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The Atrium, Victoria BC

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> The innovation point is the pivotal moment when talented and motivated people seek the opportunity to act on their ideas and dreams.

W. Arthur Porter

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The Atrium

The Atrium building located in Victoria, British Columbia is close to 18,600 m2 of office and commercial/retail space in a seven-storey structure. The building's high efficiency envelope utilizes Ultra-High Performance Concrete (UHPC) spandrel panels in its exterior wall cladding. The project required a sustainable facade solution that reflects the vibrant nature of Downtown Victoria. This was reflected in the facade design through the owner's and architect's desire to have irregular surface textured panels that can also form tight radial curves at the building corners. These requirements were met through careful use of UHPC; a material that has been available since the mid-90's (especially in Europe) and over the past decade has been gaining popularity in North America, mostly in bridge construction. The Atrium is the first building in North America to have a UHPC façade.

For building facades, architects, building officials and owners traditionally prefer natural materials such as stone and granite or manmade brick and concrete block. All these materials are capable of supporting compressive loads but have limited resistance to loads that cause bending. They are also not suitable for producing curved shapes. Introducing irregular surface texture on cladding panels made of such materials would have been possible but not practical and would be labour intensive, and extremely costly. Metal panels could be used to produce curved shapes but are not suitable for forming tight radial curves and cannot have irregular textured surface.

UHPC's flowability, mouldability and self-consolidation characteristics allowed recalling the appearance of handcrafted brick and stone in Victoria's historic buildings. Understanding UHPC's characteristics along with innovative structural design and construction techniques resulted in customized design and creation of highly durable, attractive, ultra-thin (17 mm) UHPC cladding panels for The Atrium's unitized curtain wall system. This unique project involved close collaboration between panel designer - DIALOG and precast manufacturer / UHPC material supplier - Lafarge Canada. The characteristics of UHPC; very high compressive strengths (up to 250 MPa) associated with excellent ductility, improved flexural behaviour and tensile properties - in addition to its superior durability characteristics, made UHPC the logical choice for use in The Atrium's cladding panels. Non-metal panels would have resulted in panels about four to five times thicker and heavier than UHPC panels. Additionally, since the project is located in one of the highest rating seismic zones in Canada, the heavier panels penalize natural products.

Manufacturing at Lafarge's precast facility in Calgary involved casting a total of 690 panels of flat and curved panels. The surface texture on the panels was replicated from the architect's own hand-scored pattern on a master mould. Due to limited use of the material in cladding applications, surface coating that facilitates removal of any accidental stains was used as manufacturers and architects are still experimenting with surface finishes.

Even though the decision was made that UHPC was the logical material for use in the project, we were faced with the fact that there are no design standards, codes of practice and/or guideline specifications available in North America for implementation of UHPC in structural applications. In addition most UHPC proven mixes utilize steel fibres, which greatly influence the material characteristics and performance. Presence of steel fibres would have resulted in unsightly rust stains on the face of the panels. Replication of the handcrafted surface texture (irregular wavy face ribs) and formation of tight radial curved panels were some of the other challenges. Connections of the panels to the support frame in the curtain wall were also a major concern and required simplification to accommodate construction and performance tolerances.

To overcome the technical challenges, a state of the art review of UHPC in structural applications was carried out and the structural design had to rely on first principles along with finite element computer models to predict the structural behaviour. A UHPC mix with polyvinyl alcohol (PVA) fibres was used and new material law (stress-strain curve) that allows prediction of the material behaviour had to be developed. Finally, the structural design of the panels had to be validated through full scale load testing at an independent laboratory. DIALOG had to develop the test program and design a testing frame that utilizes air mattresses for uniform load application. Other load tests were carried out after the preliminary engineering stage to arrive at the support anchor capacities and coordinate the support requirements with the curtain wall and building designers.

The Atrium

Unlike other sustainable construction projects that are usually assessed based on the environmental impact of the employed materials at the time of their production and construction, in The Atrium the importance of sustainable construction and life cycle was realized and the goal was to achieve a balance between the initial cost and the life cycle - keeping in mind that some natural materials have low environmental impact at the time of production but have a short-term life expectancy and that concrete, the most common manmade building material on the planet and a source of industrial emissions (mostly from cement production), minimizing the quantities of concrete as proven by the ultra-thin panels in The Atrium is a step in the right direction.

The ultra-thin panels directly minimized weight of the building exterior walls and consequently resulted in reduced initial cost (UHPC is costly in comparison with normal or high performance concrete), reduced earthquake forces on the support structure, and in ease of assembly into the unitized curtain wall system. Conventional precast panels would have involved swinging large, heavy panels through the air to pin them on a previously erected wall system. This process was eliminated since the panels were preassembled into the wall system.

The design maximized panel dimensions to limit the number of joints between the panels and reduced the number of bridging components to obtain a high energy efficient building envelope with smaller wall thickness in comparison with conventional walls. UHPC allowed freedom to form monolithically tight radial curves instead of smaller, segmented flat panels which would have created more seams and openings in the facade - potentially reducing the building's energy efficiency. In addition, use of a white color UHPC mix enhanced the energy efficiencies and facilitated reflection of the sun's heat energy to reduce the cooling load.

From the early stages of the project, through to completion, it was important to establish and maintain an open, collaborative team approach, with a high level of trust (between the owner, architect, developer and fabricator) in order to complete prototyping, obtain approvals and avoid delays or problems with the project schedule, which was met.

Recent developments in construction materials technology, combined with the aspiration of the construction industry to provide sustainable solutions, has resulted in completion of The Atrium; the first building in North America to utilize UHPC cladding panels as thin as 17 mm. The Atrium project adds to the current state of knowledge and encourages use of advanced construction materials to meet the sustainability goals for the future. UHPC is gaining popularity for use in construction in comparison with other advanced materials such as fibre reinforcing polymer (FRP) bars that have been available for more than two decades but their use in construction is still limited as such bars cannot be used as direct replacement to steel reinforcement. Many engineering organizations are exploring adopting the material and developing engineering standards and specifications for its use in structural applications. The design and testing results of the Atrium panels will be used by members of the "North American UHPC User's Group", formed in 2010 by a group of professional volunteers and by the recently formed (Fall 2011) ACI Committee 239 who's mandate is to develop a UHPC material design guidelines and specifications suitable for use in North America.

Use of UHPC in cladding applications will positively impact the building and construction industries as it responds to the Architects' creative designs and expectations with unlimited demands on shape and form, the Structural Engineers' ambitions for providing safe, durable and maintenance free structures, the Precaster/Erector's concerns for ease of construction, the Contractor's demands for economical designs that can be constructed efficiently and safely in a timely manner, and above all the Owner's aspiration for attractive, "Green", safe, operable, economical and profitable (including life cycle costs) buildings. The successful application of UHPC in architectural cladding, as demonstrated by The Atrium project, is expected to lead the way towards utilization of similar panels in future building facades and to efficiently utilize UHPC material properties in architectural design. The result will be long-lasting structures that require less materials and unique designs with ultra-thin panels, complex forms, texture and shapes.

d full project description

introduction

The Atrium Building in Victoria, British Columbia is close to 18,600 sq m (200,000 sq ft) public space. The building is a seven-storey structure with an open atrium at its centre and has a large skylight that allows natural daylight into the interior of the building. The project is targeted to achieve LEED® Gold rating through the Canada Green Building Council. One of the major elements in this consideration is the building's high efficiency envelope that utilizes Ultra-High Performance Concrete (UHPC) spandrel panels designed to be as thin as possible.

> **Just as energy is the basis of life itself, and ideas the source of innovation, so is innovation the vital spark of all human change, improvement and progress.**
>
> Theodore Levitt


THE ATRIUM
TELUS

Fig. 1 – Atrium Victoria

Vision and Scope

To reflect the vibrant nature of Downtown Victoria and nearby waters, the building architect (D'Ambrosio Architecture + Urbanism) desired to create surface texture on the panels as that shown in Figure 2, and to have curved panels at the building corners. The surface texture recalls the handcrafted brick and stone found in many of Victoria's historic buildings. DIALOG's scope in the project was limited to the structural design and engineering of the panels in accordance with BC Building code and to provide design forces and recommendation for supporting the panels as part of the curtain wall. Lafarge's scope was the supply of the UHPC material and the manufacturing of the precast panels for assembly in the curtain wall at an offsite facility.

Panel Geometry

The façade design utilized 690 precast panels with different plan geometry; flat, curved and partially curved. All panels were 1300 mm high and varied in width from 750 to 2150 mm (majority) 1300 mm wide. The building layout at levels 2 to 5 is depicted in Figure 3 and typical panel geometry and shape is depicted in Figure 4. The surface texture or face ribs are roughly 5mm deep and vary in width from 10 to 20 mm and are 10-20 mm apart in irregular form as shown in Figure 2.

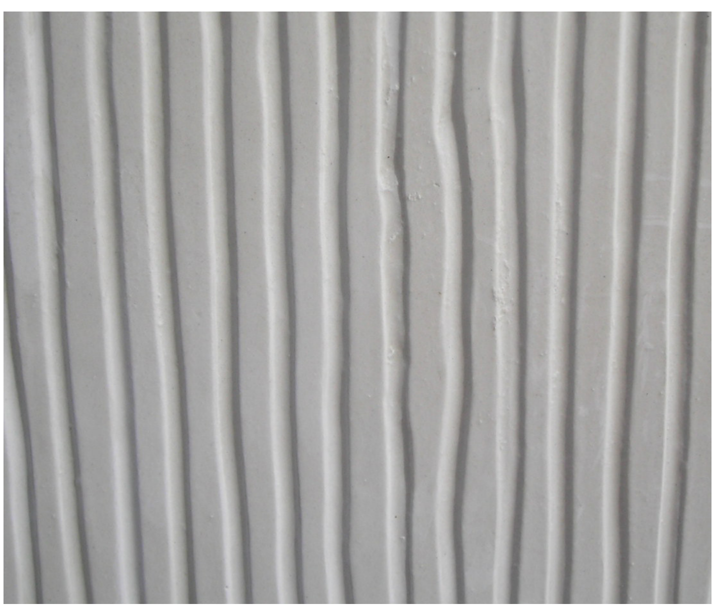


Fig. 2 – Surface Texture

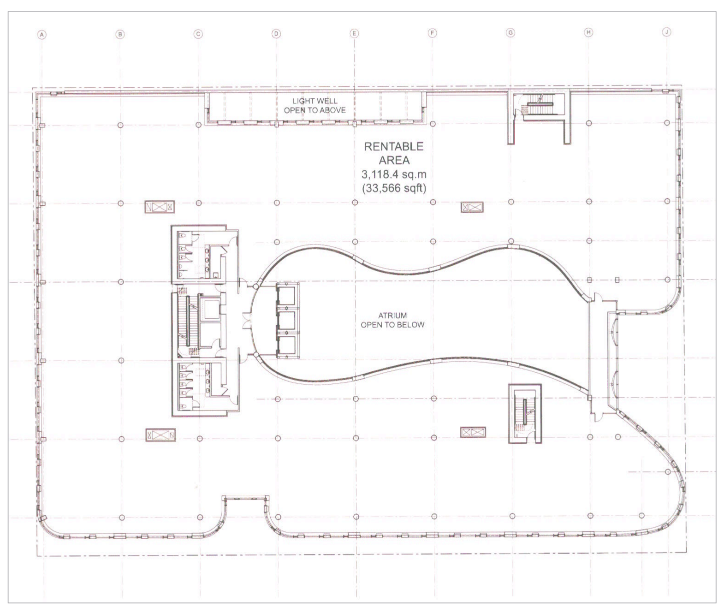


Fig. 3 – Level 205 Plan Layout

Fig. 5.1 – UHPC Panels Forming Curved Corners

Figure 5.2 Faceted Granite Façade, Husky Oil Tower, Calgary (DIALOG project)

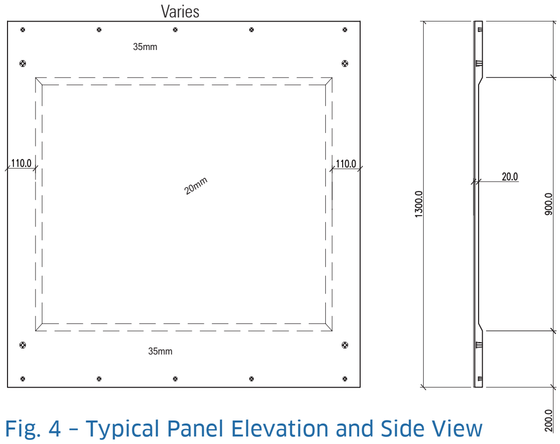


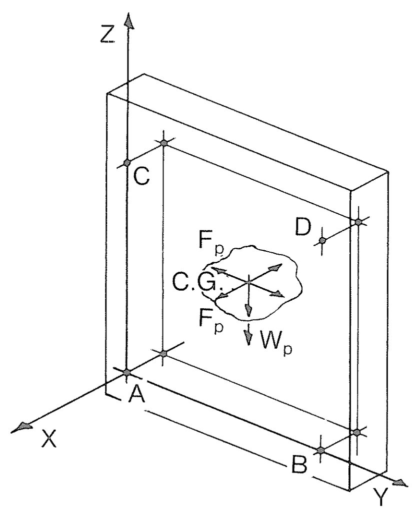
Fig. 4 – Typical Panel Elevation and Side View

The average designed panel thickness of 20mm allowed a fabrication tolerance of 3mm for a minimum structural thickness of 17mm. This thickness was used for majority of the panels that were 1300 mm wide. The thickness of the panels varied slightly depending on the width and plan shape. Perimeter thickened edges on the back face of the panels were used to encompass the support inserts and allow proper sealing of the vertical joints between the panels as well as the horizontal joints between the UHPC panels and the zinc and glass panels that are part of the wall assembly. Panels up to 1450 mm width were supported at four locations and wider ones at six locations with a mid-height back rib added. Additional inserts located 30 mm from the top and bottom edges of the panel are used for attachment of the zinc and glass panels.

A stone or granite panel of the same dimensions would have been much thicker and four to five times heavier than the designed UHPC panels. This is due to lack of tensile resistance of such materials. In addition curved panels would have required assembling multi segments of straight panels with complicated backing frames or cutting the curved shapes from thicker stone or granite blocks, which would have resulted in material wastage and extra cost. Casting the concrete in pre-shaped moulds had the advantage of providing any desired shape in addition to the ability to economically produce the required surface texture. Use of metal panels would have provided the curved shape and would have been lighter than UHPC panels but would not have provided the required surface texture with the ribbing surface texture depicted in Figure 2. The final appearance around one of the curved corners of the building (Figure 5) depicts extremely smooth curves formed by the precast panels even though that was disturbed by the flat or chorded appearance of the glass and zinc panels.

Panel Design

The panels in their final position support their self weight in the plane of the wall as well as wind loads acting out of plane or perpendicular to the wall. The panels also transmit seismic forces that act in any direction to the backing frame. In addition due to the different thicknesses within the panel and the configuration of the thickened portions of the panels (face and back ribs) in-plane forces develop from the arching action. To minimize such forces and have the panels behave as close as possible to a statically determinate elements, the CPCI Design Manual (2007) guidelines for design of precast panel connections were used in obtaining the support boundary conditions, refer to Figure 6. These boundary conditions were used in the structural analysis of the panels to permit accurate determination of force distribution and minimize internal stresses. It also permitted movements in the plane of the panel to accommodate temperature effects. The expected movement was accommodated in the support angles that are part of the backing frame and were designed by others.



Connection	Restraint*		
	X	Y	Z
A	1	1	1
B	1	0	1
C	1	1	0
D	1	0	0

*Restrained = 1
Free = 0

Fig. 6 – Typical Connection Arrangement (CPCI Design Manual, 2007)

Wind loads on the panels were calculated in accordance with the 2005 National Building Code of Canada and checked against the 2006 British Columbia Building Code. The net wind suction and pressure loads including internal pressure effects at the corner or end zones of the building were 1.91 kPa and 1.54 kPa, respectively. As the panel thicknesses were quite small, seismic loads which are function of the panel weight were not critical.

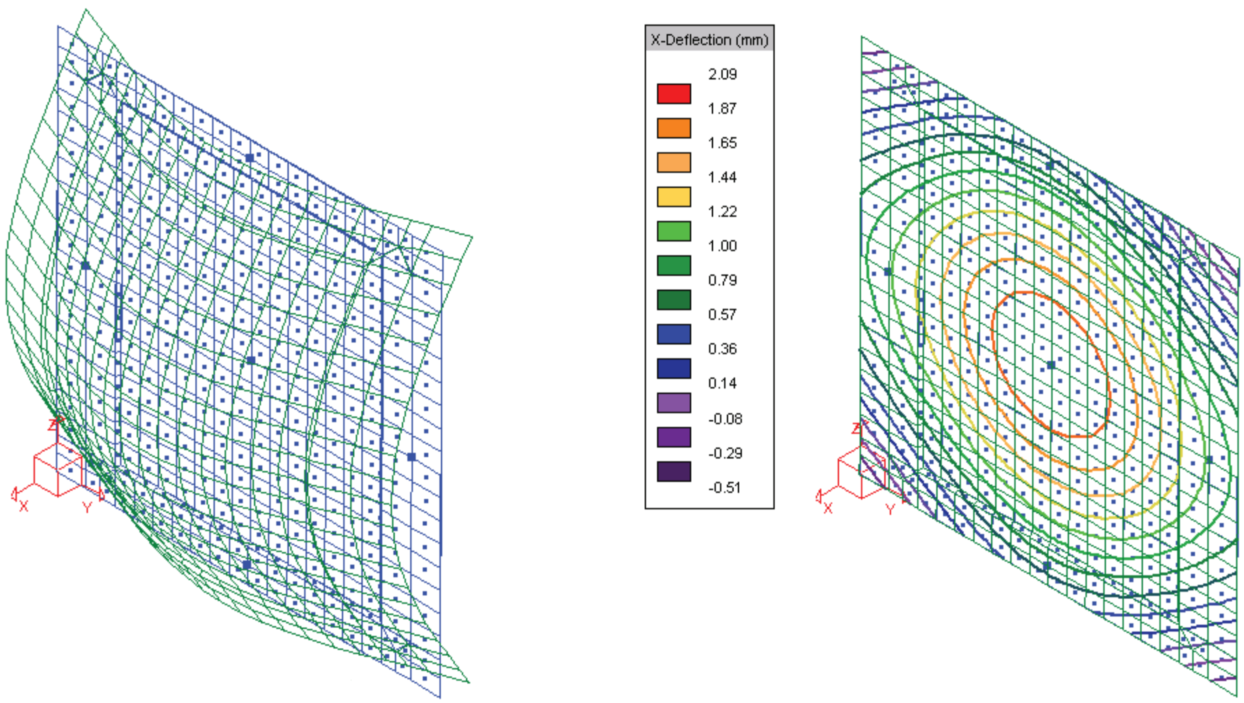
Design Challenges

Close collaboration between DIALOG and Lafarge was crucial for the successful design of the panels. UHPC material properties were investigated for many UHPC mixes, especially that no steel fibres were allowed in the mix to avoid rust stains on the surface. In addition, the desire to have panels with as light a colour as possible to reflect sunlight and reduce cooling loads, played a major role in tailoring a suitable UHPC mix. Different UHPC mixes were investigated and tested by Lafarge until a suitable mix with Polyvinyl Alcohol Fibres (PVA) was engineered. A new material law (stress-strain curve) that depicts the behaviour of UHPC under compression and tension loading was provided by Lafarge.

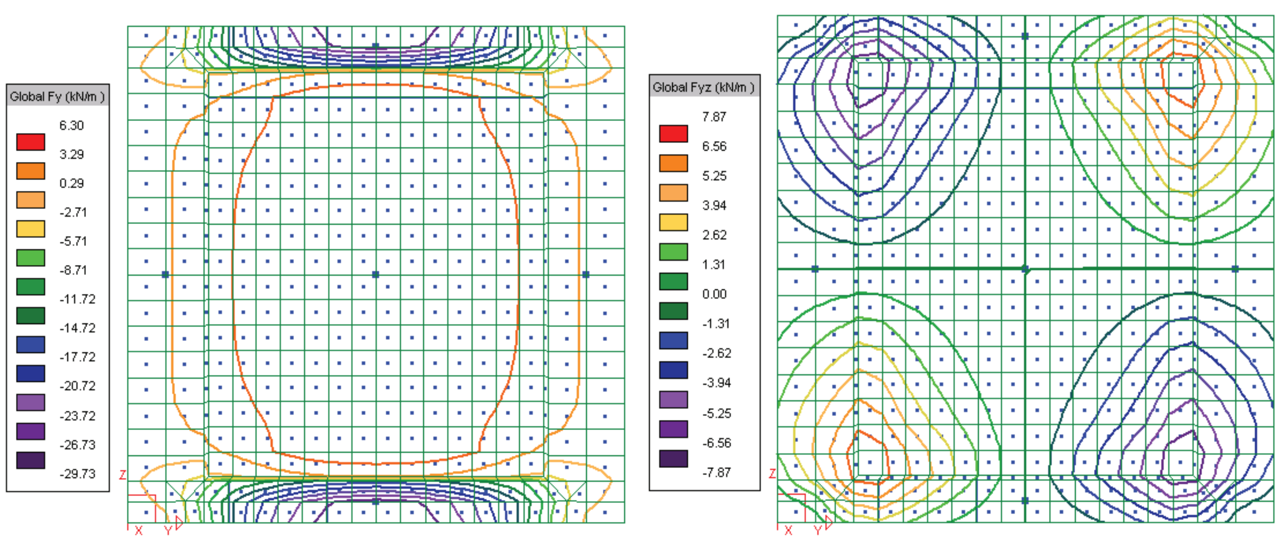
To minimize and avoid corrosion issues no conventional steel reinforcement was allowed to be used in the panels and conventional design techniques in accordance with available standards were not applicable to UHPC. Lack of North American standards and guidelines for use in structural design using UHPC made DIALOG carry out preliminary engineering based on first principles and available literature (main references used are listed at the end of this document). The results of the preliminary engineering were conveyed to Lafarge and the UHPC mix was tailored accordingly. This allowed early investigation and testing to confirm the support anchor capacities and proper modifications to the project schedule without affecting the completion date.

Detailed engineering of the panels was carried out using the finite element method of analysis. Thin shell elements were used to model the panels and obtain the internal forces and principal stresses. The principal stresses were then compared with the material mechanical properties provided by Lafarge; refer to D-AN1300FW. In addition to stresses the lateral displacement of the panels was limited to span/600 and that played a major role in the selection of the panel thickness due to connections with the glass units. Some of the analysis results under wind suction loads are shown in Figure 7.

The connections to the backing or support system were simplified through the use of bolted connections utilizing commercially available inserts placed in the thickened perimeter of the panels. Typical connection details are shown in Figure 8, while Figure 9 shows a panel during construction.



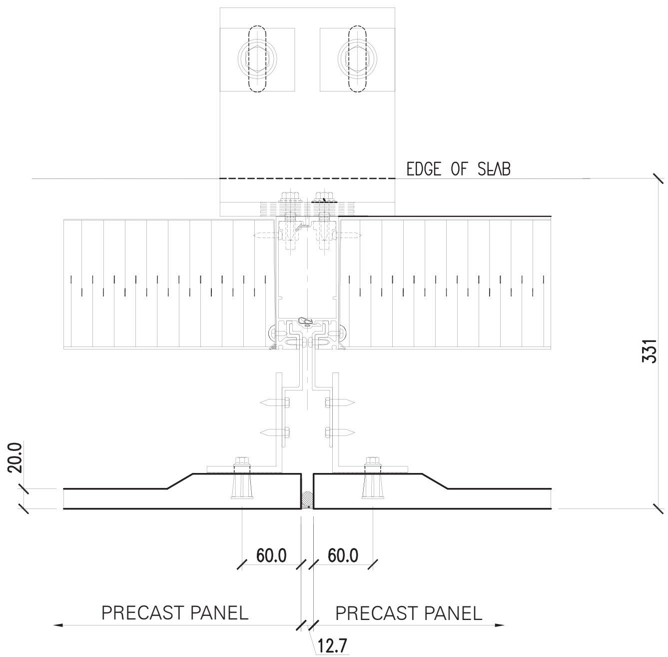
Un-deformed and Deformed Geometry and Lateral Displacement



In-Plane Axial Forces

Out of Plane Shear Forces

Fig. 7 – Sample Results Under Wind Suction Loads



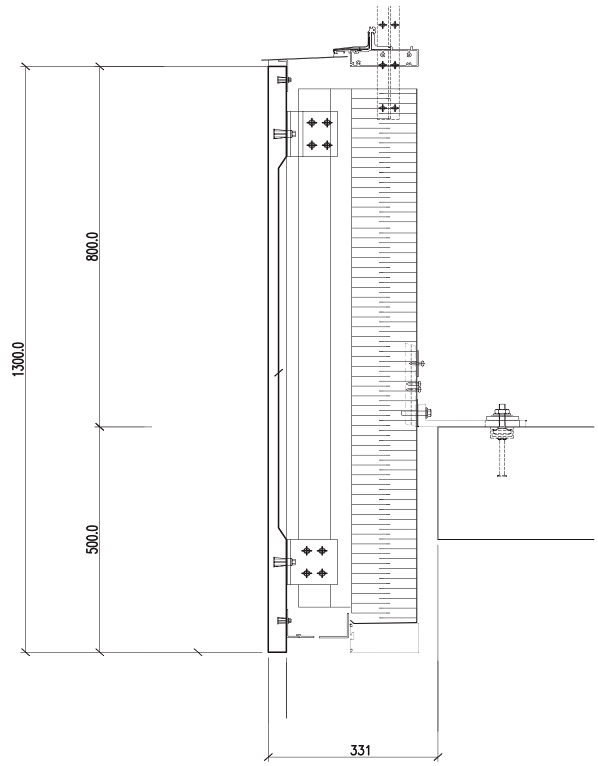


Fig. 8 – Precast Panel Connections

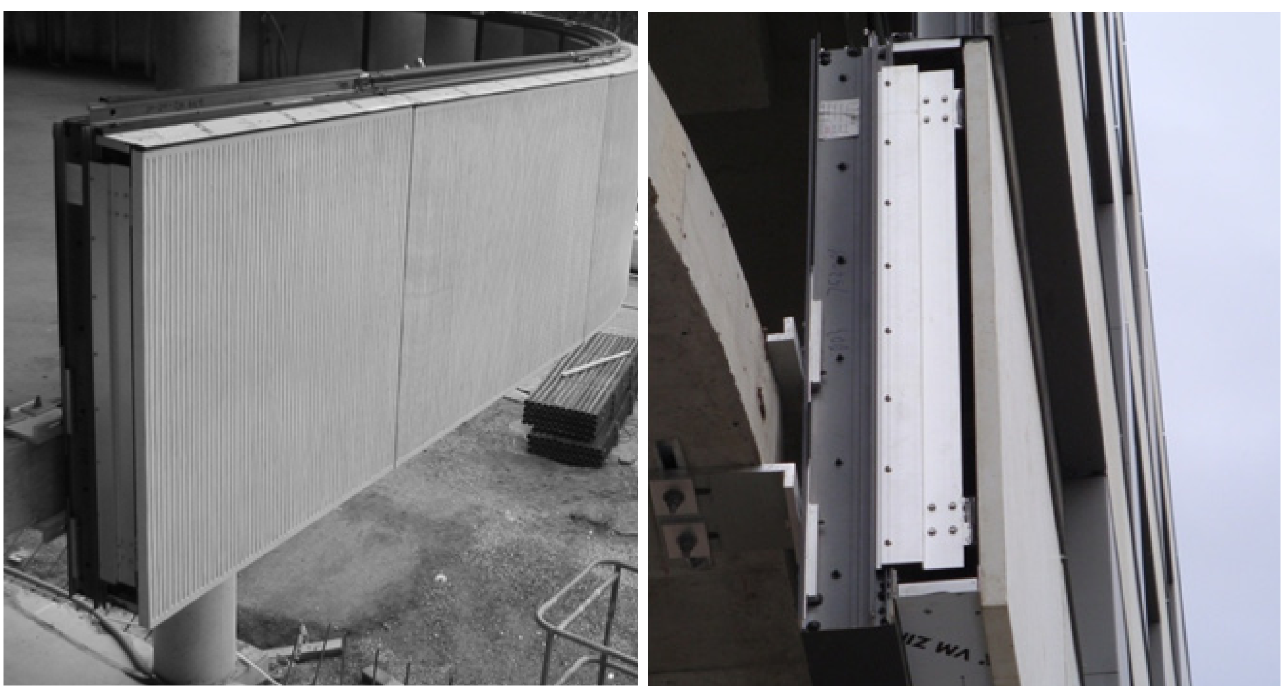


Fig. 9 – Panels During Construction

Panel Materials

UHPC durability characteristics stems from its low porosity that results from a combination of fine and small raw materials; and the fact that the material matrix becomes very dense in comparison with normal or high performance concrete. Typical material formulation is shown below; refer to D-AN1300FW for the specific material used in The Atrium.

Typical UHPC Material Composition

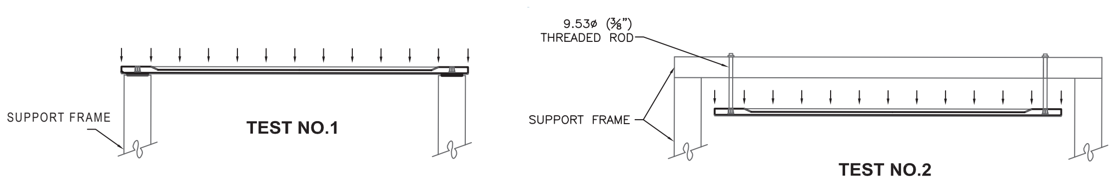
Material	Amount (kg/m3)	% by Weight
Portland Cement	712	28.5
Silica Fume	231	9.3
Ground Quartz	211	8.5
Fine Sand	1020	41
Steel Fibres	156	6.3
Superplasticizer	30	1.2
Water	129	5.2

Tests by Lafarge on UHPC mixes with steel fibres have shown that it will take 1000 years for UHPC to have the same level of chloride penetration as High Performance Concrete would have in 100 years. The mix in The Atrium building, used PVA fibres instead of steel fibres for the reasons mentioned earlier, is still expected to provide comparable results; however at present no test data is available to validate this.

With the expected increase in service life, a sustainable construction is obtained utilizing minimum amount of materials for the intended function.

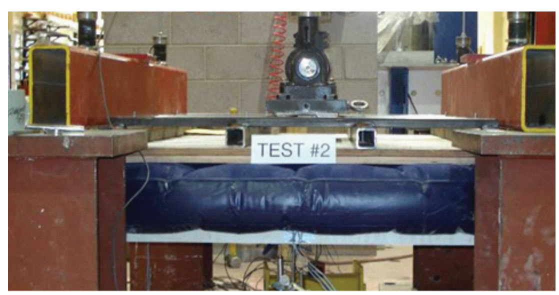
Design Validation

As use of UHPC in The Atrium was a first time application, the structural design of the panel had to be validated by carrying out full scale load testing. DIALOG developed testing program and engineered the testing frame that utilized air mattresses for uniform application of load. All tests were carried out at the University of Calgary. The panels had o be tested in horizontal position due to test equipment and schedule limitations. Figure 10 shows a schematic of the testing arrangement and a panel during tests 1 and 2; that represent panel under wind pressure and under wind suction loads. Test 3 was continuation of test 2 in which the panel was loaded to failure as shown in Figure 11. For, full description of the design and testing of the panels, refer to Ghoneim, et al. (2010). Based on the testing it was concluded that the panel design could safely be carried out using elastic finite element and section design can be based on material models that rely on manufacturer's tests and published data.



Testing Schematic

Top View of Test Set-up for Test No. 1
(texture ribs are facing up)



Side View of Test No. 2
(texture ribs are facing down)

Fig. 10 – Panel in Testing Frame

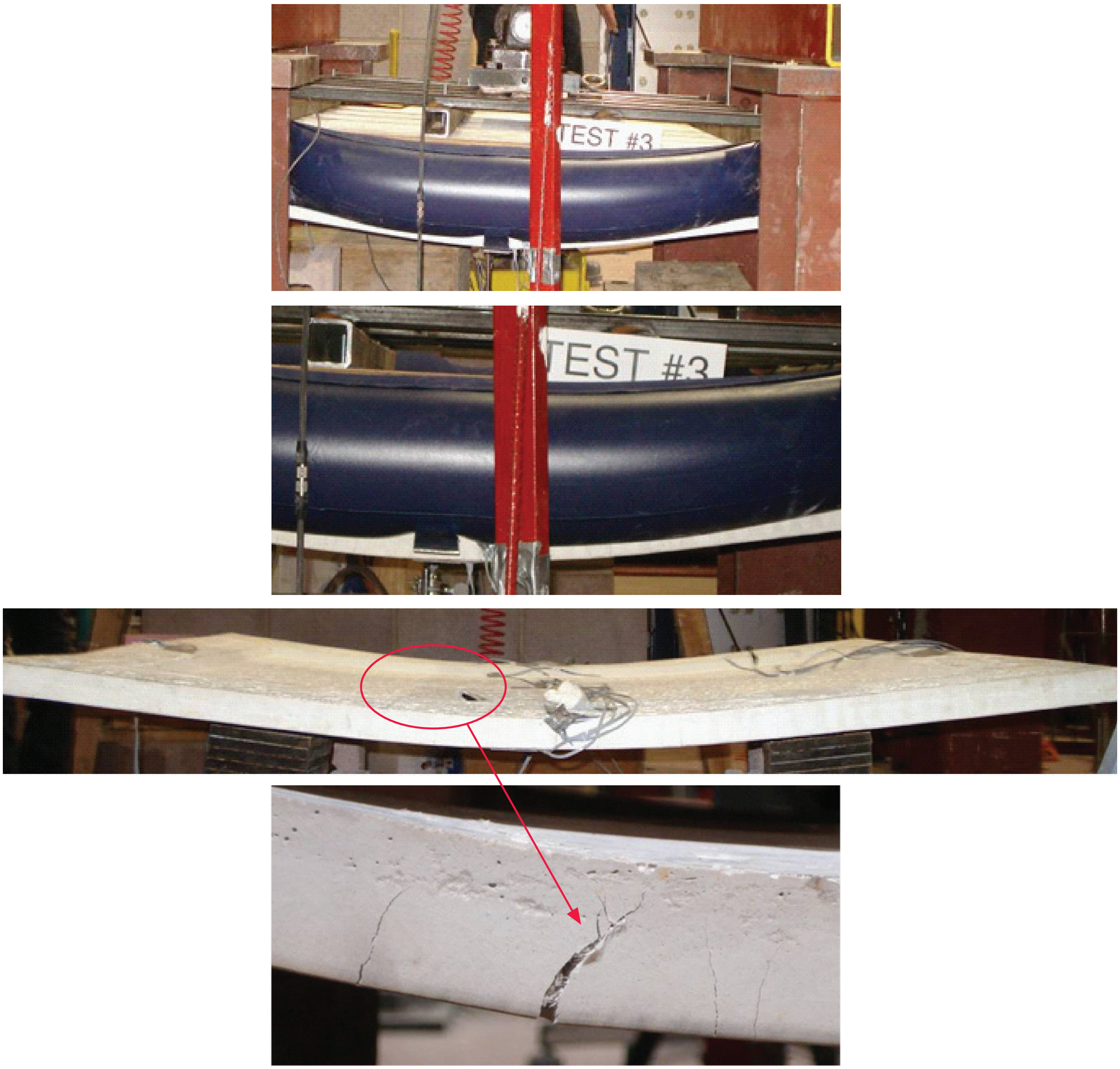


Fig. 11 – Failure of Typical Panel

Performance During Testing

All tested panels exhibited excellent ductile behaviour, which is the goal of any structural design. The amount of ductility exhibited by the panels during testing as shown in Figure 12 indicate the panels can safely support much higher loads than required; however the lateral displacement would not be acceptable for connections with the glass. This was one of the main factors in the selection of the panel thicknesses. The tested panels after cracking were able to deform excessively (ductile behaviour) under loads above those required by the design until failure at about four times the design load. This indicates that panels with lesser thickness would have been sufficient from a strength point of view but would have violated the limit movement of Span/600.

Fig. 12 – Lateral Displacement of 1700 mm Wide Panel

Panel Casting

As mentioned earlier, Lafarge's D-AN1300FW UHPC was tailored for use in manufacturing the precast façade panels and organic PVA or Polyvinyl Alcohol fibres instead of steel fibres were used in the concrete mix to avoid any possibilities for rust stains. Organic fibres were also preferred from a handling point of view for safety of the workers as steel fibres tend to cause injury and scratches. From structural point of view concrete with steel fibres would have been preferred as it exhibits better tension stiffening effects and increased ductility after cracking in comparison with concrete produced with PVA fibres. Figure 13 shows one panel during casting and the PVA fibres are visible as the thin white lines in the mix.

Fig. 13 – Panel Casting Forms

The front face texture of the panels was created by allowing the project architect to reflect his creativity by hand-scoring a clay panel which was then used to produce a negative plug and use as form face on all panels. This process allowed the architect to replicate his vision of the building façade into the panels. The surface texture replication was possible due to the mouldability, flowability and self consolidation properties of UHPC. Casting of the panels utilized displacement process and all the panels produced on this project appear to have been hand crafted (Figure 2). For economy reasons, in The Atrium simple non complicated formwork was used using plywood panels and rigid insulation. In Europe, there have been successful applications using steel formwork and other casting techniques to produce complicated shapes such as the one shown in Figure 14.

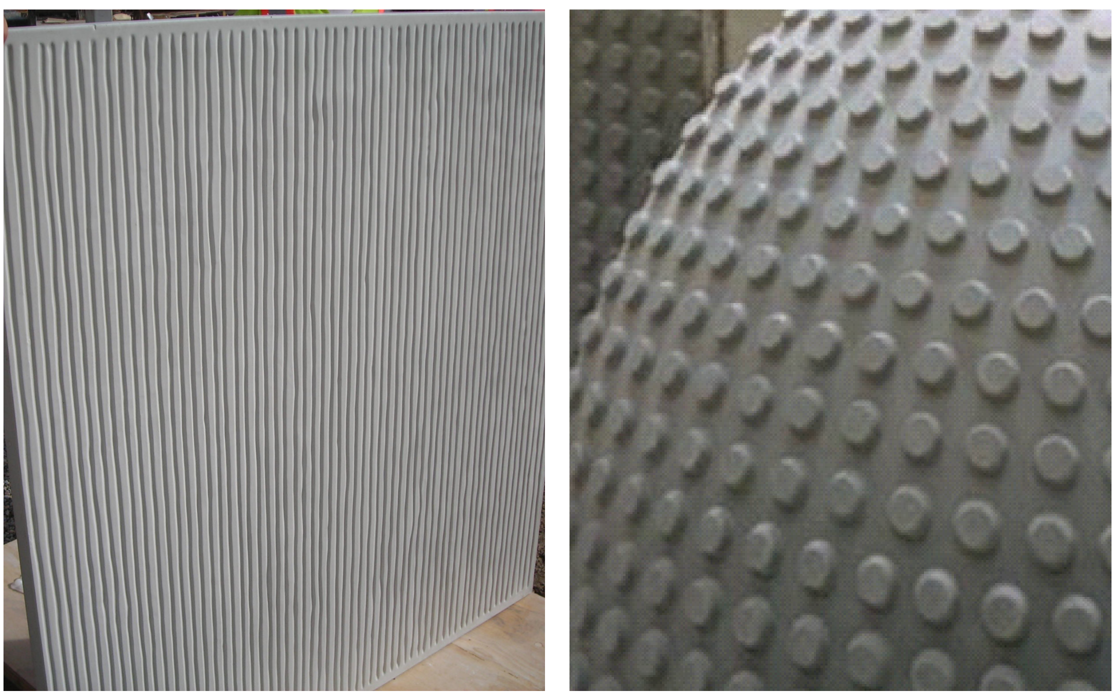
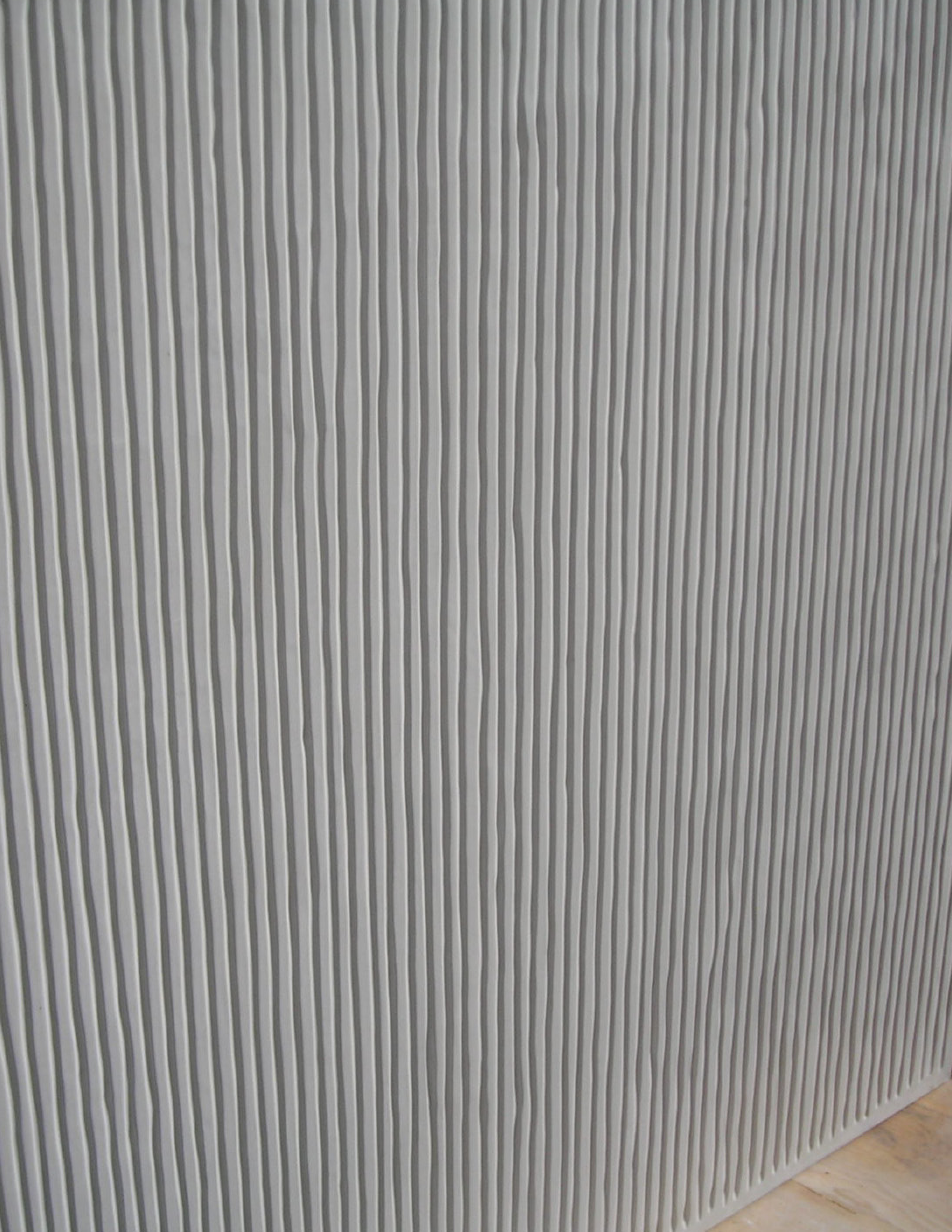


Fig. 14 – UHPC Texture and Curved Form



Project Schedule

From the early stages of the project through to completion it was important to establish and maintain an open, collaborative team approach, with a high level of trust (between the owner, architect, developer and fabricator) in order to complete prototyping, obtain approvals and avoid delays or problems with the project schedule, which was met.

Closure

Recent developments in construction materials technology, combined with the structural engineer's and architect's aspiration to provide sustainable solutions, has resulted in completion of The Atrium; the first building in North America to utilize UHPC cladding panels as thin as 17 mm. The design was based on structural engineering principles and new material constitutive laws, then validated by full scale load tests – due to lack of North American design standards and codes of practice that address UHPC. Furthermore, the design and test results will be used by members of the "UHPC User's Group", formed in 2010 by a group of professional volunteers and by the recently formed (Fall 2011) ACI Committee 239 who's mandate is to develop a UHPC material design guidelines and specifications suitable for use in North America.

The successful application of UHPC in architectural cladding as demonstrated by The Atrium project is expected to lead the way towards utilization of similar panels in future building facades and efficiently utilizes UHPC material properties in architectural design. The result will be long-lasting structures that require less materials and unique designs with ultra-thin panels, complex forms, texture and shapes.

Acknowledgements

- Department of Civil Engineering, Schulich School of Engineering, University of Calgary for carrying out the panel testing in accordance with DIALOG's requirements.
- Blue Rock Engineering for producing the precast panel shop drawings.
- Project images for 'The Atrium' by Bob Matheson Photography.

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