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Optimal design of steel structures considering welding cost and constructability of beam-column connections

Sang-Wook Jin [a], Hiroshi Ohmori [b], Seung-Jae Lee [a,*]

[a] School of Architectural Engineering, Korea University of Technology & Education, 1600 Chungjeol-ro Byeongcheon Cheonan, Chungnam 31252, Republic of Korea
[b] Graduate School of Environmental Studies, Nagoya University, Furo-cho Chikusa-ku, Nagoya 464-8601, Japan

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ABSTRACT

Structural design is a process of determining an optimal solution by repeating hypotheses and verification processes with numerous design variables. To acquire a more appropriate solution, a mathematical model for structural design is proposed to find the optimal solution. While many studies have proposed the minimum weight design for steel frames, a mathematical model should be considered in the manufacturing and installation process in order to solve practical issues. In this study, a multi-objective model was proposed to consider not only the cost of materials, but also processing and welding costs. A penalty function was also used to reflect the constructability and on-site applicability of the structure. A genetic algorithm was used to determine the optimal solution, and the results of the optimal design analysis were compared and analyzed based on a three-story numerical example. Analysis of the numerical example resulted in offering a smaller number of types of materials whose size and arrangement allowed for easier construction, compared to that of the optimal design that only considered weight. Furthermore, the welding cost allowed for the optimum design with improved on-site constructability was also considered.

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1. Introduction

A tendency for a structure to be deeply related to an architectural design has been increasing because the complex and advanced structural analysis can be easily and quickly carried out through the effective use of high-performance computers. With many factors interacting with each other in the design, such as consideration of environmental issues and a long-term plan for longer life of building, the role of structural designers has become more complex and also important.

The structural design, which plays an important role in the design process, generally includes the accumulation of three actions, a creative action to propose several structural systems for a variety of architectural plans and required performance, analysis action of mechanical properties and various indices for the structural system, and a determination action to select a structural system. Also included are a number of repetitive processes in which trial and error between assumptions at each stage is done toward the selection of final solutions, thanks to the enormous effort of engineers.

On the other hand, most steel structures are composed of standardized members produced at a factory. By using computers to do the repetitive trial and error in the structural design, the research for proposal of structural design solution becomes popular and has been carried out intensively in recent years. The aim is to find out the limit value of an objective function constructed based on the weight and stiffness of the members. However, it is not only difficult to mathematically treat those discrete variables but also inevitable to accept the enormously large calculation load as the number of design variables increases.

Since a new technique of genetic algorithm based on natural genetics which can handle discrete variables with ease has emerged [1] and spread [2], a number of papers have been published on structural optimization of space structures, trusses and steel structures using this method in the literature [3,4,5,6,7,8]. Also, there is little research focusing on the connections between beams and columns not only considering their structural performance as semi-rigid instead of rigid but also reducing the total cost of a structure in the steel frame structure field [9,10,11,12,13]. Moreover, in multi-objective optimization, genetic algorithms have been used as tools to solve problems [14], and separative objective functions including structure conditions, safety and cumulative life cycle maintenance cost, have been treated over the last decade [15,16].

Although a number of studies show that their own proposed methods are relevant in order to obtain the optimal solution in each objective function, and the methods make best use of the characteristics of optimization techniques and high-performance computers, the research is not sufficiently focused on practical structural design and the methods are not available for practical use directly on site.

* Corresponding author.
E-mail address: leeseung@koreatech.ac.kr (S.-J. Lee).

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In this paper, a structural design support scheme is proposed to concentrate on the essential design processes by saving time, while leaving a number of repetitive processes in trial and error between assumptions at each stage to a computer, for the solution selection with the use of single and multi-objective genetic algorithm [17]. In addition, through various applications to steel frame structure models such as rigid-frame, X-type braced frame and K-type braced frame, it has been clearly shown that one can obtain other alternative design solutions at lower cost and proper drift angle in the proposed structural system [17,18].

The proposed design support scheme is here extended and its validity confirmed considering not only the manufacturing cost in the process for making steel members, the welding cost for connecting beams and columns as well as steel cost which is considered until now in the scheme, but also the penalty function which is given to the optimization problem in order to ensure the constructability of the beam-column connection for a more practical use of the design support scheme.

2. Optimization method

2.1. Structural design support scheme

A genetic algorithm is an optimization method based mainly on the concept of natural selection and evolutionary process, and it provides an effective method for the resolution of a nonlinear or combination problem. This algorithm repeats optimization operations, such as reproduction, crossover and mutation. It can search for a global optimal solution, and find better solutions in a short time, when the optimization problem treats especially discrete variables.

As shown in Fig. 1, the authors proposed a structural design support scheme that produces optimal structure solutions in the cost minimization of a single objective as well as in both of the cost minimization and safety maximization as a multi-objective optimization. Optimization calculations are carried out with a distributed genetic algorithm (DGA) as proposed by Tanese [19] for single objective optimization, and a strength pareto evolutionary algorithm 2 (SPEA2) is proposed by Zitzler et al. [20] for multi-objective optimization. In this paper, the cost minimization will be first carried out for the proposed structural design support scheme.

2.2. Optimization problem formulation

The optimization problem defined as a cost minimization problem for steel structures satisfying not only the Japanese code of allowable stress design but also the given constraint conditions can be expressed as follows:

$$\begin{aligned} &\text{minimize} \quad C(\mathbf{x}), \\ &\text{subject to} \quad g_i \le 0, \end{aligned} \qquad (1)$$

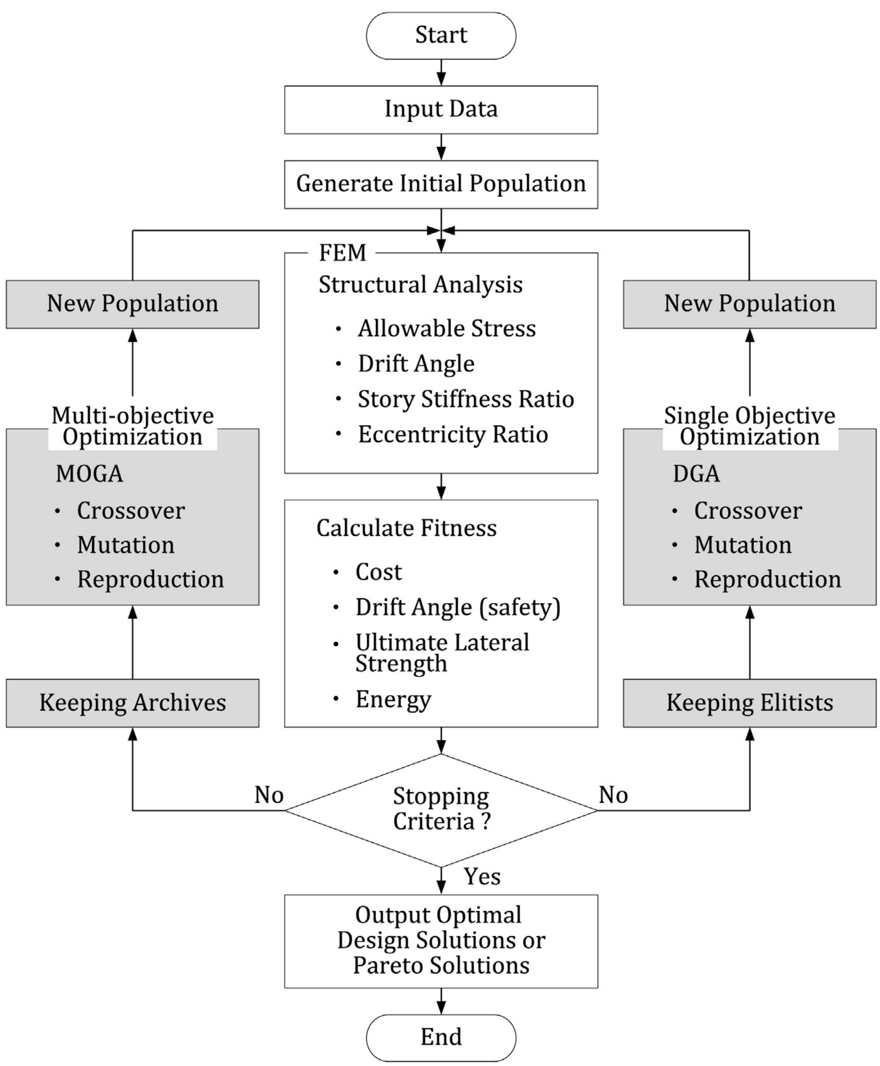

Fig. 1. Flowchart for structural design optimization.

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