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Crafted variation in FRP: Resilience by fabric materiality

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Abstract

The basic principle of living matter, being structured as fibres and matrix, is often taken as a reference for the design of FRP materials. Biological design principles, such as self-organisation and variation stand in contrast to standard design and fabrication of architectural FRP and therefore call for alternative processes. Introducing the concept of *Fabric Materiality*, the research suggests an alternative fabric based approach to design and fabrication that relies on textile's inherent attributes. Through a case study, the paper examines the potential of developing a resilient FRP structure by employing principles extracted from the biological resilient model of a bird's nest, relying on the integration of *Fabric materiality.* Transposing these principles into a FRP structure faces the challenge of structured randomness at the structure level and crafted variation at the component level. The resulting structure is extremely light, self-supportive and resists lateral loads, is varied and demonstrates resilient properties.

Keywords: FRP, architecture, composites, fabric, textile, resilience, biomimetics, self-organisation

1. Introduction

The composite material family of fibre reinforced polymer (FRP) combines advanced fibres such as glass and carbon, with a polymer matrix, offering extraordinary mechanical properties of strength and lightness. Synthetic and engineered in its material constituents, it is yet structured similarly to living matter, being structured as multi-layered arrangement of fibres and matrix. The inconceivable variety and complexity of natural living forms, shapes and structures is actually the product of several low-atomic building blocks; the constituents of biological materials are very few, mostly combined as composite fibre structures (Chen, McKittrick, and Meyers [2]). Only few main fibrous structural materials constitute the core of living materials, such as cellulose for plants, collagen for animals, chitin for insects and crustaceans and fibroin silks.

Biological paradigms and characteristics of natural systems can, therefore, be of high relevance to the design and engineering of architectural FRP, suggesting an alternative to the common mechanical-based logics of material and structural organisations (Knippers and Speck [5]). Biological materials are hierarchically structured as an integral part of their design, making no distinction between material and structure. Since the biological raw material in itself is weak, brittle and soft, its strength and stiffness is achieved by its layered internal architecture. The structural capacity of biological composites, as well as their variety, is achieved by their geometrical and hierarchical fibre architecture. By different spatial arrangements, elements of very different properties are constructed using the same fibre material; collagen composes the stiff bone as well as the flexible tendon and the soft blood vessel, in the form of a fibre composite material (Dunlop and Fratzl [3]). Differentiation through space (as opposed to over time), also termed by regionalisation, refers to those changes by area, which transform a homogenous mass of tissue into areas with different properties. Through the process, properties such as cell shape and size, its metabolism and response to signals change, so that the cell becomes specialized and suited to perform its specific role. Site-specific mechanical demands, imposed by external stresses, are answered by local changes in chemical composition and in structure, at multiple length scale. In comparison, architecture traditionally makes variation by means of form and the choice of material. Differentiation, as a natural strategy embraced by architecture, introduces the notion of variation of properties through the material itself.

While FRP is structured similarly to biological composite materials, standard FRP fabrication processes and applications do not relate to biological design principles. Key principles such as self organisation, variation and differentiation can hardly be obtained through the mould-based standard fabrication processes, in which complex or varied shapes require the fabrication of multiple complex sculpted forms as moulds. The integration of biological design principles in FRP calls for alternative fabrication processes that are free from limiting moulds and sustain variation.
Attempts for the integration of such design concepts can mainly be found in engineering research oriented towards bio-inspired composites, in theoretical architectural writing oriented towards material systems (Hensel, Menges, and Weinstock [4]) and in several architectural experimental design research, mainly conducted by ICD Stuttgart with the ITKE. It focuses on the integration of principles of biological composites into the design and fabrication of architectural FRP (Parascho et al. [8]), tackling the material on the fibre level, mainly dealing with direct robotic fibre placement.

The research presented in this paper investigates alternative design and fabrication processes for architectural FRP, relying on the fibres, but tackling it on the fabric level. Relying on the inherent capacities of the fibre constituent, under the form of fabrics, the research introduces the concept of *Fabric Materiality* in the design and fabrication of architectural FRP. It examines the potential for a FRP structure that embeds biological design principles to reach resilient properties, by employing a new, fabric based, design and fabrication approach.

The paper starts with the presentation of the concept of *Fabric Materiality* as an alternative design and fabrication process for architectural FRP, and its inherent potential for biologically inspired design of resilient structures. It then presents the design and fabrication processes of a case study, embedding *Fabric Materiality*. The paper is concluded by a discussion on the resilient properties of the structure, and the inherent potential of FRP processes relying on *Fabric Materiality* to integrate principles of biological composites.

2. Fabric Materiality : an alternative FRP fabrication process

Treating materiality as part of a larger design paradigm (Oxman [7]), *Fabric Materiality* is an approach to tightly related design and fabrication, originating from material properties. The term of *Fabric Materiality* is coined to represent the unique properties of textile materials and their processing techniques, together with the inherent design approaches these introduce. Three main characteristics of textiles are identified as defining the essential properties of *Fabric Materiality*: fabric manipulations, self-organisation and resilience. In the present research the general concept of *Fabric Materiality* is developed with regards to fibre composites, suggesting its integration in design and fabrication processes.

While the fibre constituent in FRP is mostly used under the form of fabrics, its standard fabrication processes do not rely on its inherent textile attributes. Standard FRP fabrication processes press fabrics onto rigid moulds, utilising the fabric's ability to adhere to the given rigid form in an optimal way; mechanical pressure over the mould overrules the fabric's resilient character and its capacity for self-organisation. The resulting morphology reflects only this of the rigid mould, with no presence of any typical textile form (Mallick [6]).

Fabric materiality could be embedded in the process of fabrication of FRP, enhancing textile attributes and biologically inspired design methods. Integrating textile-related techniques of form-making and material construction from the world of garment making as well as from the architectural form finding discipline suggests the freedom from moulds, and proposes ways for local differentiation for performance, optimization and ornamentation (Blonder and Grobman [1]). Relying on the natural properties of fibre architecture, both at the material level and on the structural level, enables the simple creation of complex three-dimensional surfaces, by the self-organisation capacities of the material under low-stresses and simple manipulations. Discarding moulds, it supports the simple generation of variation and coincides with characteristics of resilience.

2.1. Naturally adopting biological principles

Textile is a material system with a capacity for self-organisation in three-dimensional space; the fibre-based structure of the material and its resilient character enables the generation of complex forms by simple means. The spatial arrangement of fibres by mechanical interlocking only allows for the dynamic reaction to extrinsic forces, such as gravity, and to the induction of low-stress forces on the material by its manipulation. Being an engineered fibre-based material, its properties and behaviour are defined by its fibre architecture; as in natural materials, variations in fibre type, density or spatial configuration (i.e. knit, weave, braid etc..) define its performance. Textile characteristics of fabric manipulation and self-organisation, defined as essential properties of *Fabric Materiality*, inherently relate to key biological design principles, such as the hierarchical material construction, variation and differentiation.

2.2. Inherently resilient

This multitude of simple and weak elements that interact and construct a greater whole is a key factor of the fabric's resilient properties. It gives the material its flexibility and ability to recover to an initial or improved state after an event of stress, demonstrating soft stability and robustness. The multitude of fibre elements, interconnected by friction and mechanical interlocking, assures the resistance of the whole in case of local failure or error. As a system with high capacity for self-organisation, the textile adapts to wide range of changing boundary conditions without damage. The resilient character of textile, defined as essential properties of *Fabric Materiality*, inherently relates to structural and material logics of resilience.

3. Case study: the LifeObject

Similar to the biological model, the case study is considered on several levels of hierarchy, from the fibre to the overall structure. Although taking place on different order of magnitude than biological materials, its hierarchical design can be described from the structural macro level, through the meso level of components to the nano level of fibre itself. The different layers are interconnected, with design parameters on each level that determine its performance, informing adjacent levels of hierarchy and affecting the overall characteristics. Starting from the lowest level, the fibre is in itself a spatial organization of filaments either flat or twisted, in different grades. It is knit (for aramid fibres) or braided (for fiberglass fibres) in different patterns to form the fabric of the micro level. Moving upwards, it constructs a composite material for the tubular components of the meso-level. These are interlaced in space in relative compression, making a structural volume. (Figure 1)

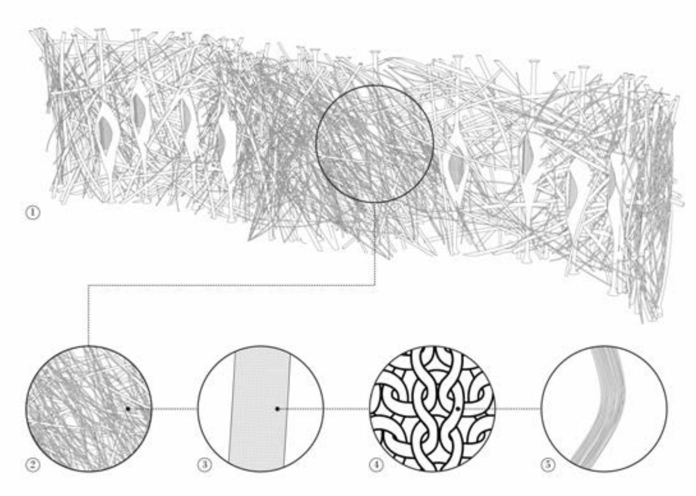

Figure 1**:** Hierarchical material construction. (1) Overall structure (2) Assembly of components (3) Tubular component (4) Knit fabric (5) Fibres

The structure of the case study is comprised of two independent elements, which are roughly defined as two free-form volumes of 11 and 16 cubic meters. Within these general abstract boundaries are placed over 1500 components of five different types, with a total length of over 2000 meters. With an estimated overall weight of 150 kg, its density as a volumetric porous material is extremely low, of about 10kgs per cubic meter. No additional joints or gluing agents are used for the construction. (Figure 2)

Figure 2: LifeObject, two porous volumes in space photo: Gianluca Giordano)

3.1. Biological resilience – the model of the bird's nest

The bird's nest was chosen as a biological model of a resilient structure, to be analysed and studied through a biomimetic process and implemented as a FRP structure. It demonstrates the principles of resilience, being diverse at its edge but simple at its core, exhibiting a high level of redundancy and of variety. By the analysis and the algorithmic processing of the CT scan of the nest of a Jordan Sparrow (Figure 3), characteristics and figures were extracted relating to the components (the twigs) and to their spatial configuration (the nest). Of special interests were the principles that stand in contrast to conventional engineering methods or logics of construction, which contribute to the resilient behaviour of the nest.

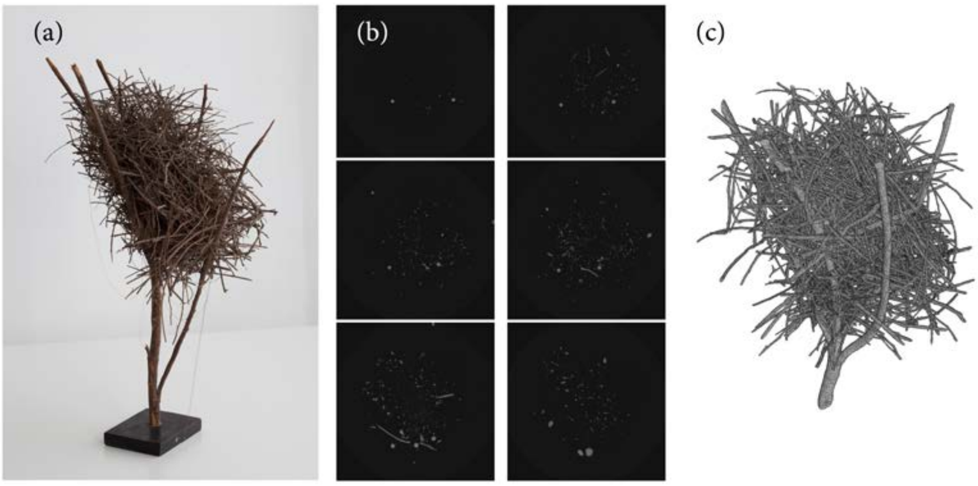

Figure 3: Nest (a) Jordan sparrow nest (photo: Amit ofek) (b) Selection of images of CT scan (c) Reconstructed digital model (model: Lior Aharoni)

The twigs that compose the nest are linear tubular or rod-like elements of varying length, flexibility and diameter. Readily found by the bird in its surroundings, they are easily manipulated and transported thanks to their lightness in proportion to the bird's own weight and physical capacity. While all twigs are of similar kind, each demonstrates difference in its shape and size, as well as in their distribution of spikes along the element. The spikes are integral to the twig, made from an identical material that is differentiated locally, holding a functional purpose in the structure, serving as stoppers to prevent the twigs from slipping or sliding.

The nest structure is composed out of a multitude of elements, relying on redundancy of weak elements rather then the seemingly efficient robustness of few. The overall double curved form is achieved by the combination of random elements held with no additional glue or joints, but by bending forces. It relies on the varying flexibility of the twigs and the reciprocal pressure applied by all elements in different directions, reaching a zero-sum of forces and stability. Although each nest would have a different random arrangement of twigs in space, and the twigs themselves are all different, all nests of the same kind share common traits. The seemingly random arrangement of the twigs by the bird, according to the local need and the readily available construction materials, follows some common numeric properties and construction logic, and therefore are visually similar. The algorithmic analysis of the nest extracted the spatial distribution, length and the angles (to nest's base plane) of the twigs, grouped into four types according to the twigs' diameter (Figure 4). The rather normal distribution of angles across types of twigs was thereafter applied in the design code, along with ratios of material distribution according to the different types.

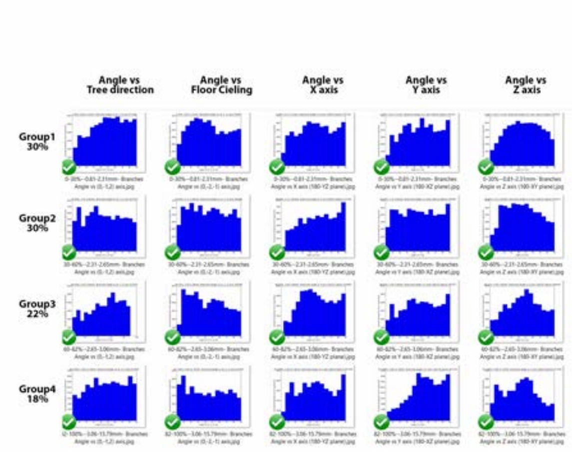

Figure 4: Angle distribution of twigs in the nest, by types (according to diameter).

3.2. Crafted variation

The twigs of the bird's nest were interpreted as tubular composite elements, made of one layer of knitted or braided fabric, of varying diameters between 8 to 50 mm. Aiming for weak and extremely light elements, material was reduced to the bare minimum, reaching an average weight of 5 to 45 grams per linear meter of cured element.

Facing the challenge of variation of the elements, while keeping a simple and sustainable fabrication process, present a substantial challenge to traditional fabrication processes relying on moulds. Embedding *Fabric Materiality* in the process, forming of the elements and their variation was assured relying on fabric manipulations and self-organisation. Fibreglass and para-aramid fibres were used to make five types of elements (Figure 5); while aramid fibres have low fibre-breakage and were found suitable for knitting, glass fibres were used as commercially available braiding. Fabric parameters such as fibre grade (para-aramid 200 Denier and 3000 Denier), additional fibres (nylon; Lycra), fabric density (wales density from 3 to 7 rows per cm), machine types (circular; flat of 5 gauge and 12 gauge) and knitting patterns (rib, piqué with variations for the circular knitting; single tuck and miss for flat knitting) were varied, to obtain the five major types of components, with variations.

Figure 5: Five types of elements were manufactured: 2 types of para-aramid knitting and 3 types of fibreglass sleeves of different diameters

The components were formed by self-organisation of the fabrics. As it is formed by a continuous loop of fibre, the knit fabric structure deforms easily and has good stretching capacity; it was therefore formed by tension. Any variation of length or diameter of the tube required only the change of knitting setting. As an integral part of the forming process, details were integrated in the elements; stoppers were created using a simple plastic rings that were introduced in the sleeve, creating a local deformation and articulation of the form (Figure 6) Variation in the number of stoppers and their location along the element, derived from the design algorithm, was easily obtained by the mere change in the number and positioning of the rings (Figure 8).

The different fabric parameters and geometric measures (diameter and length) affected the ability of the cured element to withstand bending forces and adopt a curved form under pressure. In addition, the resin composition was varied with mixture of standard epoxy system (Gvulot EP535) with 10% to 75% of flexible epoxy resin system (Graf RF32). Loading tests of the different elements demonstrated the differences in elastic modulus, and in yield point. For each type of element an average maximum ratio of deformation (radius of curvature/length) was estimated and approximate mechanical material properties were defined (elastic modulus, ultimate force).

In addition to the variations controlled by the various parameters listed above, a high rate of deviations can be found between similar elements due to their fabrication process; not using a rigid mould, the form is defined by self-organisation and is easily influenced by additional external factors (such as variation in the exact plane of orientation of the forming rings). As the impregnated fabric is not set against a rigid mould under pressure, as it is done in standard FRP fabrication processes, impregnation is not homogenous all over the fabric. (Figure 7)

Figure 7: Forming process by manual fabric manipulation introduces qualities of craft into the industrial setup of composite manufacturing

Figure 8: Variants of knit element (type:3000D), created by the simple placing of tension rings

Figure 6: Stoppers created through local deformation of the sleeve by the insertion of rings under tension (Photo: Amit Ofek)

3.3. Structured randomness

The macro level of the structure is designed with a parametric design algorithm (using Grasshopper for Rhinoceros) that populates given global volumes with components of the meso-level, through an iterative process. The closed or circular shape of the nest is translated into free-form linear volumes of the case study, altering the autonomous structural scheme of the nest to incorporate floor and ceiling planes of the given space of intervention; bending of the elements is assured by reciprocal forces between elements (component-to-component) as well as by ceiling and floor planes (floor-to-ceiling, for about 10% of elements). The pseudo-random distribution code is informed by the figures extracted from the algorithmic analysis of the nest, setting global relative distribution of material in the volume. Curves are placed within volume boundaries by an iterative process, controlled by the numeric values, assuring a material distribution that refers to the structure of the nest, both in orientation and in quantity. Floor-to-ceiling elements are interlaced with component-to-component ones; stoppers are placed at critical intersection points between the elements.

At a second stage, component types are assigned to the curves, informed by the mechanical testing and the definition of bending capacity of the different types. The global shape of the free-form volumes defined as a starting point, is obtained by the population of straight elements under bending, without any need to fabricate curved or custom-shaped components. Once placing and distribution of the elements is finalised, a list is automatically generated with complete data for each of the components: type, length and placement of stoppers, along with exact location in space.

Four element types compose the overall quantity of specifically numbered and defined components (Fibrelgass sleeve of 30 and 40 mm, Knit para-aramid of 200D and 3000D); a fifth element type (fiberglass 10 mm) that is generic, is added to complete the required material, which is manufactured by five relatively short generic sizes (100 to 180cm). The 450 specific components, with the 600 generic ones add up to a total length of 2200 meters, to populate volumes of 27m^3 .

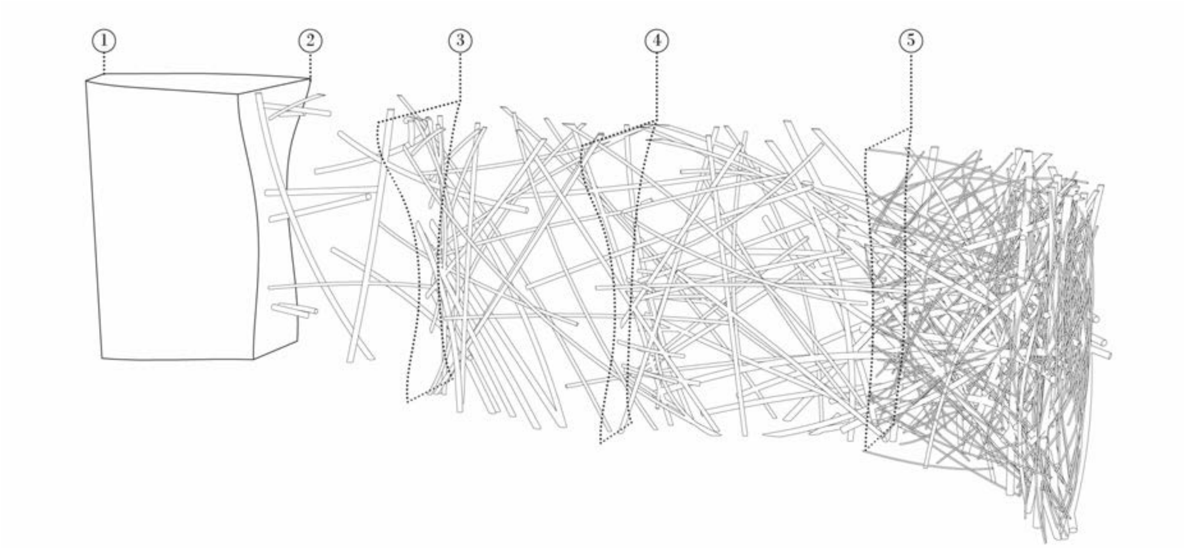

Figure 9: Phases of construction. (1) Global volume to fill (2) Guides (3) Components of predefined location (4) Components of predefined measures, bottom up placing (5) Free placing of short components

The notion of structured randomness is thereafter reflected in the construction process. The overall quantity of fabricated components is placed in a combination of predetermined spatial positioning and free placing. Out of the overall assembly of components of the structure, generated by the algorithm, a first layer of principal elements is defined; this layer, comprised of floor-to-ceiling elements as well as of component-to-component ones serves as the initial 'skeleton' for the construction process. These elements are positioned in space following the design obtained by the code; thereafter are positioned the rest of the floor-to-ceiling elements, for which a specific location is predetermined by milling of floor and ceiling plates. The placing of the remaining elements, both specifically and generically fabricated, is done freely, but according to the designated material distribution by the code; the elements assigned by the code to each section of the structure will be placed accordingly within it, but positioned freely to create a stable and resilient structure.

4. Conclusions

The case study described in this paper demonstrates the integration of the notion of *Fabric Materiality* in the design and fabrication of a FRP structure and its inherent potential for a design that embeds biological principles, for a resilient structure. Starting from the analysis of a natural model of resilience, the bird's nest, and transposing its principles and numeric values into an indoor installation of a FRP structure, affected the design, fabrication and construction of the structure. Issues of variation and control, which challenge conventional FRP fabrication processes as well as standard architectural and engineering approaches, were dealt on the component level and the overall structure.

Introducing *Fabric Materiality* in the fabrication process at the component level enabled the simple manufacturing of over 500 variants of 4 types by freeing the process from moulds. Manual work enhanced by the self-organisation of the material introduced crafted variation into FRP fabrication, affording diversity based on a simple core. The resulting tubular component, formed by *Fabric Materiality* into a naturally optimised shape, with a single fabric layer, is extremely light (10 to 45 gr/mt).

Following nature's model, the structural logic is of redundancy, relying on the multiplicity of weak elements to create the robust whole. Obtaining its curved shape by bending of straight and simple elements, and being free from any joints or gluing agents between the elements, the structure reaches stability by reciprocal internal stresses, while keeping flexibility. With a totality of over 450 predefined components, the structure weighs only 150 kilos; its estimated density is between 10 to 11 kgs/m^3. Lighter than feather, it is self-supportive and calculated structurally to withstand several parallel lateral loads. The design of the structure was the product of random iterations of the code combined with numeric values extracted from the analysis; this notion of structured randomness was thereafter reflected in the assembly process of the structure, combining elements of predefined position with free placing.

The transposition of biological design principles into a FRP structure calls for alternative processes of design and fabrication. The nature of fabric, and its integration in FRP fabrication processes relying on *Fabric Materiality,* enhances the resilient properties of the structure, suggesting an approach to resilient FRP for future research.

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