Structure of Biblical Proportions

High-strength concrete as a critical component in construction of the world's tallest cathedral—the Sagrada Família

by Deborah R. Huso

When builders began construction of renowned Spanish architect Antoni Gaudí's Temple of the Sagrada Família in 1882, the primary construction material was sandstone. However, concrete has always been a component of the cathedral, which is in Barcelona, Spain. In fact, Gaudí first used what was then a novel material—reinforced concrete made from portland cement—in construction of the pinnacle of the first bell towers of the Nativity façade in 1924 and 1925 (Fig. 1).

Over the course of nearly a century and a half, construction of the Gothic and Art Nouveau basilica has been affected by wars, the influenza pandemic of 1918 and 1919, and variable funding levels. But thanks to an increase in tourism prompted by Barcelona hosting the Olympic Games in 1992 and the consecration of the basilica by Pope Benedict XVI in 2010, the cathedral has increased its construction funding stream through admission fees. A 2026 completion, in commemoration of the 100th anniversary of Gaudí's death, was scheduled.

Alas, the recent COVID-19 pandemic has pushed back the schedule yet again, and *Junta Constructora del Temple Expiatori de la Sagrada Família* architect Jordi Fauli says his team has yet to establish a new schedule. Fauli is the ninth chief architect to oversee Sagrada Família's design and construction and the only one who will likely live to see it finished.

Building per Gaudí's Plans

As construction continues on this cathedral, the tallest of the world's churches, materials have changed dramatically. Stone remains Sagrada Família's primary building component, but concrete—high-strength concrete in particular—has become a critical construction material for the cathedral in the last two decades and also helped accelerate the basilica's erection.

"Technical advances have made it possible to overcome the challenges of the past," says Fernando Villa, Director of

Fig. 1: The Nativity façade features two 107 m (351 ft) towers flanked by 98 m (321 ft) towers. This façade was nearly completed under the direction of Gaudí *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

Fig. 2: The Passion façade features two 112 m (367 ft) bell towers flanked by two 102 m (334 ft) bell towers. Behind these, six more towers are under construction *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

Fig. 3: Close-up of two pinnacles of the Passion façade spires. The towers are decorated with mosaic tiles *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

Building and Technology for Sagrada Família. "Even though Gaudí built only a small part [of the cathedral in his lifetime], he left the path in his studies to be followed by his successors."

Sagrada Família features a Latin cross design with five longitudinal naves and three naves forming the transept (the arms of the cross). The Nativity façade is on the northeast end of the cross, and the Passion façade is on the southwest end of the cross.

The basilica's most prominent architectural features are its monumental spires. Gaudí's design included 18 spires, including 12 placed in the façades, representing Christ's apostles. Eight of the 12 spires representing the apostles are complete (Fig. 1 to 3). Four more will be constructed with the final façade—the Glory façade at the base of the cross—and six more spires are being constructed at the center of the transept (the crossing) and on top of the apse (the head of the cross). These spires are still partially concealed behind the spires on the Nativity and the Passion façades (Fig. 1 and 2), but they will soon become prominent. When completed, the four Evangelist towers will each be 135 m tall (443 ft); the Virgin Mary tower will be 138 m tall (452 ft); and the Jesus Christ tower will be 172.5 m tall (566 ft).

According to Villa, 25% of the basilica remains to be built, including finishing the central towers, the Glory façade and its spires, and a second sacristy.

Using Concrete to Surmount Architectural Hurdles

One of the most prominent design features of Gaudí's famous basilica is lack of the conventional flying buttresses present in so many of Europe's Gothic cathedrals. Gaudí's design supports the structure's roof, towers, and soaring large windows via the columns of the central transept and apse. Those tree-like columns and their striking "branches" are all made with a structure of high-strength reinforced concrete encased in exterior "drums" made of stone or precast concrete.

"It was necessary to meet new building [code] requirements," says Villa. "In fact, [high-strength concrete] was the only alternative to meet new requirements for wind load while still maintaining the width of the walls and their unusual geometry. It was also the only way to withstand the compression load while maintaining the diameter of the columns defined by Gaudí."

According to Fauli, Gaudí formulated a system of slanted columns as trees with sloping branches supporting upper levels. "He wanted to design a church without flying buttresses and only with interior columns to support [the roof, towers, and windows]," says Fauli. The thrust of the roof and the weight of the central towers is resisted by those branching internal columns. All the columns have varying systems of proportions in diameters and in slenderness established by Gaudí. The columns of his original model of the main nave follow this system, as do the new columns of the transept and of the apse (Fig. 4).

Fig. 4: The interior of the cathedral is a celebration of light: (a) Tree-like columns and their "branches" line the main nave, seen here looking toward the apse. Four types of columns have been constructed: columns on each of the four corners of the crossing support the Jesus Christ tower and partially the weight of four Evangelist towers; columns that bear the main load of the four Evangelist towers; columns in the apse and naves; and columns that separate the side naves from the main nave; and (b) The longitudinal nave on the Nativity façade side of Sagrada Família features stained glass windows that gradually transition from yellow to green to deep blue *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

The architects who have taken up Gaudí's mantle in the nearly 100 years since his death have based construction on a 1:10 scale plaster model of the main nave the Catalan architect built while studying and perfecting his design. "He designed plaster models of everything," says Fauli. "When we built the main nave, we tried to reproduce [his plaster model]."

All of the columns have an exterior "drum," as Fauli calls it, shaped by a piece of stone or precast concrete. Inside the drum, workers placed high-strength concrete over reinforcing steel. Thus, the precast concrete or stone, depending on which one is used in the column's façade, was also used as a permanent form (Fig. 5 and 6).

The 56 columns rising from the ground floor that assume the place of flying buttresses are also unique in being grouped at different heights to provide the appearance of trees and tree branches (Fig. 4). The columns and branches transfer the weight of the vaulted structure and central towers above into the building's foundation. These columns were built from a variety of different stone classes, according to Fauli, with reinforced concrete on the inside as previously noted. The columns of the branches were built with precast concrete drum pieces for the exterior and reinforced concrete on the inside.

Fauli says his team built the columns with stone or precast concrete pieces on the exterior and reinforced concrete inside, using high-strength concrete in the more crucial columns as well as in most of the crossing and apse. "In the main nave, we managed to construct all the columns with normal reinforced concrete inside," Fauli says, "but in the

Fig. 5: Construction of the interior columns was completed inside the existing façades between 1991 and 2003 *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

Fig. 6: Stone or precast concrete exterior "drums" were used to form the trunks and branches with reinforced concrete cores *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

crossing, we needed to use the high-strength concrete."

To build the branches of the transept and apse columns, workers employed precast pieces of white concrete with different colors to construct the exterior surface of the columns ("drums") and to achieve the same look as the stone columns on the ground floor. The structural system of columns also allows openings in the vaults for the skylights that fill the interior of the cathedral with striking bands of natural light. Those skylights, designed by Gaudí in the 1920s, are in the unique shape of a hyperboloid—reportedly the first such use of this form in the history of architecture.

Concrete Placements at Soaring Heights

Sagrada Família's history of stops and starts in construction meant that by the time Fauli came on the job as Junior Architect in 1990, only three of the planned 56 interior columns had been built. High-strength concrete (characteristic strength of 80 MPa [11,600 psi]; 7-day compressive strength of 45 MPa [6500 psi]) was first employed in the cathedral's construction in 1998. High-strength white concrete has also been used to provide the base of the central dome (placed at a height of 80 m [262 ft]) as well as in construction of the central towers.

With the help of lightweight fiberglass molds coated with a wax-based form release agent, workers have been able to form many parts of the cathedral, like the lateral vaults and elements of the central dome, in-place, even at great heights. Other components have been prefabricated off-site.

Weight remains a perennial concern in construction of the basilica. The inclined columns or "tree trunks" that branch into innumerable smaller branches hold up the far heavier vaults and roofs and transfer the load to the foundation. The vaults will support the cathedral's central towers, all of them three times taller than the vaults on which they rest. This creates mass at a great distance from the ground and would make the structure vulnerable to earthquakes. "The use of reinforced concrete in the church since 1985 has been calculated to support seismic movements," Fauli explains. "In the central towers, for example, the big panels of stone tensioned by steel bars will resist earthquakes, and a standing structure of steel profiles and reinforced concrete placed in the corners joins the panels and ensures resistance to seismic forces."

In this respect, reinforced high-strength concrete has enabled simpler, lighter, and faster construction of Sagrada Família's complex geometries while still supporting a massive compression load without having to bulk up the diameters of the tree-like and ethereal branches and columns that grace the church's interior.

Since 2010, Germany-based Heidelberg Cement Group's subsidiary Hanson Hispania has been the structure's major concrete supplier when large volumes are needed, though the initial mixture for the white high-strength concrete was provided by Master Builders Solutions. Several other firms have supplied concrete as well, including PROMSA and Escofet. Normally, the concrete is fabricated in the on-site concrete production plant at the Sagrada Família.

Fig. 7: Construction of central towers using prestressed stone panels reinforced by stainless steel columns joined with high-strength concrete *(© Fundació Junta Constructora del Temple de la Sagrada Família)*

According to Villa, the mixture proportions for the high-strength concrete components are:

- 475 kg/m^3 (800 lb/yd^3) of cement;
- 1030 kg/m^3 (1736 lb/yd^3) of gravel (5 to 12 mm [0.2 to 0.5 in.]);
- 800 kg/m^3 (1348 lb/yd^3) of sand (0 to 5 mm [0 to 0.2 in.]);
- 30 kg/m^3 (51 lb/yd^3) of microsilica (silica fume);
- 150 kg/m^3 (252 lb/yd^3) of water; and
- 12 L/m^3 (2.4 gal./yd^3) of high-range water-reducing admixture.

When white concrete is employed, suppliers must be careful to avoid changes in color and texture. Thus, the concrete trucks must be cleaned thoroughly before each new batch is loaded.

Building the Basilica's Final Pieces

The Glory façade, which will be at the base of the cathedral's Latin cross design, will be made up mostly of stone but with elements cast in gray high-strength concrete. Sixteen vast stone hyperboloids will be supported with slanted tree-like columns of stone (the same prestressed stone used for the central towers), with vaults and arches of high-strength reinforced concrete.

Workers began constructing the six central towers in 2014. The faces of the towers consist of prestressed stone with the bars placed inside, but the structural part used to join the different stone panels together is steel and high-strength concrete. The first stone panel of the towers was placed in 2016. The main structure of the Evangelist towers, the Virgin Mary tower, and the Jesus tower will be composed of this prestressed, post-tensioned (with ultra-high-strength stainless steel rods) polychrome stone from quarries at various locations in Europe, selected to mimic the look of the original Montjuïc sandstone Gaudí employed in the cathedral's construction during his lifetime. Nine hundred prestressed stone panels reinforced by stainless steel columns make up the six towers.

Following Gaudí's proposals for the future, architects based the design of the towers on the dome of the sacristy (it exists in an original Gaudí model), essentially stretching its design to the great heights of the towers. The dome of the sacristy and the towers are the intersection of paraboloids that contain triangular windows. The sacristy features five floors, but current technology has allowed for their elimination in the central towers, according to Fauli. The Virgin Mary and Jesus Christ tower structures will envelop a free space of 60 m (197 ft) with no floors.

Fauli explains that the panels made of stone and steel are produced and preassembled at a staging facility outside of Barcelona. Once the panels of stone and steel are placed on-site (Fig. 7), crews place the high-strength concrete mixture that joins the panels.

High-strength white concrete partially coated by blue ceramic pieces will make up the main part of the terminal or pinnacle of the Virgin Mary tower. Villa says the team selected white concrete both for its texture and high resistance to weather phenomena. Fauli confirms the Virgin Mary tower will be completed by the end of 2021.

The 14 corners of the stone panels are composed of high-strength concrete, and portions of the tower are composed of concrete as well. "The pinnacle is shaped in three parts," explains Fauli. "The first 6 meters [feature] a stone exterior with an internal structure of reinforced concrete, while the next 18 meters are composed of a pinnacle of reinforced concrete partially coated by ceramic." Lastly, at the top will be a 12-pointed star of steel and textured glass that will be prefabricated in a factory as well as on-site and then lifted into place using a crane.

The Evangelist towers will feature traditional biblical representations like the man, the lion, the bull, and the eagle, all winged, on the pinnacles. The wings of the eagle will have a span of 7 m (23 ft) and will be built with prefabricated, white high-strength concrete. The Jesus Christ tower will be the tallest and will be topped by a 17 m (56 ft) tall cross.

A Century and a Half in the Making

The Sagrada Família was designated a UNESCO World Heritage Site in 2005. It currently occupies about 9700 m^2 (104,400 ft^2). When fully completed, its footprint will consume an entire city block, and it will be the tallest cathedral in the world.

Fauli says the more than 140 years it has taken to build the Sagrada Família has been a blessing in disguise in many ways. "Gaudí would have had to use massive materials to build the cathedral," he explains. "We now have the opportunity to find the best technique for each element. We are building the central towers, for example, with prestressed stone. If we'd built them 20 years before, it would not have been possible."

But as Fauli points out, Gaudí was always trying to take advantage of new building materials. He built one of the spires of the Nativity façade in concrete coated with color ceramic pieces. "[The Sagrada Família] was a challenge for the future," Fauli says. "Gaudí was always thinking in the future and about new techniques that would assist construction."

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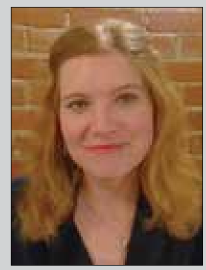

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