RETRACTABLE ROOF STRUCTURES IN JAPAN

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ABSTRACT

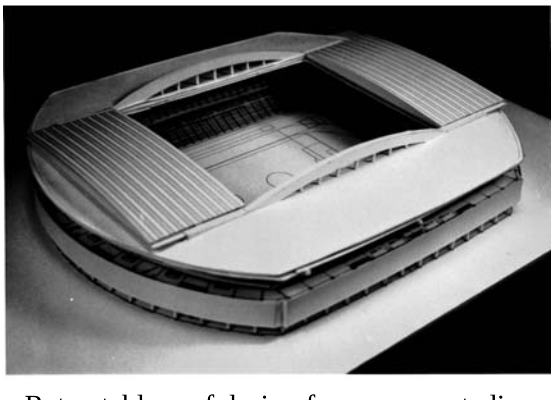
The establishment of technologies for supporting retractable roof structures has affected their safety, design and structural method, and enabled the realization of large-scale retractable roofs. In Japan, retractable roofs with area of 10,000 m^2 or more are used for domes and stadium roofs. With the establishment of design standards, guidelines related to retractable roofs, architects/engineers can now adopt this structure freely in their building design, in the same way as other conventional structures.
In the paper, the present state of the art on retractable roofs in Japan are described and focused on structural scheme of retractable roofs in Japan.

INTRODUCTION

Public "citizens' domes", which are being actively planned and constructed by prefecture and city governments, are currently the most popular large-scale sporting facilities (domes) in Japan. Some of these large-scale sporting facilities are designed as domes equipped with retractable roofs. These facilities offer a space for people to participate in sports under blue sky with natural light and wind when weather conditions are good, and in winter, they offer protection from the cold and snow. In addition, these facilities are also used for various public events and may become a symbol of the local area, offering an opportunity of invigorating the local area.

Such large facilities are designed to be used for baseball and soccer games, which are impossible to host in previous gym-sized facilities. Artificial grass is used for amateur soccer games. At present, these large-scale sports facilities are being used by the public to full capacity.

These domes are constructed and managed by prefectures or cities, with subsidies from the National Government or local bonds, or by their own local budgets. Set fees for citizens to use the domes are extremely inexpensive.



Retractable roof design for a soccer stadium

CONCEPT OF RETRACTABLE ROOFS

Problems involved in the adoption of retractable roofs include an increase in construction costs, as well as in the maintenance and management costs of its open and close function; when the advantages significantly outweigh the disadvantages, retractable roofs are often adopted.

Whether or not to adopt a retractable roof in a sports facility will be decided depending on environmental and economical consideration as well as public demand. There are often various opposing opinions regarding the adoption of retractable roofs, although retractable roofs have recently become fairly popular.

LARGE-SCALE RETRACTABLE ROOFS -Technologies to develop retractable roofs-

Characteristics of large-scale retractable roof structures in Japan are

- The general structure of large-scale retractable roofs in Japan is a steel or timber framework covered by membrane fabrics
- Even when a roof is closed, the structure is designed so that natural light enters the internal space
- Membrane-folding methods are used only in smaller retractable roof structures
- PTFE coated glass fiber fabrics are mainly used as membrane materials because of their superior dirt prevention, durability and incombustibility.

Large-scale retractable roof structures are used not only by structural technologies, but also by mechanical or crane technologies, which do not require extremely difficult techniques. Cranes are usually used to transport bulky materials, but they can also be used to move retractable roofs. In cable structures, ropeway technologies are used.

GUIDELINES FOR DESIGN OF RETRACTABLE STRUCTURES

During the 1990s when retractable roof structures have enjoyed wide use in Japan, 20 buildings per annum with retractable roofs have been constructed including those with small-scale retractable roofs, and the construction of large-scale retractable roofs has been actively pursued. However, until now, there has been no standard for the design and construction of retractable roofs in Japan.

Because retractable roof structures represent a new type of architecture that requires management of its open and close function, various problems in their construction have arisen, including those involved in the establishment of allowable stresses and strengths of special steel materials conventionally used for machines and not for architecture. It was unclear whether the allowable stresses set for machine-use material could also be used in a retractable roof structure; since retractable roofs do not move continuously as machines do, driving ropes and special steel materials are not used as frequently.

To offer answers to these problems, guidelines for design of retractable roof structures were compiled. At present, retractable roof structures are designed using these guidelines; construction is approved only if the design is in accordance with the guidelines. These guidelines were established to provide direction in the design of retractable roof structures.

Table 1 Guidelines/Recommendations for design of retractable roof structures in Japan

Recommendations for Design of Retractable Roof Structures - 1993 -	Architectural Institute of Japan	Structural Scheme/Loads and External forces/Structural Materials and Allowable stress/Driving Mechanism/Structure of each part/ Design considerations/Maintenance & control plan
Guidelines for Structural Design of Retractable membrane roof structures - 1995-	Membrane Structures Association of Japan	Materials/Structural scheme/Loads/Safety factors/Driving mechanism

The following items are explained in the guidelines to aid structural planning.

1) Safety of the structure

(Ensuring safety during opening and closing of the roof)

The safety of a structure during movement or travelling of the roof has not been examined in the conventional architectural field. Designers should take sufficient countermeasures against accidents and failures, which can be predicted from past examples.

Table 2 Ensuring safety during opening and closing of the roof

Opening and closing of a structure with inclined tracks	The possibility of brake malfunction on inclined tracks, and of breaking of cables in the cable-traction method should be considered. The method of fixing the roof between opening and closing.
Hanging-type opening and closing	The possibility of cable breaking and roof swinging should be considered in cases of cable-hanging. Countermeasures should be taken against collapse of the roof and malfunction during opening and closing.
Folding-type opening and closing	The membrane is slackened during extension and retraction. Under this condition, flapping or billowing of the membrane due to wind is particularly dangerous, and easily results in damage to the membrane. Therefore, the membrane should be secured during this phase using suspended weights or rigid elements.

2) Clarification of opening and closing conditions of the roof

It must be clearly defined in the design phase in what conditions and how the roof is opened or closed. In semi-open states, it must be clearly defined at which position use of the roof is expected. A plan must be set up on proper evaluation of loads and external forces, design of the driving mechanism, opening and closing control and instructions for the operation.

Generally, under storm or strong-wind conditions, retractable roof structures are either used closed or retracted in an open state. The selection of one of the two depends on the opening and closing method, the characteristics of the whole structure, and the planned use of the interior; the selected plan should be presented at the initial stage of planning.

The structural limit for opening and closing must be clearly defined for safety purposes so that opening/closing control can be carried out without difficulty. The conditions for opening and closing must be set up against fluctuation of the wind velocity or snow accumulation during opening or closing of the roof to ensure the opening and closing operation and to prevent the occurrence of unreasonable stress on the structures during opening and closing operations. On the contrary, retractable roof structures may be kept in the open state if the wind velocity or snowfall exceeds a certain limit. In this case, care must be taken in clearly defining the opening and closing conditions to reasonably ensure opening and closing control.

But in Snow Belt regions, it is dangerous when designing a structure to avoid snow accumulation by moving roof panels to an open state. As a practical and safety consideration, retractable roofs should be left closed during the snow fall season.

The failure of opening/closing control may lead to damage of the entire structure. Structural planning must be set up in such a manner that opening and closing operations can be carried out quickly, reliably and easily.

3) Wind-proof, snow-proof, and earthquake-resistant design

(Considerations of wind)

As problems specific to retractable roofs, wind load and the structural design to withstand it are discussed here.

In retractable roof structures, wind loads for the open state, closed state, semi-open state, and during opening and closing are different. Accordingly, if the structure is designed to withstand the maximum wind load in each of these states, cost-effectiveness decreases while increasing the size of the structure.

The maximum wind load, which the structure will withstand, differs, depending on the opening and closing method and the basic design of the structure. Therefore, the structural design should be performed, based on clarification of wind loads acting in each state, so that no problems arise during actual use or during opening and closing control. At the same time, conversion of the roof to each state should be achieved smoothly under predicted wind loads.

Points to be considered for retractable roofs in terms of wind are as follows.

Table 3 Considerations concerning wind

Behavior in open state, closed state, semi-open state	Since there are generally large differences in the behavior of a structural body due to wind in an open state, closed state and semi-open fixed state, behavior of the structure should be comprehensively examined in terms of structure and usage.
Behavior of each retractable panel	The behavior of structurally independent retractable panels under wind load generally differ from each other. Therefore appropriate clearance should be maintained between each panel based on clarification of the behavior of each panel, including their vibration characteristics.
Seal between each panel	Spaces between structurally independent movable panels should be sealed to prevent invasion of rain and wind. The seal should be flexible to accommodate deformation and vibration of panels.
Height difference between panels	As the size of the movable panels of a frame structure increases, its depth increases. As a result, the behavior of wind at different heights on the roof becomes complex, resulting in generation of a large local load. Therefore, surface-finishing materials should be attached with care.
Floating of retractable parts	Movable parts of the roof may float up by wind depending on their shape. When the parts run on rails, floating decreases the frictional force between the rails and wheels. Particularly when the rails are inclined, special attention is required since frictional force decreases greatly. In pulleys run on cables, floating causes derailment of the pulleys.
Membrane stretched over a frame	A membrane should always be tensioned so that forced vibration and flutter due to wind do not occur. Measures for removing precipitation and snow meltwater accumulated on a membrane should be devised, so that ponding does not occur due to precipitation, snow meltwater or accumulated snow.
Cable structure	Attention should be paid to stability against wind as well as to vibration and swing due to wind. Main cable materials should not lose tension under wind load.
Driving mechanism	During opening and closing, magnitudes of wind forces transferred to each driving part are not the same. Therefore, synchronous control of each driving part should be performed to prevent snaking movement of the movable parts.
Cable for mechanical parts	When the cable traction method is adopted for movable parts, attention should be paid to behavior and vibration of the cable due to wind.

(Considerations of snow)

When a retractable roof structure is constructed in a region where snow loads should be taken into consideration, then as in the case for wind, snow loads in the open state, closed state and during opening and closing should be determined based on the opening and closing control, taking safety factors into consideration. Snow load in a closed state is the same as that of a general structure; however, when the roof is opened during snow, failure of the control may lead to an accident.

Table 4　Considerations concerning snow

Behavior of each retractable panel	Deformation of structurally independent movable panel due to snow load is generally different for each panel. Deformation characteristics of each panel should be clarified through examination of its behavior during snow accumulation, and appropriate clearance should be maintained between panels.
Snow load as a long-term load	Accumulation of snow may continue for a long time. Accordingly, the effects of the long-term accumulation of snow on a structural body, creep and strength of materials should be examined.
Considerations concerning sliding snow	When sliding of snow on the roof surface is expected, attention should be paid to the manner of sliding, scattering of snow due to sliding, and impact loads of snow.
Membrane stretched over a panel	A membrane stretched over a panel requires an inclination to prevent accumulation of snow meltwater even when the surface is deformed due to snow accumulation. The shape of the stretched membrane should prevent local snow accumulation.
Snow and ice on rails and freezing of supporting cables	Snow accumulation and freezing on a rail obstructs the movement of parts. Snow-melting devices or measures for snow removal should be examined.
Movement of parts during snowfall	An appropriate plan should be made for smooth operation of retractable parts during snowfall or against initial accumulation of snow on the roof surface.

(Considerations of earthquakes)

In regions where seismic loads are expected, the consideration during opening and closing is a problem specific to retractable roofs. Unlike machines, retractable roofs are not always in motion. Accordingly, in general, the probability of an earthquake during movement of the roof is extremely low. Even in Japan where many earthquakes occur, the occurrence of an earthquake during movement is generally not considered for small retractable roof structures or crane structures. However, in large retractable roof structures accommodating a large number of spectators, sufficient countermeasures should be devised depending on the degree of damage predicted to be caused by an earthquake.

Countermeasures against earthquakes provided in many previous design examples of large frame retractable roof structures are as follows.

- For level-1 earthquake movement, the structural body should be within the elastic range, and derailment or runaway movement should not occur.
- For level-2 earthquake movement, the structural body should undergo elastic and plastic behavior, and if part of the structure collapses, collapse of the entire structure, derailment or runaway movement, and falling of other parts of the building should be prevented.

Phase difference of earthquake movements has been examined for the case of a large retractable roof dome.

(Note) Level-1 earthquake movement: earthquake movement with maximum velocity of approximately 25 cm/s.
Level-2 earthquake movement: earthquake movement with maximum velocity of approximately 50 cm/s.

Table 5　Considerations concerning earthquakes

Behavior of movable panels	When the vibration characteristics of each panel are different, the panels vibrate in different ways. Effects of the vibrations on clearance as well as on the pivot axis connecting each panel, if a such an axis is present, should be considered.
During movement of panels	◆ Seismometers should be installed in large retractable roof structures. Upon detection of earthquake movement greater than a certain level, moving parts should be immediately stopped by means of brakes or other measures. On such occasions, these measures should prevent wheels from slipping in case of small earthquakes whose probability of occurrence is high. ◆ In case of an earthquake occurring during movement of parts, measures should be taken to prevent accidents such as derailment, collision, and large swing of hanging parts. ◆ At a movable part on an inclined beam in the cable traction method, impact loads are applied to the cable.
Safety against derailment	Prevention of derailment due to lateral loads caused by an earthquake during movement is necessary.

4) Plan for maintenance control, and operation

Safety and serviceability of a building with moving units such as retractable roof structures are assured only through backup of maintenance control. In particular, if the structure is designed for different opening and closing configuration, it must be strictly controlled to meet the design concept. For this purpose, it must be clarified in what conditions the roof is opened or closed in term of design, and control and operating plan for opening and closing must be adequately set up in accordance with the design concept of the designers.

Maintenance must be assured for mechanical parts for opening and closing, although the condition of use is not as severe as in the case of cranes.

For the maintenance of mechanical parts, there are two modes of maintenance.

Table 6 Maintenance method

Post-maintenance	Post-maintenance to repair after each malfunction.
Preventive maintenance	Maintenance to replace or repair the parts or members in advance, where malfunction may occur.

Preventive maintenance is desirable in case severe loss such as grave accident is expected by the malfunctions of the mechanical portion. In order to properly carry out preventive maintenance, a maintenance team is needed, and it is necessary to clearly define the period and degree of inspection and a detailed inspection procedure.

Maintenance organization is required to identify the importance of preventive maintenance and to carry it out smoothly. Inspection, checking and repair procedures must be coordinated with the design concept.

Operation must be performed in a safe and smooth manner. Several cases of accidents with cranes have been reported such as death caused by bricks fallen off the moving unit, an operator working on the rails was hurt without being aware of the running crane, an operator struck by electricity, where the malfunction was detected but was neglected, leading to a severe accident. Therefore, due consideration must be given to the operating plan to eliminate such accidents.

Many cases have also been reported, which occurred due to improper application of fixing devices after operation. It is important to install and maintain various types of safety devices, but it is equally important to execute maintenance and control to operate the devices in their best condition.

Designers must take special care in the condition where moving is involved, and must set up a proper maintenance control plan by clearly defining the purpose of maintenance control and the items to be maintained for this purpose.

The method of maintenance and control for repair and replacement of parts must also be taken into consideration in its design. As the retractable systems become more complicated and larger, a system to correctly grasp these situations as well as maintenance and control is required. Also, there is a need to check operations subject to human error.

5) Monitoring

There are various types of retractable roof structures. To ensure reliable and safe opening and closing operation, the data must be collected from actual structures at all times. These are used to determine whether the structures are deviated from the original scope of design. Because the retractable roof structures are a new form of architecture, the necessary data must be collected by monitoring for safety backup. These data should be fed back to structural design and incorporated in opening / closing control and maintenance control to ensure safety.

SAFETY FACTOR OF MATERIALS

(Specific materials used for retractable roof structures and their safety factors)

In general, in Japan, allowable strength is set at a value calculated by multiplying the material strength by the material safety factor. This method is used in design and is called the allowable stress method. Material safety factors for various materials used in retractable roof structures and in this design method are as follows.

In cases when synthetic fibers are used for the roof membrane, the decrease in the strength of the synthetic fibers in a usual flex test is only slight and the decrease does not affect their strength. However, generation of cracks and damage in coating materials is expected, both of which may reduce material strength due to the deterioration of durability. Therefore, material safety factors should be determined based on various conditions such as the number of times the roof will be expected to open and close and the roof folding method.

Table 7 Safety factor of membrane materials which are folded or wound

Kinds of membrane material	Fiberglass fabric should be avoided
Safety factor of material	5 or greater, depending on usage conditions such as frequency of opening and closing or generation of wrikling at the time of folding

(Safety factor of cables)

In retractable roof structures, sections of the roof are retracted using cables in a way, which has not previously been considered in conventional architecture. Safety factors of the cables are determined based on the number of anticipated openings and closings, the retraction method and environmental conditions, with reference to the material safety factors applied in fields other than architecture.

With respect to the safety factor of a material, allowable stress is determined on the basis of architecture and not of mechanical engineering. As a result, safety factors lower than those used in machines are determined. Structural designers must judge the necessity of increased safety factors based on the retraction method and the number of anticipated openings and closings.

Table 8 Safety factors of Wire ropes /Running ropes Japan

Use	Allowable strength	Allowable strength	Note

	for long-term stress	for short-term stress	
Structural cable (Static use)	3 or more	2.2 or more	Fixed wire ropes for supporting structures, such as those for cable structure, reinforcement and boundary structure. No bending stress acts during opening and closing
Running rope	5 or more	3.3 or more	Wire ropes, which are bent, moved or applied with, repeated loads or impact loads during opening and closing. Those which are wound, or undergo repeated bending.

(Quality of steel materials for the retraction mechanism and material safety factors)

Safety factors of steel material used in architectural structures and of a mechanical material used for the retraction mechanism should not be determined independently, but should be determined so that a good balance between the two values is maintained.

With respect to the safety factors of a material being used in a mechanical part, the scale effect, notch effect, fatigue limit and safety factors are generally taken into consideration when determining allowable stress. This is a material safety factor, which is determined based on the assumption of continuous operation. In contrast, in retractable roof structures, materials do not operate continuously, and great consideration of fatigue is not required. Examination of fatigue is unnecessary when the repeating stress is less than 10^4.

A smaller value of either the yield point of a steel material or 70% of the tensile strength is used as a standard strength to determine allowable stress. Qualities of materials are determined by JIS (Japanese Industrial Standard).

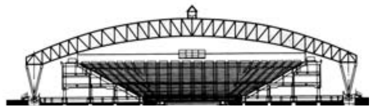
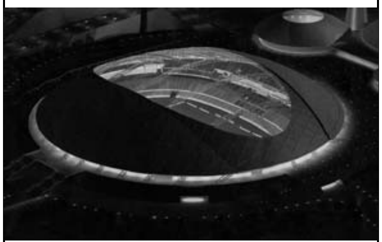
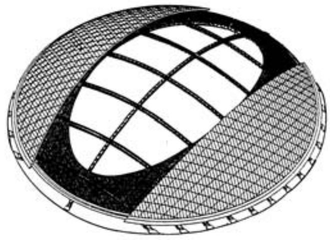
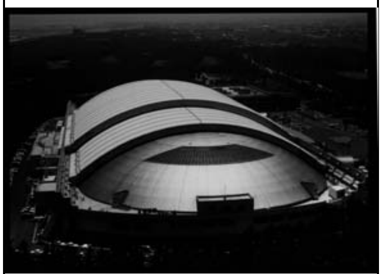
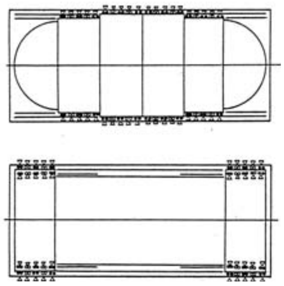
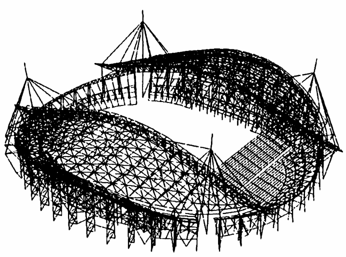
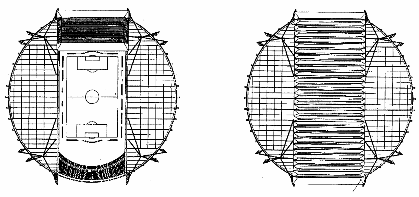
FUTURE RETRACTABLE ROOFS IN JAPAN

In Japan, various types and sizes of retractable roofs are being constructed primarily in sports facilities. Accompanying this trend, once-expensive retractable roofs can now be constructed more cheaply. In addition, maintenance of roof retraction operation can be performed at lower cost due to the establishment of inspection tools for the retraction mechanism parts, and the establishment of an inspection method at the design stage.

In the past, a large portion of the construction cost went to construction of a large roof opening area. However, more economical operational methods can be applied. Examples are shown in the Ohita Dome and the Toyota Stadium, wherein a balance between objective retraction methods and economic features is considered: for example, in the Ohita Dome, the main arches are left unmoved during the retraction; in the Toyota Stadium, the roofs are opened when it snows so that no snow load is applied to the roof, and a membrane structure is applied to reduce brightness contrast.

Designing a retraction mechanism, which maintains good balance of the upper structure, while considering the safety of the architectural structure, can reduce the construction cost of a retractable roof.

In addition to the practical objective of growing natural grass on soccer grounds, the opening of roofs has other excellent advantages. When deciding whether or not to construct a retractable roof, one must weigh the advantages against the disadvantages of the increase in the construction cost due to retraction of the roof, maintenance and management costs.
At present, more economical retraction methods are approached.

Ariake Coliseum (Tokyo,1991) 	Architect :Kenchiku Mode Kenkyujo Co.,Ltd. Engineer :Kenchiku Mode Kenkyujo Co.,Ltd. System : Overlapping roof elements (Parallel movement) Closing time : approx. 17.5 minutes Dimensions : Roof plan 125×136m, Height 40.1m Use : Tennis and multi purpose use Roofed area : 17,000m^2 Roof Structure : Steel frames Roof material : Steel plate panel 
Ohita Dome (Ohita, 1999) 	Architects :K. Kurokawa & Takenaka Corp. Engineers :K. Kurokawa & Takenaka Corp. System : Overlapping roof elements (Parallel movement on arches) Closing time : approx. 15 minutes Dimensions : Dia. 274 m Height 66.6 m Ret. roofed area : 20000m^2 Roof Structure : Steel frames Roof material : Titanium plate + PTFE coated glass fiber fabric 
Ocean Dome (Miyazaki, 1993) 	Architect : Kobe Shipyard & Machinery Works, Mitsubishi Heavy Industries Ltd. Engineers :Mitsubishi Heavy Industries Ltd. System : Overlapping roof elements (Parallel movement) Closing time : approx.10 minutes Dimensions : Plan 35,185m^2, Height 38m Roofed area 22,726m^2 Use : Swimming pool Roof Structure : Steel frames Roof material : PTFE coated glass fiber fabric 
Toyota Stadium (Toyota city, 2000) 	Architect : K. Kurokawa Design office Engineers : OveArup & Partners Japan System : Folding system Closing time : approx. 60 minutes Dimensions : Plan 40734 m^2, Height : 68.6 m Mast 92.7 m Roof area : 34,000 m^2, Ret. Roofed area 19100 m^2 Use : Soccer stadium Roof Structure : Cable suspended steel frames Roof material : Fixed roof Stainless steel Retractable roof PVC coated polyester fabric 

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