PEDAGOGY THROUGH ARTISANAL CONSTRUCTION OF THIN-WALLED CONCRETE ELEMENTS: A DIALOGUE BETWEEN ENGINEERING AND ARCHITECTURE

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ABSTRACT

Educational approaches of Reinforced Concrete (RC) are traditionally based on theoretical considerations more than on manual work and artisanal learning. This has been justified by the massive dimensions and significant self-weight of concrete works, yielding students to rarely experience the workability of concrete at its fresh state and formability possibilities. A new situation has yet appeared with recent cementitious composites, such as Textile Reinforced Concrete (TRC), allowing to build handy and lightweight load-bearing structural elements. This gives the possibility to integrate practical experiences with cementitious materials in the educational career. In this article, the interdisciplinary course *Argamassa Armada* in Salvador de Bahia, addressed to third year students in engineering and architecture is presented.

It shows that working with high performance cementitious materials at an artisanal level is possible and that students can contribute to scientific research while learning by hands-on experiences.

KEYWORDS: Textile Reinforced Concrete, Prefabrication, Pedagogy, Architecture, Formwork, Knowledge Transfer

1. Introduction

First modern concrete structures started to appear at the end of the XIXth century. At that time, material cost was still relatively high with respect to labour wages, leading to innovative structural systems. Folded thin-walled cross-sections and shell-structures ensured structural stability providing geometries that can satisfy at the same time architectonical needs. This is typically the case of ferrocement structures covering large spans by keeping relatively low self-weight (Figure 1).

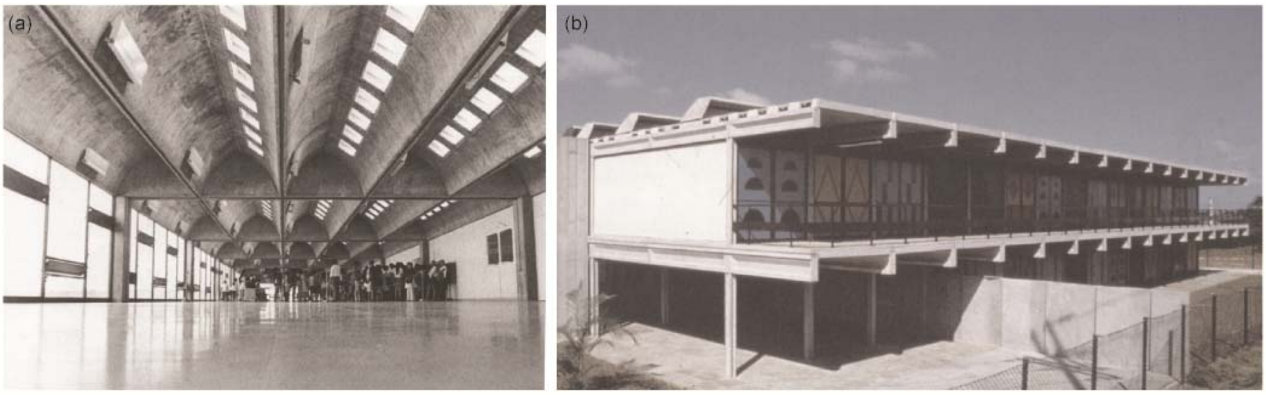

Figure 1. Thin walled ferrocement structures: (a) Taguatinga Hospital ferrocement roof shell, Brasilia 1968, Lelé [1,pp 49]; (b) ferrocement school building, Salvador de Bahia 1988, Lelé [1,pp 160].

However, the engineering and scientific concerns on durability of concrete works, and particularly of corrosion of the reinforcement, grew as well as the requirements provided in codes of practice. Today a minimum concrete cover (25 – 55 mm), is recommended in order to control the rebar corrosion. These requirements, together with the required spacing for pouring, vibrating and compacting needs, yield to higher thicknesses of the RC elements, which are currently mostly associated to robust, yet massive constructions. Consequently, due to the important self-weight, educational workshops are rarely performed with RC. Despite the widespread of concrete in practical applications, plaster or wood are mostly preferred for such educational activities.

In order to give to students the opportunity to work with cementitious materials at a structural scale, a drastic reduction of self-weight is required. The latter can be achieved if cover restrictions due to durability can be overcome. One of the possibilities is to replace steel rebars with non-corrosive reinforcement materials such as high-performance textile fabrics or stainless steel reinforcement bars. Textile Reinforced Concrete (TRC), is a relatively new, cementitious-based, composite material that is rapidly gaining popularity as it allows casting thicknesses below 20 mm [2].

As both, ferrocement and TRC are high performance composites they are prone to be used within a prefabrication construction process. One of the major actors, who pushed prefabrication of ferrocement (*Argamassa Armada*) to its limits, was the Brazilian architect João da Gama Filgueiras Lima (Lelé) [1].

In the following, the course, *Argamassa Armada* in Salvador de Bahia, offered to third year students in engineering and architecture at École Polytechnique Fédérale de Lausanne (EFPL, Switzerland) is presented. This course is integrated in the research project “Social Concrete: Renewing a building technology for the informal city” that proposes to study, develop and renew *Argamassa Armada* through an interdisciplinary project that researches its technological, social, environmental and spatial aspects. The course is carried out in the form of analysis and empirical research into the *Argamassa Armada* technology by means of full-scale prototype fabrication and testing of structural elements. The course allows students to test the use of TRC as building material that addresses the informal conditions in Brazil but also implies the development of a new architectonic language.

The reinterpretation of structural elements designed by Lelé with modern materials intrinsically promotes the collaboration between engineers and architects. It also shows how the construction of thin-walled concrete elements can be performed at significantly lower degrees of industrialization and that a strong bond between engineering and architecture students can be achieved through artisanal work.

2. Textile Reinforced Concrete material

Textile Reinforced Concrete is usually made of different layers of textile fabric embedded within a fine-grained mortar [3]. For suitable casting of thin-walled TRC elements, the concrete mix is required to have small aggregate size to ensure suitable penetration between fabric layers. The premix used within this context presents a very low aggregate size ($d_{g,max}$ = 1.60 mm) and water-to-cement ratio ($w/c \approx 0.25$) associated to high mechanical properties (average compressive strength of f_{cm} = 120 MPa and modulus of elasticity E_{cm} = 31.0 GPa). Different levels of flowability can eventually be achieved by adjusting the amount of Superplasticizer added while mixing.

With respect to the textile reinforcement, it is composed by yarns (or filaments) grouped into rovings (bundles of yarns or strands) arranged in two directions to create a grid or fabric [4], see Figure 2. Yarns are made of the pure raw material (carbon, glass, basalt etc...) and have a very small diameter ($\emptyset_{fil} \approx 5 – 30$ µm [5]) presenting thus high tensile strengths (for instance $f_{fil} \approx$ 5'000 MPa for carbon fibres [6]).

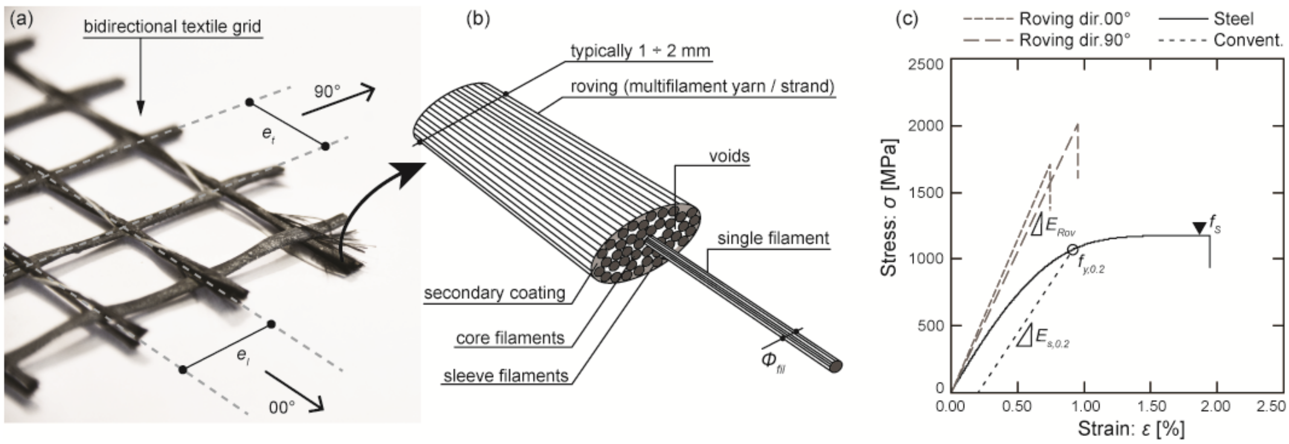

Figure 2. Textile reinforcement: (a) macro-and (b) microstructure; (c) material behaviour in tension and comparison to stainless steel.

Rovings are groups of hundreds or thousands of filaments, bundled together. Rovings are eventually woven together to form the textile fabric, that is mostly bidirectional. Within the present research, a coated carbon based textile is used. An additional micro-silica coating improves bond properties leading to short anchorage lengths [7].

		Long. 00°	**Transv 90°**	
Linear roving density:	λ_{Rov} =	2 × 800	1600	tex [g/km]
Net cross-section area:	a_{Rov} =	0.85	0.85	mm^2
Roving resistance:	$F_{u,Rov}$ =	1450	1700	N
Roving strength:	$f_{Rov} = F_{u,Rov}/a_{Rov}$ =	1700	2000	MPa
Modulus of elasticity	E_{Rov} =	230	210	GPa
Fabric spacing:	e_f =	20	20	mm

Table 1 Measured mechanical properties of the textile reinforcement

Despite the high strength of the fabric (Table 1), the linear net cross-section area, (A_{Rov} = 42.5 mm^2/m) is relatively low. Due to casting limitations, only a limited number of fabric layers (3 – 8) can be arranged within a thin walled section ($t \approx 15 \div 25$ mm). Consequently, a concentrated reinforcement is required within the tensile zones of linear members [9]. For this project, high strength corrugated stainless steel rebars were selected to enhance the TRC composite. The (RipInox)-bars do not present a well-defined yield limit, with a conventional yield strength $f_{y,0.2}$ = 1’080 MPa, a tensile strength of f_s = 1’170 MPa and a Young modulus of E_s = 150 GPa.

3. *Argamassa Armada* in Salvador de Bahia

As mentioned earlier, the course offered to the students takes its inspiration from previous works performed by Lelé. Following his death (21.05.2014) most of the *Argamassa Armada* production lines in Brazil are likely to shut down in imminent future. To avoid the loss of knowledge, a collaboration effort was established between the faculty of architecture of the Universidade Federal de Bahia (FA-UFBA, Brazil) and EPFL. Within this frame, in 2015, the first edition of a course (Unité d’Ensignement, UE) was established at EPFL, providing the students with an education on the technology of *Argamassa Armada* and exploring with them how this technique can be updated. Since then (during the last three editions of the UE), students, lecturers, researches and scientists have been working in close collaboration, reinterpreting Lelé’s elements with the potential provided by TRC.

3.1. An extension on Lelé’s work

From 1979 a major program to improve life quality in several communities (favelas) in Salvador de Bahia was set in place by the Brazilian government. To facilitate the construction of buildings and infrastructure (drainage channels, walkways, retaining walls etc…) in areas that are hardly accessible to construction machinery (e.g. cranes), Lelé developed thin prefabricated ferrocement elements. The latter were transported and assembled in place by few construction workers. Depending on site accessibility, structural elements were either precast in one of the production lines or prefabricated on site within a mobile plant (see Figure 3). The engagement of local population in the construction process is one of Lelé’s key ideas.

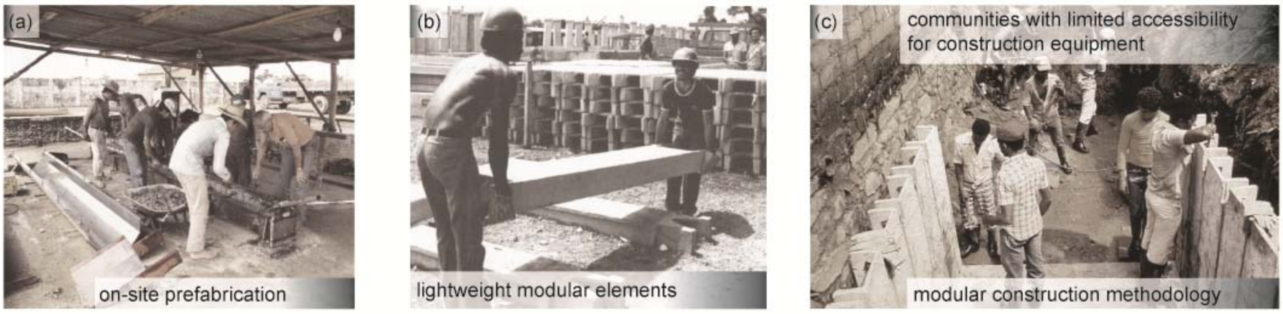

Figure 3. Lelé’s flexible construction system with lightweight ferrocement elements: (a) on-site miniplant [1,pp 141]; (b) transportability of elements [1,pp 106]; (c) assembly within hardly accessible area (favela) [1,pp 106].

The Unite d’Ensignement is based on homogeneous principles with the *Argamassa Armada* construction methodology implemented by Lelé [9]. In other words, undergraduate students with still little experience in construction (especially related to concrete) are called to build multi-functional structural elements.

The objective of revisiting *Argamassa Armada* technology is to study how technological developments make Lelé's proposition for a social concrete even more pertinent today, and to examine how concrete construction can be deployed in a way that is sustainable and durable while affording spatial quality and allowing inhabitants of the informal city the possibility of co-producing their own habitat. The main research objectives can be summarized as follows:

- How advances in concrete technology can be adapted for diverse climatic requirements or incorporate techniques of recycling or reuse;
- How construction protocols and on-site, mini-factories can be developed to minimize cost and logistical complexity so that local people take ownership of technology;
- Defining the means to diffuse and transfer the gained knowledge;
- How this technology can be adapted to various uses such as the renovation of abandoned buildings or construction on unstable terrains.

3.2. A dialogue between engineering and architecture

In the professional career, a close collaboration between engineers and architects is needed to produce masterpieces. It is curious, yet, that the manner in which such a collaboration is to be developed is not (and probably cannot be) taught, becoming a personal and independent process followed after the studies. Nevertheless, in an effort to make students aware of the need to collaborate, and to provide them with a first occasion to do so, this Unité d'Enseignement works with mixed teams of students in architecture, civil engineering and environmental engineering.

All precast elements designed by Lelé combine high architectural quality, structural performance and optimise the construction process. Consequently, they constitute an excellent example to promote interdisciplinary interchanges. In fact the course constitutes a common ground where architects and engineers meet as craftsmen rather than designers: The practical, artisanal transformation of a structural element and formwork system (i.e. a concrete reality which embodies a unity of architecture and engineering, of research and practical experience), does not demand for a division of calculus and design but on the contrary fosters a constructive understanding that takes into account the interplay of its various constituting factors. In the case of Lelé's structural system this includes social considerations and an awareness of the environment (e.g. independency of heavy machinery, access for informal construction, inclusion of unskilled workers). As the students will need to understand and go through the complete process of analysis / observation - conception - execution - testing, this leaves a deep learning impact. The gained experience and confidence of being actively involved in an innovation-process encourages the questioning and further development of any given task or reality (be it a building material, industry convention or other) in their future careers.

3.3. Course structure

This five credits optional course lasts for 14 weeks during spring semester. Most of the works are performed during course hours (Wednesday afternoon, from 1 – 5 pm) in classes (for conferences, drawing and design) and in the structural concrete laboratory (for construction). In the first sessions, invited experts (table 2) give a series of lectures on related topics.

Lecture	Author	2016	2017	2018
Rehabilitation of urban areas in Salvador	Prof. Dr. Olivia de Oliveira	X	X	X
Bamboo fiber as concrete reinforcement	Prof. Dirk Hebel	X		
Sustainability of cementitious materials	Prof. Dr. Karen Scrivener		X	
Autoconstruction in communities	Yves Pedrazzini	X	X	X
Review of Lelé's works	Adelberto Vielia			X
Textile Reinforced Concrete	Dr. Miguel Fernández-Ruiz	X	X	X

Table 2 Lectures provided during first weeks of the various editions of the UE

In a second step, the 18 students form five mixed groups to design and build one element from Lelé's construction catalogue. This process involves:

1. Analysis of 5 elements selected as case studies from João Filgueiras;
2. Analysis of the work done in the previous years (knowledge transfer);
3. Hand-drawing of the element (cross-section and axonometry);
4. Conception of a suitable timber formwork (in agreement with the chosen casting technique);
5. Preliminary structural design of the element with TRC;
6. Preparation of detailed CAD-files to cut formwork elements from large timber panels;
7. Formwork construction: assembling of formwork, placement of fabric and steel reinforcements and selection of a suitable pouring method;
8. Casting, hardening and demoulding.

During the last session of the UE the groups expose their works to several experts (table 3). The comments and dialogue with the students are used as assessment basis.

Expert	Role, Institution	2016	2017	2018
Dr. Olivia de Oliveira	Prof. FA-UFBA	X	X	X
Jose Fernando Minho	Prof. FA-UFBA		X	
Dominique Mullet	Director MFP-Prefa	X		
Dieter Dietz	Prof. EPFL	X	X	X
Dr. Miguel Fernández-Ruiz	Senior scientist EPFL	X	X	X
Dr. Sergio Ekermann	Prof. FA-UFBA			X

Table 3 Experts at final exposition

As shown in tables 2 and 3, the UE is not only a course, but also a research platform providing interdisciplinary exchange for experts at different levels (researchers, scientists and professors). Furthermore, it ensures regular technical interaction between FA-UFBA and EPFL.

3.4. Evolution of the UE

As shown in Figure 4 a rapid evolution of the course has taken place during the last years. While the first editions helped to validate the concept, the current and future versions will be dedicated to the improvement of the *Argamassa Armada* construction method on a systematic basis.

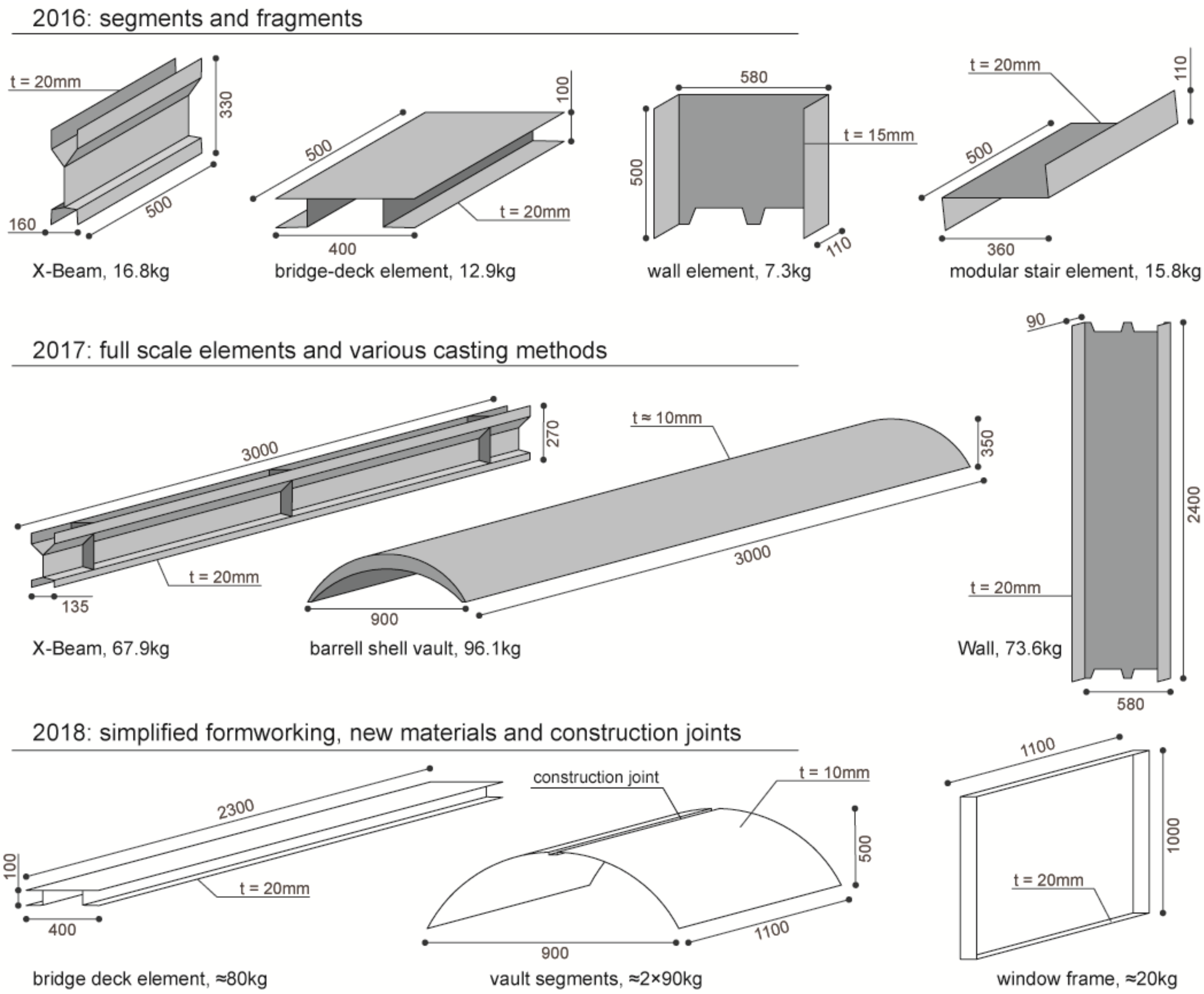

Figure 4. Elements realized in the various editions of the course.

3.4.1. First prototypes (2016)

First prototypes are segments with full scale cross-section (Figure 4). All elements were cast with a highly fluid mortar poured into stiff-formworks, Figure 5.

First results show the feasibility of *Argamassa Armada* structural elements with TRC. It was also noticed that to ensure full penetration of the mortar between fabric layers, reinforcement ratio needs to be relatively limited.

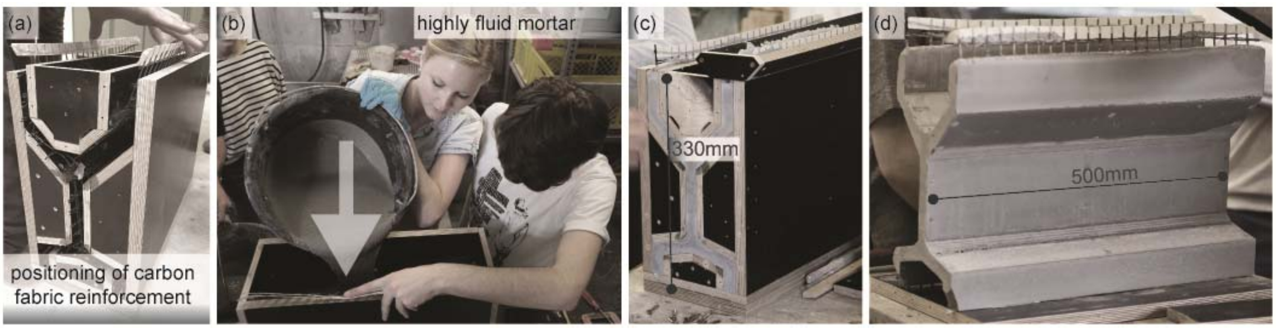

Figure 5. X-Beam: (a) formwork; (b) casting; (c) demoulding; (d) final result.

3.4.2. Full-scale elements (2017)

Based upon the previous experience, the second edition addressed two main topics:

1. Build of full scale elements that can be used for structural testing;
2. Explore different pouring techniques to optimise the casting procedure.

For instance, two groups worked on an X-shaped beam improving the formwork and designing the reinforcement according to a simplified flexural analysis. Eventually, four high-strength Ø6 rebars were arranged to reinforce the tensile zone. The web is reinforced with two layers of carbon textile fabric, ensuring sufficient shear capacity. Additional load introduction gussets assure the possibility to test the beam in a three-point bending configuration avoiding local failures.

Figure 6. X-Beam: (a) cross-section; (b) casting procedure; (c) final result after demoulding.

Also casting of thin shells was investigated, by building a thin-walled barrel shell vault. As shown in Figure 7, a single sided formwork is used in combination with a highly viscous, form-stable mortar mix to cast a barrel shell vault. Two layers of the carbon fabric reinforce the shell and a single rebar Ø6 is placed along each bottom edge. Right after casting, the free side of the mortar was covered by a thin plastic-sheet improving the mortar curing conditions.

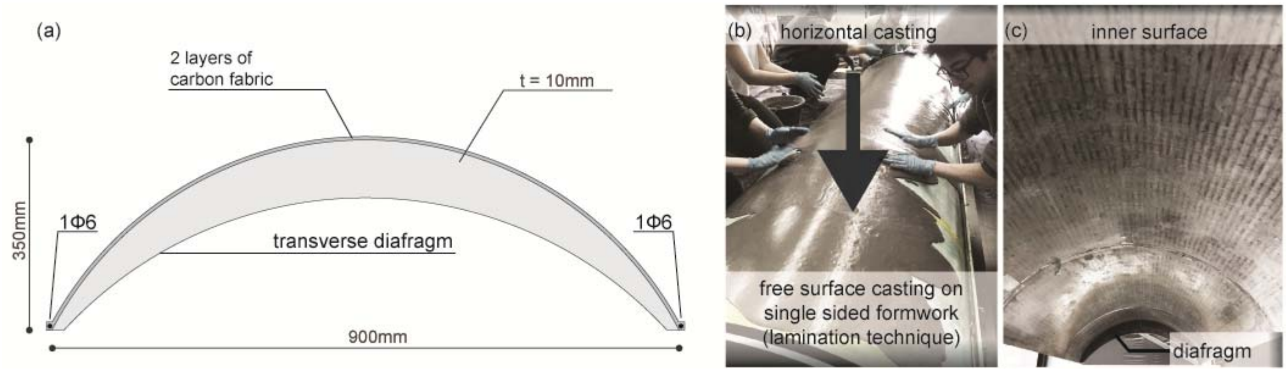

Figure 7. Barrel shell vault: (a) cross-section; (b) casting procedure; (c) result after demoulding.

3.4.3. Structural testing (2018)

During the second lesson of the current edition, a three-point bending test (Figure 8a) was performed on the X-Beam. Both, students of the current and last edition were invited to assist (Figure 8b).

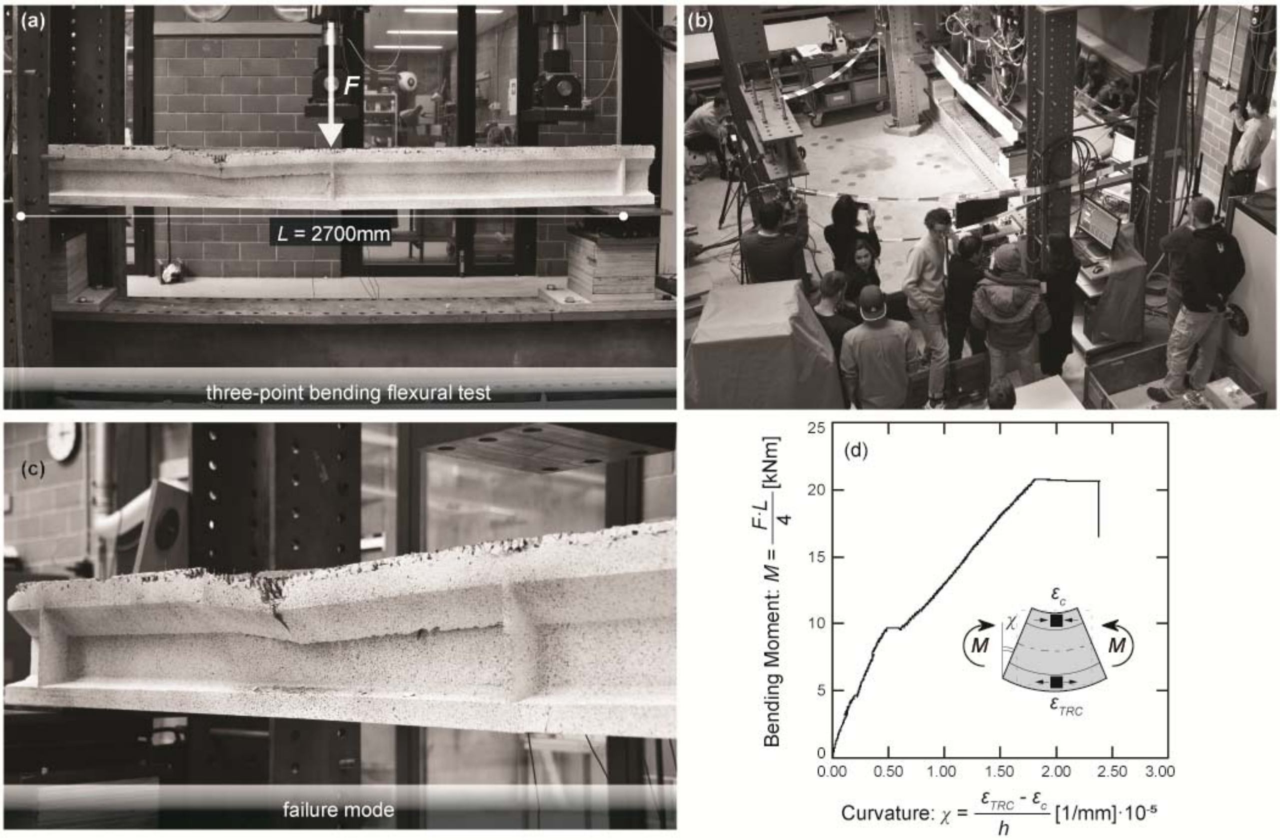

Figure 8. Load test: (a) test set-up; (b) testing area; (c) failure mode; (d) moment-curvature relation.

After testing, the failure mode due to lateral instability of the top flange (Figure 8c) was discussed with the students. Also, measurements taken with two inductive LVDTs at the top and bottom flanges were used to plot the moment curvature diagram (Figure 8d).

3.5. Current and future works

This experimental course is a platform for knowledge generation and exchange. As it is a relatively new project, it allowed to develop rapidly many ideas. Knowledge transfer between the single editions is a challenge as there are more and more experiences to transmit. For this reason, during the current and future editions, each group of students prepares a standardized construction protocol summarizing their experience in a systematic manner.

Another goal is to reduce the complexity of the moulds, minimising the use of the CNC sawing facilities, which have been extensively used so far. In this framework, the authors encourage students to be creative, and to work with different materials to find innovative and inexpensive formworking solutions without compromising the quality of the final result.

Also, many different non-corrosive reinforcement materials are currently available on the market. Consequently, in the near future, different material combinations will be tested and compared. Finally, it is foreseen to adapt the design of Lele's elements, optimizing them for these new, high performing, materials without compromising the fundamental philosophy and architectural quality.

Eventually, to increase teaching quality, future editions will evolve based on a set of evaluation sheets. The latter will be distributed to students at the beginning, the end and one year after completion of the UE.

4. Conclusions

The course presented in this article brings together in a synergic manner various interests.

First, the collaboration between researches in architecture and engineering who are interested in the workability and performance of new cementitious materials. Second, building lightweight, thin-walled concrete elements allows students to experience and gain confidence with cementitious materials by manual learning.

Within the framework of an interdisciplinary activity, students with different educational backgrounds are forced to exchange on a practical level. The latter helps them to gain confidence with the project partners and to develop interdisciplinary communication capability which is fundamental in practical activities nowadays.

Finally, building with *Argamassa Armada* as developed by Lelé, the research tests Textile Reinforced Concrete as contemporary building technology taking in account its social innovation (building in the informal city) and its potential for the development of a new architectonic language.

5. Acknowledgments

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