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# Optimal Composite Material Wing Design via Disjunctive Conic Cut

Tamas Terlaky
LEHIGH UNIVERSITY

08/23/2019
Final Report

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The project's aim is to use novel Mixed-Integer Conic Optimization (MICO) techniques to design aircraft wing structures that take full advantage of new composite materials and manufacturing techniques. Considering the freedom provided by these design options is key to develop cutting-edge wing designs. However, obtaining (guaranteed) near-optimal solutions for the resulting large-scale structural design problem is very challenging for current solution approaches. The MICO solution approach allows to capture this complexity and obtain near-optimal solutions. In particular, as a result of this project, novel results have been obtained and published regarding the solution of discrete truss topology and ply-angle problems.

**15. SUBJECT TERMS**
Aircraft wing design; structural optimization; composite material, discrete truss topology design; discrete-ply angle design; mixed integer second order cone programming; structure stability; global optimization.

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Industrial and Systems Engineering Department,
Lehigh University

and

Department of Aerospace Engineering,
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*Final Report for*
Grant FA9550-15-1-0222

# Optimal Composite Material Wing Design

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Submitted to: Dr. Fariba Fahroo (fariba.fahroo@us.af.mil)
Program Officer,
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# Contents





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# 1 Summary of Achievements

In this report we summarize the accomplishments obtained as a result of the support from the AFOSR grant FA9550-15-1-0222. For that purpose, in this section we discuss the main problem underlying the proposal's work, its importance. Then, we provide and a brief summary of the objectives achieved during the project's research work. Detailed results are publicly available in the publications that are listed in Section 4 of this report.

*Composites* are a unique class of materials made from two or more distinct materials that when combined are better (stronger, tougher, and/or more durable) than each would be separately. They are non-corroding, non-magnetic, radar transparent, and they are designed to provide strength and stiffness where it is needed. Not surprisingly, composites are becoming ever more important as they are used to improve aircraft, automobiles, boats, pipelines, buildings, roads, bridges, to name just a few products. This trend will continue as improved manufacturing techniques are developed to make it possible to produce composite materials at higher volumes and at a lower cost than is now possible.

Thanks to the development of nano and textile composites, fiber tow steering manufacturing techniques, and composites with functionally graded properties; composite materials are set to have an enormous impact in the performance of structural designs. This is specially the case in aircraft wing design, where it pays off to use high-performance materials and sophisticated design techniques to optimize the wing's structural elements distribution in order to maximize the performance of an aircraft operating at distinct flight conditions.

On the other hand, the large amount of design freedom provided by new composite materials and manufacturing techniques, as well as the relatively little experience with their use in structural design, makes the problem of designing near-optimal structures a very challenging one, for which engineering intuition alone is not sufficient. Thus, the design of next generation's high-efficiency aircraft wings that make full use of state-of-the-art materials and manufacturing techniques requires the use of numerical optimization. This is currently the case even when considering conventional composite materials.

However, even current state-of-the-art optimization solvers are unable to obtain near-optimal solutions for these large-scale structural design problems that take full advantage of new composites and manufacturing techniques. This is due to the problems' large size and complexity, which arises from the need for non-linear constraints/objectives, and a large number of discrete variables (e.g., truss sizes, ply angles, and plate thickness), to produce properly accurate models. For example, many results on composite wing design are obtained using first-order optimization techniques that do not guarantee that the problem's global (best) solution is obtained.

This high-level of complexity of state-of-the-art structural design optimization problems can be naturally captured by the class of *mixed integer conic optimization* (MICO) problems; that is, optimization problems in which the objective is linear on the (decision) variables and, besides some variables being integer (discrete), the constraints of the problem can be written in terms of linear constraints plus the constraint that the variables belong to a cone. Two well-known examples of MICO are: *mixed integer linear optimization* (MILO), where the cone is the non-negative orthant, and *mixed-integer second-order conic optimization* (MISOCO),



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where the cone is the *second-order cone*. MICO encompasses a vast class of decision-making problems and integrates major elements and concepts of conic, linear, and discrete (or combinatorial) optimization into a novel paradigm offering powerful modeling methodologies and the capacity to solve the corresponding models to global optimality for large classes of decision making problems. In particular, a very rich class of composite material wing design problems can be modeled using MICO techniques. Thus, novel developments and improvements in MICO solution methodologies substantially impact the capacity to solve large classes of decision making problems to global optimality.

The main challenge driving the proposed research work is to develop novel theoretical and numerical MICO techniques that will allow to overcome current barriers in the solution of structural design problems to take full advantage of new materials and manufacturing techniques; and in more generality, for the large class of decision making problems that can be formulated as MICO problems. Towards achieving this goal, **the main research objectives accomplished** in this research work are:

**Objective 1 (Global Solution of Truss Topology Sizing Problems [11, 6, 8]).** *Truss topology sizing problems considering the complex physical constraints (i.e., Euler buckling, and Hooke's law) of the model, and having discrete decision variables become extremely difficult to solve as the size of the truss grows. In Shahabsafa et al. [11], Shahabsafa [6], we address this issue by proposing a novel MILO reformulation and associated solution algorithm for this class of problems. As demonstrated through extensive numerical experiments, the proposed approach and solution methodology outperforms alternative solution approaches considered in the literature by providing high-quality solutions for large-scale real truss sizing problems; and in particular, for the design of the truss topology of an aircraft wing.*

*Furthermore, in Shahabsafa et al. [8], Shahabsafa [6], we extend these results and solution methodologies to the case in which instead of a single force profile scenario, the truss structure must support multiple force scenarios. The need to consider multiple scenarios in truss topology problems arises from the need for a structure to operate in different conditions (e.g., take-off, landing, and cruising conditions for an aircraft wing truss), or the need for the structure to robustly support an uncertainly known force scenario.*

**Objective 2 (Stability and Optimal Characterization for Truss Topology Design and Sizing Optimization [9, 6, 4, 7]).** *Kinematic stability of the truss topology design and sizing optimization (TTDSO) problems is a crucial aspect which is often overlooked in the mathematical optimization models used to solve this type of problems. In Shahabsafa et al. [9], Shahabsafa [6], we propose a novel MILO reformulation for the discrete TTDSO problem, with Euler buckling constraints, in which random perturbations of external forces are used to efficiently obtain structures that are guaranteed to be kinematically stable for large-scale problem instances. This is further illustrated by extensive numerical experiments performed on cantilever, Michell, tower and aircraft wing design instances that have been made available to the public in our* `GitHub` *repository [7]. This repository will help to speed-up results in the area of truss topology design by providing a publicly available test bed of relevant instances of the problem, against which new solution approaches can be benchmarked.*



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*Additionally, in Lei et al. [4], we propose a novel sequence of MILO relaxations of the continuous TTDSO problem that as the rank of the sequence increases, provide increasingly tighter lower bounds for the TTDSO problem. Although the computation resources needed to compute these lower bounds is substantial, numerical results show that this approach can be used to guarantee the quality of feasible solutions obtained for the continuous TTDSO problem by methodologies that do not certify global optimality of the solution on distinguished problem instances.*

**Objective 3** (**Global solution of Ply-Angle Design problems [3]**). *The discrete ply-angle problem is a classic structural optimization problem that has been solved with solid isotropic material with penalization (SIMP) type methods and genetic algorithms (GA) methods. Both SIMP and GA type methods have been successful in dealing with large scale instances of the problem. However, the solutions provided by these methods are not guaranteed to be globally optimal. In He et al. [3], we address this issue by proposing a novel MISOCO reformulation of the ply-angle problem. By solving the MISOCO formulation of the problem to numerical precision, the global optimality of the problem's solution is guaranteed.*

*We show the effectiveness of the approach by performing numerical experiments in two types of problems: a composite stacking sequence problem in which structure weight is the objective function and the design variables are the discrete ply-angles; and a composite plate optimization problem in which both structure weight and compliance are considered as objective functions and the design variables are the discrete ply-angles and discrete plate thicknesses.*

**Objective 4** (**Advances in algorithmic solution of MISOCO problems [10, 6, 2, 1, 5]**). *A large class of decision making problems, including structural design, financial engineering, and power generation and transmission problems, among many others, can be reformulated as MISOCO problems. This allows these problems to be solved to global optimality by using a combination of MILO and conic optimization techniques (i.e., interior-point methods). However, efficiently combining these solution techniques requires novel results and substantial improvements in the adaptation and generalization of algorithmic steps taken during the solution of MILO problems so they can be used in the MISOCO solution algorithms.*

*In Shahabsafa et al. [10], Shahabsafa [6], one of these steps is considered; namely when it is useful to add second-order conic cuts; that is, additional second-order conic valid constraints to the problem. By characterizing cases in which adding these cuts does not help to speed-up the optimization algorithm, the MISOCO solution algorithm can avoid computing or trying to use unhelpful cuts.*

*The fact that MISOCO problems can be solved to global optimality stems mainly from the fact that after fixing the value of integer variables in the problem, the resulting second-order cone optimization (SOCO) subproblems can be efficiently solved to global optimality using interior-point methods. Thus, any advances in interior-point methods positively and substantially affect the efficiency of MISOCO solution algorithms. In Mohammad-Nezhad and Terlaky [5], we advance the understanding of the convergence to optimality of interior-point methods for a large class of MISOCO problems. As a result, we propose a novel an efficient algorithmic approach to go from a near-optimal solution of the problem, to an*



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*optimal solution of the problem, during the algorithmic solution of a SOCO problem. In practice, these could lead to important speed-ups of the MISOCO solution algorithm in the final iterations of the algorithm.*

*In Cay et al. [2], Cay [1], another key algorithmic step is considered; namely, how to obtain feasible solutions for the subproblems solved in the MISOCO solution algorithm using interior-point methods. By providing an algorithmic approach to compute feasible solutions for the second-order conic optimization problems, the number of calls to the interior-point solver during the MISOCO solution algorithm is dramatically reduced.*

The rest of the report is organized as follows: In Section 2, we list the personnel involved in this project's research work. In Section 3, we list the presentations made to disseminate the work accomplished during this project. To finish, in Section 4, we list the publications supported by AFOSR grant FA9550-15-1-0222.

## 2 Personnel Supported by AFOSR grant FA9550-15-1-0222

The following is a list of individuals who have worked on research supported in whole or in part by the AFOSR grant FA9550-15-1-0222:

- Professor Tamás Terlaky, George N. and Soteria Kledaras '87 Endowed Chair Professor, Industrial and Systems Engineering Department, Lehigh University.
- Professor Joaquim R. R. A. Martins, Chair, Multidisciplinary Design Optimization Laboratory (MDO Lab), Department of Aerospace Engineering, University of Massachusets.
- Associate Professor Luis F. Zuluaga, Industrial and Systems Engineering Department, Lehigh University.
- Mohammad Shahabsafa, Ph.D. student (completed 2019), Industrial and Systems Engineering Department, Lehigh University.
- Ali Mohammad-Nezhad, Ph.D. student (completed 2018), Industrial and Systems Engineering Department, Lehigh University.
- Sicheng He, Ph.D. student, Department of Aerospace Engineering, University of Massachusets.
- Ramin Fakhimi, Ph.D. student, Industrial and Systems Engineering Department, Lehigh University.
- Weiming Lei, Ph.D. student, Industrial and Systems Engineering Department, Lehigh University.



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## 3 Presentations Supported by AFOSR grant FA9550-15-1-0222

1. "Truss topology design and sizing optimization with kinematic stability", ICCOPT 2019, Berlin, Germany, 2019 August.
2. "Warranty of kinematic stability in truss topology design optimization", MOPTA 2019, Bethlehem, PA, 2019 August.
3. "A binary expansion method in finding a good lower bound of weight in truss sizing design", MOPTA 2019, Bethlehem, PA, 2019 August.
4. "Truss topology design and sizing optimization with kinematic stability", IISE 2019, Orlando, FL, 2019 May.
5. "A Novel Approach to Discrete Truss Design Problems", University of Calgary, Calgary, Canada, 2018 May.
6. "A binary expansion method in finding a good lower bound of weight in truss sizing design", Ph.D. student Seminar, Lehigh University, Bethlehem, PA, 2019 February.
7. "A Novel Approach to Discrete Truss Design Problems", Hong Kong Polytechnic University, Hong Kong, 2018 March.
8. Plenary presentation: "On Mixed Integer Second Order Cone Optimization", 4th Optimization Methods and Software Conference, Havana, Cuba, 2017 December.
9. "Warmstart of Interior Point Methods for Second Order Cone Optimization via Rounding over Optimal Jordan Frames", INFORMS Annual Meeting, Houston, TX, 2017 October.
10. "A Novel Approach to Model and Solve Discrete Truss Sizing Problems", INFORMS Annual Meeting, Houston, TX, 2017 October.
11. "Parametric analysis of semidefinite and second-order conic optimization", INFORMS Annual Meeting, Houston, TX, 2017 October.
12. "A Novel Approach to Model and Solve Discrete Truss Sizing Problems", MOPTA 2017, Lehigh University, Bethlehem, PA, 2017 August.
13. "On the Identification of the Optimal Partition for Semidefinite Optimization, MOPTA 2017, Lehigh University, Bethlehem, PA, 2017 August.
14. "Pathological Cases for Disjunctive Conic Cuts in Mixed Integer Second Order Cone Optimization Problems", EUROPT'17, HEC, Montreal, QC, 2017 July.
15. "Pathological Cases in Deriving Disjunctive Conic Cuts for Mixed Integer Second Order Cone Optimization Problems", IFORS XXI, Quebec City, QC, Canada, 2017 July.



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16. “Novel approaches to model and solve the truss sizing problem”, NemFest2017, Georgia Tech., Atlanta, GA, 2017 May.

17. “Novel approaches to model and solve the truss sizing problem”, Department of Mechanical Engineering & Mechanics Research Seminar, Lehigh University, Bethlehem, PA, 2017 April.

18. “Optimal truss topology design with buckling constraints”, INFORMS Annual meeting, Nashville, 2016 November.

19. “Composite structural optimization by MISOCO”, MOPTA 2016, Lehigh University, Bethlehem, PA, 2016 August.

20. “MISOCO Models and Disjunctive Conic Cuts for Truss Topology Design Problems ”, INFORMS Optimization Society Conference 2016, Princeton University, Princeton, NJ, 2016 March.

21. “The power of Mixed-Integer Conic Optimization in high-performance Structural Design”, AFOSR, Arlington, VA, 2015 December

22. “Aircraft wing design via numerical optimization: Are we there yet?”, ISE Research Seminar, Lehigh University, Bethlehem, PA, 2015 May.

# 4 Publications Supported by AFOSR grant FA9550-15-1-0222


[1] Cay, S. B. (2018). *Exploiting Structures in Mixed-Integer Second-Order Cone Optimization Problems for Branch-and-Conic-Cut Algorithms.* PhD thesis, Industrial and Systems Engineering, Lehigh University. Available at `https://preserve.lehigh.edu/etd/4224/`.

[2] Cay, S. B., Pólik, I., and Terlaky, T. (2018). The first heuristic specifically for mixed-integer second-order cone optimization. Technical report, Industrial and Systems Engineering Department, Lehigh University. Available at `http://www.optimization-online.org/DB_FILE/2018/01/6428.pdf`.

[3] He, S., Hwang, J. T., Martins, J. R., Shahabsafa, M., Lei, W., Mohammad-Nezhad, A., Zuluaga, L. F., , and Terlaky, T. (2019). A mixed-integer second-order cone programming framework for discrete ply-angle topology optimization problem with disjunctive conic cuts. Technical Report 19T_014, Industrial and Systems Engineering Department, Lehigh University. To be submitted to *Structural and Multidisciplinary Optimization*, available at: `https://engineering.lehigh.edu/sites/engineering.lehigh.edu/files/_DEPARTMENTS/ise/pdf/tech-papers/19T_014.pdf`.

[4] Lei, W., Shahabsafa, M., Fakhimi, R., He, S., Zuluaga, L. F., Martins, J. R., and Terlaky, T. (2019). Continuous truss sizing optimization: a binary expansion method in finding a close lower bound of total weight. Technical report, Industrial




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and Systems Engineering Department, Lehigh University. In preparation, will be available at: https://engineering.lehigh.edu/sites/engineering.lehigh.edu/files/_DEPARTMENTS/ise/pdf/tech-papers/19T_015.pdf.

[5] Mohammad-Nezhad, A. and Terlaky, T. (2017). Quadratic convergence of Newton's method to the optimal solution of second-order conic optimization. Technical Report Technical Report 17T-014, Industrial and Systems Engineering, Lehigh University. Submitted to *Mathematical Programming*, available at https://engineering.lehigh.edu/sites/engineering.lehigh.edu/files/_DEPARTMENTS/ise/pdf/tech-papers/17/17T_014.pdf.

[6] Shahabsafa, M. (2018). *Mixed Integer Conic Optimization and Its Applications*. PhD thesis, Industrial and Systems Engineering, Lehigh University.

[7] Shahabsafa, M. (2019). The data of the truss instances. https://github.com/shahabsafa/truss-data.

[8] Shahabsafa, M., Fakhimi, R., Lei, W., He, S., Zuluaga, L. F., Martins, J. R., and Terlaky, T. (2019a). Solving large-scale multi-scenario truss sizing optimization problems. Technical Report 19T_013, Industrial and Systems Engineering Department, Lehigh University. To be submitted to *Structural and Multidisciplinary Optimization*, available at: https://engineering.lehigh.edu/sites/engineering.lehigh.edu/files/_DEPARTMENTS/ise/pdf/tech-papers/19T_013.pdf.

[9] Shahabsafa, M., Fakhimi, R., Lei, W., He, S., Zuluaga, L. F., Martins, J. R., and Terlaky, T. (2019b). Truss topology design optimization with guaranteed kinematic stability. Technical Report 19T_12, Industrial and Systems Engineering Department, Lehigh University. Submitted to *Structural and Multidisciplinary Optimization*, available at: https://engineering.lehigh.edu/sites/engineering.lehigh.edu/files/_DEPARTMENTS/ise/pdf/tech-papers/19T_012.pdf.

[10] Shahabsafa, M., Góez, J. C., and Terlaky, T. (2018a). On pathological disjunctions and redundant disjunctive conic cuts. *Operations Research Letters*, 46(5):500–504.

[11] Shahabsafa, M., Mohammad-Nezhad, A., Terlaky, T., Zuluaga, L., He, S., Hwang, J. T., and Martins, J. R. (2018b). A novel approach to discrete truss design problems using mixed integer neighborhood search. *Structural and Multidisciplinary Optimization*, 58(6):2411–2429. Available at: https://link.springer.com/article/10.1007/s00158-018-2099-8.



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Optimal Composite Material Wing Design

**Grant/Contract Number**
**AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".**

FA9550-15-1-0222

**Principal Investigator Name**
**The full name of the principal investigator on the grant or contract.**

Tamas Terlaky

**Program Officer**
**The AFOSR Program Officer currently assigned to the award**

Fariba Fahroo

**Reporting Period Start Date**

06/15/2015

**Reporting Period End Date**

06/14/2019

**Abstract**

The project's aim is to use novel Mixed-Integer Conic Optimization (MICO) techniques to design aircraft wing structures that take full advantage of new composite materials and manufacturing restrictions. Considering the freedom provided by these design options is key to develop cutting-edge wing designs. However, obtaining (guaranteed) near-optimal solutions for the resulting large-scale structural design problem is very challenging for current solution approaches. The MICO solution approach allows to capture this complexity and obtain near-optimal solutions. In particular, as a result of this project, novel results have been obtained and published regarding the solution of discrete truss topology and ply-angle problems.

**Distribution Statement**

DISTRIBUTION A: Distribution approved for public release.

**This is block 12 on the SF298 form.**

Distribution A - Approved for Public Release

**Explanation for Distribution Statement**

**If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.**

**SF298 Form**

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**Archival Publications (published) during reporting period:**

See pages 7 and 8 or the Report.

**New discoveries, inventions, or patent disclosures:**

**Do you have any discoveries, inventions, or patent disclosures to report for this period?**

No

**Please describe and include any notable dates**

**Do you plan to pursue a claim for personal or organizational intellectual property?**

**Changes in research objectives (if any):**

N/A

**Change in AFOSR Program Officer, if any:**

N/A

**Extensions granted or milestones slipped, if any:**

One year extension granted in 2018 till June 14, 2019.

**AFOSR LRIR Number**

**LRIR Title**

**Reporting Period**

**Laboratory Task Manager**

**Program Officer**

**Research Objectives**

**Technical Summary**

**Funding Summary by Cost Category (by FY, $K)**

| | Starting FY | FY+1 | FY+2 |
|---|---|---|---|
| Salary | | | |
| Equipment/Facilities | | | |
| Supplies | | | |
| Total | | | |

**Report Document**

**Report Document - Text Analysis**

**Report Document - Text Analysis**

**Appendix Documents**

## 2. Thank You

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