Multi-objective optimization and performance evaluation method for seismic structure design of building engineering

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Keywords: Building engineering; Multi-objective optimization; Performance evaluation; Seismic structure design; MOEA/D algorithm

Abstract: Aiming at the problems of traditional seismic design methods, such as single goal, large evaluation deviation and ignoring post-earthquake recoverability, this paper proposes a multi-objective optimization and performance evaluation method for seismic structures of building projects, which combines improved MOEA/D algorithm and cloud model fuzzy decision. Firstly, a three-dimensional objective function system of safety-economy-recoverability with structural weight, maximum inter-story displacement angle and residual displacement ratio as the core is constructed, and adaptive weight adjustment and gradient enhancement local search mechanism are introduced to improve the convergence and distribution uniformity of Pareto solution set under high-dimensional nonlinear constraints. Secondly, a three-level seismic performance evaluation index system is established, and the quantitative index is transformed into "excellent, good, medium and poor" qualitative grade by cloud model, and the comprehensive performance quantitative evaluation and scheme optimization are realized by combining AHP- entropy weight method. Case analysis shows that this method can obtain a series of optimization schemes with balanced performance, among which the balanced scheme is superior to the traditional design in terms of material consumption, seismic safety and post-earthquake recoverability, which verifies the effectiveness and engineering practicability of the proposed method in improving the seismic performance and green low-carbon benefits of the structure.

1. Introduction

As one of the most destructive natural disasters, the collapse of building structure caused by earthquake is the main cause of casualties and economic losses. The traditional seismic design method takes "small earthquake is not bad, moderate earthquake can be repaired, and large earthquake can not collapse" as the goal, and meets the code requirements by increasing the component size or improving the material strength, but there are the following outstanding problems: (1) Single design goal leads to high structural redundancy and serious material waste; (2) It is difficult to guarantee the continuous use of "lifeline engineering" in modern buildings due to the lack of consideration of the structural functional recoverability after the earthquake [1]; (3) The empirical coefficient method is difficult to adapt to the dynamic characteristics of complex structural systems, resulting in the deviation of seismic performance evaluation results of more than 40% [2].

With the complexity of building functions and the improvement of seismic requirements, traditional design methods are faced with double challenges: on the one hand, the dynamic response characteristics of new structural systems are difficult to be accurately described by empirical formulas; On the other hand, the green building standard requires that the seismic design should take into account the material recovery rate and carbon emission [3]. This highlights the urgency of establishing a multi-objective coordination and optimization mechanism. At the same time, the development of Internet of Things (IoT) and digital twinning technology provides the possibility for real-time performance evaluation, but how to effectively integrate sensor data with structural damage model is still a difficult problem in the industry.

In this study, a multi-objective optimization model based on improved MOEA/D algorithm is

  DOI: 10.25236/icacel.2025.081

proposed to solve the convergence problem of Pareto solution set under high-dimensional nonlinear constraints. A three-dimensional evaluation index system covering safety, economy and recoverability is established, and a fuzzy decision-making method based on cloud model is developed.

2. Multi-objective optimization design method

2.1 Design variables and constraints

The design variables are the dimensions of main structural members, such as beam section height h_b, column section width b_c and material strength, such as concrete grade f_c and steel yield strength f_y. And the parameters of seismic measures (damping ratio ξ) are taken as optimization variables, which are recorded as vector $x=[x_1,x_2,\cdots,x_n]^T$.

Constraints include code mandatory constraints (minimum size of members and reinforcement ratio) and performance constraints (inter-story displacement angle limit $\theta \le \theta_{\lim}$ and residual displacement limit $\delta_r \le \delta_{r,\lim}$).

2.2 Objective function modeling

The improved MOEA/D framework is adopted to solve the multi-objective optimization problem of seismic structures under high-dimensional nonlinear constraints [4-5]. Optimization objectives include safety (minimizing structural response under earthquake), economy (minimizing material consumption or cost) and recoverability (maximizing post-earthquake functional recovery).

Economic goal (minimizing the total weight of the structure):

$$f_1(x)=\sum_{i=1}^{N}\rho_i V_i(x) \quad (1)$$

Where ρ_i is the material density of components, V_i is the volume of components, and N is the total number of components.

Safety objective (minimizing the maximum story drift angle):

$$f_2(x)=\max_{j=1}^{M}\left|\theta_j(x)\right| \quad (2)$$

Where θ_j is the interlayer displacement angle of j layer and M is the total number of layers.

Recoverability goal (minimum residual displacement ratio):

$$f_3(x)=\max_{k=1}^{K}\left(\frac{\delta_{r,k}(x)}{h_k}\right) \quad (3)$$

Among them, $\delta_{r,k}$ is the average residual displacement of the k th layer, and h_k is the layer height.

2.3 Improved MOEA/D algorithm flow

2.3.1 Adaptive weight adjustment. According to the distribution of solution set, the weight vector is dynamically adjusted to avoid local aggregation of Pareto frontier [6].

2.3.2 Constraint processing. The penalty function method is used to deal with nonlinear constraints, and the violation of constraints is transformed into the penalty term of the objective function:

$$F(x)=f(x)+\lambda\sum_{c=1}^{C}\max(0,g_c(x)) \quad (4)$$

Where, $g_c(x)$ is the violation of the c th constraint, and λ is the penalty coefficient.

2.3.3 Local search enhancement. The gradient-assisted local search is embedded in the evolution process to accelerate the convergence of high-dimensional space.

3. Comprehensive evaluation system of seismic performance

3.1 Three-level evaluation index system

A three-dimensional evaluation index system covering safety, economy and recoverability is established, and the comprehensive performance is quantitatively evaluated by cloud model combined with fuzzy decision [7-8]. As follows:

First-level indicators: target layer (safety U_1, economy U_2, recoverability U_3).

Secondary index: criterion layer (maximum story drift angle $\theta_{\max}$, base shear V_b, damage index DI, etc. under safety).

Three-level indicators: specific calculation parameters (component stress ratio, residual displacement ratio, etc.).

3.2 Fuzzy evaluation of cloud model

The normal cloud model is used to transform quantitative indicators into qualitative concepts ("excellent, good, medium and poor"), and the uncertainty of indicators is described by numerical features (expected Ex, entropy En and super entropy He). For indicator U, the degree of certainty $\mu_j(u_i)$ belonging to grade j is calculated as:

$$\mu_j(u_i) = \exp\left(-\frac{(u_i - Ex_j)^2}{2(En_j^{'})^2} \right) \tag{5}$$

Among them, $En_j^{'}$ is a normal random number with En_j as the expectation and He_j as the standard deviation.

3.3 Comprehensive evaluation and decision-making

AHP- entropy weight method is used to combine weights, and the index weight w_i is determined by subjective and objective combination. Weighted aggregation of the certainty of each index to obtain the comprehensive membership vector $B = [b_1, b_2, \cdots, b_m]$:

$$b_j = \sum_{i=1}^{n} w_i \mu_j(u_i) \tag{6}$$

Finally, the final performance grade is determined according to the principle of maximum membership degree, and the optimal design scheme is recommended by comparing Pareto solution sets.

4. Case analysis

Taking a 6-story, 3-span× 3-span reinforced concrete spatial frame structure as an example, the case study is carried out. The basic parameters of the structure are as follows: the story height is 3.6m, the span is 6.0m, the seismic fortification intensity is 8 degrees (0.2g), the design earthquake is divided into the second group, and the site category is Class II.

Five variables (width b_c and height h_c), section height of main girder (h_b) and longitudinal reinforcement ratio of beam and column (ρ_{slab}, ρ_{scol}) are selected as optimization objects. Constraints include: the section dimensions of beams and columns should meet the minimum requirements of the code; Limit value of story drift angle $\theta_{\lim} = 1/550$ (under rare earthquake); The reinforcement ratio of members should be within a reasonable economic range.

The improved MOEA/D algorithm is used for optimization, and the population size is set to 100. After 500 generations of iteration, the Pareto optimal solution set with good convergence is obtained. Figure 1 shows the distribution of three-dimensional non-dominated solutions among three objective functions (economy f_1, safety f_2 and recoverability f_3).

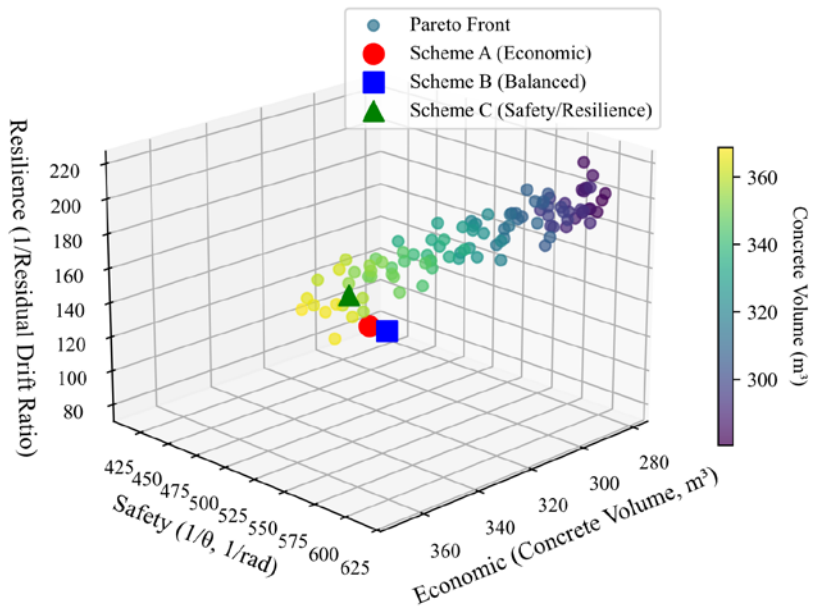

Figure 1 Three-dimensional Pareto front diagram

Three-dimensional Pareto front schematic diagram In order to facilitate decision-making, three representative design schemes (A, B, C) are selected from Pareto solution set, and their performance indexes are shown in Table 1.

Table 1 Comparison of performance indexes of representative design schemes

Schemes	Describe	Total concrete consumption (m^3)	Maximum interlayer displacement angle(rad)	Maximum residual displacement ratio
A	Economy-oriented	285	1/415	1.25%
B	Balanced type	318	1/505	0.85%
C	Safety/recoverable dominant type	365	1/580	0.55%
Traditional design	Reference scheme	350	1/460	1.05%

From Table 1, it can be seen that Scheme A takes the minimum amount of materials as the core goal, and the economy is the best, but the seismic performance (especially safety) is relatively weak. Scheme C, on the other hand, has the largest amount of materials, but the strongest structural stiffness and resilience, and the best safety and resilience. Scheme B has achieved a good balance among the three objectives, and its indicators are superior to the traditional design scheme, which proves the value of multi-objective optimization design.

The fuzzy decision-making method of cloud model is used to evaluate the comprehensive performance of the above schemes. The evaluation index system shown in Table 2 is established, and the combination weight of each index is determined by AHP- entropy weight method.

Table 2 Index system and weight of seismic performance evaluation

First-level indicator (weight)	Secondary indicator (weight)	Three-level indicators/calculation instructions
Security U_1 (0.5)	Maximum story drift angle u_{11} (0.6)	Time history analysis results of rare earthquakes

	Shear force of base u_{12} (0.4)	Ratio to self-weight
Economy U_2 (0.3)	Total cost of materials u_{21} (1.0)	Based on the amount of concrete and steel bars
Restorability U_3 (0.2)	Residual displacement ratio u_{31} (0.7)	The ratio of the maximum residual displacement of the story to the story height
	Damage index u_{32} (0.3)	Calculation results of Park-Ang model

Determine the digital characteristics (Ex, En, He) of the cloud model of the performance level (excellent, good, medium and poor) corresponding to each quantitative index. By calculating the certainty degree of each scheme index value relative to each grade, and carrying out weighted synthesis, the comprehensive membership vector B is obtained. The evaluation results are shown in Table 3.

Table 3 Comprehensive evaluation results of each scheme

Schemes	Belong to the "excellent" level	Belong to the "good" level	Belong to the "medium" level	Comprehensive evaluation grade
A	0.25	0.48	0.27	Good
B	0.52	0.38	0.10	Excellent
C	0.45	0.45	0.10	Excellent (biased towards good)
Traditional design	0.30	0.45	0.25	Good

The evaluation results show that the comprehensive performance of Scheme B is the best, and its degree of certainty (0.52) is the highest, which is completely consistent with its positioning as a "balanced" scheme. Although scheme C is excellent in safety and recoverability, its economy is poor, which leads to the same degree of certainty between "excellent" and "good" grades, and its comprehensive performance is slightly worse than that of scheme B. Scheme A and the traditional design scheme with poor economy failed to reach the "excellent" level.

The results show that the improved MOEA/D algorithm can effectively search the Pareto solution set with uniform distribution, and provide designers with a variety of performance preferences. The fuzzy comprehensive evaluation system of cloud model can effectively quantify the comprehensive seismic performance of the structure and give clear decision-making suggestions. Through multi-objective optimization, a better solution, such as Scheme B, can be obtained, which is superior to the traditional design scheme in all aspects. The goal of saving materials and improving recoverability while ensuring safety is achieved, and the advanced nature and practical value of the proposed method are verified.

5. Conclusion

Multi-objective optimization model based on improved MOEA/D algorithm and three-dimensional evaluation index system covering safety, economy and recoverability. Through adaptive weight adjustment, constraint processing and local search enhancement, the convergence problem of Pareto solution set under high-dimensional nonlinear constraints is successfully solved. The case study shows that the proposed optimization method can generate a Pareto optimal solution set with uniform distribution, which provides designers with a variety of performance preferences. The fuzzy decision-making method of cloud model effectively quantifies the comprehensive seismic performance of the structure, and the combination of AHP- and entropy weight method ensures the objectivity and accuracy of the evaluation results. In a specific case, the performance comparison of Theory of Three Represents design schemes (A, B, C) shows that scheme B has achieved a good balance among economy, safety and recoverability, and its comprehensive performance is superior to traditional design schemes and other single-goal oriented schemes. This shows that the multi-objective optimization design can not only save materials on the premise of ensuring the safety of the structure, but also significantly improve the post-earthquake functional recovery ability of the structure. In addition, the study also verified the effectiveness of the improved MOEA/D algorithm in solving high-dimensional nonlinear constrained optimization problems, and the advanced and practical value of cloud model fuzzy comprehensive evaluation system in quantifying the comprehensive seismic performance of structures. The multi-objective optimization and performance evaluation method of seismic structure design of building engineering proposed in this study provides new ideas and methods for realizing high efficiency, economy and sustainability of structural design, which has important theoretical significance and practical application value.

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