Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 71 (1994)

Artikel: Retractable roof using the 'reciprocal frame'

Autor: Choo, Ban Seng / Couliette, Paula N. / Chilton, John C.

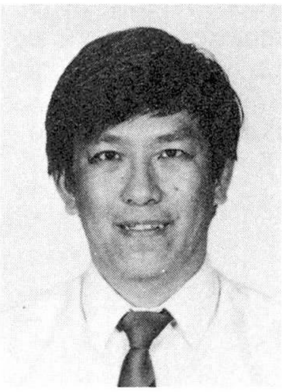
DOI: https://doi.org/10.5169/seals-54118

Retractable Roof Using the 'Reciprocal Frame'

"Cadres réciproques" pour les toitures escamotables

"Wechselseitige Rahmen" für einziehbare Dächer

Ban Seng CHOO
Civil Engineer
Univ. of Nottingham
Nottingham, UK



Paula N. COULIETTE
Civil Engineer
Univ. of Nottingham
Nottingham, UK

John C. CHILTON
Civil Engineer
Univ. of Nottingham
Nottingham, UK

SUMMARY

The 'Reciprocal Frame', recently patented, is a three-dimensional beam grillage structural system used primarily in roof construction. The beams in the grillage both support and are supported reciprocally by each other. The plan view of the beams is similar in appearance to the lines forming the iris of a camera shutter. Its versatility in form and consistency in strength make it a competitive design for sports arena and stadia. Structural design, drive device, roof operation and covering are discussed.

RÉSUMÉ

Breveté récemment, le principe des "cadres réciproques" consiste en un système de grilles de poutres tridimensionnelles dont les poutres portent et s'appuient réciproquement. La disposition des poutres ressemble aux lignes d'un diaphragme d'appareil photographique. Par la diversité des formes et la résistance généralement disponible, ce genre de couverture offre une solution concurrentielle pour des salles de sport et des stades. La discussion porte sur le calcul du projet, le mécanisme d'entraînement, le mode d'ouverture et de fermeture, ainsi que le type de toit mobile.

ZUSAMMENFASSUNG

Beim kürzlich patentierten Prinzip der "wechselseitigen Rahmen" für einziehbare Dächer handelt es sich um ein dreidimensionales Trägerrostsystem. Alle Träger stützen sich wechselseitig. Die Trägeranordnung ähnelt den Linien des Zentralverschlusses einer Kamera. Dank Formenvielfalt und der durchgängig vorhandener Festigkeit resultiert eine wettbewerbsfähige Lösung für Ueberdachungen von Hallen und Stadien. Tragwerksentwurf, Antrieb, Arbeitsweise beim Ein- und Ausfahren sowie Abdeckung werden diskutiert.

1. INTRODUCTION

Across the globe architects and engineers are exploiting the versatility of retractable roofs for sports stadia and arenas. In North America, the Toronto Skydome [1,2], the Olympic Stadium in Montreal [2], and the Civic Arena in Pittsburgh [2], are well known examples of structures with retractable roofs. The structural design of each one is unique. In the Skydome, three separate roof sections retract and nest over the top of a fixed panel; each panel is a different size and shape from the others. The Montreal Olympic Stadium has a fabric roof that can be rolled up into a tower but because of difficulties in retraction, it now remains permanently retracted. The Civic Arena in Pittsburgh features a successful retractable dome where six separate sections pivot about a pin and roll along curved rails before coming to rest over two cantilevered fixed sections.

Additionally, there are several structures which are in operation in Japan, such as the Mukogawa High School Swimming Pool, the Ariake Colosseum, and the Fukuoka Dome [3]. Apart from these buildings, which have successfully opening and closing roof systems, there are many other designs being developed for retractable roofs on sports complexes all over the world. One such design being worked on at the University of Nottingham is the Reciprocal Frame Roof [4], see Figure 1. A related reticulated roof in the form of a spherical dome was proposed by Emilio Pérez Piñero in his patent 9102733 of 1961 [5]. The likeness of these two structures to the iris of a camera shutter makes them possible solutions for retractable roof systems.

2. THE RECIPROCAL FRAME ROOF

2.1 Architectural Aspects

As the Reciprocal Frame Roof has the same configuration as a camera shutter, it is easy to visualize its opening and closing. The static configuration has considerable visual impact and appears very dynamic when viewed from the floor. The primary beam structure seems to be rotating about an axis, in empty space, at the centre of the roof. During the retraction process, like the leaves of an iris diaphragm, each beam rotates individually about its external support, opening and closing the structure, see Figure 2 A to D. A major advantage to using the Reciprocal Frame Roof as a retractable roof system is the versatility in floor plan design as this is not limited by the need to provide extensive running rails (either in a straight line or constant curve) that are required by most other systems. Since the outer and inner polygons in the structure need not have the same shape, this roof can cover stadiums with virtually any geometry.

2.2 Structural Components of the Roof

The primary structure of the Reciprocal Frame is a circuit of beams spiralling around an imaginary centre. Each beam in the grillage both supports and in turn is supported by the other beams in the structure, hence the name reciprocal. The beams are placed tangentially around a central closed curve so that they rest upon the preceding beams creating the closed circuit. An enclosed polygon is formed with a set of radiating beams equal to the number of sides of the polygon. The outer ends of the beams in the grillage are supported by columns or walls. These columns or support positioning on the walls also form a polygon but its shape need not be the same as that of the inner polygon. As the beams rest on each other, there is a rise from the outer to the inner polygon which depends on the height between beam centre lines at their intersection, number of beams, etc., creating a three dimensional structure.

2.3 Structural Behaviour

The configuration of the beams in the Reciprocal Frame Roof causes applied vertical loading to be converted into downward thrust acting through the outer supports. In a regular circular or polygonal form carrying a uniformly distributed vertical load, the beam reactions are all equal to the total roof load divided by the number of beams. However, when a point load is applied

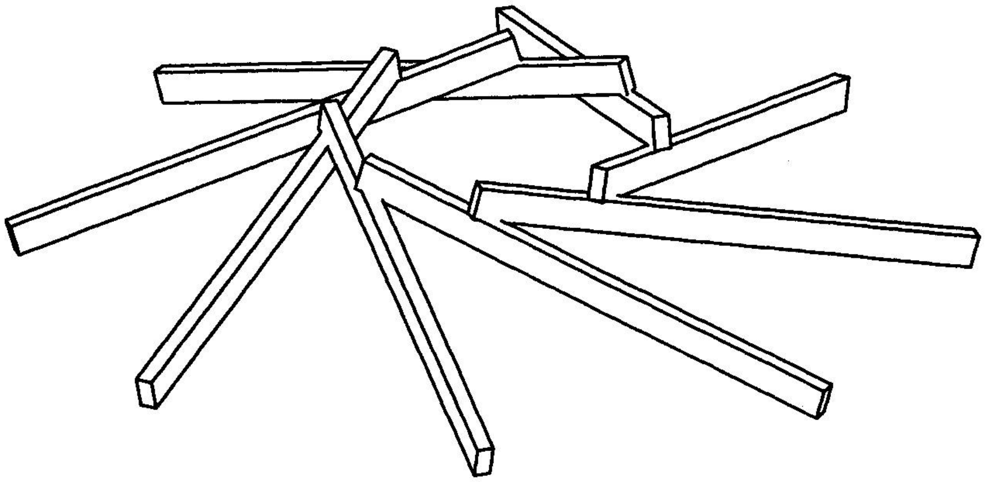


Fig.1 Three-dimensional view of Reciprocal Frame

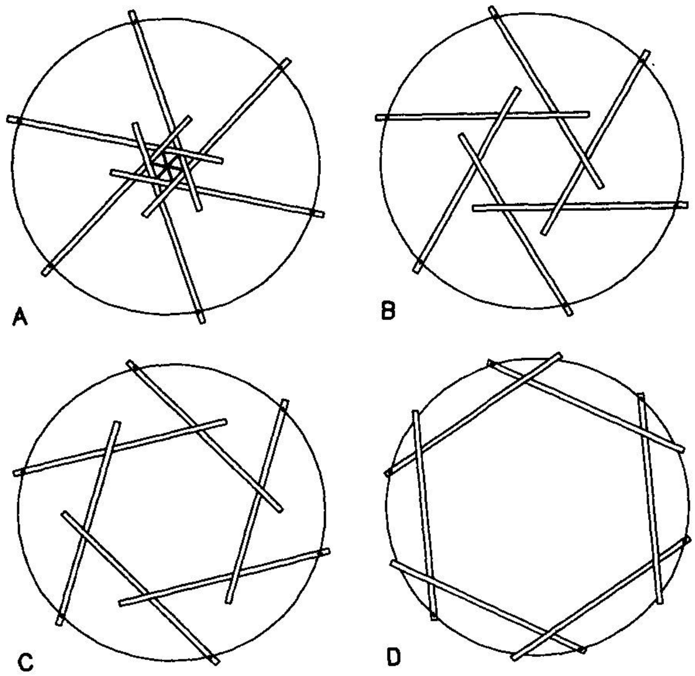


Fig.2 Plan views of retractable Reciprocal Frame structure

to an individual beam it will be partially carried by all the beams in the grillage and individual beam reactions will depend on the position of the load and geometry of the grillage. Any load applied to the structure affects all beams and similarly the deflection of one beam produces displacement in all beams. Since the elements of the Reciprocal Frame are resisting the loads by bending, no central compression ring or external tension ring is required. When the roof retracts, it is simply changing the shape of the inner polygon and therefore similar load distributions and characteristics occur. These features are particularly interesting when the structure is subjected to wind and snow loading. Non-symmetrical loads, for instance, a snow load on one side of the roof, are distributed more evenly throughout the structure.

3. ROOF OPERATION

3.1 Geometry of Opening/Closing System

To open the Reciprocal Frame Roof, each beam rotates about its outer support. The degree to which each rotates depend upon the number of beams in the grillage and the shape of the inner and outer polygons. However, if the beams are of the same lengths, it is important that they all rotate simultaneously and by the same amount about their outer supports. Due to the complex three-dimensional geometry, displacement of one beam greatly affects the shape and structural integrity of the roof. As the roof opens, each beam rotates about its outer support, both vertically in the plane of the beam and horizontally toward the outer polygon. Since the beams are all interdependent, it is important that they are always being supported by the previous beam. Opening the roof moves the inner support of the beams along a curved path towards the outer support, as shown in Figure 3, therefore, the beam must be at least as long as the maximum distance to the support. This distance is only slightly longer than each beam but the exact distance depends on the shape of the polygons and number of beams in the structure.

3.2 Drive Mechanism

The beams of the roof can rotate independently using individual synchronized motors or can be connected by an outer ring which is mechanically rotated, in turn rotating each of the beams through the required distance. However, use of such a ring greatly inhibits the amount of opening in the roof because the radius of rotation of the beam and the radius of the entire roof (radius of ring) are different. To account for this difference, it is possible to insert a connecting link between the ring and the beam at an angle which turns the beam without requiring a large rotation of the ring. Without the ring, the need for massive track structures (as in the Skydome, etc.) disappears.

3.3 Joints and Supports

The beams are connected to the outer supports using a hinge which allows for vertical and horizontal rotations. If tapered beams are used, the vertical rotation of the beam could be greatly reduced or possibly eliminated. The inner joints must allow for both continual support of the preceding beam and the movement of both beams. To accommodate this motion and maintain support, a rolling joint must be used. It is important to note that the joint does not connect to either beam but simply rolls between the two, acting only as a guide for the retracting movement and maintaining the position of support required.

4. DESIGN

4.1 Design Advantages

There are several advantages in using the Reciprocal Frame Roof as a retractable roof structure. First of all, it or equivalent structures, such as a salt storage building of 26 metre span made of 11 tapered, glued laminated beams using an analogous planar grillage as reported by Natterer, have already been successfully used as a static roof structure [6]. Also, because of its unique load distribution there is no need for internal support and, therefore, can be used in large arenas and stadia. Another benefit to the structure is that the strength is in the principal design and not a specific material allowing freedom in choosing the building material. The 'beams' discussed in this article refer to the basic structural members. These members can actually be steel, timber or concrete beams or steel or timber trusses, or even planes of space frame. Another benefit to this design is that it is not limited by shape. Both the outer polygon and inner polygon can be of any shape to suit the need. Because they need not have the same shape, the roof can be used to cover oddly shaped buildings and still maintain its retractable characteristics.

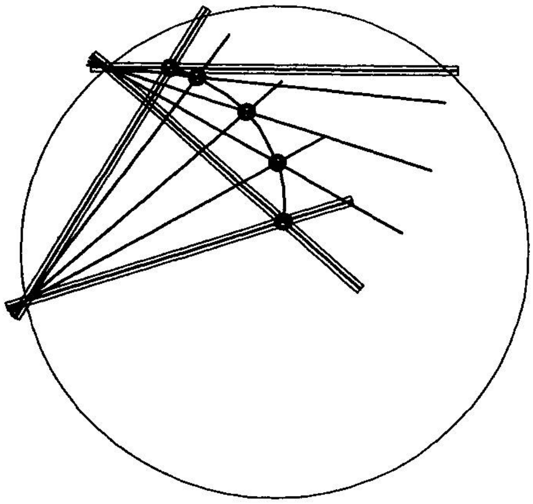


Fig.3 Curved path of intersection point of beams

4.2 Details of Design

Because the retractable Reciprocal Frame is a new concept, which has not yet been considered for use in a "real" project, specific details have not been addressed completely. However, these details have not been completely overlooked. Such topics as roofing material, drainage, and other potential difficulties in the design have been reviewed.

The Reciprocal Frame Roof allows for flexibility in choosing the cladding material. If static panels are used, the beam and panel would act as a plane in retraction. It is also possible to use a fabric membrane which folds when the roof is open and stretches out when the roof is shut. Another design consideration in making this roof structure practical is drainage. However, the roof has a natural slope to it and the solution would be found in directing the flow of water to a strategic point. As with any roof, the use of proper detailing and sealants would eliminate leaking. The most obvious of the obstacles to overcome in the Reciprocal Frame Roof is the hole in the centre which is formed because the beams can only completely close theoretically if they have no thickness. This problem however, can easily be solved by attaching small panels to the sides of the beams, at the central polygon, which come completely together when the beams are in their closed position.

A further consideration is that of disproportionate collapse. As each beam depends on all of the others for its support, the removal of or damage to any one beam may result in collapse of the whole structure unless it is appropriately designed. One way of overcoming this potential weakness is to provide suitable supports and to design the beams to act as cantilevers under the reduced loading required for the accidental limit state whilst utilising the reciprocal action for full ultimate loading. However, if the opening leaves of the roof are constructed from space frames, the structural stability does not rely totally on individual beams and the problem of disproportionate collapse can be avoided.

5. CONCLUSIONS

In conclusion, the Reciprocal Frame Roof has considerable potential for use as a retractable covering for sports arena and stadia. It has a powerful geometry with a dynamic visual impact. The design is very versatile and can be used with a wide variety of floor plans. Some examples of which can be seen in Figure 4.

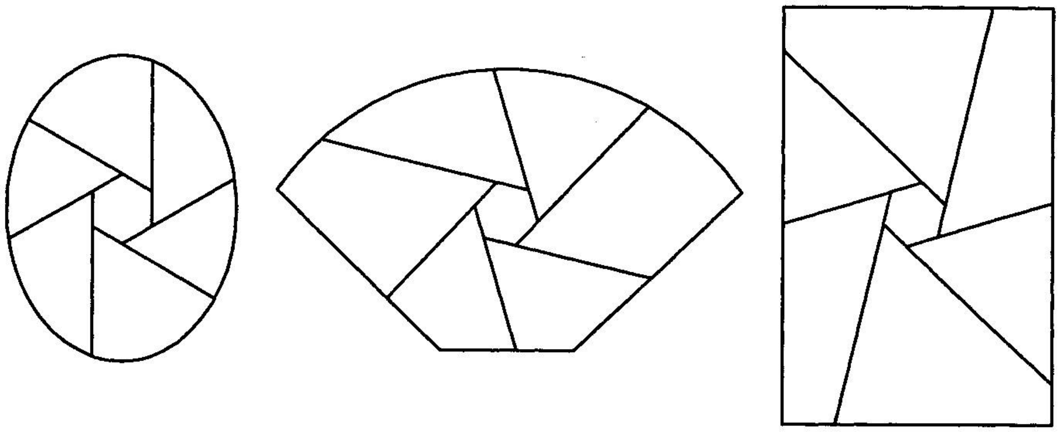


Fig.4 Reciprocal Frames over various plan shapes

REFERENCES:

1. ROORDA, J., SHERBOURNE, A.N., SRIVASTAVA, N.K., "Toronto Skydome" Proceedings from the International Association for Shell and Spatial S tr u ct u es - Canadian Society of Civil Engineers International Congress on Innovative Large Span Structures, Toronto, Canada, July 1992, Volume 1, pp.51-115.

2. O'CONNER, LEE., "Toronto Skydome: The House that Engineers Built," Mechanical Engineering, October 1992, pp.54-57.

3. NARITA, H., "Examples of Retractable Roofed Domes in Japan" Proceedings of the International Association for Shell and Spatial Structures - Canadian Society of Civil Engineers International Congress on Innovative Large Span Structures, Toronto, Canada, July 1992, Volume 1, pp.498-509.

4. CHILTON, J.C. and CHOO B.S., "Reciprocal Frame Long Span Structures" Proceedings of the International Association for Shell and Spatial Structures - Canadian Society of Civil Engineers International Congress on Innovative Large Span Structures, Toronto, Canada, July, 1992, Volume 2, pp.100-109.

5. ESCRIG, F. "Las Estructuras de Emilio Perez Pinero" in Arquitectura Transformable, Textos de Arquitectura, Escuela Technica Superior de Arquitectura de Sevilla, Spain 1993, pp. 30-32.

6. NATTERER, J., HERZOG, T. and VOLZ, M. Holzbau Atlas Zwei, Institut fur Internationale Architektur, Munich, p. 179.