Structural Design for Freeform Fabrication using Composite Materials

Roy Johanson
Noboru Kikuchi
Panos Papalambros

Design and Computational Mechanics Laboratories
The University of Michigan
Department of Mechanical Engineering and Applied Mechanics
Ann Arbor, MI 48109

ABSTRACT

Advances in the development of methods to perform topology optimization offer the ability to design novel structures composed of dense composite materials. These structures, which possess superior mechanical properties, can only be produced through the use of layered manufacturing techniques. In this paper, we demonstrate a technique for the design of layered structures composed of composite materials. In addition, this procedure allows the design of the composite materials used for fabrication of such components on a microstructural level.

INTRODUCTION

Structural optimization has been an active area of research since the early 1970s; see for example Botkin [4]; Fleury [5]; Bendsøe [3]. The two basic optimization problems typically addressed in structural optimization have been sizing and shape optimization. In sizing optimization, variables define local geometric characteristics such as height, width, thickness, and radius of specific portions of the structure. A typical design task is to find the minimum weight shell structure to withstand applied thermo-mechanical loads. In shape optimization, the optimum shape of a structure is sought by varying the boundary shape defined by an appropriate spline function, with the design variables defined in a function form.

In most design problems, the topology of a structure is not known *a priori*. Topology is related to the number of holes in a structure. If the topology is fixed, the configuration is defined easily by spline functions. Significant difficulties are encountered when the topology of a structure must be designed, since its representation with spline-type functions is unwieldy. As a result, design problems involving both shape and topology have not been solved satisfactorily. Several approaches to the topology optimization problem have been proposed: see, for example, Rozvany [9], and the proceedings of a recent NATO Advanced Study Institute [3]. The homogenization method, described by Bendsøe and Kikuchi [2] and used in Project Maxwell, is unique in that it yields the optimal shape and topology at a macro- and micro-level of description.

HOMOGENIZATION DESIGN METHODOLOGY

We can formulate a generalized topology optimization problem by introducing microstructural perforations into the structure, and then minimizing the mean compliance subject to a constraint on the total volume of material used. Formally,

$$\underset{a,b,\text{and }\theta}{Minimize} \sum_i \int_{\Omega} f_i u_i d\Omega + \sum_i \int_{\Gamma_t} t_i u_i d\Gamma_t \qquad (1)$$

subject to equilibrium equations, and

$$\int_{\Omega} (1 - ab) d\Omega \leq \Omega_s \qquad (2)$$

Here, u is the vector of virtual displacements, f is the applied body force, t is the applied traction on the boundary Γ_t, i is the number of finite elements used to discretize the structure, and Ω_S is the total volume of solid material forming the porous structure. The microstructural model used in this method is shown in Figure 1. There are three design variables per element: void dimensions a and b, and void orientation angle θ. Variables a and b are restricted to values [0,1], i.e., 0 to 1 inclusive.

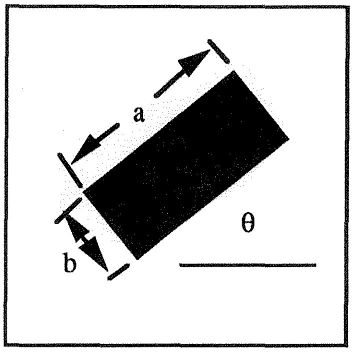

Figure 1: Element Microstructural Model

The equilibrium equation and its associated loading and support conditions, i.e., the structural analysis problem, are solved using the finite element method. The domain for stress analysis is the initial design domain. This domain is discretized into finite elements, with the design variables a, b, and θ for each element evaluated at the centroid. The number of design variables for the present problem is quite large, e.g., five to thirty thousand variables, and it is difficult to apply standard mathematical programming techniques. The optimization method used for this problem is a simple resizing scheme based on the optimality conditions. For details, refer to Bendsøe and Kikuchi [2].

We have demonstrated the applicability of this technique for structural layout design on an extensive and growing body of examples. These examples range from the design of simple plane stress/plane strain structures to the design of automotive body panels, suspension components, and complete vehicle structural layouts. References 1, 7, and 8 contain a variety of these demonstration and validation examples.

MATERIAL DESIGN EXAMPLES

Some recent works by Bendsøe and collaborators [11,12] describe the construction of optimal structures using materials of prescribed constitutitive behavior. In [11], Bendsøe et. al. show that the lower bound on compliance optimization for a single load case is obtained using an orthotropic material with the material directions aligned with the principal stresses and without shear rigidity. The optimal structure thus obtained is stable only under the loads that it was designed for; any other loading condition will cause its collapse. When there are multiple load cases, reference [12] obtains an optimal design using anisotropic materials, with the elastic properties varying along the continuum.

Recently, Sigmund [10] has demonstrated the feasibility of designing materials with prescribed elastic behavior. By using a properly formulated topology optimization model, it is possible to create materials which possess such behavior. Most of Sigmund's structures were realized by using a truss topology optimization model on a material microstructural level. As suggested by Sigmund, it is also possible to develop these materials by using a continuum topology optimization approach, similar to that used for the above examples. Essentially, the optimization problem becomes an inverse homogenization problem: given a particular elasticity tensor E_{ijkl}, determine a material microstructure that possesses such a constitutive matrix. Details of the technical approach can be found in Sigmund [10]. We present two recent examples of the application of such a technique.

Material with Poisson's ratio = 1.0

In this case, we seek to design a material which possesses equal strength in each of the principal directions, and thus possesses a poisson's ratio of approximately 1.0. Note that this material has no shear stiffness. The microstructure of this material is shown in Figure 2. Dark areas indicate areas of solid material in the unit cell, and light areas indicate areas of no material. Note also that this particular microstructure works because of the hinges that are formed in the corner areas. Thus, such a microstructure would be relatively difficult to construct. If we relax the material constraint, and design a material with a Poisson's ratio of 0.8, it is possible to create a microstructure which is physically realizable.

A lattice made of this material resembles an octagonal honeycomb structure. The structural response of this material is similar to that of a more typical honeycomb structure.

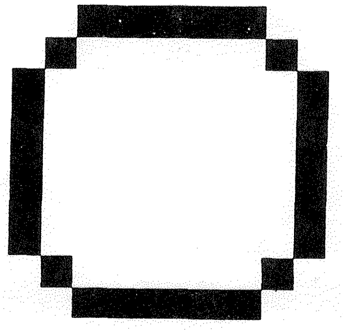

Figure 2: Isotropic Material Microstructure

Orthotropic Material

In this example, we designed an orthotropic material which possesses stiffnesses in the two principal directions in the ratio of 4 to 1. Figure 3 illustrates the microstructural layout of this material. The stiffness in the vertical direction is nearly one-quarter of the stiffness in the horizontal direction. In this case, we have designed a material which also possesses some shear stiffness, and is thus more easily physically realizable than the above example. In this figure, the different grey-scale shading can be interpreted as areas of different material density, where darker shades indicate higher material density and lighter shades indicate less dense material.

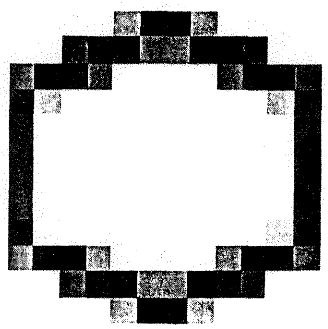

Figure 3: Orthotropic Material Microstructure

Figure 4 shows an example of a material lattice composed of these microstructural unit cells.

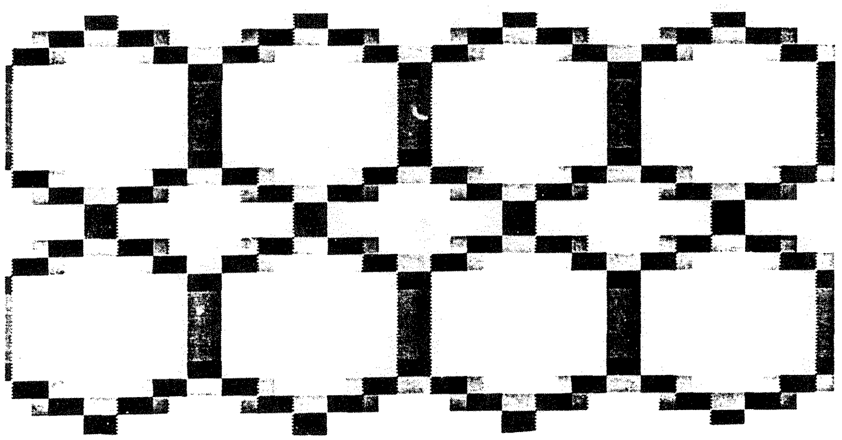

Figure 4: Lattice composed of Designed Material

It is conceptually possible to create structures using this method which possess virtually any physically realizable combination of material properties. Extension to the design of three dimensional material microstructures is underway. Integration of this technique with advanced fabrication techniques to allow the realization of these novel microstructures is the logical next extension of this research.

CONCLUSIONS

Effective computational tools exist for the structural layout design of typical engineered structures. In addition, these tools offer the potential to design structures which take advantage of the unique possibilities inherent in freeform fabrication technology. It is possible to simultaneously perform layout design and material microstructure design using these techniques. One area of ongoing work involves the integration of the macro- and microscale design procedures. This structural layout design procedure has been extended to the design of multibody welded structures and to problems involving the layout of structures with specified dynamic response characteristics. Additional ongoing work involves extending the methodology to new classes of structures, such as performing layout optimization for structures formed from composite laminates.

ACKNOWLEDGEMENTS

Thanks to Mr. Øle Sigmund and Mr. Jun Fonseca for the development of the material microstructure design examples, and to Ms. Tenny Chang for her assistance with processing the data from the examples. This work was supported in part by NSF grant DDM-9300326, ONR grant N00014-94-1-0022, and TACOM grant DAAE07-93-C-R125. This financial support is gratefully acknowledged.

REFERENCES

1. Ma, Zheng-Dong, N. Kikuchi, and H-C Cheng, (1992) "Topology and Shape Optimization Technique for Structural Dynamic Problem", Recent Advances in Structural Mechanics, Proceedings, ASME Winter Annual Meeting, pp.133-143.

2. Bendsøe, P.M., and Kikuchi, N., (1988) "Generating Optimal Topologies in Structural Design Using a Homogenization Method", *Comp. Meth. Appl. Mech. Eng.*, 71, 197-224.

3. Bendsøe, M.P. and C.A. Mota Soares, (eds)., (1992),*Topology Design of Structures*, NATO ASI, Kluwer.

4. Botkin, M.E. and Bennet, J.A., (1985), "Shape Optimization of Three Dimensional Folded Plate Structures", *AIAA J.*, 23(11) 1804-1810.

5. Fleury, C., and Braibant, V., (1986), "Structural Optimization: A New Dual Method Using Mixed Variables", *Int. J. Num. Methods in Eng.,* 23, 409-428.

6. H. C. Cheng, (1994), The Optimal Shape/Topology Design of Structures for Dynamic Problems Using a Homogenization Method, Doctoral Dissertation, The University of Michigan.

7. Johanson, R. et. al., (1993), "Design of a Lower Control Arm in Project MAXWELL," Proceedings, 1993 Solid Freeform Fabrication Symposium, Austin, TX, pp. 123-129.

8. Johanson, R., N. Kikuchi, and P. Papalambros, (1994) "Computational Tools for Optimal Structural Layout Design," Proceedings, 2nd Annual International Body Engineering Conference, Detroit, September, 1994.

9. Rozvany, G. and M. Zhou, (1993), *Optimality Criteria Methods for Large Structural Systems*, Research Report, Universitat-Gesamthochschule-Essen, March.

10. Sigmund, Øle, (1994), "Tailoring Materials with Prescribed Elastic Properties." Technical Report, Technical University of Denmark, April.

11. Bendsøe, M. P. et. al., (1993) "An Analytical Model to Predict Optimal Material Properties in the Context of Optimal Structural Design," to appear, *J. Applied Mechanics*.

12. Bendsøe, M. P., Diaz, A., Lipton, R., Taylor, J.E. (1993), "Optimal Design of Material Properties and Material Distribution for Multiple Loading Conditions," DCAMM - report No. 469, Technical University of Denmark