Part XVI: Shells, Domes, and Hyperbolic Paraboloids

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ABSTRACT

This is the 16th article in a series examining various deck types. The article, which is more about shapes *than actual deck* types, *will explore roofing system aspects likely to be encountered on shells, domes, and hyperbolic paraboloids.*

The type of substrate is among the most important considerations when selecting a shell-, dome-, or hyperbolic paraboloid-shaped roof system. For designs featuring these shapes, concrete of some variety may often be used, although other materials can certainly be deployed. For instance, many vintage barrel roofs were iron bowstring trusses carrying wood plank decking (that is, board sheathing, a topic covered in Part 12 of this series). Other shapes may use ordinary steel decking, which can be carried on rather unique supports.

Long, clear spans within a building are highly desirable. Years ago, the author was engaged on a church project after the congregation removed two columns from their fellowship hall because there was not enough room for their dining tables. While the dedication to food is understandable, the roof and walls experienced predictable distress as a consequence. These nontraditional roof shapes are interesting and merit a closer look.

SHELLS

Shell construction can be a favorable design option because it can create spacious occupancies without interruption by columns, which would be the case with traditional low-slope roofs. However, exterior columns, walls, and foundations need to be very robust because of these long spans.

Concrete shell construction can be made from thinner sections due to the embedded steel.[1] A good example is the Sydney Opera House in Australia (**Fig. 1**). This "fast-track" project began in the late 1950s while the final design and drawings were still being developed. The design subsequently was revised repeatedly. When construction of the unique shell roof eventually began, some of the podium columns were determined to be structurally inadequate and had to be demolished and replaced.[2] But that issue was only part of the reason that the project cost more than 14 times the original budget and was 10 years late in its delivery.[3] When mistakes emerge in fast-track construction, they manifest in concrete and steel—later in time and money.

Figure 1. The Sydney Opera House features spacious occupancy without interruption by columns, which would be structurally required in traditional buildings with low-slope roofs.

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Figure 2. Two views of a uniquely structured gas station. A National Historic Landmark near Winston-Salem, North Carolina, exemplifies a shell-like design. The exterior is more of a wall than a roof, there is no membrane, and exterior weatherproofing is merely a paint coating.

Another notable example of shell construction is the vintage fuel station depicted in **Fig. 2**. It is the only remaining scalloped-shell structure in the world, and it stands today as a National Historic Landmark near Winston-Salem, North Carolina. The structure is a frame of bent greenwood and steel wire onto which concrete was applied much in the same manner as stucco would be applied.[4] This unique structure exemplifies a shell design whereby the exterior is more of a wall than a roof. Consequently, there is no membrane covering and the weatherproofing is merely a paint coating. Shells of this type fell mostly out of favor because of the high cost of the custom formwork, which was likely unique to the specific building and had no potential use on other projects.

Other reinforced concrete thin shells may be "folded-plate" designs. **Figure 3** demonstrates such a profile; additionally, there can be many other variations of this form, including prismatic, trough-type, and tapered folded plates; corrugated curves; butterfly shells; Z shells; cylindrical barrel vaults; and combinations thereof. Again, these surfaces may have only a polymeric coating for the roof membrane.

DOMES

This discussion does not extend to domes with tension membranes, coated fabric, or retractable roofs, as may be found on some sports arenas. Instead, it focuses on buildings configured with hard domes. These are the variety about which building enclosure consultants may be asked for advice regarding selection of coatings and membranes, maintenance needs, thermal upgrade, and other issues. **Figure 4** depicts such a dome and adjoining bell tower where chronic leakage was experienced. Widespread patching using both ethylene propylene diene monomer (EPDM) and Neoprene rubber had been carried out on the copper seams and panel ends. Whatever repairs would have been appropriate on this copper would not have involved rubber patches.

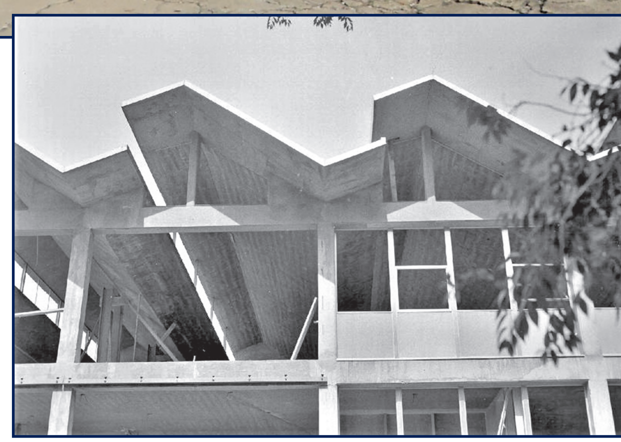

Figure 3. Reinforced concrete thin shells may be designed as "folded-plate" structures. These shapes may have only a coating for the weather covering.

Domes have remarkable stability when built properly and can span great distances without internal supports. Despite their thinness, domes are some of the sturdiest structures in existence. An oculus (eyehole) at the peak may be the only source of internal lighting, as in ancient cathedrals. For example, at the

Figure 4. This church dome and the adjoining bell tower were experiencing chronic leakage even though ethylene propylene diene monomer (EPDM) and Neoprene rubber had been used to patch the seams and panel ends. Whatever repairs would have been appropriate on this copper would not have involved rubber patches.

Figure 5. Under rooftop service loads, the oculus ring is in compression. Further down the slope, ribs transfer load to the perimeter ring, which experiences tension.

Pantheon in Rome, the oculus is entirely open, allowing both rain and snow to fall onto the marble floor, which has drains to manage the precipitation.

For modern domes (such as sports facilities), the entry of weather elements would not be permissible, so the peak of the dome is closed in some manner. Whether or not an oculus is present, under service loads, the apex is in compression, and the ribs transfer load to the perimeter ring (**Fig. 5**), which then experiences tension as it resists the dome's natural tendency to flatten out. Exerting outward influence to the walls, the perimeter ring is where the "robust" part of the structure is located. Many domes have no deck and may be merely clad with glazing units, which may become a source of work for the building enclosure consultant (**Fig. 6**).

HYPERBOLIC PARABOLOIDS

As complex shapes, hyperbolic paraboloids are in the family of quadric surfaces that includes simple parabolas, cones, ellipses, and numerous variants thereof. Commonly referred to as a "saddle," these quadric surfaces are mathematically expressed as a second-degree polynomial equation in the x, y, and z coordinate axes; they are appreciated best when considered in three dimensions, especially when viewed with software that permits rotation of the object. Of the quadric surfaces, hyperbolic

Figure 6. Many domes have no deck at all and may be clad with glazing units only. Those glazing units may become a source of work for the building enclosure consultant.

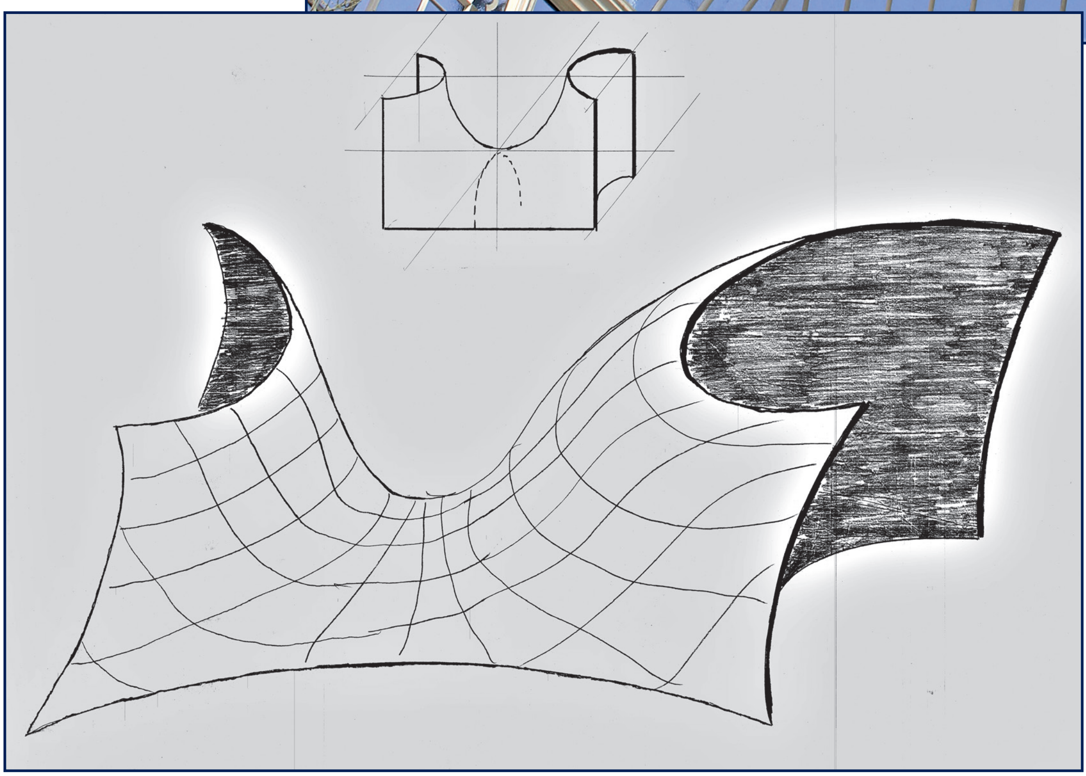

Figure 7. The author's sketch of a hyperbolic paraboloid, the most difficult of quadric surfaces to draw.

paraboloids are the most difficult to draw; the author has attempted to do so in **Fig. 7**. Like domes (and most shells), hyperbolic paraboloid structures have no internal columns, and they can host a wide range of events such as musical performances, recreational vehicle and boat shows, indoor motorcycle races, tractor pulls, and the like.

The J.S. Dorton Arena in Raleigh, North Carolina, is a notable example of hyperbolic paraboloid (**Fig. 8**). Completed in 1952, it was the first structure in the world to use a cable-supported roof (that is, the roof is supported by the type of wire rope that would be used in suspended bridges or as guy wires for communication towers).[5] Its 300 ft (100 m) clear span in both directions was a technological feat for the period, and it was the precursor for other sports stadiums such as the Astrodome in Houston, Texas.

Decades ago, the roof covering on Dorton Arena was a Neoprene membrane with white Hypalon coating, as was practice for the time for external spread of flame rating. It has a steel deck that was coated with asbestos, undoubtedly as a fire-safing measure for the intended type of occupancy. The decking was bolt-clipped onto the grid of draped steel cables (**Fig. 9**).

Other paraboloids encountered by the author have been constructed from cast-in-place concrete with merely a coating applied (**Fig. 10**); because of generous slope all across the surface, coating alone can perform satisfactorily as a weather barrier if a quality product

Figure 8. Completed in 1952, the J. S. Dorton Arena in Raleigh, North Carolina, is a notable hyperbolic paraboloid. The convergence of the two concrete parabolas creates a challenge for the management of stormwater runoff. Figure: https://ncmodernist.org/nowicki.htm.

Figure 9. J. S. Dorton Arena, which was the first structure in the world to use a cable-supported roof, has an asbestos-coated steel deck that is bolt-clipped onto the grid of draped steel cables. Figure: James L. Brandt Papers, MC 00472, NC State University Libraries Special Collections Research Center.

Figure 10. Paraboloids are often constructed from cast-in-place concrete with only a coating applied. Because of the generous slope across the entire shape, coating can perform satisfactorily if a quality product is selected and applied well. However, it is critical to correctly size the internal drainage devices to manage stormwater.

is selected and applied well (that means surface preparation). Note that unless stormwater spills randomly off the edge, it may be challenging to correctly size the internal drainage devices because the continuously variable slope frustrates ordinary stormwater calculations.

SUMMARY REMARKS

The varied shapes explored in this article are nontraditional, but they are nonetheless likely to be encountered by the building enclosure consultant. Whether the structures involve steel decking carried on a grid of wire rope or a concrete deck of a dome cast monolithically with the walls, to properly assess these types of structures, consultants must be familiar with the various systems. An example of an issue that may occur with these types of systems might involve shapes that have received only a coating or adhered membrane but now must be brought into compliance with the governing thermal code. At other times, low-slope glazing may be the central complaint by owners and the focus of leak investigation. Another possible issue is consideration of modern specialty fasteners and/or adhesives that may be decidedly better than when the original assembly was constructed.

Other potential challenges with these systems include the risk that the external fire rating diminishes as slope increases; the effects of sliding ice and snow; and difficulties in the management—or even calculation—of stormwater runoff. In decades past, the practice of "back-nailing" a built-up roof was deployed to avoid slippage and the slow downhill creep of covering; that practice is no longer commonplace, but rotation (tilting) of fasteners can still occur if the slope is great and when the roof mass is substantial.

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