Towards Interactive Force-Sensitive Digitally Encoded Materials for Architectural Models and Construction

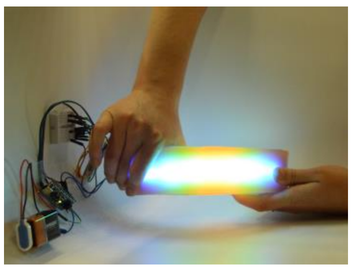

Figure 1: We prototyped a simple beam that visualizes axial and bending stress on the physical beam itself.

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Abstract
Architects and engineers use various tools for structural analysis during modeling or construction. However, the representation of such analysis is often on a two-dimensional screen. We present our vision of embedding digital elements in the beams and columns used for architectural models and construction, particularly to analyze and display structural information directly on them. This would potentially lead to seamless structural study and engaging human interaction. We developed a prototype of a simple beam that visually depicts axial and bending stress, as external forces are applied to it. Our future vision is for encoding such digital structural feedback into Nano-scale physical objects, leading to scalable digitally encoded building materials for architectural modeling and construction.

Author Keywords
Structural analysis; interactive display; building block; digitally encoded objects; electronics; prototype; HBI.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous; J.5. Arts and Humanities: Architecture.

Introduction

Architects, builders and structural engineers use various tools for structural feedback during modeling or construction [9–13]. Most of these tools are employed during the design stage, for instance for virtual simulation of stress and strain experienced by structural elements. Certain tools can also structurally analyze a 3D-reconstructed object from a dynamic set of images. Though these tools accurately capture the object geometry, the feedback is disconnected from the physical object itself. We propose a more integrated and interactive approach to providing element structural feedback- displaying the structural information on the building unit itself by digitally encoding it. We design a linear structural element, a simple beam, which incorporates embedded hardware and LEDs to display visualizations of axial and bending stress on the beam itself.

Recent research in HCI has seen the growth of interactive small-scale digitally encoded objects. Assemblies of these objects are used for various applications such as self-reconfigurable robots [6,7] and automatic shape changing fabric [8]. We envision the use of such objects in the architectural domain, vis-a-vis digitally integrated objects that provide dynamic structural feedback.

To this extent, we developed a prototype of a simple beam that represents a digitally encoded building block for structural feedback (Figure 1). Embedded sensors detect forces applied by the user, and the device responds with color map visualizations of stress using embedded LEDs.

Digitally encoded structures have many applications. If they are implemented in scale models during the design process, they can help architects and engineers communicate about aspects of the structural design, and explore various configurations. When a structure is in its complete form made from digitally encoded materials, it will be in a state of constant feedback to the viewer and designers. Issues such as wear and tear, structural failures, and unpredictable loading would be apparent on the surface of a building acting as a 'health monitor' for a structure. This monitor could reveal structural problems that could then be addressed sooner. Beyond safety, personally interacting with a physically encoded building system would eliminate a barrier that has always existed between humans and the structures that they inhabit, allowing inhabitants to develop a better understanding of the building structure. Finally, models of these structural elements could be an innovative educational tool used to help children or students develop an intuition for structural mechanics.

Background and Related Work

Finite Element Method for Structural Analysis

The finite element method (FEM) is a powerful technique for finding numerical solutions to complex problems in structural mechanics. In the FEM, the structural system is subdivided into simpler parts, called finite elements, and variation methods from calculus are applied to solve the problem [2,14]. These finite elements have physical properties such as thickness, density, Young's modulus, and Poisson's ratio. For example, straight or curved one-dimensional elements have axial, bending, and torsional stiffness. This type of element is suitable for modeling cables, braces, trusses, beams, stiffeners, grids and frames

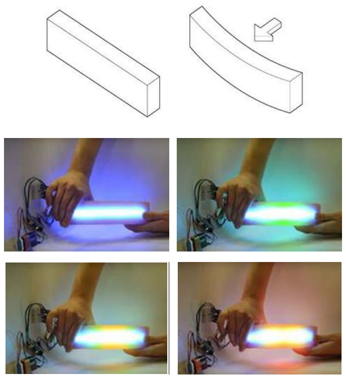

Figure 2: Color mapping of the beam in bending. The areas with greatest stress are shown in red and minimal stress in blue. Note that the center of the beam gradually changes color from blue to red as the force increases.

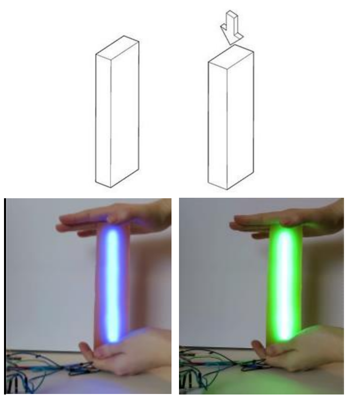

Figure 3: Color mapping of stress in the beam during axial loading.

[14]. Our current prototype serves primarily as a proof of concept, which takes input from embedded sensors and displays a rough approximation of the stress profile experienced by the beam. Future complex prototypes would greatly benefit from FEM to create a more accurate, detailed depiction of axial and bending stresses.

Computational tools for structural analysis
Various tools are employed by structural engineers for one-, two- or three-dimensional finite element analysis of building structures, particularly for modeling axial and bending stiffness in one-dimensional beams [10,12,13]. Most of these commercial tools are meant for virtual simulation of applied forces and moments during the design stage, rather than being used for sensing and analyzing actual physical objects. Researchers have also developed tools that can structurally analyze a physical object from dynamic set of images, by reconstructing the object in 3D [4]. By using embedded sensors and LED display, we followed a more integrated approach, which visualizes the approximated axial and bending stress directly on the beam itself.

Towards digitally encoded materials
The fields of medical technology and nanotechnology have increasingly used small-scale digitally encoded objects for various purposes. For example, there has been a recent interest in using digitally encoded drug tables to combat counterfeiting [1,3]. Use of small scale digitally encoded objects in human computer interaction is relatively new and has various applications [6–8]. For example, Topobo is a 3D constructive assembly of motorized blocks which have the ability to record and playback physical motion [7]. By snapping together a set of motorized components, people can quickly assemble dynamic biomorphic forms like animals and skeletons, animate those forms by pushing, pulling, and twisting them, and observe the system play back those motions. As the need for smaller scale interactive objects continues to grow, researchers are now trying to digitally encode objects on a molecular level [5]. Such Nano-scale objects would seamlessly integrate the digital and the physical, leading to usage of such digitally encoded materials for scalable construction. Though our current prototype of a simple beam is on a much larger scale, future prototypes would incorporate these sensors on a much smaller material scale. These scalable materials would be seamlessly used for scale models and construction.

Prototype Design
To demonstrate our vision of using digitally encoded beams for construction, we built a prototype of a simple beam block that displays a color map of axial and bending stress when external forces are applied (Figure 1). We used Smooth-On [15] to cast the beam out of silicone rubber. The block embeds a multicolor LED strip and a flex sensor along the length, and two force sensors on the top and bottom side (Figure 4). As this is a first prototype, the control circuit, including an Arduino microcontroller, was placed outside the block for convenience. The beam displays two types of stress: radial bending perpendicular to the length (Figure 2), and axial compression parallel to the length (Figure 3). The sensors and the Arduino assembly measure the applied forces, and trigger the LED strip to display the stress color map. These color maps are inspired by structural simulation tools such as SolidWorks [12].

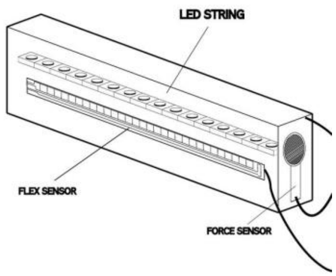

Figure 4: The beam block contains a flex sensor, two force sensors and a LED strip.

Though this is a first step in using digital encoded objects to enhance the interaction of humans and buildings, the prototype is still far from our future vision of digitally encoded materials for modeling and construction. Future prototypes would aim at reducing the size of the block and developing multiple blocks that would fit together, each independently displaying its own stress color map.

Preliminary Evaluation

To get initial feedback, we exhibited the prototype in our lab's semi-annual open house and gathered feedback from 12 passers-by. In general, reactions were positive. Most people appreciated the prototype as an interesting interactive construction object. Two architects commented that this would be a useful tool for studying structural elements of complex buildings during the modeling stage. They suggested creating more blocks and incorporating other structural parameters such as sheer stress and strain of 2-D objects, which would make our invention more useful. A few people also recommended that it could be employed in Lego sets for kids, to educate them on structural elements.

Conclusion

We have described our vision of encoding digital elements in physical objects for dynamic structural feedback and discussed various applications. We have presented our prototype of a simple beam that self-visualizes the axial and bending stresses it experiences. Our future vision is to encode these digital elements into Nano-scale physical objects, leading to digitally encoded building materials.

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