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Fully Constrained Design: A general and scalable method for discrete member sizing optimization of steel truss structures

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ABSTRACT

Fully Constrained Design (FCD) is a new method for discrete sizing optimization of steel structures that balances computational efficiency with solution quality for application to large-scale problems. The proposed method is based on optimality criteria, but does not require gradient information and handles discrete variables. Based on benchmarking studies, FCD produces superior quality solutions to optimality criteria (>4%), but inferior to heuristic methods (<2%). FCD is approximately 10× less computationally efficient than optimality criteria and 100× more efficient than heuristic methods. We present a successful industry application of FCD that yields cost savings of 19% compared to conventional design methods.

1. Introduction

Engineers are often challenged to design steel structures that use the least amount of economic and environmental resources possible to satisfy the system's functional requirements. The design of these structures can be decomposed into three components: (i) *topology*, which concerns the number and connectivity of members; (ii) *shape*, which pertains to the location of structural joints; and (iii) *sizing*, which involves defining member cross-sections [1]. This paper presents a flexible, general and scalable algorithm to optimize the sizing of steel members given a fixed topology and shape.

The objective of the optimization process is to minimize the cost of the structure while satisfying design performance requirements for safety and serviceability. Engineers strive to meet these design requirements and also stay within or under the engineering time allotted for in the design budget. In this case, the total weight of the structure is used to estimate cost. Steel weight is commonly used as a surrogate for cost in the structural design industry and has been demonstrated to be accurate for structures of similar shape and topology that use industry standard member sizes [2]. Engineers commonly select from this discrete set of steel profiles during the member sizing process to avoid significant cost premiums associated with the use of non-standard section sizes [3]. However, as discussed by Sarma and Adeli [4], weight is only one of five main factors that influence the total cost of a steel structure. The other factors include the cost of rolled sections, the number of different section types used in the structure, the number of connections and the geographic location of the project site. Developing a cost model that incorporates all of these factors is outside of the scope of this paper and is discussed in Section 6 as a topic of future research.

Member sizing optimization is traditionally an iterative process that is performed manually by the engineer. The number of possible design alternatives (i.e., the design space) for sizing problems is an exponential function of the number of design variables and the number of possible choices for each variable. Even for a relatively simple 10-bar truss problem as described in Section 4.1, the number of possible sizing configurations is greater than 1.0E + 10. Finding optimum designs within such a large design space using manual methods is very difficult. Often engineers leave vast areas of the design space unexplored that potentially contain better performing design configurations [5,6].

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Optimization algorithms enable engineers to leverage computer processing power to systematically search the design space for optimal member sizing configurations. Since engineers must select member sizes from a finite list of manufactured sizes to avoid cost premiums as discussed above, the sizing variables in the optimization process are discrete. Researchers have developed and applied a variety of optimization algorithms to discrete sizing problems for steel truss and frame structures over the past 50 years as surveyed by Arora [7]. These algorithms can be broadly categorized as deterministic or non-deterministic. Deterministic methods such as mathematical programming [8–11] and optimality criteria [12–14] were first applied to discrete sizing problems in the 1960s. These algorithms need an initial design configuration to begin the search and require gradient computations in the exploration process, namely the calculation of the first derivative of the objective and constraint functions with respect to the design variables. In some cases, the objective and/or constraint functions are discontinuous or irregular, making the gradient search difficult [15]. In addition, the constraint functions may vary depending on local regulatory requirements and stakeholder preferences [16], thus requiring the customization of the algorithm for each unique set of constraint functions. The implementation of the algorithm can be time consuming and error prone in such cases [17].

Another group of optimization techniques that have emerged recently do not require gradient information for the objective and constraint functions and use probabilistic transition rules rather than deterministic ones. The basic idea behind these stochastic techniques is to simulate a natural phenomenon, such as survival of the fittest, the immune system, swarm intelligence and the cooling process of molten metal through annealing. A detailed review of these algorithms as well as a comparison of their performance for discrete sizing problems is provided by Hasancebi [18,19]. These heuristic search and optimization methods have a couple of advantages when compared to the deterministic methods discussed above. First, they separate domain knowledge from search, making them generally applicable to a wide variety of problem formulations without customization. Second, there is no limitation on the continuity of the search space since no gradient information is required.

A disadvantage of heuristic methods, however, is that they require significantly more computational resources than deterministic techniques [20]. Research on the convergence of these algorithms has shown that the number of evaluations required to reach a given solution quality grows as a function of the square root of the size of the problem [21]. To keep computation times manageable, researchers have focused on applying heuristic methods to truss and frame structures involving fewer than 100 sizing variables. Further research is required to compare the performance of these methods to deterministic techniques for large-scale member sizing problems involving hundreds or even thousands of variables which are common in industry practice.

The goal of the research presented in this paper was to develop a discrete member sizing optimization method that is (i) flexible (i.e., can accommodate different objective and constraint functions without modification); (ii) general (i.e., does not require the search space to be continuous) and (iii) scalable (i.e., can be applied to large structures involving greater than 100 sizing variables in a time frame that is at least comparable to conventional design practice). To achieve these objectives, the proposed optimization algorithm, which we call the Fully Constrained Design method, employs a new way of handling constraints and generating new designs that is presented in Section 3. We benchmark the method against the best performing existing deterministic and heuristic optimization methods in Section 4. In Section 5, we benchmark the method against conventional industry practice on a large stadium roof structure to demonstrate the scalability of the method. Finally, we summarize the benchmarking results and discuss the suitability of the method for general industry application in Section 6.

2. Mathematical model for discrete sizing optimization introduction

A general discrete sizing structural optimization problem can be formulated as:

$$\text{Minimize}: \quad W = f(x^1, x^2, \ldots, x^d), \quad d = 1, 2, \ldots, D \tag{1}$$

$$\text{Satisfying}: \quad G_q = f(x^1, x^2, \ldots, x^d) \leqslant 1, \quad d = 1, 2, \ldots, D \text{ and } \quad q = 1, 2, \ldots, M \tag{2}$$

$$x^n \in S_n \quad \{X_1, X_2, \ldots, X_p\} \tag{3}$$

In this formulation, W is the weight of the structure, which is a scalar function. The set of design variables are represented as x^1, x^2, ..., x^d. The design variable x^n belongs to the set S_n, which describes the available list of discrete member section values. The inequality $G \leqslant 1$ represents the constraint functions, which must be less than unity in this case. The structural constraints considered in the numerical examples in Section 4 include member stresses and nodal displacements. The letters D and M are the number of design variables and constraint functions, respectively. The letter p is the number of available section size choices for a given design variable.

3. Fully Constrained Design method

3.1. Description

The Fully Constrained Design (FCD) method for member sizing optimization is based on the optimality criteria approach discussed in Section 1. FCD possesses a new approach to constraint handling and the generation of new designs that overcomes the observed limitations to the flexibility and generality of the optimality criteria method, namely (1) the requirement that the objective and constraint functions are continuously differentiable in terms of the design variables, and (2) the requirement that the algorithm be customized for each unique problem formulation.

The proposed method does not require gradient information. It involves creating a one-to-one mapping between each member size design variable and a governing constraint. Based on the value of the governing constraint, the section size of each member variable is adjusted incrementally from an ordered list of choices.

Fig. 1 provides an overview of the FCD process. Steps 1–5 are identical to the optimality criteria method; steps 6–10 are unique. Each process step is described in more detail below.

Step 1 – Start: The optimization process begins with the creation of an analytical model that contains an initial configuration of member sizes. This initial configuration of member sizes can either be chosen at random or be based on a previous design solution.

Step 2 – Analyze structure: The analytical model is used to calculate the structure's response to the defined loading. The responses calculated in the numerical examples discussed in Section 4 include the maximum stress (σ^n_{max}) for each member, the maximum deflection (Δ^n_{max}) for each member, and the global deflection (Δ_{Gmax}), considering all of the members in the structure. The value of the objective function, total steel weight (W) in this case, is also calculated.