The Lusail Towers and Podiums: an UHPFRC Innovation Story

Jenine Principe (corresponding author) – Architect, PhD, C&E Engineering, Paris, France, Email: principe@ceingenierie.fr

Jean-Marc Weill – Architect-Engineer and Director, C&E Engineering, Paris, France, Email: principe@ceingenierie.fr

Abstract
The paper will describe the normative context and the calculation methodology applied for the Ultra-High Performances Fibre-Reinforced Concrete (UHPFRC) (Ductal® White PVA Fibers) panels realized for the Lusail Plaza Podium buildings, a project by Foster + Partners in Qatar. C&E Engineering, together with the manufacturing company Doha Extraco, provided more than 25.000 panels.

The unusual scale of intervention, the crossing of different structural engineering cultures (the complex superposition of American and European codes), the use of BIM software as a universal technical tool, the use of a new material such as UHPFRC, obliged us to reframe our design habits. Starting from this hypothesis, the paper, will focus on:

- how the differences between the design objectives and the technological constraints (the machine, the materials, and the construction process) affect the quality of the final result;
- the role of the architectural and technological knowledge in the design process and on its outcome;
- the possibility to deduce a common practice from the experience in order to generalize the applied design process.

The paper will also illustrate the international framework of the project (the panels were manufactured in Qatar, designed in France, and 3D-modeled in India and China), which required an innovative coordination set-up.

The Lusail Plaza design process is built on the idea of "reasoning about actions" (Simon, 1966): starting from an initial situation, a set of possible choices and constraints restrict the applicability of the actions that will affect positively the design.

Keywords: UHPFRC, Design Criteria, Innovation, Technique and Culture

1. Introduction

Gilbert Simondon, a French philosopher who worked on the connection between technique and culture, wrote that a technical gesture can pledge the future, changing the relation of the man with the environment and, for extension, the environment itself (Simondon, 1965). This concept can be clearly understood thinking about the industrial revolutions when the rapid evolution of techniques shaped the modern society and our way of living.

Architecture and Engineering, which are currently undergoing a huge transformation due to the Forth Industrial Revolution, are strongly impacted by new means of industrial production, cyber-physical systems, and digital-computational technologies (Forcael *et al.*, 2020). The digital tools can be considered a disruptive technology, i.e. capable of radically transforming the design process. There is no doubt that many of the new formal characteristics that have appeared in design are influenced by the computational systems that have allowed them: an increased complexity that could not have been managed without the new tools, which let us control all the project information and not only a representative sample. And it is precisely in the abundance of information – its quantity – and on its evaluation – its quality – that lies the core issue of the digital design: a matter whose solution ca be only partially solved thanks to technology, since the "big data" interpretation is still a responsibility of the designer.

Perfectly fitted in this background, the Lusail Plaza Project, by Foster + Partners involved a team of specialist literally spread all over the world: main client: Lusail Real Estate Development Co (Doha, Qatar); designer: Foster + Partners (London, UK); supervision consultant: Dar (Beirut, Lebanon); main contractor: midmac, MIC Construct (Doha, Qatar); contractor's lead designer: Arcadis (Amsterdam, Netherlands); sub-consultants: UHPFRC manufacturing: Doha Extraco (Doha, Qatar); UHPFRC specialist: C&E Engineering (Paris, France); BIM specialist: Neilsoft (Pune, India). With a total area of 1.1 million sm, the project includes 4 towers surrounded by 12 minor buildings – the Podiums – all arranged symmetrically around a central plaza.

C&E Engineering was responsible of the development of the executive models, drawings and calculation notes of the UHPFRC façade and roof panels of 6 of the 12 podiums, which included more than 25.000 panels. The intrinsic complexity of the project – due to its scale, to the remote working and so on – was ulteriorly improved by the difficulties linked to the information management and by the use of an innovative material such as UHPFRC.

This paper will focus on the relation between design processes and technological innovations – precisely UHPFRC and Building Information Modeling – and on their role in the construction sector.

Figure 1. The Podiums. Photo by midmac.

2. Lusail Plaza Podium Buildings: UHPFRC Façades and Roofs

2.1 General Project Description

The Podium buildings have a double façade (i.e. an internal and an external layer) characterized by a white modular (1.5 m, 4.92 ft) façade, realized in UHPFRC panels (Ductal® White PVA Fibers). C&E Engineering, together with Neilsoft – BIM modelling – and with the manufacturing company Doha Extraco, worked on the optimization of the panel shapes and on the fixing system conception. To reduce the number of calculation checks and to standardize the 3D modelling, the panels were subdivided in main and sub-types: the main type dimensions are 4.5*1.5 m (14.76*4.92 ft) with a minimum thickness of 20 mm (0.79 in) and a maximum one of 80 mm (3.15 in). It is fixed by 6 brackets, 2 dead-load joints and 6 wind joints, connected to 5 different secondary steel structures, with a span of 3 or 1.5 m (9.84 or 4.92 ft). The external panels and their fixing system were checked considering a "fall-out" scenario i.e., a case in which one of the dead-load brackets suddenly loses its load-bearing capacity.

The roof panels are mainly fixed using grout, but in several cases brackets were required to reach the steel structure underneath. Each panel and its support system were modelled in a BIM software (up to LOD 500), linked to a cloud platform where the 3D models were shared in real time with the other actors involved in the operation. Also the construction drawings – around 450 and up to 1:5 scale – were directly extracted from BIM models.

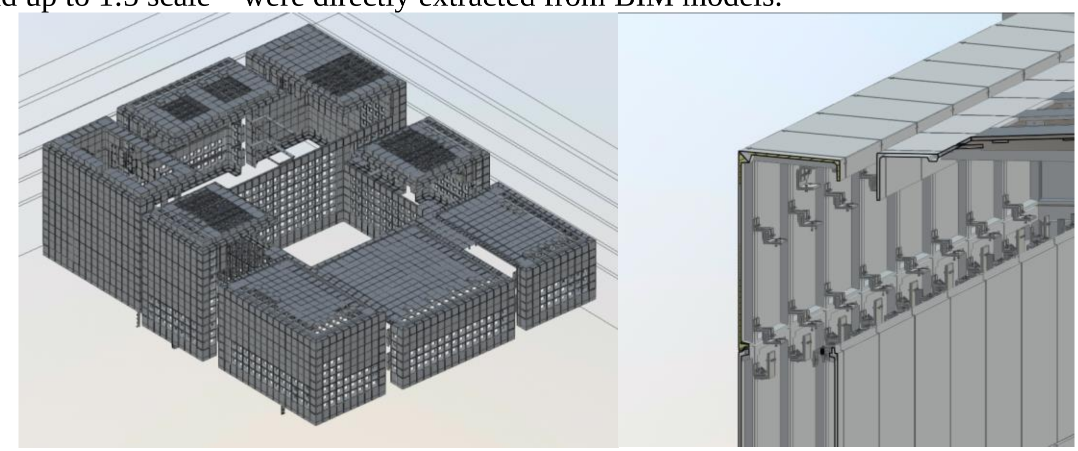

Figure 3. One of the 6 BIM models. Global view and details.

2.2 Structural Analysis

Ductal® White is an UHPFRC with PVA fibres, giving the material a ductile behaviour under flexion. The properties of the material without heat treatment at 28 days are the followings:

Table 1. Ductal White properties

Young modulus	$E = 45$ GPa
Poisson-Ratio	$\nu = 0.2$
Creep coefficient	$\varphi = 1.0$
Fibre length	$L_f = 12$ mm
Weight	$\gamma = 23$ kN/m^3
Temperature elongation coefficient at 28days	$\lambda = 12$ µm/m/°C
Characteristic compressive strength	$fck = 120$ MPa

Characteristic value of Limit of Proportionality	*sLOP= 16.51 MPa*
Characteristic value of Module of Rupture	*sMOR = 16.56 MPa*
Characteristic value of limit of elasticity under tension	*fctk,el = 8.2MPa*
Characteristic value of post-cracking strength	*fctfk = 3.8MPa*

The behaviour curves below were used for stress and displacement analysis, which was conducted using the Allowable Stress Design (ASD) method:

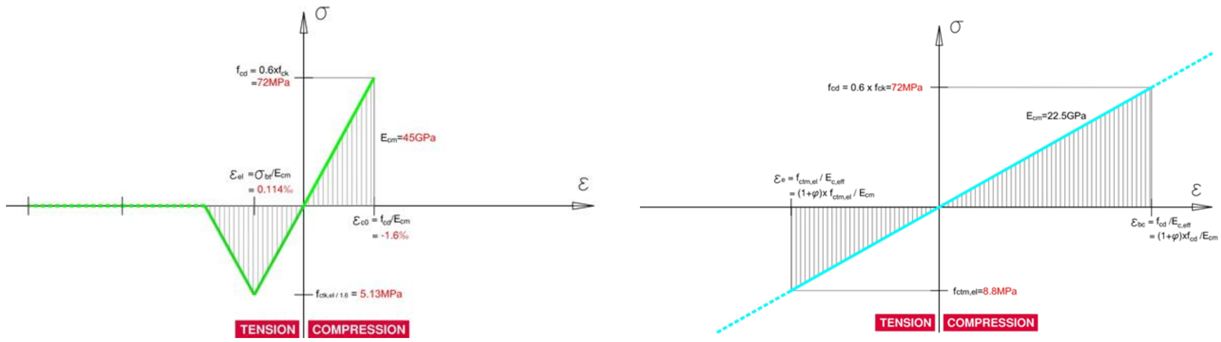

Figure 4. On the left, stress curve and, on the right, displacement curve as used in the ASD analysis.

For the stress analysis, the behavior curve is defined with an instantaneous elastic modulus (E_{cm} = 45.000 MPa). The tensile elastic stage is limited to $\varepsilon_{el} = \sigma_{bt}/E_{cm}$ = 0.114‰, since no crack opening is usually admitted. A global tensile strain of 0.364‰ is however still acceptable, if the cracking value is below 0.02 mm. The limitation of compressive strain is fixed to ε_{co}= 1.6‰.

A two-step safety strategy was applied: the first step consisted in the application of a 1.6 safety factor on the material tensile capacity (a factor more conservative of the one used for metallic fibers, which is 1.3); the second step consisted in keeping the material in the elastic range, limiting the cracking value to 0.02 mm (however, in the 90% of the cases, a 0 crack limit was respected). The nonlinear capacity of the material is not used.

For displacement analysis, the behaviour curve is defined with a delayed elastic modulus (E_v), taking creep into account by using a coefficient equal to (1 + φ). E_v is given by $E_{cm}/(1 + \varphi)$. Considering φ equal to 1, we obtain E_v = 22.500 MPa.

Table 2. Coefficients and factors

Coefficient for long-term effects on compressive strength	$\sigma_{cc,\ ASD}$	0.6	[-]
Fibre orientation coefficient global effects	K_{global} (K)	1.35	[-]
Fibre orientation coefficient local effect	K_{local}	1.8	[-]
Partial safety factor of material Premix	γ_{cf}	1.6	[-]
Height of the bending test prism	H	70	[mm]
Characteristic length	L_c	53.3	[mm]
Length of fibers	L_f	14	[mm]
Creep coefficient	φ	1	[-]

The verification method the non-reinforced Ductal® PVA White is not specified by National addition to Eurocode 2 (NF P 18-710, 2020). However, it is possible to adapt what established by the codes for metallic fibers UHPFRC. In the following tables the hypothesis used for UHPFRC calculation are summarized.

Table 3. UHPFRC General hypothesis

CRITERIA	RETAINED VALUES FOR CALCULATION	SOURCE
Navier-Bernoulli Hypothesis	Plane sections remain plane	*NF P 18-710 [3.1]* *EN 1992-1-1 [3.2]*
Durability	Limit calculated crack width established	*NF P 18-710 [3.1]*
Partial safety factor for fibre	$\gamma_{cf} = 1.6$	*ID Card from LAFARGE [3.4]*
Factor of dispersion in fibre distribution for global analysis	$K_{global} = 1.35$	Suitability tests
Factor of dispersion in fibre distribution for local analysis	$K_{local} = 1.8$	Suitability tests

Table 3. ASD calculation

CRITERIA	RETAINED VALUES FOR CALCULATION	SOURCE
Stress-strain law	Linear elastic	*NF P 18-710 [3.1]* *ID Card from LAFARGE [3.4]*
Maximum compression stress in UHPFRC area element	$\sigma_{bc} \leq 0{,}6 \times f_{ck}$ = 72 MPa	*NF P 18-710 [3.1]* *ID Card from LAFARGE [3.4]*
Maximum tensile stress in UHPFRC area element	$\sigma_{bt} \leq f_{ctfk} / K_{global}$ = 5.13 MPa	*NF P 18-710 [3.1]* *ID Card from LAFARGE [3.4]*
Strain limitations	The strain limitations are relative to the stress limitations.	*NF P 18-710 [3.1]* Behaviour curves described in Chapter §4
Crack width limit	No crack opening in the service stage.	*NF P 18-710 [3.1]*
Creep factor	$1 + \varphi$ = 2.0	*NF P 18-710 [3.1]* *ID Card from LAFARGE [3.4]*
Deflection limit	Wout_of_plan ≤ L/500 Win_plane ≤ L/500	*Confirmed by the contractor*

2.3 Podium buildings: a concrete innovation story

As it is well known, we can have two different kinds of innovation, of product and of process. In the Lusail Plaza project, we can find the first one in the use the UHPFRC while the second one is mainly expressed in the use of BIM software. However, in every innovation story there are several contradictions, often due to the difficulties linked to the assimilation of new products and techniques by the construction sector, reluctant to abandon technologies and methodologies which have been in use for centuries.

This is particularly true for UHPFRC concretes, whose contradiction has, in this case, three levels: ontological, productive, and normative.

Ontological. Undoubtedly falling within the panorama of advanced materials − thanks to the mix-design optimization at the nanometric scale which is responsible for the high density and resistance − in the collective thinking UHPFRC are still assimilated to conventional concretes, both in their production methods and in their morphological and aesthetic expression. This often led to continue demonstration of the material capacity, going well beyond the usual calculation note: for the Podium façades, it was required to add an honeycomb net behind the panel, in order to avoid a brittle fracture in the case of an unexpected event. The solution – in contrast with the very essence of the material, which was conceived to obtain a ductile concrete thanks to the addition of fibres – was discarded only after performing an impact load test.

Productive. UHPFRC production methods maintain a strong continuity with the past, which is manifested entirely in the permanence of the mold which, although innovating in technology, it is the emblem of a technique that remains essentially the same. It is true that digital manufacturing breaks down the limits of its construction through numerical control machines, 3D printers and so on, but it is equally true that the creation of the mold is a question that remains entirely artisanal, undoubtedly evolved, but in the technologies more than in its logics. The 25.000 and more panels were entirely realized using wood molds, modified several times during the prototype shaping process.

Normative. Very few countries have a complete normative background for the UHPFRC calculation, including France (NF P 18-470, 2016; NF P 18-710, 2020) which developed its standards in the framework of the Eurocodes. However, for the Lusail Plaza project the American standards were applied (IBC, 2018; ASCE/SEI 7-16, 2016; ACI 318, 2004). The European and American standards have very different philosophies: the former in fact consider two limit states – service and ultimate – both used for checking the capacity of structural elements; the latter uses or the Allowable Strees Design (ASD) or the Load and Resistance Factor Design (LRFD). Only LRFD is comparable with the Eurocodes (EC), with which it differs, for example, in the safety approach: the EC uses material's partial safety factors, while in the ACI provisions the nominal moment capacity of the section is reduced by an overall strength reduction factor. In LRFD, the material can pass its yield strength (Hawileh *et al.*, 2009) – as a compensation the loads are increased – while in EC, the material can reach its whole capacity – always considering the safety factors – only in the ultimate limit states calculation. At the contrary, ASD keeps the material capacity in the elastic range, without using load factors in combinations. As said before, for the Lusail Plaza project, the UHPFRC behavior curve as given by the producer was calculated according to EC – please see paragraph 2.2 –, while the loads and their combinations were given by ACI codes.

If applying the LRFD method, the calculation resulted too conservative, since the material characterization was incoherent with the applied loads. Moreover, for aesthetic reason, an almost-0 cracks rule was also mandatory so implying to have the material under the elastic limit, so in contrast with the LRFD approach. For these reasons, it was decided to switch to ASD for concrete calculation, while the LRFD was maintained for connections check.

The same level of complexity was found in the design process articulated around the BIM software: besides changing the way a building is drawn or visualized, BIM is also defining new processes from design to maintenance phases (Safikhani *et al.*,2022).

However, the implementation of the BIM process is still to be completely assimilated in the construction sector. In Lusail Plaza, for example, 3D models have been used to resolve constructability problems, to perform interference analysis, to organize purchases and deliveries of materials, to verify progresses on site and so on. Yet, a lot of information were still transferred using Request for Information files, schedules, physical submittals and 2D drawings.

This demonstrates how we are in a transition phase, where process innovations collide with actors and methodologies unable to keep up with the new structures. In particular, the clash develops around several factors: the functionality and accessibility of BIM tools, the demanding data management, the cost of hardware and software upgrades, the training required to prepare the engineers and the construction workers, the lack of well-established protocols to define roles and responsibilities (Safikhani *et al.*,2022). Moreover, in more or less 10 years there have been a passage from 2D − which is only a mechanization of a system of representation remained unchanged for centuries − to a new approach which can be defined a paradigm shift: a 3D BIM model becomes a new way of building, where the distinct phases of design and construction overlap almost completely and are probably aimed at losing definitely their boundaries (it suffices to think about the potential of digital manufacturing, including 3D printing).

The described scenario among new materials, new processes and different codes, is representative of a current a-synchrony between design process and innovation: the latter, in fact, does not always have enough time to settle in the cultural – and in this case also normative – tradition of the project and become an integral part of it. However, in this missed alignment there is space for evolution: the often "uncertain" progress that characterizes the project over time generates an accumulation of knowledge, a pre-figurate set of solutions which significantly reduces the distance between the design common practices and the technological innovations.

3. Conclusion: Reasoning about Actions

The experience of the Lusail Plaza project opened a broader reflection on the positioning of the design in a context of very rapid evolution. In the past the limited resources, the need to use local techniques and materials as well as the scarce circulation of information guaranteed an easier cultural continuity in construction practice, and therefore in design processes. The industrial revolutions unbalanced this relationship, since the "industrial" material culture has neither become a real collective heritage. The industrial products are accepted for the advantages they offer, but the widespread understanding of their technologies is made difficult by the complexity and specializations required by the production process, with the consequent determination of a caesura between material culture and social culture (Truppi, 1994).

This also causes an upheaval in the figure of the designer, who is unable to assimilate and process the technological innovations, thus ending up disqualifying or ignoring them completely or, on the contrary, placing them at the center of the project and transforming them in mere technicalities. The problem of technological innovation ends up inserting itself, therefore, in a wider and tighter conflict between artistic and technical invention, between theory and praxis.

In the contemporary world, the ancient relationship between theory and praxis – where the weight of the poietic dimension prevented a correct explanation of the technical action in the absence of a strong theoretical foundation – is overturned and the practice becomes "executing", thus losing the purpose of making architecture.

In the perspective of a reconciliation between culture and praxis, therefore, it is necessary on the one hand to bring technique back to theory, recovering "the imaginative dimension" (Truppi, 1994) within the constructive process and, on the other, the theory back to the technique through the project since, if it is true that the project, as the core of Architecture, must be able to define the theoretical matter of the building, its principles and its structure, it is also true that without the action of "practical thinking" or, so to speak, of the art of building, the project becomes fleeting (Truppi, 1994).

Therefore, a double legitimation is needed to restore unity and effectiveness to design and to the figure of the designer: the first relating to the field of technology and technique, to ensure that they are internal to the project, and the second relating to the field of culture, so that the project understands, shares and integrates the needs and aspirations of the community (Nardi, 1988).

Naturally, technological innovation also fits into this reconnection, since it cannot in itself constitute a positive element if it is not part of a process of cultural interpretation; that is, if it develops in the absence of a designer capable of acting as a mediator between the cultural implications of the project and the executive techniques (Nardi, 1992).

3. Acknowledgements

We would like to express our gratitude to all our main partners in this project: Doha Extraco, midmac, MIC Construct, Arcadis, GHD, and Neilsoft. We would also thank our colleagues who worked on the project: Yanni Zhao, who started the project, Yousra El Abassi, Lou Bruni, Roxane Boutin, Jeanne Le Jossec and Yuning Song.

4. References

- Bétons – Bétons Fibrés à Ultra-Hautes Performances – Spécifications, performance, production et conformité, NF P 18-470, 2016.
- Bétons – Complément national à l'Eurocode 2 – Calcul des structures en béton, Règles spécifiques pour le Bétons Fibrés à Ultra-Hautes Performances, NF P 18-710, 2020.
- Forcael, E., Ferrari, I., Opazo-Vega, A. and Pulido-Arcas, J., "Construction 4.0: A Literature Review", *Sustainability*, Vol. 12, No. 22, 2020.
- Hawileh, R. A., Ferrari, I., Rahman, A. and Malhas, F., "Comparison between ACI 318-05 and Eurocode 2 (EC2-94) in flexural concrete design", *Structural Engineering & Mechanics*, Vol. 32, No. 6, 2009, pp. 705-724.
- Identity Card of Material, DUCTAL® White PVA Fibers, Lafarge-Holcim, 2020.
- International Building Code, IBC, International Code Council, 2017.
- Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-16, American Society of Civil Engineers, 2016.
- Nardi, G., "Progettazione ipotesi e definizioni. Quel labile confine tra tecnica e cultura", *Costruire per abitare*, n. 65, 1988, pp. 240-244.
- Nardi, G., "La cultura dell'innovazione", *L'Arca*, n. 65, 1992, pp. 86–87.
- Principe, J., UHPFRC: Towards a Concrete Future for Architecture, PhD Thesis, University of Naples "Federico II", Naples, 2020.
- Safikhani, S., Keller, S., Schweiger, G. And Pirker, J., "Immersive virtual reality for extending the potential of building information modelling in architecture, engineering, and construction sector: systematic review", International Journal of Digital Earth, Vol. 15, No. 1, 2022, pp.503–526.
- Simon, H., *The science of artificial*, MIT Press, 1966.
- Simondon, G., "Culture et Tecnique", *Bulletin de l'Institut de philosophie*, Université Libre de Bruxelles, Vol. 14, No. 3-4, Bruxelles, 1965.
- Standard Building Code Requirements for Reinforced Concrete, ACI 318-05, American Concrete Institute, 2004.
- Truppi, C., "La dimensione tecnologica del progetto", *L'architetto tra tecnologia e progetto*, Eds. La Creta, R. and Truppi, C., FrancoAngeli, Milan, 1994.