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Optimal Design of Laminated Composite Structures Including Local Failure Criteria and Manufacturing Constraints by Advanced Mixed Integer Nonlinear Optimization Techniques

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We consider discrete multi material and thickness optimization of laminated composite structures including local failure criteria and manufacturing constraints. Our aim is to solve to global optimality multiple load minimum compliance (or mass) problems subject to a mass (or compliance) constraint. The parameterization of the optimal design problems follows an extension of the Discrete Material Optimization scheme, see e.g. [1] and [2], which allows simultaneous determination of the appropriate laminate thickness and the material choice in the structure.
The manufacturing requirements for laminated composite structures may place additional requirements on the lamination sequence that must be reflected in the optimization problem. We explicitly model manufacturing limitations as linear or mildly nonlinear inequality constraints. Moreover, we impose limitations on the fiber angles variations between adjacent plies using an implementation that is based on the perimeter method for variable topology shape optimization of elastic structures, see e.g. [6]. Our models guarantee the favorable mathematical properties of the chosen parameterization, see e.g. [1] and [2].
Figure 1 illustrates the obtained designs when simultaneous material and thickness optimization has been performed for a layered clamped plate under uniform loading. A material deposition and a ply drop constraint have been applied in this particular case. The candidate materials are an orthotropic material oriented at 4 distinct directions {-45°, 0°, 45°, 90°} and void.

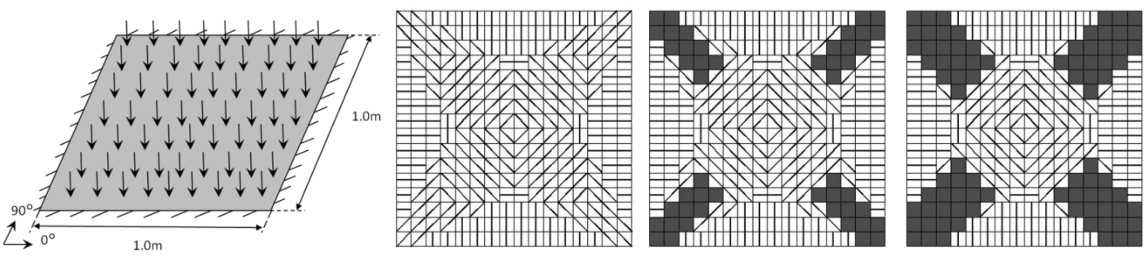

Figure 1. Optimal design for a classical laminated plate benchmark example.

The considered problems are stated as non-convex mixed integer problems. We resort to different reformulation techniques to state them into their nested form [10] as nonlinear convex mixed 0-1 programs. We have developed and implemented special purpose global optimization methods and heuristic techniques for solving this class of problems. The continuous relaxation of the mixed integer problem is being solved by an implementation of a primal-dual interior point method for nonlinear programming, see e.g. [7]. An efficient heuristic technique then applied to obtain discrete feasible solutions to the stated mixed 0-1 convex problems by solving a finite sequence of well-posed optimization problems. Although the obtained feasible solutions provide a measure of closeness to a global optimizer, there are no theoretical guarantees on the quality of the obtained feasible designs. We attempt to find improved feasible designs following the application of the heuristics by applying a gap improvement method/heuristic that is based on the feasibility pump heuristic, see e.g. [8]. Our primary aim is to develop modern optimization methods which are capable of solving the considered nonlinear mixed 0-1 problems to proven global optimality. We propose a combination of the convergent Outer Approximation [3] and [4] and Local Branching [5] algorithms to perform the global optimization.

In order to model local failure criteria we state the original non-convex mixed integer problems as mixed integer 0-1 linear problems following the approach of simultaneous analysis and design, see e.g. [11]. The reformulated mixed 0-1 optimal design problems are solved by the commercial branch-and-cut software for mixed integer programming CPLEX version 12.5 [10].

The efficiency of the proposed models are examined on a set of well-defined discete multi material and thickness optimization problems originating from the literature and from wind energy applications. The inclusion of manufacturing limitations along with structural considerations in the early design phase results in structures with better structural performance without the need of manually post-processing the found designs.

REFERENCES

[1] E. Lund and J. Stegmann. On structural optimization of composite shell structures using a discrete constitutive parameterization. *Wind Energy*, Vol. **8(1)**, 109-124, 2005.

[2] J. Stegmann and E. Lund. Discrete material optimization of general composite shell structures. *International Journal for Numerical Methods in Engineering*, Vol. **62**(14), 2009-2027, 2005.

[3] M. A. Duran and I. E. Grossmann. An outer-approximation algorithm for a class of mixed-integer nonlinear programs. *Mathematical programming*, Vol. **36**(3), 307-339, 1986.

[4] R. Fletcher and S. Leyffer. Solving mixed integer nonlinear programs by outer approximation. *Mathematical programming*, Vol. **66**(1-3), 327-349, 1994.

[5] M. Fischetti and A. Lodi. Local Branching. *Mathematical Programming*, **Vol**. 98, 23-47.

[6] R. B. Haber, C. S. Jog and M. P. Bendsøe. A new approach to variable topology shape design using a constraint on perimeter. *Structural Optimization*, **Vol**. 11(1-2), 1-12, 1996.

[7] J. Nocedal, A. Wächter and R. Waltz. Adaptive barrier update strategies for nonlinear interior methods. *SIAM Journal on Optimization*, **Vol**. 19(4), 1674-1693, 2009.

[8] M. Fischetti, F. Glover and A. Lodi. The feasibility pump. *Mathematical Programming*, **Vol**. 104(1), 91-104, 2005.

[9] IBM. *IBM ILOG CPLEX V12.5 User's Manual for CPLEX*, 2013. http://www.ibm.com

[10] M. P. Bendsøe and O. Sigmund. Topology Optimization - Theory, Methods and Applications. *Springer*, Berlin, 2003.

[11] R. T. Haftka. Simultaneous analysis and design. *AIAA Journal*, **Vol**. 23(7), 1099-1103, 1985.