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Wind resistant size optimization of geometrically nonlinear lattice structures using a modified optimality criterion method

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ABSTRACT

Lattice structures normally have slender members and light weight, high flexibility and small damping ratios. Hence, their structural behavior may be affected by the geometric nonlinearity and they are prone to large displacements and safety issues due to wind loads. Optimal design of such nonlinear and flexible structures is difficult and complicated. This paper presents an automatic optimizing flow for the integrated wind-induced response analysis and wind-resistant optimal design of linear and non-linear lattice structures based on the modified Optimality Criterion (OC) algorithm. The method for structural dynamic analysis and wind-induced response of lattice structure is developed by combining Proper Orthogonal Decomposition (POD) with Load Dependent Ritz (LDR) vector method, together with the Harmonic Excitation Method (HEM) and Load Response Correlation (LRC) method. Meanwhile the quadratic programming method is used to evaluate the Lagrange multipliers in the modified optimality criterion method. Based on the derived design sensitivity analysis results for the nodal displacements, element stresses and nonlinear critical load factor of linear and nonlinear space frame structures in a companion paper, an automatic optimizing flow is then established by adopting the Application Programming Interface (API) of SAP2000 to integrate the wind-induced response, design sensitivity analysis and wind-resistant optimal design of space frame structural system. The proposed automatic optimizing flow is then applied to the optimized process of a lattice structure under dynamic wind loading. It is found that for the lattice structure, the geometric non-linear analysis and the constraint of nonlinear critical load factor need to be considered in their optimization, meanwhile updating on the time-history of wind loads and Equivalent Static Wind Loads (ESWL) is necessary as result of the variations in the design member size during the optimization process. It is also found that the maximum displacement constraint is the most important factor in the optimization of the lattice structure and maximum stress of structural elements are normally found to be inactive constraints during the optimization procedure. In the case that a low limit for the maximum displacement is pre-set, the nonlinear critical load factor becomes the important constraint. Optimized results from this study would be helpful to those involved in wind resistant analysis and optimization design research for such lattice structures.

1. Introduction

The lattice structures are characterized by light weight, slender members, high flexibility and small damping ratios. Because of these, the lattice structures are quite sensitive to the wind load. The wind-resistant design of lattice structures mainly relies on the experience of engineers and repeating calculations. However, the sizes of structural members and the material cost by such design methods are not necessarily optimal.

Although great advances have been made in automating the design process [1], an effective structural optimization method is not available for nonlinear structural systems under dynamic wind actions [2]. There are two major categories of approaches for structural optimization method. The first category mainly includes discrete structural optimization method. The genetic algorithm, simulated annealing, evolutionary optimization are three common-used discrete optimization

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methods. A very simple and robust algorithm for finding the (near) minimum weight of a structure composed of elements assigned from a finite list of available parameters had been presented using discrete structural optimization by removing redundant material [3]. Based on a tree graph, a hybrid continuous-discrete approach was proposed [4] for large discrete structural problem. The number of analyses in the proposed algorithm can reduce to the order of two. Wang et al. [5] proposed an improved Genetic Algorithm (GA), named Micro-GA, to search for optimal cost base isolation design of bridges subject to transient earthquake loads. A design procedure employing a Teaching–Learning Based Optimization (TLBO) technique for discrete optimization of planar steel frames was proposed for the problem of engineering design applications [6]. Other meta heuristics optimization methods, such as random search method [7], harmony search method [8] and Artificial Bee Colony (ABC) optimization method [9] have been suggested in the literature. A critical review was conducted for truss optimization with discrete design variables [10].

The other category for structural optimization approaches mainly include continuous structural optimization method which including Mathematical Programming (MP) techniques and Optimality Criterion (OC) [11]. The OC approach has gained tremendous popularity since it is particularly suitable for large-scale structures with weak dependence on the size of the structure or the number of design variables [12]. Previous research on wind-resistant optimal design of structures based on OC method mainly focuses on the tall buildings [13]. Based on constraint conditions of the top displacement and inter-story drift, Chan [14] optimized the section sizes under static equivalent wind loads by Optimality Criterion (OC) algorithm. Chan and Chui [15] developed an integrated wind tunnel load analysis and automatic least cost design optimization procedure to assist structural engineers in predicting the wind-induced response based on the High Frequency Force Balance (HFFB) technique and the serviceability design of tall steel buildings. Huang and Chan [16,17] performed some effective work in the optimal design based on reliability and wind-induced serviceability.

Compared with wind resistant optimal design for tall buildings, studies on wind-resistant optimal design of lattice structures are rarely reported in the literature. Early researchers applied sizing optimization methodology to truss structures [18]. Krishnamoorthy and Venkatesh [19] used genetic algorithms to optimize the space truss structure within an object-oriented framework. Sadollah and Bahreininejad [20] proposed a method for the nonlinear elastic analysis and optimum design of guyed masts. Sivakumar and Rajaraman [21] presented an object-oriented optimization approach for a steel lattice structure. It is noted that in the most optimization studies for space truss or lattice tower, the external loading mainly concentrates on static loads. Only a few literatures focus on the optimal design under dynamic wind loading. The constraint of the nonlinear critical load factor is not considered in their optimization process either. As the high flexibility and large slenderness, the lattice structures are prone to nonlinear instability due to intensive dynamic wind load. The restraint of nonlinear critical load factor is needed to be considered in the wind resistant optimal design of such high-rise structures. Therefore, it is much needed to develop a proper procedure for the wind-resistant optimal design for such lattice structures, which can properly consider various restraints including the nonlinear critical load factor and significantly reduce the computing time and ensure accurate results.

It is noted that most discrete optimization techniques which are based on certain search algorithms and suitable for certain types of problems, like GA and ABC etc, have undergone fast development in recent years. However, due to the large computational effort involved in the reanalysis of the structures, especially huge calculation time for dynamic analysis under dynamic wind loading, they are yet impractical for large-scale structural optimization problems. Meanwhile the OC approach has gained tremendous popularity due to its high efficiency. The OC approach is particularly suitable for large-scale structures since it only has a weak dependence on the size of the structure. The convergence of the OC approach does not depend on the starting design and weakly depends on the number of design variables [22]. Moreover, the sensitivity analysis results in OC approach provide explicit information regarding the way to modify the structure so as to ensure satisfaction of governing design conditions, as well as how much to modify the structure so as to achieve an economical design. The information of sensitivity analysis results in OC approach is also helpful for structural designers to understand the structural behavior more efficiently [22]. Although the convergence of OC approach to the optimum is not always guaranteed, the fact that the convergence of OC approach only depends on the structural behavior make it suitable for the wind resistant optimal design of lattice structures.

To meet the above demands, this paper proposes an automatic optimizing procedure for wind resistant design of lattice structures based on the modified Optimality Criterion (OC) algorithm [23]. With the Application Programming Interface (API) [24] of general finite element software SAP2000, an approach integrating the Proper Orthogonal Decomposition (POD) [25] analysis of dynamic wind loading, load dependent Ritz vibration modes analysis, Harmonic Excitation Method (HEM) [26] for wind-induced response, Load Response Correlation method (LRC) [27] for evaluation of Equivalent Static Wind Loads (ESWL) [27] is first developed. Based on the derived design sensitivity analysis methodology for nodal displacements, element stresses and nonlinear critical load factor of linear and nonlinear space frame structures in a companion paper [28], an optimal flow based on the modified Optimality Criterion (OC) algorithm is then proposed to carry out the wind-resistant optimal design of lattice structures to satisfy the constraint conditions of node displacements, element stresses, and nonlinear critical load factor under the derived ESWL. Finally, the automatic optimizing procedure is applied to a 3D practical lattice structure to illustrate the applicability and effectiveness of this optimal design method.

2. Analytical methods for wind-induced response and equivalent static wind load

As the major work in this paper concerns about the wind-resistant optimal design of lattice structures. The procedure for numerical analysis on wind-induced response and the corresponding ESWL for such structures is first briefly introduced. The dynamic equation of motion for a lattice structure under dynamic wind loading can be stated as:

$$[M]\{\ddot{y}\} + [C]\{\dot{y}\} + [K]\{y\} = \{p(t)\} \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices respectively, $\{p(t)\}$ is the vector of external wind loadings which are normally random process. The lumped mass matrix and Rayleigh damping matrix are normally adopted for the dynamic analysis of lattice structure. Random vibration analysis based on frequency domain method are normally adopted to evaluate the wind-induced response of the lattice structures. Meanwhile the dynamic wind loading vector can be further expressed with $\{p(t)\} = \{p_1(t), p_2(t),...,p_n(t)\}^{\mathrm{T}}$, where $p_i(t)$ is the time history of fluctuating wind load acting on the i-th degree of freedom. The vector of fluctuating wind loading $\{p(t)\}$ can be decomposed into a series of productions with eigenvalue and eigenmode by applying POD [25] technique as follows:

$$\{p(t)\} = [\Gamma]\{a(t)\} = \sum_{i=1}^{n} a_i(t)\{\varphi\}_i \tag{2}$$

where $a_i(t)$ is the i-th principal coordinate given as

$$a_i(t) = \{\varphi\}_i^{\mathrm{T}}\{p(t)\} \tag{3}$$

and $\{\varphi\}_i$ is the corresponding i-th principal eigenmode that can be derived from the following eigenvalue equation

$$[\Gamma]\{\varphi\}_i = \lambda_i\{\varphi\}_i \tag{4}$$