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Structural Performance Modeling and Multi-Objective Optimization Design of Huizhou Architecture under BIM Platform

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Abstract Aiming at the structural performance and multi-objective optimization problems of modern Huizhou style buildings, this paper proposes a set of overall structural performance modeling and intelligent optimization design methods based on BIM platform. Firstly, the refined BIM model is constructed by Revit, and combined with Navisworks collision detection to solve the design conflicts and improve the design accuracy. Relying on the BIM model to carry out structural performance analysis, the project duration was shortened by 15% after optimization. Secondly, a mathematical model was established with the maximum inter-story displacement angle and the equivalent gross weight of the structure as the dual objectives, and the national norms (shear-to-weight ratio, stiffness-to-weight ratio, axial compression ratio) as the constraints, and the design variables covered the stiffness and position of the extension arm/ring truss, and the column cross-section dimensions. In view of the complexity of the model, the GA-RBF coupling algorithm (dynamic synergy between NSGA-II and RBF neural network) is innovatively adopted, and the RBF proxy model is utilized to replace the time-consuming simulation. Taking the Anhui Hui building as a case study, under the excitation of 270° transverse wind direction, the GA-RBF algorithm reduces the displacement of the top floor from [-0.15, 0.15] m to [-0.06, 0.06] m (vibration damping of 60-70%), and the acceleration from [-0.04, 0.04] m/s² to [-0.01, 0.01] m/s² (vibration damping of >25%), which is significantly better than the traditional FM formulation. Based on multi-objective hybrid swarm optimization, the decentralized control strategy reduces the total mean square error (J_2) of the control force by more than 80% compared to the centralized control, which has J_2 = 1096.14 kN, and the actuator configuration is flexible and the parameters are adaptive (α-value spanning 11.923-13.482). The method of this paper deeply integrates BIM accurate modeling, multi-objective optimization theory and intelligent algorithm, which can take into account the structural safety, economy and construction efficiency, and provide technical support for the modernization of Huizhou-style buildings.

Index Terms BIM platform; Anhui South Hui architecture; GA-RBF; NSGA-II; multi-objective optimization

I. Introduction

The historical Hui architecture of South Anhui Province is an important part of national culture. As the world cultural heritage of mankind, its unique architectural form and colorful design ideas have built a rich and fulfilling material world for our descendants, and also shaped a spiritual world with the most oriental humanistic environment characteristics, which is unique in the world architectural art and culture circle [1]-[4]. Architectural art is the product of human material creation and spiritual creation, it is closely connected with people's lives, it is completely integrated into all people's lives [5], [6]. As a result, the Huizhou architectural complex in South Anhui Province is more capable of realizing its unique aesthetics as other traditional culture and art [7]. At the same time, the artistic beauty of the Huizhou architectural form, in the aesthetic experience of both “artistic factors” and “natural factors”, which enriches its aesthetic connotation [8], [9]. However, with the change of time and the increasing number of new buildings, how to inherit and develop the essence of the traditional architecture in southern Anhui has become a matter of concern for many people.

In the field of structural analysis of Huizhou-style buildings in southern Anhui, traditional architectural design methods face many problems, such as insufficiently comprehensive design solutions, unpredictable architectural effects, and difficult construction [10], [11]. With the popularity of Building Information Modeling (BIM), more information can be obtained from it to effectively solve various complex challenges [12]. The use of BIM technology enables the systematization of the overall information of a building and provides digital and informative operations for every aspect of the building, thus improving the efficiency and accuracy of the planning of the building [13]-[15]. The overall structural performance modeling and optimization strategy of Anhui Hui buildings in southern Anhui supported by this tool can help architects to better understand and simulate the building effects, improve the quality and efficiency of design, and thus bring innovative insights into the design of new buildings in southern Anhui [16]-[19].

The core objective of this paper is to propose a set of overall structural performance modeling and multi-objective optimization design methodology for Anhui South Anhui Huizhou style buildings based on the BIM platform, in order to solve the structural performance and multi-objective balancing challenges faced in modern Huizhou style building design. Firstly, we focus on the specific practice of BIM technology in the project design stage. Through detailed data collection and analysis, Revit software is used to accurately construct a BIM model of the building structure that contains details of prefabricated components. Using Navisworks for collision detection, design problems such as clashes between pipes and beams and columns were effectively solved, and the design accuracy was significantly improved. The article also establishes a multi-objective structural optimization mathematical model for buildings. The model takes the key structural elements (stiffness and position of extension truss, ring truss, and cross-section size of column) as design variables. The optimization objective is set to pursue the smallest maximum inter-story displacement angle and the lightest equivalent gross weight of the structure. To ensure safe structural compliance, the model strictly incorporates shear-to-weight ratio constraints, stiffness-to-weight ratio constraints, and steel-concrete column axial compression ratio constraints as constraints. The article also proposes an efficient and intelligent optimization solution strategy, the Dynamic Coupling Algorithm (GA-RBF) based on the Modified Genetic Algorithm (NSGA-II) and Radial Basis Function (RBF) neural network. The basic concepts of multi-objective optimization (MOO) and the advantages and basic flow of the NSGA-II algorithm applicable to this problem are introduced. The core innovation lies in the dynamic coupling of NSGA-II with RBF neural networks. The core of this coupling mechanism is that the RBF neural network is utilized to establish a fast agent model between the design variables and the performance objectives, replacing the time-consuming BIM structural performance simulation.NSGA-II is responsible for efficiently searching the optimized solution space with the assistance of the agent model, generating a new population through selection, crossover, and mutation operations, and retaining the excellent solutions using the elite strategy.

II. Building structural performance modeling and multi-objective optimization model based on BIM platform

II. A. Application of BIM technology in the design phase of engineering projects

II. A. 1) Key points of the phase of autonomous application of BIM technology

In Project X, the main points of autonomous application of BIM technology in the design phase are as follows:

(1) Data collection and analysis. At the beginning of the project, the design team understood the site conditions, building functional needs and user requirements in detail through field surveys and communication with the owner. The result is that the site conditions are complex, including irregular terrain and potential underground facilities, and this information has been recorded in detail, and as an important input parameter, it is included in the creation of the BIM model.

(2) BIM model creation. Using Revit software, the design team first created a basic structural model of the building, including three floors above ground and one floor below ground. The model contains detailed information about the main components such as prefabricated floor slabs, prefabricated wall panels and prefabricated beams and columns. To ensure the accuracy of the model. The team modeled the size, material and connection of each component in detail.

(3) Collision detection and optimization. After the initial construction of the model, the team utilized Navisworks software to perform collision detection on the BIM model, focusing on the intersection of pipes and beams and columns, and the misalignment of wall panels and floor slabs, in order to identify problems in advance and make adjustments accordingly.

II. A. 2) Application results

(1) Design accuracy improvement aspects. Through the accurate modeling and collision detection of the BIM model. The design team found and solved several design conflicts, which significantly improved the accuracy and reliability of the design. Through the clash data between components before and after optimizing the design scheme based on the BIM model, it can be seen that the vast majority of component clashes in the design scheme can be found and resolved based on the BIM model. After targeted optimization, it helps to improve the overall design accuracy.

(2) Construction efficiency simulation analysis. Through the construction simulation, the team found and solved a number of construction difficulties and optimized the construction process and schedule. After applying BIM technology to simulate the construction plan and adjusting and optimizing it, the total construction period of the project was shortened by about 15%, which significantly improved the construction efficiency.

(3) Structural analysis and optimization. In the design stage, the design team used BIM model to calculate and analyze the stress distribution and seismic performance of prefabricated beams and columns, and the specific analysis model principle expressions are as follows:

$$\sigma_{ij} = \frac{1}{v}\sum_{k}\left(\sigma_{ij}^{(k)} + \frac{\partial \sigma_{ij}^{(k)}}{\partial x_k}\delta x_k\right) \tag{1}$$

In Equation (1), σ_{ij} represents the components of the stress tensor, V represents the volume of the prefabricated member, k is the discrete unit number of the member, $\sigma_{ij}^{(k)}$ represents the stress component of the k th discrete unit, x_i is the coordinate of the k th discrete unit, and δx_k is the amount of small change in the coordinate. Equation (1) can accurately analyze the stress changes of prefabricated beams and columns under different loading conditions by calculating the distribution of stress tensors and discrete units, thus optimizing the design and connection of the beams and columns to ensure the overall stability and seismic performance of the structure.

II. B. Mathematical model for structural optimization

On the basis of solving the design conflicts and completing the structural performance analysis of the key components by using BIM model, in order to systematically improve the overall structural performance and economy of the Huizhou building, it is necessary to establish a set of scientific multi-objective optimization design framework, and this section is devoted to constructing a mathematical model for this optimization. At the same time, the stiffness, position and column cross-section size of extension truss and ring truss are taken as the design variables, the design control indexes in the current national code are taken as the constraints, and the maximum inter-story displacement angle and the structural equivalent gross weight are taken as the objective functions. The main constraints are:

II. B. 1) Building Structure Shear Weight Ratio Constraints

When calculating the horizontal seismic action, the ratio of the standard value of the horizontal seismic shear on each floor of the structure to the representative value of the gravity load on each of its upper floors (i.e., the shear-to-weight ratio) should meet the *minimum* requirements so that the calculation of the horizontal seismic action is not too small. That is:

$$V_{Ekl} \geq \lambda \sum_{j=1}^{n} G_j \tag{2}$$

where V_{Eki} is the shear force at level i corresponding to the standard value of horizontal seismicity; λ is the horizontal seismic shear coefficient; G_j is the representative value of gravity load at level j.

II. B. 2) Structural rigidity-weight ratio constraints for buildings

Under horizontal seismic action, for concrete structures, the unfavorable effect of the second-order effect of gravity grows nonlinearly as the lateral stiffness of the structure decreases, thus causing the instability and collapse of the structure. The ratio of the lateral stiffness of the structure to the gravity load (stiffness-to-weight ratio) is the main parameter affecting the gravity effect. Therefore, in structural optimization, the structural stiffness-to-weight ratio limit needs to be satisfied, i.e.:

$$EJ_d = \frac{11qH^4}{120^u} \geq 1.4H^2 \sum_{i=1}^{n} G_i \tag{3}$$

where EJ_d is the elastic equivalent lateral stiffness of the structure in one main axis direction, and the lateral stiffness of the structure is converted to the equivalent lateral stiffness of the vertical cantilever bending member according to the principle of equal displacement of the vertices of the structure under inverted triangular distribution of loads; q is the maximum value of inverted triangular distribution of loads; u is the elastic horizontal displacement of the structure under the action of this load; H is the height of the house; G_i is the representative value of the gravity load at the i th floor.

II. B. 3) Axial Compression Ratio Constraints for Section Concrete Columns

The axial compression ratio of the section concrete column is:

$$\mu_N = \frac{N}{f_c A + f_a A_a} \tag{4}$$

where μ_N is the axial compression ratio of steel and concrete; N is the design value of the axial force of the column considering the seismic combination; A is the cross-sectional area of concrete after deduction of the steel section; f_c is the design value of the axial compressive strength of concrete; f_a is the design value of the compressive strength of steel section; A_a is the cross-sectional area of steel section.

The axial compression ratio constraints of the section steel and concrete column are:

$$\mu_{N,\max} \le [\mu_N] \tag{5}$$

where $\mu_{N,\max}$ is the maximum value of axial pressure ratio for each column; $[\mu_N]$ is the limit value of axial pressure ratio.

II. C.Automatic optimization design based on GA-RBF coupling algorithm

In order to solve this model efficiently and intelligently and obtain a high-quality Pareto optimal solution set, an advanced intelligent optimization algorithm, the dynamic coupling algorithm GA-RBF of NSGA-II and RBF neural network, is introduced and improved in this section.

II. C. 1) Multi-objective Optimization Algorithm Basis and Improvement

Multi-objective optimization (MOO) aims to capture multiple conflicting and disproportionate aspects of the evaluation of potential solutions in order to identify their strengths and weaknesses and provide a sound technical basis for decision support. Multi-objective building performance optimization can be mathematically reduced to a multi-objective optimization problem:

$$\min f_m(x) m = 1, \ldots, M \tag{6}$$

where f_m is the specific objective and x is the set of n architectural design variables. The solution to the multi-objective problem (6) gives objective $f_1(x), f_2(x), \ldots f_M(x)$. When these objectives conflict with each other, they form a multidimensional space Z (different from single-objective optimization), as well as a typical decision space X. The decision space and objective space in multi-objective optimization are shown in Fig. 1.

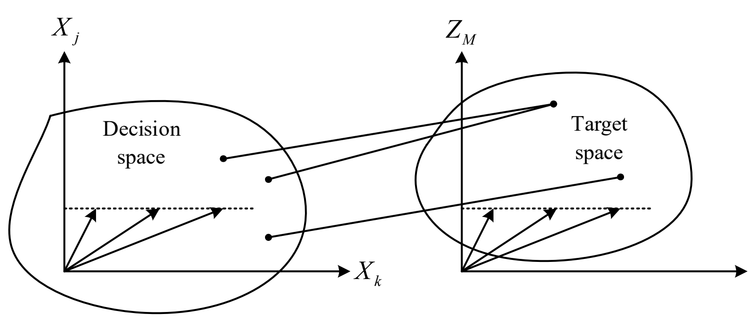

Figure 1: Decision Space and Objective Space in Multi-objective Optimization

Thus, the solution is not the only optimal design, but a set of non-dominated solutions. A solution is called non-optimal (or optimal Pareto) if there is no other feasible solution that improves one objective without inconveniencing the deterioration of the other. The set of nondominated solutions constitutes the so-called Pareto front, and in the case of only two objectives, this front can be represented by a curve as in Fig. 2.

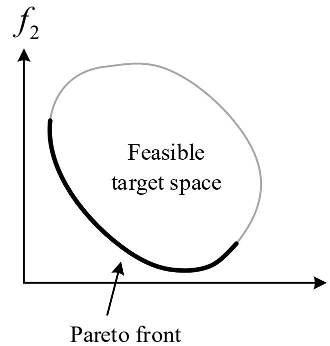

Figure 2: Pareto Frontier of the min-min dual-objective optimization interval problem

II. C. 2) Multi-objective optimization result search: based on a modified genetic algorithm

Due to the nonlinear and combinatorial nature of the building structure and performance, this multi-objective optimization model is suitable to be computed using one of the best multi-objective evolutionary algorithms, the Non-dominated Sorting Genetic Algorithm-II (NSGA-II), which has the advantages of low computational complexity, with an elite protection mechanism, and a more homogeneous distribution of the individuals on the Pareto front surface. Parameters such as elite retention rate, mutation rate, crossover rate, population size, and maximum number of iterations need to be set in the optimization process.

The basic idea of NSGA-II algorithm is: firstly, the initial population with initial size N is randomly generated, and after passing through the non-dominated sorting, the first generation of offspring population is obtained according to the three basic operations of genetic algorithm (GA), selection, crossover, and mutation: secondly, starting from the second generation of the order, the parental population and the offspring population are merged together in order to perform the fast non-dominated sorting, and at the same time, the calculation of the crowding degree of individuals in each non-dominated individual's crowding degree in the layer, and according to the nondominance relationship and individual's crowding degree, the appropriate individuals are selected to form a new parent population. Finally, a new offspring population is generated by the basic operation of genetic algorithm, and so on, until the conditions are satisfied.

The NSGA-II algorithm is dynamically coupled with the RBF neural network algorithm for multi-objective optimization, and its flowchart is shown in Fig. 3. This algorithm is able to maximize the advantages of intelligence and efficiency of intelligent algorithms in dealing with complex decision-making problems.

This coupled optimization algorithm first generates an initial population of feasible retrofit solutions for a building by randomly shuffling the initial design thermal parameters within constraints for the identified retrofit nodes, and calculates the objective function values for building optimization using the neural network simulation model and other performance objective function formulas, which are used for the evaluation of feasible solution fitness, and in the iteration, an elite retention strategy is used to retain the better fitness of the solution. After completing one round of selection, the offspring population, i.e., the set of solutions with higher fitness left after one round of selection, is re-selected, crossovered, mutated and combined to obtain a new parent population, and the fitness of solution individuals in the new parent population is re-calculated and solutions with higher fitness are retained, and the iterative process is repeated until the judgment of the solution's performance level and distribution meets the termination conditions, or the maximum number of iterations is reached and the optimization is stopped, the The final output is a set of non-dominated solutions of the building optimization and transformation scheme. In this coupled optimization process, due to the use of neural network simulation model instead of performance simulation software for the evaluation of performance objectives, so that the reconstruction of the building performance model and the dynamic performance simulation process no longer occurs in the iteration, the overall reduction in the number of performance simulation, and therefore can greatly improve the optimization of the search efficiency, shorten the optimization process of the total time-consuming.

III. BIM-based building case studies

Based on the BIM performance model, multi-objective optimization framework and GA-RBF coupling algorithm constructed in Chapter 2, this chapter selects a typical Huizhou building case to verify the engineering applicability of the described method through empirical analysis. The focus is on its ability to optimize the structural dynamic response and control effect under wind load and seismic excitation.

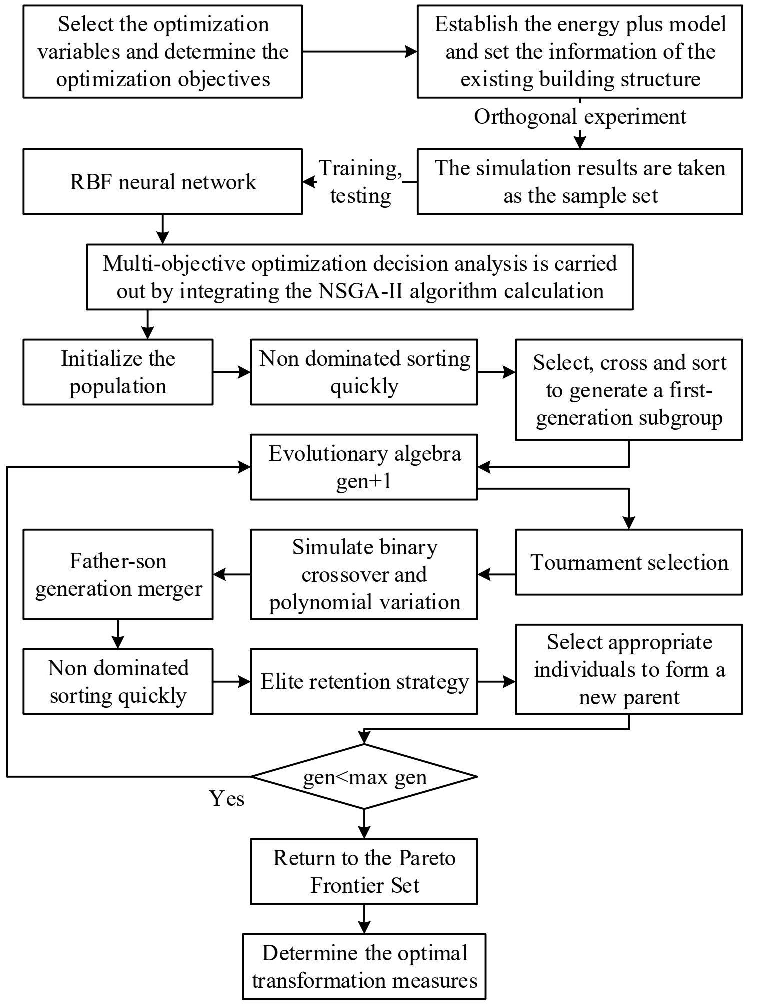

Figure 3: Flowchart of the GA-RBF algorithm

III. A. Description of the architectural baseline

The benchmark building of the classic southern Anhui Hui architecture is selected as the research object of this paper, and its main structure has 74 floors of 360 meters high. Since the 60th floor is the topmost floor where people live, the installed floors based on BIM technology and structural optimization model are smaller than the 60th floor. The mass and inter-story lateral stiffness distributions of the main structure are extracted from the finite element model of the building structure, and the mass distribution and inter-story lateral stiffness distribution are shown in Figure 4.

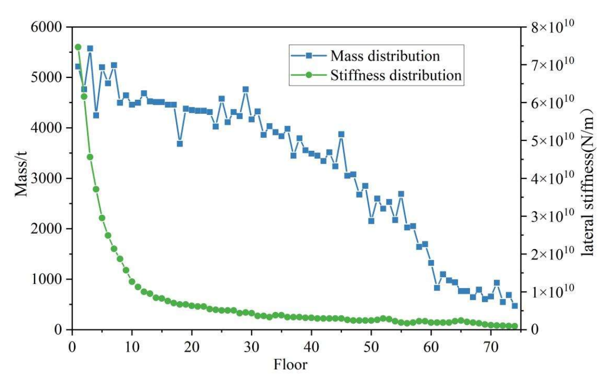

Figure 4: Mass distribution and interlayer lateral displacement stiffness distribution

As can be seen from Fig. 4, as the floor increases in height, its building mass and interstorey lateral stiffness tend to decrease in general, but there are also special cases of individual floors, such as the 18th floor, the mass of which plummets to 3,682 tons, while the mass of the 29th floor increases to 4,763 tons.

III. B. Optimization results under crosswind aerodynamic excitation

After clarifying the mass and stiffness distribution characteristics of the benchmark building, this section relies on the GA-RBF algorithm to carry out the structural optimization design under transverse wind aerodynamic excitation and evaluate its effectiveness in suppressing wind-induced vibration (displacement/ acceleration).

The GA-RBF constrained multi-objective evolutionary algorithm is used to optimize the design of the building under crosswind aerodynamic excitation. The main parameters of the two algorithms are set as follows: maximum number of evolutionary generations: 5000, population size: 100, crossover probability: 0.85, and mutation probability: 1/5.

The optimization methods compared include the Giaralis FM formulation and the Warburton FM formulation.

In order to validate the optimal parameters of the TID obtained by the GA-RBF algorithm, the transfer functions and the time courses of the top floor displacements and accelerations were analyzed. Figures 5 and 6 show the time-course response of the building's top floor displacements and accelerations (lasting for 20 minutes) for a 270° wind angle at the 70th degree of freedom of the reference building (top floor) induced by the force at the 70th degree of freedom, respectively. It can be observed that for the displacement and acceleration responses, the optimal TID obtained by the GA-RBF algorithm provides the best damping effect.

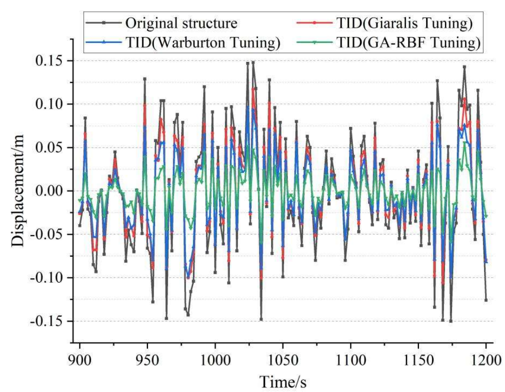

Figure 5: Displacement on the 70th floor at a 270° wind direction Angle

It can be observed that the displacement of the original feature is between [-0.15, 0.15] during the 20 minutes from 900-1200s, and the displacement is reduced by about 20% and 30% by the Giaralis FM formula and the Warburton FM formula, respectively, whereas the GA-RBF coupling algorithm designed in this paper has the best damping effect, and the damping reaches about 60-70% or so.

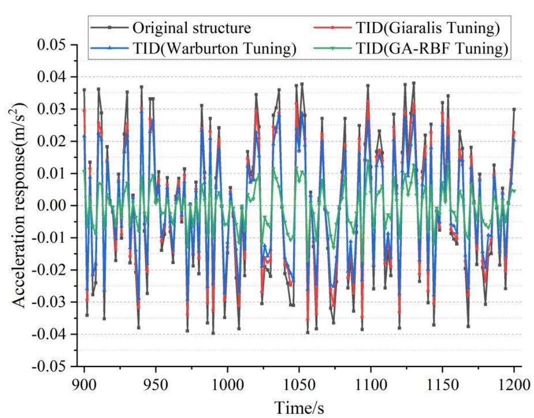

Figure 6: The acceleration time history of the 70th floor at a 270° wind direction Angle

The acceleration response is the same, the acceleration response of the original feature is between [-0.04, 0.04] m/s^2, and after optimization by the GA-RBF coupling algorithm, it reaches between [-0.01, 0.01], and the damping efficiency reaches more than 25%.

III. C. Optimization solution based on multi-objective algorithm

In addition to wind loads, seismic actions are also critical design conditions for buildings. In this section, the multi-objective hybrid swarm optimization algorithm is further employed to compare the performance differences between centralized and decentralized control strategies under seismic excitation, and to deepen the validation of the applicability of the algorithm in complex dynamic environments.

III. C. 1) Multi-objective algorithm optimization solution results

In order to facilitate the comparison and analysis of the results of each decentralized control optimization, this paper also carries out the centralized control optimization design for this structure. Fig. 7 shows the initial population solution, the final non-inferior solution, and all the leaders selected during the whole optimization process when the centralized control optimization is carried out by using the multi-objective hybrid swarm optimization method, and it can be seen that the leaders determined according to the leader selection mechanism of the geometric center of the boundary points proposed in this paper can cover the range of interest of the structural vibration control strategy well, and thus there are not too many unrealizable solutions (J1 tends to be infinitely small, J2 is too large) and non-inferior solutions in the final non-inferior solution. There are too many unrealizable solutions (J1 tends to be infinitely small and J2 is large) and meaningless solutions (J1 tends to be infinitely large), which satisfies the requirement of evolutionary diversity of the population. At the same time, it can be seen that the optimal solution set of GA-RBF algorithm based on multi-objective optimization shows good continuity and distribution, and there is no phenomenon of losing the optimal solution in a certain interval, which makes it easy for the designer to select the results of interest from it.

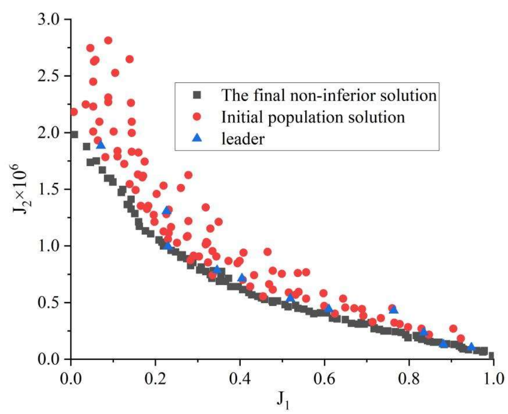

Figure 7: The optimization process of Centralized control

III. C. 2) Optimization results of multi-objective hybrid swarm algorithm

Only one decentralized control condition exists for the 4-subsystem decentralized control scheme of this algorithm, therefore, its final non-inferior solution set is no longer plotted, and only a set of results is selected for comparative analysis in the time course validation of the optimization results, and the optimization results of the multi-objective hybrid swarm algorithm are shown in Table 1. With J_1=0.3, a set of optimization results from each of the centralized and decentralized control conditions (2Subs$_1$, 2Subs$_2$, 3Subs$_1$, 3Subs$_2$, 3Subs$_3$, and 4Subs) is selected for the time-varying response analysis (El Centro wave seismic excitation with a holding time of 60 s and a peak value of 0.37 m/s^2). Both centralized and decentralized control use absolute acceleration feedback, and the full state of the structure is estimated by establishing the corresponding Kalman filter, based on which the optimal state feedback gain is used to generate the control force command applied to the structure, with a maximum allowable force of 1200 kN for a single actuator.

The decentralized control condition 2Subs$_1$ subsystems are divided into:2 to 4 and 5 to 7; condition 2Subs$_2$ subsystems are divided into:2 to 7 and 8 to 9; condition 3Subs$_1$ subsystems are divided into 2 to 5, 6 to 7, and 8 to 9, and condition 3Subs$_2$ subsystems are divided into 2 to 4, 5 to 7 and 8 to 9; condition 3Subs$_3$ subsystems are divided into 2 to 4, 5 to 6 and 7 to 9; and condition 4Subs subsystems are divided into:2 to 3, 4 to 5, 6 to 7 and 8 to 9.

Table 1 gives the optimal design parameters of the control device positions, numbers and corresponding controllers corresponding to the optimal individuals of centralized and decentralized control (the number of subsystems is 2, 3 and 4, respectively) selected from the Pareto optimal frontier curves, and it can be found that the total mean square deviation of the control force for each of the optimal decentralized control conditions is the same and significantly smaller than that of the centralized control, but the sum of the number of actuators for each of the conditions is similar.

Table 1: Optimization results of MOHO algorithm

Control strategy		Concentration	$2Subs_1$	$2Subs_2$	$3Subs_1$	$3Subs_2$	$3Subs_3$	4Subs
The number of actuators at the optimal placement position	1	2	2	3	2	2	3	2
	2	2	3	2	2	3	2	3
	3	2	3	2	3	3	3	2
	4	2	2	1	3	2	2	3
	5	3	2	2	2	2	2	2
	6	2	3	2	1	2	1	2
	7	3	1	3	3	2	3	3
	8	3	3	2	3	3	2	2
	9	2	3	2	2	3	3	2
	Na	21	22	19	21	22	21	21
J_1		0.35	0.35	0.35	0.35	0.35	0.35	0.35
J_2/kN		1096.14	183.18	182.06	181.52	183.51	182.03	183.84
α		14.028	13.482 13.219	13.249 13.084	12.745 12.528 12.263	12.382 13.037 12.183	12.389 12.667 12.056	12.410 11.923 12.528 12.732

Table 1 compares the optimization results of the centralized and decentralized control strategies (2/3/4 subsystems). The data show that the total mean squared deviation (J_2) of the control force for all decentralized control conditions ($2Subs_1$~4Subs) is significantly lower than that of the centralized control (centralized control J_2=1096.14 kN, decentralized control J_2 ranges from 181-184 kN), which suggests that the decentralized control strategy is more effective in suppressing the structural vibration.

Although the total number of actuators for decentralized control (Na = 19-22) is similar to that of centralized control (Na = 21), its spatial distribution is more flexible (e.g., $2Subs_1$ 3 deployed on floors 2-4, and only 1 on floors 5-7), which suggests that the optimization algorithm is able to accurately allocate the subsystems according to their characteristics Control resources. Under the same control effect (J_1 = 0.35), the controller parameters (α) of each decentralized working condition differ significantly (e.g., α values spanning 12.263-12.745 in $3Subs_1$, and 11.923-12.732 in 4Subs), which corroborates that the GA-RBF algorithm is able to adaptively match the different subsystem dynamical characteristics to generate customized solutions. Although more local controllers need to be deployed for decentralized control, it can reduce actuator energy consumption and structural fatigue damage due to the significant reduction of control force fluctuation (J_2), which is economically valuable for the long-term operation and maintenance of the building.

IV. Conclusion

In this paper, a set of structural design methods for Huizhou buildings integrating BIM technology, multi-objective optimization and intelligent algorithms is proposed, and its effectiveness is verified by a typical case of 74 floors and 360 meters, and the main conclusions are as follows.

Under 270° crosswind excitation, the GA-RBF algorithm reduces the top displacement amplitude from the original [-0.15, 0.15] m to [-0.06, 0.06] m (vibration damping 60-70%), and the acceleration response is compressed from [-0.04, 0.04] m/s² to [-0.01, 0.01] m/s² (vibration damping efficiency > 25%), substantially better than Giaralis and Warburton FM formula.

Seismic response decentralized control is superior, the decentralized strategy (2Subs~4Subs) reduces the total mean square error (J_2) of control force by more than 80% compared to centralized control (J_2=1096.14 kN → decentralized control J_2=182.46 kN); the number of actuators is similar (Na=19-22) but with optimized spatial configurations, and the controller parameters are self The number of actuators is similar (Na=19-22) but the space configuration is optimized, and the controller parameters are adjusted adaptively (α-values spanning 11.923-13.482), verifying the flexibility of the algorithm in multi-subsystem collaboration.

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