Innovative Design with Ultra-High Performance Concrete: a Case Study

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Summary

In this paper, the authors present a demonstration project carried out to illustrate the huge potential of UHPC as regards with the architectural, the structural, and the construction design. The project consists in designing a 20 m tall staircase joining the uptown of Quebec City to its downtown. The intent of the designers was to produce a structure with a very lightness appearance, which is well integrated with the surrounding nature, and which have a minimum impact on the existing site. Apart from the stainless steel rods used to support the handrail, the entire structure is made of thin unreinforced prefabricated elements of UHPC. It is significant to notice that the staircase designed in this project could not be made with any other material than UHPC. The paper emphasizes the importance of the collaboration between the architect and the engineer at all stages of the project.

Keywords: ultra high-performance concrete, aesthetics, precast, architecture, engineering, tectonic, innovation, construction, design

1. Introduction

The history of architecture shows that the advent of a new construction material invariably upset the conventional beliefs by questioning models commonly accepted until then. But, on the contrary of what one could believe, the development of an innovative material do not yields in itself to the rise up of a new architecture, at least not directly or immediately. It is rather the manner in which the architects, or the engineers, look at the material which will yield brand new shapes or structures. From a cultural as well as a scientific point of view, the attitude of designers with respect to technique (focused on the support or the opposition to progressive values such as changing) play a major role in the development of innovations in construction. Furthermore, it is the ability to consciously handle a new material in different ways which provides the best opportunities to yield significant architectural achievements.

This state of mind guided all the research carried out in Laval University in order to explore new uses for ultra-high performance concretes (UHPC). Our approach is based on the faith that the potential of UHPC to generate new architectural forms results essentially from the particular properties of the material, providing that one accept to question the commonly accepted standards. This approach bet on a tight collaboration between architects and engineers during the entire design process. The objective is to conceive projects with main architectural attributes strongly governed by the intrinsic material properties, in such a way that the project could not be made with any other material. This quest for distinctiveness is expected to lighten the huge architectural potential of UHPC, a brand new material which was used in only few projects until now. The project described in this paper consist to design a UHPC pedestrian staircase joining the Quebec City uptown to its downtown.

2. The necessary collaboration between architects and engineers

The attitudes of architects pertaining to construction are strongly different from those of engineers, especially in North America where these two disciplines are associated with different academic trainings and professional practices. This distinction had take place progressively, but never cease to increase up to now [1]. On one hand, architects describe, explore by trial and error, linger on the object and its effects, subordinate the constructive considerations to ideas and, ultimately, aim to reach an ideal difficult to identify. On the other hand, engineers quantify, accurately calculate, rigorously control the process and its efficiency, and generally subordinate the ideas to the constructive constraints aiming to reach a cost-effective solution to a definite problem. The disjunction between the architecture and the engineering approaches deprive both of them to take advantage of each other forces. This often yield architects to propose solutions too difficult to built or engineers to customary apply proven formula. The creative approach we extol bet on a tight architect-engineer collaboration throughout the design process in order to find an imaginative and ingenious use for an innovative material.

3. Design approach based on the exaltation of the material

Pierre Von Meiss [2] classify the attitudes of architects with regards to construction during the design process in five categories referring to technological issues: exaltation, representation, falsification, submission, and domestication. Throughout history, all those attitudes had make the proof of their ability to produce architectural masterpieces. This is true for the exalting approach which grants the material or technique the power to produce a distinctive architectural code which become, in itself, the essence of the architectural expressiveness. Among others, Candela, Nervi, Perret, and more recently, Ando or Calatrava had produce works which eloquently attest the fruitfulness of this approach in order to enlighten the intrinsic qualities of concrete. This approach is experimental in essence, driven by intuition and sensibility, and always guided by technical considerations. The form is not pre-established; it comes form the formal intuition of the designer, strengthened by its confrontation to the constructive considerations.

We deliberately adopt this approach for designing the staircase, drawing occasionally from the domesticated approach concepts for what they can bring in terms of subtlety and fineness. We had follow our (architect's) intuition and our (engineer's) scientific rigour in order to design an object taking the best advantage of the extraordinary properties of UHPC (high flexural strength without rebars, lightness, and the ability to mould it into complex shapes and thin formworks).

4. The Marchand Staircase

In 1608, Quebec City was built on a rocky headland which has greatly influenced its further development until now. Many pedestrian staircases have been built along this headland, at different periods, and they clearly contribute to the distinctive character of the Old City. Some of them (made of wood, cast iron or steel) are quite representative of the use of new materials at the time of their raising. It happens that Quebec City actually plan to add a new staircase (the Marchand staircase) of about 20 m in height near Salaberry hill street, in a sector still remains wild. A wood structure was first considered for economic reasons, but UHPC is now considered as a very serious alternative, ironically for the same reasons, as a result of the design project described in this paper which was carried out in collaboration with the town authorities. Our willing efforts to explore new ways of using up-to-date concrete technology was thus shared by the persons in charge of the project who demonstrate a praiseworthy good will to support the progressive values of the XXI^{rst} century[1].

[1] As in most cities of patrimonial value, the trend is generally to favour the preservation of historic techniques which constraint the decision making process which rules the architectural or urban development.

The fragility of the cliff ecosystem (made of protruding rocky surfaces scattered over varied vegetation), as well as its irregular topography on a steep slope, was quickly identified as an important feature. To preserve as much as possible the natural site, it was first decided to minimize the number and the footprint of the bearing points on the cliff, to rise up the staircase from the ground, and to choose a path which follows as much as possible the natural outline of the cliff. Still, the material itself suggested some interesting ways to explore how to reach this objective:

- the precast of light elements allows an easy handling of the main components without disturbing the natural site;
- unlike steel, UHPC can be easily moulded and it is thus possible to produce monolithic pieces of complex shape which are structurally efficient without additional bracing;
- the high tensile strength of UHPC without rebars (unlike ordinary concrete) allows the making of very thin elements and the use of long cantilevers which increase significantly the span of slender elements.

After a careful analysis of the site, a path was drawn to closely follow the cliff's outline by using four identical flights in order to simplify precasting (Fig. 1). Each of these flights stands on two bearing points only. The landings act as points of articulation to settle the travel path as a function of topography and existing vegetation. They are simply supported at the cantilevered ends of the stringboards. The success of the project rest, for a good part, in the design of those stringboards which have to be, not only structurally efficient, easy to produce and handle, but also elegant in shape in order to illustrate the constructive qualities of UHPC. Inspired by the poetics of construction, that Frampton called tectonic [3], which seeks to exalt the material and technique, our design process was made of successive trials and errors involving architect/engineer interactions. This process yields to adopt a one piece stringboard element of about 10 m long standing on two bearing points only 4 m apart due to the slope of the cliff (Fig. 2). The use of cantilevers, suggested by the material itself, provides a better distribution of the flexural moment diagram which help to reduce significantly the stresses into the structural elements. The V-shape cross section of stringboard is 60 cm in height by 1,20 m in width. It contains no rebars since UHPC (only reinforced with short steel fibres) could sustain a 20 MPa flexural stress up to first cracking while the material further exhibit a highly ductile behaviour. With a 5 cm only wall thickness (except at the ends of cantilevers where the section is lightly thicker to support landings), the stringboard is still well oversized since the maximum flexural stress caused by the factored loads never exceeds 10 MPa. Limited to four units only, those monolithic stringboards are piled up easily which facilitate their transportation.

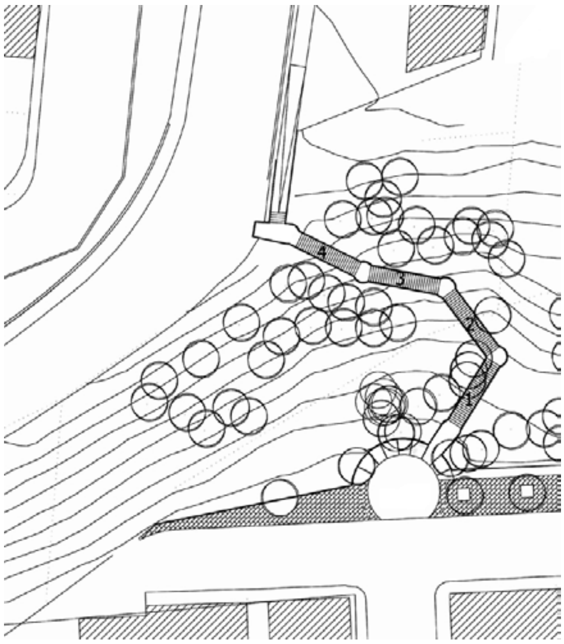

Fig. 1 View in plan of the staircase

Fig. 2 Front view of a stair flight

Each of them merely weight 1500 kg so they can be easily handle at job site with only light lifting equipments. The entire staircase requires less than 6 m^3 of UHPC which eloquently illustrate the structural efficiency of the material. The structural analysis of the staircase is described elsewhere [4].

The landings, which ensure the continuity of the path between stringboards, are simply made of circular plates of 2,4 m in diameter and only 6 cm thick. Those plates can be easily truncated in order to fit any angle formed by two adjacent stringboards. The extreme thinness of landings and the apparent lack of support reinforce, as wished by the designers, the strong feeling of lightness which emanate from the entire staircase. Similar plates of the same thinness are used as junction elements between bearing points at the bottom (footing) and at the top (belvedere) of the staircase,. These both elements (footing and belvedere) are made of cast-in-place ordinary concrete massive structures in order to accentuate the contrast between the heaviness of the construction belonging to the urban space, and the lightness of the staircase which link them together.

Each cantilevered step is exactly the same with a total width of 1,8 m (1,2 m between bearing points). Those steps also contribute to enlighten the specificity of the material. Their geometry take advantage of the flexural and the torsional strength of the material as well as its ability to be easily cast into moulds of a complex shape with very thin slots (Fig. 3). Is it a block in which subtractions were carried out, or is it a series of side by side tetrahedrons? This ambiguity in the step reading, a kind of unusual triangular block from which depend the security of the pedestrian during its walk, raises questions about its nature, its structural logic, its manufacture and its relationship with the rest of the structure. Viewed from the bottom, the risers look massive but, viewed from the top, they look light, brittle, and made of distinct elements joined together only by their tips. The reading of the function and of the nature of the steps is thus radically different from that of a conventional staircase.

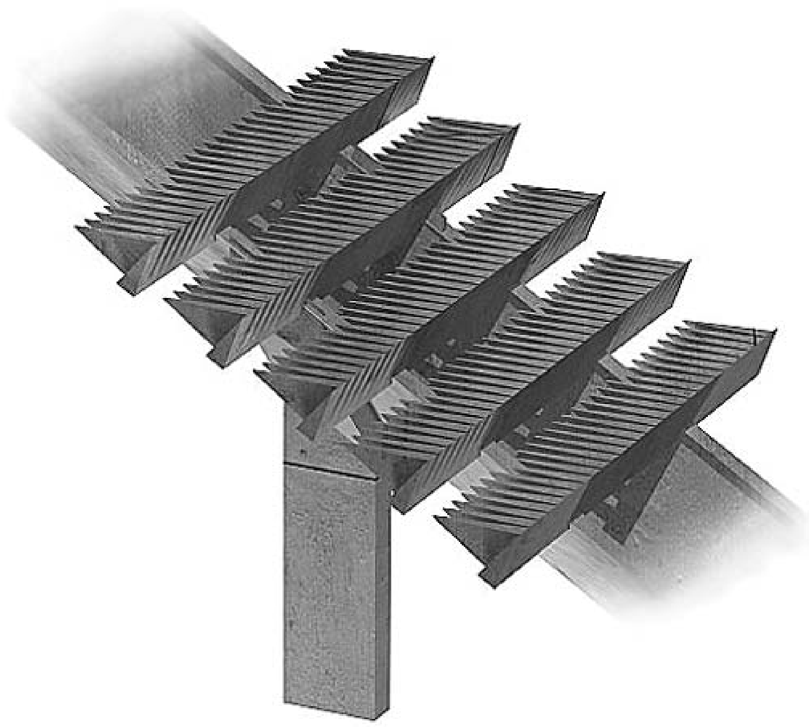

Fig. 3 Axonometric view of the steps

When pedestrians go down the stairs, the invisibility of the stringboard increases the feeling that the stairs float into the air, which contrast strongly with the impossibility to see through the structure downward.

Similarly, when pedestrians rise up the stairs, the heaviness of risers disappears as the eyes of the pedestrian go down revealing the contrast with the transparency of the treads which reveals the bearing stringboard. No other material, monolithic as well, could provide such an insight about the way in which the staircase is linked to the ground.

The handrail is an unavoidable security device for a public staircase. The link between the handrail and the rest of the structure may have a major influence on the way in which pedestrians perceive and understand the structure. Notwithstanding the aesthetics properties of the architectural work, it seems important to appeal the user's sense of touching since the UHPC may have a very pleasant tactile texture ranging from a rough to a very smooth finish depending on its mixture composition and the nature of the formwork. Concrete thus acquires a new status, which counteract the long time upheld negative perception of people against concrete.

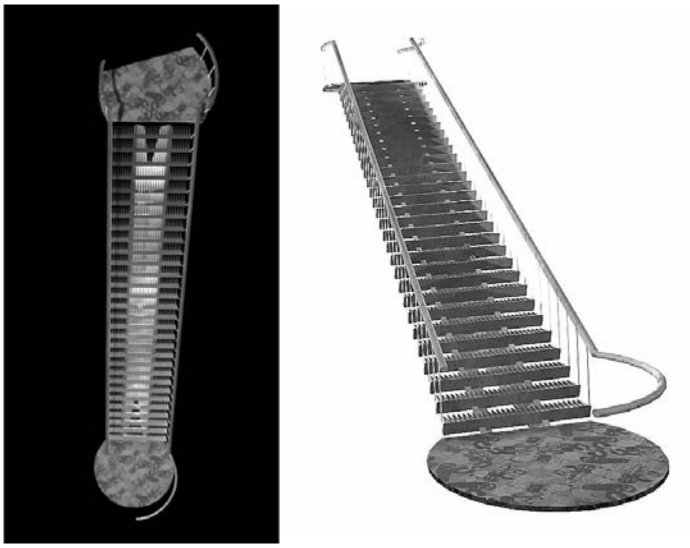

Fig. 4 Axonometric view of a stair flight

The handrail is only supported by thin stainless steel rods (only 19 mm in diameter) embedded into a concrete outgrowth at both ends of the steps. With the exception of joining bolts, those rods are the only component of the staircase which is not made of BUHP. According to the design concept, they act as an almost immaterial link between the handrail and the stand-alone staircase frame suggesting that this handrail freely float over the concrete structure. A global view of the staircase, and all its main components, is shown in Fig. 4. The set of steps on the stringboard forms a triangular section which provide a high resistance against torsion in case of asymmetric loading.

UHPC mixtures usually contain silica fume in order to increase their compressive and flexural strengths. It was decided to add a significant amount of silica fume (about 20% in mass of cement), not only for strength purposes, but also because it gives to concrete a dark gray color which is quite the same that the color of the salient limestone easily seen on the surface of the cliff through vegetation. This contributes to a close integration of the staircase with its surrounding and, during winter, the contrast with the whiteness of snow is such that the structure could hardly be associated to concrete. This is quite interesting as regards with the questioning about the true nature of the material: it is a matter of concrete, but not an ordinary concrete.

The exceptional durability of UHPC is another very significant advantage of the material when one considers the rigorous weather conditions of Quebec City in winter. The service life of UHPC is most likely expressed in terms of centuries and, during this period, the material requires no maintenance unlike steel and wood which require regular checkups in order to prevent, or repair, rust or putrefaction damages. Further considering the relatively low initial cost of the precast UHPC elements, the project becomes very attractive, even from an economic point of view.

5. Conclusion

The construction of a staircase is evidently not an important event in itself. Such a structure is not expected to be produced in many duplicates either. However, when considered as an exhibition project, the staircase acquires the status of an innovative work, which highlight the architectural potential of this brand new material, while minimizing the risks incurred. In that way, it opens the doors for more challenging projects by revealing to the architects the design possibilities offered by the intrinsic properties of that material. It also emphasizes the importance of collaboration between architects and engineers at all stages of the creative design process. Notwithstanding the role of architects and engineers, it still remains that the integration of innovations into construction also requires a strong commitment of the sponsor, the builder and, very often, the political power and/or the insurance broker. The future of UHPC depends entirely on the ability of those different contributors to work together in order to take advantage of its architectural, structural and constructive properties; and to use it in a completely different way than ordinary concrete.

6. Acknowledgements

The authors want to acknowledge M. Louis-Daniel Brousseau, architect in the town planning department of Quebec City, which was the initiator of this project. They also acknowledge Quebec City and Laval University for their financial support.

7. References

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