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Embedding Designed Deformation: towards the computational design of graded material components.

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ABSTRACT

Recognising that the process of making materials affords opportunities not available when using existing natural or off-the-shelf materials, the focus of this paper is upon abstraction strategies by which the mechanical properties of composite materials might be engaged within digital architectural models. A proof of concept is developed around the process of designing, making and simulating a graded thermoplastic mono-composite sheet, which exhibits controlled deformation under loading.

Keywords

Digital design, composite materials, graded materials, material properties

INTRODUCTION

Today, material performance is regarded as one of the richest sources of innovation [5,21] . This emerges from the knowledge that far from being inanimate 'stuff', materials respond to forces in complex ways [7]. The ability to actively and productively use these behaviours within design is linked to advances in computation, fabrication and material science, and opens up new material, tectonic and sustainable possibilities for architecture [6, 19].

Accordingly, architecture is shifting to practices by which the computational generation of form is directly driven and informed by material characteristics. At the same time, there is a tendency towards the individual composition of material. Recognising that the process of making materials affords opportunities not available when using existing natural or off-the-shelf materials, this paper looks to the concept of composites as a basis from which to develop both a designed material prototype and a simulation strategy that incorporates material properties within digital models.

The focus of the paper is upon the abstraction strategies by which the material properties of composite materials might be better engaged within digital architectural models. Specifically, the paper considers one aspect of the conceptual framework that underlies composite materials, the rules of mixtures, and the distinctions in thinking by which this might be implemented within an architectural 3D model. A proof of concept is presented that integrates relationships between the constituent properties, their configuration within the material, and the macroscopic properties of a structure under load.

The proof of concept is developed around the process of making and simulating a graded thermoplastic mono-composite sheet. The mono-composite sheet is varied at the meso-scale, with the result of graded stiffness. Via this approach the bending behaviour of the sheet can be controlled. A digital model that pairs a parametric model and finite element analysis has been developed that accurately simulates this bending behaviour and outputs material fabrication information. The proof of concept is confined to the design and simulation of a sheet material.

COMPOSITES

Composites, which represent some of the oldest building materials as well as the most modern, combine multiple materials to create a new material with properties beyond that of its components [6]. As materials that are capable of being designed for specific contexts and performances, they rest on two basic ideas. The first of these is that, if a material does not exist, it can instead be made through the combination of two or more component materials [2]. Secondly, that the properties of this new material, for example the mechanical relationship between form and force that it exhibits, is dependent upon the organization of these components within the material. Following this, if a material's properties depend on its internal structure, and that structure can be designed, it then becomes possible to control load transfer and therefore mechanical deformation in bending, flexure, tension and shear so that the material meets specific purposes and exhibits controlled behaviours. These might be to counteract load in a particularly efficient way, or to change shape in an abnormal way under loading so as to perform a certain function [4]. As designed synthetic materials, composites form the basis for an expanded architectural practice, but their use implies the navigation of an unknown space, outside the properties of more familiar materials.

In their modern conception, composites are most typically comprised of fibres that reinforce a matrix [22]. They are at the leading edge of materials technology with applications such as aircraft and transportable structures on account of their high strength and low weight, properties that emerge from the orientation of the fibre. However, it is the matrix phase which most affects the cost, processing and level of specificity that a composite is able to achieve. For this reason, thermoplastic polymers are increasingly favoured over more traditional thermoset plastics since they allow for significantly easier working methods and far greater precision. Underlying this shift are many advantages: thermoplasts can be recycled many times without loss of properties, are cheaper than thermoset resins, and require much less energy to process. By virtue of their easier working methods and increased precision, thermoplastics such as polyethylene (PE) and polypropelene (PP) significantly extend the capacity of composites for the specific, and afford the opportunity to rethink a relationship that, in its limited modern focus upon stiffness and lightness, production methodology and price, has perhaps tended towards the generic.

Thermoplastics make it more possible to vary a property within a material, creating what are known as graded materials. Such materials can be either structurally or functionally graded (FGMs), and are commonly found in nature, in bio-tissues of animals, such as bones and teeth, and plants [14]. While a homogenous or isotropic material has the same properties in every direction, and most composites are anisotropic, with different properties in different directions, graded materials are characterized by non-uniform distributions of the component materials, thus varying in property and creating multiple functions within the material [11]. Because of this, they allow the full integration of material, contextural and structural considerations in the design of material components [24]. As distinct from fibre reinforced composites, where the orientation and distribution of the fibre determines the properties, in graded materials it is often control over the volumes of the component materials that becomes the means of optimising the material for specific applications.

The move to thermoplastics and graded composites expands the scope of application and spatial possibility for composites, and the design parameters that an architect can draw into their design process. However designing graded composite materials is a very different task to specifying traditional materials.

FROM SELECTION TO DESIGN

Historically, architects were limited to selecting natural materials based on their understanding of their extrinsic properties and performance [1]. With the industrial revolution, material advances such as iron, steel and reinforced concrete altered the course of architecture [6], impacting upon design methodologies, general conceptions of form, and modes of production [19]. The new engineered materials allowed for standardized properties and for specialization, and replaced a practical experience of materiality that was intuitive and empirical.

Exemplified in modernist tectonic thinking, specification and specialization allowed buildings to be broken down into material specific systems, which could again be differentiated into, for example, nodes that connect and beams that carry, and then again into beams that are sized differently according to their loading. In this manner, a building could be assembled from parts that reduce in scale at each level, with each level distinct from the orders above and below it, and structurally supporting those levels that come afterwards [3]. Here, materialisation and the control of properties becomes largely about minimizing behavioural change and neutralising its effects [10].

In one view, designed materials with graded properties could be considered as continuing this tradition of differentiation and specialization, but at a new scale where the opportunity is to work at the level of the material itself. Addington suggests such a possibility in the context of smart materials: "*smart materials are often considered to be a logical extension of the trajectory in materials development toward more selective and specialized performance*" [1]. But designing material properties from the bottom up, rather than shaping them from the top down, suggests changing possibilities for the association of parts and wholes. One example can be found in Beesley and Hanna's discussion of Peter Testa's Carbon Tower, in which they argue that the ability for fibre reinforced composites to incorporate what would otherwise be joints and abrupt changes in material implies a break from the tradition of reductionism, and an almost complete abandonment of the principles of hierarchies in building systems [3]. A second example, which pursues material specificity while maintaining the idea of parts, can be found in the thinking of Viollet-le-Duc, who extended his notion that it would be "*more natural to give these materials the forms suitable to them, and to arrange the architectural features accordingly*" into material itself: "*We ought to be able to analyse a building, as we take a puzzle to pieces, so that the place and function of each of the parts cannot be mistaken... each piece of dressed stone is an indispensible member, complete in itself, - a kind of* *organ which, subjected to analysis, finds its exact place and function in the whole*" [17].

REPRESENTATION

While graded composites hold much potential for design, they also introduce significant added complexity to the design process. Materials that are designed for a particular performance require representations that link that performance to the design process. Similarly, materials that vary continuously in their composition cannot be accurately represented at just the bulk level. As Delanda 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*" [7].

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 [1] and regulated materiality to empty spaces between the lines [18]. But architecture is now increasing its ability to engage material properties within the digital design process and an accompanying adjustment of the tools, methods, models, and media employed by designers to develop appropriate design strategies is underway; these digital tools are better able to describe the complex and novel underlying organisational structures that are required. The use of analytic, parametric and constraint based software as well as scripting and physics-based calculative tools forms the basis of this exploration [13, 25, 26].

While 3D modeling tools have allowed architects new approaches, and in particular extended the ability to incorporate properties linked to fabrication, for the most part they remain geometrically focused, that is to say concerned with the geometrical attributes of components and the topological and compositional relationships that associate them. This approach is well suited to integrating extrinsic material properties, such as bulk dimensions, volume and centre of gravity, but lacks the capacity to capture those material properties not easily described through explicit geometry. In the case of a component for example, mechanical properties can be empirically tested, measured and then encoded in abstract relationships within a parametric or scripted model, so that they are filtered through bulk geometric characteristics because constant material properties are assumed. Such an approach works well if the deployment of the component matches the empirical testing exactly, but these approaches cannot be applied directly to the design of composites with graded properties because it is the underlying materiality that is being varied, below the level of the component.

Approaches to integrating composites and graded materials remain a challenge, because they require early stage modeling tools and strategies that incorporate varying organisations and combinations of properties. This requires a different set of conceptualisations. How then can we think about designing below the level of the component, using a digital model to make relationships between the constituent properties, their configuration within the material, and the macroscopic properties of the structure, keeping in mind that the purpose is to make models *for* incorporating the design of material as distinct from models *of* material? [16]

CONSIDERING MATERIAL AS A SET OF CONDITIONS

As materials that are designed specifically for deployment, composites do not pre-exist that deployment, 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 describe a particular state or a set of circumstances and are also a proposition on which another proposition (the deployment) depends.

The first of these conditions relates to scale, and the second to configuration. All materials can be thought of as nested structures, whereby the properties emerge from interactions across scales. All materials 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*" [20]. While these material objects exist across different scales, they establish interdependent relationships between each other, exhibiting what CS Smith variously described as the "*interwoven importance of atoms and aggregates*" and "*the deep entanglement of macro and micro*" [23]. Composites allow us to engage with this diagram directly, by understanding that the properties of the whole system depends on the properties of the constituent materials, their concentrations and / or orientations, and the response of the material to conditions of load and restraint. These parameters can be understood through reference to three interconnected scales - the micro, meso and macro - and through reference to the concept of the rules of mixtures, simple equations used within material science to determine a property of a composite in terms of the properties, quantity and arrangement of its constituents.

The micro scale – small compared to that of the components— encompasses interactions and arrangements that occur at a molecular scale, and is typically measured in nanometers. Many of the properties of matter are determined by the properties of molecules and atoms - in the case of polymers for example, the length and branching of molecular chains determines the structural properties of the plastic as a whole. In the architectural context, this is not a scale of design but rather of selection based on desired properties [2].

The meso scale exists between the micro and macro scales, at one scale below that of the component, and can be measured in millimeters. At this scale, material elements are organized either via inherent properties or by design into physical structures that are much larger than the micro scale, but much smaller than the macro scale of the material. In many different kinds of materials and systems, the properties and interactions at this scale determine the overall properties of the material. Examples include cracks and imperfections in metals [2] and turbulence.

The macro scale – large compared to that of the components— is the bulk scale of the material element. It has a shape, is restrained and accepts loads, and exhibits resultant properties, in this case a mechanical response to force.

At the meso-scale, configuration becomes important. The component materials within a composite may be configured in different ways, for example as particulates, long or short fibres within a matrix, or as sandwiches or laminates. The chosen configuration is often driven by the length scales of the constituent materials, the means of fabrication, the loading that is expected, the scale of the bulk object etc. In a graded material, a particular configuration will be varied across the material.

There are approaches to the representation of graded materials that geometrically model these configurations, however it is recognized that major disadvantages include the requirement for a lot of memory, and being too complex [10]. Materials science provides a different approach, based on simple equations to capture compositional distribution at this scale, called 'rules of mixtures' [2]. These equations are used to approximately calculate a property of the composite with regard to properties, volume fraction and arrangement of the constituent materials. They rely on the assumptions that at the macroscale, a composite behaves like a homogenous solid with its own set of thermo-mechanical properties, and that the mechanical behaviour of a composite results from load sharing between the two constituent materials. That is to say that a certain proportion of load will be carried by one component material and a certain amount by the other. The proportion of load carried by each can be determined by volume-averaging the load within a unit or element of material [12]. If the material is isotropic or anisotropic the unit to which the rules of mixtures is applied is that of the object, but if the material is graded the unit needs to be at the scale of a unit smaller than the object.

There are many rules of mixtures, each describing specific material arrangements. For example, to calculate the bounds between which the e-value of a non fibrous composite should lie, two rules of mixtures are used: the Voight (upper) and Reuss (lower) bounds. Each is a simplifying assumption that needs to be calibrated for particular cases, however the benefit of this numeric approach is that it provides a way of engaging the meso scale, and thereby designing the relationship between load and resultant behaviour, while avoiding the modeling of individual geometries.

The following section describes, through the making of a graded mono-composite sheet, how these distinctions in thinking that can be made within an architectural digital model so that it is able to involve another level of material parameters for the purpose of simulating a graded material.

RESEARCH STUDY

This study investigates the control of deformation in a bending active sheet structure, where the 3D shape is embedded within the internal organisation of the material.

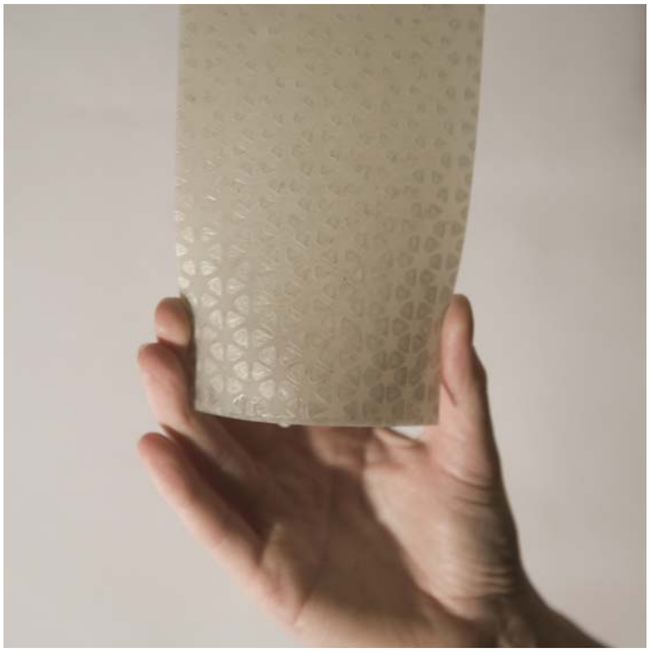

Fig 1. Graded mono-composite sheet

The system is based on the idea that a very simple compressive force might drive a more complex deformation. The sheet is a graded mono-composite which combines two phases of the same thermoplastic, low density polyethelene (LDPE) and ultra high molecular weight polyethelene (UHMWPE). In contrast to most composite systems, which are almost impossible to recycle since it is very difficult to decompose the component materials, recycling is simplified to melting of the composite and reprocessing. The resultant composite retains bending flexibility far beyond that of traditional fibre reinforced composites, is lighter and achieves 3-5 times the strength and stiffness of an unreinforced polymer.

COMPONENT MATERIALS

The mono-composite sheets developed for this study were produced in collaboration with RISØ DTU in Denmark. They combine low density polyethylene (LDPE) and ultra high molecular weight polyethylene (UHMWPE). PE is a thermoplastic polymerized ethylene, and both polymers are already common to building practice. Its different phases can be categorized according to the way that their molecules relate to one another: chain length, chain branching and molecular density. LDPE has a relatively short molecular chain (a chain of molecules made up of simple repetitive units) with many branches. These branches create many overlaps and tangles with immediate neighbours. This gives it the property of high local resistance but low resistance to bending. UHMWPE has relatively long chains, which no branching. As a result it is much stiffer.

So as to have most influence over the bending behaviour, the LDPE and UHMWPE components of the sheet are organized as a laminate structure. The core of the material is a zone of LDPE while the LDPE and UHMWPE co-exist along the faces. The UHWMPE sheets are laser-cut to achieve the desired material distribution. Each face is divided into quad elements of size 8mm * 8mm, with each element then containing a percentage of the two polymers. The layers are then assembled and the material is consolidated at 135 degrees celsius.

DEVELOPING BEHAVIOUR

To control the bending of the sheets the ratios of LDPE to UHMWPE at each face need to be varied. In order to gauge this effect, several sheets were made up with differing but consistent LDPE to UHMWPE ratios: 50-50, 30-70, 10-90. A simple quad pattern was used, which offset element edges inwards to achieve these ratios geometrically. This pattern was chosen as it ensured sufficient flow through of the LDPE to bond the sheet together. The sheets were pin-jointed and bent in a jig, with the resulting offset bending behaviour used to calibrate the 3D model.

COMPUTING BEHAVIOUR

In the above cases, the geometry of the sheet (length, width, thickness) as well as the loading and restraint conditions, ie. everything that might be representable within a traditional CAD program, is exactly the same, yet each sheet bends uniquely. To simulate this behaviour a digital model was developed within Rhinoceros, using Grasshopper and the finite element analysis tool Karamba.

An underlying parametric model was generated based on the empirical measurement of bending behaviour of an undifferentiated LDPE sheet. The surface of the model was divided into elements of 8mm * 8mm, matching the divisions of the physical sheets. Each element edge was assigned as a beam member within Karamba. Within Karamba, structural elements can be assigned an e-value, which describes the stiffness of a material or its resistance against deformation. For UHMWPE this value is 14000 kN/cm², and for LDPE it is 3000 kN/cm². The properties of the two component polymers are brought separately into the model. These values, as well as the desired volume ratio of each, are taken through a custom Grasshopper node that firstly calculates the resulting e-value for that element at each face, and then taking into account the sandwich structure. The resulting value is applied to the beam elements that define that element locally. In this way, each element is represented within the structural model via its edges, and the stiffness of each element is designated individually. The parametric model therefore provides a base onto which material is distributed at the meso-scale, and this material information informs the finite element analysis that then determines the macro-scale deformation.

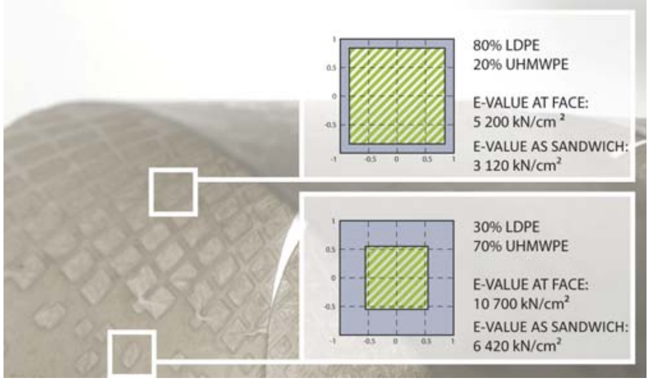

Fig.2 Diagram describing a material element and the distribution of component materials within it

Fig.3 Realised bending behaviour – different responses to the same loading

A direct link was established between the distribution of material on the 3D model and a flat 2D cutting pattern. The pattern could then be laser-cut and the sheet fabricated, enabling a process of calibrating the relationship between digital and physical through empirical testing.

GOAL-BASED MATERIAL DESIGN

The model also implemented a goal-based material design approach that sought to match a desired geometry by optimizing the distribution of material at the micro-scale. Using Grasshopper's inbuilt Genetic Algorithm Galapagos, the performance of different the specification of material combinations could be linked to their performance in meeting a given target surface under bending, allowing for the generation of an optimum combination. It is not within the scope of this paper to describe the genetic algorithm in detail, as the purpose is rather to demonstrate that a goal-based computational design method can be used to drive material distribution, however the basic steps of the algorithm are as follows:

1) The first generation is populated with random individuals

2) For each individual in each iteration, the fitness is computed

3) The individuals then populate the next generation, based on their fitness, by either ‘surviving’ or ‘mating’. The mating process is controlled through the parameters of population coupling, mate selection, coalescence and mutation

4) The process repeats until the maximum number of generations has been reached or until a specific fitness value has been reached.

This approach was tested in two conditions, firstly when the target surface was within the range of possible deformation, and secondly when the target surface was deliberately defined to be unattainable. The surface was divided into 6 material zones, defined by six points and constituting those units on the surface closest to each point. The algorithm was able to adjust the ratio of LDPE and UHMWPE in these zones, and to move the location of each zone. Fitness was measured as the sum distance of each element on the surface to its corresponding element on the target surface. In the first case the genetic algorithm produced results that very closely approximated the target surface, and in the second found an answer that distributed the deviation evenly.

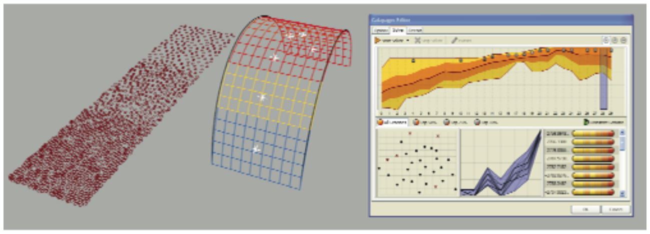

Fig.4 Optimisation model

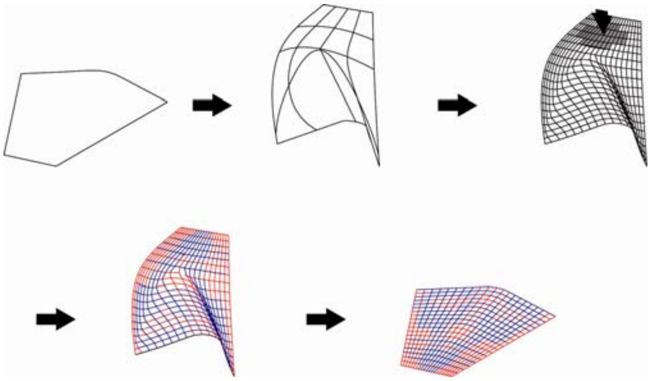

Fig.5 Diagram describing form and analysis

APPLICATION TO THE DESIGN OF A CHAIR

To further explore the distribution of material, this approach was then applied to the design of a chair (PE is a common material for outdoor furniture). As described in *fig. 5*, a flat sheet can be bent to form a chair in such a way that it becomes bending-active. While the material is continuous, the load when someone sits in the chair is not equally distributed, but rather finds the most direct path out. Knowing how tension transfers through the chair makes it possible to distribute higher concentrations of UHMWPE, which is stiffer and has a large capacity for tension, according to load within the material. Materials are distributed so as to counteract the force of the person sitting in the chair.

CONCLUSION

This research explored a way to design and simulate a graded material within a CAD environment, by linking numeric descriptions of meso-scale material distribution to a combined parametric and finite element analysis model. This approach allowed material specification below the level of the component, and for the results to be observed as properties at the level of the component. The implementation has been effective, as demonstated through the example of a mono-composite sheet, however it is recognized that more complex representations and behaviours as well as detailed material testing, measurement and validation are still required to address real architectural problems.

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