International Journal of Solids and Structures 48 (2011) 3011–3019

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Optimal design of trusses with geometric imperfections: Accounting for global instability

Mehdi Jalalpour, Takeru Igusa, James K. Guest *

Department of Civil Engineering, Johns Hopkins University, Baltimore, MD 21218, United States

ARTICLE INFO

Article history:
Received 11 April 2011
Received in revised form 20 June 2011
Available online 1 July 2011

Keywords:
Topology optimization
Robust design
Global stability
Geometric imperfections
Buckling
Geometric uncertainties
Perturbation

ABSTRACT

A topology optimization method is proposed for the design of trusses with random geometric imperfections due to fabrication errors. This method is a generalization of a previously developed perturbation approach to topology optimization under geometric uncertainties. The main novelty in the present paper is that the objective function includes the nonlinear effects of potential buckling due to misaligned structural members. Solutions are therefore dependent on the magnitude of applied loads and the direction of resulting internal member forces (whether they are compression or tension). Direct differentiation is used in the sensitivity analysis, and analytical expressions for the associated derivatives are derived in a form that is computationally efficient. A series of examples illustrate how the effects of geometric imperfections and buckling may have substantial influence on truss design. Monte Carlo simulation together with second-order elastic analysis is used to verify that solutions offer improved performance in the presence of geometric uncertainties.

1. Introduction

Structural optimization offers a systematic approach to material layout in engineering design. Its most general branch is topology optimization where both structural component sizes and system connectivity are simultaneously optimized (Bendsøe and Sigmund, 2003). Structural optimization naturally drives design towards sparse and slender structures. Such structures are typically more susceptible to the deleterious effects of fabrication errors, including decreased resistance to buckling in the presence of geometric imperfections. This work presents a topology optimization algorithm that includes the effects of geometric variability in the manufacturing process, with the goal of improving design robustness. We focus on truss structures, and extend a recently developed perturbation-based approach (Guest and Igusa, 2008; Asadpoure et al., 2011) by accounting for nonlinear structural behavior.

Truss topology optimization typically follows a ground structure approach. The design domain is discretized with a nodal mesh that is connected by a dense set of potential structural members. Boundary conditions and applied loads are assumed known, and optimization is used to determine the distribution of cross-sectional areas (Kirsch, 1989; Bendsøe et al., 1994; Achtziger et al., 1992; Bendsøe and Sigmund, 2003). Members with areas below a certain threshold are deemed inefficient and are removed from the ground structure, thereby changing connectivity of the system.

There exists a rich literature on the design of trusses using optimization. We are concerned here with those works that are related to buckling. This area has recently generated significant interest among researchers due to technological advancements, including improved material strengths and manufacturing capabilities, that allow for design of more slender structural components. Buckling can be viewed as a combination of local (Euler) and global (system) buckling. One natural approach for developing designs that resist local buckling is to include the Euler buckling criterion in the constraints (Neves et al., 1995; Stolpe, 2004). However this formulation poses several fundamental and numerical challenges (Duysinx and Bendsøe, 1998; Kirsch, 1996; Zhou, 1996). Guo et al. (2001), for example, describe how this formulation may lead to a division of the feasible domain into disjoint subdomains, with the optimal solutions at the boundaries making them difficult locate with conventional optimizers. Cheng and Guo (1997) proposed the method of epsilon relaxation to overcome a similar difficulty.

While these methods account for the effects of local buckling, solutions can still be globally unstable, as in the common case of a chain of collinearly connected elements. While these collinear elements can be merged into one longer element through a method known as node cancelation, Zhou (1996) demonstrated that this increases the potential for Euler buckling, leading to suboptimal solutions. Achtziger (1999) circumvented this using local buckling constraints that account for the node cancelation effect via an exact

* Corresponding author.
E-mail address: jkguest@jhu.edu (J.K. Guest).

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doi:10.1016/j.ijsolstr.2011.06.020