RATIONALISATION OF COMPLEX UHPFRC FACADE SHAPES

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Abstract

Designing a facade component in UHPFRC requires clear strategies in the form rationalisation and the moulding approach. UHPFRC is a rather new material that needs design rules. It will necessarily proceed from technological means available. Indeed process enables "Typologies" of façades. In this paper, a focus on material and technological constraints will give us a first attempt on design rules related to UHPFRC in the defined domain of facades applications: Economical, Physical, Constructive and Topological. To asses it, the method explored here will be a feedback on recent projects. In a first introductory part, the relationship between manufacturing and design with UHPFRC will be presented. Intrinsic material constraints will be presented in this part. In a second part, the method will be applied on three types of moulding: table mould, injection, and pressed moulding. Related projects will be fruitful case studies for the initial concept developed in part one.

Résumé

La conception d'éléments de façades en BFUP nécessite une démarche claire dans la rationalisation des formes et dans le choix des moules. Le BFUP est un matériau relativement récent qui cherche encore ses propres règles de conception. En partant des moyens technologiques disponible, on peut faire émerger des « typologies » de façades. Une étude des contraintes technologiques et matériaux (économiques, physiques, constructives et topologiques) nous donnera une première idée des règles associées au BFUP dans le domaine des façades. La méthode utilisée pour y parvenir est un retour d'expérience sur des projets récents. La première partie introductive présente la relation entre conception et fabrication avec des BFUP. Les contraintes propres au matériau y sont également détaillées. Dans la deuxième partie, la méthode est appliquée à trois types de moules : Moule table, moule par injection, moule embouti. Des projets en relation servent à illustrer les concepts développés dans la première partie.

1. ABOUT RATIONALISATION

Hardly a month goes by without a new book or magazine dealing with geometry appearing in architectural bookstores. Dedicated, for the most part up until now to (descriptive) representation, geometry has made a re-appearance in the field of architecture with new forms, also described as "free-forms". The complexity of the forms obtained is very high, thanks to the progress and the easier access of data processing over the last two decades. The question today is no longer the mastery of complex geometry - the computer takes care of that for us - but the consequences of the forms produced. The corollary question is that of form rationalisation: why make a form in one way rather than another? Rationalisation is not unique, it follows from rules that we set for ourselves and that guide us in our choices. We should speak instead of rationalisations in the plural. In the field of construction, these rules are mainly of three types: *Physical, Constructional* and *Topological.*

Physical: this is the link between a physical phenomenon and the form that is given. It can, for example, be a funicular form (which only takes up tension and compression), iso-stress curve or equal slope surfaces (piles of sand).

Constructional: these are the forms resulting from manufacture and implementation. Overall, the three constructional rules are simplicity, rapidity and availability.

Topological: this is the ratio between forms. This constraint is purely geometric. Without being exhaustive, three topological conditions can be suggested:

- *Homogeneous/heterogeneous*: two forms - are they of the same type or not?
- *Continuity/discontinuity*: does one form extend into the other? For example, Rhino software (Mc Neel) proposes four levels of continuity according to the curve equation and its derivatives: position (G1), tangent (G2), radius of curvature (G3) and radius of curvature variation (G4) (For more definitions see *Architectural Geometry* [1] and *Inside Rhino* [2]). This condition is very important for the design of the façade corners.
- *Obedience/disobedience*: two forms - do they work together visually or are they in opposition? The notion of "obedience" was invented and developed by the architects and researchers Alain Borie, Pierre Micheloni and Pierre Pinon. In their book "*Forme et deformation*" [3], they enumerated five types of obedience: *centralisation, parallelism, axialisation, tangency* and *perpendicularity*.

Sometimes contradictory, these rules force us to compromise. Acceptable compromises are not infinite and typologies of forms associated with materials and systems of construction emerge. Compliance or non-compliance with a rule is neither good nor bad; they simply make sense within an architectural project. The role of the building designer is to control the sense of the forms produced.

2. ABOUT UHPFRC

The Ultra-High Performance Fibre-Reinforced Concretes (UHPFRC) are regarded as an expensive material. The cost is often exaggerated by the fact that UHPFRC are a new material, and that they are too often misused. In fact, the UHPFRC are neither super-concretes nor mineral resins. They are a material in its own right with its own "*language*" which has still, in part, to be discovered. The objective today is to discover the "*order*" of UHPFRC and to find what they "*want to be*" in the meaning of the architect Louis I. Kahn [4]. For a building designer, it would seem aberrant to make a monolithic steel structure or to laminate concrete. However UHPFRC are sometimes used in an aberrant way. The cost of UHPFRC depends on three main factors:

- *Volume of material*
- *Complexity of moulds*
- *Number of moulds required.*

Depending on the case, the number and complexity of moulds multiplies the cost between raw and finished material by three or six. UHPFRC is a cast material, preferably in the workshop. It is therefore preferably prefabricated, which implies the presence of joints. The size of joints depends on physical criteria (expansion, implementation etc.), but also on visual criteria: too big and we no longer see its continuity, too small and we see all the imperfections between two components. In general, we seek an equal distribution of the fibres in the component and in the three spatial directions, which makes it an almost homogeneous material. As for steel, material is saved by putting it only where it is effective. Thin-walled or T-sections are thus preferred. The absence of transverse reinforcement and the flow of the fibres encourage rounded forms, without sharp angles. Four typologies of complex façades can be derived from four casting methods:

- *Table moulding*
- *Injection moulding*
- *Pressed moulding*
- *Vacuum moulding*

It would be an exaggeration to describe good design rules in an exhaustive way, for the good reason that they are still being invented. Which is why, in order to present the ways of designing complex façades in UHPFRC, the first three typologies will be illustrated by a project example in Ductal® FO (UHPFRC with organic fibres produced by LAFARGE). The fourth will not be treated here because it is still under development. It presents the advantage to produce easily developable surface. The three projects presented were designed by the prefabrication company from the architectural image, which introduces an additional cost. The architects and consultant engineers should always design from the beginning the form in accordance with the construction system. Each project will be handled according to the following three themes:

- *Generation of the form*
- *Subdivisions and connections*
- *Static diagram and implementation*

3. TABLE MOULDING

3.1 Rabat Airport - Moucharaby

The Terminal 1 façade at Rabat airport is the first Ductal® project on the African continent. The design envisaged cladding the façades with a suspended moucharaby inspired by traditional Moroccan patterns. On the landside, the Ductal® moucharaby is attached to the curtain wall leaving enough space to be able to clean the glass. The basic pattern is a polygonal figure, frame size 3.50 x 3.50 m². The section of each strand measures 100 x 100 mm². The introduction of appropriate reinforcement was made complex by the numerous broken lines of the layout and the size of the sections. The choice of material went to non-reinforced Ductal-FO, cast on a table mould by the Moroccan company BE ARCH.

Figure 1: Images of the completed project [Photos KLARTE / LAFARGE]

3.2 Generation of the form

The table moulding system requires planar or polyhedral geometries. The objective is to make the least number of moulds. The ideal would have been to make one mould the size of a frame (3.50 x 3.50 m²), but that size is not suitable for road transportation. The basic frame was divided in half vertically to create a flat motif 1.75 x 3.50 m². The panels were cast on a horizontal table with removable wood prisms coated with flexible polyurethane placed at void locations. The cylindrical surface of the landside façade was divided into 1.75 m wide flat sections. The pattern was then readjusted, in order to match the horizontal crosspieces of the curtain wall with the panel support points. The curtain wall uprights are independent of the pattern.

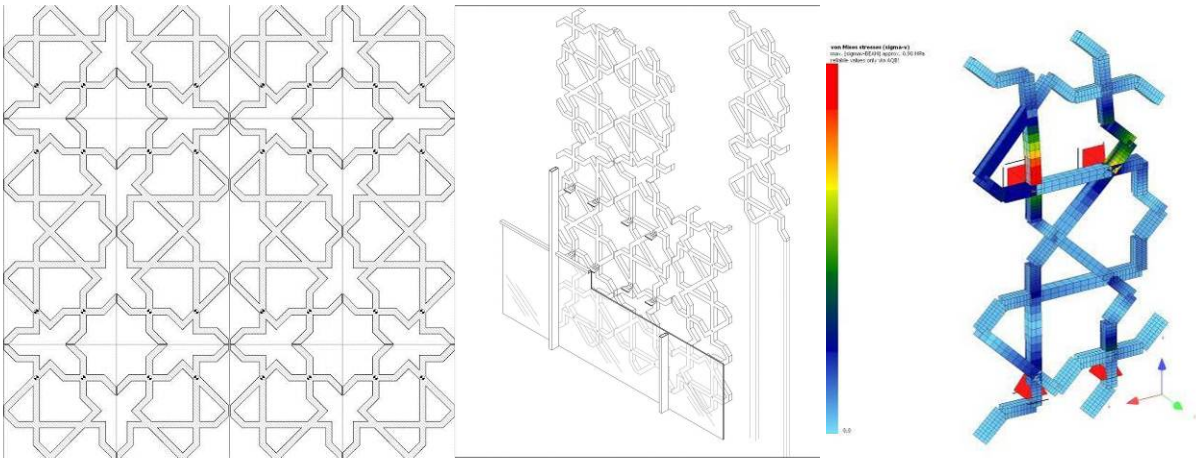

Figure 2: Basic pattern and assembly principle [Drawings C&E Ingénierie]

3.3 Subdivisions and connections

The Ductal® moucharaby is delimited at the edges of the building. The limit of the pattern is emphasised by a border, made up of prismatic Ductal® elements. Seen from the front, the lower section of the moucharaby forms an arc of a circle to enhance the entrance to the building. The bi-cylindrical curve thus obtained is made from rectilinear elements, attached to the uprights of the curtain wall. As for the facets of the cylinder, the difference from the real curve is not noticeable. Each panel is re-divided at the moment of casting when the mould plugs are inserted. The joint between the elements is 20 mm.

Figure 3: Mould table before casting and first panels produced [Photos C&E Ingénierie]

3.4 Static diagram and implementation

All the panels are mutually independent. They are held at four points, articulated at the bottom and with vertical expansion at the top. The opposite approach would put the material in tension, and fail to utilise the performance in compression (Characteristic strength between 100MPa and 150MPa).The Ductal® is fixed onto the welded plates of the curtain wall via adjustable angles. The subdivision of the moucharaby required the extension of some panels (1.75 x 5.25 m²), so that all have at least four attachment points. In total, eight sockets were inset at the time of casting each Ductal® panel: four for lifting and four for final fixing.

3.5 Design rules of the table moulding

- *Planar or polyhedral geometries*
- *Repetitive pattern, based on the faces of the polyhedron*
- *Size of the mould according to road transportation*
- *Trimming panels by the introduction of mould plugs at the moment of casting*
- *Joint between panels from 10mm to 30mm*
- *Panels statically independent*
- *Prioritise isostatic schemes*
- *4 supports in final position: 2 hinges in feet and 2 horizontal fasteners in head*
- *Features adjustable fasteners*
- *Lifting with additional inserts, with straps or with templates.*

4. INJECTION MOULDING

4.1 Façade of the Rue Blanche EPAHD

As part of the renovation of the facility for the elderly (EPAHD) on rue Blanche in Paris, the architects wanted to compose the new garden façade using a Ductal® lattice. This enables the fire brigade access balconies to be concealed. It is made up of five types of blade of different thicknesses, entangled in such a way as to evoke a bamboo forest. The white colour of the Ductal® contrasts with the green of the new façade behind. The lattice is folded into seven flat planes. To produce the reinforced Ductal-FO strands, the FEHR SA Company made use of the injection moulding system.

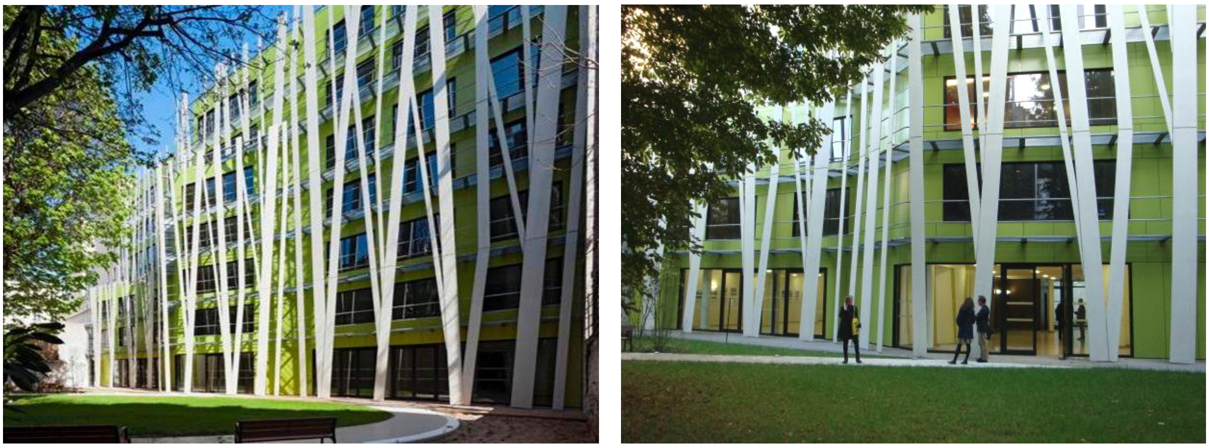

Figure 4: Completed project [Photos Hervé Abbadie / Lafarge and C&E Ingénierie]

4.2 Generation of the form

The injection moulding system leads to the generation of extruded geometries. These geometries are obtained from a rectilinear wire-frame network associated with five different types of cross-sections, thicknesses and widths. These cross-sections are smooth and aligned on the exterior plane of the façade, rounded on the access balcony side. The blades can cross in an "X" or "Y". The injection moulds must, of necessity, be watertight. Thus they have at least one removable side. In this instance, the moulds have the form of a rectilinear blade 6.00 m in length. The mould is then resealed by plugs at the moment of casting. The entire façade can thus be created with only five moulds: one per cross-section.

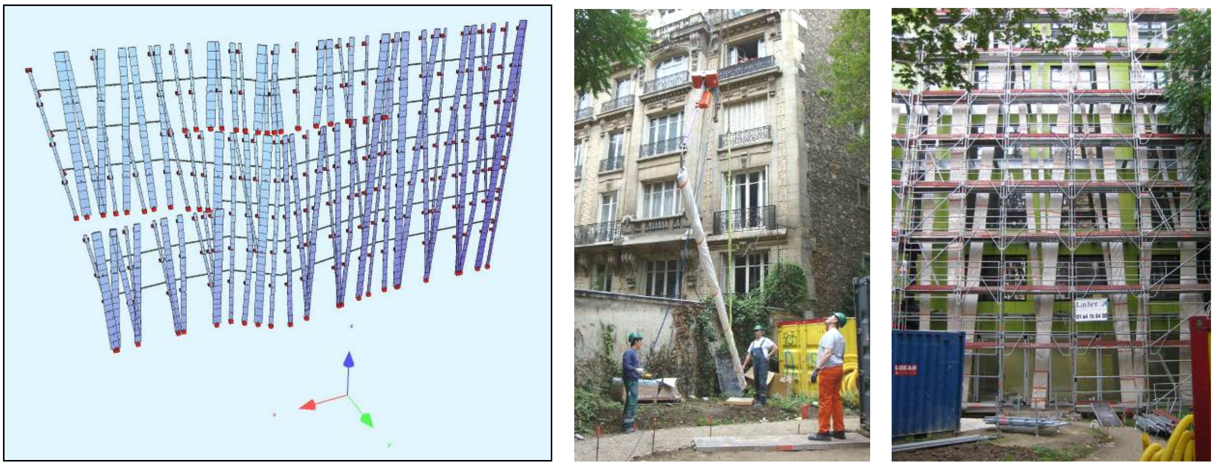

Figure 5: SOFiSTiK calculation model and lifting of the first blade [Photo C&E Ingénierie]

4.3 Subdivisions and connections

The larger blades (approximately 6.00m) make up two levels: all the elements are prefabricated and assembled mechanically on site. There are thus two types of connection between elements, whether the blades are aligned or not. In the first instance, the connection is assured by two stainless steel parts, inset at the time of casting and assembled on site with a bolt. In the second, the parts are assembled by a pin system. Once slid into place, the system is blocked by the horizontal bearing of the level above. The shape of the secondary part is cut out in the negative in the main part, and bevelled taking into account the joint.

4.4 Static diagram and implementation

The entire lattice is set on the ground or terraces, and held horizontally at the level of the fire brigade access balconies. The blades thus rest one on top of the other. Full length, the first blade is assembled with a bolt onto a plate pegged into the concrete support. At balcony levels the blades are held by a connecting rod arrangement, which transmits the horizontal but not the vertical components. The blades are all hinged together at each junction, so as not to transmit bending moments. The Ductal® parts were assembled from the bottom up, by sliding them between the access balconies and temporary scaffolding.

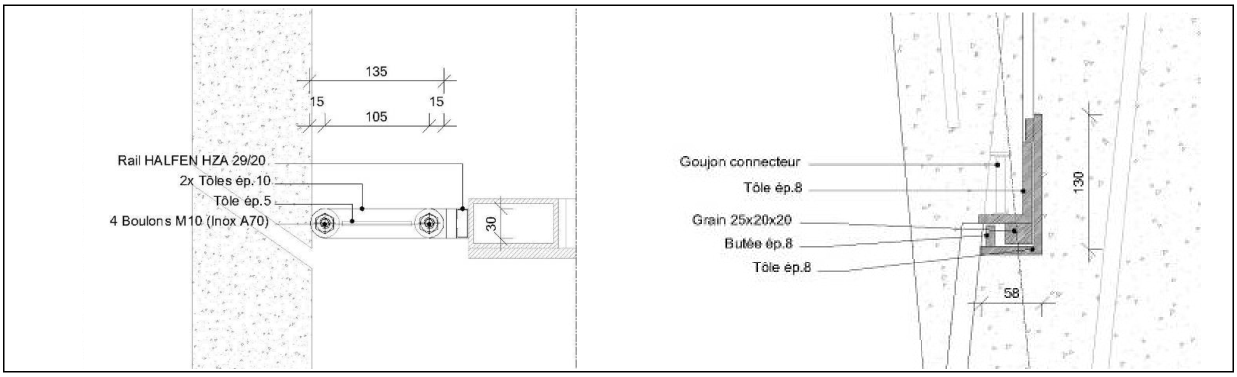

Figure 6: Hinges between pieces [Drawings C&E Ingénierie]

4.5 Design rules of the injection moulding

- *Extruded geometries*
- *Mould based on cross-section*
- *Length of the mould according to road transportation*
- *Trimming pieces according to mould length and to connections between pieces*
- *Joint between panels from 10mm to 20mm*
- *Panels statically independent or support one on another*
- *Prioritise isostatic schemes*
- *Hinges between pieces (axe, kernel, etc.)*
- *Lifting with additional inserts, with straps or with templates.*

5. PRESSED MOULDING

5.1 Waterproof façade of the Pierre Budin nursery

The concept of the Pierre Budin nursery in the 18th arrondissement of Paris was to wrap the building with a mineral "orange peel". The undulating surface unfolds continuously on the three exterior façades (north, west and south). The height of the façade varies due to the slope of the street and of the upper parapet, which decreases on the west and south façades. The non-reinforced Ductal® FO ensures water tightness and part of the thermal insulation. The

BONNA SABLA and IL CANTIERE companies used the process of pressed moulding to create the 67 panels (2050 x 4200 mm²).

Figure 7: Pictures of the northwest corner and panel installation [Photos C&E Ingénierie]

5.2 Generation of the form

The pressed moulding process leads to the creation of periodic geometries. This process consists of applying a contra-mould (here polystyrene) when the Ductal® is still liquid in order to evacuate it on the sides and form ribs. Given the static and waterproofing requirements the prefabricated panels must necessarily be ribbed on their outer edges. The thickness at the centre of the panel is only 30 mm, as against 235 mm for the ribs. The periodic surface is generated from a Bézier surface half frame multiplied by network and symmetry. The surface thus obtained is continuous by tangency and radius of curvature in order to ensure homogeneous shade variation from one panel to the next. The connection of the corner panel is a real challenge in itself, both geometric and constructional: the surface changes its nature and the moulds are not reusable. In addition, it is one of the most visible elements of the façade. The surface angle is designed with T-Splines, to ensure continuity of the radius of curvature with the adjacent panels.

5.3 Subdivisions and connections

The division should be based on periodicity, in order to have the most repetitive moulds possible. Thus, with the exception of the corner panels, all of the façade panels have been created with only two Ductal® moulds bases. The surface was divided based on lines of vertical inflection, but it could very well have been divided based on waves of greater amplitude, which changes the perception of the panels: in the one case axially symmetric, in the other centrally symmetric. The change in levels was achieved by moving the upper and lower demoulding wedges before casting. Some think the façade would be better without the presence of joints. In that case the Ductal® would have had to have been covered by a coating. For the story: a silicone gasket was intended to close the joints that are apparent today. The effect on the south façade pleased neither the company nor the architects who, by common agreement, abandoned the idea and took down the joints already completed. Today, the presence of the joints reinforces the massive mineral character of the façade (even though when a panel is tapped at its centre, the sound is hollow). The joint treatment takes as its inspiration measures already developed for precast concrete. The airtightness and waterproofness must include at least two barriers:

- Horizontally: a sill/drip groove arrangement returns the water to the outside. At the top the arrangement is inverted, with a Ductal® coping.
- Vertically: two foam impregnated joints with a decompression chamber to block water infiltration.

5.4 Static diagram and implementation

The heaviest panel weighs 1.4 tons. The series of panels rests on the ground on a concrete heel, which follows the slope in steps. The assembly is achieved by a pin system, which enables the panel to be placed and then to dock it at 9 mm from its neighbour. Steel angles with oblong slots maintain the panel horizontally. The top panel is supported on the lower by a toggle system, fixed after casting onto the panels. Lifting is carried out by lateral sleeves for tilting and upper sleeves for positioning. The general contractor COTRACOOP, who installed the panels, took a day to install the first panel and then installed an average of four per day. Problems of tolerance and coordination appeared due to the large number of participants. Generally it is preferable for the smooth running of the construction site to limit the number of intermediaries between design, calculation, fabrication and installation.

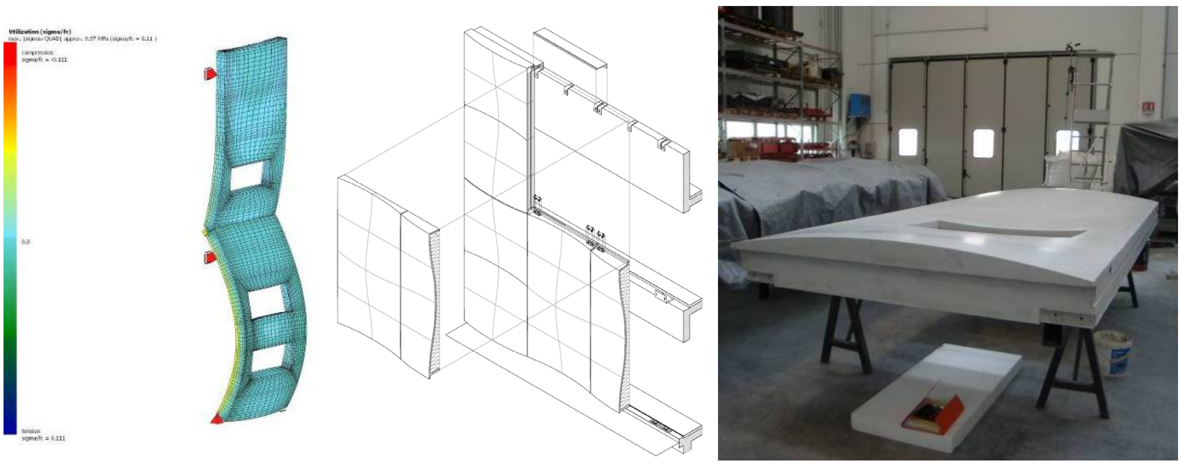

Figure 8: SOFiSTiK calculation model and the first panel [Images C&E Ingénierie]

5.5 Design rules of the pressed moulding

- *Periodic geometries*
- *Mould based on the pitch of the periodicity*
- *Size of the mould according to road transportation*
- *Trimming according to periodicity*
- *Joint between panels from 10mm to 20mm*
- *Panels support one on another, and horizontally maintained*
- *Prioritise isostatic schemes*
- *Hinges between panels (axe, kernel, etc.)*
- *Features adjustable fasteners*
- *Lifting with additional inserts*

6. CONCLUSION

The last decade has seen an expansion of facades with complex geometries. Ways of distinction (in the meaning of Bourdieu [5]) for the clients or the architects, complex geometries are now subject of many studies, which are trying to theorize and to optimize their applications in the field of construction [6]. Properly used, the UHPFRC are very efficient in designing complex surfaces. The casting method should be chosen according to the type of desired geometry, and then the building designer should apply to them the rules related.

PROJECT DATA

	RABAT AIRPORT	**EPAHD RUE BLANCHE**	**PIERRE BUDIN NURSERY**
Location	Rabat (Morocco)	Paris - 9th District	Paris - 18th District
Construction	2011	2009-2011	2009-2012
Client	National Airports Office (ONDA)	Paris Habitat	City of Paris – SLA 18
Architect	Klarte – Rabat (Marocco)	Philippon-Kalt Architectes – Paris 13	ECDM – Paris 11
Prefabrication company	BE ARCH Rabat (Marocco)	FEHR SA Reichshoffen (67)	BONNA SABLA Lamanon (13) IL CANTIERE Podernone (Italy)
Façade engineering	C&E Ingénierie - Paris	C&E Ingénierie – Paris	C&E Ingénierie – Paris
Indicative dimensions:	1,75m x 3,50m for 100mm thickness	172 blades Total length : 905,50m Area : 40m x 22m high	67 large panels, area 650 m² 4,20 m x 2,05 m, 30 mm thick (235 mm at ribs)

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