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Structural Optimization of Tall Buildings using NSGA-II and Resizing Techniques

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Abstract

The problems of lateral displacement control and usability of a structure are treated as the main part in high-rise buildings. Lateral displacement and usability control can be effectively managed through stiffness design. In this paper the non-dominated sorted genetic algorithm, NSGA-II, which may be used to satisfy many objective functions is applied to the structural design of high-rise buildings. However, the rate of convergence is slower because the number of structural analysis and the amount of calculation increases. The resizing technique is efficient for displacement control because of the redistribution within the structure. An important objective is to improve the convergence speed by using the optimal design technique because the algorithm finds an optimal solution without sensitivity analysis and complex calculations.

Keywords: NSGA-II, resizing technique, structural optimization, tall building.

1 Introduction

In case of high-rise buildings, the control part related to such factors as relative storey displacement and vibration is important. High-rise buildings will be structurally designed through the repeated process of structural analysis to select the sections that satisfy strength and stiffness requirements. In the case of strength design, the performance of the cross-sections can be obtained by repeated structural design to ensure the strength of the members. Therefore, it is possible to control excessive local damage and deflection, vibration. But, structural design can be controlled more effectively through stiffness design to satisfy relative storey displacement, deflection for usability and satisfaction of building users within prescribed limits. Thus, in this paper optimal design through stiffness design of high-rise building will be undertaken.

Existing optimal design techniques include various methods such as OC (Optimality Criteria), the GA (Genetic Algorithms), the NSGA (Non dominated sorted genetic algorithm) etc. Goldberg [1], Rajeevand and Krishnamoorthy[2], and Chan [3] have studied optimal design techniques. Optimality criteria means the method to converge to a desired solution iteratively after setting the criteria that defines the optimal solution. Although OC is effective, it has the disadvantage that there is no guarantee that a global optimal solution will be obtained all the time [4]. GAs find numerical optimal solutions by expressing structural problems mathematically, and the technique pursues various solutions through mating and mutation. The GA has the advantage of finding a range of minimum and optimal solutions by evaluating the fitness of various solutions. But, it has the disadvantage of taking more time to obtain the optimal solution because the amount of mathematical calculation becomes greater as the number of design variables increases.

The NSGA is a non-dominated sorted genetic algorithm which is widely used in the field of multi-objective optimization. However issues such as the complexity of operation, the lack of sorting conditions and the difficulty of determining the shared variable values have been raised. The NSGA-II algorithm that compensates for these shortcomings has been proposed. Many engineering problems require the solution to satisfy many objective functions rather than the solution to satisfy a single objective.. Though, it is almost impossible to find only a single optimal solution to satisfy all objective functions [5]. Therefore, various optimal solutions may be obtained through optimal design techniques for the multiobjective design such as NSGA and NSGA-II. This study uses NSGA-II..

In this paper optimal design for the multiobjective stiffness design of high-rise building is undertaken. The structural analysis and calculation amount is significantly greater and the rate of convergence is slower in using the optimal design technique because the number of the members and design variables becomes greater in high-rise building [6]. Therefore, the major problem is to reduce the number of structural analyses and the amount of calculation. This study uses a resizing technique within the NSGA-II. The resizing technique controls displacement by using a unit load technique based on energy theory, to redistribute the size of the members according to their contribution to the displacement. This method can control the quantity by selecting a suitable cross-sectional area for the members to control displacement because of balancing the performance of the cross-section of each member according to their contribution to the displacement [7]. The rate of convergence to achieve an optimal solution should be improved as well as the displacement control of the high-rise building using the resizing technique within optimal design method. A major object is to reduce the number of structural analyses and to reduce the computational time.

2 Formulation

The structural problem was expressed by the mathematic problem to apply the optimum technique. The objective functions consist of minimization of the sum of quantity by each member and maximum displacement of the top-story nodal point.

Displacement was considered as the restrictive conditions. The restrictive conditions and the objective functions are as follow: The sectional area of W section in AISC-Data base was used as the design variables to consist of the objective function.

2.1 The objective function

$$Minimize\ f_1(x) = \sum_{i=1}^{M} \rho^i A^i L^i \quad (1)$$

$$Minimize\ f_2(\mathrm{x}) = D_{max} \quad (2)$$

The purpose of the study is to optimize the two object functions. The sum of the total volume of the building material was selected as the first objective function. And the maximum nodal displacement displacement of the top-storey of the buildings was selected as the second objective function. Therefore, the composition of algorithm and the study were arranged focusing on the optimization and minimization of the two objective functions. The equation (1) expresses the formulation of the objective functions of the material volume. Here ρ, A, and L are density of each member, the sectional area of member, and the length of member. $f_1(x)$ indicates the total volume of the member and M the number of members of the applicable individuals. Here $f_2(\mathrm{x})$, in Equation (2), indicates the maximum displacement of the top of the model. The objective function consists of $f_1(x)$ and $f_2(\mathrm{x})$.

2.2 The constraint conditions

$$\frac{D^i_{actual}}{D^i_{allow}} \leq 1.0 \qquad i = 1, \ldots, N \quad (3)$$

Here N is the number of the top nodal point. The displacement constraints are 2N in number which is double the number of the nodal point and is required to limit each displacement in both the x axis and y axis of the top–storey nodal point. Also, if the main purpose will be lateral displacement control, displacement to N which is the same as the number of nodal points can be reviewed considering the displacement of x axis only. The restrictive function is the restrictive conditions concerning the displacement and Equation (3) is the restrictive function about the displacement. $\mathrm{D}^{\mathrm{i}}_{\mathrm{actual}}$ and $\mathrm{D}^{\mathrm{i}}_{\mathrm{allow}}$ of Equation (3) is the actual displacement and permissible displacement of each nodal point. The restrictive conditions (constraints) that the ratio of permissible displacement to actual displacement of the top-storey nodal point in Equation (3) should be less than 1 were set. [2][3][4].

The restrictive conditions is the step which is done before determining the ranking of the non-dominated sets right after the resizing technique was done in the flow chart of the algorithm shown in Fig 1. The study composed the restrictive functions as mentioned above. If the restrictive conditions are established using the result values which analyzed the structure of individuals that the individuals of parents and children right after resizing and the resizing technique were applied. The resulting values were analyzed and the structure saved the designs which were done by generating individuals. And the resulting values which analyzed the structure saved in the previous step were used to judge the establishment of the restrictive or constraint conditions. The designs were divided into groups. The groups were the group which satisfies the restrictive conditions and the group which does not satisfy them.

3 The resizing technique

The resizing technique was applied in the work in this paper to raise the structural safety and convergence speed of the NSGA-II. The resizing technique is the one which reduces the displacement of buildings by calculating the displacement participation factors of each member about the top-storey displacement and dividing these into each ones using member forces only which is the result to analyze the structure based on the energy theory. If the unit dummy force method based on the energy theory is used, the displacement participation factors for each member can be adjusted. The following equation is used to calculate the displacement participation factors and the adjusting factors. They are expressed in Equations (4) and (11) as the structural quantity is not changed before and after resizing.

$$\delta = \sum_{i=1}^{M} \left\{ \int_0^l \frac{N_i^L N_i^U}{E_i A_i} dx + \int_0^l \frac{M_i^L M_i^U}{E_i I_i} dx + a \int_0^l \frac{V_i^L V_i^U}{G_i A_i} dx + \int_0^l \frac{T_i^L T_i^U}{G_i I_\pi} dx \right\} \tag{4}$$

$$\text{Minimize } \delta = \sum_{i=1}^{M} \frac{\delta_i}{\beta_i} \tag{5}$$

$$\text{Subject to } \sum_{i=1}^{M} \rho A_i L_i = \sum_{i=1}^{M} \beta_i \rho A_i L_i \tag{6}$$

The constrained optimization problem in Equation (5) and (6) can be transformed into an unconstrained optimization problem by introducing the Lagrange multiplier:

$$\text{Minimize } \delta_t = \sum_{i=1}^{M} \frac{\delta_i}{\beta_i} + \lambda_i \rho A_i L_i = 0 \qquad i = 1, m \tag{7}$$

Where δ_t and λ are the transformed objective function and the Lagrange multiplier, respectively. Taking derivatives of the transformed objective function with respect to β_i and λ and setting them to zero, the group modification factors can be given in Equation (11).

$$\frac{\vartheta \delta_t}{\vartheta \lambda_L} = \sum_{i=1}^{M} \beta_i \rho A_i L_i - \sum_{i=1}^{M} \rho A_i L_i = 0 \tag{8}$$

$$\beta_i = \sqrt{\frac{\delta_i}{\rho A_i L_i} \frac{1}{\sqrt{\lambda_L}}} \qquad i = 1, m \tag{9}$$

where

$$\frac{1}{\sqrt{\lambda_L}} = \frac{\sum_{i=1}^{M} \rho A_i L_i}{\sum_{i=1}^{M} \sqrt{\delta_i \rho A_i L_i}} \tag{10}$$

$$\beta_i = \alpha \sqrt{\frac{\delta_i}{\rho A_i L_i} \frac{\sum_{i=1}^{M} \rho A_i L_i}{\sum_{i=1}^{M} \sqrt{\delta_i \rho A_i L_i}}} \tag{11}$$

Equation (4) is the displacement participation factor of the member that must be controlled. The N, M, V, and T each indicate the axial force, moment, shearing stress, and torsion and L and U the actual load and unit load. Then A, I, and I_{π} each indicate the sectional area, second moment of area, and polar moment of inertia of area of each member. Next E, G, and a each indicate modulus of elasticity, modulus of transverse elasticity, and shape factor of each member. Finally K indicates the total number of members. [5][6]

Equation (11) is the one which calculates the adjusting factors of the variables. The variables is resized without any change of the total volume of the building by multiplying the adjusting factor of the variable obtained from Equation (11) by each current member. Therefore, each member gets to have sectional performance which was modified according to each displacement participation factor and works effectively to adjust the displacement of the top-storey nodal points. Also, the overdesign or under design can be prevented by adjusting the sectional performance using the structural analysis.

The study examines the method of applying the resizing technique by dividing the cases into three cases where case 1 uses the resizing technique in all the generations, case 2 uses it in five generations, and case 3 uses it in ten generations.

4 Composition of NSGA-II Algorithm using the resizing technique

This study tries to improve convergence speed to obtain optimum solution using the resizing technique in the NSGA-II which is the existing multi-objective optimum design technique. The resizing technique obtains the displacement participation factors through the structural analysis of parents and children populations after generating them. The follow step is the flow chart of the composition algorithm of the NSGA-II in this study. The flow of the algorithm is as follow:

Step 1) Generate initial population

Categorize the members of the application models. An individual composes a determinant as it is categorized. And compose the population which consists of individuals of N.

Step 2) Tournament Select

Generate children population of N in the initially generated excellent individuals with the tournament.

Step 3) Crossover and Mutation

Obtain diversity of optimum solution

Step 4) Application of the resizing technique

Resize each individual of parents and children populations

Step 5) Categorize population according to the restrictive conditions

Determine the ranking by dividing populations into the group which satisfies the restrictive conditions and the group which doesn't do them after the structural analysis of the generated populations using the resizing technique.

Step 6) Generate new population

Divide the groups into each one according to the number of the initially generated populations from the top groups by combining the group which satisfies the restrictive conditions with the group which doesn't do them.

Step 7) Generate the optimal population by repeating the above 2 to 6 steps.

5 Application of the example

The algorithm was applied to a 40 storey steel frame building by selecting it as the example model to judge efficiency and adaptability of the algorithm which composed in this study. The height of the example model is 146.4m. In the case of the example model, the design variables of the beams and columns were designated. For a bay of width 7.62m and a storey height of 3.66m, the planar framework has a height-to-width aspect ratio of 6.4.

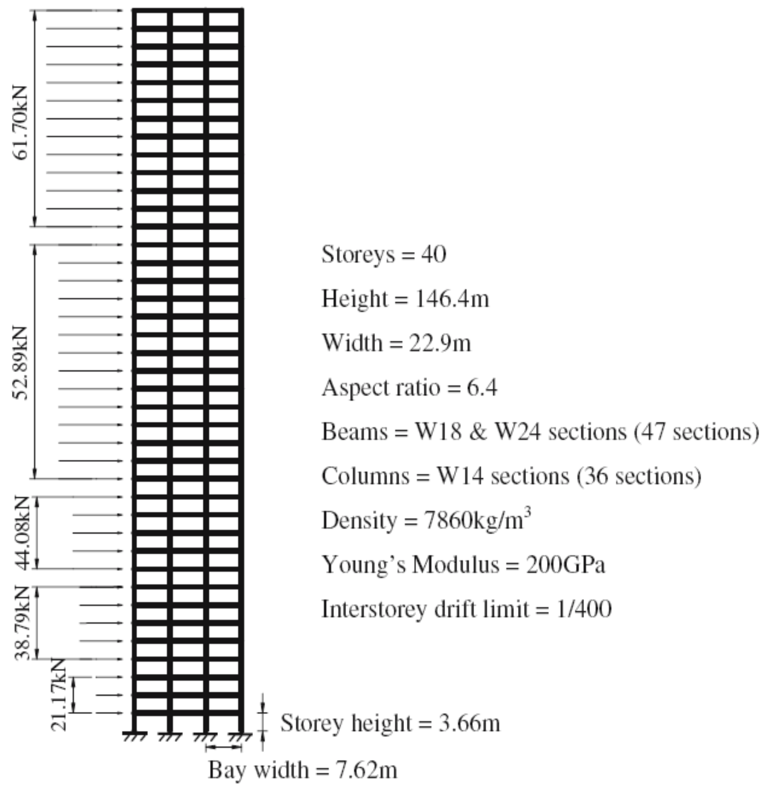


Figure. 1. A 40-storey three-bay rigid building frame

With such a high aspect ratio, the design of the frame should be governed by the lateral drift criteria rather than the element strength requirements [4]. All beam-to-column connections were assumed to be rigidly connected. Floor slabs were assumed to form a rigid floor diaphragm on every floor. A fixed support condition was provided at the base of each column at the ground level [4]. In the case of beams, 47 cross sections of W18 & W24 were used and in the case of columns, 34 cross sections of W14 were set as the design variables. The model to apply NSGA-II algorithm using the resizing technique is shown in Figure.1. The displacement participation factors were reviewed in all the members and all of them were resized. Load and material properties of the model to apply the algorithm is shown in Figure. 1. For the weight factor of the resizing technique, the quantity was not changed before and after resizing by setting it as 1.0.

Figure 2. Shows the member groups of Figure. 1. Each group consists of every two floors. Table 1 is the result adopting the NSGA-II and using resizing technique. The case 1, (b), is the structural analysis of the NSGA-II using the resizing technique for all generations. The case 2,(c) and the case 3, (d) are structural analysis of the NSGA-II using the resizing technique for each 5 generations and each 10 generations. The structural analysis and the time required and the number of structural analysis of Table 1 are shown in Table 2. When NSGA-II is adopted for the exercise model, the result of sixty generations then in case 2 a similar result for (a) NSGA-II is obtained. The results of (a) NSGA-II is similar to the result of when case 2 reaches to the 63th generation and case 3 reaches to the 70th generation. After that the NSGA-II uses the resizing technique, case 1,2,3 reach the 60th generation, 63th generation and 70th generation do not very differ from the result of (a)NSGA-II. However, the analysis time is sharply reduced by 50min in the case 1, 17 min 15 sec in case 2, and 15 min 40 sec in case 3. In addition, this optimization is highly effective in terms of the number of analyses, 1200 times in case 1, 5600 times in case 2, and 4800 times in case 3. Especially, it can be seen that the number of structural analysis is reduced by approximately two-thirds of the traditional NSAG-II in cases 2 and 3

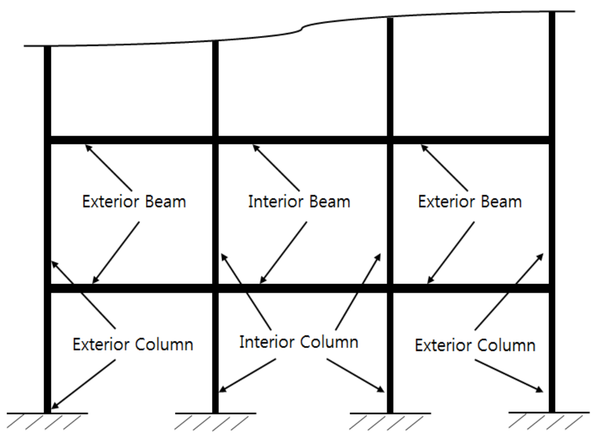
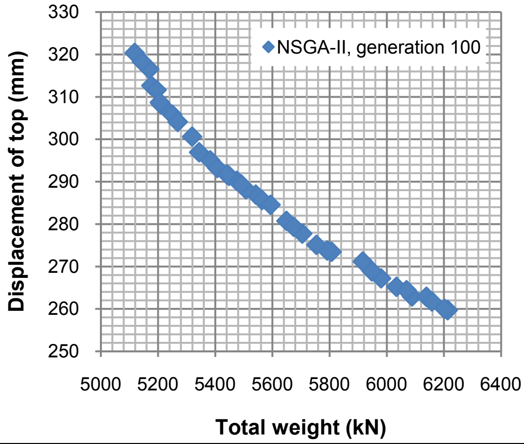
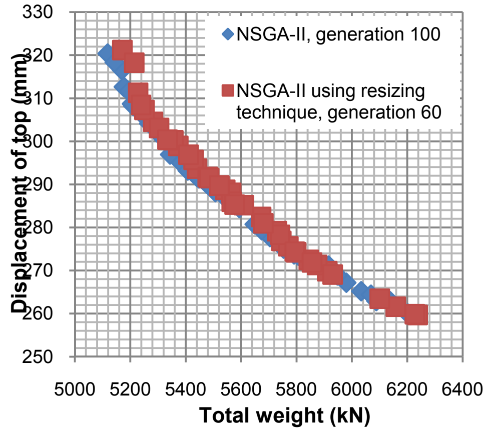


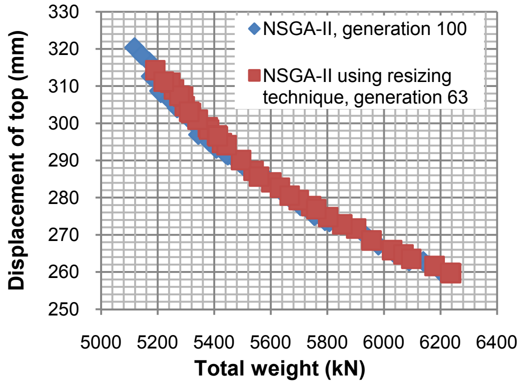
Figure 2. Grouping of example model



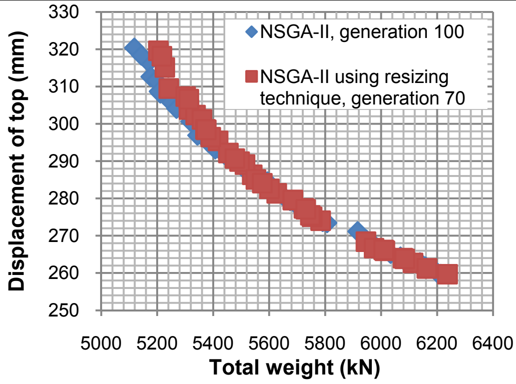
(a) NSGA-II



(b) Case1 : NSGA-II using resizing technique (all generation)



(c) Case2 : NSGA-II using resizing technique (Every 5 generation)



(d) Case3 : NSGA-II using resizing technique (Every 10 generation)

Table 1 comparison of NSGA-II and NSGA-II using resizing technique results

Terms / NSGA-II	Computational time	The time required	The number of structural analysis (until generation 60,63,70)
(a)NSGA-II	17 min	-	4000
(b)NSGA-II using resizing technique All generation	80 min 30 sec	50 minutes (until 60th generation)	12000 (7200)
(c)NSGA-II using resizing technique Every 5 generation	28 min 40 sec	17 minutes 15 sec (until 63th generation)	5600 (2580)
(d)NSGA-II using resizing technique Every 10 generation	22 min 10 sec	15 minutes 40 sec (until 70th generation)	4800 (2806)

Table 2 Comparison of NSGA-II and NSGA-II using resizing technique results

6 Conclusion

In this paper, a resizing technique is adapted for the NSGA-II to improve convergence speed. The results show that the convergence speed and structural analysis number are reduced by approximately two-thirds. As a result, the time required of case 3 is less than case 2, but the number of structural analyses of case 2 is less than case 3.

Acknowledgement

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