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Composite Territories:

Engaging a bespoke material practice in digitally designed materials

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Abstract. Today, material performance is regarded as one of the richest sources of innovation. Accordingly, architecture is shifting to practices by which the computational generation of form is directly driven by material characteristics. At the same time, there is a growing technological means for the varied composition of material, an extension of the digital chain that foregrounds a new need to engage materials at multiple scales within the design process. Recognising that the process of making materials affords perspectives not available with found materials, this paper reports the design and assembly of the fibre reinforced composite structure Composite Territories, in which the property of bending is activated and varied so as to match solely through material means a desired form. This case study demonstrates how one might extend the geometric model so that it is able to engage and reconcile physical parameters that occur at different scales.

Keywords. Composites; Material properties; Multi-scale.

Composites

Introducing the then new field of nanotechnology, Richard Feynman was one of the first to elaborate the many potentials of being able to manipulate and control things on a small scale. Addressing materials, he noted that "*up to now, we have been content to dig in the ground to find minerals… But we must always accept some atomic arrangement that nature gives us… What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them?*" (Feynman 1960).

Composites, which represent some of the oldest building materials as well as the most modern, pose the same questions to architecture, albeit at a slightly larger scale. In their modern conception composites are comprised of fibres that reinforce a matrix, with the properties of the bulk object being dependant upon the organisation of these components within it. Now, a shift to thermoplastics in the matrix phase of fibre reinforced polymers (FRP) allow for significantly easier and cheaper working methods, and far greater precision. Thermoplastics are not as brittle as thermoset-based composites, and are far more impact resistant and highly flexible. Polyethylene (PE) and polypropylene (PP), for example, significantly extend the capacity of composites to meet specific performance conditions, and further the idea that digital technologies can provide new access and relevance for materiality.

Figure 1: Composite Territories installation

Synthetic material as a set of conditions

As materials that are designed specifically for a given deployment, composites do not pre-exist, and are therefore very different to natural materials. Not being found objects, they can be more productively considered as a set of conditions, since they are designed for a particular bespoke state and performance.

Because a composite material's properties depend on its internal structure, designed through the specification of volume ratio, layering, and orientation, it becomes possible to control load transfer and therefore deformation in bending, flexure, tension or shear so that the material meets specific purposes and exhibits controlled behaviours. These interdependent relationships between micro and macro scales, within a context of performance, exhibit what CS Smith (1981) variously described as the "*interwoven importance of atoms and aggregates*" and "*the deep entanglement of macro and micro*".

Where traditionally material strategies have been based on differentiation and hierarchy, or upon the inherent properties of a natural material, GFRP allows material to be tailored to a form, to shift complexity from mechanical or geometric solutions into the material itself. For this reason, composites cannot be treated as simply a case of technology transfer, to be specified in the same way as other materials, but require deeper re-conceptualisations and new digital modelling approaches to be fully engaged within the architectural design process.

Incorporating Material Properties

As Delanda (2002) has argued, it is "*precisely those abilities to deal with complex, continuously variable behaviour that are now needed to design structures with the new composites*". Yet most tools for architectural representation do not support the active description of materiality. Instead, materials are conceived of as homogenous and static bulk elements and, unable to engage in deep entanglements of structure, form and loading, architectural representation has instead privileged the description of the surface (Addington and Schodek, 2005) and regulated materiality to empty spaces between the lines (Lloyd Thomas, 2006).

3D modeling tools are generally geometrically focused, that is to say concerned with the geometrical attributes of components and the topological and compositional relationships that associate them. Designed materials like FRP necessitate new relationships between architectural design practice, representation and material behaviour, to model processes that exist across multiple scale and to specify material change guided by simulation. Parallel knowledge fields to architecture have developed appropriate tools and methods, yet they need to be repurposed within architectural design practice, as our scale of operation necessitates the integration of digital simulation, prototyping and testing.

Parameterising a Model at Multiple Scales

Architectural modelling typically follows traditional drawing practice: a gradual refinement from greater to smaller scales. However fields such as chemistry and material science have developed processes of multi-scale modelling, a concept that focuses on relating parameters which occur at different scales. Within architecture, the transfer and exploration of this concept provides a means to extend the geometric model, to link local variation with global performance, and to support the exploration of how we might design with composite materials.

Many problems are characterised by underlying phenomena that span a large and hierarchically organised sequence of scales (Weinan 2011). Materials, for example, combine "*macrocosm and microcosm [which] consist of innumerable material objects. Each material object has a form. Each material object is capable of supporting and transmitting forces*" (Otto 1992). The information that we have about these processes is often only partial, and located or applicable at the macro or the micro scale. Rather than attempting to capture everything at one scale, multi-scale modelling is the application of modelling techniques that relate or 'bridge' macro and micro scales (Elliot 2011), by coupling together different kinds of description. It is a broad practice, which means different things within different domains.

Within material science, the macro and micro scales are often characterised by fundamentally different theoretical models, typically molecular dynamics and continuum mechanics. Continuum mechanics, which is typically used to model material and behaviour at the macro scale, assumes that materials are homogeneous even at the smallest scales. This assumption limits the ability to incorporate fine grained structure and material inhomogeneity, which can be a significant driver of material properties. The models that can capture differentiation at these smallest scales are molecular dynamics and quantum mechanics models, but because of computational issues these simulations are currently constrained to approximately 10^7-10^8 molecules, or about fifty nanometers. The problem of modelling larger entities is not simply computational – the mathematical complexities are so great that it is impossible to apply them directly to common problems (Weinan 2011). A multi-scale approach is therefore necessary for material scientists to accurately make descriptive models because each individual theoretical framework is inadequate on its own.

Within engineering, multi-scale modelling links the structural domain (macro) with the material domain (micro). Here the domains are much larger than those addressed by materials science, the models more often concerned with predictive rather than descriptive questions, and simulations are made using FEA software. For engineers, the central problem is one of optimisation: the structural level is the particular scale of interest, and the material level is varied so as to achieve a specific global effect. This involves the iterative solution of one problem at the structural level (stability) and many problems (identification of the best unit cells) at the material level (Coelho & Guedes 2008). Within an engineering multi-scale optimisation model, the macro-scale provides the environmental constraints for the micro-scale (loads, topology), while the micro-scale provides the data (forces, stiffness matrices) for the macro-scale (Coelho & Guedes 2008).

An Architectural Context

Multi-scale modelling for architectural design is obviously not the same as multi-scale modelling in material science, but perhaps not so far from its application within engineering. How might we begin to understand this concept as an operative architectural process? In architectural design, the macro and micro scales can be equated to the overall structure and the material component, where the material component is varied so as to activate a specific macro performance. Considering the active use of material properties, change at the material scale need not be limited to an optimisation of material but could instead have significant formal implications at the macro scale. As with the approaches detailed above, our attention shifts to identifying the processes and parameters associated with each scale, and to the connections by which to couple these different levels of description.

While the practice of multi-scale modelling is varied, it is possible to abstract some key aspects to inform an architectural design application:

- There is a global and a local scale, with distinct processes that occur at each scale.
- The representation of information or the framework of each scale may be of very different nature.
- Each scale has a design problem, and these problems are interdependent.
- Scales can be related through either sequential or concurrent coupling.

Figure 2
Composite Territories installation

Figure 3
Composite Territories installation

Composite Territories

The installation Composite Territories (figs. 1,2 & 3) brings these different research questions together in one demonstrator (Ramsgard Thomsen and Tamke, 2009). The structure is a variable stiffness, bending active glass fibre reinforced polymer (GFRP) gridshell, approximately 8x5x3.5m in dimension. Exhibited in February 2012 in Copenhagen, the installation initiated ongoing research into approaches capable of incorporating highly specified material performance within the design of bending active structures. The idea underlying the instrumentalisation of GFRP within Composite Territories is that, by precisely controlling and varying the stiffness of a structure, it is possible to encode a complex 3D form into flat, 2D strips. To investigate the implications, the installation proposed a gridshell in which formal complexity is located within the material, via specification, rather than being determined by the constant properties of the material and the level of geometric complexity achieved at the node, as is typically the case.

Under loading, a flat strip bends to assume a 3D form. This is a mode of failure known as Euler buckling, where compressive forces can cause the strip to bend and ultimately fail. The ability to resist buckling is linked to the direction and quantity of fibres within the strip. To most directly control this behaviour, fibres can be oriented along the length of the strip in the direction of highest stress, resulting in a condition of anisotropy – different properties in different directions. By controlling this anisotropy through very small adjustments in section width, achieved through an additive process of specifying and then consolidating different numbers of layers of unidirectional GFRP tape, it is possible to control comparatively large shifts in bending behaviour.

The design process employed micro and macro modelling strategies to specify and simulate bending so that, under self-load, the structure matches a desired form through only material means. Here the approach was to use the micro scale to determine and utilize the bending of each element under load. The bend strips aggregate behavior converts than on a global scale the 2D pattern to the 3D form. To specifying the stiffness of each element, a specific thickness needs to be specified so that each beam will deflect under loading so as to best match the underlying form. This initial specification was then refined through consideration at the scale of the structure, where topology aids in achieving strength and minimising material use.

Initial Testing – different layers, different bending behaviours (micro level)

As the intended structure is dependent on the micro scale, initial tests were made in order to understand and measure the bending behaviour of individual GFRP strips. A series of empirical tests were undertaken on single beams to establish the relationship between load, number of tape layers and deflection. Cantilever bending tests were performed to determine the stiffness of the material samples. The tests took the later loading condition in the structure into account by applying the weight through an extension of the beam. Measurement was taken as well after a period of time (20 minutes) in order to accommodate the initial relaxation of the composite. The material parameters considered within the tests were very narrowly focused: the fibre orientation within all material elements was unidirectional along the axis of the member, and only the number through layers was varied. These tests generated a look-up table (Diagram 1) that captured the deflection of elements with increasing amount of layers under a series of set loading conditions, which was later used to actively utilise this material property within the digital design process.

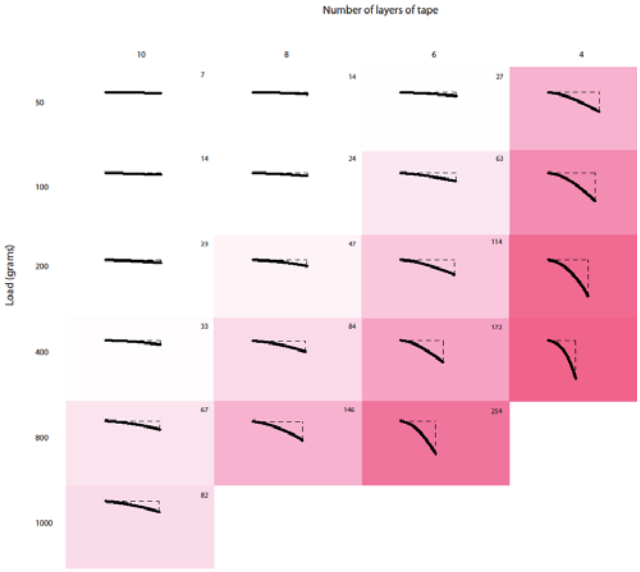

Diagram 1: Matrix of deflection of different layered beams under increasing weight

Design of the underlying surface and pattern (macro level)

The overall shape of the installation defines the macro level. On this architectural level it reflects the gallery space and architectural design intention by creating passages, views and spatial situations. The archetypical elements of column, arch and cantilever are combined in this shape (fig. 4) to combine and test GFRP against these well understood tectonic elements. The shape was modeled as a single Nurbs surface. A bespoke branching tool was developed in Grasshopper™ to grow a non-standard pattern over the underlying surface. This tool allowed for precise control over the beams maximum length and branching angle, as well as the joining of separate branches. Hereby different densities and orientations of the grid could be achieved – both to reflect structural as well as architectural considerations. The definition of the axis lines was further used for material specification and digital production scripts.

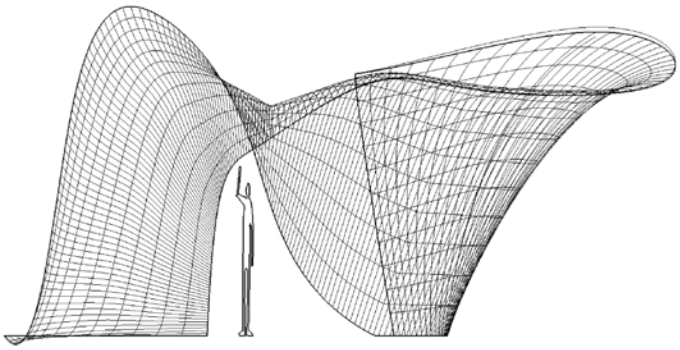

Figure 4: The initial shape defines the design target on the macro level

Parameterising Composite Territories at Multiple Scales

In graded material systems, the relationship between material differentiation and shape under loading is very sensitive. The challenge was to determine the right amount of GFRP layers for every strip so that the resulting shape would fit best to the target shape while being under load from the neighbouring elements. The determining structural property is the bending stiffness generated through varying amount of layers. Finite Element analysis can be used as an analytical tool, however an initial specification process needs to precede simulation, which must also consider load, deflection and target in order to determine a specific bending stiffness.

Our computational approach to integrate the local level into the global analysis was to feed back the stress-strain curves generated from material testing into the design process. A recursive algorithm was written that started from the peak of the structure and iterated over each member within the structure, assessing the local loading condition (the load of those elements it supports), the deflection that is required to match the underlying 'target geometry' and, through reference to a look-up table containing the load-deflection relationship generated during material testing, assign a number of layers. Once the load and required deflection is calculated, the closest load-deflection relationship determines the layer assignment for that beam element. While an iterative simulation process capable of optimizing material organization would render this step unnecessary, such an approach would also be prohibitively time expensive. Recognising that only axial loads are taken into consideration, this approach provides an achievable method of quickly specifying bending stiffness by increasing the information from material testing directly incorporated within the design process.

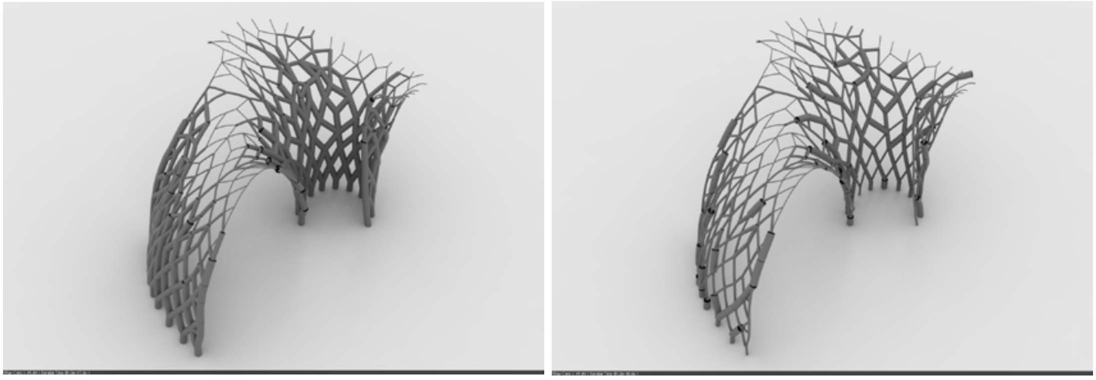

Figure 5 and 6: Layer Thicknesses (exaggerated) after initial specification and final ones after negotiation of required bending and FE analysis

Taking Structure into Account

An approach to layer specification that only considers the micro condition cannot take advantage of macro topological conditions. If only the initial specification process is used, the structural specification tends to 'max out' at 30 layers (fig. 5). To refine the specification process, the data gathered from empirical testing was used to calculate the Material properties (E-modulus, specific weight) necessary to calibrate a Karamba FE model, which included material definitions and beam thicknesses. The simulation showed the emerging loadpaths within the structure and the utilization of the single beams. This information could be used to link from the macro to the micro scale, where the layer thickness could be reduced in areas where there is no impact on the bending performance. The establishment of this feedback loop allowed resulted in greatly reduced beam thicknesses (fig 6 and diagram 2) while the reiteration of the FE simulation showed a similar close fit to the design target.

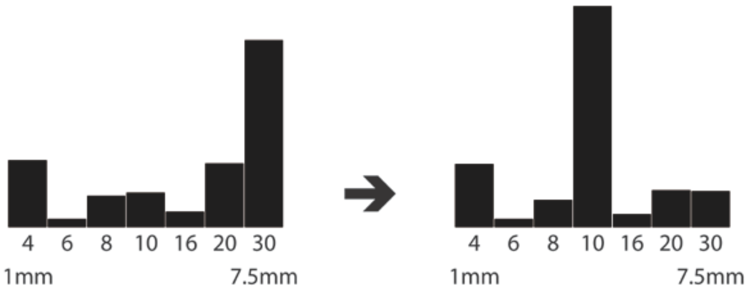

Diagram 2: Distribution of Beam thickness before and after link of Macro and Micro scale

Fabrication Information and Construction

All information required for assembly was transferred directly from the 3D model to each beam via a template. By assessing each beam and its neighbouring beams, we were able to create a common intersection shape (fig.7) which informed the geometry of each end. Printed templates, which specified neighbouring elements, orientation and fixing positions facilitated assembly without any further information being needed.

Figure 7: Stiff joints are attained through overlay and afford easy assembly

Evaluation and discussion

While a FARO 3D scan demonstrated that the predictive model was very close to the built reality (fig 8), the ability for the design process to incorporate the bending behavior was revealed as lacking in several key areas. Partly this concerned accuracy and precision. The approach to cantilever testing allowed us to understand the bending effect, but did not afford a rigorous means of measurement at the material scale. Access to mechanical material testing would have solved this problem, as well as have allowed the calculate properties such as

Young’s modulus, which instead had to be estimated using generic information sourced from the internet as a starting point.

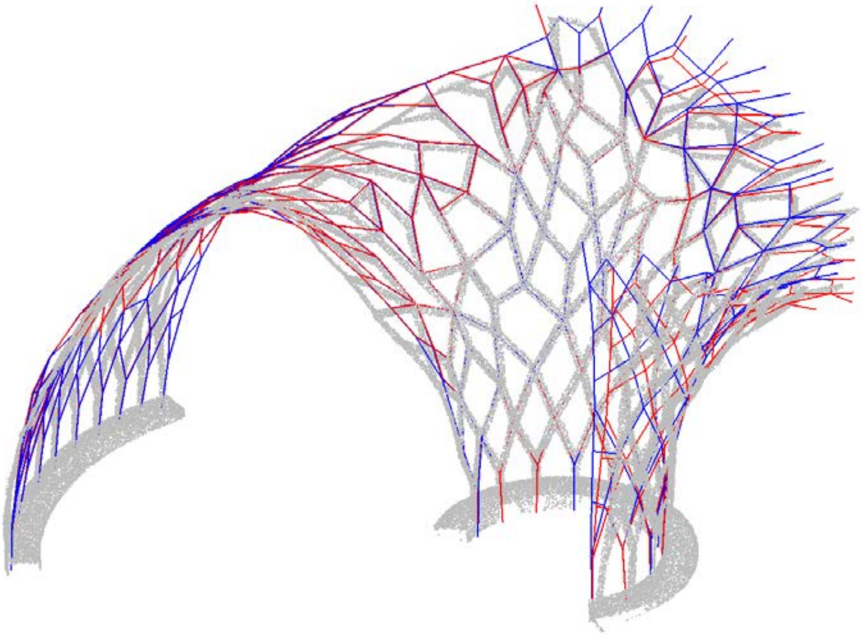

Figure 8: Overlay of initial Geometry (blue) simulated (red) and 3d Scan (grey)

Further, there was only a limited ability to link material and FEA simulation. As it was built from a representation of axis and nodes the FEA approach was able to simulate the bending behavior of the whole system, but did not include the elastic bending of the individual strip elements. That the FEA results were close to the 3d scan gives further inside into the interplay of the scales and how they can here be understood conceptually.

Were considerable forces have to be induced to bend the single strips into the overall shape the in this way induced prestress of the up to 1cm strong beams can be neglected for considerations on the global level. The bending of single elements is of little importance on the macro level. Here network effects generate a shell like behavior of the overall. The scales are yet interdependent as the overall shape is the result of the carefully curated bending of each strip under load.

The question arises how design can engage with situations where the micro level –the definition of material properties within a single beam – has to be considered for the functioning of a network condition on the global level, and how the emergent behavior of this network can become part of architectural design.

Conclusion: multi-scalar modelling as an operative architectural tool

Composite Territories shows the possibility of specifying inherent material properties for design using a multi-scale approach. Performative materials that are capable of addressing highly specific and varying design criteria extend yet simultaneously challenge our contemporary architectural practice, necessitating new methods and tools to encode design intent and performance. This is not simply a case of technology transfer but an extension of the digital chain that requires a re-conceptualisation of the link between design, simulation and making.

In taking this initial step towards understanding how multi-scalar modelling might be developed as an operative architectural tool, it has become evident that the kind of relationship constructed between scales, and the ability to link very different types of representation, are important aspects for architectural design practice and may differentiate multi-scalar approaches in architecture to those of other domains.

In contrast to engineering, where the relationship of macro and micro scales is one of optimisation, the architectural design context extends to explore the emerging and active behaviour of a material system. The process we have described was not well linked to the geometric design process, but opened up a new design space based upon material specification on top of a geometric definition. Extending the model into the geometric definition will be a next step. The approach we have taken did not use numeric simulation for both scales, as is typically the case in material science. Instead simulation was used for one level of representation, while empirical testing formed the basis for the other. In this way the design process is kept open to other tools that exist within the architectural legacy, such as the physical testing and measurement of the prototype, while computation is used to bridge these representations. In accepting a tradeoff from precision to speed, multiscalar modeling has the potential to pursue architectural design simultaneously with global and material considerations. How to gain insights into the emerging effects of more complex network conditions remains an open question.

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