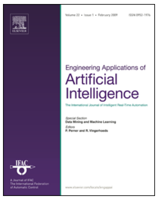
Engineering Applications of Artificial Intelligence 38 (2015) 168–182

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

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



Shape optimization of free-form steel space-frame roof structures with complex geometries using evolutionary computing

Maggie Kociecki, Hojjat Adeli*

Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, 470 Hitchcock Hall, 2070 Neil Avenue, Columbus, OH 43220, USA

ARTICLE INFO

Article history:
Received 24 December 2013
Received in revised form
12 July 2014
Accepted 12 October 2014
Available online 26 November 2014

Keywords:
Genetic algorithm
Optimization
Shape optimization
Structure
Roof structure

ABSTRACT

Recently the authors presented a two-phase genetic algorithm (GA) for minimum weight design of free-form steel space-frame roof structures consisting of discrete commercially available rectangular hollow structural sections (HSS). Subsequently the algorithm was extended to topology optimization of structures. This article presents a new methodology for simultaneous sizing, topology, and shape optimization of free-form steel space-frame roof structures with complex geometries using evolutionary computing. Two methods of altering the geometry of the structure are presented, one a simple method to be used for roof structures with relatively regular geometries, and the other for more complicated geometries. The goal is to achieve additional structural efficiencies by altering the geometry of the roof structure while simultaneously optimizing the roof member and column cross-sectional dimensions and the roof topology. Esthetics is a significant consideration in the structures of the type considered in this research. As such, preserving the general form created by the architect is considered in the proposed shape optimization algorithm. To achieve this, heuristic limits are imposed to avoid drastic or undesirable changes in their architectural form. The methodology is applied to two real-life free-form steel space-frame roof structures. They are two of the thirteen train stations making up the Ottawa Light Rail Transit (OLRT) system to be completed in Ottawa, Canada, in 2018. Efficiencies in the range of 10–16% are reported for the two examples.

1. Introduction and problem definition

In recent years evolutionary computing has been used extensively in various optimization problems including design optimization (Adeli and Sarma, 2006; Baraldi et al., 2011; Chabuk et al., 2012; Sgambi et al., 2012; Hsiao et al., 2012; Raich and Liszkai, 2012; Tao et al., 2012; Campomanes-Álvareza et al., 2013; Fuggini et al., 2013; Luo et al., 2013), optimization of traffic signals (Putha et al., 2012), road maintenance optimization (Gao and Zhang, 2013), optimization of highway alignment (Shafahi and Bagherian, 2013), optimization of earthquake energy dissipation systems (Hejazi et al., 2013), vibration control of structures (Jiang and Adeli, 2008) network design optimization (Szeto et al., 2014), life cycle optimization in building asset management (Hegazy et al., 2012); transportation routing optimization (Chow, 2014), and optimization of stopping patterns for passenger rail transportation (Lin and Ku, 2014) among others. Recently authors presented a two-phase genetic algorithm (GA) for minimum weight design of free-form steel space-frame roof structures consisting of rectangular hollow structural sections (HSS) (Kociecki and Adeli, 2013). The methodology was applied to two roof structures subjected to the AISC LRFD code (AISC, 2005) and ASCE-10 snow, wind, and seismic loading (ASCE, 2010). The structures considered are two of the thirteen train stations making up the Ottawa Light Rail Transit (OLRT) (http://www.ottawalightrail.ca/en/) system to be completed in Ottawa, Canada, in 2018. Both examples have a diamond grid pattern and their members are subjected to torsion in addition to bending and axial forces. The optimum solutions obtained using the new methodology for dimension optimization resulted in savings of 12% and 4%. The initial design in both cases was an actual design performed in a design office by a team of designers including the first author iteratively using a general-purpose structural analysis software over a period of days. The advantages of the two-phase GA shape optimization algorithm are three fold: (a) automation of the design process of a complicated and one-of-a-kind structure; (b) relieving the designer of days of iterative design process; and (c) achieving a considerably lighter and therefore more economical design.

Subsequently, the dimension optimization algorithm was extended to topology optimization of free-form steel space frame roof structures (Kociecki and Adeli, 2014). Topology optimization rearranges members within a structure to achieve a more efficient design. Roof structures considered in this research are made up of a diamond grid pattern where each grid element has four joints and four frame members (Fig. 1). In some cases, for example, when high minor-axis bending occurs, structural performance can be

---

* Corresponding author.

http://dx.doi.org/10.1016/j.engappai.2014.10.012
0952-1976/© 2014 Elsevier Ltd. All rights reserved.

improved by using triangular grid elements or cross members rather than diamond grid elements. By performing topology optimization, a diamond element is transformed into two triangular elements by adding a cross member (Fig. 1). The optimum solutions obtained using the new methodology for topology optimization resulted in additional weight reduction of up to 4%.

The objective of this paper is to extend the previous algorithms further to shape optimization with the goal of achieving additional structural efficiencies. This is done by altering the geometry of the roof structure while simultaneously optimizing the roof members and column cross-sectional dimensions and the roof topology. Esthetics is a significant consideration in the structures of the type considered in this research. As such, preserving the general form created by the architect is considered in the proposed shape optimization algorithm. To achieve this, heuristic limits are imposed to avoid drastic or undesirable changes in the architectural form.

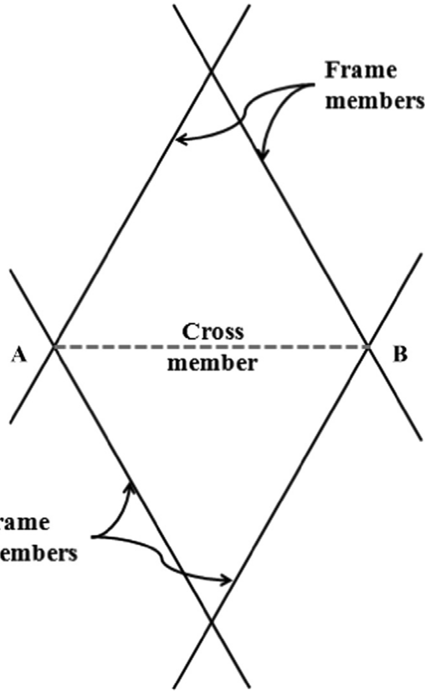


Fig. 1. Diamond grid element with frame and cross members.

An example of the structural forms considered in this research, referred to as Station 1, is shown in Figs. 2 through 6. Fig. 3 is a 3D perspective view of the structure while Fig. 4 shows the top view, Fig. 5 shows a side view along the length, and Fig. 6 shows another side view along the width. The forms consist of a series of diagonally arranged arches in two directions along the length of the structure (Fig. 3). The arches along the width are the primary arches, and the arches at an inclination of about 60° relative to the longitudinal axis in the top view are the secondary arches. The shape and depth of the primary arches are altered to optimize the load-carrying capacity of the roof structure and minimize its weight.

As with the dimension and topology optimization algorithms presented in Kociecki and Adeli (2013, 2014), the structures are divided into regions to improve constructability by introducing regularity. The total weight of the structure is expressed as:

$$f(d,b,d_c,b_c,t_i,t_q)=\rho\left\{\sum_{i=1}^{n}\left[bd-(b-2t_i)(d-2t_i)\right]L_i + \sum_{q=1}^{n_c}\left[b_c d_c-\left(b_c-2t_q\right)(d_c-2t_q)\right]L_q) + [b_x d_x-(b_x-2t_x)(d_x-2t_x)]L_x\right\} \tag{1}$$

where n is the number of groups of members in the roof structure with the same wall thickness, t_i is the wall thickness of members in roof group i, L_i is the total length of members in roof group i, n_c is the number of groups of columns with the same wall thickness, t_q is the wall thickness of members in column group q, L_q is the total length of columns in column group q, d_x, b_x, and t_x are the depth, width, and thickness of cross members, respectively, L_x in the total length of cross members, and ρ is the unit weight of steel.

Members of the roof structure are subjected to axial force, major-axis bending, minor-axis bending, shear force in the x and y-directions, and torsion. Columns are used in pair in a V-shape form. They are pinned at the top and fixed at the bottom (Figs. 2 through 5). The basis of design is the AISC LRFD specifications and design constraints are defined by chapters D through H of the LRFD code (AISC, 2005).

Fig. 2. Station 1 along the Rideau River in Ottawa, Canada (Ottawa Light Rail Transit (OLRT) (http://www.ottawalightrail.ca/en/)).