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Two-phase genetic algorithm for topology optimization of free-form steel space-frame roof structures with complex curvatures

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A B S T R A C T

A two-phase genetic algorithm is presented for simultaneous sizing and topology optimization of free-form steel space frame roof structures consisting of discrete commercially available rectangular hollow structural sections. The algorithm is applied to two real-life space roof structures intended for Ottawa Light Rail Transit (OLRT). It is shown that the algorithm is effective for topology optimization of real-life roof structures with complex curvatures in multiple planes.

1. Introduction and problem definition

Design and resource optimization has been one of the most active areas of research in recent years (Hegazy et al., 2012; Luo et al., 2013; Gao and Zhang, 2013). Biologically-inspired optimization techniques such as genetic algorithms (GAs) and particle swarm optimization (Tao et al., 2012; Shafahi and Bagherian, 2013) have been among the most popular optimization techniques. Since the pioneering work of Adeli and Cheng (1993), and Jenkins (1998) in the early1990s, a large number of articles have been published on civil/structural engineering applications of genetic algorithms (GAs). Recent examples of GA and evolutionary computing include cost optimization of composite floors (Kim and Adeli, 2001), structural system identification (Marano et al., 2011; Fuggini et al., 2013), damage detection and structural health monitoring (Jafarkhani and Masri, 2011; Raich and Liszkai, 2012), nonlinear structural control (Jiang and Adeli, 2008), optimization of earthquake energy dissipation systems, structural cost optimization (Sarma and Adeli, 2001; Adeli and Sarma, 2006; Plevris and Papadrakakis, 2011), dependability assurance in the design of a long span suspension bridge (Sgambi et al., 2012), construction (Hsiao et al., 2012), and transportation engineering (Putha et al., 2012).

Recently the authors presented a genetic algorithm (GA) for minimum weight sizing optimization of free-form steel space-frame roof structures consisting of discrete commercially available rectangular hollow structural sections (HSS) (Kociecki and Adeli, 2013). The methodology was applied to two roof structures subjected to the AISC LRFD code (AISC, 2011) and ASCE-10 snow, wind, and seismic loading (ASCE, 2010). They are two of the 13 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 additional to bending and axial forces. The initial design in both cases was an *actual design* performed in a design office by the first author iteratively using a general-purpose structural analysis software over a period of days. The optimum solutions obtained using the methodology resulted in savings of 12% and 4% for the two examples. The advantages of the proposed GA 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.

The objective of this paper is to extend the algorithm to topology optimization of free-form steel space-frame roof structures consisting of rectangular hollow structural sections (HSS) with the goal of achieving additional structural efficiencies. An example of such a structure, referred to as Station 1 in this paper, is shown in Figs. 1–5. Fig. 2 is a 3D perspective view of the structure while Fig. 3 shows the top view, Fig. 4 shows a side view along the length, and Fig. 5 shows another side view along the width.

The goal of topology optimization is to use a fixed structural geometry defined by the designer and optimize both the member cross-sectional dimensions and the topology by adding (or subtracting) members to the structure. In other words, rearranging the members within a given shape to achieve a more efficient design. For practical and aesthetic reasons, it is assumed that every frame member in the roof has the same width, *b*, and the same depth, *d*, (Fig. 6). Columns, however, can have the same width, b_c,

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and depth, d_c, or different width and depth. Both roof frame and column member thicknesses can vary.

The roof structures considered are made up of a diamond grid pattern where each grid element has four joints and four frame members (Fig. 7). In some cases, for example, when high minor-axis bending occurs, structural performance can be improved by using triangular grid elements rather than diamond grid elements. By performing topology optimization, a diamond element is transformed into two triangular elements by adding a cross member (Fig. 7). Cross members are hidden by wood panels and will not alter the esthetics of the structure.

To improve constructability by introducing regularity, the designer often divides the structure into regions based on similar response characteristics (e.g., internal forces and moments). In this case, each member in a region has the same cross-sectional dimensions. As an example, the roof structure of Fig. 1 may be divided into six roof regions and five column regions shown in Figs. 8 and 9. As cross members are added they make up their own design regions separate from these 11 regions predefined by the designer.

The total weight of the structure is expressed as

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

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 is 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 as explained in Kociecki and Adeli (2013). Columns are used in pair in a V-shape form. They are pinned at the top and fixed at the bottom (Figs. 2–5). The basis of design is the AISC LRFD specifications and design constraints are defined by chapters D through H of the LRFD code (AISC, 2011).

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

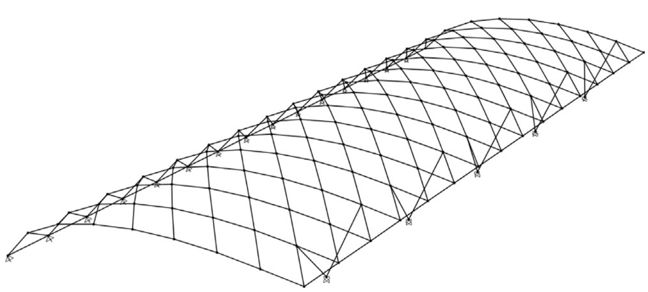

Fig. 2. Perspective view of a free-form steel space-frame roof structure (Station 1).

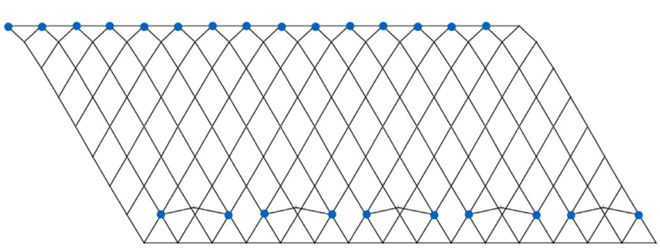

Fig. 3. Top view of Station 1 shown in Fig. 1.

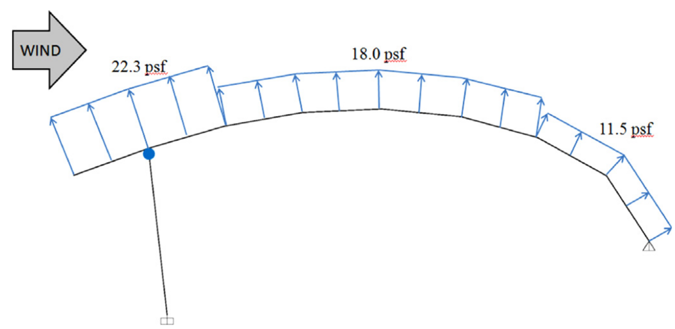

Fig. 5. Side view, along the width, and wind loading (Station 1 shown in Fig. 1).

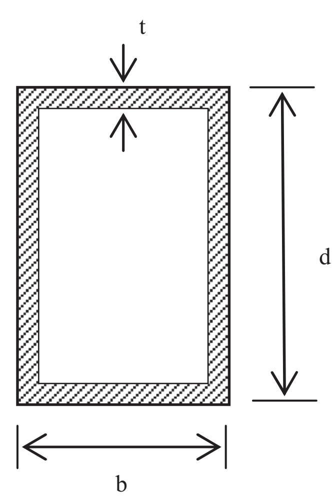

Fig. 6. Typical cross-section of roof members.

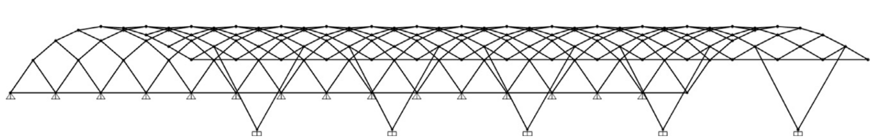

Fig. 4. Side view, along the length, of Station 1 shown in Fig. 1.