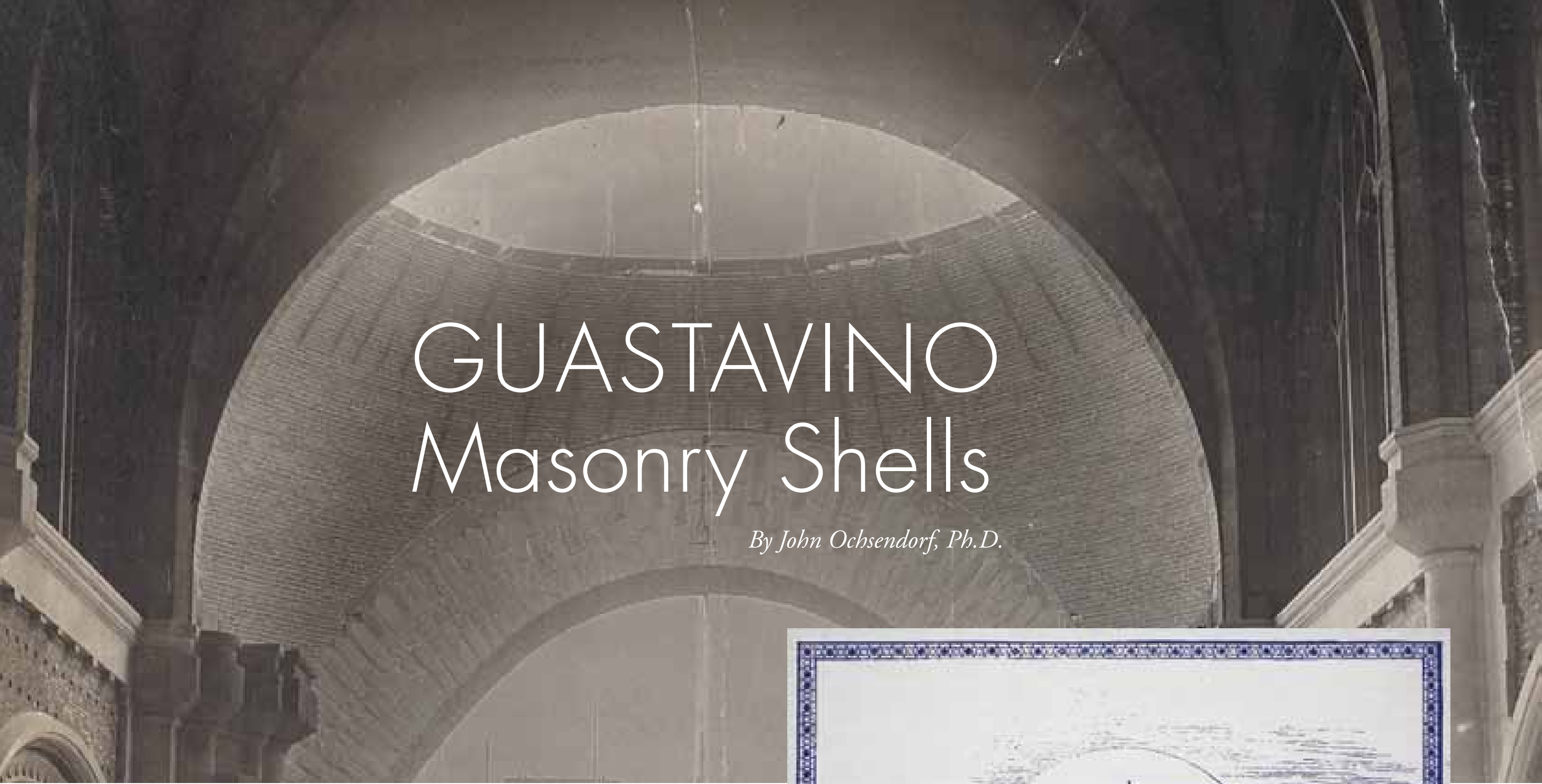

GUASTAVINO Masonry Shells

By John Ochsendorf, Ph.D.

In the late 19th and early 20th centuries, the Guastavino Company designed and built some of the most exceptional masonry structures in history. By adapting a traditional Mediterranean vaulting method to the demands of American construction, Rafael Guastavino Sr. (1842-1908) and Jr. (1872-1950) had a major impact across the United States. Between 1889 and 1962, the firm installed structural masonry vaults in more than 1,000 major buildings across the country, including long-span domes for numerous government facilities, museums, and religious buildings. By 1910, they were able to construct vaulting on an industrial scale, with more than 100 projects under construction simultaneously. A company advertisement from 1915 illustrates some of these domes (*Figure 1*). This article provides an overview of Guastavino vaulting and identifies noteworthy structural achievements by Rafael Guastavino, Jr. as well as calculation approaches for masonry vaults. Finally, the article describes the potential for Guastavino-style vaults to be built in the future.

Figure 1. Advertisement for the R. Guastavino Company (ca. 1915) (Source: Avery Library, Columbia University).

History and Construction

The Guastavino method of masonry construction uses thin ceramic tiles, roughly 6 x 12 x 1 inches, which are laid flat in multiple layers. This method was considered to be revolutionary in the 14th century, when it was first described as being a lightweight and inexpensive method of construction compared to traditional stone vaulting (*Figure 2*). The tile vault appears to have been developed by Moorish builders near Valencia, Spain, though it quickly spread to become common throughout the Mediterranean region. The method is known as the *bóveda tabicada* in Spanish and is sometimes called the *timbrel vault* (so-named by Guastavino Sr.) or the *Catalan vault* (so-named by 20th century Catalan architects).

When compared to traditional stone vaulting, tile vaulting uses much less material and can be built much more quickly. Because the thin bricks are laid flat, with their narrow edges in contact, the total thickness of the vault is less than conventional masonry, and therefore the self-weight and corresponding horizontal thrust values are reduced. In the traditional tile vault, the tiles are joined with plaster of Paris, which sets quickly enough that the interior of the vault does not require any support from below during construction. By contrast, a traditional stone arch must be supported on wooden centering, or formwork, and will only support its own weight once the keystone is in place. By building out from a wall in successive arcs, tile vaulting can be constructed with minimal to no formwork.

In addition, the inherent fire resistance of the tile vault was a major selling point for the Guastavino Company in the late 19th century. Though other builders had brought the tile vaulting method from Spain to the Americas as early as the 16th Century, Rafael Guastavino

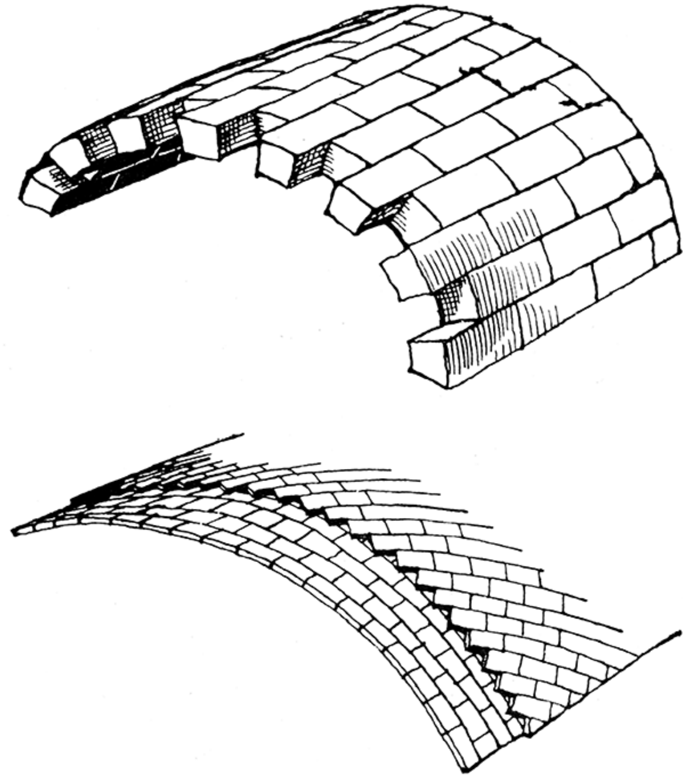

Figure 2. Comparison of the traditional stone vault (a) and the Guastavino tile vault (b) (Source: Moya, 1947).

Sr. and Jr. introduced numerous innovations to the traditional tile vault, which allowed them to secure dozens of U.S. patents to protect their product.

Guastavino Sr. was educated as both an architect and an engineer at the school of "masters of works" in Barcelona in the 1860s, by the same professors who would later teach the Catalan master Antoni Gaudi (1852-1926). In Barcelona, Guastavino Sr. constructed a series of major industrial factories as well as numerous houses, all using the traditional tile vault as the load-bearing structure for floors and staircases. His last major work before immigrating to the United States in 1881 was the La Massa Theater in Vilassar de Dalt, with a 56-foot span built of unreinforced masonry only 4 inches thick. This astonishing thinness is possible because of the double-curvature of the masonry shell, which allows for compressive load paths to be transferred to the supports in multiple directions.

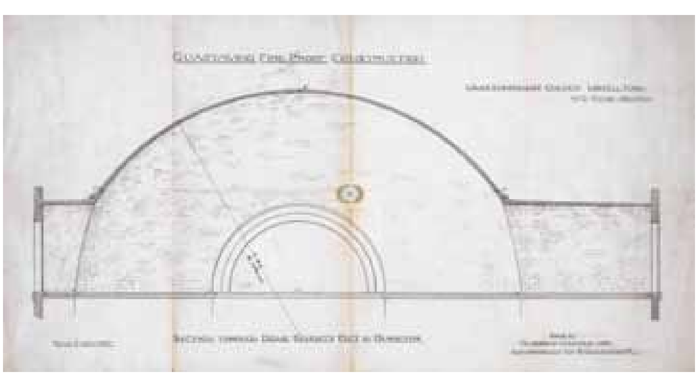

Figure 3. Grace Universalist Church by Rafael Guastavino Jr., Lowell, Massachusetts, 1895 (Source: Avery Library).

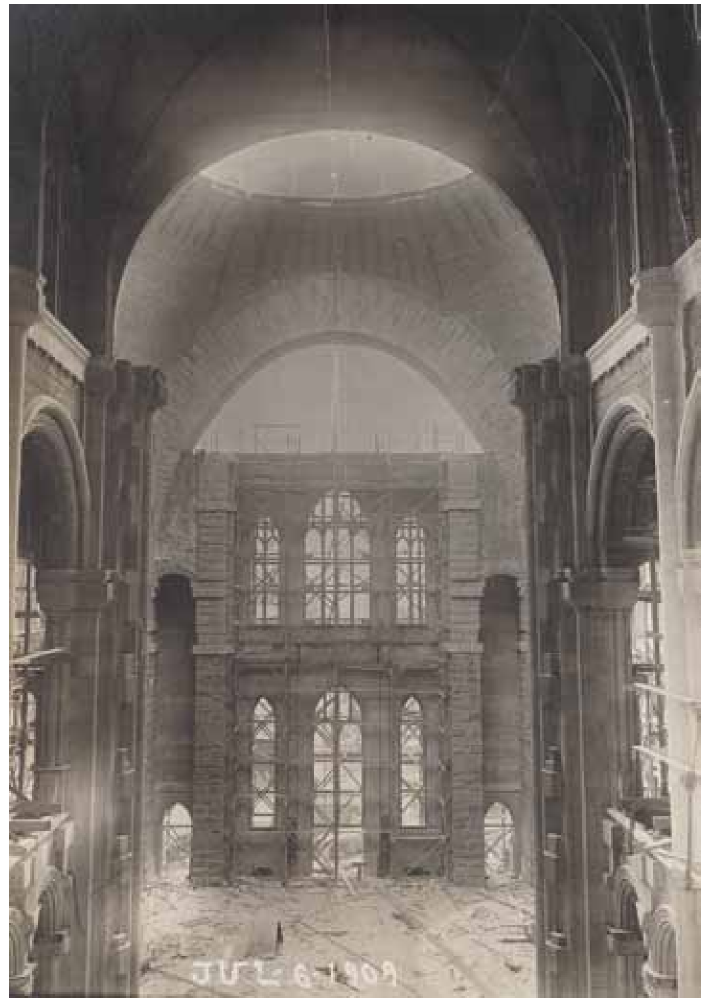

Figure 4. Crossing dome of the Cathedral of St. John the Divine by Rafael Guastavino, Jr., New York City, 1909 (Source: Avery Library).

With minimal English and few professional contacts in the United States, Guastavino Sr. initially struggled to earn a living as a newly-arrived immigrant. Eventually he got his break when he was contracted by the leading firm of McKim Mead and White to build structural tile vaulting throughout the Boston Public Library in 1889. This launched his American career and led to dozens of other contracts for structural tile installations in the 1890s. His son, Rafael Jr., had no formal education in architecture or engineering, but after apprenticing under his father, went on to build some of the most daring masonry structures in history.

Structural Achievements by Rafael Guastavino Jr.

Guastavino Jr. supervised the construction of an impressive church dome in 1895 when he was only 23 years old (*Figure 3*). The 70-foot span tapers in thickness from 6 inches at the support to only 4 inches at the crown of the dome, and the span-to-thickness ratio of roughly 200 is twice as thin as an eggshell by proportion. This dome was built in less than two months and was self-supporting throughout construction, with minimal formwork to guide the geometry. Because tensile hoop forces would appear in the lower region of the spherical shell – below about 52 degrees as predicted by membrane theory – Guastavino provided a tensile band of steel to resist the outward thrust at the intersection of the buttressing barrel vaults and the dome. As

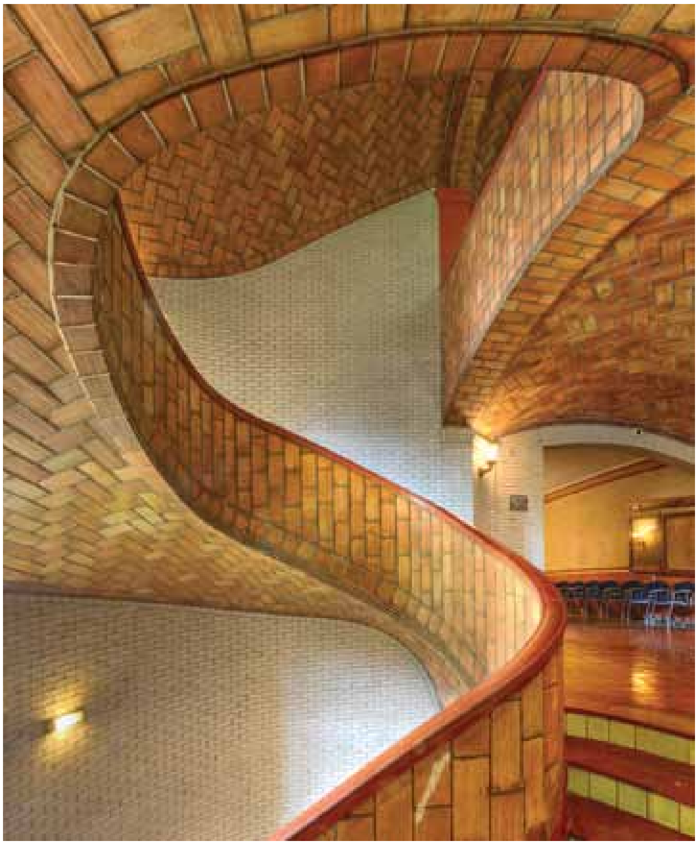

Figure 5. Tile vaulted staircase of Baker Hall, Carnegie Mellon University, Pittsburgh, 1914. Courtesy of Michael Freeman.

with his father's dome at La Massa, structural shells of this scale and proportion would not be constructed in thin shell concrete until decades later. In some ways, the Guastavino shells are superior to the later reinforced concrete shells because of the absence of formwork as well as the minimal reinforcing steel. Hundreds of Guastavino domes have functioned as safe structures for more than a century, and none have ever failed in service.

The largest dome ever built by the company is the 135-foot span for the Cathedral of St. John the Divine in New York City (*Figure 4, page 27*). Shortly after his father's death, Guastavino Jr. proposed the dome as a temporary solution over the crossing of the cathedral. By following a spherical geometry, the dome could be built using only cables to guide the placement of tiles, while the masons were supported on the concentric rings of tile as the project cantilevered out into space. This great feat of construction was completed in only 15 weeks during the summer of 1909, and was heralded as an achievement to rival the great masonry domes of antiquity. As in other Guastavino domes, the total thickness at the crown is just over 4 inches, and steel tensile reinforcement at the base helps to restrain the outward thrust of the dome. More than a century old, the dome still stands today as a testament to Guastavino Jr's skill in both structural design and construction.

Though smaller in scale than the large domes, Guastavino spiral vaulted staircases represent an additional category of structural achievement. The main staircase of Baker Hall at Carnegie Mellon University is a masterpiece of Guastavino construction, with a 4-inch thick shell of masonry spiraling in three dimensions (*Figure 5*). The load-bearing masonry structure is made only of brittle ceramic tiles and does not contain reinforcing steel. The stair is constrained by a cylindrical brick structure, which resists the outward thrust of the vaulted staircase. Though calculating the ultimate load capacity of such a structure is extremely difficult even today, the Guastavino Company conducted many successful load tests, and the survival of the stair for the last century is proof of its adequate load capacity.

Mechanics of Masonry

Rafael Guastavino Jr. calculated the forces in his vaulted structures using compressive equilibrium solutions defined by graphic statics, and he often shaped the structures to respond to the flow of forces, placing masonry where the resulting thrust lines acted (*Figure 6*). The goal of the calculation is to demonstrate safe equilibrium solutions under all possible load cases, and to ensure that the resulting thrust lines do not exit the masonry. This follows in the tradition of limit analysis of masonry as developed by Jacques Heyman since the 1960s. The stresses in traditional masonry structures are quite low, and the safety of such structures is typically governed by stability and not by strength.

By contrast, it is very difficult to demonstrate the safety of thin masonry shells using finite element methods, which seek to minimize the strain energy by invoking assumptions about the material behavior. Such elastic solutions predict substantial tensile stresses in traditional masonry and are highly sensitive to small movements of the supports. The calculation methods used by the Guastavino Company are similar to those used by the leading concrete engineer Robert Maillart and the great shell builder Felix Candela: they are based primarily on static equilibrium and not on the vain search for exact stress distributions in a hyperstatic structure. While assessing the safety of Guastavino structures remains a challenge today, new methods of equilibrium calculations can help today's engineers to discover load paths that these masonry shells have effortlessly found for more than a century.

Several recent projects have demonstrated the potential for structural masonry shells to be built today. For the Pines Calyx project in England, two masonry domes span approximately 40 feet as the primary structural system (*Figure 7*). Similar to the unreinforced Guastavino masonry shells, the domes are constructed of three layers of thin tile, and the outward thrust is resisted by a tension tie at the

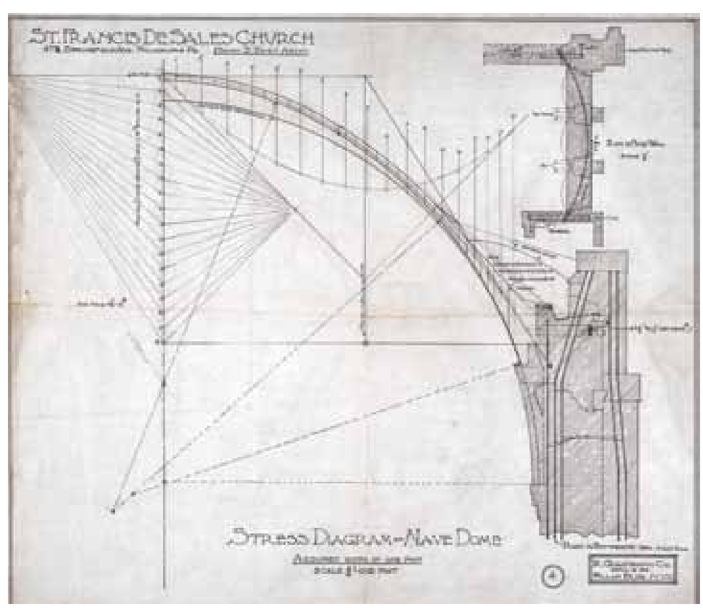

Figure 6. Graphic statics used by Guastavino Jr. to calculate the compressive forces in the dome of St. Francis de Sales Church in Philadelphia, 1909 (Source: Avery Library).

Figure 7. Structural tile dome, Pines Calyx, St. Margaret's Bay, England (2005).

base. The domes were self-supporting during construction, and a central oculus admits natural light and ventilation. Equilibrium calculations based on the membrane theory and graphic statics were used to demonstrate the safety of the structure during construction and under asymmetrical live loading. Due to the use of local materials and the minimization of structural steel, the embodied energy in the structure is dramatically lower than conventional steel or reinforced concrete structures.

Conclusions

The thin structural shells of the Guastavino Company are some of the most impressive masonry structures in the world. In particular, the large domes and remarkable staircases by Rafael Guastavino Jr. are worthy of additional study by both engineers and historians. More than 600 existing projects in more than 40 U.S. states contain examples of Guastavino masonry vaulting, though new projects are being rediscovered each year. The engineering calculation of thin masonry shells presents an open challenge, and the engineer must find three-dimensional compressive solutions that lie within the thickness of the masonry. Attempts to prove the safety of existing structures can also lead to the discovery of new structural forms that have not yet been invented. The minimization of reinforcing steel and the use of local materials can inspire engineers to design and build new masonry vaults in the future, with the hope of matching the success and longevity of Guastavino tile vaulting.▪

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For More Information

A public exhibition on Guastavino vaulting, including original design drawings and a full-scale replica vault, is on view at the Museum of the City of New York until September 7, 2014.

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