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Tailoring static deformation of frame structures based on a non-parametric shape–size optimization method

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ABSTRACT

In this study, a non-parametric shape–size optimization method is developed for tailoring the static deformation of large-scale frame structures. This deformation control design is one of the important problems in the stiffness design of frame structures, and enables us to create a smart or a high performance structure for a specific ability of deformation. As the objective functional, we introduce the sum of squared error norms for achieving the desired displacements on specified members, and assume that each frame member varies in the off-axis direction with changing cross sections. The shape gradient function, the size gradient function, and the optimality conditions for this problem are theoretically derived with the Lagrange multiplier method, the material derivative method, and the adjoint variable method. The optimal shape–size variations that minimize the objective functional are determined by using the H^1 gradient method for frame structures. With the proposed method, the optimal arbitrarily formed frame structures with the optimal cross sections can be obtained without any shape and size parameterization while maintaining their smoothness. The validity and practical utility of this method for tailoring the static deformation of frame structures are verified through design examples.

1. Introduction

Because of their lightweight, resource-saving, and eco-friendly features, frame structures composed of straight or curved members ranging over multiple scales have been widely utilized in many engineering applications, e.g., stadiums, bridges, automobile bodies, and micro electro mechanical system parts. Despite the fact that a frame structure has the appearance of being assembled simply by slender members, it is characterized by large interaction between beams and columns with different functions that leads to a “complexity” problem (De Biagi and Chiaia, 2013). Hence, an effectively designed frame structure can perform with excellent mechanical characteristics such as high load-carrying capacity and high natural frequency. Ohsaki et al. (2014, 2016) introduced generating linkage mechanisms of frame structures and developed a simple systematic approach to design frame structures with partially rigid joints for the highest load-carrying capacity. In recent decades, design optimization has been one of the essential techniques for achieving effective structures. Thus, a smart and/or high performance frame structure for a specific ability can be designed by employing such design optimization techniques. For controlling the stiffness or tailoring the static deformation of frame structures under external loads, we propose a non-parametric shape–size optimization method with large design variables in this study.

Numerous optimization techniques for frame structures have been reported, and design optimization for frame structures can be classified roughly into three kinds: (1) shape optimization to design the geometry of a frame structure under certain conditions, (2) size optimization to treat the cross-sectional area of each member as a design variable, and (3) topology optimization to obtain the layout or the load-path using the ground structure method. In the topology optimization of frame structures, Ohsaki (1995) developed a global algorithm based on the genetic algorithm for topology optimization of trusses. Kaminakis and Stavroulakis (2012) carried out topology optimization for compliant mechanisms to design auxetic materials based on evolutionary-hybrid algorithms. Bobby et al. (2014) proposed a performance-based topology optimization method to minimize the weight of a tall building under wind loading. Asadpoure and Valdevit (2015) carried out topology optimization of 2D periodic lattices for the minimum weight considering the compressive and the shear stiffness constraints. Based on the ground structure method, Zegard and Paulino (2015) presented a methodology for topology optimization of arbitrary 3D structures. However, topology optimization using the ground structure method is unsuitable for large-scale frame structures.

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Shape–size optimization employed in this study has the merits including increasing the design variables (compared to a single shape or size optimization) to improve the structural performances, and adopting the adjoint variable method that can design the large-scale structures efficiently. In the study of shape optimization for frame structures, Wang (2007) reported a heuristic optimization algorithm called the evolutionary shift method for minimization of the maximum bending moment of a frame structure. Tschida and Silverberg (2013) proposed a cellular growth algorithm, which is a kind of evolutionary algorithm, for shape design of truss structures. Kociecki and Adeli (2015) developed a genetic algorithm for the design optimization of free-form steel space-frame roof structures with complex geometries. Besides shape optimization using the geometry as a design variable, size optimization using the cross-sectional area as a design variable is also utilized to improve the mechanical properties of structures. In the study of size optimization for frame structures, Aydogdu and Saka (2012) proposed an ant colony optimization method for weight minimization of irregular steel frames including the elemental warping effect. Flager et al. (2014) reported a fully constrained design method for weight minimization of steel truss structures. Some other studies that dealt with size optimization for frame structures have been reported, most of which aimed for weight minimization (Cameron et al., 2000; Degertekin and Hayalioglu, 2013; Flager et al., 2014; Hasançebi and Carbas, 2014; Hasançebi and Azad, 2014; Kaveh and Mahdavi, 2014; Kaveh et al., 2015; Maheri, 2014; Maheri and Narimani, 2014). In the study of shape–size optimization for frame structures, Gil and Andreu (2001) presented a shape–size optimization method for 2D truss structures considering stress and geometrical constraints to obtain the minimum weight. Miguel and Miguel (2012) performed shape–size optimization of truss structures to minimize the weight using modern metaheuristic algorithms.

In addition to the weight minimization problem, the stiffness design problem of frame structures has been studied by scholars. The stiffness design problem can be classified into the design of stiff structure and the design of compliant structure. In the design of stiff structure, stiffness or natural frequency is commonly considered as the objective functional. The design of compliant structure is also called the homology design, which is a design problem for controlling the displacements on specific members to desired values. With respect to the design of compliant structure, Pucheta and Cardona (2010) performed shape optimization for compliant mechanism design based on precision-position and rigid-body replacement methods. Limaye et al. (2012) proposed a ground structure method for compliant mechanism design. Albanesi et al. (2013) reported a compliant mechanism method for designing medical equipment based on the inverse finite element method. Ohsaki et al. (2013) performed the optimization of retractable structures to obtain a designated deformation based on the tabu search method. However, most of these works are classified under the parametric method, in which the objective structure is parameterized by using parametric curves and surfaces (e.g., B-spline curves and Bézier surfaces), design elements, or CAD parameters, and then the optimal parameters are explored in the vector space by combining mathematical programming with sensitivity analysis to generate the optimal geometric model. The parametric method needs designers having considerable knowledge and experience, and is time-consuming. Furthermore, it is difficult to adopt the parametric method in designing large-scale structures. To overcome these shortcomings, the non-parametric method is proposed in design optimization of structures. The non-parametric method is also called parameter-free method, which uses all nodal coordinates as design variables, so it allows the most design variables and avoids the time-consuming parameterization process (Le et al., 2011).

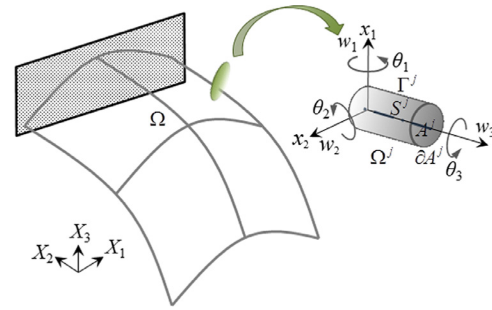

Fig. 1. A frame structure composed of Timoshenko beams.

In our previous work, we developed a non-parametric shape optimization method for frame structures (Shimoda et al., 2014), where the maximum stiffness problem was treated. In this method, we derived the shape gradient function (i.e., the sensitivity function in function space) by applying the material derivative formula to a virtual three-dimensional domain involving a cross section, which was a key technique for the success. This method consists of three main processes: (1) theoretical derivation of the shape gradient function, (2) numerical computation of the sensitivity function, and (3) determination of the optimal shape variation based on the H^1 gradient method for frame structures (Shimoda et al., 2014). In the present work, to tailor the static deformation of frame structures composed of arbitrarily curved members, we extend this method to optimize the shape and size of frame structures, wherein the geometry and the cross-sectional area of a frame structure are treated as design variables except for fixed nodes.

In the following sections, first, we formulate the governing equation of frame structures and the optimization problem for achieving desired static deformation. Second, we derive the shape and size gradient functions, and the optimality conditions using the Lagrange multiplier method, the material derivative method, and the adjoint variable method. Third, the obtained shape and size gradient functions are applied to the H^1 gradient method for frame structures, which is a gradient method with an elliptic smoother in Hilbert space considering regularization that can maintain mesh regularity and shape–size smoothness (Azegami et al., 1997). In the gradient method, determining the vector of shape variation (or the scalar of size variation) needs to solve the P. D. E. (partial differential equation) (or the Poisson's equation) with positive definiteness. Hence, the fictitious linear elastic analysis and the fictitious heat transfer analysis are performed to determine the optimal shape variation and the optimal size variation, respectively. Fourth, the obtained optimal shape and size variations are used to update the shape and the cross-sectional area simultaneously. Last, to validate the proposed optimization method, four design examples are optimized for tailoring the static deformation of frame structures ranging from nano, micro to huge scales.

2. Governing equation of frame structures

As shown in Fig. 1, curved or straight members $\{\Omega^j\}_{j=1,2,\cdots,N}$ consisting of infinitesimal straight beam elements compose a frame structure for simplicity, which is represented by a bounded domain $\Omega=\bigcup_{j=1}^{N}\Omega^j$ where N is the number of members (Hughes 1987). Considering the general versatility of the optimization system that will be explained in Section 5.3, we adopt the Timoshenko beam theory considering the first order shear strain in the present work, which can be transformed to the Euler-Bernoulli beam by neglecting the transverse shear strains. The notations(x_1, x_2, x_3) and (X_1, X_2, X_3) indicate the local coordinate system with respect to a member and the global coordinate system,