadium. The design of the tracks seem problematic to the author (they have to provide torsional resistance also).

2.1.2 Rotational Systems.

A system is classified as rotational if the moving segments of the roof slide on circular tracks.

The rotational systems are used for circular stadiums. They provide a near minimum surface enclosure to the spatial requirements. They all have a dome (spherical) closed shape but when it comes to the open position then there are a lot of differences between the various systems. The dome–shaped roof is familiar to the spectators and they feel more comfortable with it. A major advantage of the rotational systems is that they stay on the stadium even in the open position so they are suitable for small sites. They do not need off the stadium parking space.

Although the engineering community has a lot of experience designing domes, the design of these structures is completely different. The dome has to be divided into segments that are self supported, so the engineer cannot take advantage of the "shell–action" of the structure. The rotational systems use mainly arches to create the dome–like segments. Because of that the overall height of the system is usually large. The segments glide on individual tracks and can park in any position of the stadium circumference. This way providing shade or dead air conditions for the stadium.

The dome can be divided into circular sectors which are connected at the top with the opposite side sector this way creating a bow–tie shape when seen from above. The segments are made of arches that span the whole diameter of the stadium. These segments rotate and park on top of each other along a great circle of be seen in figure 5 (by Carruthers & Wallace Ltd.) prepared for the Toronto stadium (scheme 3).

The dome is separated into three bow–tie segments which in the open position still covers 33% of the stadium. This is a major disadvantage of the system since it will create sunny and shaded areas in the field and/or seats. All the arches (ribs), that the system is constructed of, span the whole diameter of the field so they are subjected to great forces even for the gravity load. The system also uses three tracks.

Phillips Barratt and Kaiser recently designed and proposed an innovative and ingenious rotational system for the Toronto Stadium shown in figure 6 (scheme 4). The dome is divided into three independent segments that seem cantilevering over the stadium and stack over each other in any position of the stadium. The true action of the segments is not cantilever since the segment is constructed by arches, the plane of which, is normal to the plane of symmetry of each segment, thus spanning only a portion of the diameter of the stadium. A small remaining hole left at the top of the dome must be constructed in a cantilever fashion. When there is a fixed segment then the tracks can be less than three. Careful planning of the stadium seats and the place the segments are parked can give a stadium with 85% of the seats uncovered.

2.1.3 Combination Systems.

Combination systems are the ones combining translational and rotational systems in the construction of the roof. The system can cover circular or oval stadiums. The most popular and also attractive is the system with two dome–like structures at the ends of the stadium and translational segments in between, designed by R. Robbie and M. Allen (figure 7, scheme 5). For the continuity of the system the translational systems are barrel vaults that stack over the circular segment.

This system combines the advantages and disadvantages of both systems. Most important of all is the need for parallel and circular tracks which is inconvenient for small sites. We have to stress though that the site at Toronto was truly small, but the designers were able to fit their system.

Another design (figure 8, scheme 6) by Iffland Kavanagh and Waterbury, called by the designers rota–translational roof system, is divided into seven bow–tie segments and then slide along linear tracks to uncover the hole stadium. The compatibility of the circular and linear tracks needs special attention.

2.2 Lightweight Retractable Roofs.

There are two possible systems for lightweight retractable roofs:

1. The folding systems that use light frames covered with fabric which folds as the frames slide to their open position. The light frames can slide on linear or circular tracks giving rise to translational or rotational systems.

2. The retracting systems that use cable nets to support the fabric and guiding cables to bring back the fabric in the closed position.

2.2.1 Folding Systems.

There are basically two types of folding lightweight roofs. None of them has been used or proposed for a stadium before so there description will be limited to the conceptual level.

The rotational system are applicable for circular or oval stadiums and is shown in figure 9. The light frames span the distance between the perimetric beam and the top of the pylon. The fabric is stretched over the frames and when the system opens it folds between successive frames. A major disadvantage of the system is that it is not redundant at all.

The translational system is applicable for oval or rectangular stadiums and is shown figure 10. The light frames retract in one or two directions to uncover the stadium while the fabric folds as previously in between. The same disadvantage applies for this one also.

2.2.2 Retracting Systems.

There is only one retractable lightweight roof for a stadium. The one for the Montreal Olympic Stadium(4) (figure 11). The retractable portion of the roof (which covers the field of the stadium only, since the seats are permanently covered by the structure) is designed as a canopy. The canopy an ingenious invention of the German engineer Frei Otto, consists of a light plastic membrane which when not needed is pulled up and suspended from the top of a mast. When required, it descends along guide cables, spreads out and once anchored down, provides the roof.

The Montreal Olympic Stadium has a canopy which is suspended from 26 points and anchored in 17. The membrane is a PVC-covered Kevlar, further coated with polyurethane to protect the roof from ultraviolet rays. The system is considered unsuccessful for such a large scale roof and in the specific case of the Montreal Stadium is considered a disaster. It took ten years to be completed and costed a lot more than anticipated. Even though the fabric technology is evolving rapidly and some of the problems the engineers in Montreal encountered, have already been solved by the industry, the use of canopies to cover stadiums is still considered out of scale. It can be done for smaller projects but not for a stadium. The mast, that supports the canopy has to lean over the stadium in order to place the roof at the center of the stadium. The required size of the tower and the difficult nature of the construction details make the scheme too expensive.

3. Summary.

The structural systems for the retractable roofs have been examined and a systematic classification has been presented. The roofs are first classified as rigid or lightweight and then if rigid it can be classified as translational, rotational or a combination of the two, and if lightweight it can be classified as folding (translational or rotational) or retracting.

The basic concepts underlying the design of the individual systems are described and a criticism from the structural engineering point of view is offered. A summary of the features of each scheme is presented in table 2.

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Table 1. Classification of Retractable Roofs

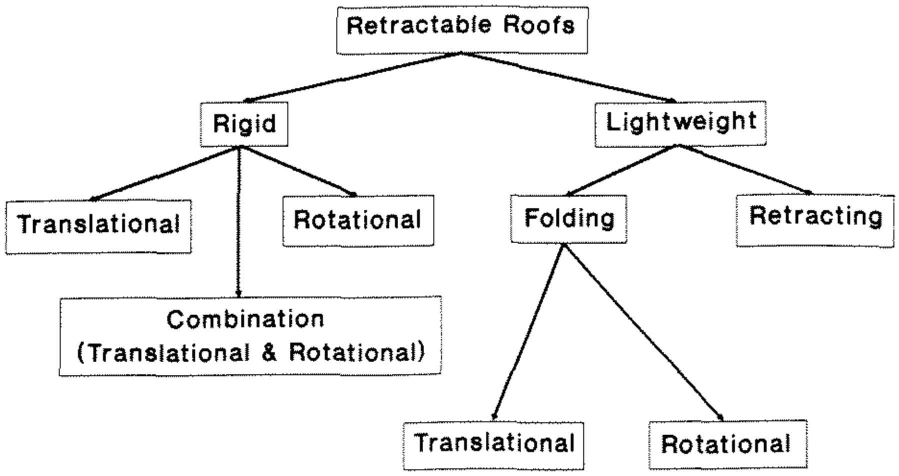


Table 2. Summary of Features

Feature	Scheme						
	1	2	3	4	5	6	7
Degree of Openness of Field	H	H	H	H	H	H	H
Degree of Openness of Seats	H	L	M	H	H	H	L
Ease of Construction	L	H	H	H	M	M	L
Need of Few Tracks	H	H	M	M	M	M	-
Overall Height	M	L	H	H	H	H	L
Depth of Structure	H	L	M	M	M	M	-
Structurally Redundant	H	L	H	H	H	M	L
Displacements	M	H	M	M	M	M	H
Reliability of Operation	H	H	H	H	H	M	M
Durability	H	M	H	H	H	H	L
Self Storing	M	L	H	H	M	H	-
Weight Of Structure	H	M	H	H	H	H	L

Legend : H=High M=Medium L=Low -=Not Applicable

Table 1. Classification of Retractable Roofs

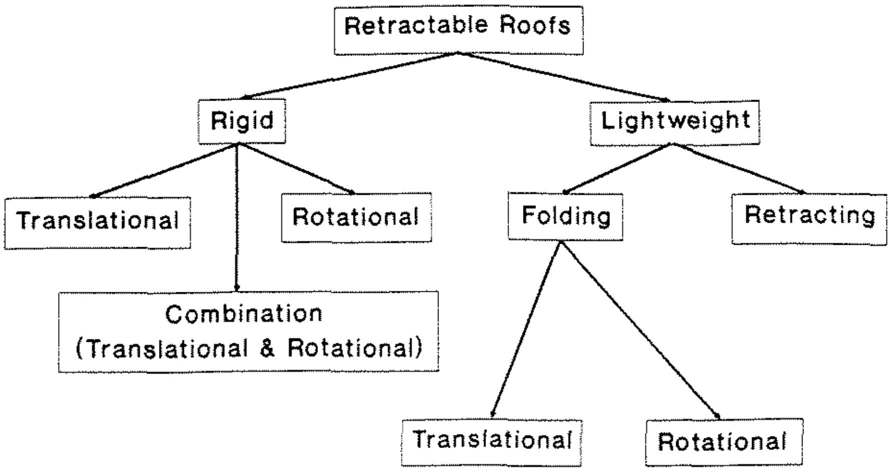
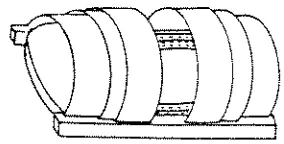


Table 2. Summary of Features

Feature	Scheme						
	1	2	3	4	5	6	7
Degree of Openness of Field	H	H	H	H	H	H	H
Degree of Openness of Seats	H	L	M	H	H	H	L
Ease of Construction	L	H	H	H	M	M	L
Need of Few Tracks	H	H	M	M	M	M	-
Overall Height	M	L	H	H	H	H	L
Depth of Structure	H	L	M	M	M	M	-
Structurally Redundant	H	L	H	H	H	M	L
Displacements	M	H	M	M	M	M	H
Reliability of Operation	H	H	H	H	H	M	M
Durability	H	M	H	H	H	H	L
Self Storing	M	L	H	H	M	H	-
Weight Of Structure	H	M	H	H	H	H	L
Legend : H=High M=Medium L=Low -=Not Applicable							



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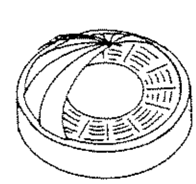

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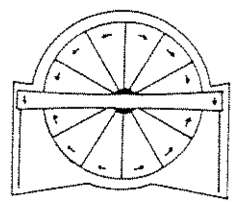

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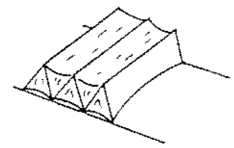

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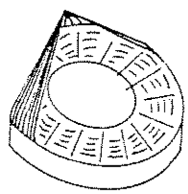

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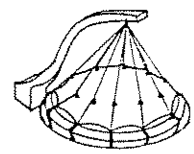

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Figure 1. Conceptual Designs of Retractable Roofs.
a. Rigid Translational. b. Rigid Rotational. C. Rigid Combination
d. Folding Translational. e. Folding Rotational. f. Retracting.

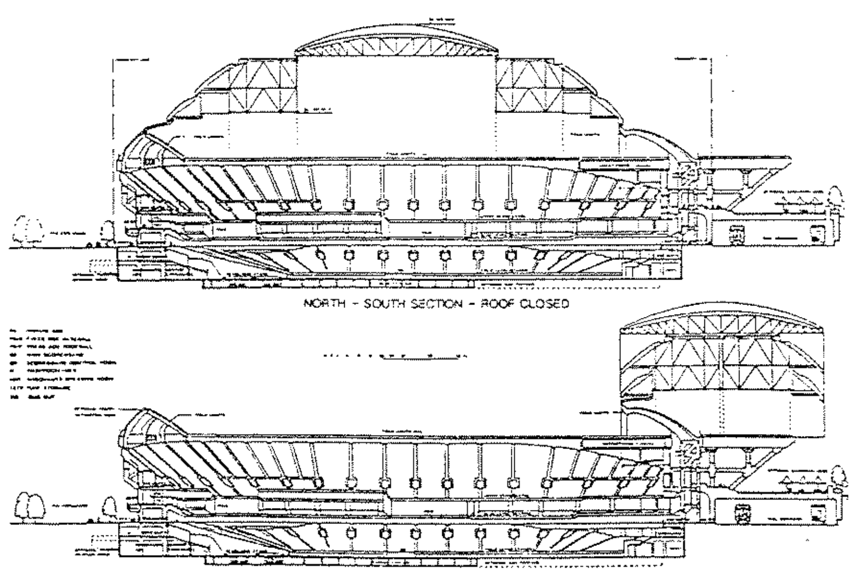

Figure 2. Translational System by Yolles and Partners (Ref. 3).

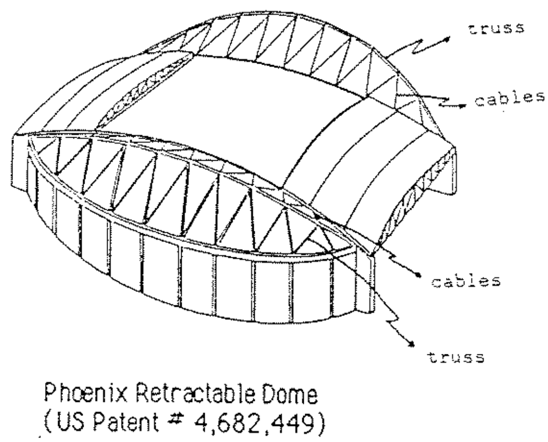

Figure 3. Translational System by Berger and Partners (Ref. 2).

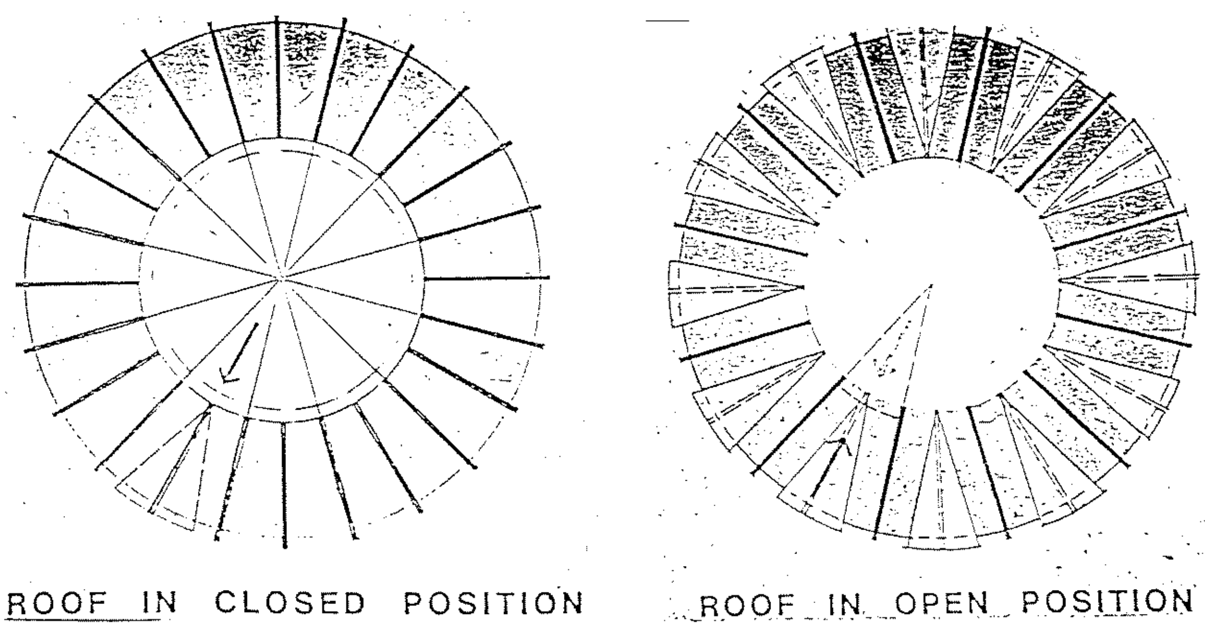

Figure 4. Translational System by Iffland Kavanagh and Waterbury.

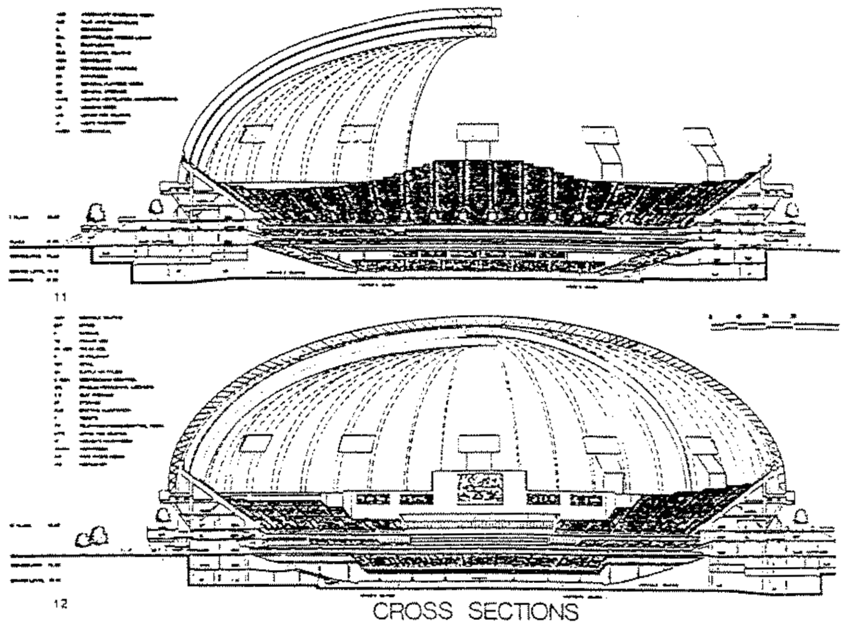

Figure 5. Rotational System by Carruthers and Wallace (Ref. 3).

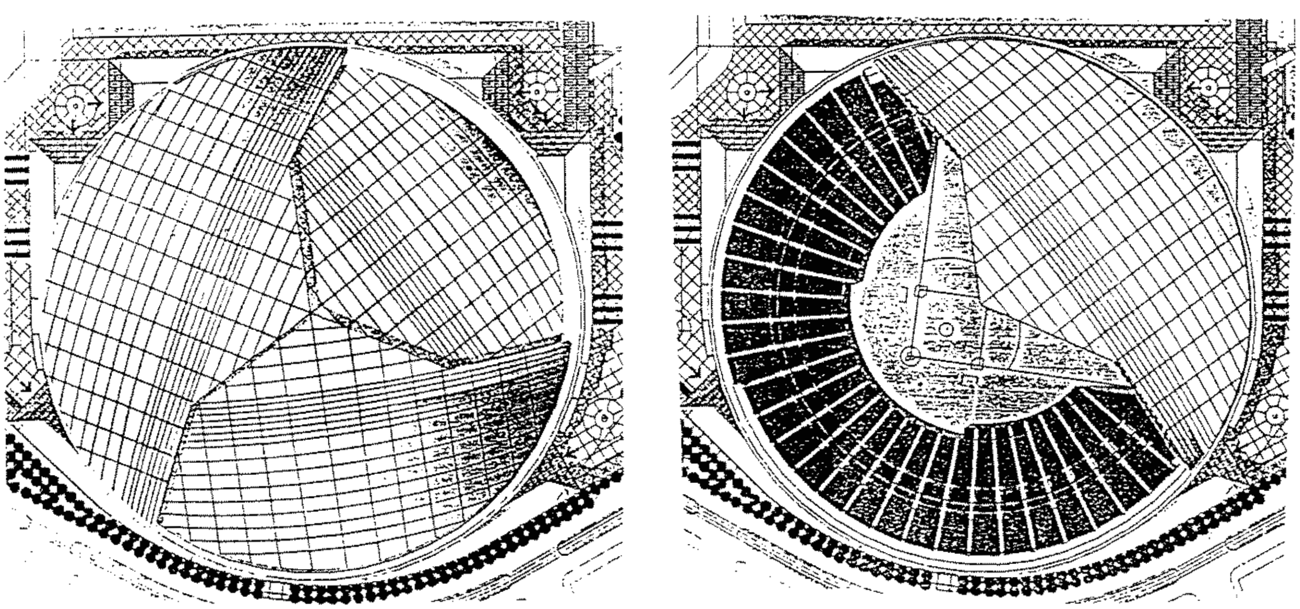

Figure 6. Rotational System by Phillips, Barrat and Kaiser (Ref. 3).

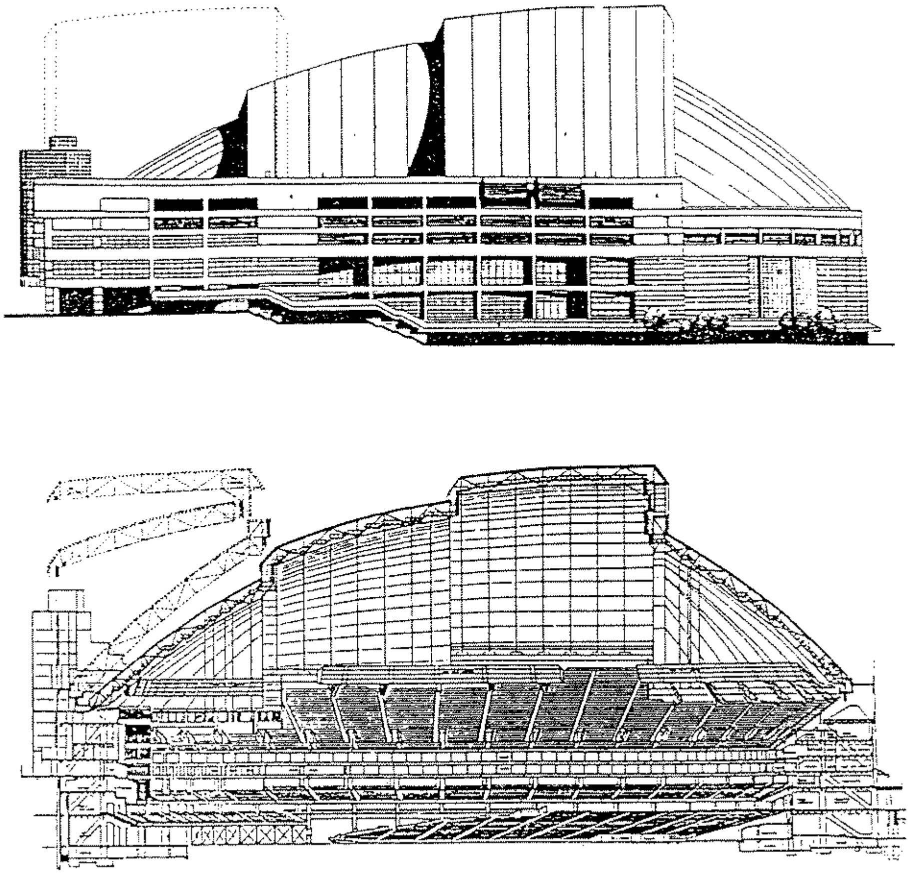

Figure 7. Combination System by Ellis–Don (Ref. 3).

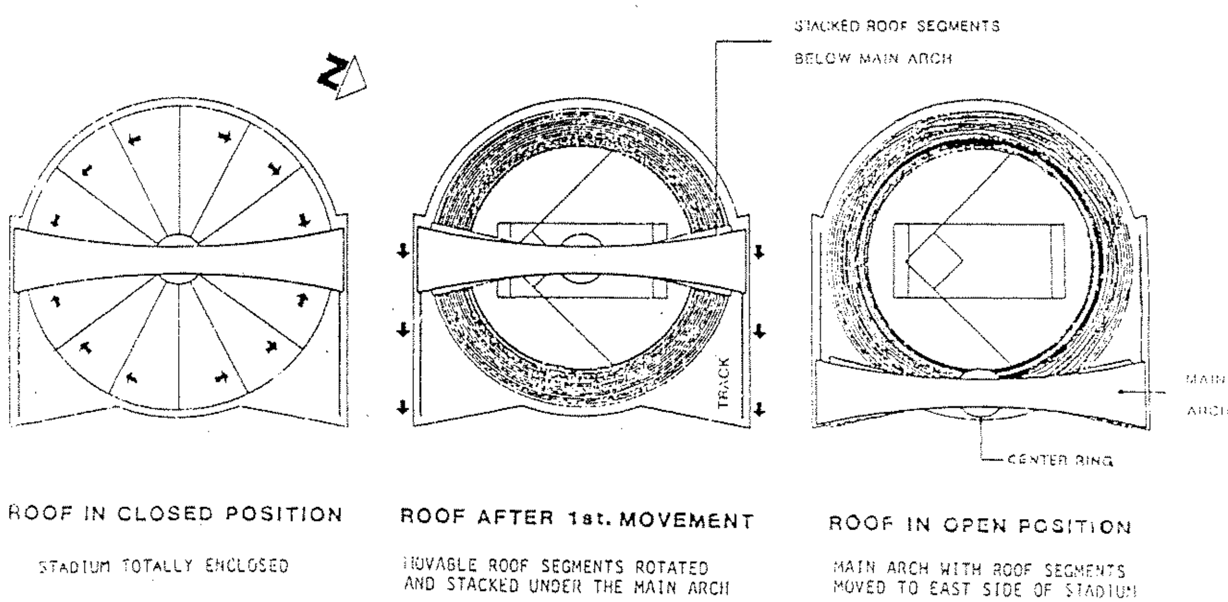

Figure 8. Combination System by Iffland Kavanagh and Waterbury

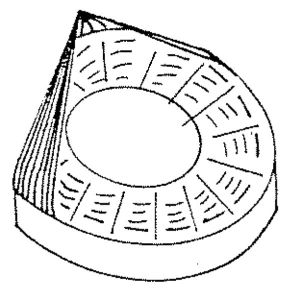

Figure 9. Lightweight Rotational Folding System.

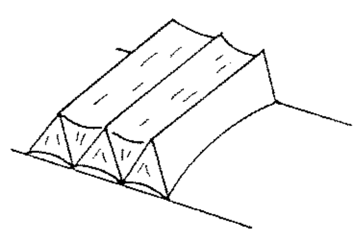

Figure 10. Lightweight Translational Folding System.

Figure 11. Lightweight Retracting Fabric System. (Lavalin Brochure).