Do Concrete Shells Deserve Another Look?

Industry professionals give mixed opinions

BY CHRISTIAN MEYER AND MICHAEL H. SHEER

The modern era of thin concrete shells began in 1922 with the construction of a 52-ft-diameter (16-m), 1.2-in.-thick (30-mm) reinforced concrete dome in Jena, Germany.[1] This revolutionary structure resulted from a collaboration between Walter Bauersfeld, of the German optical company Zeiss, and Franz Dischinger, of the German engineering firm Dyckerhoff and Widmann. Their design and construction technique was introduced to the U.S. by Anton Tedesko, another Dyckerhoff and Widmann engineer. In 1936, while consulting with the Chicago firm of Roberts and Schaefer, Tedesko designed the first large thin concrete shell in the U.S.: a 232-ft (71-m) span, 340-ft-long (104-m) barrel shell for an ice hockey arena in Hershey, PA.[1]

In the three decades following the introduction of thin shells in the U.S., a number of innovative designers, such as Pier Luigi Nervi (Fig. 1), Eduardo Torroja, Vasilii Vlassov, and Felix Candela (Fig. 2), advanced the state of the art by introducing new design theories and construction techniques and experimenting with shells of different forms. It was during this time that a variety of landmark shells of double curvature, such as hyperbolic and elliptical paraboloids, were constructed (Fig. 3 and 4).

Based on the number and variety of shells built from the 1920s to the early 1960s, this period can be considered

Fig. 1: Pier Luigi Nervi, Palazzetto dello Sport, Rome

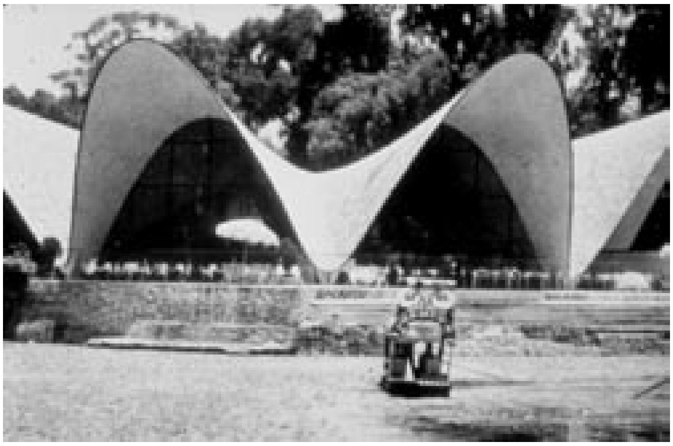

Fig. 2: Felix Candela, Xochimilco Restaurant, Mexico

Fig. 3: Nicolas Esquillan, Paris Exhibition Hall

the golden age of concrete shell construction. Subsequently, concrete shells began to receive less attention. Fewer technical papers were published on their design methods and construction techniques, and the number of signature structures built declined noticeably.

To explore the reasons for the decline of interest in this exciting structural form, we interviewed a number of engineers, architects, and other building professionals to determine their opinions and if they believe the advantages of concrete shells in terms of economy, aesthetics, and utility, once so widely agreed on, still exist—in short, whether concrete shells deserve another look.

ARE THIN CONCRETE SHELLS NO LONGER BEING BUILT?

While the majority of those interviewed stated that significantly fewer thin concrete shells are now being built, a small number of experts insisted, to the contrary, that more shells are being built now than ever before. It appears that this disagreement arose out of reference to completely different methods of construction.

Fig. 4: HOK, Priori, St. Louis

Those who claimed that concrete shells are now out of fashion referred primarily to shells built the “traditional” (labor-intensive) way. For instance, Matthys Levy of Weidlinger Associates responded that he had not been involved in a thin concrete shell project since the late 1970s. However, he was a principal in the design and construction of the Georgia Dome in Atlanta, a lightweight tensegrity structure completed in 1992. He surmised that 40 years ago, this dome might have been built as a concrete shell.

Similarly, Khaled Shawwaf, of DYWIDAG Systems International (DSI), stated that his company has not been involved in the construction of an architectural thin concrete shell in the U.S. since the 1970s. Instead, his firm has been a leader in the development of utilitarian concrete shell forms, such as egg-shaped concrete digester tanks for sewage treatment plants. Shawwaf believed that the increased popularity of such concrete shells has not transferred to architectural concrete shells.

Dan Cecil, a structural engineer and partner at Leslie E. Robertson Associates, and Michael Flynn, an architect with Pei Partnership, both responded that shells are being built with regularity in the U.S. However, steel, rather than concrete, was the material of choice.

Those who responded that concrete shells continue to be built with regularity were referring to structures built with novel methods of construction, with which they were intimately familiar. Two specific methods were mentioned—the use of air-inflated forms and modular formwork.

David South, President of Monolithic Constructors and Chair of Joint ACI-ASCE Committee 334, Concrete Shell Design and Construction, replied that construction of thin shells nearly came to a standstill until air-inflated forms were introduced. Variations of air-form technology have been used before. Particularly noteworthy is Italian

Fig. 5: Kallangur Shopping Center, Queensland, Australia, constructed using the Bini-Shell System

designer Dante Bini's system, in which reinforcing steel and concrete are placed over a layer of fabric while it lies flat on the ground. The fabric is then inflated to create the desired shell form. Numerous so-called Bini-Shells have been built primarily for utilitarian and bulk storage purposes, but also as enclosures of supermarkets (Fig. 5) and recreational facilities such as swimming pools and tennis courts. It has been estimated that more than 1000 domes were built worldwide between 1966 and 1986 using the Bini-Shell system.[2]

In the late 1970s and early 1980s, David and Barry South developed a system in which polyurethane foam is spray applied to the inside of an inflated fabric form. The foam gives the form the stiffness required to support the weight of reinforcing steel placed on the inside. Shotcrete is then applied to the interior of the form and, finally, the form is either removed and reused or simply left in place.[3] According to David South, spans in the range of 100 to 200 ft (30 to 60 m) are common, and spans of up to 1000 ft (300 m) are currently feasible. His Texas-based company shipped 150 air forms in 2001 and has participated in the construction of shells in 48 states and over 30 countries (Fig. 6).

A second alternative forming method currently being used to construct shells in the U.S. is the Modular Forming system by Formworks Building, Inc. Although Modular Forming has yet to be used to construct shells of the size possible with air-form techniques, a company representative pointed out that the system sells well throughout the U.S. He also cited this as evidence that

Fig. 6: Monolithic Dome Institute, Public Works Complex, Price, UT

Fig. 7: Heinz Isler, Chamonix Shells below Mont Blanc

Fig. 8: Heinz Isler, Bürgi Garden Center, Camorino

there is demand for stronger and smaller-scale thin concrete shells that are highly energy efficient. The system consists of modular structural steel forms (tabbed in the appropriate locations to receive reinforcing steel) that are bolted together on site. Because the forms and reinforcement have sufficient strength to support the weight of the shotcrete before it hardens, shoring is unnecessary and the construction cost is significantly reduced.

In Europe, the work of Heinz Isler[4] is living proof that thin concrete shell structures may indeed be as popular as ever (Fig. 7 and 8). Isler's office designs two to 12 shells per year, not all of which are in his native Switzerland. Yet, since labor costs in Switzerland are comparable to those in the U.S., the "Isler factor" ought to be considered when exploring the possible reasons for the diminished popularity of shells in the U.S. Reliable data on the number of shells built in the U.S. are hard to come by, but it is fair to say that barely any signature structures of the architectural quality and impact of an Isler shell have been built in the entire U.S. in recent years.

Disregarding the Isler factor for now, it remains to be explained why a majority of responders believe that thin concrete shell construction is no longer of any noteworthy interest, whereas a minority strongly disagrees. This discrepancy may be explained with the hypothesis that the first group, which is generally affiliated with large East Coast design firms, either are unfamiliar with the alternate construction techniques or believe that the types of structures that can be built with such alternate construction techniques cannot fulfill their clients' requirements as well as other structural systems.

Regional differences in design criteria may offer another explanation. For example, Formworks sells many modular forms in Oklahoma, where the potential for tornado-related structural damage places a premium on the durability and strength of space-enclosing elements. Leland Gray, of Leland A. Gray Architects in Phoenix, AZ, who is currently involved with air-formed thin concrete shell projects, stated that poor dissemination of information may be the reason why air-form technology is not used more widely. He believes that the perception of air-formed shells has never transcended their originally intended use as bulk storage enclosures. The majority of shells produced with air-form methods resemble igloo-shaped storage units and lack the architectural flair and variety of form that excite architects and their clients who desire signature structures.

WHY HAVE THIN CONCRETE SHELL STRUCTURES LOST THEIR POPULARITY?

The near-unanimous response to this question was, "They cost too much to build." The cost most often mentioned is for labor to erect the shoring and formwork. Compared with material costs, these labor costs are considered prohibitive in the U.S. The type of formwork and shoring varies from labor-intensive to extremely labor-intensive, depending upon the shell geometry and method of construction. Surfaces with straight generators, such as cylinders and hyperbolic paraboloids, can be formed with nearly flat panels supported by straight members. Using traditional construction methods, however, domes are more difficult to erect.

Edward DePaola of Severud Associates mentioned that the construction of shells also requires highly skilled labor. Tolerances for formwork are tight, and the shoring may have to be designed to restrict or sometimes permit the movement of the shell during curing. Thin shells can be quite sensitive to small variations in geometry, so small errors in thickness and reinforcing steel placement can have significant effects on internal forces as well as global stiffness and stability. As a result, the required quality and cost of labor make thin concrete shell structures less competitive with other structural systems. He did, however, add that the problem may be solved with the development of innovative forming systems: "Flexible and easily adjustable forms would make complicated shapes easier and much less expensive to build."

The respondents were generally aware of the benefits of thin concrete shells, that is, the efficient use of materials; relatively low cost and general availability of materials (concrete and reinforcing steel); their fire, blast, and impact resistances that provide safety and may lower insurance costs; energy efficiency; clean and uncluttered interior and exterior surface appearance; and the possibility of many visually interesting geometries.[5] Yet, all of these benefits do not seem to justify the high cost of construction. Innovators like Bini, South, and Pearcey clearly realized that the best way to reduce these costs is to develop alternate construction techniques.

WHY HAVE ARCHITECTS LOST INTEREST?

Next to cost, the most frequently cited reason for the decrease in popularity of concrete shells was that they have fallen out of favor with architects. Yet, engineers and architects seemed to disagree over the cause of such a development.

The majority suggested that the nature of thin concrete shells does not fit the more recent trends of architecture. However, some architects stated that it is not so much that they had objections to thin shell forms, but rather that other structural systems can better meet owners' demands for modern large-scale buildings.

Ed DePaola voiced an opinion popular among his structural engineering colleagues when he responded that the biggest reason thin concrete shells are no longer being built is that they are "not architecturally in vogue" and "not the style of the day." Some even consider them passé. Anthony Webster, an engineer teaching at the Columbia University School of Architecture, added that "many architects are uninterested in structural economy/elegance now and more interested in weird, provocative aesthetics."

Ricardo Bitella, a structural engineer working for Arup, suggested that one reason architects prefer to work with structural systems other than thin concrete shells is the lack of flexibility of the final form. When designing a concrete shell, he noted, architects are not as free to make geometric changes as they are with other types of systems such as structural steel or conventional reinforced concrete.

The architects contacted acknowledged the trend, but seemed to focus less on objections to shell aesthetics and more on the advantages of competing structural systems that better suit the demands of modern large-scale buildings. Michael Flynn, an architect with Pei Partnership in New York City, believes that thin shells are no longer used for arenas and stadiums because the architectural focus of these buildings has shifted. The focus of the modern arena is no longer the structure itself, but its use. For example, Nervi's sports palace in Rome (Fig. 1) was, by itself, the attraction. By showing for all to see how the building carried load, the structural system became the focal point. He pointed out that today, arena roofs are cluttered with lights, catwalks, screens, scoreboards, and banners, and that architects and users of these spaces want visitors to marvel at such building contents rather than the building itself. As a result, unexciting utilitarian construction systems (steel trusses, bar joists, and metal decks) are often used to support the roofs above these arenas. Finally, Flynn noted that the recent popularity of retractable roofs also suggests the use of steel framing systems rather than thin concrete shells.

At least one of the architects contacted believed that the aesthetics of thin concrete shells are part of the problem today. Greg Waugh of Kohn Pederson Fox replied that concrete shells have a "brutalistic feel of heavy masonry," and that the prevailing architectural trend was best exemplified by the "titanium curves" and "lighter, airier feel" of Frank Gehry's work. Gehry's architecture is indeed currently quite popular and instantly recognizable. Yet, at the same time, the complex curved forms of a Gehry structure, made of metal skins, seem to shed a different light on the cost issue addressed previously. It could be argued that such free-form shells built in concrete could be very competitive with costly metal panels, which require elaborate production methods. Also, one might argue that Isler's shells symbolize the exact opposite of "heaviness."

DO WE STILL HAVE THE NEEDED TECHNICAL EXPERTISE?

It is well known that shell structures are difficult to analyze and to design properly. According to conventional wisdom, a particularly thorough understanding of the structural behavior of such structures is required to design them. It is also known that academic curricula typically impart only the basic theory and the rudiments of structural design principles on young engineers, who then must gain the deeper insights while working on actual structures in engineering practice.

At the peak of interest in concrete shells in the U.S., most major civil engineering departments offered courses in analysis of shells, and many schools also had special courses on design of concrete shells. A survey of current curricula revealed that none of the departments in the top of the *U.S. News and World Report* list of America's best colleges offered special courses on shell structures. Most of the designers of the celebrated signature structures of the 1950s and 1960s are no longer with us, and much of the collective expertise in shell design has gone with them. However, it can be assumed that many currently active structural engineers have taken courses and could gain the necessary practical experience if the demand for such expertise was revived.

Advances in software engineering have also decreased the need for the ability to accurately analyze shell structures using closed-form solutions. Moreover, the more interesting modern free-form geometries had never lent themselves to closed-form analytical treatment and could only be analyzed numerically or with the aid of scale models.

WHAT NEW DEVELOPMENTS SUGGEST ANOTHER LOOK?

Various developments in general construction technology and, in particular, concrete material science have taken place during the last few decades that certainly have the potential to impact shell construction. The extraordinary progress made in materials technology alone suggests that it is improper to refer to technologies of the 1950s and 1960s when evaluating the potential of this type of construction in the new millennium.

Better shotcreting technology, stiffer fabric forms, and novel types of fiber-reinforced cement composites were mentioned as material advancements that have lowered the cost of shells. According to David South, controlled shotcreting to eliminate rebound and nearly constant shell form monitoring are essential during air-formed shell construction. The costs associated with these construction requirements can be minimized by advancements in material technology. For example, reducing rebound by using polypropylene fibers or accelerators saves material and labor costs in both application time and cleaning.

Richard Crandle mentioned that new fabrics are being produced that provide greater form stiffness during construction and allow a variety of shell forms to be built with inflated formwork. Even stiffer and more durable fabrics will help air-form technology achieve larger and more unique shell shapes.

Shell construction costs can also be reduced through improvements in reinforcing technology. Alternative concrete reinforcement, such as steel or glass fibers, has the potential of eliminating an entire step in the construction sequence and with it the need for reinforcing bars and the significant costs associated with their precise placement. It is now possible to engineer high-performance fiber-reinforced cement composites[6] that can achieve strain hardening comparable to that of structural steel. Their fracture properties and energy absorption capacities are at least one order of magnitude larger than those of regular fiber-reinforced concrete.

Jörg Schlaich and his coworkers have built a unique glass-fiber-reinforced shell for a garden exposition in Stuttgart, Germany.[7] With a thickness of 0.4 in. (10 mm) and covering about 6900 ft^2 (640 m^2), its weight of 4.5 lb/ft^2 (21.5 kg/m^2) was almost comparable to that of a tensile fabric roof. A combination of this material technology with novel construction techniques has the potential of not only reducing the cost of shell construction but also offering architects novel shapes and forms to experiment with.

WHAT ELSE IS NEEDED TO REVIVE INTEREST?

The short answer to this question was twofold: 1) make thin concrete shells cheaper to construct; and 2) make them attractive again to architects and project owners. These two answers are not mutually exclusive. A reduction of construction costs will obviously improve the competitiveness of concrete shells and thereby increase the likelihood of their being selected. But according to some responses, such cost reductions alone will not be sufficient, as thin concrete shells need to be repopularized and reintroduced into the minds of builders if they are to be considered as a viable structural solution at all.

The responders were unanimous that any new construction methods or processes would have to significantly reduce the construction costs associated with traditional shell construction. Jack Christiansen argued that prefabrication and modularization are required to streamline the procedure. If traditional forms of timber or steel are built, they must be utilized such that the builder can take advantage of the "sequential movement" and reuse of pre-built sections of formwork and shoring. Barrels are less expensive than other shell geometries because forms and shoring are standard in shape and size and can be reused by moving them longitudinally below the shell roof. In addition, more visually interesting shapes such as hyperbolic paraboloids (both cantilever and gabled), and segmental domes consisting of saddle-shaped shell segments can be built by using straight stringers to create warped surfaces that are then reused and moved sequentially.

As suggested by John Abel of Cornell University, the increasing popularity of design-build projects within the construction industry may decrease the cost of thin concrete shells because it rewards the type of relationship between the design and construction teams that leads to efficient shell construction. One benefit of design-build projects is that constructibility is considered at a very early stage of the design process. This greatly increases the possibility that a design will be produced that is economically feasible to build. Moreover, "the designer can work with the builder to devise construction processes that are efficient, for example, by together designing reusable form modules that are appropriate for the shell."

Successful shell designers, such as Torroja, Candela, and Isler, maintained close relationships with the builders of their shells to both train them in proper shell construction techniques (so that they could cooperate again and again) as well as to sharpen their own insight into effective design and construction procedures. John Abel believes that increased communication between designer and constructor is bound to reduce construction costs for difficult-to-build structures such as thin shells. However, as mentioned previously, improved materials, structural systems, and construction techniques alone are not enough to reintroduce concrete shells. It is almost equally important that the building and design community be properly informed about such advances.

According to some of those affiliated with the Monolithic Dome Institute, air-formed structures, which apparently are frequently built without the involvement of an architect, seem to have an image

Fig. 9: Santiago Calatrava, Tenerife Auditorium

problem that needs to be overcome before finding more widespread acceptance. According to Leland Gray, nests of similar looking domes do not remind anyone of the beauty and grace of a single Candela shell. Crandle agrees that the introduction of architects into the design phase of air-formed shells is essential to increase the aesthetic appeal of their product before it can attract attention throughout the U.S. Such improvements are likely to result in a greater variety of shell forms. Hyperbolic paraboloid forms are simply more interesting than domes and barrels.

OUTLOOK

It is a widely held perception that thin concrete shells are not as popular today as they once were, when famous designers such as Torroja, Nervi, and Candela erected structures that became landmark examples of modern architecture. However, the engineers, architects, and builders interviewed were far from unanimous that concrete shells are no longer popular. Air-formed structures and shells built with modular forms enjoy considerable popularity, if only in geographically limited regions. Yet, responders widely agreed that cost is the main reason why large thin concrete shell structures are no longer being built. On the other hand, there can be no doubt that for certain signature structures and their celebrated designers, cost is not a primary issue and maybe seldom was. Architects (such as Frank Gehry, I.M. Pei, Rem Kohlhaas, and Philip Johnson) who wish to build such signature structures to attract special public attention tend to spare no expense to reach their goal, and the owners and developers who retain such designers for their skill and level of celebrity are not likely to make cost the overriding issue.

The works of Heinz Isler are proof that spectacular shells are still being built. Because labor costs in Switzerland are not much different than in the U.S., cost alone cannot be the primary explanation for the decrease in popularity of thin shells. Aesthetic preferences that vary from country to country must play an important role as well. Yet, the recent success of Santiago Calatrava (Fig. 9), both in Europe and the U.S., seems to

Fig. 10: Santiago Calatrava, Zurich Train Station

indicate that such regional differences in aesthetic preference alone cannot be responsible either. In fact, some of Calatrava's structures can be considered to transcend the traditional concept of concrete shells by breaking them up into networks and filigree work (Fig. 10).

The experts could not agree on the other reasons why thin concrete shells are no longer as popular with architects and owners as they once were. Advances in technology have led to alternate structural systems such as tensegrity structures, tensile fabrics, and large steel structures that can more readily cover large spaces such as stadiums. Advances in concrete technology have been almost as dramatic, but have not yet been realized in large-scale applications. It's possible that architects and developers simply are not sufficiently familiar with these advances and their potential for large signature structures. A concerted effort to familiarize the building community with these advances may have some impact. By giving thin concrete shells another look, educating the public in general and the building community in particular about the innovations made possible by recent advances in concrete technology, maybe great designers will revive a tradition that produced some of the most magnificent architectural landmarks of the 20th century.

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Selected for reader interest by the editors.

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