GRADED TERRITORIES:
TOWARDS THE DESIGN, SPECIFICATION, AND SIMULATION OF MATERIALLY GRADED BENDING-ACTIVE STRUCTURES

ABSTRACT

The ability to make materials with bespoke behavior affords new perspectives on incorporating material properties within the design process not available through natural materials. This paper reports the design and assembly of two bending-active, fiber-reinforced composite structures. Within these structures, the property of bending is activated and varied through bespoke material means so as to match a desired form. Within the architectural design process, formal control depends upon design approaches for material specification and simulation that consider behavior at the level of the material element as well as the structure. We describe an evolving approach to material specification and simulation, and highlight the digital and material considerations that frame the process.

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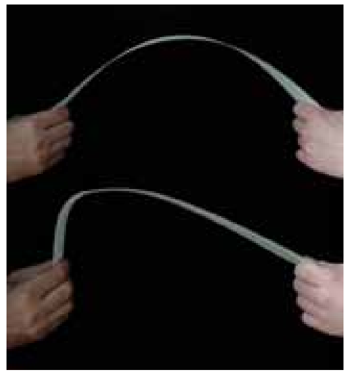

figure 1

figure 2

1 NEW MATERIALS, NEW STRUCTURES

Most architectural structures have been compression-based, and the shape of the structure, as opposed to the calculation of material properties and stresses, has been the primary factor governing stability. The process of designing the correct geometry involved careful reference to guarded systems of geometric compositional rules, developed around long experience of particular materials. Large-scale models were a key tool against which this structural understanding could be represented, tested, and proven—if the model was stable, then the building would be too (Heyman 1998).

In response to the development of new materials and their application within new structures from the 18th through the 20th centuries, this geometric understanding was replaced by an approach based on the calculation of material properties, loads, and deflections. An accompanying interest emerged in specifying materials based on their mechanical properties and behavior under loading, and of materials and structures based on properties other than compression. Examples include the tensile form-finding and thin shell projects of Otto, Isler, and Candela (Isler 2008). These structures are termed form-active, meaning that their form and the forces applied to it are interdependent; they differ from previous types of structures in that they are form-found, based on material behavior and structural characteristics (Menges 2010).

Today, designed materials extend the opportunities for the specification and design of form-active structures. Thermoplastic matrix composites, in particular, represent an important innovation; they greatly simplify composite production, allow for higher precision in the placement and orientation of fiber, and are easily recycled, while possessing mechanical properties equivalent or better than traditional thermoset matrix composites. These advances allow the use of fiber-reinforced composites beyond their current framework. For architects and engineers, the implication is of a practice built around the precise specification of material properties to meet specific performance conditions—a new level of design operation in which global performance can be tailored at the material scale (Nicholas 2011). For example, within a composite structure, a change in geometry can be created by grading of material stiffness. This can be observed in a single strip of material, where the differentiation of stiffness along its length changes the resulting shape from a symmetrical curve in a homogenous material setup to a nonsymmetrical one (Figure 1), as the shape is determined through the interplay between force and the graded material. By combining stiffer and more flexible elements, the same differentiation can occur at the level of the structure. To further develop this practice requires representation and simulation approaches that embed an in-depth understanding of material behavior within the design process.

2 ACTIVE BENDING AND ITS REPRESENTATION

The productive use of the elastic behavior of materials has a history in vernacular architecture. Yet only a few examples were constructed in the 20th century. The Mannheim gridshell is the most prominent example (Happold 1975). Here, the use of elastic deformation was mainly utilized as an economic construction method for double-curved shell structures which themselves were mostly form-found based on hanging models or simple analytical approaches. Newer gridshell examples continue to avoid active bending by "locking" the material after an initial bending. An example is the Savill Building, where two layers of larch laths are bent and then interlocked to create a single beam (Harris 2003).

The exploration of active bending continues in an academic context, through experimental structures as the Hybgrid project at the AA London in which plastic-based members are bolted together (Verde 2003) or the CITA's Thaw installation (Ramsgaard Thomsen 2011) (Figure 2), which explores the making of a woven structure made of ash slats braced together by steel joints. In the latter the joints are fixed, but each member uses the elastic behavior of the wood slats not only to generate shape but also to activate dynamic behavior when actuated. In Thaw the dynamic structure adapts as forces move through a woven field of friction-based interconnectivity. These projects explore behavior within a networked structure, where both material pliability and strength are activated. Parametric

figure 1

Homogenous and nonhomogenous strips in similar loading conditions.

figure 2

Thaw installation, Oslo.

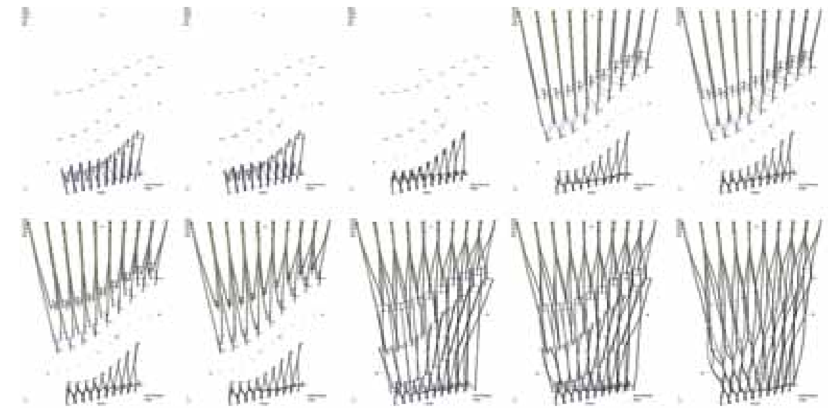

figure 3

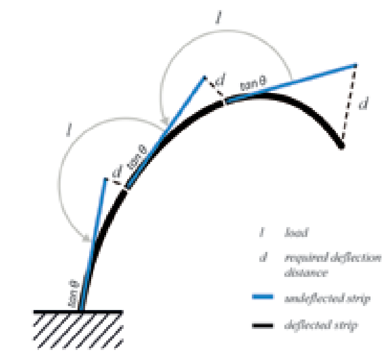

figure 4

drawing techniques are used to determine geometrical relations within the structure, but they are not used to predict the overall structural behavior.

Recent developments in simulation techniques make it possible to form-find and analyze structures that derive their complex curved geometry solely from an erection process in which they are elastically deformed. This approach underlies the 2009 Membrane Restrained Arch by the UDK Berlin (Alpermann 2009) and the 2010 ICD/ITKE pavilion at the University of Stuttgart (Lienhard 2011). In the latter, strips of homogenous material are bent and fixed in supports on-site, creating a space of sequential arcs. Cutouts in the strips provide interconnectivity and stabilize the overall structure.

These representation and simulation approaches are still new, and have been applied to the design of structures of constant material properties. They have not been employed in the design of bending-active structures with designed materials, where the challenge is to incorporate the specification of material properties into the design of structures that activate those properties. Here, the ability to connect digital and material parameters when making both the material and the structure is limited by the simplification and elimination of forces within the design and simulation process. For example, form-finding using dynamic relaxation, often seen as a primary example of including material properties within design, excludes all material behavior other than axial loads.

Investigations undertaken in the frame of the Thaw project point at another representational approach more suited to the needs of an architectural design process, as it "opens up the possibilities for a more dynamic framework in the early stages of design" (Attar 2009). Here a physics solver provides a decentralized approach with full collective physical interdependency and the possibility of integrating participating external forces. This lightweight dynamics simulation can already be used as a complementary method for initial conceptualization and to iterate design concepts (Deleuran 2011). The underlying computational methods are still geared toward visual results and generally lack accuracy, which prohibits, at the moment, the application of this approach in the finely balanced situations that characterize the work with graded materials.

3 COMPOSITE TERRITORIES INSTALLATION

The installation Composite Territories is a variable stiffness, bending-active glass fiber-reinforced polymer (GFRP) gridshell, approximately 8 × 5 × 3.5 m 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 instrumentalization of GFRP within Composite Territories is that by precisely

figure 3

Thaw installation: time-based simulation with physics engine.

figure 4

The relationship between load and deflection underlies initial material specification.

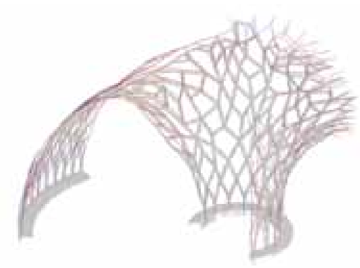

figure 5

figure 6

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. By 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 behavior. To understand and measure the bending behavior of GFRP, and to generate a base of information from which to actively utilize this material property within the digital design process, 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. So as to isolate bending at the material level, the material parameters considered within the tests were very narrowly focused: the fiber orientation within all material elements was unidirectional along the axis of the member, and only the number through layers was varied. The testing resulted in a lookup table that captured all possible relationships between loading and bending deflection for each layering arrangement element. The lookup table was embedded within a computational design tool for specifying the number of layers of each strip element within a gridshell so that, under self-weight and fixed-in compression loading, the structure would deflect to match a predefined "target shape." The role of this target shape was to synthesize architectural concerns such as circulation and views with material parameters, and to orient the material specification process toward a desired outcome.

The layering specification of each element considers the levels of both element and structure, via a two-stage process. First, an initial thickness is specified through direct reference to results of material testing. An iterative algorithm assesses the particular loading condition of each single beam and the deflection that it should make to best match the underlying surface at that point, and consults a lookup table to find the closest match from the testing process. As a result, a number of layers and a weight are assigned to that beam, and the process continues. This initial specification stage, which considers only the bending of a single beam element, is then refined through analysis at the macro scale of the structure, where topology aids in achieving strength and minimizing material use. At this stage, data gathered from the empirical testing was also used to calibrate a Karamba model, which includes material definitions and beam thicknesses. Here we could connect layer specification and local bending with the global simulation of the structure.

While a FARO 3D scan demonstrated that the predictive model was very close to the built reality (Figure 5), 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 allowed the calculation of properties such as Young's modulus, which instead had to be estimated using generic information sourced from the internet as a starting point.

Further, there was only a limited ability to link material and finite element analysis (FEA) simulation. The FEA approach was able to simulate the bending behavior of the whole system, but was not able to link this to include the elastic bending of the individual strip elements. These shortcomings led to the questions of how to more accurately measure material behavior, while still linking it to the specification process, and how better to simulate bending-active structures so that the models accurately capture both local and global behavior.

figure 5

Comparison between 3D scan, target, and simulated finite element analysis (FEA) geometry.

figure 6

Composite Territories installation at ggggallery, Copenhagen, 2012.

4 INTEGRATING MATERIAL, ELEMENT, AND STRUCTURE—SMARTGEOMETRY 2012

The workshop Composite Territories at the Smartgeometry Conference 2012 (sg2012 workshop) specifically addressed these limitations. At the sg2012 workshop the authors linked architectural and engineering experience with access to the Rensselaer Polytechnic Institute's material testing facilities. The four-day workshop with 10 participants probed the implications of mechanical material testing and a time-based FEA approach for the accurate and reliable representation of a bending-active structure within a design context.

4.1 Design

The sg2012 design focused on the instrumentalization of elastic deformation where shape is only acquired through the bending of flat strips—either under self-weight or the compressive loading of the end positions. The benefits lie in the system's simplicity, where material properties determine the geometry while joints are simple and standardized. The design objective was to develop a lightweight, resource-efficient structure.

The design was limited to two distinct structural conditions to isolate the property of bending. The first was a cantilever, restrained at one end. In this condition, bending was induced by the self-weight of the structure. A cantilevering strip typically combined 5 sub-elements of potentially different bending stiffness and had a total length of 2.5 m. The second condition was a fixed-in compression arch—a strip restrained at both ends, which typically combined 10 sub-elements and had a total length of 5 m. This reduction of structural and formal complexity allowed the workshop participants to perform an FEA on their own.

In order to link the material behavior with design intent, we reused the goal-based approach used in the Composite Territories installation, where first a shape is defined and later negotiated within the framework of material grading and the possibilities of the overall system.

4.2 Material Making and Testing

The material used in the sg2012 workshop was a single layer 70 percent glass fiber polymer composite supplied by Polystrand. The heat press process was used to layer the material and manipulate the stiffness of the assembly. During the process of layering, the material properties of the assembly changed and the method of superposition could not be applied. Because of this impact of the processing, it was crucial to load-test each combination of assemblies in order to feed data back to the computer for proper modeling.

Because the design comprised independent cantilever strips and arches with no interaction between them, the properties of interest were stiffness in bending and, to a lesser extent, stiffness in tension. We used the Instron Universal Loading Testing Frame available at Rensselaer Polytechnic Institute to load-test the material (Figure 7).

Assorted layering of strips was tasted in tension and bending. For tension we used dog-bone samples, while for bending we used plain strips of composite assemblies. Both tests were carried out in the direction of the fibers, and multiple tests were performed to obtain average values. The samples were tested in deformation-controlled settings where specimens were tested up to failure in tension and only up to "reasonable" deformations in a three-point bending test.

The tension tests revealed linear behavior far beyond loads experienced in the final model. The "reasonable" deformation in bending was defined as one that the final model will not exhibit. The bending load test was a standard four-point bending test. It revealed highly nonlinear bending stiffness especially for the specimens fabricated of a small number of layers.

4.3 Material Specification

In graded material systems, the relationship between material differentiation and shape under loading is very sensitive. Within the simulation process, the starting point is very important. For these reasons, a specification process needs to precede simulation, but to still consider load, deflection, and target in order to determine a specific bending stiffness.

figure 7

One computational approach to estimate the stiffness to be specified is to feed back the stress-strain curves generated from material testing into the design process. An algorithm was written to iterate over each member within the structure, assessing its 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 lookup table containing the load-deflection relationship generated during material testing—assign a number of layers. Once the load and required deflection are 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. Instead, this approach provides an achievable method of quickly specifying bending stiffness by incorporating the information from material testing directly within the design process.

4.4 Translation

In order to get a more complete understanding of the materials bending the data from the parametric modeling environment where translated to the FEA software Sofistik. Here, not only did the element-based system used so far have to be changed into a node-based one, but moreover the FEA needed the initial flat state of the strip geometry—where the model so far represented the design target. A Python script provided the FEA with all necessary parameters as node coordinates, conditions for connections and support at each node, material properties (E-modulus, specific weight), and specifications for all potential combinations of beam dimension and material. Finally, the programming of the load cases within FEA was automatically generated by the script and continuously written into a file that was read by the simulation software.

A back channel from FEA into the design environment read the resulting displacement vector at each node under load and displayed the deformation of the model in the design environment. Though not used to its full extent within the sg2012 workshop, this approach grants an understanding of global and local behavior of the model—and provides the framework for automatic iteration of material properties to reach an intended shape.

4.5 FEA Simulation

FEA is based on a displacement method, where a matrix solver finds an equilibrium of node displacements matching external load conditions. Bending-active structures present a condition unusual in typical practice, since the deflections largely contribute to the form-finding process. Common software packages are rarely able to assist in such a design process as they are made for smaller deflections. A special matrix solver, FE element type, and the usage of third order theory analysis are necessary for the analysis.

The usage of GFRP gives great potential for large deformations since the stiffness is low and the strength is high. But GFRP is also very light, and therefore bending in the cantilever structure under gravity only takes place if the cantilevers are relatively long. The support-constrained bending is more easily solved, as the resulting structure is more stable under changing load conditions.

figure 7

Mechanical testing on the Instron Universal Loading Testing Frame, Rensselaer Polytechnic Institute.

figure 8

Superimposed deflection diagrams of the six layer configurations that were used.

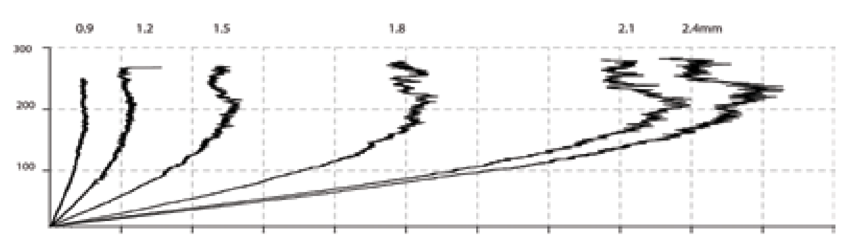

figure 8

The introduced bending is the primary shape-determining component, and the analysis of this aspect becomes a central part of the design progress. The two different load scenarios included strips being bent, loaded by pushing the support points together to form arches, and bending through gravity. These analyses, especially the push-analysis, are quickly numerically unstable and need adjustment when the push increments are too large. Once the process is set up, different stiffness distributions can be tested so that the formal design can occur using the FE software as a design tool (Figure 9).

Further development of the design and its tooling would investigate the connectivity of elements within complex structures. The difficulty here is to define the restraints within the limits of the incremental load assembly analysis, because the buildup of the structure has to be simulated step by step, and each step has implications for the form. The ITKE pavilion demonstrates this difficulty, where the single interconnection between beams is introduced after the bending and simulation process (Figure 10).

5 DISCUSSION

The evolving approach to material specification and simulation developed across the Composite Territories installation and sg2012 workshop investigation reveals several considerations as important. These include behavior at multiple scales, time-based simulation, and the importance of the starting condition.

In the Composite Territories installation and sg2012 workshop investigation, the making of material links variables at one scale to material behavior that is simultaneously present on two different scales: the element and the structure. In Composite Territories, shell action was dominant at the level of the structure, with bending primarily affecting the local beam level. The design approach, which combined representation of material behavior at the element level with simulation at the structural level, incorporated both levels but was not able to interweave them. In the sg2012 workshop investigation, where the larger structure is simply a long strip made from sub-strips, bending behavior prevailed at both scales. In this investigation, the simulation process within Sofistik combined both local and global levels within one simulation.

This was based on the shift to a time-based process whose starting point was a flat, unstressed state. The process incorporates the assembly, and particularly the gradual stressing of the structure, within the simulation model. It matches the process taken within the 2010 ICD/ITKE pavilion, as well as that taken within Thaw, where material behavior is introduced through the calibration of elements in a constraint-based system. As well as being able to calculate loads incrementally, such a process is highly dependent on its starting condition, which should be an unstressed state. This determination of the starting condition is simpler for geometries that can unfold flat, such as a strip, than for geometries that cannot. This limited the complexity of the sg2012 workshop structure in comparison with Composite Territories and raises the question of how to move beyond the strip, which requires strategies for networked systems.

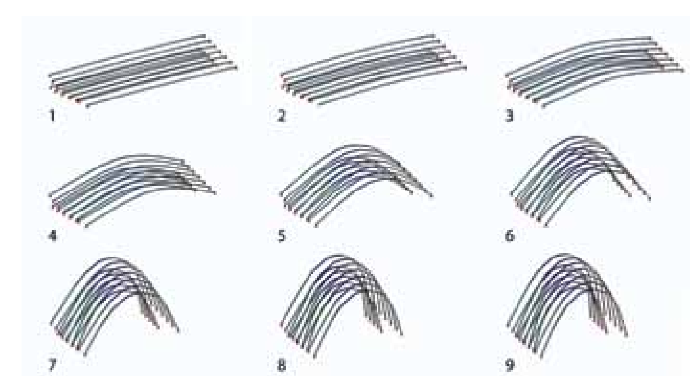

figure 9

figure 9

Stills from FEA: pushing of the initially flat strips within Sofistik.

figure 10

Examples of varied bending within the built structure.

figure 10

6 CONCLUSION

Composites have a unique potential to extend our understanding of bending-active structures and the inclusion of material properties in design. Material specification provides the platform; however, appropriate tools that can provide architects and engineers with the necessary feedback at the design stage are not yet at hand. As a means toward developing these tools, the research presented indicates how computational design processes can integrate material properties to develop novel structures that are based on highly specific material properties and behaviors. Analysis of these projects identifies behavior at multiple scales, time-based simulation, and the importance of implementing incremental loading, since each step has implications for the final form.

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GENERATION AND INTEGRATION OF AN AERODYNAMIC PERFORMANCE DATABASE WITHIN THE CONCEPT DESIGN PHASE OF TALL BUILDINGS

ABSTRACT

Despite the fact that tall buildings are the most wind affected of architectural typologies, testing for aerodynamic performance is typically conducted during the later design phases, well after the overall geometry has been developed. In this context, aerodynamic performance studies are limited to evaluating an existing design rather than a systematic performance study of design options driving form generation. Beyond constraints of time and cost of wind tunnel testing, which is still more reliable than computational fluid dynamics (CFD) simulations for wind conditions around buildings, aerodynamic performance criteria lack an immediate interface with parametric design tools. This study details a framework for empirical data collection through wind tunnel testing in a uniform airflow of mechatronic dynamic models (MDM) and the expansion of the collected dataset by determining a mathematical interpolating model using an artificial neural network (ANN) algorithm developing an aerodynamic performance database (APDB).

The philosophical provocation for our research is found in the early 20th century, when Frederick Kiesler proclaimed the interacting of forces "co-reality," which he defined as the science of relationships. In the same article Kiesler proclaims that "form follows function" is an outmoded understanding and that design must demonstrate continuous variability in response to interactions of competing forces. This topographic space is both constant and fleeting; form is developed through the broadcasting of conflict and divergence, as a system seeks balance and one state of matter passes by another—a decidedly fluid system.

However, in spite of the fact that most of our environment consists of fluids or fluid reactions, instantaneous and geologic, natural and engineered, we have restricted ourselves to approaching the design of buildings and their interactions with the environment through solids, their properties and geometry. The research described herein explores alternative relations between the object and the flows around it as an iterative process, suggesting an additional layer to the traditional approach of form follows function by proposing that form follows flow.

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