A UHPFRC CLADDING CHALLENGE: THE FONDATION LOUIS VUITTON POUR LA CRÉATION “ICEBERG”

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Abstract

This paper presents a case study of the “Iceberg”, an opaque envelope for the future “Fondation Louis Vuitton pour la Création”. Located in the Jardin d’Acclimatation (Garden of Acclimation) in Paris, France, it is designed by Frank Gehry and Ghery partners. The project is characterized by the high geometric complexity that is so familiar to his architecture. The cladding is created from 19,000 unique, prefabricated panels cast in white Ductal® Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) by Lafarge; each one moulded individually and installed using a butt joint. The following topics are discussed, based on the research and development program, as presented by the design team and contractor:

- vacuum moulding technology;
- UHPFRC characterization and specific design values for the project;
- reinforcement of panels to withstand maintenance loads;
- industrial development for the production of 19,000 non-repetitive panels; and
- a small joint/earthquake resistant/tight tolerance point fixing system.

Résumé

Ce papier présente une étude de cas sur le développement de l’”Iceberg”, l’enveloppe opaque du Project de la Fondation Louis Vuitton pour la création conçu par Frank Gehry et Gehry Partners en cour de réalisation dans le jardin d’acclimations à Paris. Le projet se caractérise par la grande complexité géométrique propre à l’architecture de Frank Gehry. La vêture est composée de panneaux préfabriqués en Ductal® blanc par Lafarge, non répétitif, moulé individuellement et installé bord à bord. L’article détaille les points clefs des études et du programme de développement présentés par les acteurs impliqués. Les points clefs sont les suivants :

- Technologie de moulage sous vide (MSV)
- Caractérisation du matériau et valeur spécifiques de calcul pour le projet
- Renforcement des panneaux pour prendre en compte les charges de maintenance
- Développement industriel pour la production de 19000 panneaux courbes non répétitifs.
- Joints bords à bords, haut niveau de tolérances et fixations ponctuelles.

Figure 1: Rendering - The Fondation Louis Vuitton pour la Création (Image: FLV)

1. INTRODUCTION

The architectural style of Frank Gehry is well-known for its sculptural dimensions and fragmented forms. This geometrical complexity has many implications as it questions the entire construction process, from initial design through to erection. Every step must be rethought; a process that depends heavily upon digital means such as extensive 3D modeling, parametric design, scripts for analysis and form generation. It also questions the materials used for construction – not only how to shape and design them, but also how to deal with the absence of repetitivity. The "Fondation Louis Vuitton pour la Création" falls into this realm. Its 9,000 m2 opaque envelope is, split into 18 entities that are situated in between or next to 43 glazed envelopes. The project is approximately 150 meter long by 50 meter wide and 45 m high. The entire project is surrounded like a cocoon by 12 large glass "sails" which act as umbrellas for the outdoor spaces.

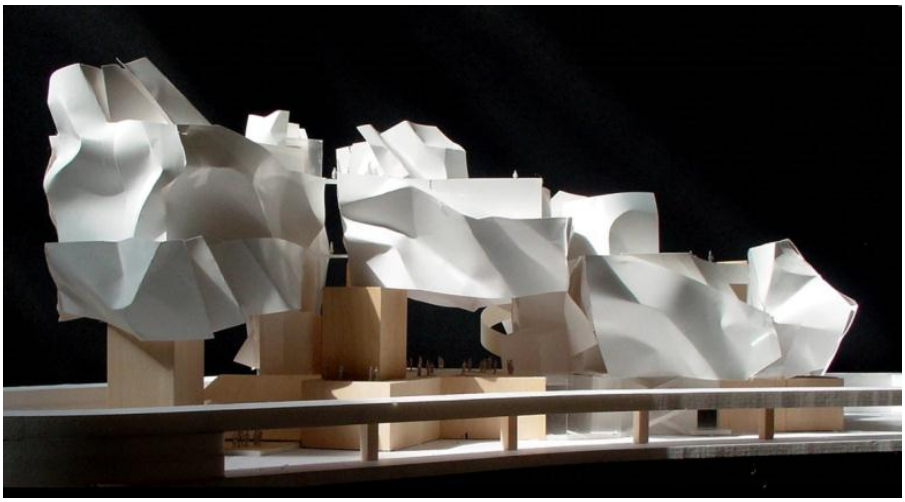

Figure 2: Original Iceberg model view (Image: Gehry Partners)

Right from the start, the architects wanted to steer away from the metal shingle cladding they had experimented with. The design intent is to utilize a white, cementitious material which would constitute the surface called "Iceberg". This surface was to be smooth and continuous, without overlap. The challenge was to find a material to act as a cladding for the main opaque envelope. After a long research period and consideration of 6 different materials, the decision was made to construct the cladding with prefabricated Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) panels. The following paper presents a project case study by focusing on the main points of technological development, as carried out by the design team and the contractors.

Figure 3: (*left*) Stainless steel cladding, Disney Concert Hall, Los Angeles, USA.
(*right*) UHPFRC cladding, the "Iceberg" at Fondation Louis Vuitton pour la Création, Paris, France (both designed by Gehry Partners).

2. MATERIAL CHARACTERIZATION

The material used, "Ductal® FO B3", is based on the UHPFRC technology. This family of materials differs from High Performance Concrete (HPC) and Very High Performance Concrete (VHPC), having fibres, a high binder content and very low water/cement ratio (< 0.26) that provide differentiating ductility and durability properties.

A material characterization has been performed in order to provide characteristic values for design use with a Technical Evaluation from CSTB (Centre scientifique et technique du bâtiment). The characteristic value in compression is between 115 MPa and 135 MPa, depending on fibre content. Even if we stay at material level, two characterizations must be differentiated, corresponding to two different uses: reinforced and unreinforced.

For a non-reinforced structure, like thin plates, CSTB has defined a rule based on fragile material behaviour. Since a post-cracking plastic hinge gives a reduced brittleness failure, a safety coefficient with a value of 3 is applied on the Limit of Proportionality (LOP) of 15mm plates. This necessary condition is not sufficient. The design value obtained should be superior to the Modulus of Rupture (MOR) divided by 1.3 (material coefficient in precast) x 1.5 (load coefficient in case of light elements).

$$\sigma_d = \frac{LOP}{3} \ with \ \frac{MOR}{LOP} > 0.65 \left(= \frac{1.3 \times 1.5}{3} \right)$$

To satisfy the MOR criteria, a percentage of 4.3% of organic fibres (Poly-Vinyl Alcohol [PVA]) has been selected. (See Figure 4)

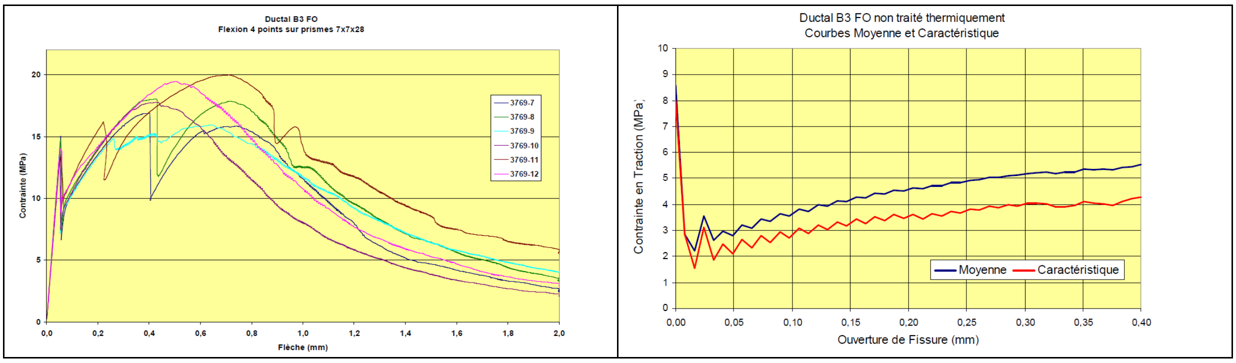

Figure 4: Flexural bending test and back analysis result.

For reinforced elements, a "reinforced concrete" approach has been followed. It is no longer based on cladding principle (CSTB) but on post cracking strength ($\sigma_{0,3mm}$) and elastic limit (f_{ctk}) in accordance with AFGC Recommendations and Eurocode. The table below summarizes the flexural design values:

Non-reinforced plates	
Flexural design value σ_d (with no reinforcement)	5,1 MPa
Reinforced plates	
Elastic limit f_{ctk} (SLS calculation)	8,3 MPa
Post cracking strength $\sigma_{0,3mm}$ (ULS calculation)	3,3 MPa

In terms of process and geometrical stability, an additional critical mechanical property has to be evaluated carefully. Indeed, the shrinkage (at (20± 2)°C et (50±10) % RH) observed in the material consists of drying and endogenous shrinkage (self desiccation), as follows:

Drying shrinkage	0,26 mm/m (after 114 days)
Self dessication shrinkage	0,21 mm/m (after 95 days)

3. PANEL DESIGN AND PROTOTYPING

3.1 Standard panels

Due to the non-repetitive nature of the architectural surfaces, the curvature is unique for each panel. The unrolled format (i.e., dimensions after developing the surface) of these panels fall into two main categories: standard geodesic rectangles of constant developed length and height; and edge panels found at every surface boundary. The unrolled dimensions of the standard panel have been set to the following:

- Length (standard panels) : L = 1490mm (1500 – 10mm horizontal joint)
- Height (standard panels) : H = 393mm (400 – 7 mm vertical joint)
- Thickness (all panels) : T = 25mm

The final values of these three dimensions are the result of a back-and-forth process which addressed several criteria factors as described below:

- Architectural intent - a desire for long, elongated panels, with a high aspect ratio;
- Fabrication limits - the longer the panel, the higher the fabrication tolerances may be;
- Economy - big and less panels means less casting and erecting operations, thereby reducing the price per square meter;
- Weight - each panel had to weigh less than 40kg to be easily erected by two operators in difficult access conditions;
- Resistance - each panel had to resist all service load without damage or incur any accidental load without falling

The unique, curved and twisted geometry of each of the 19,000 panels and the tight installation tolerances require a very determined fixation system with the least restraint possible. Therefore, a 4 point fixing system at the corners of the panels was chosen. Pin, sliding and out-of-plane supports are combined to avoid any in-plane restrains. For this reason, no arch action could be considered and the panels essentially resist loads in bending.

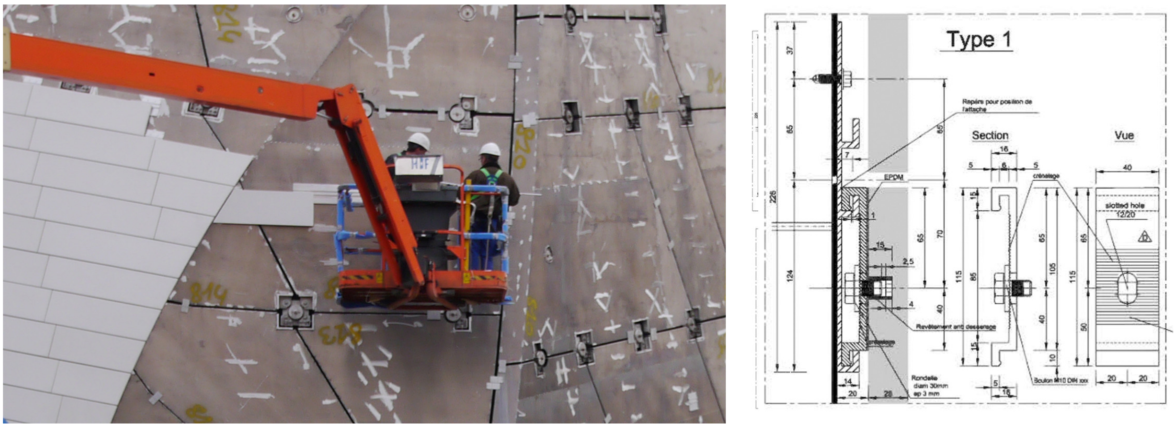

Figure 5: Erection and fixing system by HRE (Hofmeister Roof Engineering).

3.2 Loads on panels

Permanent loads and climate loads are uniformly distributed on the surface of the panel. The 25 mm thickness has been determined in accordance to § 3.1 criteria so that all panels can resist these loads (flexural calculated value < 5.1 MPa = design value) without reinforcement.

Self weight	0.65 kN/m² / vertical
Wind	Max +/- 1.5 kN/m²
Snow	Max 0.3 kN/m²
Temperature	+/- 30°

3.3 Service live load

The complex shapes of the building and glazed canopies make access to the Iceberg façade very difficult. Some areas are reachable by cranes, however the majority of the surfaces are only accessible by climbers. Therefore, climber loads must be considered as live loads, for which no degradation of the panel is acceptable. The design team evaluated the magnitude of the impact on the Iceberg's walls, based on a full-scale mock-up. In parallel, the consequence of such loads has been carefully investigated regarding the panel resistance. Preliminary calculation rapidly demonstrated that climber load was the critical load case, requiring either reinforcement or additional support for the panels. In order not to treat every panel for the highest climber load, a detailed evaluation of the magnitude of the climber applied force on the wall has been carried out. Figure 6 shows a program developed to assess the exact climber load depending on local conditions (length an angle of the rope versus Iceberg inclination angle). The calculated load is then dispatched into 4 categories (<500N / <1000N / <1500 N / < 2500N) and applied to the 3D model of the project as an attribute of each panel.

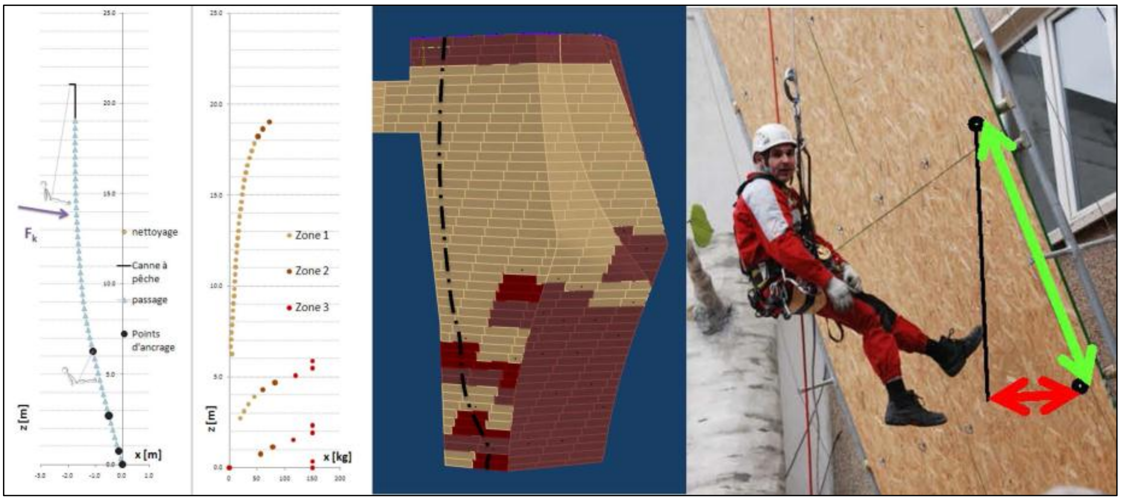

Figure 6: Climber load calculation, climber load attribution and
load verification with professional climber (société Aplomb).

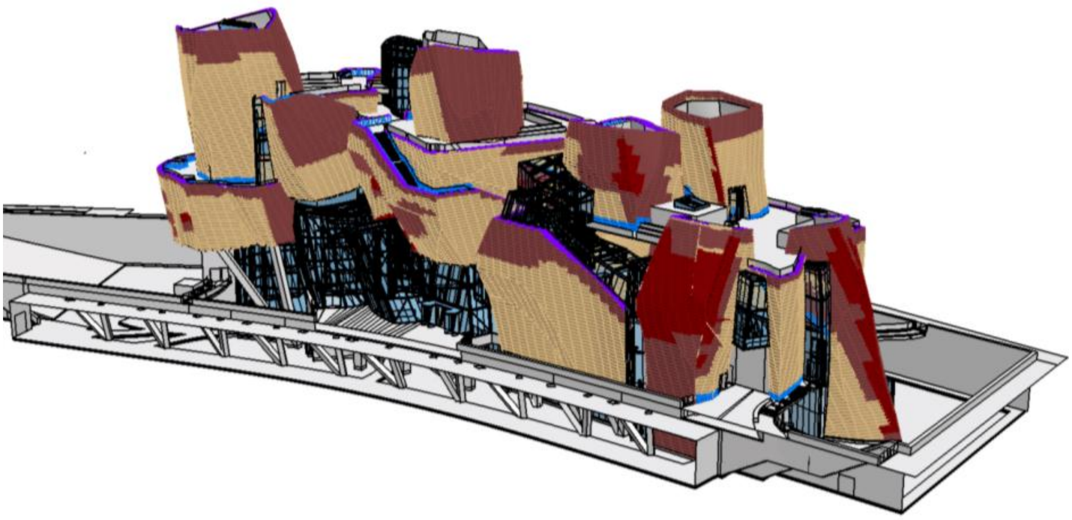

Figure 7: Iceberg – 3D Model

3.4 Panel reinforcement

In order to limit the panel's restraints and simplify the erection process, the design team chose to reinforce the panels rather than add complementary support. Simply increasing the thickness of all panels was not possible in terms of weight and dealing with different thicknesses was incompatible with the visible edges. Ribs on the back-face of the mould were considered at one time but deemed not compatible with the flexible mould process. It was then evident that the reinforcement of the panel should have the potential to be applied on the panel after casting and curing, as additional equipment only used on highly loaded panels. This would guarantee a homogenous aspect of the façade, even combing reinforced and simple panels.

The concept of applying a flexible strip on the back face of the panel naturally imposed itself in order to be compatible with the variable curvature conditions. With a shear resistant bonding to the UHPFRC, the panel would act as a composite section with a tension element and a compression in the material. Following this approach, investigations were conducted with respect to materials and connections, for example: stainless steel or carbon fibres for the strips; and mechanical or chemical (glue) attachment to the panels. It was then determined that stainless steel fibres would be better suited for this application than carbon fibres. Finally, it was decided that the gluing of stainless steel strips with bi-component epoxy would be the best approach, with the ability to play on the strips' thicknesses, number and widths in order to fine tune the structural response.

A composite approach is followed for the design. Compatibility of deformations is provided by the glue between the stainless steel and the UHPFRC. The SLS governing criteria is to avoid any visible crack at SLS, even in the non-visible face of the panel. Consequently, a safe approach is to consider that no visible crack also means no microcracks; which means no damage and stresses below the elastic limit in the UHPFRC. Considering the ratio of stiffness between Ductal® B3 FO (including creep) and stainless steel (210 GPa / 35 GPa = 6), it leads to a stress criteria for stainless steel stress at the interface of 50 MPa at SLS.

Using a reinforcing material with a higher elastic limit such as carbon is unnecessary. For instance to carry the 1.5 kN central load, we obtain the following equivalent preliminary thickness of stainless steel.

Thickness of UHPC	Equivalent stainless steel layer necessary
14 mm	1.500 mm
18 mm	1.000 mm
22 mm	0.500 mm
26 mm	0.125 mm

A 25 mm thickness for the non reinforced panel is compatible with a 0.125 "spread" for stainless steel (i.e., 2 strips of 50 mm width and 0.5 mm thickness).

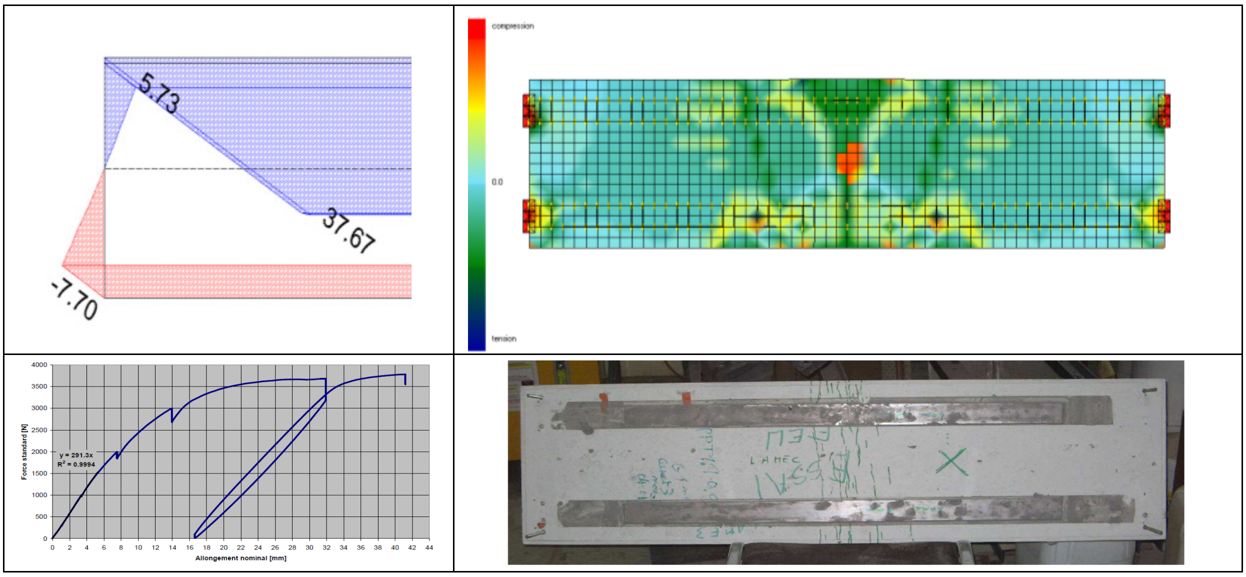

Figure 8: Non Linear Stress Analysis

4. FORMING PROCESS

4.1 First stage development of the forming process

It took two years to develop a solution and a production process that could meet the project demand for 19,000 different panels with 19,000 different geometries. This development was carried out by Lafarge, Cogitech Design and the design team, along with input from the prime contractors. These interactions made it possible to develop a solution that would be technically and economically reliable and close enough to meet the initial requirements. The demand further evolved during these two years, in order to consider the architect's "wishes" as well as the technical constraints.

The entire process relied on the fact that the surface was "developable" and the geometry of a developed panel would be rectangular. By addressing various project constraints, appropriate solutions were then identified, as follows:

Constraint	Solution
Weight: 35 kg maximum - to be carried by hand	Maximum panel dimension: 1493 x 390 x 25 mm. Weight: 34 kg
Mechanical constraints: depending on the installation zone	Steel linings are added locally
Color: White	(L;a;b)=(87.8; -0.8; 2.4), ΔE=2.5. 3% of TiO2 is added to the white Ductal®
Geometrical precision: mm	Reinforcement of the mould. Process as normal as possible
Process: industrial and economical	Use of a standard silicon mould to produce 100 panels; use of a single polystyrene support to bring to the panel to desired shape; recycling of the polystyrene.

Figure 9: Moulding process at Cogitech, 2006 (1).
Ductal® is poured into a silicon mould (2, 3). Mould is closed and vacuum packed (4, 5).
Mould is put on a polystyrene support, with final 3D shape.

Figure 10: (1) Prototype 2006: square panels by Cogitech (2) Prototype 2008: 300 x 30 cm panels by Cogitech (3) Prototype 2008: 150 x 30 cm panels by Bonna Sabla.

4.2 Second step: industrial development and production

The main challenge during the industrial phase was to maintain the same fabrication tolerance level achieved in the laboratory (within millimetres) and maintain a very high standard of architectural aspect, at a rhythm of approximately 100^+ panels per day.

Bonna Sabla dedicated a team and set up a new plant in order to optimize the “MSV” (Moulage Sous Vide) process and bring it into an applicable industrial production. The main goal was to finalize the mould design, keeping it flexible enough to follow the curvature, and rigid enough to keep the tight tolerances of the panels within the very drastic aspect criteria. In short, the combination of two opposite properties; flexibility and rigidity.

Figure 11: MSV Moulding Process (industrial scale)
at Bonna Sabla, Conflans-Sainte-Honorine plant.

A specific moulding stand was devised to pour the material horizontally into the silicon mould. Once the material is cast, the mould is closed with a lead and sealed using a vacuum bag. Both are then transferred onto a support that has been specifically milled to the required shape. This assembly silicon mould, vacuum bag and milled support are put to rest for 24 hours. Then, the panels are demoulded and stored very carefully to avoid any concaving of the surface because of differential (a water exchange between front and back faces).

4.3 Milling of the polystyrene support

Each of the 19,000 panels is unique, with a specific tracking number for a specific location on the project. Their supports are defined with 3D numeric files, made by milling a polystyrene block with a 3-axis milling robot. This results in an economical advantage since the supports, which stay clean during the moulding process, are fully recycled.

Figure 12: Milling of a polystyrene block at Bonna Sabla, Conflans-Sainte-Honorine plant

4.4 Quality control - automatized measuring process

All of the 3D data is used to create id cards for each panel. This data exchange is part of the digital tracking chain – established from the main contractor, to Bonna Sabla and back to the main contractor at the time of delivery, before erection. The 3D data was also used for an automatized process of measurement, put in place to compare the theoretical surface with the actual panel measurements. Each panel is controlled with a 5-axis robot, equipped with a laser head. The precision of the robot is 1/100° mm. All of this information (dimensional and aspects) are recorded in the ID data of each panel as part of the quality plan.

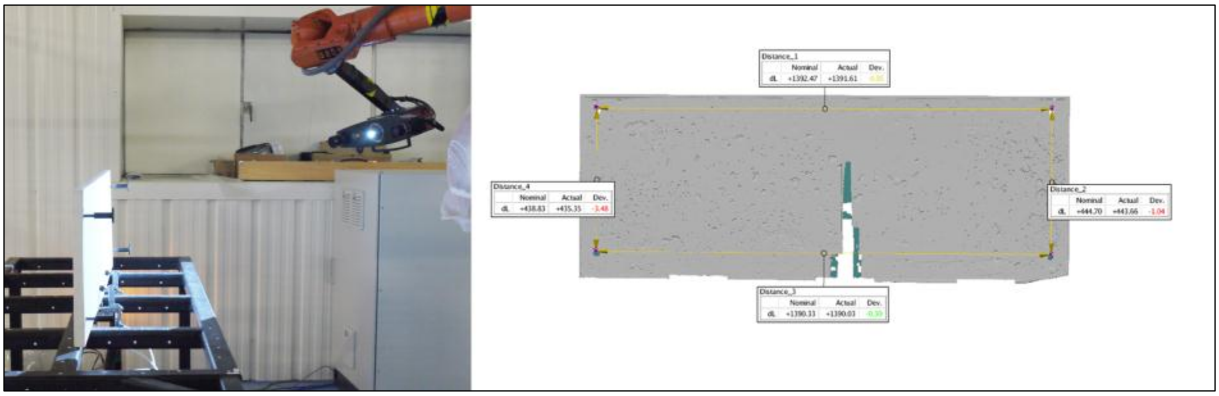

Figure 13: Automatic control
Systèmes de Stéréovision de pointe GOM Atos II – Kuka 5 axis

4.5 Flat and curved panel optimization.

All of the panels are theoretically curved but, in many areas, the radius of the curvature is so great that the difference between a curve panel and a flat one falls into the range of tolerance of a flat panel. In short, it would be very difficult to tell if the panel is supposed to be flat or curved. An algorithm, using a 2 mm bounding box, was applied to each panel. If the panel fit within the bounding box, it would be considered flat, if not, it stays curved. This approach enabled the prefabricator to open a new line of production that could be dedicated to the fabrication of flat panels at a substantial cost optimization.

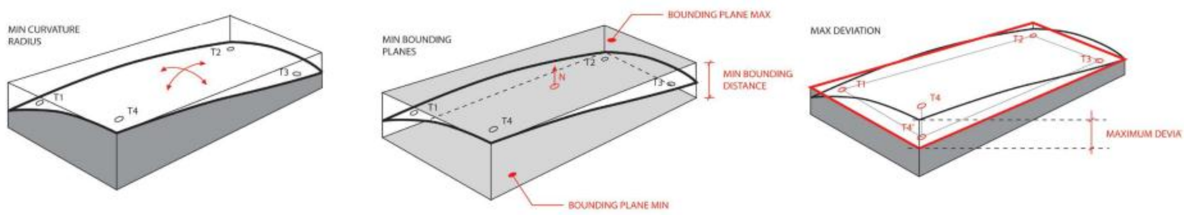

Figure # 14: Flat in-curve analysis principle
developed by RFR/TESS and Gehry Technologies.

5. CONCLUSIONS

The Ductal® UHPFRC Iceberg is the original vision of the architect, combined with the ambition of the "Fondation Louis Vuitton pour la Création", for a high quality, innovative building. It was decided from the very beginning of the project that all parties; the architect, owner, façade consultants, general and specialized contractors and technical authorities – should work together in order to respond to this challenge. The final result, as is often the case with innovative projects, is largely due to the success of this collaborative process.

Figure 15: View of Tower 1 south west.

ACKNOWLEDGEMENTS

The UHPFRC used in this project is a white Ductal® material supplied by Lafarge and fabricated by Bonna Sabla as a subcontractor of Hofmeister Roof Engineering (HRE) and Vinci Construction, France. The robotic measuring, automatized control was subcontracted to TPSH by Bonna Sabla. The fabrication documents for the panels were done by Gehry Technologies' subcontractor, HRE. Thanks also to Thomas Maigne and Tobias Nolte for their work and valuable input as well as Sylvain Quidant and his team at Cogitech, for their significant input during the early development of this project.

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