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TENSEGRITIES FOR SKELETAL DOMES: THE GEORGIA DOME; A CASE STUDY

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Abstract

In the second part of this century, a new generation of domes appeared: the skeletal domes in cable structures which provide the opportunity to hold new records for the maximum free span ever achieved in covering a single building. The author reviews such a building erected for the 1996 Olympics. His paper aims to contribute to the dissemination of the architectural message hiding in tensegrity domes.

Keywords: structuralism in architecture, Olympics architecture, cable domes.

Introduction

According to traditional images transmitted through the course of history, domical structures originated since ancient times and were usually built as masonry artifacts, are envisioned only as structural continua of homogeneous material. Yet, a new generation of domes (especially those that have germinated in the present century) have been expressed in a totally opposite structural vocabulary, i.e. adopting a skeletal articulated structure supporting a non-structural surface instead of the structural shell of masonry or concrete as previously mentioned. In a sense, to the untrained observer insensitive or at least unconcerned with problems with statics, the two types of domes speak in practical terms in an indistinguishable difference of expression especially the huge megadomes of present day overcome the spectator with the glamour of their unprecedented scale leaving little room for other emotions. Obviously such a generalization excludes those with specific knowledge or interest in structural expressions including construction characteristics who will focus instead on structural details which in reality for skeletal structures are extremely intriguing. Yet, although skeletal domes are naturally at the opposite end of the spectrum from that of shells, nevertheless in the overall structural behaviour, the two actually share equal concepts of stability and resolution of the internal forces. In fact, compression hoop forces occur in the same areas in the dome whether the structure is of the skeletal type or a shell and similarly the same occurs for areas in tension so that in reality the overall behaviour is similar in both cases. Such a paradox is in reality quite superficial since no basic contradiction really exists.

Aside from overall architectonic generalization, the structural design of skeletal domes follow the same criteria used for space trusses or space frames according to the type of connection. However, focus on the former which expresses in more pure terms the behaviour of the skeletal structures in question, i.e.: the consideration of just axial tension and compression axial forces. Yet, while the local behaviour of tension and compression is strictly respected in any member, the overall effect of curvature in these skeletal domes is definitely reflected adding further to the effect of the structure on the whole.

The Georgia Dome
Georgia Dome, Atlanta, Georgia, 1992

The Georgia Dome completed in 1992 in Atlanta, Georgia, is located on a site where the 1996 Olympics will take place. This structure in the family of cable (tensegrity) domes follows a few years after several other previous ones: one in Seoul, Korea, built for the 1988 Olympic games and in the United States: the dome over the Illinois State University Arena and the Suncoast Dome in St. Petersburg, Florida. This last one with a circular floor plan had a maximum diameter of 690 feet (290 meters) holding the record for the maximum free span ever achieved in covering a single building. Now the Georgia dome, with its elliptical configuration, is covered by a roof with an area of approximately 400 000 square feet extending 630 feet (193 meters) along the minor axis and 790 feet (240 meters) along the major axis. Descriptions of this structure in the technical literature refer to it as the first Hyper-Tensegrity dome since its surface includes sections of a hyperbolic paraboloid. Designing architects for the project were Weidlinger Associates, New York. While the construction engineering, fabrication and direction per se was carried out by Bird Air. In its basic schematic simplification, a tensile dome of this kind will have a compression ring at the base in opposition to the typical tension ring that conventional domes have. Then peculiar to these domes are concentric hoops in tension at different levels. In this particular case this dome employs three of such hoops. Above the last hoop crowning the dome is a 184 ft. truss along the longer axis of the ellipse. Such a dimension is measured between the first and the last of the vertical compression members within the truss. This truss includes nine vertical compression members of equal length measuring

35 feet each between top and bottom chord, some of which extend partially above the upper chord to support an additional upper cable that completes the exterior shape of the dome. The lower chord of this structure is carried by the last tension ring and stands up vertically because of the vertical compression members of the truss itself, giving the feeling that the truss is floating in space as the rest of the structure does. This truss, because of its special loading condition is stressed in such a manner so that the bottom chord as well as the upper chord and the diagonal members are all in tension while only the vertical members are in compression. Consequently top and bottom chords and diagonals are made out of tension cables creating indeed a unique truss per se, while only the compression members consist of steel pipes. Each hoop carries 26 vertical compression members (half of the 52 columns at the ground) extending vertically from one hoop to the next. Such compression members are then stabilized by diagonal cables and are located so that like in any tensegrity structure they do not touch each other and give the visual illusion to be floating in space. These vertical posts (for a total of 78) vary in length including 61 feet for members over the first hoop, 80 feet for those over the second hoop and 49 feet for those over the third hoop. These members, wish a maximum diameter of 24 inches, are sealed hollow tubes for preventing any internal erosion. The cables per se varying between ten different sizes from 1.25 to 4.9 inches (10 cm) in diameter consisted of two types: parallel strands and wire ropes. Parallel strands, more ridged and more difficult to handle in the field, yet less expensive, were used for tension hoops as well as for the top and bottom chord and diagonals of the truss, while the more flexible wire ropes were used for the rest. These cables were delivered to the job in continuous lengths that reached up to 1200 ft. wound around spools during their transport to the site. Precut in the factory to the exact length with their end-fittings attached, the cables were ready to be installed reducing the cost in comparison to what was usually done before in other jobs when the cutting took place in the field. The total length of the cable is in the order of magnitude of approximately 5 miles. The joints connecting the vertical post and the cables weighted up to 2 tons each and carried the patented name 'weidments'. The joints housed the cables in square cut grooves in their upper part and clamp them with a cover that is tightly bolted to the main body of the joints. Between the cables and the plate an aluminium bar acting as a filler is used. Notice that the joints on the upper part of the post differ substantially from those at the lower end of the post because while the former are at the surface level, the latter are connected to the tension hoops. The compression ring at the base of the dome consists of a 26 feet wide, 8 feet deep concrete structure supported by 52 columns. The connectors, because of their sizeable weight, (up to 2 tons) were indeed a

challenge. In previous tensegrity domes they were built out of cast steel but in this particular case they were fabricated with welded steel parts. The membrane roof itself stretched over the network of steel cables consisting of 114 diamond shaped teflon coated fiberglass panels shaped along the profile of the hyperbolic paraboloid surface and clamped to the cables themselves. The membrane by the trade name of 'SHEERFILL' is partially transparent allowing 15% of daylight to pass through creating a glowing surface over the space below. The individual membrane panels which differ from one another reached dimensions up to 80 × 180 ft. and were rolled around steel pipes for easy transportation. When arrived to the job site, each roll was lifted by cranes passing through the network of cables. Then the individual membrane panel was unrolled and fastened to the cables with aluminium hardware. Along the seams between one panel and the next, 18 in. wide strips of membrane was heat bound to guarantee a water proof seam.

The erection procedure for the roof carried by Bird Air corporation consisted in assembling most of the cable network on the ground including the central truss and then lifting it up to the level of the compression ring. The lifting was done using individual jacks located on top of each column supporting the concrete ring. The jacks pulled the cables during an operation that lasted approximately one week lifting the whole assembly in eight intermediate steps. At this point a second operation that lasted several months included the erection of the three tension hoops and the supporting vertical posts. To minimize the load to be lifted, the 184 ft. central truss was supported by two cranes rather than hanging from the cables. Noteworthy is to recognize the level of complexity that these structures require during their erection and the consequential risk that may be involved. In this project for instance the failure of one of the connectors on the upper hoop caused the collapse of one of the posts that was part of a platform supporting some workers, killing one who fell down to ground level below and injuring two others on October 17, 1991 .

The overall geometrical configuration of the dome includes a variety of criteria of major interest. For instance, the individual diamond shaped panels of the roof membranes were curved into a convex and concave paraboloid configuration, and a hyperbolic paraboloid was formed by lifting two of the corners of the – diamond. The overall curvature of the dome was attained by the size and the vertical spacing of the concentric hoops. Starting from the compression ring to the first hoop above it, the slope includes an angle of 45 degrees and then it gradually reduces from hoop to hoop. In this manner since the load increases from the top down it was logical to increase the slope as one proceeds downwards because in so doing the tensile forces will increase at a lower rate.

Total budget for the 70,500 spectator stadium included \$175 million. A cost study of this structure by the designer team indicates that considering only the cables, posts, and connectors in isolation from the rest of the structure, their relative percentage in the cost could be distributed as: 50% for the cables, 30% for the connectors and 20% for the posts excluding therefore the other major components such as the cost of the roofing membrane, the compression ring, and supporting columns which are all essential elements of the dome per se.

Final Remarks

In conclusion, we realize that tensile structures that have mostly become of age in this second part of the century constitute a new structural topology that could be traced back to the first appearance of suspension bridges in the technology of civil engineering. However, a considerable period of incubation had to elapse before the concept was applied to buildings. In the fifties, in fact, among the first applications of tensile structures to buildings was the sports arena in Raleigh, North Carolina, by Deitrick and Novicki, 1953, which left quite an iconoclastic impression in the field. Also, sharing equal fame for the impact that they produced worldwide was the paper mill Burgo, Mantova, 1962, by Pier Luigi Nervi who interpreted in more realistic terms the theme of the suspension bridge within the context of building structures. Then, even with more glamour one cannot forget the impact felt wordwide by Kenzo Tange's National Gymnasium, Tokyo (1961–4). However, after such an initial phase, tensegrity structures had fallen into a dormant period until the last few years, when they gained a new impetus through the dynamic interpretation of Fuller's tensegrity by David Geiger. Hence, the combination of tensile structures per se with the elegant articulation of tensegrities, culminate in the tensegrity domes which now stand on the top of a hierarchy of structural systems organized in terms of efficiency.

With the tensegrity domes, architectural structures can now enclose the maximum column-free spaces ever achieved before, while at the same time the structural unit weight expressed in lb/ft^2 of roof surface has never been lowered. Indeed tensegrity domes and similar other offsprings derived from the same concept have created a reality that would continue to expand. Just like at the introduction of suspension bridges over a century ago, tensile structures revolutionized bridge engineering, with permanent new principles. Similarly, far from being an ephemeral fad, these systems mark the beginning of a new structural thinking. In fact, through the tensegrity domes already built, one could see how close the present has

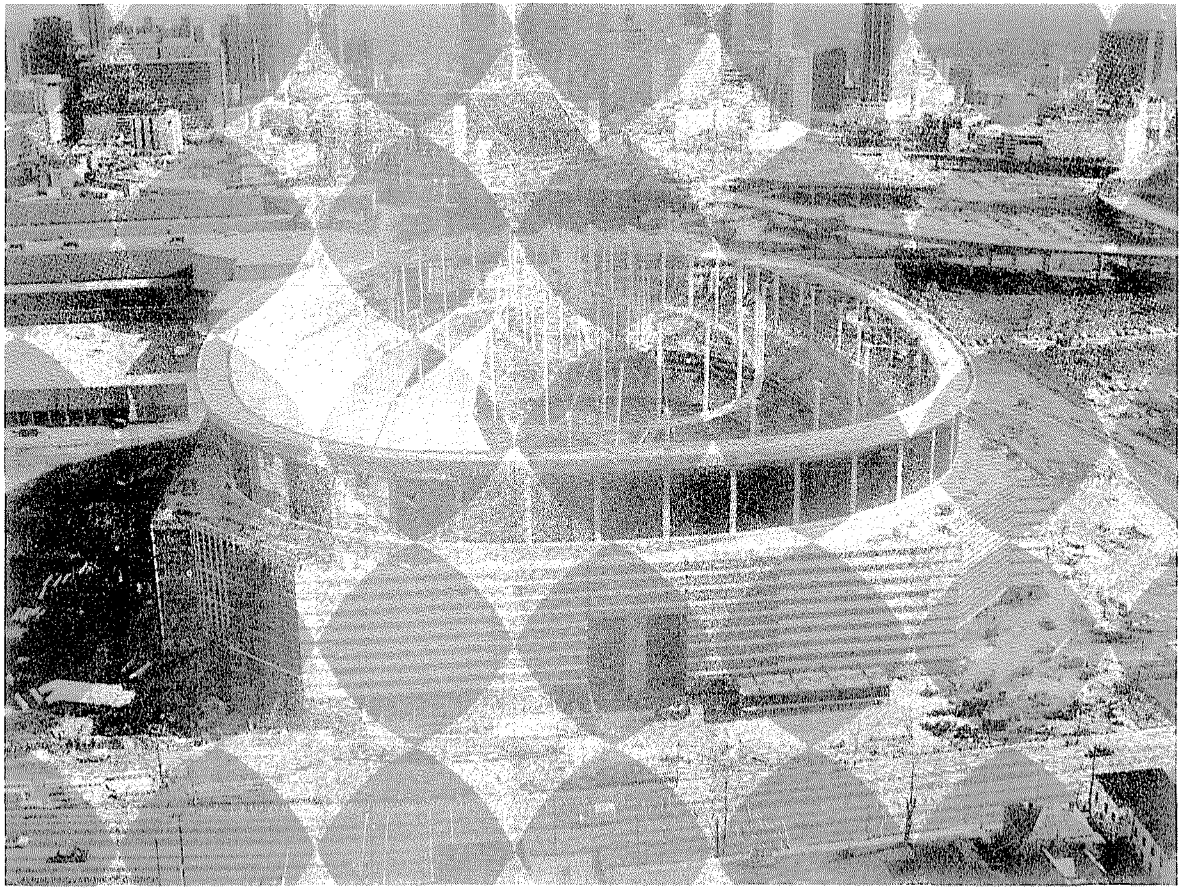

Fig. 1.

brought us to the aphorism of Le Recolies aiming at structures of zero weight and infinite span.

The erection of the Georgia Dome in the city scape of present day Atlanta reflects indeed the energetic program of revitalization that has been underway for a number of years in the heart of the new south. It is not accidental, in fact, that the virtuosity of new building technology symbolized by tensegrities was chosen. These avant-garde structural systems not only stand out for their own merit but also for the record that they have gained for covering the largest column-free span ever built. It will carry a message to a worldwide audience, when in three years from the present it will be seen by all those attending the Olympic games. Yet, aside from the fame that the G Dome will predictably attain for the general public, its message softly spoken by the structuralist component of architecture demands desperately to be spread with more emphasis right now within the design circles. Hence this paper aims to contribute to the dissemination of such a message among those professionals open to structuralism per se and to its avant-garde role in the architectural realm.