Adaptation

Composite

Fiber

Integrative

Morphogenesis

Adaptive Growth of Fibre Composite Structures

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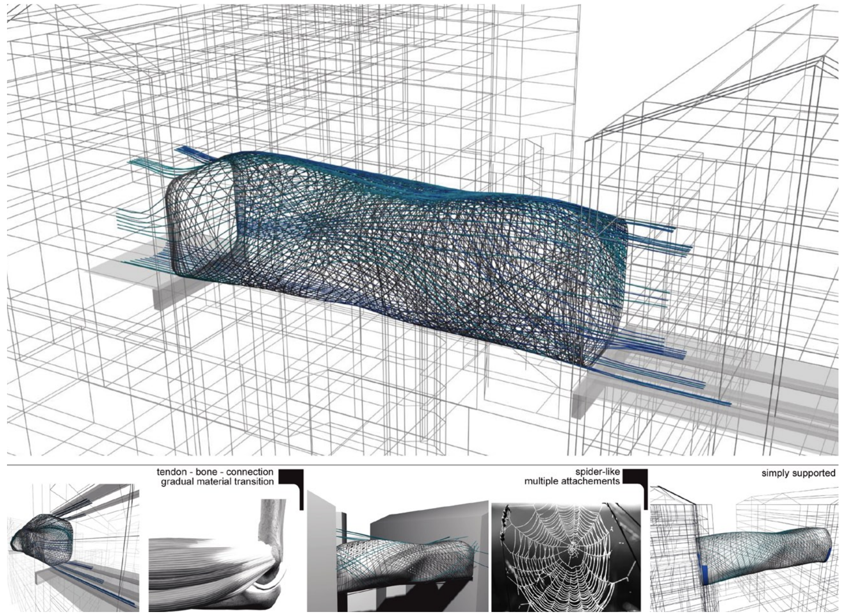
THE CORE IDEA OF THIS RESEARCH IS THE INCORPORATION OF THE MORPHOGENETIC PRINCIPLES FOUND IN NATURAL SYSTEMS IN THE GENERATION OF FIBRE-COMPOSITE STRUCTURES BY EXPLOITING, AT THE MAXIMUM, THE INTRINSIC PERFORMATIVE CAPACITIES OF THE MATERIAL SYSTEM IN USE. The intention is the integration of form, material, structure and program into a multi-performative system that will satisfy simultaneously several, even conflicting objectives, in order to achieve an optimal compromise. This process involves the combination and implementation of concepts and methods based on precedent studies in the field of biomimetics, as well as form-finding digital and physical experiments that inform a coherent design methodology, leading to a structural system able to be fabricated using cutting-edge technology.



1 Introduction

A main goal of this research is to propose a biologically inspired computational approach on form generation and on design methodologies that is not teleological and linear but parallel and with multiple interdependent hierarchies.

The overall design methodology aims at becoming a generic shape-finding and fibre path-finding method for *tow-steered* composite structures implementing the dynamic process of *adaptive growth*.

The idea stems from biological entities and the way they develop under load, distribute and organize material by responding to internal factors and environmental conditions. This mechanism allows every load bearing natural construction to "adhere to a uniform stress distribution" and to achieve an optimal design "of high reliability and minimum consumption of material and energy" that will enable them to survive the "tough competition" of natural selection (Mattheck 2005). Therefore, the process of adaptive growth leads to a seamless and gradient differentiation of material distribution, porosity, degrees of transparency and varying mechanical properties, generated by the same constituents.

By informing the design process by the concept of adaptive response and environmentally sensitive growth met in natural systems a composite shell structure (figure 1) is being developed whose structural performance, mechanical properties and microclimatic conditions vary as a function of material organization and distribution in response to extrinsic stimuli. Therefore, the material utilised becomes the generative driver of the evolution of the system, by exploiting its inherent performative and modulation capacities and by establishing a synergetic relation between its material thresholds and environmental dynamics.

2 Context: Natural and Artificial Systems

Shape configuration of shells and fibre articulation are being examined thoroughly in natural composites (figure 2) in order to inform the design methodology as fibres constitute the basic elements of shells, affecting their overall performance and configuration.

The resourcefulness of material use, the underlying structural systems and the capacity to respond to a variety of environmental forces, constitute natural systems, interesting paradigms to human architectures. In order to understand and exploit their morphological complexity, the field of biomimetics can play a crucial role. Even though biomimetics

FIGURE 1. (TOP RIGHT) FIBRE-REINFORCED MONOCOQUE SHELL STRUCTURE AND ATTACHMENT TECHNIQUES

literally means to mimic biology, the basic concept that can be extracted from this field is mainly to understand the underlying ideas and principles.

Natural composites are successful not so much because of what they are made of but mainly because of the way in which they are assembled. Nearly all loads of biological structures are carried by fibrous composites. Fibers are extremely good at withstanding tension, but perform poorly in compression. However, nature gives several solutions to this problem, with matrices such as cellulose and lignin that glue them together and prevent them from buckling.

Thus, the same constituents—matrix and fibres—have an identical structure, but depending on the conditions in which they grow, as well as their position and performance within the system, they tend to change their shape, topology, and organization. The major mechanism involved in this optimization process is the so-called *adaptive growth*. This intelligent survival strategy enables biological structures, such as trees and bones, to adapt flexibly their original optimum designs, to changes in the loading conditions (Mattheck 2005).

The artificial equivalent, that gets closer to the biological paradigm is the *tow-steering* design technique mainly utilised in aerospace engineering and in sailing technology (3dl technology). According to this technique, each laminate is made by combining layers with various fibre orientations, material properties, or thickness; however, the most innovative thing is that fibres can be laid up curvilinear, extending the 'tailorability' of the design and responding favourably to favourable loading conditions and programmatic requirements (Waldhart 1996). By allowing the stiffness to vary from one point to another, this manufacturing technique becomes a step forward of the classical 'stacking sequence' method as it avoids the over redundancy in spatial organization and opens the possibility for a gradient material distribution where is needed, leading to an energy and resource-saving construction analogous to that found in biological systems.

The fiber articulation enabled by the tow-steered method seems an appealing technique to be used in an architectural context where programmatic and diverse environmental factors will contribute to the generation of a structure. The variable-stiffness concept has to extend not only to the load-bearing capacity of the structure but also to the manipulation of its organizational logics that are intricately connected to its differential optical effects and climatic intensities.

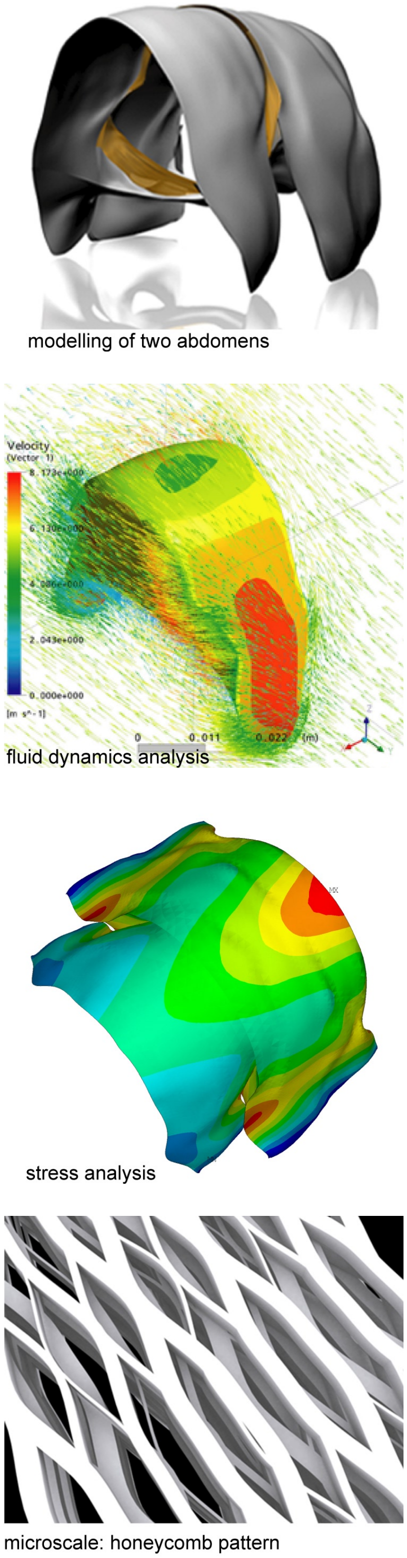


FIGURE 2. (LEFT IMAGES) DIGITAL MODELING AND ANALYSIS OF MACRO- AND MICRO-SCALE OF THE EXOSKELETON OF A LOBSTER

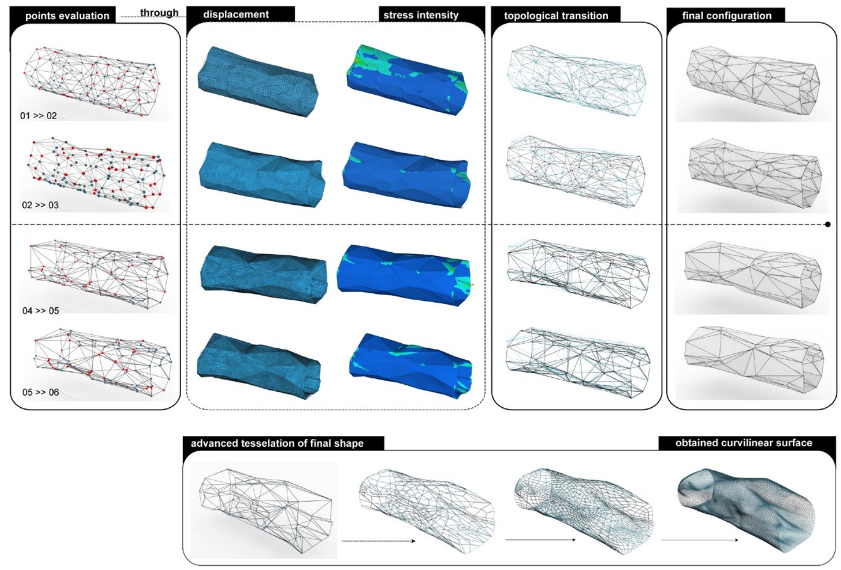
3 Design process

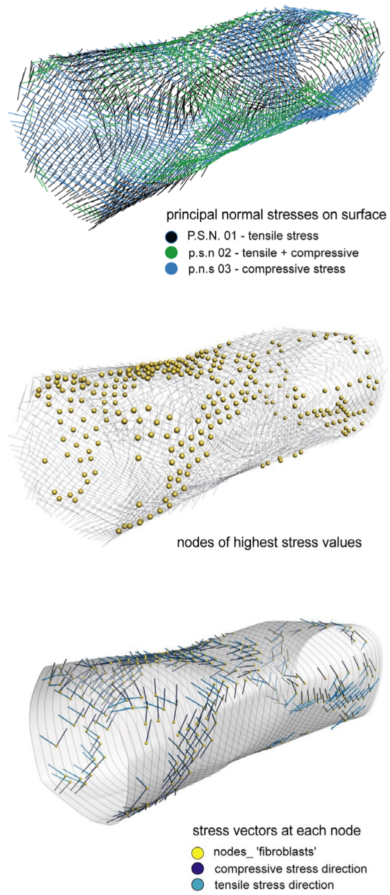
A computational method, inspired by 'biological self-optimization', a term cited by the biologist Claus Mattheck for adaptive growth (Mattheck 1998), is being developed from which the topology of the main surface is first evolved [shape generation] and thereafter the fiber reference-paths [fibre generation]. Both strategies are interlinked following an ontogenetic process of morphogenesis, while simultaneously are being informed by environmental and structural factors that generate porosity [porosity generation].

Ontogenesis refers to the evolution of individual organisms instead of entire populations and species; it is the way hierarchies of components constituting the individual interact and organize by adaptive response to their environment. Plants and bones are distinctive examples of Ontogenetic adaptation, in which stress works as a growth promoting agent; they adapt and respond to variable conditions by material deposition and by changing their form and structure.

The design intension is to bridge two existing buildings with a long-span monocoque shell operating as a passage and an exhibition place. Typical objective functions, for a structure like this aim at improving its structural behaviour, its strain energy, stress levelling and weight reduction while satisfying directional strength and stiffness. Additionally, its programmatic requirements, movement-flow and microclimatic environmental conditions become key aspects of the generation process.

During the shape-generation process, points act as morphogen cells which self-orgnanize, acquire their position and role within the system triggered by stress, which, as in natural systems remains the growth promoting agent. During, the fibre-generation pro-





cess, new nodes extracted from the structure act as fibroblasts cells, which again triggered by stress concentrations, start to release fibres in the direction of the principal stresses.

3.1 SHAPE GENERATION

The environmental setting is being simulated and the design domain is being defined: the system is comprised by a random distribution of points along a cylindrical shape with a ratio of five meters and a span of ten meters.

A Delaunay algorithm is being applied for the tessellation of the structure which connects the neighboring points while maintaining the area free of intersections. Each of these nodes is being classified with different loading conditions (load vectors or supports) according to its position within the system.

The resulting structure is being evaluated through a *Finite Element Analysis* which for a given set of materials, density and elasticity, produces a value for the objective function, that in this case, is stress and strain levelling.

The nodes that indicate the lowest values of stress and displacement act as attractors for their neighboring nodes and the systems is being self-organised in search of equilibrium. The rate of attraction is analogous to the rate of proximity.

The algorithm iterates again, according to values obtained each time by stress analysis, until a constant stress state on the surface is achieved, according to the axiom of uniform stress (figure 3).

The nodes work as receptors for detecting local stress peaks triggering a homeostatic growth process; they constitute repeated modules, of identical structure, whose function alters depending on their position and role within the system.

3.2 FIBER-PATH GENERATION

This obtained geometry is further analysed through finite element analysis to get information on the occurring type of stresses, their magnitude and directions. The nodes which indicate the highest stress concentrations along the structure are extracted in order to act as homeostatic agents that restructure their environment to regulate tension, by releasing fibres along the direction of the quantitatively largest principal stresses (figure 4).

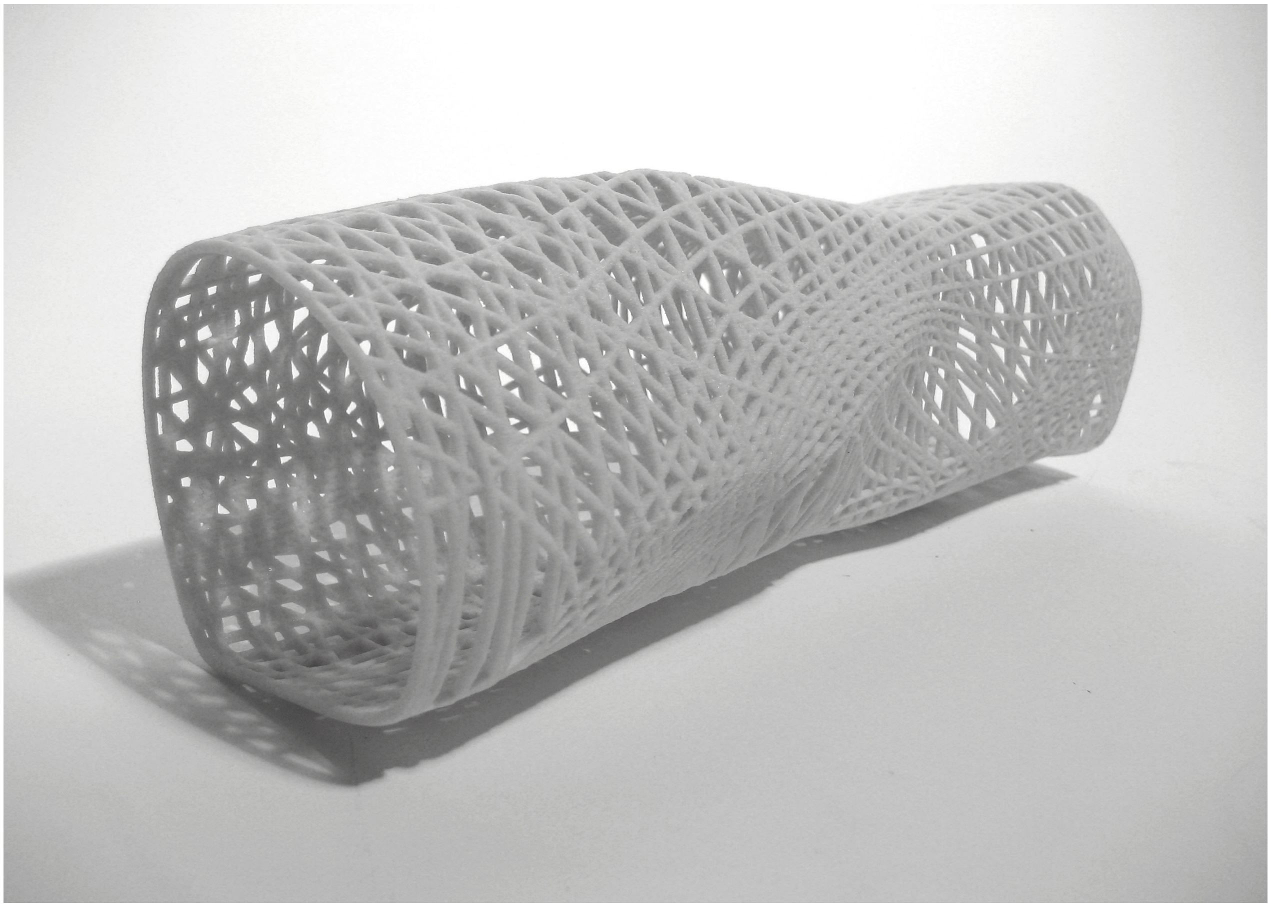
This optimum arrangement minimizes shear and transverse stresses between the fibers while increasing the maximum load capacity (Mattheck 2005). Therefore, the pattern that emerges out of the arrangement of the fibre courses, in anticipation of the loading conditions, comprises the force-record of the structure (figure 5).

3.3 POROSITY GENERATION

Another mechanism is responsible for the generation of porosity as an additional property of the system. Both structural and environmental analyses are being conducted in order to modulate the internal environmental conditions of the structure by demoting slightly

FIGURE 3. REPETITIVE PROCESS OF SHAPE GENERATION AND TESSELLATION

FIGURE 4. FIBRE-PATH GENERATION PROCESS: COURSES RUN ALONG THE DIRECTION OF THE FORCE-FLOW.



its stiffness capacity. This process is informing simultaneously both the global shape and fibre articulation by the creation of apertures on the shell, which will allow lighting infiltration and air ventilation (figure 6). The careful identification of areas of weakness can ensure that important parts of the structure are protected.

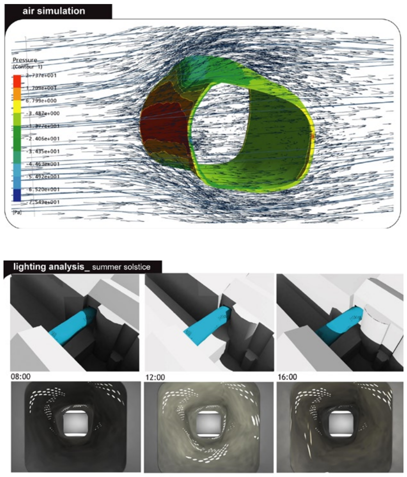
Specification of the optimal position of apertures derives from experiments and analyses (figure 7): material distribution analysis shows the areas with the least stress concentration, where material can be reduced, fibre volume fraction analysis exhibits areas with the least fibre density which would facilitate the creation of voids, solar exposure analysis displays the distribution and availability of incident solar radiation on the model and prevailing winds analysis defines the best possible position and shape of the openings, in order to accommodate ventilation by avoiding strong currents and water penetration.

4 Manufacturing and fabrication

The design process is intricately linked with the chosen manufacturing method, that of steered-fiber lay-up. The splines generated, represent the reference paths which is the curve traversed by the centre of the applicator head of the tow-placement machine during the fabrication of a single course (figure 8). Moreover, fibre paths alter locally in such a way so that they do not disrupt the continuity of stress flowing in the fibres when they approach the voids; they do not terminate abruptly at the edge of the holes but appear to follow contours around them.

The whole structure is going to be pre-fabricated, transport on site and craned into place. First the mould is being milled into pieces which can be easily interconnected and dismantled to extract the shell (figure 9). The shell is a one-piece component constructed by superimposed fibre courses laid up by the tow-steering application head and high-strength adhesives and tape-laying machines will be used to attach the shell to the existing

FIGURE 5. 3D PRINTED MODEL OF THE FIBRE REFERENCE PATHS EXHIBITS THE FIBRE VOLUME FRACTION AND POROSITY OF THE STRUCTURE



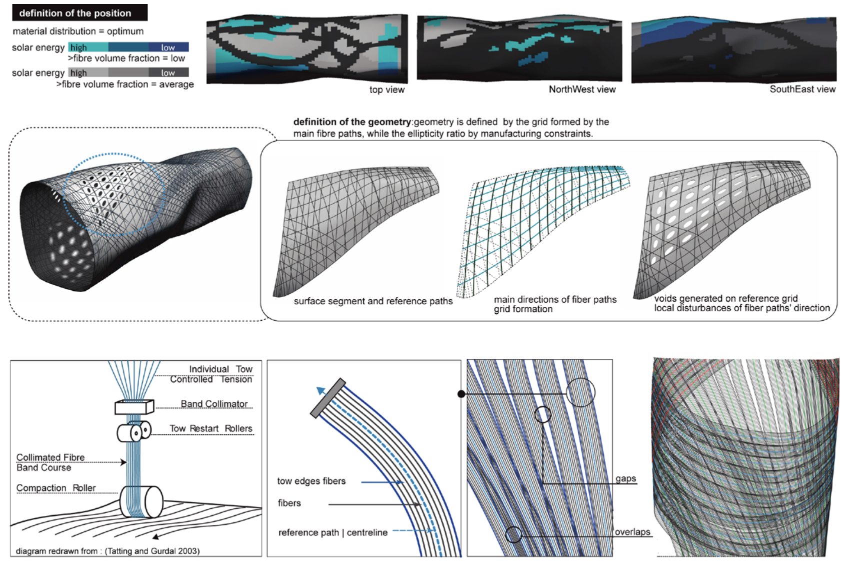


FIGURE 6. AIR FLOW AND LIGHTING ANALYSIS OF THE STRUCTURE AFTER THE CREATION OF THE APERTURES

FIGURE 7. DEFINITION OF THE POSITION AND GEOMETRY OF THE APERTURES

buildings that support it. This type of monocoque construction is extremely lightweight, easily transported, and of low-maintenance.

5 Conclusions

The above research sets a new combination of techniques, concepts and methodologies in order to come up with a coherent system whose form, materialisation and manufacturing logics are integrated and interrelated. Matter is considered to be pregnant with its own constraints that are not imposed on any fixed geometry, but its behaviour in interaction with applied forces is implicated in the generation process and at the final outcome.

A great deal of redundancy and differentiation emerges out of the intricate contextual relationships of repeated components, leading to a structure that is not limited to its load-bearing capacity but to a wide range of performance criteria.

Function and structure are intrinsic to the generation process of the system, in search of stress equilibrium; it is an "embodied physiology" (Turner 2007).

A further aim of this work is to be extended and be applied to varying architectural problems. The main design strategies, which were shape generation, fiber-path articulation and porosity generation, can be regarded as three separate design processes that are not limited to the domain of fibre composite structures.

Each one can be implemented into different design problems, informing different aspects of a project; by defining either the overall shape of a shell according to the axiom of uniform stress, or by tessellating a surface along the force-flow (principal normal stresses) or by tuning the microclimatic conditions and generating porosity into a given system without disrupting its structural efficiency.

A long term goal of the project is the further development of the algorithmic process which is already established with the self-organization of the points. It is a major challenge to set-up a computational system that will incorporate various factors, which will create new design paths through their interrelations. The creation of an open system as such, would allow for a better interaction between the variant inputs of the process and it would promote the continuous development of the design methodology, by introducing new features.

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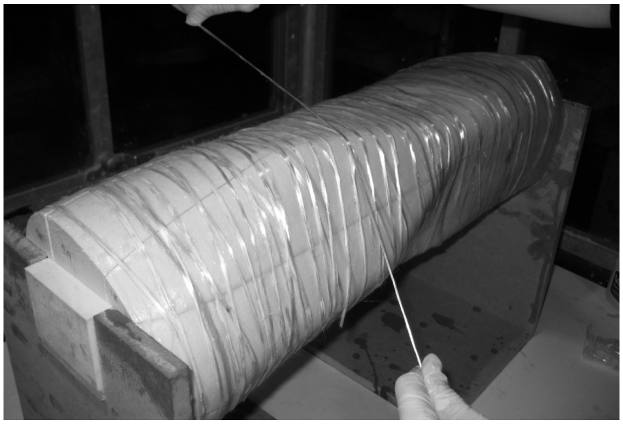

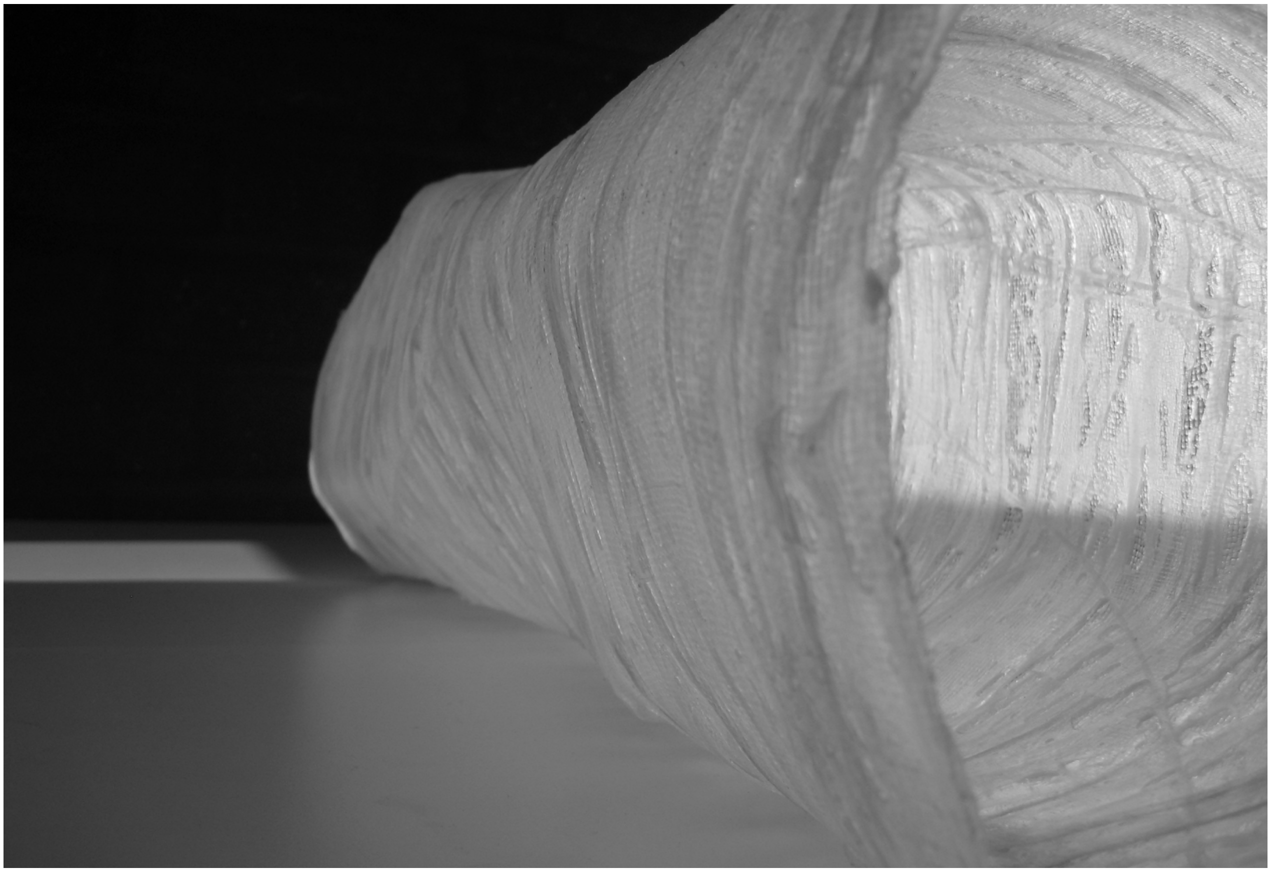

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FIGURE 8. (OPPOSITE TOP 4 IMAGES) TOW-STEERED METHOD: PLACEMENT OF FIBRE-COURSES

FIGURE 9. (OPPOSITE BOTTOM) FABRICATION OF A SMALL PROTOTYPE: THE NUMERICAL CONTROLLED METHOD IS REPLACED BY HAND LAY-UP.