COMPLETING THE SAGRADA FAMILIA

The Sagrada Familia, one of the world's most iconic buildings, is designed and constructed outside the normal rules of time, space and budget. It is an inspiration for the potential of architecture to aid spiritual wellbeing… and for a different take on how to build. But can the church ever be completed? Now thanks to innovations in engineering, the end is nigh. Tristram Carfrae of Arup explains how

The Sagrada Familia is a brilliant building, visited by about three million people a year. But it is not the most visited attraction in Barcelona. That title goes to the Nou Camp, like many other honours for Barcelona FC.

It is a church — not a cathedral — owned, designed and constructed by The Sagrada Familia Foundation. They do almost everything themselves. Pretty much the only thing they don't do is engineering. The engineering for several decades has been done by a Spanish firm, 2BMFG. Arup was fortunate to join the party four years ago as a second engineer. The project had been going for 130 years prior to us joining so we can only ever claim a modicum of credit.

I am used to working in the interface between architecture, structural (and other) engineering and construction. But at the Sagrada Familia you must also work with theology, with which I am unfamiliar. I can be pulled up short when I say something like 'we don't need those seven columns, we could probably do it with four', only to be told there are seven graces and seven sins, not four.

When the Sagrada Familia started in 1877, the site was in an area of the city plan yet to be built out, a place of piggeries and other small farms. The original architect was not Antoni Gaudi but Francisco Villar, whose design was a somewhat conventional neogothic approach. The crypt of Villar's church was largely built when he decided to resign over a disagreement with his client. That is when they took the audacious and ambitious step of appointing Gaudi. He was in his early 30s and had not yet built or designed anything of scale or consequence.

The church relied entirely on private donations: it was not part of the Catholic church at that time. It was an independent private institution. Gaudi's ambitions greatly eclipsed his predecessors, his vision was of a much larger and taller structure. And in that difference is the seed of how we became involved in the project.

GAUDI BECAME MORE AND MORE ASCETIC. HE TOOK TO SLEEPING AT THE CHURCH, UNDER HIS DESK, LITERALLY

How the church sat in the surroundings was significant. Although it was a symmetrical church in plan, Gaudi had a great interest in the skewed views on to the structure, he thought the straight elevations were not as interesting as taking a three-quarter view on to the structure. He had an idea to cut away parts of the planned city blocks to allow these views but he did not have as much sway over the city as he may have wanted. Some of it happened: the blocks east and west of the church remain empty and one avenue has been carved out at 45 degrees, up to the hospital, another great Modernista building. The avenue is now mainly pedestrianised. Some of the spirit of how Gaudi may have wanted the building to be seen does perhaps survive.

Gaudi's appointment was in 1883 and it was about 20 years later that he dedicated himself exclusively to the project. He became more and more ascetic, to the point that even though he had a beautiful house in Parc Guell (which he had designed) he took to sleeping at the church, under his desk, literally. He went to church every evening to pray and it was on his way there one evening in 1926 that he was knocked down by a tram and died. At that stage he had built a small part of the building from bottom to top: the wall of the apse, the east entrance with the nativity facade, and the four towers of the apostles.

It is quite odd that somebody should build the church like that, without even attempting to start the rest of the building. I think the reason may have been he was attempting to give a pattern for the whole building for the future generations who would have to complete the structure, even though he wrote that he expected other people to interpret the design, take it forward, re-interpret it and not follow slavishly what he left behind.

It was not so long after Gaudi's death that we had the great misfortune of the Spanish Civil War. The building containing all the plans and models was blown up. Gaudi worked largely in one to ten plaster models: while they weren't totally destroyed, they were greatly damaged. There are people still in the basement of the church piecing together the fragments of plaster. These are now so valuable that they first scan the piece and generate a copy through 3D printing, which they try to match with others… and after many years of this, they are down to the smaller bits.

Gaudi was not shy of using modern materials, of embracing advances that were coming along. For example, he used reinforced concrete as well as stone. Part of the debate now is 'what would Gaudi do today?' as opposed to what he may have planned to do a hundred years ago.

We have rules. If a one-to-ten plaster model exists, you follow it exactly. If drawings exist, you are never quite sure when they were drawn and if they were Gaudi's final thinking, so a degree of interpretation is allowed. If nothing exists, then it is up to us to interpret the spirit of the design.

While the main body of the church and its towers are scheduled to be complete in 2026, it could be another century before the decorative sculpture is completed. The Nativity facade is the only one worked on in Gaudi's lifetime. Image: Paul Pensom

The Mary Tower is the second tallest tower and required a switch from reinforced concrete and stone to a new approach using post-tensioned stone in order to lighten the load over the nineteenth century crypt below.

Gaudi went through three phases of design, rethinking the whole church each time. The first, around 1890, may look neo-gothic but the idea of the catenary, the curve of the hanging chain, was already present in the design, an approach that would enable avoiding lateral thrust and therefore flying buttresses on the outside. He saw buttresses as undesirable props, not integral to the design, and they also blocked the light.

The shape of his apostle towers, when inverted, can clearly be seen to follow the catenary form, hanging chain, which is a large part of the structural motif of the church.

In the second era, apparent in drawings from around 1915, Gaudi tried harder to make the structure follow the force paths. But he had yet to convince himself that a column could branch in free space, instead there are platforms and tying elements at different levels. He never designed the roof in the third style, so it is the second style that is used for the roof, grafted on to later elements which are followed in the main body of the nave.

Before that third phase of design was developed, Gaudi became very keen on how structure and form and catenary action were connected. He evolved a way of using hanging chain models to work out force paths. It was an amazingly complex thing to do with lots of little hanging bags of lead shot, connected, precisely mimicking the weight of the masonry that would be at that location, hanging in an upside-down version of the church structure.

The consequence of working with the hanging chain model is that nothing is vertical. Everything is leaning in, aiming upwards to the pinnacle.

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The spectacular nave, with a forest of columns sloping inward, demonstrates how Gaudi was influenced by forms derived from the catenary modelling, which guided his understanding of the forces. This form avoids the need for flying buttresses and lightens the load from the walls, thereby permitting more windows and light. The stone was originally sourced from a quarry in the city, on Montjuic hill. It is now closed but the cathedral foundation has stockpiled stone for the completion. The interior was made watertight only this century, being consecrated in 2011 by Pope Benedict XVI. With the utility of the interior, the building has been able to greatly grow its visitor numbers and revenues, which now make a major contribution (along with independent donations) to the cost of construction.

The third design, from around 1921, is what the nave is constructed from. In section it is a hanging chain model, the main columns inclining inwards, but in the long direction, down the nave, he marches this section in absolute regularity, every 15 metres. The section is correct but then it is just extruded, no attempt to lean anything in the other direction… this perhaps makes it more comprehensible than if it was leaning all over the place, it helps give it the majesty. It is a very large space: it will be the tallest church in the world when completed.

Gaudi became obsessed with geometry. Every single part of the third design is a ruled surface. It is generally either a hyperboloid or a hyperbolic paraboloid. This has consequences. One of them is where you can have fantastic intersections of these different surfaces, as in the ceiling of the nave. You have things that might look like decoration but are purely geometric, driven by his choice of the hyperboloid as the fundamental form. You can see the hyperboloid on the underside of the Mary tower, which sits on the apse, above the crypt which was built for Villar's church.

The building was made watertight in 2010, when it was consecrated by the Pope. When I first entered this space four years ago I thought this was the grandest, most uplifting space I have ever been into. You get a flood of light through the stained-glass windows in a wonderful way because the flying buttresses are not there. The upper windows are clear, permitting even more light into the church, creating a feeling of lift.

The church I encountered four years ago was only 60 per cent constructed. By 2026 the church will be 170 metres tall, the tallest church in the world and it will be the tallest building in Barcelona…but it will be one metre lower than Montjuic hill. Gaudi thought it would be an insult to challenge God and the natural beauty he created.

Our challenge is to build 40 per cent of the church in ten years when it took 130 years to build 60 per cent. The rate of construction has had to go up by a factor of ten. A complete change in approach was required to get that done. Besides speeding it up, we must do more of the construction off-site as there will be less and less site to work on in-situ. From having on site, the concrete batching plant, a timber yard, a masonry yard, the sculptors and the design office, we find they all must be moved offsite to finish the church.

On top of this, there was a particular technical challenge. The Mary Tower, sitting above the crypt, would weigh too much for the foundations of 1877 if built conventionally in stone or in the stone-clad reinforced concrete of recent years. The puzzle was how to build a tower that would work and yet be true to the design. That was the spur to invite us into the team: did we have any good ideas as to how this might be achieved?

The geometry of the tower, although there were no models or detailed drawings, was extrapolated from one of the models that had been reconstituted of the sacristy. The design is of hyperbolic paraboloids that rotate about a central axis and intersect to give us the shape. In this modern day we work in Rhino and we write a Grasshopper script and elongate the form of the sacristy and from that get the Mary tower modelled on computer. The tower has fourteen sides and the intersecting

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Hyperboloid structures and ruled surfaces came to dominate the forms of Gaudi's third phase of design development, which can be seen in much of the nave vault. Natural forms and religious symbolism are also key drivers of Gaudi's approach. To complete the building requires interpretation of drawings and models from the three phases of the design, which were worked and reworked over more than 30 years of Gaudi leading the project.The main nave is 45m high and is surrounded by four aisles and crossed by the transept. The vault and pillar system is unique and is built using varying strengths of stones, depending on the load requirements – the columns are porphyry, basalt, granite and the local sandstone (the majority of the structure or its facing). Form derives from geometry that is linked to both innovative structural thinking and religious symbolism.

hyperbolic paraboloids give us this scalloped shape: it has a catenary shape on elevation but a scalloped shape on plan. As an engineer, it is quite hard to work out how that works as a structural form – or whether it works at all. How will it behave? Particularly when you add in the narrow triangular window openings that are cut in it.

The first task I set myself was to look at how that would work in masonry. If we made this from stone, was there any chance of it behaving as a structure? The masonry can take compression only, not tension (as the joints would open). Our modelling showed that under a service wind, the wind it was likely to experience in its lifetime, it behaves reasonably well. But under the ultimate wind, the wind we design for to give a factor of safety, it doesn't work well at all. The windward face would go into tension, very few parts of the structure would be doing any job at all, and the forces are very concentrated in some areas. Masonry on its own would not be a good idea.

However, I thought that if we made panels on a much bigger scale, and that we could join together, would this be a strategy that might work? I am glad to say it proved to be the case. We modelled the panels as finite elements and looked to see if the panels can be made to work with the stresses. We saw that as masonry alone they won't handle the tension but if we post-tension it, add steel inside the masonry and pre-compress the panels before we assemble them on site, we can generate a compression stress field. When we add the wind and gravity stresses our modelling showed that this approach could eradicate almost all the tensile forces with this pre-compression of the panel. This is not easy: you don't want to overdo pre-compression. We just put in enough stress to make it work.

In the ultimate wind load situation, we may still get some pesky tension forces that we don't like... but is it really a problem? If a crack starts would the crack propagate, because the tensile forces concentrate at the end of the crack, or would the cracking dissipate because we relieve it by opening the joint? The quick and dirty way of finding out is to model the removal of the elements in tension and see what happens next. The good news is that the tension forces dissipate. They are parasitic stresses, not ones fundamentally needed to hold the tower up. If the joint opens by one or two millimetres in a wind I am not expecting the church to ever experience, then that's OK.

One of the wonderful things of working on the project is that The Foundation not only has their own architects but their own builders. So all the conversation and modelling of what might be possible is happening in dialogue with design and construction. When the builders hear about this approach, they think it sounds quite exciting. Up to date they have been doing everything in reinforced concrete and then cladding with stone, because that was the only way to achieve the earthquake resistance required. When we talked about this new approach they saw that threading stone on steel and stressing it up might be easier than doing two layers of doubly curved formwork, reinforcement, poured concrete, glued stone on front and back.

Within a month of my putting the post-tensioned stone idea forward the builder had made a panel. We put the mock up together in the same area, slightly below ground, where Gaudi had done preparatory work out of the public eye. The builder was ecstatic with the outcome: he reckoned he could make one of these panels every day where it was taking him a week to do an equivalent concrete panel. The advantage of having made it was also that we could test it. We had done theoretical work but stone is a natural material and doesn't always behave in the way you predict. I am delighted to say it performed in line with our predictions. We could proceed.

I have never worked on a project where collaboration has been better. It is partly because there is only one objective: to build the best church in the world. Nothing else gets in the way. And it is partly because the contractual boundaries don't exist as they do in most construction projects. In a way, Arup is the only part of the team with a contract so if we can ignore it, then we can all get on with it.

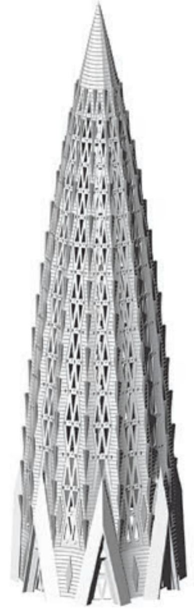
Because we don't share a common language, because I have failed to learn Catalan, it forces us to communicate in different ways. Hand sketches on the wall in meetings, sketches on top of Rhino models, projecting Rhino models on to the whiteboard and then drawing over the top of it. Then somebody takes a record of that with a phone or tablet, and then you move on while somebody is then adjusting the Rhino model. Lots of different generations, joined together; a collaborative enterprise that embraces everybody bringing in their own method, their preferred communication style, and yet it seems to work across the team.

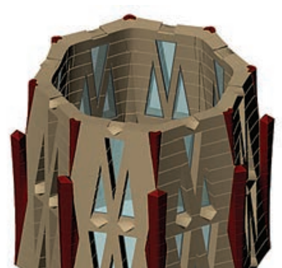
The builders, for example, develop their own model to see if they can make it: a one-to-one scale in wood to see if they can access the right places to do up the bolts.

I get frustrated by people — mostly of my generation — saying you must be able to sketch.

Drawing is an immensely valuable tool but the key thing is that you must be able to communicate, tell stories, and that doesn't mean there is only way of doing it. There are many ways and this project really shows that.

This article is based on a talk by Tristram Carfrae, deputy chairman of Arup, at The Building Centre and a discussion with BE editor-in-chief Lewis Blackwell. The full talk and extensive imagery can be seen at http://tiny.cc/g2yesy





Engineering drawing of the Mary Tower, top, and a component ring, right, which show how the tower is built from stone blocks post-tensioned with stainless steel rods and bolts. Above: Areas shown in brown took 120 years to build. The orange towers and other elements will all be completed between now and 2026.

Gaudi's catenary model, used to calculate force paths.

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