EXPLORING UHPFRC POSSIBILITIES

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Abstract

Historically the spread of a new "*Construction system*" proceeds very slowly, mainly by induction and by imitation of similar projects. Except in the universities and in the R&D departments, it is unusual in practice to question the possibilities of a "*Construction system*" both in terms of applications of plastic expression. This paper presents some significant works of the International Workshop "*Optimizing material and geometric exploration*". This workshop, conducted by the department of Architecture of the university Federico II (Naples) and the School of Architecture Paris-Belleville, reverses the link between "*project*" and "*Construction*" usually practiced in Architecture. Instead of first developing a purpose and intentions and finding then the best technical solution, the process here starts with the choice of a "Construction System" (in this case the UHPFRC) and explores its possibilities in terms of architectural possibilities and of technical applications. This kind of practice requires synthetic thinking and iterative research. The best projects of the workshop are then cast to check the viability. The aim of this workshop is both to explore the possibilities of the material and to transmit the good ways to design with.

Résumé

Historiquement la diffusion d'un nouveau « système constructif » procède très lentement, essentiellement par induction et par imitation de projets similaires. Mis à part les universités et les cellules de Recherche et Développement, il est rare dans la pratique qu'on s'interroge sur les possibilités d'un « système constructif », tant en termes d'applications que d'expression plastique. Cet article présente quelques travaux significatifs effectués dans le cadre du Workshop International « *Optimisation des matériaux et exploration géométrique* ». Ce workshop, mené en partenariat par la faculté d'architecture de l'université Federico II de Naples et l'école d'Architecture de Paris-Belleville, inverse le rapport entre « *projet* » et « *construction* », tel qu'il est habituellement pratiqué dans les écoles d'Architecture. Au lieu de développer une intention ou un propos, puis de se demander quelle solution technique convient le mieux, cet enseignement part du système constructif (en l'occurrence le Béton Fibré à Ultra-Hautes Performances), pour explorer ses possibilités tant en termes de capacités architectoniques que d'applications techniques. Ce genre d'exercice nécessite une pensée synthétique et une recherche itérative. Le workshop conduit au coulage de certains projets pour vérifier leur faisabilité. Le but de ce workshop est autant d'explorer les possibilités du matériau que de transmettre aux architectes les bonnes façons de concevoir avec.

1. INTRODUCTION: THE SPREAD OF A NEW CONSTRUCTION SYSTEM

1.1 Exploring by analogy

The choice of a "construction system" is usually done by induction and analogy, looking at something similar that has been already realized (We consider as "construction system" not only a material but the combination between a material and its implementation). A designer should proceed by three main steps in order to achieve the full potential of a new technology:

- *thinking to the application*, i.e. the new construction system should be designed for a specific application;
- *finding the fittest designs*: the first designs, often inspired by projects done with similar construction system, are rarely efficient, while more appropriate designs will emerge slowly;
- *developing crafts and skills*: projects, technologies and crafts will be invented or adapted to the new construction system.

The Ultra-High Performance Fibre-Reinforced Concretes (UHPFRC) are considered as an expensive material, because the cost is exaggerated by the fact that UHPFRC is too often misused. The reason for this may be the design principles significantly differ from those related to traditional reinforced or prestressed concrete. Then to really understand the architectural implication of innovative technologies is necessary to go back to the relation between the material and its shape, re-thinking the design process, which should be seen as the interrelation among creative, productive and building phase. The UHPFRC are a material with its own "*language*" which has still, in part, to be discovered [1]. The objective today is to find the "*order*" of UHPFRC and to understand what it "*want to be*" in the meaning of the architect Louis I. Kahn [2].

On this ground, "pioneering" countries have launched extensive experimentation and tests to build up the needed knowledge at the base for the development of innovative technical solutions and captivating architectural concepts. In France, in particular, joint work between Lafarge, Eiffage, Vicat, AFGC, (Association Française de Genie Civil) and Setra (Service d'études techniques des routes et autoroutes), has led to the first UHPFRC design guidelines in 2002, revised and updated in 2013 by AFGC [3], allowing a significant step forward towards the standardization, identifying the characteristics and properties of the material, guidance for design, providing detailed instructions about the preparation of the mix-designs, laboratory testing, solutions for transport and installation.

1.2 UHPFRC in Italian context

In the Italian field of building, the spread of innovation has always find some difficulties, since the construction market secular tradition often hinders the full acceptance of new elements. Another explanation can be found in the lack of knowledge of users and operators, which can be also attributed to the asymmetry, typical of the contemporary society, between the developers of new sciences and technologies and who are affected by them.

The causes probably are the differences of perspectives and objectives among the actors involved, the few forms of budget support, the private low willingness of investment in risk capitals and the poor communication between the industries and the research field. One of the solution is to exploit an integrated approach, realizing mutual support frames, in which each actor offers his specific competences to aim a common purpose.

This strategy has been developed by some Italian companies, like "Il Cantiere" and "The Italian Lab", to reposition themselves on the globalized market, providing high-quality products, resulted from the transfer of the craft "made in Italy" knowledge to the industrial field, and investing in R&D to obtain the highest performances from the material.

Other companies, like "Italcementi", preferred to finance different innovative products, able to substitute comparable goods with a lower performance level, covering in this way a large part of the market. In each case, the knowledge must be a fundamental element of the production factors, in order to make innovation one of the main driver of competitiveness.

2. WORKSHOP: "MATERIAL OPTIMISATION AND GEOMETRIC EXPLORATION"

With the goal of exploring the possibilities of this UHPFRC technology in term of geometries and applications, the School of Architecture Paris-Belleville (ENSA-PB) and the Department of Architecture of University of Naples Federico II (DiARC) have established in 2015 an annual program of research and design workshops focusing on "Material Optimisation and Geometric Exploration with Ultra High Performance Fiber Reinforced Concrete" [4]. The workshop is divided in two weeks: one week dedicated to the development of the projects, and one dedicated to the realisation of prototypes. During the 2015 and 2016 workshops a total of 12 concept projects and 8 built prototypes have been developed, with the aim of spreading the required knowledge for a correct and successful application of UHPFRC technology, investigating three categories of application: the structural concept, the building component and the furniture. The UHPFRC used is Ductal [5], manufactured by Lafarge-Holcim company. The following sections give an outline of some key topics explored through the experimental design applications.

2.1 Adaptive system: "As Strong As Paper"

Design team: A. Angelone / A. Dehais / I. Amato / J. Wahlgren / S. Totaro

The project "As Strong as Paper" (ASAP) use the geometry and the mechanical performances for reducing the thickness of UHPFRC. The "resistance of form" is the explored approach to effectively use the shape factor to increase the strength of a structure. The folded papers or the origamis are considered as one of best example of "resistance of form": A material without bending strength (paper) gets a great stiffness only by the geometric configuration of the folds (Fig. 1).

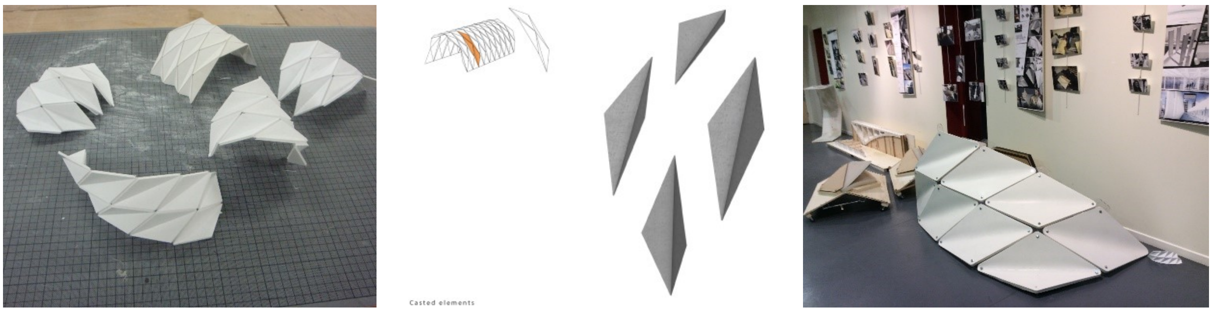

Figure 1: Folding Pattern (pictures Raphaël Fabbri)

The folding pattern should be repetitive in order to minimize the number of moulds. The pattern finally chosen is one of the simplest: consisting of four "mountain folds" in cross and of two aligned “valley folds” at each node. All the faces are identical isosceles triangles. A single UHPFRC element is made with two triangles. If the angle between the triangles is the same for all the elements, then the general surface is a cylinder Fig. 2).

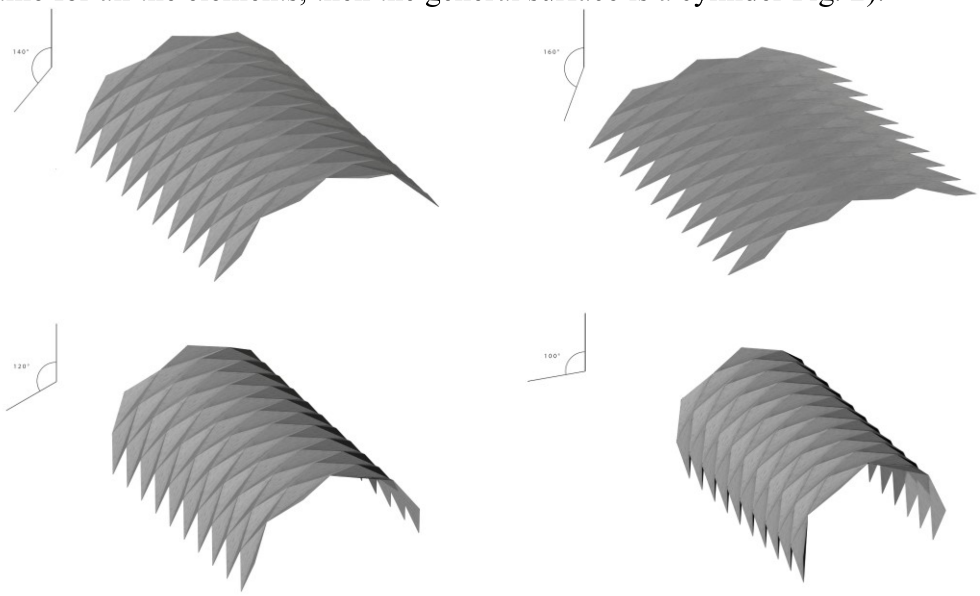

Figure 2: Cylinder in function of the angle between the triangles

Statically the elements are connected by the corners, four by node. The lever arm for the bending moment is equal to the distance between the “valley edge” and the node above. The internal forces are calculated according to the relative positon of the thrust line. That way, the structure has more strength than the nominal thickness of the elements (30 mm). The more the angle between two triangles is small, the more the curvature of the cylinder is big (or the radius is small) and the more the bending strength is big.

If all the triangles are equal, but the angles are different, the folding pattern could “cover” almost every kind of surface. For modelling the “cover” of a “reference surface”, two methods are applied: one based on topological properties and one based on physical equilibrium. The topological one uses the distance between the nodes of the folding pattern. Knowing the position of the first triangle (its three vertices are placed on the “reference surface”), we can find one by one the adjacent triangles by intersections. An adjacent triangle has got two common points with the first triangle and the third one is deduced by the intersection between the two spheres (the centres are the common points and the radii are the lengths of the edges) and the “reference surface”. This method is easy to solve but the difficulty is to create a loop that fit with the topological configuration of the façade. The physical method tries to reach iteratively the equilibrium between agonistic forces. Like in the paper origami, there are “strong forces” (like dimensions of faces or the fixed points) and “weak forces” (like the hinge movement or the pull to the reference surface). The software used for the equilibrium is “Grasshopper” (plug-in for Rhino/Mc Neel) with the physics solver “Kangaroo” [6]. This method is easier to implement and to manipulate (Fig. 3).

The last issue is how to cast with the same mould different angles (Fig. 4). The mould is made with a silicone pocket fixed between wood boards hinged together. The UHPFRC is cast in the flat position. By screwing a turnbuckle, the angle is changed as the mix is still liquid. After about 16 hours and the stiffening, the mould is opened and the element retrieved.

Two problems occur in the fold when the angle is too small: The "orange skin" surface and the decrease of the thickness. The minimum possible angle is about 90°.

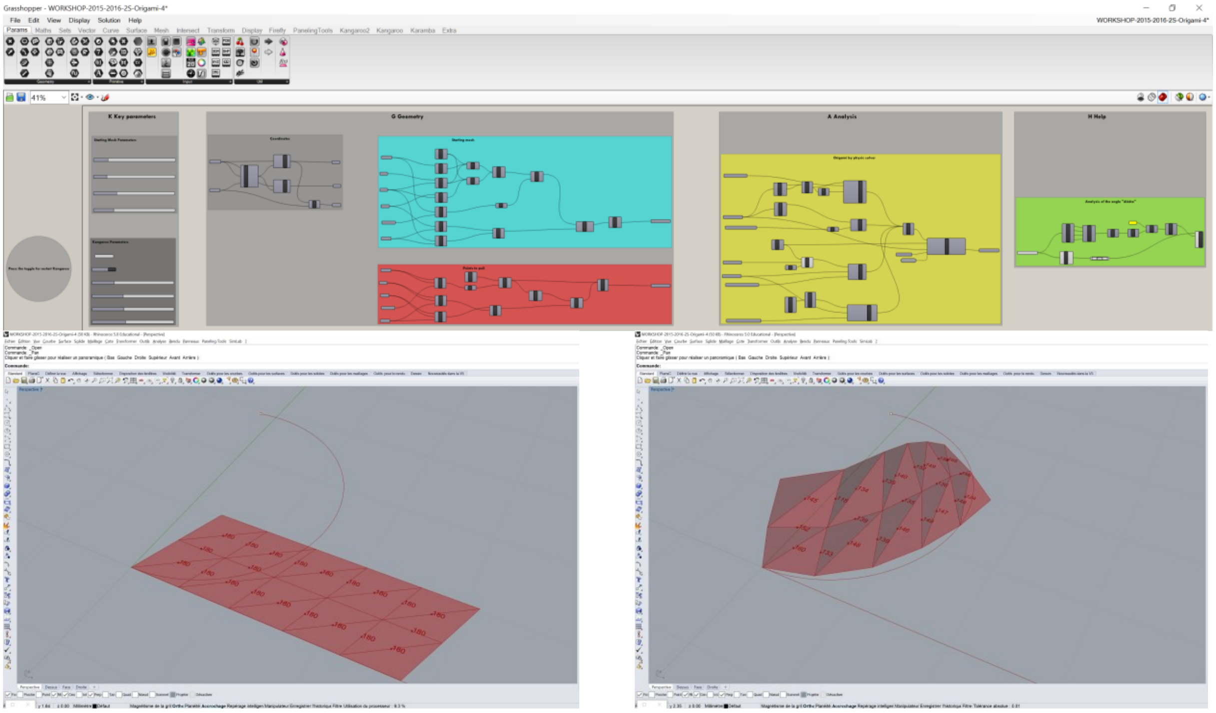

Figure 3: Physical method with software Grasshopper/Kangaroo (images Raphaël Fabbri)

Figure 4: Flexible mould (images Raphaël Fabbri)

2.2 Balancing the weights: "Spiral Stair"

Design team: S. Jammet / G. Napolitano / E. Pizzuti / R. Scognamiglio / B. Tartarone

The mechanical performances and the absence of reinforcement allow to reduce the thickness of elements in UHPFRC. The advantages are many: economy of material, economy of shoring or elements carried by hand, thin and smooth shapes. The project "Spiral Stair" takes advantage of these possibilities (Fig. 5). The "spiral stairs" in precast concrete are existing since the beginning of the reinforced concrete. The project is made with identical self-standing elements which could be carried by one or two men (less than 50kg). This design saves time and buttress during the implementation.

Each element is consisting of a L-shape step, a hollow core cylinder and a helical “spine”. The elements are stackable without shoring. The central column is filled with normal concrete cast on site. This column could be used as a part of the structure of the building. The “spine” is not only an aesthetic element, it is necessary for the self-standing during the implementation. For stackable elements, the equilibrium is verified when the projection of the centre of gravity is still inside the “supporting area”. The “supporting area” is the convex surface which include all the supporting points. The centre of gravity of the stairs changes in function of the number of steps.

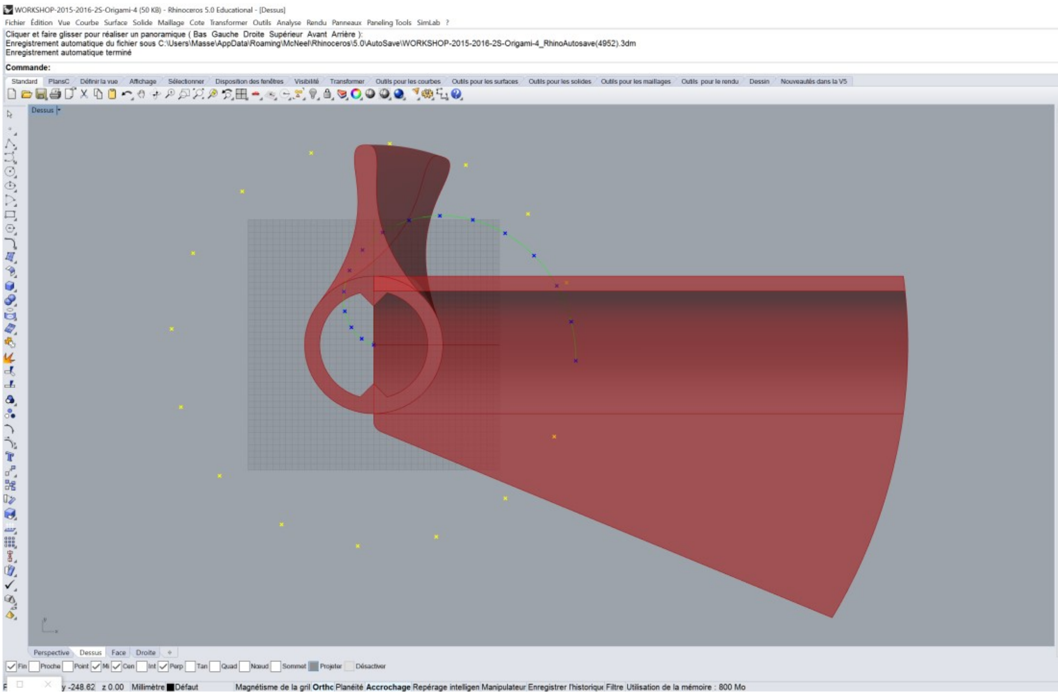

Figure 5: Equilibrium of the stairs (images Raphaël Fabbri): Red – UHPFRC element; Yellow – Centres of gravity of each element; Blue – Centres of gravity of the stairs in function of the number of steps; Green – Spiral curve that goes through the projection of the successive centres of gravity

Each element has the same weight (about 36 kg). With only one step, the centres of gravity of the stairs and the element are the same. With two steps, the centre of gravity of the stairs is located in the middle point of the centres of gravity of each element. With three steps (Fig. 6), the centre of gravity of the stairs is located in the barycentre of the three centres of gravity of the elements, and so on. The curve that goes through the projection of the successive centres of gravity is a spiral. This curve has to stay inside the “supporting area” consisting of the contact line between two steps, the central core and the “spine”. The position and the dimension of the "spine" is adapted iteratively in such a way to keep the "spiral curve" inside the boundary of the “supporting area”.

Figure 6: “Spiral Stair” (pictures Raphaël Fabbri)

The elements are casted upside down in order to keep below (and then less visible) the surface with more bubbles, regularly occurring on the upper side of a casted element (Fig. 7). The relative small size of the element allows to make the mould with solid material: Wood panel, plaster and coating painting. The complexity forces us to divide the mould in four external parts and an internal core in silicone.

Figure 7: Casting process (pictures Raphaël Fabbri)

2.3 Material, form and force: “fUtbridge”

Design team: C. Capasso / D. Cattolico / G. Pinto / L. Moscardella / Z. Wang

For the UHPFRC, the ratio between the compression stress and the tension stress is around 15/1. It means that, under a simple bending moment, the ultimate limit is reached by the tensile stress, whereas the compression is only at 10 % of its capacity. The ratio between the compression stress and the “equivalent bending” stress is around 10/1, due to ductility in tension. To be efficient, this material should work mainly in compression. The prestressing is a way to use fully its compression characteristics. Designing anticlastic surfaces is another way. The anticlastic surfaces are mainly used for membranes and cable nets, in order to have only tension inside the structure. But with abutments correctly placed, the surface could be only in compression.

The “fUtbridge” project crosses a river with a double levels deck (Fig. 8). Statically the “fUtbridge” is based on the anticlastic surfaces properties with abutments. Under vertical loads, the surface works like an arch in elevation and like two antagonistic arches in view of top. In this situation, the support reactions are obviously in vertical direction but in horizontal direction too (transverse and longitudinal). The shape of the bridge is a revolution surface generated by the rotation of a parabola about an axis and cut at the level of the balustrade (Fig. 9). The surface is split by plans containing the axis of revolution and with a constant angle between them. Each segment is split again in the middle plan and bordered by stiffeners. In that way, all the elements are uniform and could be casted with only two moulds (one left and one right).

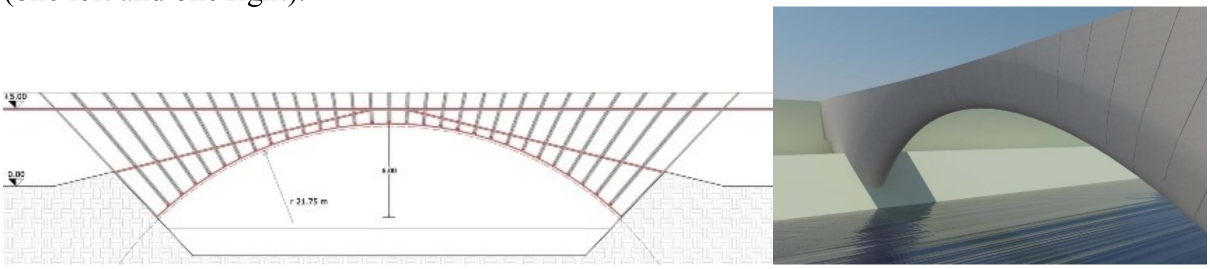

Figure 8: “fUtbridge” concept and render

For the implementation, the “fUtbridge” could be assembled on a scaffolding or in cantilever without temporary supports. The thin thickness of the segments (between 50 mm and 80 mm) simplifies this last implementation method by reducing the anchor forces needed on the riverbanks. UHPFRC is particularly suitable for this application, thanks to the high compression strength and low creep for the arch behaviour, and the great durability in such exposed conditions (de-icing salts and proximity to watercourse). With the same design, the “fUtbridge” could be adapted to different spans, only by limiting the number of segments.

Figure 9: Mockup of “fUtbridge” scale 1/10 (pictures Mattia Leone)

2.4 Smart implementation: “Cantilever walk-away”

Design team: C. Guilvard / C. Mazzuoccolo / J. Principe

The cost of the square meter in the big cities is so expensive, that the urban planners try to recover each “lost space”. The railways are occupying great areas and they are dividing entire boroughs. Like in the Tolbiac neighbourhood in Paris (XIIIe arrondissement), the railways are covered in order to create public spaces, equipment and housing. In most of the cases, the technical costs of the crossing are less than the benefits (from an economical and urbanistic point of view). One big technical issue is the interruption of the train traffic: in the big railway stations, the trains cannot be suppressed for long time (less than 48 hours). In France, the covering of railways is allowed only during traffic interruption. Whatever the material, the structure and the covering should be executed very fast.

The project called “Cantilever walk-away” proposes a fast way to cover railways. The best typology for bridging in compression is to create an arch. An arch with three hinges is the easiest type for implementation: in case of displacements of the abutments, the arch continues to work without additional internal forces. The arch with three hinges is consisting of two half-arches joined together at the top. The design of "cantilever walk-away" is a precast beam that can work alternatively as a cantilever (during the implementation for example) and as an arch (Fig. 10). Each precast beam has a length of twenty meters and consists of a funicular arch (parabola), with a total span of the arch of forty meters. The UHPFRC are particularly adapted for this application: compared to steel, this solution is lighter (the compression stress is the half of the steel, but the volumetric weight is one third) and the durability is increased.

Figure 10: Mockup of "Cantilever walk-away" scale 1/10

In this particular case, the implementation issue is fundamental. The greater part of the work will happen before the traffic interruption. The construction starts with the foundations on the both sides of the railways (Fig. 11). Then the precast beams are installed vertically on hinges and balanced by counterweights. During the train interruption, the beams rotate simultaneously around their hinges and they close the arch. After this phase, the precast slabs cover the gap between the arches and the traffic can restart safely. The final spatial-functional layout and the finishing of the horizontal slabs can be completed without affecting the railway traffic. The UHPFRC solution is profitable when the same mould is used for at least twenty beams.

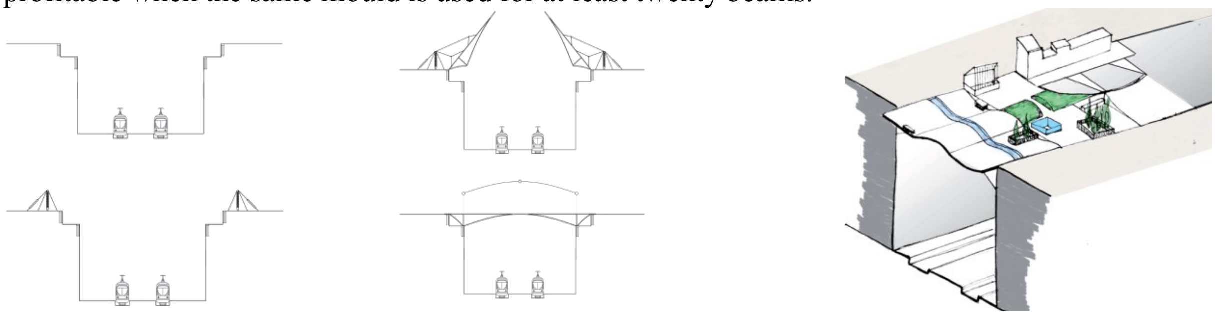

Figure 11: Implementation sequence

3. CONCLUSIONS AND FUTURE APPLICATIONS OF UHPFRC TECHNOLOGY IN THE ITALIAN MARKET

The study of UHPFRC's performance characteristics and design principles is necessary in contexts like Italy where an improvement of technical and procedural knowledge is needed, in order to allow a progressive market penetration of concrete innovation in the construction process supply chain, despite the fact that interesting experiments and design explorations, especially related to architectural and product design applications conveyed by experiences of "advanced craft" [7], have already been done. Significant application experiences in France, Germany, US and Japan have highlighted the key role linked to the spread of the technical skills necessary to a correct conceptual, design and construction approach.

In Italy, an important working baseline is constituted by the CNR-DT 209/2013 "Preliminary studies aimed at the development instructions for the use of high performance concrete" [8]. In its first release, the document only mentions the category of UHPFRCs among the broader family of "high performance concrete" materials, without investigating further the peculiarity of this technology, the potential benefits for structural design in terms of mechanical and durability performance.

Furthermore, assuming that the Italian territory is characterized by large areas affected by seismic, hydrogeological and volcanic risk, buildings rehabilitation and reinforcement can represent the occasion not only to make full use of UHPFRC characteristics and to explore new possible application in the mitigation field, which is always extremely actual in Italy, but also to improve the resilience of urban systems and the energy efficiency of buildings. At the same time, it is possible to stress complementary topics, such as the sustainability features of UHPFRC compared to conventional reinforced concrete technologies in terms of embodied energy and CO2 emissions [9], as well as cost-benefit assessments based on LCC (Life Cycle Costs) approaches, which contributed in some cases to a significant "technology shift" in specific fields of applications, such as the replacement of highway bridges in the US [10].

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[5] See www.ductal.com.

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