Retractable roof for a multi-purpose centre in San Sebastián

J. Martinez Apezteguia, J.L. Azkue Arrastoa
Department of Structures, Lanik Ingenieros, Calle Chofre 11-18, 20.001 San Sebastian, Spain

Abstract

This paper describes a system developed for the construction of circular ground plan roofs that can be partially opened in their middle section.

The system has recently been applied to the project for the roof of an 100.3 m diameter coliseum that is about to be built. This paper goes into the particular solutions that are applied in the project both as regards its structure and the elements that enable the roof to open and close.

1 Introduction

Bullfighting is a tradition that is strongly rooted in Spain and has led to the construction of large bullrings. These consist of a round ruedo (sand enclosure) around which terraces are arrayed in rings. Bullring capacities are quite variable, ranging from 3,000 to 25,000 spectators. Almost all cities of over 20,000 inhabitants have bullrings, the outside dimensions of which normally range from 50 to 120 metres in diameter.

These buildings are normally highly underused. There are very few bullfights in the year, and they are traditionally held in the open air. These buildings are therefore uncovered, a factor that prevents events of a more varied nature being held in them without the risk of adverse weather conditions. Bullring managers have for years considered the possibility of covering them in order to enhance their viability. But the need to remain faithful to these buildings' original function implies that their roofs should be retractable, at least partially so, and this has always come up against the problem of the excessive cost of retractable roofs.

The project of a new bullring in the city of San Sebastian has given rise to a viability report that has shown the need to supply the building with a
retractable roof. In this project an aperture system has been applied that enables a large portion of the central section of the roof to be withdrawn. The applied solution is more economical than other alternatives analysed. The building has finally been conceived as a large closed auditorium with a capacity for 17,000 spectators and is capable of staging a wide variety of cultural and sports activities. On occasions it may even be converted into a bullring.

The most remarkable feature about the aperture system described in this project is the way in which the roof is subdivided and the movements the mobile elements thus describe.

2 The principle behind the aperture system

2.1 Geometrical conditions

The construction system here described is based on some principles aimed at achieving particular functional characteristics at the lowest possible cost. Here is a list of the most important ones:

- The surface uncovered on aperture must account for a significant proportion of the full roof area; no less than one third or one quarter.
- The aperture must take place in the central part of the structure and its shape must approach symmetry.
- In the open position, the mobile elements that close the aperture must be concealed above the fixed part of the roof. They must not take up additional surfaces or volumes.
- Mobile elements must be limited in number so that the amount of mechanisms is kept to a minimum.
- Due to the fact that the roof is basically round in shape, its structural layout must cater for the large dimensions required. In this sense, typologies of a dome or vault–like kind are to be favoured because they allow for structural economy.
- Whenever possible, mobile elements should not have a cantilever structural behaviour because this would increase the project's cost.

2.2. System characteristics

On the basis of the principles laid out above, an aperture system was developed based on a particular geometrical roof disassembly process that combines with a suitable conception for the trajectories of its mobile parts.

We shall firstly go into the characteristics of the theoretical solution, based on full surface utilization of the system. Then we shall look at some more realistic solutions.

A - The roof has the shape of a dome or spherical cap. Thus, the main part of its structure carries out a membrane–like behaviour. The ensemble rests exclusively on its outer edge by way of a traction ring that supports the membrane's radial strength. This layout prevents the transmission of significant
horizontal reaction forces to the supporting structure.

B - The roof is subdivided into two basic parts:
- The fixed part - that we shall refer to as "ring" - accounts for the permanent part situated on the exterior. It has a basically ring-shaped base and on its inner side has a large aperture with a pointed egg-shaped appearance along its major axis (fig. 1).
- The mobile part - two elements that we call segments-, which slide along the ring with movements in the opposite sense to open and close the roof (elements 2 and 3 in fig. 1). To achieve correct sliding and superposition movements of mobile elements on fixed one, the outer surface of the ring and the inner surface of the segments are spherical and concentric. Its radii are slightly differentiated to avoid interference between the physical elements that make up these surfaces.

C - The determination of the ring interior and segment exterior contours is given by the maximum superposition condition of the mobile surfaces, a condition that is required to achieve the greatest possible aperture. The segment's exterior line (M–T–N) is therefore a circular arc in space and an elliptical one on a horizontal projection, which in the roof open position must coincide with arc M_3–B_3–N_3 of the exterior circle (fig 1b). Correspondingly, the interior ring contour will coincide with the exterior contour of the segments in the roof closed position (fig. 1a).

The development of the segments on the central symmetry plane S–C and C–T is the same as the development of the same diameter line in the fixed part B_1–S and T–B_2. The semiangle of the cone that spans the spherical cap, α is thus subdivided into two halves within the main movement plane (fig. 1Q).

D - The displacement of the segments from the closed position to the open position involves a rotary movement of both elements about an imaginary horizontal axis perpendicular to the plane that marks the movement B_1–C–B_2. This axis passes through the centre of the afore-mentioned spheres (point 0). The points that are representative of the segments describe circular arcs that form parallel lines through assimilation with those on the ground surface.

2.3. Geometrical alternatives

2.3.1 Alternatives maintaining cap relief
The solution proposed in fig. 1 corresponds to the position of maximum aperture for a particular spherical cap. In practical terms, it is more recommendable (for the same cap relief) to adopt solutions such as in fig. 2, in which both the segments and the ring ovoid are truncated at the ends of their longer axis. This position involves a reduction in the surface of the aperture although the aperture space lost is the least useful because it is far from the centre. However the reduction in segment length will have positive structural effects. Apart from this, the existence of sides truncated by parallels facilitates other aspects associated with the guide.

In general, any aperture with a projection included in the basic geometry
of fig. 1 may provide a solution. Another interesting alternative is the one offering a perfect ring (fig. 3). In this case, the segments are semicircular, although this solution reduces the possible availability of useful aperture. Depending on semiangle $\alpha$, the open circle will to a greater or lesser proportion exceed half the roof diameter.

### 2.3.2 Alternatives modifying the cap relief

Another element that significantly affects the aperture surface, within the same working principle, is the **superelevation** or **rise** of the roof ($\beta$), expressed by the cap's height–diameter ratio. This ratio is fully linked to the principal cone's semiangle, $\alpha$. In this sense, it is interesting to consider two extreme cases. One would be that of the semispherical cap (fig. 4) in which the radius of the sphere coincides with that of the roof's circular plane ($\alpha = 90^\circ$). In this case, the rotation axis could be real because the segments' extreme points are on the rotation axis. The superposition of the segments on the ring is complete. The maximum aperture ratio reaches 71% of the roof's surface area. However, the great development of fixed and mobile surfaces as well as the lack of proportion between the height of the roof and its diameter make this a scarcely practical solution.

In the opposite situation, it is worth considering the case for a flat roof, with an infinite cap radius (fig 5). Here the movement of the segments involves linear movement along the same plane. The maximum aperture ratio is 39%, the smallest in relation to the cap relief. This possibility could be of interest for small-sized roofs in which structural costs tend to be smaller with regard to mechanism costs. It seems evident that a straight and horizontal movement would probably imply less cost in terms of the systems facilitating that movement; however, a plane development structure largely causes bending–type behaviour that would hamper the membrane effect.

The choice of a rise or superelevation of the roof is therefore a key factor for the cost. The best solution for each application calls for balance between functional and economic aspects.

### 3 Opening and closing mechanisms

A set of intermediate elements are needed to transmit reactions between segments and the ring as well as to make them move. In the proposed system they have been rendered as follows:

Each one of the mobile segments is held up by several supports, of which there must be at least three. In the most realistic solution (fig. 2), two of the supports would be located on sides P–R and S–T. Depending on the geometrical proportions of the segments, it is possible to place a further two supports on the same sides or on the rear arc (P–Q–S for segment 2). The greater the proportion of the sides to the aperture (i.e. the more truncated the segments), the greater the justification for placing only two supports on either side. On the other hand, the greater the longitudinal development of the
segment (the less truncated it is), the more convenient it will be to place only one support on each side and the remaining ones (one or more) on the rear arc.

The movement of the segments calls for a driving system which guides them in both horizontal and vertical senses, and a tracking mechanism that supplies the energy to move them. The driving system guarantees the stability of the segments and the transmission of their weight throughout the run. This system is achieved by way of an ensemble of girder-rails, there being one for each segment support point. These girders have a circular development and are placed in parallels corresponding to the support points, also being fixed to the ring. The vertical drive is developed by way of the respective rolling carriages whose wheels vary in number according to the dimensions and weight of the mobile segments. As regards the horizontal guide, this is also achieved by way of a carriage. The axes of their rolling elements are located on a plane that is significantly perpendicular to the roof. Both the vertical and the horizontal carriages, especially the latter, may be substituted by way of low-friction slides.

As regards the tracking mechanism, it obviously allows for many different solutions, either by way of pinion rack or capstan mechanisms or hydraulic cylinders. In this case, reference will be made to the pinion rack systems because they are the ones included in the specific application described in this paper.

4 Economic considerations

Initial parameters are normally laid down in each particular project: exterior diameter, minimum aperture surface, the aperture's minimum dimensions, opening and closing speed, thermal and acoustic insulation, etc. The study of the particular solution fulfilling these conditions at the lowest possible cost requires complex analysis given the large number of interrelated variables.

To simplify the analysis, one may choose to group the set of cost components together in certain basic categories:

- Structure
- Closure systems
- Mechanisms

On the other hand, there are certain geometrical variables with important implications. The two most significant ones are: a) The roof's superelevation, $\beta$, as determined by the ratio between the height and diameter of the cap, and b) the proportions of the aperture expressed by way of the fraction: $\delta = \text{length/width}$ (in fig. 2, length $R-T$, width $Q-M$).

The following general considerations must be made:

From the structural point of view, heightening the cap benefits the membrane effect and reduces maximal strengths. It must be remembered that the greater the roof diameter, the greater the relative cost of the structure will increase with regard to its total cost. It would therefore be worthwhile gradually increasing fraction $\beta$. However this tendency is not indefinite; there are obvious
limits because if the height is disproportionately increased, the benefit achieved by reducing strengths would be cancelled out by the disadvantage of increasing the structural development.

From the point of view of the closure, the tendency is the opposite. Since the unit price of the closure element is relatively independent of the form, increasing the superelevation calls for an increase in the surface development and leads to added expense. In low superelevations, the increase in development is limited, but not so in the case of high superelevations.

As regards the drive and guide mechanisms, increasing the superelevation clearly represents added cost. A larger superelevation means increasing the lifting forces needed to move the mass of the segments, with the subsequent repercussion on the mechanism potential. Furthermore the increase in the superelevation calls for greater development of guides, girder–rails etc., and this also adds to the cost.

The other variable mentioned, the aperture proportions (d), also has important effects. The truncation of the segments has favourable effects on the structure's cost; it is beneficial for the mobile parts because it reduces the free span in the central edge. It also benefits the fixed part because it likens the structural performance to that of a dome. Furthermore, on reducing the length–width ratio, the development of the lateral parallel elements tends to increase. It may also permit two support points to be placed within the lateral guides themselves, thus enabling secondary guides to be supressed. All this tends to cheapen the drive mechanism. However, this fraction should not be overreduced because this would limit the aperture's useful surface area and takes away from the roof's functionality. It would thus seem logical to impose a proportion that will ensure that the aperture's length will never be less than its width (in fig. 2, RT > QM).

5 A Multi-Purpose Centre in San Sebastián

5.1. Basic points

For the construction of this building a project has been carried out that will ensure great freedom in the choice of roof parameters. The basic points are as follows:
- Exterior diameter: 100.3 m at the support circumference.
- Central aperture: at its minimum dimension, no smaller than the ruedo or sand enclosure (50 m).

5.2 Geometrical solution adopted

The truncated segment scheme, similar to fig. 2, was used as a basis. After analysing various alternatives, the two fundamental variables were determined. Height/diameter ratio: $\beta = 1/7$.
Length/width ratio: $\delta = 1.1$. 
We took the ring's superior level (98.3 m) as the spherical cap's diameter reference.

On the ring's interior contour the corners were rounded, thus achieving a more harmonious shape. The roof's overall scheme is that represented in fig. 6.

5.3 Structural solution

Both the ring and segment structures were designed by way of space structure procedures. Apart from the exterior contour, which is round, all contours have a considerably irregular geometry. Another factor affecting design is the placement of the girder–rails that impose very rigid aligments as regards the situation of the respective parallels. A space grid has been selected because it enables one to satisfactorily resolve the afore–mentioned requirements and even facilitates a network that is harmonious with the overall aesthetics. The solution adopted is to be found in fig.7.

The ring network is triangular. However the segment network has a four–sided layout. To homogenize load distribution between them as much as possible as well as to achieve a satisfactory degree of lightness in the segments, these are sustained on four support points, two on the sides and a further two on the rear contour. This calls for the installation of four girder–rails on each segment. The would–be increase in cost produced by the presence of four girder–rails is fully compensated for by a lighter and more economical support structure in the segments.

After analysing the structure, it is observed that the fixed part really has a membrane behaviour that is quite similar to that of a dome. Strong compression occurs on its interior contour (about 180 tons) whereas on the outside very regular traction is generated (about 230 tons) which is canalized through a traction ring that is projected for this very end.

5.4. Aperture mechanism

Segment movement is carried out by way of two motor and reducer sets which act on the respective pinion–rack systems. These traction groups are placed in the segments, moving in time with them, whereas the racks are situated on their respective girder–rails.

The horizontal drive system is carried out by way of a horizontal rolling system which is also supported on lateral girder–rails. As regards the vertical guide and the transmission of gravitational loads, it is carried out by rolling on the four girder–rails, two lateral ones (the main ones) and two at the back (secondary ones).

The segment closing movement calls for the application of a lifting force that clearly calls for non–uniform energy throughout the run. Given that the time required for closure or aperture is about 10 minutes, the power of the traction mechanisms (4 units) is not excessive: 8 Kw per mechanism.
The whole tracking system is supplied with its respective synchronization, automatism, protection and control subsystems. It also includes the control of external agents that limit movement, such as snow and wind.

5.5. Closure

Two closure systems have been combined to achieve adequate thermical conditioning that is compatible with sufficient natural light:

The closure of the fixed ring is made up of a light Deck-type *Sandwich* composed of a corrugated steel sheet support, steam-proof thermical insulation and water-proofing by way of a PVC solded sheet. Between the closure and the space grid there is also an acoustic ceiling that helps to improve the building's acoustics.

As regards the segments, they are covered with multi-cellular polycarbonate material with high filtering qualities which eliminates the direct action of the sun and reduces the glasshouse effect.

6 Conclusion

Many of the systems used until now in the construction and assembly of retractable roofs are based on the disassembly of the roof in a series of sectors that move and superimpose themselves by rotating around a vertical axis.

On the other hand, the system that is exposed here is original in that the displacement of the mobile elements describes a rotary movement around a horizontal axis. This makes it necessary to lift and lower important masses. But this apparent inconvenience is fully compensated for by the economic benefit afforded by the system which achieves a structure with a much more convenient behaviour.

During the development of the project for a new Activities Centre, wide-ranging alternatives were studied. The design described in this project was clearly the best both for economic and functional reasons.
**RQ 1. BASIC IDEA OF RETRACTABLE ROOF**

**Fig 1A. CLOSED POSITION**

**Fig 1B. OPEN POSITION**

**RQ 2. ROOF WITH TRUNCATED SEGMENTS**

**Fig 1C. MAIN SECTION (B-B)**

**Fig 2A. CLOSED POSITION**

**Fig 2B. OPEN POSITION**
FIG 3. ROOF WITH CIRCULAR APERTURE

FIG 4. SEMIESPHERICAL RETRACTABLE ROOF

FIG 5. FLAT RETRACTABLE ROOF
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FIG 7. SPACE FRAME OF THE ROOF