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Bauingenieur Article in Ger-

The Cross of the Basilica Sagrada Família in Barcelona

B. Sagmeister, M. Cortés, J. Weißenburger, T. Fildhuth, S. McKechnie

ABSTRACT The Basílica i Temple Expiatori de la Sagrada Família is one of the most important Catholic churches. Just in time for the 100th anniversary of the death of architect Antoni Gaudí, the Jesus-Christ-Tower was inaugurated on June 10th, 2026, under the authority of Pope Leo XIV. It is crowned by a cross (**Figure 1**) 16.9 m high and 13.5 m wide, with a total weight of 110 metric tons, making Barcelona the home of the world's tallest church tower with 172.5 m. The following article describes the concept, design and construction of the cross, which is made of duplex steel and an UHPC shell, which is covered by embedded ceramic tiles.

KEYWORDS

Sagrada Família, Duplex Steel, UHPC, Glass Pyramids

Das Turmkreuz der Basilika Sagrada Família in Barcelona

ZUSAMMENFASSUNG Die Basílica i Temple Expiatori de la Sagrada Família ist eine der bedeutendsten katholischen Kirchen. Zum 100-jährigen Todestages des Architekten Antoni Gaudí wurde am 10. Juni 2026 unter Leitung von Papst Leo XIV der Jesus-Christus-Turm eingeweiht. Er wird gekrönt von einem 16,9 m hohen und 13,5 m breiten, begehbaren Kreuz (**Bild 1**), sodass Barcelona nun den höchsten Kirchturm der Welt mit einer Höhe von 172,5 m besitzt. Das Gesamtgewicht des Kreuzes beträgt 110 Tonnen. Nachfolgend wird sowohl über das Konzept, die Architektur und das Tragwerk als auch über die Ausführung des Kreuzes aus Duplex-Stahl und einer außenseitig mit Keramik bekleideten UHPC-Schale berichtet.

1 Background of the Building Construction and Design

1.1 History of Architectural Designs

Antoni Gaudí (June 25, 1852 – June 10, 1926) was a world-famous architect of Catalan Modernisme during his lifetime. He worked for 43 years at the Sagrada Familia project (1883-1926), with the last ten years working exclusively at the Temple (**Figure 2**). He is responsible for the extraordinarily magnificent design of the exterior façade and the warm, lightfull, cozy interior. He died in 1926, so the 100th anniversary of his death was taken as an opportunity to complete the highest of the church's 18 towers, the Jesus Tower, which stands at 172.5 m. It is crowned with an accessible cross measuring 16.9 m in height and 13.5 m in width and depth. The inauguration ceremony for the Jesus Tower took place on June 10th, 2026, the centenary of Gaudí's death.

During the Spanish Civil War, most of the drawings and architectural models were destroyed. However, scale models and moulds of a Cross and in the shape of the Greek letter 'τ' have nevertheless been preserved. In Christianity, both symbols represent pain, salvation, God's blessing, and eternal life. In those models Gaudí used the helicoidal surface with the same 'double spin' geometrical operations that he developed for the columns of the nave to obtain the shape of the Cross. Besides these models, the architects used the descriptions of the Cross published in the albums of the Temple in Gaudí´s lifetime and all the written records by his collaborators, such as the following:

'The lightrod that will rise up to 170 m will be the cross, cardinal cross that will have four arms so the shape of the cross can be seen from everywhere; Cross made of white glaze glass



Fig. 1. Cross de la Sagrada Família on central Jesus Tower
Source: iStock, Eloi Omella
Bild 1. Kreuz der Sagrada Familia auf dem zentralen Jesus-Turm
Foto: iStock, Eloi Omella

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Fig. 2. Basílica i Temple Expiatori de la Sagrada Família
Source: iStock, Eloi Omella
Bild 2. Basílica i Temple Expiatori de la Sagrada Família
Foto: iStock, Eloi Omella

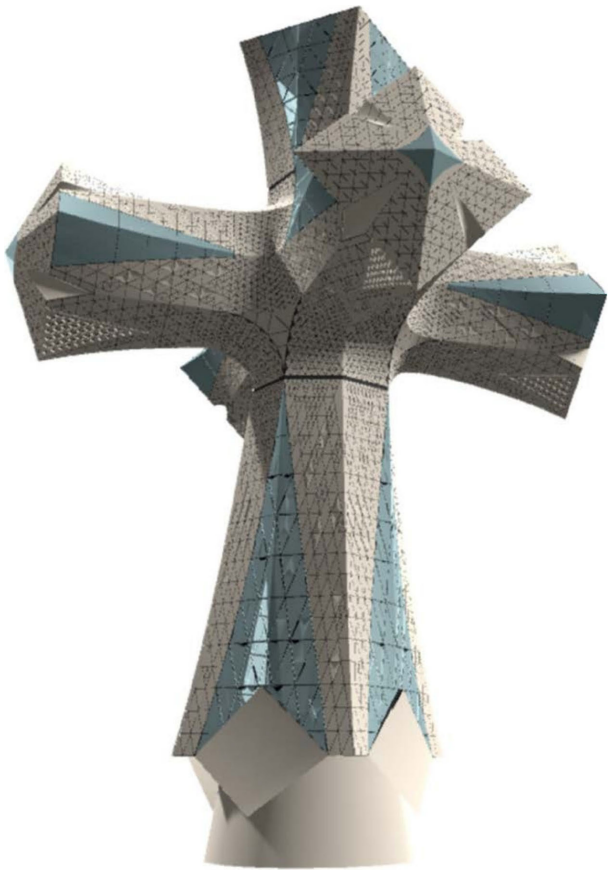


Fig. 3. Construction Overview of the Cross in the Tender Package
Source: Fundació Junta Constructora del Temple Expiatori de la Sagrada Família
Bild 3. Konstruktion des Kreuzes gemäß den Ausschreibungsunterlagen
Foto: Fundació Junta Constructora del Temple Expiatori de la Sagrada Família

(mosaic) in order to reflect the sun rays during the day; luminous cross by means of electricity to make the symbol of redeption shine at night.' J. Martí Matlleu (Secretary of the board and to Antoni Gaudí) in 'Vida Olotina', Olot 1915 [1]

The lack of detailed specifications requires the architects planning for the client, the Fundació Junta Constructora del Temple Expiatori de la Sagrada Família, to have a great deal of empathy for the architectural vision; they are constantly aware of the magnitude and responsibility of the challenge. On the other hand, the experts responsible for this exceptional building are free from constraints such as heritage protection and are able to proceed pragmatically, safely, appropriately, and in a goal-oriented manner. This applies in particular to the selection of building materials, where, in addition to functional suitability, the longevity of the materials is of paramount importance. Here, the benchmark is not 50 or 100 years, but rather that the lifetime in the maritime sea climate should be as long as technically possible.

1.2 Structural Concept of the Cross

The client collaborated with the engineering company Ove Arup & Partners Ltd. in London on the structural design and tender process. The decisive factor in this choice was the company's extensive experience with all kinds of materials, from concrete and steel to natural stone cladding and glass structures.

After careful consideration, a load bearing hybrid design was chosen, where steel and concrete transfer the load together. The main argument against an all-steel structure was the structural difficulty of achieving a watertight and durable ceramic wall cladding onto the steel structure. An all-concrete structure would have been too heavy not only for the supporting structure but also for the cranes and the assembly. Arup's engineers proposed a ribbed structure made of welded duplex-steel. This corrosion-resistant steel Type 1.4462, which has a two-phase microstructure consisting of austenitic and ferritic phases, offers high strength and good corrosion resistance at a cost-effective alloying cost, and is weldable. The ribbed structure was to be stiffened by a UHPFRC shell ('Ultra-High Performance Fiber Reinforced Concrete'), a fiber concrete without additional reinforcing bars, that bears considerable tensile stresses in cracked state [2]. The material is referred to below by the less specific but better known term UHPC for 'Ultra-High Performance Concrete' which is also used in the Austrian standard applied to this project. In Germany, the material is referred to as UHFB ('ultra-high-strength concrete'); in Switzerland, it is also called UHFB, but there the abbreviation stands for 'ultra-high-performance fiber-reinforced concrete.' The load between the steel ribs and the concrete shell was to be transferred by special head bolts, whose load-bearing capacity was determined by preliminary tests on small-scale test specimens.

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A product complying with French standards [3, 4] was specified as material. The UHPC not only serve as bracing, it also acts as a support layer for the ceramic cladding attached to the outside and transfers the wind and earthquake loads from the fields to the ribs (**Figure 3**).

The cross is accessible to small groups of visitors from the inside via a staircase. Thermal insulation and natural stone cladding were therefore installed on the inside of the structure. The interior also houses technical equipment for spotlights, which send their rays into the sky at night through the windows at the tips of the cross. The temporary use of the rooms by people required the Barcelona-based specialist company 'PGI engineering' to be involved in the design phase to determine how natural ventilation could be used to create a comfortable indoor climate for visitors. The lighting concept was created and visualized by 'LKL Design Hub', Barcelona. The sealing of the glass components to the steel and concrete components and the selection of suitable tile adhesives were also carefully considered during the design process.

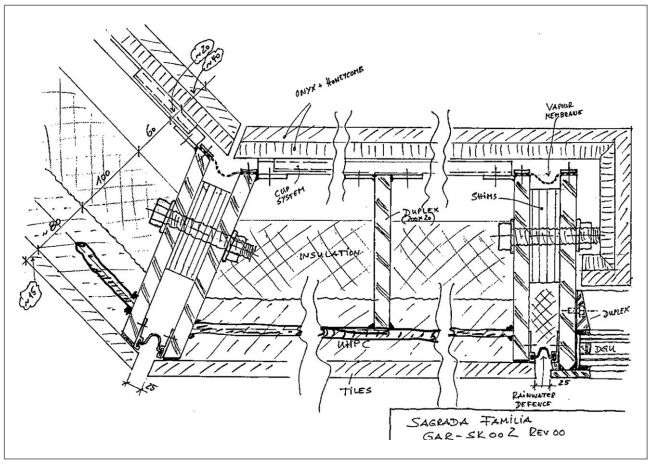


Fig. 4. Designsketch Regarding Detailing in Tender Phase
Source: Josef Gartner GmbH
Bild 4. Ausführungskizze zur Detailausbildung während der Ausschreibungsphase *Grafik: Josef Gartner GmbH*

1.3 Tender Phase

In spring 2020, Josef Gartner GmbH from Gundelfingen, Germany, received the tender documents (Fig. 3) and put together an interdisciplinary team to tackle the task. Gartner, a subsidiary of the Permasteelisa Group, is an internationally positioned facade manufacturer, meaning that design, analysis, component testing, stainless steel welding, glazing installation, and on-site assembly are among its core competencies. External support was called in for the UHPC work. Since the modules for the component were to be completely prefabricated in Germany, no French or Spanish company was chosen. Instead, a collaboration was agreed with the German consulting office durcrete GmbH for advice on material selection and dimensioning of the UHPC (Ultra-High-Performance Concrete). The German company Sudholt-Wasemann GmbH, a precast plant specializing in machine components made of UHPC, was chosen as the precast plant for the execution.

The project gained momentum, with the client and Arup holding the first video conferences with preliminary sketches (**Figure 4**). Then COVID-19 struck and the world came to a standstill. The term 'standstill' should be taken literally here to mean a construction freeze, as the confinement measures prevented any work from continuing. Added to this was a decline in revenue for the building, which will cost several hundred million Euros and is still not complete. A significant portion of the construction costs comes from the admission fees of nearly 5 million visitors per year. The completion date for the entire church was pushed back by years. Planning for the cross was also not resumed until autumn 2022. But as Gaudí replied when asked about the construction period, the same applies today: 'My client is in no hurry.'

2 Final Design of the Cross

2.1 Structural Analysis

The structural analysis and verification during the construction-/ execution design phase were carried out by knippershelbig GmbH, Stuttgart. The English editions of Eurocodes BS EN 1992-1-1 [5], BS EN 1993-1 [6] mit BS EN 1993-1-4 [10] und BS EN 1994-1-1 [7] as well as BS 8298 [8] for natural stone cladding served as the basis for the structural design. The Austrian guideline 'UHPC' of the ÖBV [9] combined with test results and BS EN 1992-1-1 [5] were used for the dimensioning of the UHPC. The structural design tasks included the structural analysis (global and detailed) of the composite structure of corrosion-resistant steel and UHPC, consideration of construction and assembly methodology, load transfer of the internal staircase, and consideration of the glass framing and its fastening.

Verification and dimensioning are based on a purpose-built, newly developed global FE-model of the complete cross (**Figure 5** left) and on highly detailed submodels of the Fust (legs), the central node (Nucleus, see Fig. 5 right), the four lateral cantilever arms and the top arm. Detail checks were performed both via the detail FE-models and analytical calculation sheets developed for the numerous details of the cross construction. Due to the asymmetrical loads, the calculation was performed on the entire system. For the global model, the corrosion-resistant steel frame structure was modeled using beam and shell elements; the UHPC shell was entirely simulated with shell elements (Type QUAD). The detailed submodels were entirely made with shell elements for precisely considering stability effects (e. g., local buckling of flat steel beams) and the load share between concrete envelope and corrosion-resistant steel grid. Particular complex details, such as the connection rings between the different parts of the cross, were analyzed using volume elements in FE-submodels. Rhinoceros 3D with Grasshopper was used as 3D modeling software, and Sofistik was applied as FEA package.

The verifications for the serviceability limit state (SLS) and the ultimate limit state (ULS) were performed in accordance with **Table 1**. Due to the high computational effort required for the very large and complex FE models, geometrically nonlinear analyses based on third-order theory were first performed on specifically selected load case combinations involving cracked concrete. These showed virtually no differences compared to geometric linear analyses, so that the geometrically linear theory could be used for the large number of analyses. The assumption

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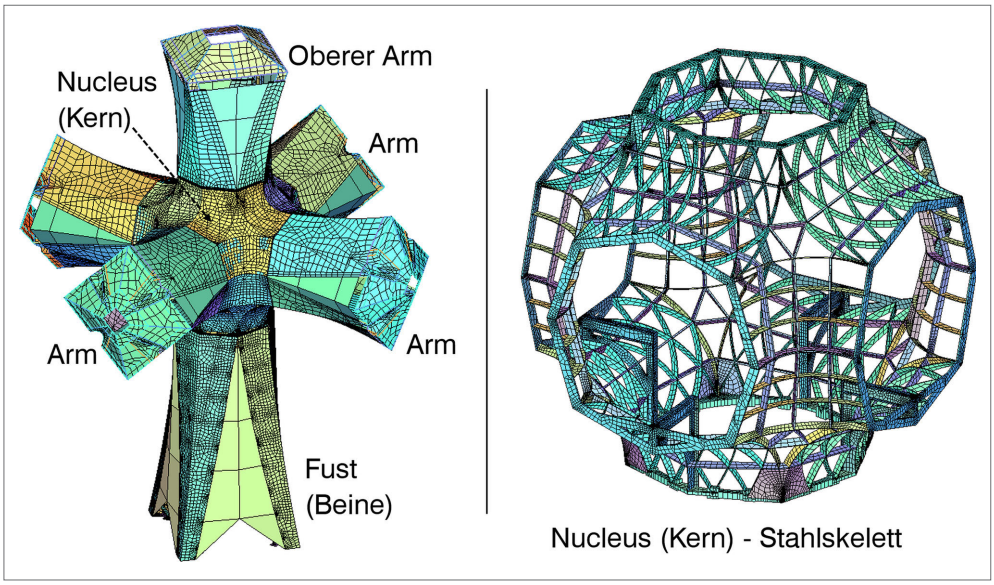


Fig. 5. Left: Global FE-Model, Right: Shell Elements of Steel Ribs of the Nucleus
Source: knippershelbig GmbH
Bild 5. Links: Globales FE-Modell, Rechts: Rippenstruktur des Nucleus modelliert mit Schalenelementen *Grafik: knippershelbig GmbH*

Table 1. Verification Concept
Tabelle 1. Nachweisschema

Type of Verification	FE-Type	Assumptions concrete model	Steel model (frame)
SLS	geometrically linear	cracked concrete no concrete tension	bi-linear material model
ULS	geometrically linear	cracked concrete no concrete tension	bi-linear material model
ULS Buckling Analysis	geometrically linear with imperfections applied	stiffness of concrete reduced to original value	stiffness under buckling analysis reduced to original value
ULS Seismic	geometrically non-linear with TH-II	cracked concrete no concrete tension	bi-linear material model
Fire	geometrically non-linear with TH-II	cracked concrete no concrete tension	reduced Young´s modulus

of cracked concrete without considering the tensile strength of UHPC is conservative.

For the Duplex steel, a bi-linear stress-strain material model was applied following some initial, careful comparison with non-linear Ramberg-Osgood approach to BS EN 1993-1-4 appendix C [10] (stress-strain curves with hardening); the steel was thus verified to remain within the quasi-elastic f_o-limits. Linear buckling verification was performed globally on the structure and local buckling checks were performed for its members. The stiffness of the concrete was reduced for buckling analysis and imperfections were derived from buckling eigenmodes. Flat steel elements prone to buckling were individually equipped with stiffeners, webs or flanges. During the analyses, additional diagonal bracing elements were added to the steel grid structure where necessary. Bolted connections of the main elements of the cross were simulated using springs.

The ground response spectrum for seismic loads for Barcelona due to Spanish code [11] was not applicable due to the position of the cross on top of the main tower of the cathedral. Thus, a specific response spectrum for the top of the tower was issued by ARUP to take the significantly higher acceleration at this location into account.

Spanish codes [12, 13] and BS EN 1990 [14] were the basis for SLS and ULS load combinations. Seismic load was often governing the design; wind loads, although quite high, played a role in only few cases. **Figure 6** shows an example distribution of horizontal wind loads with a maximum value of 3.74 kN/m².

During the tender phase, it was assumed that the horizontal wind and seismic loads would be of a similar magnitude. The final structural calculation, which determined the natural frequencies with reduced stiffness due to crack formation, showed that this assumption was too optimistic and that the seismic loads significantly exceed the wind loads in a number of cases. The first mode shape was torsional, while the second and third natural frequencies were lateral bending deformations of the cross structure, which is anchored at its base. The torsion and bending cases lead to very high shear stresses, particularly at the base support and the connection between the base Fust and the Nucleus. These could only be absorbed by additional measures such as double bar reinforcement in the UHPC and specific combinations of shear keys and bolting and required extensive verification.

The Barcelona-based engineering company 'ARcBCN Consulting Engineers' performed a simulation of the building using the actual fire loads and determined a maximum

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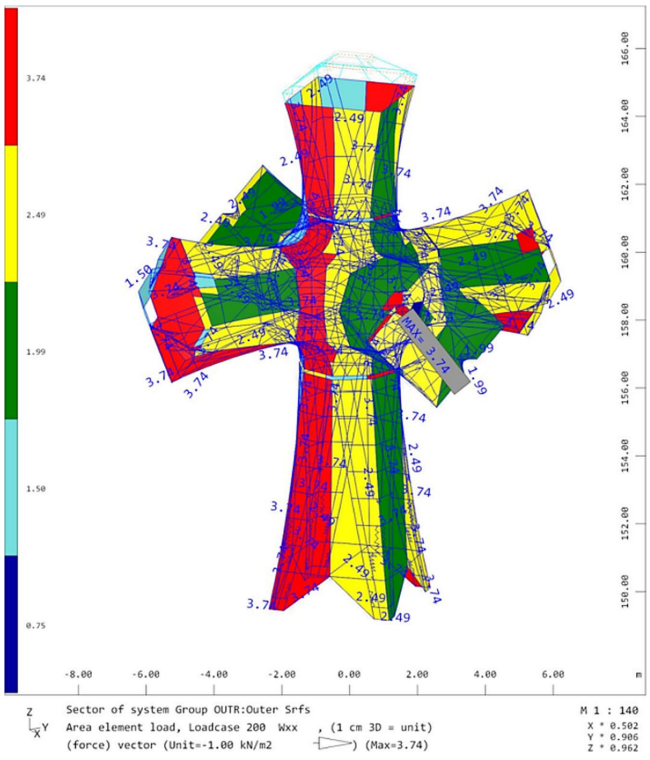


Fig. 6. Load Assumptions Regarding Wind Loads in Structural Analysis
Source: knippershelbig GmbH
Bild 6. Annahme zur Windlastverteilung in der Tragwerksberechnung
Grafik: knippershelbig GmbH

temperature of 332 °C. In the 'fire' load case verification, material parameters such as tensile strength that are valid for this temperature were then adjusted using the reduction factors from BS EN 1993-1-2 C [15] and verified accordingly.

2.2 Steel Construction and UHPC Composite Shell

The load bearing structure of the cross consists of a stainless steel grid welded from flat steel elements. Stiffeners and angles are used wherever necessary to prevent local buckling. Duplex stainless steel 1.4462 (EN 10088 / BS EN 1993-1-4 [10]) was used exclusively for the grid. Stainless steel thickness ranges from 6 mm to 12 mm, typically, with particular elements having higher thickness of up to 20 mm. The reinforcement bars B500A NR welded in-between the flat steel grid elements are from stainless steel Grade 1.4362 acc. to Approval by the German Institute for Building Technology (DIBt) Z-1.4-228 [22] and have nominal diameter of 8 mm. The basic axial orthogonal grid of rebars is 100 x 100 mm, ranging down to 70 x 70 mm for particularly loaded zones. In case of double reinforcement necessary for high shear and axial tension, the mesh openings are reduced to 65 x 65 mm, which is the minimum necessary for the UHPC to pass, determined by experiments. The rebar mesh orientation is typically 90 ° with respect to the surrounding steel frame. This angle is modified to 45 ° in case of high shear loads. Via reinforcement, the outmost part of the stainless flat steel grid is embedded in the UHPC. In the analyses, no cohesion between the embedded part of the steel grid and the UHPC is assumed; however, interface friction between concrete and steel is applied. The concrete shell is 55 mm thick and is covered with tiles on the exterior face. The embedment of the flat steel ribs is 40 mm.

Figure 7 shows the fabrications process of the flat steel grid of the Fust legs and the test assembly in the Gartner premises. The left part of Fig. 7 illustrates the 3D-model used for the development, where the blueish curved plates are the connection elements between the legs themselves and the top ring. Note the back plating in the right part of Fig. 7 used as a counterformwork for the concrete and double rebar bundles at the highly loaded inferior part of the legs (center of Fig. 7).

2.3 UHPC

The original design was based on a highly fiber-reinforced UHPC, in which the integrated steel fibers transmit tensile stresses of $f_{ck} \geq 8$ MPa after a concrete crack. The connection to the steel structure was to be made using specially welded stud bolts. The required microfiber content of up to 275 kg/m³ expected with this solution requires concrete mixes that are quite

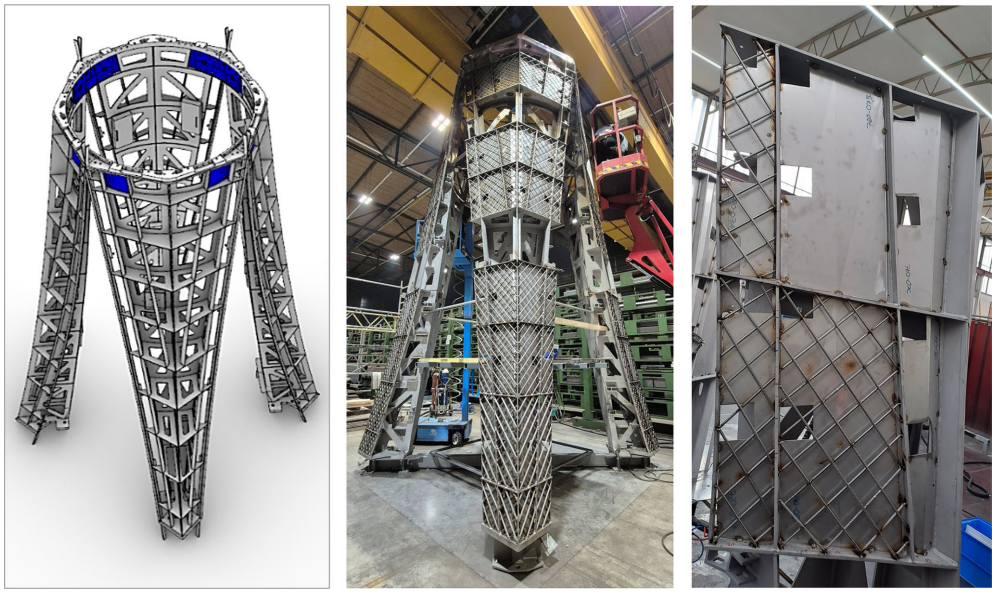


Fig. 7. Left: Stainless Steel Grid 3D model; Center: Steel Structure of the Fust; Right: Reinforcement and Counterformwork on the Back
Source: knippershelbig GmbH/Josef Gartner GmbH
Bild 7. Links: 3D-Modell der Stahlkonstruktion; Mitte: Stahlstruktur des Fußes; Rechts: Bewehrungsnetz und rückseitige Gegenschalung *Grafik: knippershelbig GmbH/ Josef Gartner GmbH*

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Table 2. UHPC-Formulation
Tabelle 2. UHPC-Rezeptur

Nanodur Compound 5941, grey, from Dyckerhoff, Germany	1 050 kg/m³
Quarz aggregates, round, diameter 1 to 3 mm	880 kg/m³
Ordinary pit sand, diameter 0 to 2 mm	430 kg/m³
PCE superplasticizer	16 kg/m³
Shrinkage Retarder	6 kg/m³
Stainless-steel fibers l = 16 mm, Ø 0,2 mm Supplier: Krampe Harex, Germany	80 kg/m³

Table 3. Material Characteristics of UHPC
Tabelle 3. Materialeigenschaften des verwendeten UHPC

Compression strength at 100 mm cube $f_{c,\,cube}$	131,9 MPa
Young´s Modulus E_c	46 100 MPa
Tensile stress at first crack LOP, determined at plates 55 mm, Bending Test $f_{cf,fl}$	18,4 MPa
Max. tensile stress in cracked state MOR, Bending Test on plates 55mm $f'_{cf,fl}$	12,1 MPa
Adhesive tensile strength of embedded tiles with dovetailed backs	2,5 MPa
Adhesive tensile strength of glued tiles with smooth back	3,1 MPa

viscous; even if all the possibilities offered by concrete technology – such as adjusting particle size distribution, optimizing the superplasticizer, cooling the mixture, using vacuum mixers, and so on – are fully exploited. In addition, the fibers must also be in the right place and in the right direction to be fully effective. However, the fiber orientation factor k, which takes this circumstance into account, is not a material property, but a production property that depends, for example, on the pouring location, flow distance, and embedded parts. At the time the tender design was finalized, it was not yet clear which production process, formwork, and field size could be used to produce the elements. None of the parties involved would have thought it possible at the time that, in the end, two-sided, largely vertical formwork with a 55 mm wide pouring opening, field sizes of approximately 4 m², and mixing batches of 50 kg would be used. During construction design, it became clear that the original approach of using fiber reinforcement alone was, in fact, not feasible, as the additional reinforcement mesh described above (Fig. 7) became structurally necessary. The limited spacing between the Ø 8 mm stainless steel rebars then enforced a UHPC formula with increased flow properties in order to fill each gap. Extensive optimization tests, such as the pouring test shown in **Figure 8**, were carried out at the prefab plant in order to adapt the initial mix developed by the German binder supplier Dyckerhoff GmbH and to determine the required fiber content by balancing structural requirements, manufacturing feasibility, and economic viability. The rebars in the concrete act both as in-plane tension reinforcement and for in-plane and out-of-plane shear transfer between the concrete and the flat steel ribs. No shear dowels were needed this way.

Both the rebars and the stainless-steel microfibers in the mixture served to increase ductility and reduce the crack width in the SLS, mainly to protect the ceramic tiles against cracking. The verification of the crack width according to the Austrian ÖBV guideline [9] resulted in a maximum calculated value of 0,03 mm for an allowable limit of 0,05 mm. For transient loads, such as wind, minor, extremely thin cracks are accepted in the Nucleus zone. For seismic loads, no cracking limitation is assumed. Cracking, if it should ever happen, is generally expected and accepted at the points where the embedded flat steel ribs (40 mm) reduce the concrete thickness (55 mm) to a cover of only 15 mm. This areas complies with the ceramic tile joints.

The ingredients and formulation of the UHPC can be seen in **Table 2**.

Information on the raw materials used, shrinkage behavior, and characteristic parameters of the long-proven formula can be found in [16]. **Table 3** shows a selection of the project-specific material properties determined by imabs, the Institute for Materials Testing & Building Materials Research GmbH at Munich University of Applied Sciences.

The flexural tensile tests were conducted as four-point flexural tensile tests in accordance with the specifications of the ÖBV guideline [9]. The centric tensile strength can be calculated from the test results and, depending on the evaluation method or standard, ranges between 30 % and 45 % of the values determined above.

The bond strength of the tiles was tested after various prestorage conditions, including in a climate chamber at 70 °C, prestorage underwater, and after 25 freeze-thaw cycles. The lower value for the tiles embedded in concrete with dovetail joints, compared to the tiles bonded over their entire surface, can be explained by the fact that no load transfer occurs across the entire surface in this case. Fractures frequently occur within the tile, at the junction between the dovetail and the tile slab.

Figure 9 shows tests conducted on test specimens developed by Arup to determine the bond strength between UHPC and the steel structure using welded reinforcement mesh. In these tests, forces and deformations were not only measured using sensors. In addition, the crack patterns and crack widths were recorded and evaluated on both the UHPC and the tiles embedded in concrete or bonded to the surface using optical methods (Digital Image Correlation, DIC). After the maximum load was reached, the tensile bond strengths of the tiles were tested to rule out any detachment from the substrate.

2.4 Steel Construction Fust

As an example for the steel construction, parts of the Fust structure are explained below. The 'Fust' (stem) part of the cross is assembled from four prefabricated legs, each 7.2 m tall. During production, the steel structure form pre-cut elements was welded and pre-assembled in shop to adjust tolerance (Fig. 7). Next, after disassembly and transport to the prefab company, the UHPC was poured and the tiles were applied. The prefabricated elements are assembled and power-tight connected by bolting to an octagonal ring with 3 m diameter (**Figure 10**) at the top of the fust. Due to the complexity of the loads acting on the ring and its shape, design verification was made using a volume element submodel in Sofistik (Fig. 10, right).

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Fig. 8. Pouring Test in Closed Formwork with PMMA Backside to Demonstrate Sufficient Flowability *Source: durcrete GmbH*
Bild 8. Gießversuch in bewehrter, geschlossener, geneigter Schalungsbox mit Plexiglasscheibe, um die ausreichende Fließfähigkeit zu überprüfen
Foto: durcrete GmbH

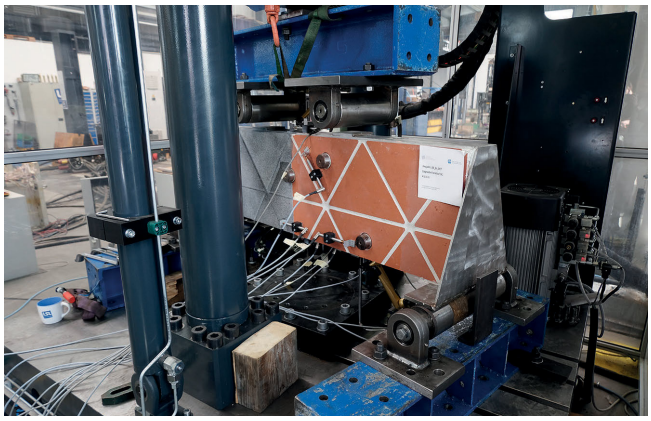


Fig. 9. Tests on Bond Strength and Tile Behavior *Source: imabs GmbH*
Bild 9. Versuche zur Verbundfestigkeit und Fliesenverhalten
Foto: imabs GmbH

Wherever possible, bolting was made using bolt-nut connections according to code. However, many of the connections between the main prefabricated components of the cross were not accessible for placing nuts and thus threaded blind hole connections were necessary both for shear and axial tension connections. Most of the tension bolts A2-70 and A4-70 for these connections were partially prestressed to increase the serviceability level quality (Zielebene II according to DASt guideline 024 [17]). For these connections, procedure tests ('Verfahrensprüfungen') were performed by the German company 'Stranghöner Ingenieure GmbH'. The relevant bolts were verified without prestress as category D tension connections.

The bolting connections between the main components of the cross necessitated sufficient tolerance to allow onsite assembly on the tower. Therefore, bolt holes were typically slotted or oversized. Wherever feasible, load transfer was made using axial-force only and shear-only bolts or shear keys. Shear connections necessitated careful filing of the oversized holes after installation to allow for shear-bearing load transfer. Additional complexity at the connections rings between the cross components came from the fact that not only bolts but also electrical cables and ducts needed to pass through individual holes in the steel connection rings.

2.5 Ceramic Tiles

Cerámica Cumella Sl, a long-established Catalan company, was commissioned to produce the largely handmade ceramic cladding. The project incorporated over 13,000 tiles in seven different shades of white. Of these, more than 1,800 were handcrafted, custom-molded unique pieces produced from 94 distinct molds. The remaining tiles comprised over 3,100 large triangles – each with an edge length exceeding 300 mm and across 52 die-cut variants – as well as more than 8,000 small triangles with edge lengths up to 150 mm, available in 18 die-cut variants.

In order to create a construction that was as durable and long-lasting as possible, it was an important design requirement that both the UHPC substrate and the tiles remain crack-free under permanent loads. Small cracks were only permitted in very limited areas under wind loads. The simplest way to achieve this would be to elastically decouple the tiles from the UHPC base

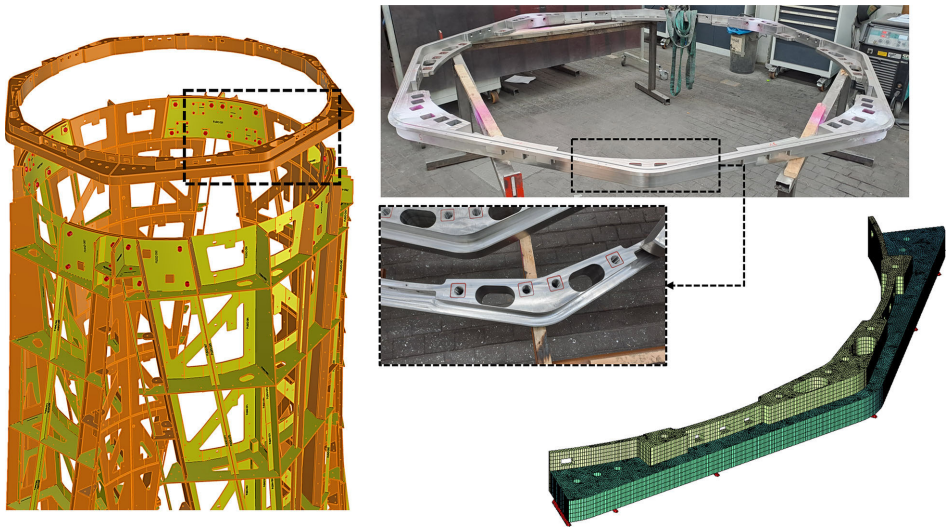


Fig. 10. Left: Top Steelwork of the Fust with Connection Ring; Right: Octagonal Connection Ring and Respective FE-Model of the Ring
Source: knippershelbig GmbH/Josef Gartner GmbH
Bild 10. Links: Modell der Oberseite des Fust mit Verbindungsring; Rechts: Oktogonaler Verbindungsring und das dazugehörige Volumenmodell
Grafik: knippershelbig GmbH/Josef Gartner GmbH

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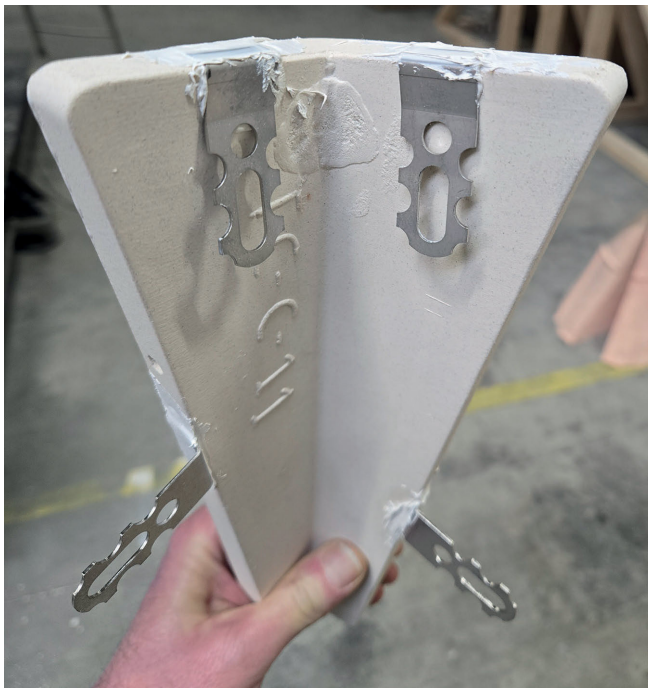


Fig. 11. Steel Clamps for Embedding Tiles with Smooth Backside
Source: durcrete GmbH
Bild 11. Stahlklammern für Fliesen mit glatter Rückseite
Foto: durcrete GmbH



Fig. 12. PMU Softbody-Test from Inside Position
Source: Josef Gartner GmbH
Bild 12. Test zu weichem Aufprall der Glaskonstruktion von Innen
Foto: Josef Gartner GmbH

layer. However, the elastic tile adhesives required for this are inevitably plastic-modified and therefore have a limited-service life. For this reason, the following three design variants were specified.

- As many tiles as possible were manufactured with dovetail-shaped recesses on the back. They were inserted into the formwork and embedded in the UHPC to create a permanent, solid bond. For this majority of tiles, it was necessary to minimize and limit the cracks in the UHPC.
- Handcrafted special formats were only available with a smooth back for manufacturing reasons. Here, 1 mm thick stainless steel retaining clips were inserted into slots milled into the side of the tile and set in concrete in the UHPC (**Figure 11**). A layer of foil was applied to the back of the stoneware to allow the tiles to deform freely as a result of shrinkage and creep of the UHPC, as well as external temperature influences. To verify durability and longevity, Gartner conducted relevant tests.
- To repair damaged or missing tiles, a two-component polyurethane-based synthetic tile adhesive from Mapei [18] was selected following extensive material testing.

The rigid bond between dovetailed tiles and concrete is initially subjected to significant stress due to the shrinkage of the early-stage concrete, but also later on in the building due to differences in temperature between the tiles and the base material. The following two measures were taken to minimize this stress.

Firstly, in accordance with the German standard DIN 18515-1 for 'Tiles fixed with mortar' [19], the maximum area of the tile was limited to 0.12 m² and the maximum side length to 0.49 m. Furthermore, the joints of the inserted tiles were filled with foam material in the formwork. Only after the concrete had shrunk significantly were the tile joints filled with mineralic, stiff grout.

2.6 Glazing and Interior Design

The special glass used in this project is a rarity, as is the curved configuration of the glass and carrier frames. Consequently, the glass frames for a lateral arm were subjected to 'proof-of-concept' testing prior to the commencement of the main contract. These evaluations were conducted in spring 2024 as a PMU (Performance Mock-Up) on the Gartner premises, preceding the VMU (Visual Mock-Up). The testing regime included air/water penetration tests as well as impact (hard- and soft body) tests (**Figure 12**). Similar procedures were carried out for the tips of the lateral arms, which were specifically engineered to facilitate ventilation within the arm structure. The safety glass used consists of 2 x 6 mm double curved float glass plus a third layer of glass pyramids, textured and transparent glass forming a collage. The inner layer consists of solar control glass, and the lamination material combines PVB and SG interlayers.

In order to adhere to Gaudí's architectural vision, the following specification was implemented in accordance with the Sagrada Família archives: 'As indicated by the Temple Albums, Gaudí wanted the cross to shine by day and illuminate by night. For this reason, white glazed ceramic and glass have been used; two materials that are radiant and, at the same time, withstand atmospheric exposure.' [1]

As a result of extensive research and development, a third layer of glass with pyramid-shaped collages was added to the

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Fig. 13. Pyramid-shaped Elevations on the Ceramic Tiles and on the Curved Glass Panes of the Fust (left) and Arm (right)
Source: Josef Gartner GmbH
Bild 13. Pyramidenförmige Erhöhungen auf den Fliesen und Glasscheiben am Fust (links) und am Arm (rechts).
Foto: Josef Gartner GmbH

laminated safety glass for this purpose. **Figure 13** shows this on the foot (left) and the arm (right) on the assembly platform at a height of 54 meters. The techniques involved in the creation of this collage include fussing, casting and milling of glass pyramids. The pyramids on the side glazing are milled, while the pyramids on the base and cross-top glazing are made of cast glass (Fig. 13, right), which has been partially polished to achieve a transparent look. All glass types are 3D-curved to follow the complex geometry of the cross. The Barcelona-based specialist company Cricursa produced all the exterior glazing for the project.

White Onyx and Alabaster are the stones selected for the interior wall cladding, while flooring areas feature panels with a black slate surface (**Figure 14**). The geometry of the 40 mm thick stonework is aligned with the stainless steel ribs of the individual structural components. The complex tridimensional mounting system for the stone panels consists of six-axis adjustable brackets designed by Gartner. The stone processing was carried out by local stone masons in Catalonia, Spain, utilizing specialized components provided by Gartner.

3 Production and Installation

3.1 Mock-Up

In the summer of 2024, a mock-up of the cross was produced to test whether the planned manufacturing methods would work. This sample component of half of the arm (longitudinal section) including the interior finish was presented to the public in Barcelona in the fall of 2024 on the forecourt of the Basilica.

It quickly became apparent that tolerances in the three-dimensional and double-curved shell construction would be the dominant issue in production. Due to heat distortion during welding, the tolerance of the steel construction is considerable, even when using experienced skilled workers. The installation of the reinforcement mesh and the inner sheets for the counter-formwork, which was necessary at certain areas, was technically demanding. The ceramic tiles itself shorten and warp differently depending on their position in the kiln and are also delivered with different tolerances, even for a uniform type. Due to the custom design for this project, uniform calibration by pre-sorting the tiles was not possible. In contrast, the formwork surface milled out of foam using CNC formwork robot is as precise as the drawing, but for this very reason it does not fit the steel base frame and the single tiles. In intensive discussions, adjustments and tolerances were discussed and permissible compensatory measures such as widening the joint widths of the tiles were determined.

3.2 Realisation of Steel Works

Material Properties and Welding Requirements for Duplex steel, a magnetic non corroding steel, presents specific challenges regarding processing. Although all welders certified for rust-resistant steel welding are technically qualified for duplex steel, the processing remains more complex compared to other stainless steel grades. Consequently, the welding team was specifically selected based on test specimens welded with duplex steel before the serial production for the project started. Additional welding inspections and work samples were required for the welding of the reinforcement bars NiCr 1.4362. Early in the project, the characteristic curves of the welding machines were successfully optimized for duplex steel. Furthermore, a specific welding wire from a particular manufacturer was identified as being exceptionally well-suited for the project.

The specified execution class is EXC2 in conjunction with WIC2 according to EN 1090-2:2018 'Execution of steel structures and aluminum structures' [20]. Mastering the geometrical tolerances of the steel structure, assembled by welding precut flat steel plates partially via full-penetration welds, was highly complex due to the warping and deformation of the material from the welding process. Through intensive effort and labor, the side-arm components (with a length of 3,700 mm) were manufactured within a tolerance range of 9-11 mm. The weld seams underwent Dye Penetrant Testing (PT), Visual Testing (VT), and Ultrasonic Testing (UT).

Cleaning the steel structure prior to casting of UHPC proved to be a complex undertaking. Due to the high-density reinforcement and rib structure, weld spatters had to be removed manually beforehand. Over 44,000 welded connections between the reinforcing steel and the duplex ribs required cleaning. Subsequently, the entire steel structures up to 5,000 mm in width, (**Figure 15**) were glass-bead blasted to remove annealing colors and ensure long-term corrosion resistance. Nonstructural elements like window frames are made of stainless steel 316 (V4A).

The bolting connections between the main components of the cross necessitated sufficient tolerance to allow onsite-assembly on

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Fig. 14. View into the Inside of the Cross *Source: Josef Gartner GmbH*
Bild 14. Ansicht des Kreuzes von Innen *Foto: Josef Gartner GmbH*



Fig. 15. Steel Works of a Horizontal Arm made of Duplex-Steel and Stainless Steel Reinforcement incl. Rotating Transport Frame
Source: Josef Gartner GmbH
Bild 15. Stahlbau eines horizontalen Armes mit Duplex Stahl und Chromstahlbewehrungsnetz inklusive des drehbaren Transportgestells
Foto: Josef Gartner GmbH

the tower. Therefore, bolt holes were typically slotted or oversized (Fig. 10). Wherever feasible, load transfer was made using axial-force-only and shear-only bolts or shear keys as, e.g., at the connection plates of the Fust legs shown in **Figure 16**. Shear connections necessitated careful filing of the oversized holes after installation to allow for shear-bearing load transfer.

3.3 UHPC

Based on the experience gained from the mock-up, it was decided that the formwork skin (**Figure 17**) laid on the wooden structure should be as large as possible. The tiles were inserted into the pre-milled recesses in the foam structure, with the protruding foam bridges serving as placeholders for the subsequent joints. Since there are several hundred types of tiles that differ in geometry or color, it was important that the factory numbering on the back of the tiles was correct and that warehouse management was well organized. The steel structure with the integrated reinforcement mesh was then lifted onto the formwork and the correct spacing was set. The concrete was then poured directly onto the flat areas to the finally specified thickness of 55 mm. For the steeper concreting sections, sheet metal is arranged on the rear side as counterformwork. Here, the concrete was filled in step by step through smaller openings (Fig. 7, right), whereby both the correct ventilation and the complete filling were checked. After completion of all concrete, which took about 3 weeks for one component, the components were lifted off, the remaining tiles were glued in the corner areas, and the tiles were grouted. The components were then transported by heavy-duty truck to the building site in Barcelona, where the assembly and the remaining finishing of the submodules were carried out.

3.4 Transport and Erection

Weight reduction was a key issue, first in order to meet the assumptions of the structural analysis and second to ensure that approved transport weights and crane capacity were not exceeded.

The main components consist of 3D-shell structures. As these cannot be supported on their exterior surfaces due to the fragile ceramic tiling and glass-structures, custom-engineered support structures had to be developed and built for all components of the cross. The lateral arms represented one of the most significant challenges in this regard, as they are entirely cladded in either glass or tiles. To address this, a radial bracing system ‚wagon-wheel' suspension system with the weight of over 3,600 kg was engineered (Fig. 15). A central shaft was inserted along the longitudinal axis of the lateral arm and braced against the internal steel ribs using tension- and compression-members. This design allowed the lateral arms, with maximum transport dimensions of 3,500 x 3,500 x 7,500 mm to be shipped via low-

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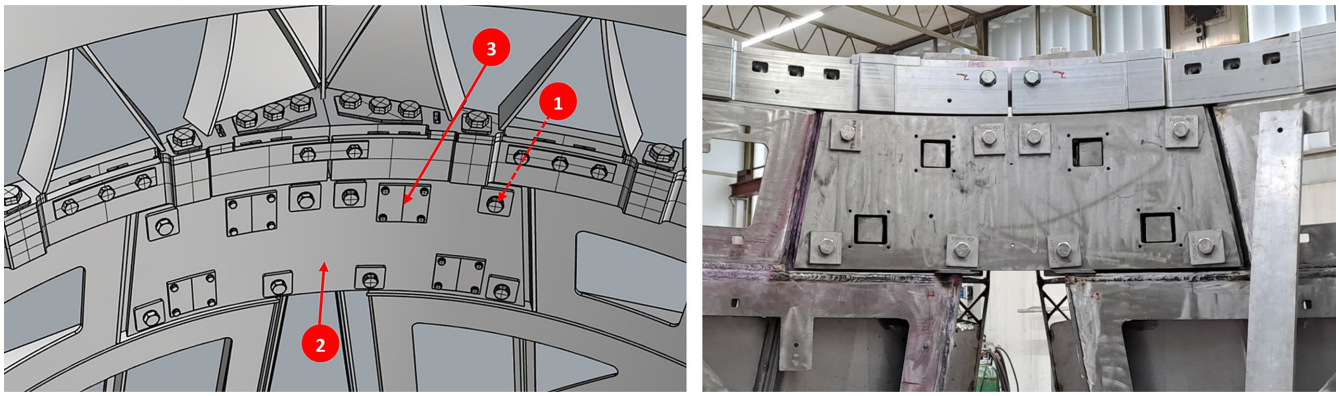


Fig. 16. Curved Connection Plate (2) of the Legs of the Fust with Tension Bolts (1) and Shear Keys (3) *Source: knippershelbig GmbH/Josef Gartner GmbH*
Bild 16. Gekrümmte Verbindungsplatte (2) and den Säulen des Fusts mit Zugbolzen (1) und Schubknaggen (3)
Foto: knippershelbig GmbH/Josef Gartner GmbH

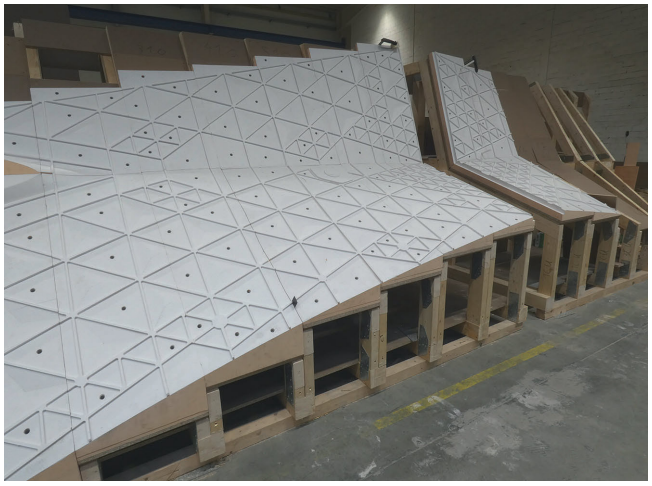


Fig. 17. Formwork Skin on a Wooden Scaffolding, Prepared for the Positioning of Tiles. *Source: durcrete GmbH*
Bild 17. Schalhaut auf hölzerner Rüstung, vorbereitet für das Einlegen der Fliesen. *Foto: durcrete*



Fig. 18. Nucleus arriving at 07:00 a.m. at the Sagrada de Família (Carrer de Mallorca) *Source: Josef Gartner GmbH*
Bild 18. Ankunft des Nukleus um 7:00 Uhr morgens vor der Sagrada Família (Carrer de Mallorca) *Foto: Josef Gartner GmbH*

loader without compromising the integrity of the fragile exterior surfaces. Furthermore, the transport frame had to ensure that the arm could be rotated 360 degrees along its longitudinal axis to facilitate the installation of the UHPC components. Additionally, the transport orientation of the arm was rotated 45 degrees relative to its final installation position; this adjustment was necessary to remain within the required maximum transport dimensions.

To improve dimensional tolerances and structural implementation, the Nucleus was manufactured and subsequently transported with only two separate half-shells (**Figure 18**). Given these specifications, the Nucleus – including its transport frame – reached a total width of up to 5,200 mm. This necessitated meticulous and proactive logistical planning. Permits had to be secured up to three months in advance for fixed time-slots and were ultimately only granted for three-lane motorways and transport activities between 10:00 p.m. and 6:00 a.m. Consequently, following the completion of the UHPC works, transport restrictions in France forced the Nucleus to be shipped via Belgium and by ferry to the northern coast of Spain. From there, it completed the final journey to Barcelona, Catalonia, by road. The transport routes were selected in close cooperation with the freight forwarders, a process that also gave rise to the concept of transporting the Nucleus by sea to avoid France. In total, this specific transit took 18 days, making the six-day transit time via truck for the lateral and top arms appear marginal by comparison.

It should be noted that no interim storage facility was designated in Barcelona, due to the bustling downtown location of the church. Consequently, arrival times had to be planned with absolute precision and were strictly prohibited from falling on weekends. To accommodate potential waiting times prior to entering the city under police escort to the Basilica, a monitored parking area outside the city limits was utilized. Upon arrival, the lateral arm components were unloaded from the trailers via mobile crane and positioned within the reach of the tower crane, as the trucks were unable to access the crane's pickup zone. However, this procedure had to be further adapted for the Nucleus, as these components were far too wide for the construction site gate; they were subsequently hoisted by the mobile crane directly over the perimeter fence to the tower crane's pickup point and further to the assembly level in a high of 54 m (**Figure 19**).

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Fig. 19. Installation of the Lower Nucelus Element to the Fust
Source: Fundació Junta Constructora del Temple Expiatori de la Sagrada Família
Bild 19. Montage des Nukleus-Unterteils an die Fußkonstruktion
Foto: Fundació Junta Constructora del Temple Expiatori de la Sagrada Família

The large tower crane will remain part of Barcelona's skyline for a while longer. It will be partially disassembled, but will still be needed to take down the scaffolding on the Jesus Tower and to construct the Glory façade.

4 Acknowledgements

El Consejo General de la Arquitectura Técnica de España (CGATE) rightly awarded the client the Spanish National Construction Award 2025 for its work on the basilica. This award recognizes projects that make a significant contribution to quality, sustainability, and social sustainability. More pictures of the rection and description of the building see the brochure [21]. The companies involved in this project would like to thank the foundation for its goal-oriented cooperation and stimulating discussions at a high professional level, which never focused on formalities but always on creating the best possible building for humanity. The authors would like to thank all those involved in the project for their support in the form of images, data, discussions, and information for this publication.

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