Project MAXWELL: Towards Rapid Realization of Superior Products

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Abstract

We describe a new methodology for the design and manufacture of mechanical components. The methodology is a synergism of a new, mathematically rigorous procedure for the concurrent design of shape and material composition of components, and a new manufacturing process called MD* for their realization. The concurrent design strategy yields information about the global shape of the component and its material composition. The fabrication of such designs with novel microstructural configurations require unconventional manufacturing processes. MD* is a shape deposition process for the free-form fabrication of parts from single or composite materials and is ideally suited for realizing the aforementioned designs. Project MAXWELL, therefore, promotes the use of layered manufacturing beyond prototyping tasks and offers the possibility of their integration into the mainstream product development and fabrication process. .

1. INTRODUCTION

Project MAXWELL proposes a methodology that is a synergism of a new mathematically rigorous procedure for the concurrent design of material composition and shape of components, and a new manufacturing process for their realization. At the University of Michigan (U-M), a methodology has been developed for designing the *form and material composition* of mechanical and structural components based only on a description of the loading conditions and packaging requirements. At Carnegie Mellon University (CMU), a new manufacturing process has been developed for the free-form fabrication of parts from *single or composite materials* by thermal spray shape deposition. Project MAXWELL aims at integrating these two novel technologies, for realizing strategic benefits rooted in the rapid realization of novel mechanical and structural components. Furthermore, the design methodology illustrates the importance of layered manufacturing techniques such as MD* beyond prototyping tasks.

The project hypothesis is the existence of an integrated methodology for the rapid realization of mechanical and structural components that could not have been designed and/or manufactured before. Such parts will possess superior structural and mechanical properties (*e.g.*, lower weight to stiffness ratio), and will satisfy packaging and other manufacturing requirements (*e.g.*, ease of assembly). The project goal is proof of concept through design, manufacture, and testing of actual parts.

The current application domain is in automobile design and manufacture and includes sheet metal/composite panels, brackets and suspension components, and special structures for side impact energy absorption. The process is also suitable for the design and manufacture of prosthetic devices in bioengineering applications.

In this paper, we first motivate the concurrent design of form and material in the context of structurally superior products. Next, we provide an overview of the relevant methodologies developed at U-M and CMU respectively. Finally, we describe the current status and future goals of project MAXWELL.

2. CONCURRENT DESIGN OF STRUCTURE AND MATERIAL

2.1 Design of the Global Structure Using the Homogenization Method

A fundamental approach to the thermo-mechanical characterization of general composite materials was first put forth by James Clerk Maxwell (1831-1879) and was later generalized as the theory of mixtures to provide a rigorous foundation for studying the mechanics of composite materials (see, e.g., [FUN65]). Project MAXWELL aims at transforming those early ideas into engineering reality.

Necessity of topological design in addition to size and shape design is widely recognized by structural engineers. If topological changes are not allowed, size and shape optimization procedures can improve a design by approximately 5~15%. Topological modifications can often yield 30~50% improvement. An example illustrates this. The beam in Figure 1 is subjected to a bending moment. A hollow beam is more effective than a solid beam. For the same amount of material, the beam design on the right, which involves topological changes, is better than the one on the left, which is derived by shape optimization.

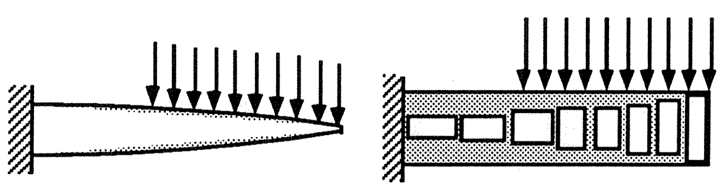

Figure 1: Shape Design and Topology Change of a Structure

The homogenization method is based on the above observation. The topology and shape problem is formulated as a new optimization problem *involving material distribution*. Given a solid with a prescribed volume, we generate *microscale voids* in design domains where a solid structure is *not* required for supporting loads. Therefore, instead of designing the shape and physical dimensions of the cross section of a structure, we generate infinitely many microscale voids within the configuration wherever the stress is small. If a portion in the domain is highly stressed the homogenization method prevents the creation of microscale holes and that portion remains solid. Furthermore, the orientation of a non-circular void has a significant effect on the overall material response. Therefore, in the new optimization problem, the design variables are the density of microscale voids and their orientation over a specified domain. By removing material completely from portions of the domain densely packed with voids, the optimum shape of the structure is identified, while its topology is determined by accounting for the number of "global" holes (see also Figure 2)

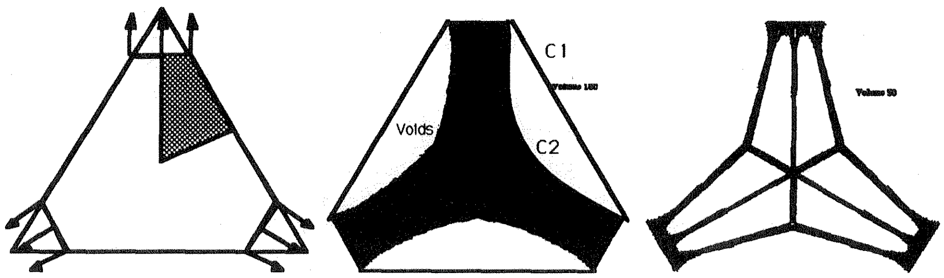

Figure 2: Identification of the Shape and Topology

This intutive method of "shaping and drilling" a structure is based on the theory of homogenization -- a mathematically rigorous method developed in the mid-1970s for the study of mechanics of composite materials. Most composite materials possess a fine scale microstructure composed of fibers, whiskers, inclusions, and matrices. Applied mathematicians in France, Italy, and the former Soviet Union [LUR84, SAN80, TAR77] developed the homogenization theory to derive the constitutive equation of a composite material, i.e., to evaluate the average stress-strain relation of the structure. Since we are interested in generating infinitely many microscale holes to form a possibly perforated structure, the stress analysis of such a structure requires the derivation of an equivalent effective average stress-strain relation. A homogenization approach enables the design of topology and shape without using spline functions. Difficulties in geometric modeling are avoided, and stress analysis iterations are performed on a fixed finite element mesh.

2.2 Introduction of Microstructure

Although the optimization process permits the perforation of the domain, the resulting optimum configuration is often a homogeneous solid. In our design optimization scheme, we consider the domain to be a very specialized, fictitiously constructed, composite material consisting of solids and voids. In order to determine the best microstructure, we allow the design domain to include other composite materials, e.g., ones that can improve strength, toughness, vibrational characteristics, acoustics, impact resistance and impact energy absorption.

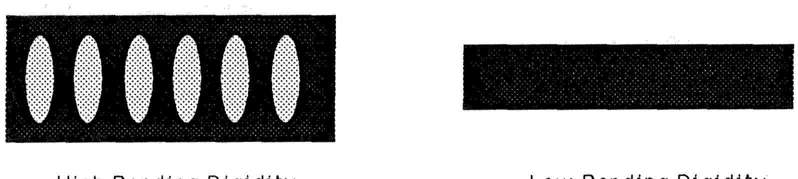

Figure 3: Benefits of Composites

Non-homogeneous composite materials result in significant improvements in thermo-mechanical properties without increase in weight. For example, while bending rigidity of a beam or shell-like structure is proportional to Young's modulus of the material, it is also proportional to the *cube* of its thickness. Therefore, a design criterion such as bending rigidity can be daramatically improved by using composites with a stronger material in the outer surfaces and weak and lighter materials in the inner core, Figure 3. Composite structures can also improve vibrational characteristics without increasing weight or changing the overall configuration. If large dumping is desired, a material with high dumping characteristics can be inserted.

For crashworthiness, an important issue in automobile panel design, complex microstructures must be introduced. Plastic deformation or destruction of the fine microstructure can absorb large amounts of energy. In front- or rear-end crash situations, the need for fine scale microstructures is often eliminated by building simple reinforcing frames that absorb crash energy in the available space. For side impact, however, space for design is much more limited and use of fine scale structures may be very advantageous.

Use of such structures has not been realized in practice due to the lack of an attractive manufacturing process that delivers non-homogeneous and anisotropic materials. For example, it is impossible to create internal voids within a component (such as in Fig. 2) by conventional NC machining. Instead, one has to build voids in the workpiece material prior to machining. As a result, the void orientation which often has a significant impact on overall material response cannot be handled explicitly. In MAXWELL, we propose to use CMU's MD* process where a the component is built up layer by layer, allowing the possibility of creating and orienting the voids as desired. Therefore, MD* enables serious consideration of these unusual and highly efficient structures for the first time.

3. OPTIMIZATION MODELS FOR CONCURRENT DESIGN OF MACRO- AND MICRO-STRUCTURES

3.1 A Simple Formulation of the Optimization Model

Relating microstructure to global shape requires a new approach to design optimization and is enabled by homogenization. Concurrent design optimization can be performed to obtain the best microstructure in addition to optimal shape and topology.

Let f be the objective function, such as the total weight, cost, or other scalar quantitity. Suppose g is a vector function representing the set of design constraints introduced by mechanical and manufacturing requirements. Then the design problem can be posed as the following optimization problem

$$\min_{d} \; f(d,u) \qquad g(d,u) < 0$$

where d is the set of design variables and u is the state variable vector describing the thermo-mechanical behavior of the structure defined by the state equation

$$L_d(u) = 0$$

The operator L_d of the state equation is a function of the design variables.

The overall formulation is similar to standard optimization except for the design variables. For the layout design described in the previous section, design variables are the size of a rectangular hole in the unit cell characterizing the microstructure and its angle of rotation. If two different materials are considered, the design variables might define the constitution of the unit cell. For example, if we consider three different microstructures, Figure 4, we might choose to design the layout of the lamination, the mixture, or the fiber density of the resulting composite material.

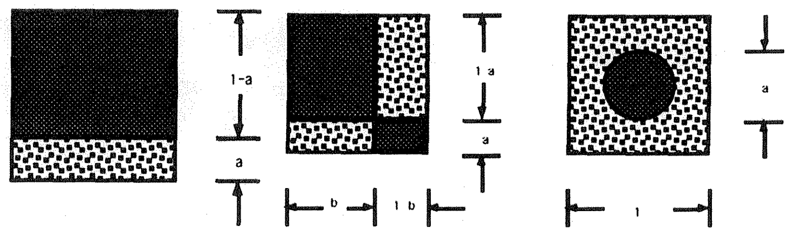

Figure 4: Design Variables at the Microstructure Level

This approach allows inclusion of material composition in the model, but is insufficient for concurrent material and structural design, since the configuration of the microstructure is specified *apriori* (although the designer has considerable flexibility in choosing the size of the lamination, mixture, and fiber). Clearly, the chosen microstructural configuration need not be the optimum. Therefore, we must derive the optimal microstructure and optimal global layout for the structure concurrently.

Applied mathematicians at Courant Institute, University of Paris, and in the former Soviet Union, have conducted research on optimal composition, without considering global structural configuration; see [KOH86] for a survey. These methods concentrate on finding the lower bound on the complementary energy of a generalized mixture of two different materials. Typically, sequential lamination is used to yield a closed-form homogenized effective stress-strain relation. These elegant theoretical developments have not led to substantive engineering applications. Furthermore, these studies have primarily concentrated on optimum composite structure independent of the stress field generated in the structure. Namely, material constitution is obtained in its ideal setting independent of the true stress field. That is not acceptable for structural configurations carrying thermo-mechanical loads.

3.2 An Optimization Model for Concurrent Macro-Micro Layout

To overcome these limitations, we formulate a new design problem that optimizes both the microstructure and the global structural configuration. We consider minimizing an objective function that represents the complementary energy of the unit cell consisting of two materials. The constraints are the equilibrium equations and the periodic boundary conditions. We further require that the average stress over a unit cell is equal throughout the global structure under a specified volume fraction of the two materials forming the composite. To minimize this objective function defined over the unit cell, we apply the same method as in layout optimization of the global structure. That is, the microstructure is designed by using a *refined* microstructure; see Figure 5.

Thus, two microstructures are introduced, one to determine the layout of a global structure and the other to define the optimum material layout in the microstructure. This allows designing a possibly non-homogeneous, anisotropic, composite structure, optimal with respect to topology, shape and material.

In contrast to the applied mathematics approach, our choice of objective function in material design need not be restricted to the complementary energy. If we wish to design a structure and its material such that it can absorb, say, crash energy the objective function may be defined as the integration of the complementary strain energy over the period of crash. There has been limited research in structural optimization with nonlinear state equations. Methods for linear state equations must be extended for historydependent nonlinear state equations, in order to meet challenges such as side impact energy absorption in automotive body design.

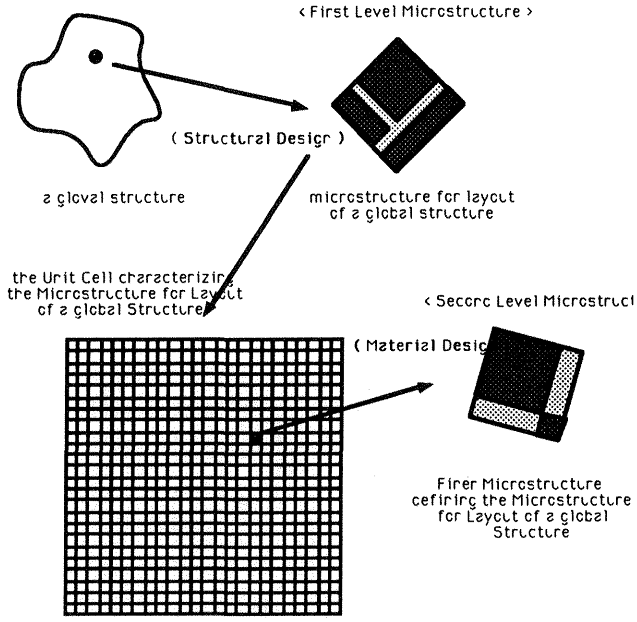

Figure 5: Concurrent design of Structure & Material using a two-level microstructure

The true benefits of deriving such optimal topologies and microstructures in a rigorous fashion can only be measured after the designs are transformed into physical products and tested. However, conventional manufacturing such as NC milling and truing are insufficient for the realization of such designs, since it is not possible to affect the "inner core" of the object being machined. On the other hand, layered manufacturing techniques are ideally suited for such fabrication tasks since they can create internal voids and complicated external geometries simultaneously. Therefore, our design method in MAXWELL promotes the use of layered manufacturing *beyond* prototyping tasks into the mainstream product development and fabrication phase. In MAXWELL, we use the MD* process, a layered manufacturing technique developed at CMU, for the realization of designs resulting from the homogenization method.

4. FABRICATION BY THE MD* PROCESS

In the MD* (recursive Mask and Deposit) process developed at CMU, parts are manufactured by successively spraying cross-sectional layers. Each layer may contain several different materials. The geometry of the part is not constrained and its shape and material composition can be changed continuously during fabrication. To create a part, its geometric model is first sliced into cross-sectional layers, typically 0.001 to 0.005 inches thick. For each material in a layer, a disposable mask is made that exposes the area where that material occurs. The mask is placed upon the top layer of the growing part shape and a robotically manipulated thermal spray gun traverses the areas exposed by the mask. Masks are made from paper stock cut with a laser. Several alternative strategies are feasible for creating support structures for the part as it grows, including retaining a part of the mask or spraying the support material in place after the primary materials are deposited.

Deposition of more demanding materials, such as steel, is feasible. However, support material is required to act as a surface to which the sprayed material will adhere and to "release" the part when completed. Low-melt alloys, such as tin-based compositions, satisfy these requirements for arc sprayed steel. The sprayed steel bonds locally to a tin/bismuth composition by superficially melting and abrading a very thin layer of the low-melt alloy, which is melted away when the part is fully completed. After a layer of steel is deposited, using pressure sensitive paper masks to expose the areas where steel is to be sprayed, the mask is removed. Finally, the steel is masked off with a complementary mask and the support materials sprayed down.

Selective material deposition is also feasible with the MD* approach. Building composite structures with several different materials within a layer can be accomplished by using multiple masks to form each layer. This enables the capability to create integrated electromechanical devices, e.g., mechanical structures with embedded electronics and unique composite, multi-material structures as elaborated in Section 3. Availability of the MD* manufacturing process provides the requisite technology for the realization of novel designs (at the macro- and micro-structure level) generated by the homogenization method.

In the context of Project MAXWELL, MD* is particularly relevant since it addresses another current manufacturing challenge -- robust processes for forming and joining *composite structures*. While the material properties of composites dramatically expands the possibilities for new product designs, current composite manufacturing technologies severely limit the possible geometries. MD* has the potential to create *dense* composite and laminate structures of arbitrary geometric complexity, while masking also enables selective material deposition. Therefore, different regions within a layer can be composed of different materials. For example, integrated electro-mechanical assemblies are feasible such as encapsulated computer packages with embedded electronics.

5. CURRENT STATUS AND FUTURE GOALS OF PROJECT MAXWELL

Project MAXWELL is a synergistic integration of two novel research efforts, one in design and the other in manufacturing, for the purpose of establishing of a sound methodology for the rapid realization of superior products. Basic research directly relevant to MAXWELL has been ongoing at the participating institutions for over three years. The U-M results to date can be summarized as the development of a three phase prototype system for the concurrent design of superior structural components.

Phase I: Based on the specified boundary conditions (type and magnitude of loads) and designable space (packaging specifications) the homogenization method is applied to derive a grey scale image representation of the material composition and distribution that is optimal relative to desired structural performance measures.

Phase II: Using computer vision and geometric modeling techniques this image is interpreted and translated into a realistic structure, e.g., a radically new perforated or multi-material composition reminiscent of biological structures.

Phase III: A parametric optimization model based on finite element analysis is formulated and solved to determine a complete dimensional and material description of the structure.

Ongoing research at CMU directly relevant to MAXWELL can be summarized as the development of MD* process for the rapid manufacture of single or multi-material components. Therefore, in MAXWELL we have

Phase IV: The manufacture of the Phase III output (*i.e,* discrete parts of arbitrary geometry and possibly varying material composition) using the MD* process.

Currently the U-M system can deal with 2D and 2.5D components (sheet metal panels, brackets, beams, etc.). The capability of MD* includes the manufacture of most designs developed at U-M. Therefore, current efforts in MAXWELL are geared towards enabling the fabrication and testing of some sample 2D/2.5D parts produced in Phase III.

Phase V: The final phase in MAXWELL is the testing phase, where the Phase IV products will be subjected to various mechanical tests. Qualitative indices of performance in Phase V will include measures such as weight to stiffness ratio, impact energy absorption rates and fatigue life.

Based on the test results in Phase V, iterations through Phases II, III, and IV may be necessary. During the iterations, in Phase IV, the manufacturing process could now include a conventional metal removal process (*e.g.,* milling) in addition to MD* depending on the suggested changes to geometry (shell interior or exterior) in Phase II. Ongoing work focuses on three dimensional components and extensions to all five phases of MAXWELL are envisioned.

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