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Effect of Construction Errors in Cable Forces of Single-Story Orthogonal Cable Network Structures Based on GA-BPNN

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Abstract: The construction process of cable net structure is complicated, which leads to the strong randomness of construction errors. The safety state of the cable net structure is very sensitive to construction errors. Obtaining the coupling relationship between construction errors and cable force response efficiently and accurately is critical to developing the construction technique of cable structures. This paper proposed an analysis method based on a genetic algorithm optimized back propagation neural network (GA-BPNN) to judge the influence of construction error on the cable force of single-layer orthogonal cable network structures. Taking the speed skating stadium of the 2022 Winter Olympic Games as the research object, this paper analyzed the structure form of the venue. According to the characteristics of cable network structure and GA-BPNN calculation, the principle of construction error analysis was put forward. The influence of construction errors of load-bearing cables and stable cables on cable force response was analyzed. The influence degree of different component errors on structural cable forces was obtained, and the most unfavorable key components were obtained. For the key components, the influence trend of different construction errors on cable force was analyzed, and the fitting formula was given. Driven by GA-BPNN, it can realize the analysis of structural and mechanical responses under the action of multi-type, multi-component, and multi-combination construction errors. The results show that the research method efficiently and accurately obtains the performance law of structural cable force under the influence of construction error, effectively predicts the influencing factors of the structural safety risk, and effectively avoids structural safety accidents caused by construction error. The construction errors analysis method based on GA-BPNN proposed in this paper can provide a reference for similar structural analysis and application.

Keywords: GA-BPNN; cable network structure; construction errors; changes of cable forces; intelligent analysis

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1. Introduction

1.1. Background

The single-story orthogonal cable network structures are mostly used in large-span spatial structures such as large stadiums [1,2]. Single-layer orthogonal cable network structures give full play to the high-strength performance of cables. Under the same size and load conditions, the steel consumption [3,4] of cable-net structures is 30–50% of that of traditional steel structures, which effectively saves resources. The cable members are connected with the peripheral rigid members by pins, and the intermediate nodes are also connected by bolts [5]. The structure assembly rate reaches 100%. The construction process of cable net structures has a low impact on the environment [6]. This kind of structural form is defined as flexible cable network structures. It means that the cable elements of the structure should be applied pre-stress to maintain the stability of the design form and obtain load-bearing stiffness [7,8]. To be specific, the conditions for the composition of this structure are a complex structure and a large number of elements [9]. As a result, it is common to generate errors during the processing of materials and the construction of the structure. The cable network structure is sensitive to construction errors, especially length errors in the cable elements [10,11]. In addition, the resulting construction errors can easily cause changes in the structural cable forces, which may make it hard to meet the design requirements. It mainly influences the cable forces and shape of the whole structure aspects and even reduces the safety performance of the structure seriously.

Analyzing the impact of construction errors on structural safety has been a main topic of research in space structures during the construction process. Chen et al. [12] analyzed the extent to which different sizes of errors in the ring beam. They also analyzed tie ropes affect the internal forces on the top of the cable dome, then proposed corresponding treatment measures. Ruan et al. [13] analyzed the effect of cable length errors and outreach node coordinate errors on cable forces by random error analysis method. Since then, they have defined reasonable error control standards. Chen et al. [14] proposed a sensitivity analysis method for unit length errors. This method was based on the target of exploring the effect of construction errors on the load-carrying capacity of cable tension structures. Wu et al. [15] carried out a method for analyzing the vibration pattern of a cable dome with the consideration of construction deviations. Specifically, this kind of method has a high degree of robustness. Thai et al. [16] carried out the static and dynamic analysis of the cable structure, which investigated the effect of the initial cable length errors.

1.2. Research Gap

There is little research on cable length errors in single-story orthogonal cable network structures. Moreover, traditional construction error analysis is difficult to deal with large volume error conditions. Moreover, the error of the finite element analysis method can quickly and accurately analyze the mechanical response of the structure under the action of multi-type, multi-component, and multi-combination construction errors. The main objective of this paper is to efficiently and accurately analyze the safety feature of structures under the influence of errors. In this study, the influence of construction errors of load-bearing cables and stable cables on cable force response is analyzed. The influence degree of different component errors on structural cable force is obtained, and the key components with the most unfavorable influence on cable force are obtained. For key components, the influence trend of different construction errors on cable force is analyzed, and the fitting formula is given. Moreover, by analyzing the mechanical response of the structure under the action of construction error, this study can provide a basis for the safe maintenance of the structure. Genetic algorithm back propagation neural network (GA-BPNN) [17] has provided new ideas and tools for the analysis of this research. Based on this algorithm, it is possible to analyze the trend of the cable forces under different working conditions accurately and quickly.

1.3. Literature Review

GA-BPNN has been used extensively for structural performance evaluation and parameter optimization. Xie et al. [18] established a prediction model with construction cost based on GA-BPNN, which analyzed the trend of construction cost changes effectively. Fan et al. [19] proposed a back propagation neural network optimized genetic algorithm for piezoelectric ceramic creep prediction algorithm. It solved the problem of difficult positioning accuracy effectively. Liu et al. [20] proposed a method to effectively predict the skid resistance of newly built rollers at the design stage. To be specific, this method made an effective application of GA-BPNN for the better prediction of slip resistance. Liu et al. [21] attempted to predict the compressive strength of modified straw fiber concrete by establishing the GA-BPNN system. Therefore, the achievements made by Liu et al. have effectively contributed to the application of plant rice straw fibers in civil engineering. Xu et al. [22] used the GA-BPNN method to evaluate the quality of the residential buildings, which effectively preserved the local cultural heritage.

1.4. Research Significance and Organizational Structure

As it is difficult to analyze construction errors combined with the characteristics of the GA-BPNN in cable network structures. This paper proposed a GA-BPNN-based method for analyzing the effect of construction errors on the cable forces of single-story orthogonal cable network structures. Taking the roofing network in the speed skating stadium of the 2022 Winter Olympic Games as the object, the principles of error analysis are proposed. Furthermore, this method obtained the key force members in the structure by arranging the same error in a single tension cable. Meanwhile, it obtained a coupling between the rate of change of the cable forces and the errors based on the key force members. Driven by GA-BPNN, the influences of different construction errors on structural cable forces are analyzed quickly and accurately. On the one hand, this research method can evaluate the safety state of the structure as a whole. On the other hand, it provides the basis for the establishment of the safety control measures of the construction process. The organizational structure of this paper is as follows:

In the second section, the characteristics of the cable network structure are analyzed, and the analysis principle of construction error is established. The change rate of cable force before and after the error is used to evaluate the influence of construction error on the mechanical response of the structure.

According to the analysis principles in Section 2, the maximum rate of change of cable forces in the structure when construction errors occur to single load-bearing cable and stable cable is analyzed in Section 3. According to the change rate of cable force under the same error, the most critical load-bearing cables and stable cables are obtained.

In Section 4, the data samples of the rate of change of cable force are formed for the construction errors of multiple types, multiple components, and multiple combinations. Finally, driven by GA-BPNN, the mechanical response of the structure under the action of comprehensive construction error is analyzed.

The fifth section is the conclusion of this study.

2. Construction Overview and Error Analysis Principles

2.1. Construction Overview

The main structure of the speed skating stadium in the 2022 Winter Olympic Games is the cast-in-place reinforced concrete construction. The roof of this stadium is the largest single-story and two-way orthogonal saddle-shaped cable network structure in the world. The plan dimensions of the cable network is 198 m $\times$ 124 m, and the building elevation is 15.8 m~33.8 m. This network is supported on a circumferential steel ring truss with curtain wall cables on the outside of the truss. The cable network structure consists of load-bearing and stabilizing cables, both of which are high vanadium closed. Specifically, the load-bearing and stabilizing cables are both double ones. There are 98 load-bearing cables with a diameter of 64 m and 60 stabilizing cables with a diameter of 74 m. Moreover, there are 120 curtain wall cables around the circumference of the roof ring trusses, which are used to stabilize the roof of the stadium. The structural layout plan of the speed skating stadium is shown in Figure 1.

The cable network structure in this research is symmetrical, which means only 1/4 of the structure was taken for the analysis of construction errors. In addition, 1/4 of the structures taken for the research can represent the structure as a whole. The cable network number of the 1/4 structure is shown in Figure 2, and the materials of cable cables are shown in Table 1. In the 1/4 span structure, there are 25 load-bearing cables along the major axis, whose numbers range from 1 to 25 according to the length of the cable. Along the minor axis, there are 15 stability cables, whose numbers range from 1 to 15 according to the length of the cables. Curtain wall cables total 30, whose numbers are 1–30 from the major axis to the minor axis.

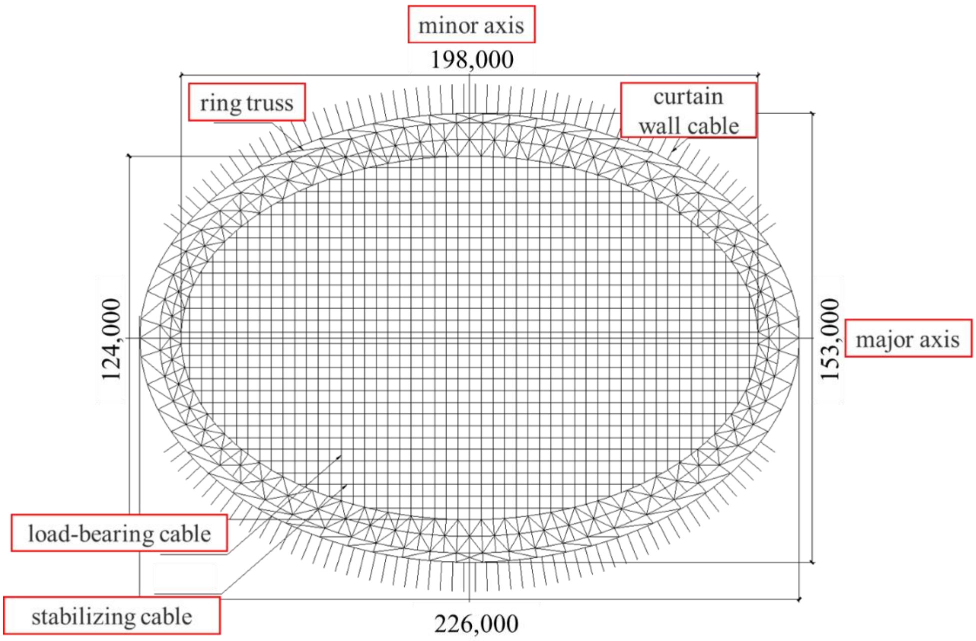


Figure 1. Layout diagram of speed skating hall structure.

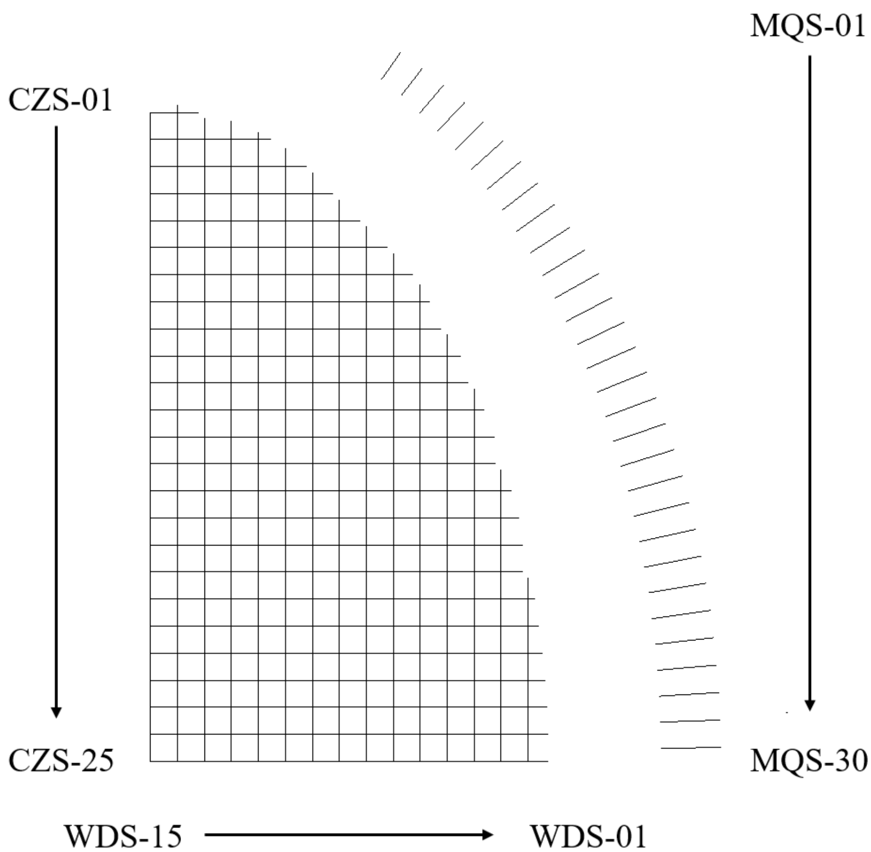


Figure 2. The cable network number of the 1/4 structure (CZS is the load-bearing cable, WDS is the stabilizing cable, and MQS is the curtain wall cable).

Table 1. Cable materials.

Type	Diameter/mm	Material Quality	Length/m	Form Cable Force/kN
load-bearing cable	Φ64	high vanadium sealing cable	18~123	1409~1747
stabilizing cable	Φ74		54~196	2251~3091

2.2. Error Analysis Principles

During the construction of the cable network structure, the cable length error is caused by the installation deviation of the lug plate. As shown in Figure 3, the cable span during the design process is L, and the installation deviation (ΔL) between the lug plates is due to construction errors. After the construction error occurs, the cable shape changes. Therefore, the internal forces of the cable will also be redistributed. In this study, the installation deviations were selected as spans of $-1/2000$ to $-1/3000$ and $1/3000$ to $1/2000$. Driven by construction error, the cable force response is obtained.

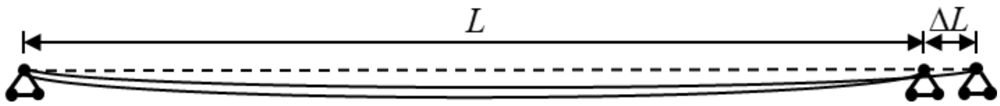


Figure 3. Morphological changes of cable under the action of construction errors.

Midas/Gen finite element software was used to build the overall structural model of the speed skating stadium of the 2022 Winter Olympic Games. The main parameters are calculated as shown below. The difference in 3D coordinates of the ring beam trunnion construction (bearing error) is simulated by setting nodal forced displacements to the boundary. As for the random errors in the dowel length of the cables, they are simulated by unit warming or cooling. Moreover, the temperature can be calculated by the ratio of the error value and the coefficient of linear expansion [23]. The cable length error can be simulated by applying a temperature load to the relevant cable section using Equation (1).

$$\Delta T = \frac{\Delta L}{\alpha L} \tag{1}$$

where ΔT is the amount of temperature change, ΔL is the amount of change in cable length, L is the original length of the cable, and α is the tension cable coefficient of expansion. Based on the original reports of the elements, this research takes $\alpha = 1.92 \times 10^{-5}$. The construction error conditions are set up in the finite element model to obtain the force values for each of the tension cables in the structure. The change in cable force is obtained by comparing the cable force values after the effect of the error with that in the standard conditions. The rate of change in the cable force for each cable is calculated from Equation (2).

$$\varsigma = \frac{F_i^* - F_i}{F_i} \tag{2}$$

where F_i is the force value of the No.i cable in the standard condition, F_i^* is the force value of the No.i cable under construction errors. The maximum rate of change of cable force is calculated according to the formula Equation (3). In this study, the maximum rate of change of cable force is divided into the maximum rate of increase and the maximum rate of decrease.

$$\varsigma_{\max} = \begin{cases} \max(\frac{F_i^* - F_i}{F_i}) \\ \max(\frac{F_i - F_i^*}{F_i}) \end{cases} \tag{3}$$

According to the literature [24,25], the cable force in the construction process is much smaller than the cable force under the design load, so this study did not consider the cable force under the design state and the cable force under the ultimate state. The standard working conditions referred to in this paper are those in which the structure becomes a form under self-weight. By calculating the change in cable forces, the maximum rates of reduction and increase in them for different construction errors can be obtained. During this research, the maximum rate of change of cable forces in the overall structure will be used as a basis for the cable force response. It is mainly based on an analysis of the effects of construction errors. Then, the most significant load-bearing and stabilizing cables can be obtained based on the maximum rate of change of the cable force. To be specific, the basic method is that set up different element error conditions in analyzed critical load-bearing and stabilizing cables. Furthermore, analysis of the maximum rate of reduction and the maximum rate of increase on the cable forces in the whole structure. As a result, the trend in the effect of the error on the cable force is fitted to the error conditions of the key elements. In this research, the span of the cable is selected based on engineering experience and construction error limits. Taking the cable span between −1/2000 to −1/3000 and 1/3000 to 1/2000 as the highlights of the analysis [26], the interval of the error is 1/250. As for the whole structure, it is necessary to analyze the effect on the structural rigging in case of different construction errors on different elements. Providing the dataset for the GA-BPNN calculation allows a large number of samples to be formed based on the analysis. As a result, it will be possible to obtain the maximum rate of change of cable forces under different construction error conditions. Fast and accurate neural networks ultimately provide a reliable basis for the safe maintenance of structures. The analysis process of the influence of construction error on structural cable force is shown in Figure 4. In this study, the same length error is first applied to each load-bearing cable and stability cable to obtain the maximum rate of change of cable forces in the structure under the action of construction error of a single cable. Therefore, by comparing the mechanical response caused by the length error of each cable, the key load-bearing cable and stable cable are identified. For key cable components, length errors of different degrees are set to obtain the coupling relationship between errors and mechanical response. In view of the complex construction error conditions, a variety of length errors are set in the different cables at the same time to obtain the rate of change of cable force. Finally, driven by GA-BPNN, the mechanical response of the structure under the action of multi-type, multi-component, and multi-combination construction errors is analyzed quickly and accurately.

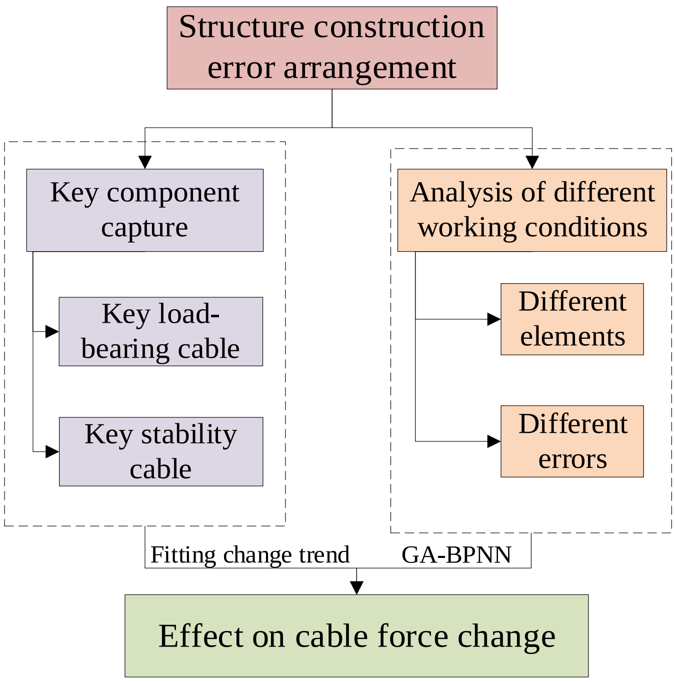


Figure 4. Analysis of the influence of construction error on cable force.

3. Construction Error and Cable Force Sensitivity Analysis

3.1. Impact of Load-Bearing Cable Construction Errors on Cable Force Response

The study, driven by the principles of error analysis, analyzed the rate of change of cable forces when length errors occur in load-bearing cables in structures. There are 25 load-bearing ropes that were used as the subject of this research. Specifically, the most critical load-bearing cables will be obtained by setting the same length error on different load-bearing cables. It is used to analyze the response of the overall rate of change of the structural cable force. Based on setting different element length errors in the most critical load-bearing cables, the rate of change of the structure's cable force can be analyzed. The equation for the maximum rate of change of cable force response for different length errors in the most critical load-bearing cables can be defined.

(1) Acquisition of critical load-bearing cables

At 1/4 of the span of the structure, set length errors of 1/2000 of the span for each individual load-bearing cable separately. According to Equation (1), the cell temperature variation is set in the finite element model so as to simulate the length error of the structure. It will contribute to obtaining the force values for each cable in a structure. The comparison of the force values of each cable under the effect of the error and the standard working conditions is noteworthy. For different load-bearing cables, the rate of change of force for each cable when the length error occurs can be calculated using Equation (2). Meanwhile, the maximum rates of increase and decrease in the overall structure force is obtained from the rate of change of each cable force. The maximum changing rate of the cable force of a single load-bearing cable with a length error of 1/2000 span is shown in Figure 5. In Equation (1), $\frac{\Delta L}{L}$ is 1/2000. The temperature required to simulate the length error is 26.04 °C. The cable force value before and after the temperature rise was calculated in the finite element software, and the maximum rate of change of cable force in the structure was obtained according to Equation (3). In this study, the maximum rate of change of cable force is divided into the maximum rate of increase and the maximum rate of decrease.

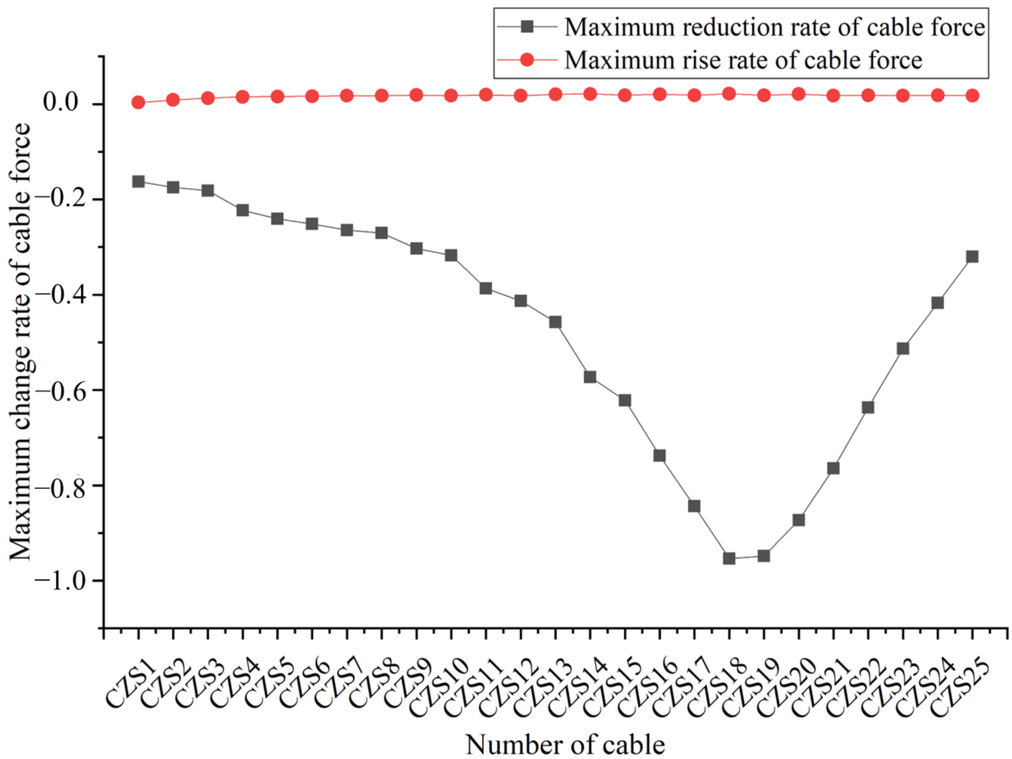


Figure 5. The maximum change rate of cable force of the whole structure when the length error of 1/2000 span of a single load-bearing cable occurs.

From Figure 5, the analysis result reveals that the rate of increase in the overall cable force of the structure is not significant. Especially when element errors occur in single load-bearing cables. However, it indicated that a significant reduction in the overall cable force of the structure would occur when length errors arose in single load-bearing cables. The greatest impact on the overall load of the structure is caused by the length error of the No.18 load-bearing cable. It results in a reduced rate in the load of up to 95.4%. As a result, load-bearing cable No.18 is one of the most critical load-bearing elements in the load-bearing cables of this structure.

(2) Effect of different errors on the cable force of structures

Load-bearing cable No.18 is a critical load-bearing element of the structure based on the former analysis. According to Equation (1), the length error of a component can be simulated based on the temperature. Similarly, the rate of change of the cable force can be calculated from Equation (2). Specifically, it can be calculated by comparing the value of the cable force under the error effect and the standard operating conditions. As for the whole structure, the maximum rate of change of its cable force under different errors can be obtained, as shown in Figure 6. In this study, errors were set in CZS18 compared to the cable lengths −1/2000, −1/2250, −1/2500, −1/2750, −1/3000, 1/2750,1/2500,1/2250, and 1/2000, respectively. The temperature of simulation error is calculated according to Equation (1). According to Equation (2), the change rate of cable force before and after the error is calculated. Capture the maximum rate of change of cable force in the structure according to Equation (3).

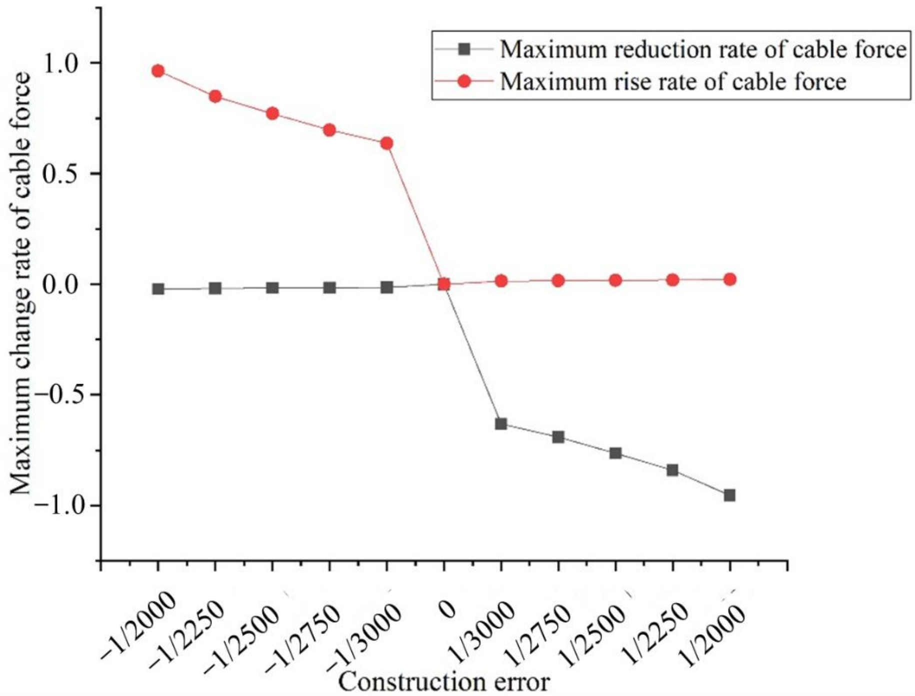


Figure 6. The maximum rate of change of cable force under different errors.

According to Figure 6, the variation function of the cable force under different errors can be fitted, as shown in Equations (4) and (5). Equation (4) has shown the trend in the maximum rate of decrease in the cable force for different error effects. At the same time, Equation (5) has shown the trend of the maximum rate of increase in the cable force under the influence of different errors. According to the engineering specifications [27,28], the rate of reduction of the cable force after forming the structure cannot exceed 10%. Moreover, the value of the cable stress cannot exceed 0.4 times the allowable stress. Due to the limitation of the engineering specifications [27], the increase in the length of the load-bearing cables should be strictly controlled in this structure.

$$\begin{cases} y = 43.221x + 1.899 \times 10^{-4} & (-1/2000 \le x \le -1/3000) \\ y = -1918.892x + 7.29 \times 10^{-3} & (1/3000 \le x \le 1/2000) \end{cases} \tag{4}$$

$$\begin{cases} y = -1919.326x - 1.23 \times 10^{-2} & (-1/2000 \le x \le -1/3000) \\ y = 43.465x - 2.44 \times 10^{-4} & (1/3000 \le x \le 1/2000) \end{cases} \tag{5}$$

3.2. Impact of Stabilizing Cable Construction Errors on Cable Force Response

Based on the principle of error analysis, this research analyzed the rate of change of cable forces for length errors in structurally stabilized cables. There are 15 stabilizing cables that were used as the subject of this research. Specifically, the most critical stabilizing cables will be obtained by setting the same length error on different stabilizing cables. The primary target is to analyze the response of the overall rate of change of the structural cable force. Based on setting different element length errors in the most critical stabilizing cables, the rate of change of the structure's cable force can be analyzed. The equation for the maximum rate of change of cable force response for different length errors in the most critical stabilizing cables can be defined.

(1) Acquisition of critical stabilizing cables

At 1/4 of the span of the structure, set length errors of 1/2000 of the span for each individual stabilizing cable separately. According to Equation (1), the cell temperature variation is set in the finite element model so as to simulate the length error of the structure. It will contribute to obtaining the force values for each cable in a structure. The comparison of the force values of each cable under the effect of the error and the standard working conditions is noteworthy. For different load-bearing cables, the rate of change of force for each cable when the length error occurs can be calculated using Equation (2). Meanwhile, the maximum rates of increase and decrease in the overall structure force is obtained from the rate of change of each cable force. The maximum changing rate of the cable force of a single stabilizing cable with a length error of 1/2000 span is shown in Figure 7. In Equation (1), $\frac{\Delta L}{L}$ is 1/2000. The temperature required to simulate the length error is 26.04 °C. The cable force value before and after the temperature rise was calculated in the finite element software, and the maximum rate of change of cable force in the structure was obtained according to Equation (3). In this study, the maximum rate of change of cable force is divided into the maximum rate of increase and the maximum rate of decrease.

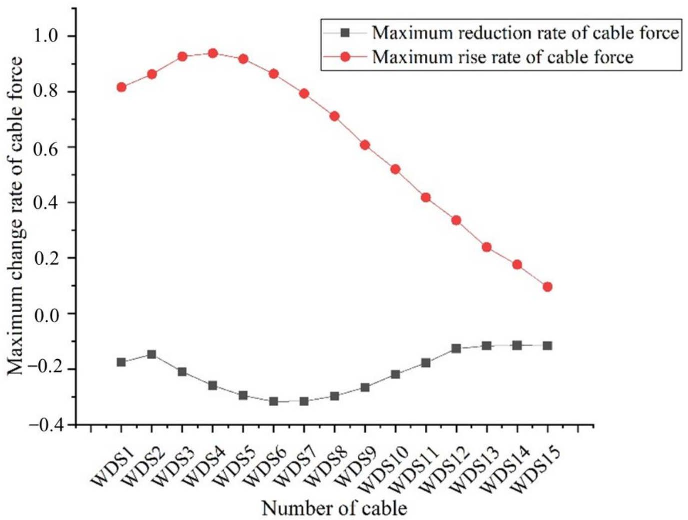


Figure 7. The maximum change rate of cable force of the whole structure when the length error of 1/2000 span of a single stabilizing cable occurs.

From Figure 7, the analysis in this research found that the rate of increase in the overall cable force of the structure was pronounced. It was more obvious, especially when member errors occurred in a single stabilizing cable compared to the rate of decrease in the cable force. However, the rise of cable forces in this research did not result in stresses exceeding 0.4 times the allowable stress. Therefore, the rate of drop of the cable force will be considered the main factor in determining the most critical force member. The greatest impact on the overall load of the structure was caused by the length error of the No.6 stabilizing cable. It led to a reduced rate in load of up to 31.6%. As a result, load-bearing cable No.6 is one of the most critical stabilizing elements in the stabilizing cables of this structure.

(2) Effect of different errors on the cable force of structure

Through analysis, it is found that stability cable 6 is the key stress member. According to the principle of error analysis, the length errors of different spans are applied to stability cable No.6. According to Equation (1), the length error of the component is simulated by temperature. By comparing the error action with the cable force value under standard working conditions, the change rate of cable force is calculated by Equation (2). For the whole structure, the maximum change rate of cable force under different errors is obtained, as shown in Figure 8. In this study, errors were set in CZS18 compared to the cable lengths −1/2000, −1/2250, −1/2500, −1/2750, −1/3000, 1/2750, 1/2500, 1/2250, and 1/2000, respectively. The temperature of simulation error is calculated according to Equation (1). According to Equation (2), the change rate of cable force before and after the error is calculated. Capture the maximum rate of change of cable force in the structure according to Equation (3).

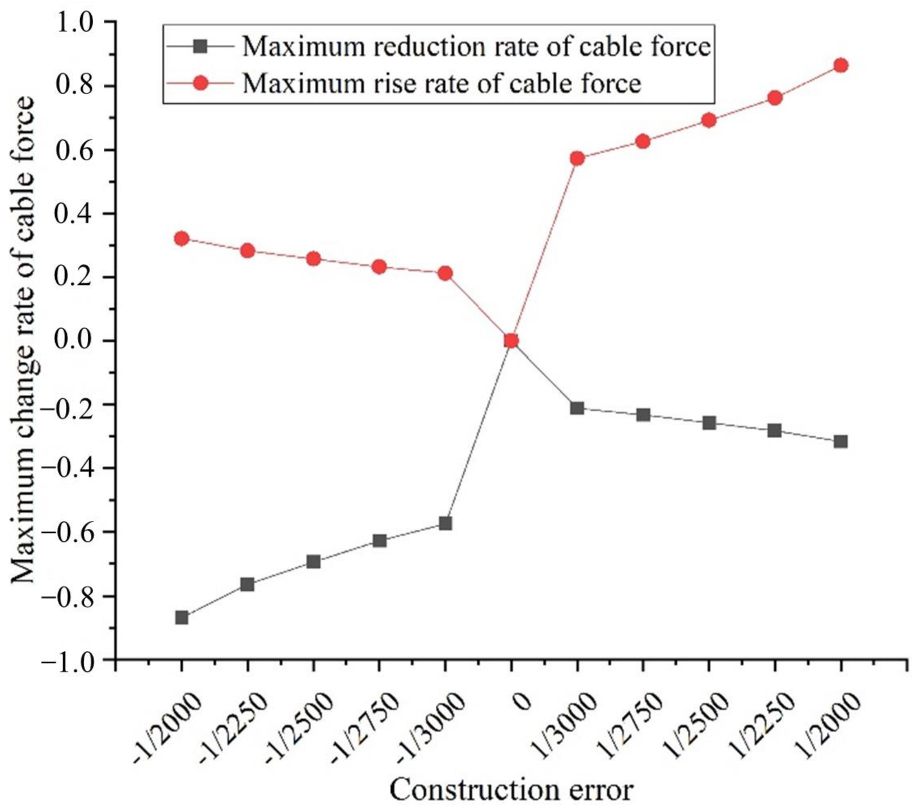


Figure 8. The maximum rate of change of cable force under different errors.

According to Figure 8, the variation function of the cable force under different errors can be fitted, as shown in Equations (6) and (7). Equation (6) has shown the trend in the maximum rate of decrease in the cable force for different error effects. While Equation (7) has shown the trend of the maximum rate of increase in the cable force under the influence of different errors. According to the engineering specifications, the rate of reduction of the cable force after forming the structure cannot exceed 10%. Again, the value of the cable stress cannot exceed 0.4 times the allowable stress. Due to the limitation of the engineering specifications [27], the increase in the length of the stabilizing cables should be strictly controlled in this structure.

$$\begin{cases} y = 1749.693x + 8.52 \times 10^{-3} & (-1/2000 \le x \le -1/3000) \\ y = -622.364x + 5.82 \times 10^{-3} & (1/3000 \le x \le 1/2000) \end{cases} \tag{6}$$

$$\begin{cases} y = -647.066x - 3.26 \times 10^{-3} & (-1/2000 \le x \le -1/3000) \\ y = 1735.345x - 5.59 \times 10^{-4} & (1/3000 \le x \le 1/2000) \end{cases} \tag{7}$$

4. Intelligent Analysis of the Effect of Different Construction Errors on Structural Cable Forces

It is worth considering the effect of the length errors occurring in multiple cables generally. The corresponding construction error conditions are set up in the finite element model in this research. Based on the principle of error analysis, different length errors are set for different cable elements. In addition, under the effect of construction errors, this research can obtain the force values for each cable in the structure. According to that, the maximum rate of change of the cable force of the whole structure can be obtained. It is mainly obtained by comparing the cable force of each cable under the error condition and the standard condition. During this research, a large number of construction error conditions will be developed, from which the corresponding maximum rate of change in cable force. After that, the corresponding data will be used as a dataset. Based on the principle of GA-BPNN [29], the effect of errors on the structural cable forces under different operating conditions is analyzed. Therefore, the effect of errors on the cable forces will be used as a reliable basis for maintaining the safety of the structure. In this research, the input to the neural network is the error in the length of each cable. In addition, the output is the maximum rate of change of the cable force in the structure.

4.1. The Principle of GA-BPNN

The weights and thresholds assigned to the BP neural network are random. When there are multiple minima in the network, the network will easily fall into the local minimum and fail to reach the global optimum. In addition, the randomly assigned weights and thresholds also have an impact on the speed of convergence. If the global search capability of the genetic algorithm can be exploited, the weights and thresholds of the BP neural network can be optimized. As a result, the speed of convergence can be improved, and the accuracy and stability of the prediction model can be enhanced as well [30,31].

Genetic algorithm optimization of the BP neural network can be divided into three parts. They are BP neural network structure determination, BP neural network genetic algorithm optimization, and BP neural network prediction [32]. In particular, the structure of the BP neural network is determined based on the number of input and output parameters of the fitting function. From this structure, the number of optimization parameters of the genetic algorithm is determined, which can determine the code length of the individual genetic algorithm. As for the first step of the BP neural network prediction, it will obtain the optimal individual by genetic algorithm. Then, the assignment of initial weights and thresholds to the network will predict the sample output after training [33].

The method of the BP neural network prediction uses genetic algorithms to optimize BP neural networks. Then, apply them to the prediction of creep in piezoelectric ceramics. Specifically, use a genetic algorithm to search globally for the weights and thresholds of the BP neural network to locate the range of optimal solutions. Make sure the populations of weights and thresholds are clustered in several places in the parameter space. Then, use the ability of the BP algorithm to find the optimal solution locally to obtain the optimal solution. It can significantly improve the prediction accuracy of the structural cable force. The GA-BPNN is set up as follows.

(1) Code the chromosomes. In neural networks, it is necessary to code the chromosomes. It helps to ensure that the network weights and thresholds cover the data with high accuracy. The coding length is expressed as Equation (8).

$$L = \alpha_1 \times \alpha_2 + \alpha_2 \times \alpha_3 + \alpha_2 + \alpha_3 \tag{8}$$

where L is the code length, α_1, α_2, α_3 are the number of neurons in the input layer, the hidden layer, and the output layer, respectively.

(2) Determine the fitness function. During the evolution of a neural network, the value of the fitness function should be continuously increased. In the process of training a neural network, the sum of squared errors of the BP network is used as the objective of the genetic algorithm. It is expressed in mathematical language as Equation (9).

$$\theta_m = 1/2\sum_{i=1}^{N} (\overline{y}(i) - y(i))^2 \tag{9}$$

where $\overline{y}(i)$ and $y(i)$ are the desired and actual output values of the network, respectively. N is the number of sampled data pairs for the training input and output of the network. When solving for the fitness function, introducing a sufficiently small positive value (ε) will ensure the validity of the fitness function. The fitness function is the inverse of the sum of squares of the errors, shown in Equation (10).

$$H(fit) = (\theta_m + \varepsilon)^{-1} \tag{10}$$

(3) Selection. Select the chromosomal individuals based on individual fitness. The probability of the No.i chromosome being selected is p_i, shown in Equation (11).

$$p_i = H(fit)_i \Big/ \sum_{i=1}^{n} H(fit)_i \tag{11}$$

where $H(fit)_i$ is the fitness of the No.i chromosome, n is the population size.

(4) Crossover. Arithmetic crossover is generally used to produce two new individuals. The mathematical expression for generating a new individual is given in Equation (12).

$$\begin{cases} x_A^{t+1} = \delta x_B^t + (1-\delta)x_A^t \\ x_B^{t+1} = \delta x_A^t + (1-\delta)x_B^t \end{cases} \tag{12}$$

where x_A^{t+1} and x_B^{t+1} is the new individuals from the arithmetical crossover by x_A^t and x_B^t, δ is a uniformly distributed random number between 0 and 1.

(5) Variation. Genetic mutation is required to avoid premature maturity. Assume that x_{max} and x_{min} are the maximum and minimum values of the initial individuals, respectively. Then the new gene value (x_n) after mutation is expressed as Equation (13).

$$x_n = x_{\min} + \mu(x_{\max} - x_{\min}) \tag{13}$$

where μ is a uniformly distributed random number between 0 and 1.

4.2. Analysis Process of Structural Cable Forces and Training of Neural Networks

By analyzing the basic principles of GA-BPNN, it was found that the method can effectively analyze the variation of structural cable forces. The forces are under the action of different construction errors. In this research, the maximum rate of change of the cable force in the structure was used as the input to the neural network. There were also different cable length errors, which were regarded as the output. The maximum rates of increase and decrease in the cable force were mainly considered as the critical effect. Moreover, the influence of construction errors on the safety of structures can be figured out clearly by analyzing the maximum changing rate of cable forces. For example, the partial construction errors of the stabilizing cables and the corresponding maximum changing rate in cable force of them are shown in Table 2. Based on the basic principles in Section 4.1, the flow of the structural cable force analysis based on the GA-BPNN is shown in Figure 9.

Table 2. Construction Errors and corresponding maximum change rates of cable forces (partial samples).

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Maximum Decline Rate	Maximum Increase Rate
a		c		b		−c									−0.24769	1.375694
	c		b		d		−e								−0.38166	1.637991
		e		d		−b		−c							−0.0903	0.151219
			c		b		−e		−c						−0.11244	0.61981
				b		e		−d		−e					−0.1421	0.574179
					−c		d		−e		b				−0.22223	0.101203
						−d		−c		b		d			−0.696	1.667778
							b		d		b		e		−0.55755	1.410635
								d		−e		e		−c	−0.16042	0.243047
c	d	−b	−c	e											−0.12157	0.103243

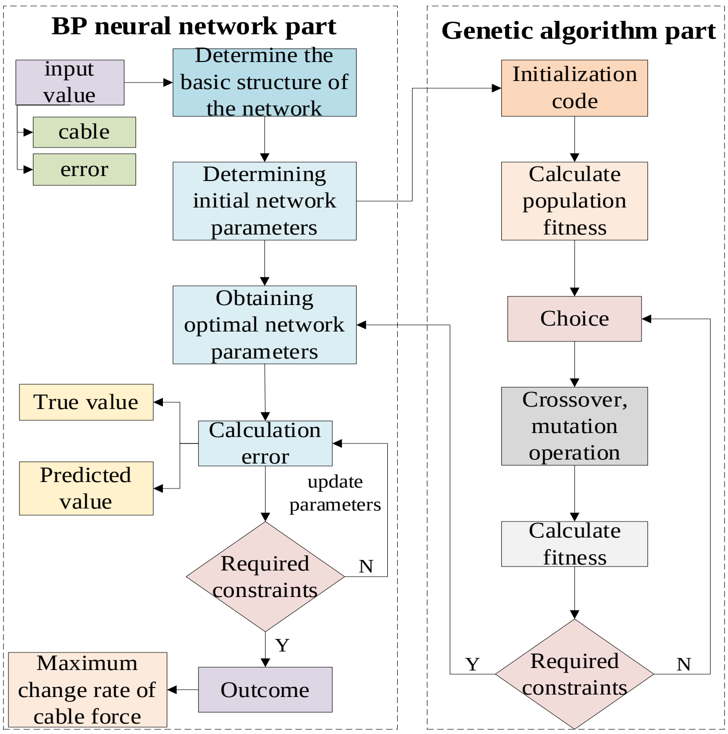


Figure 9. Analysis flow of structural cable force based on GA-BPNN.

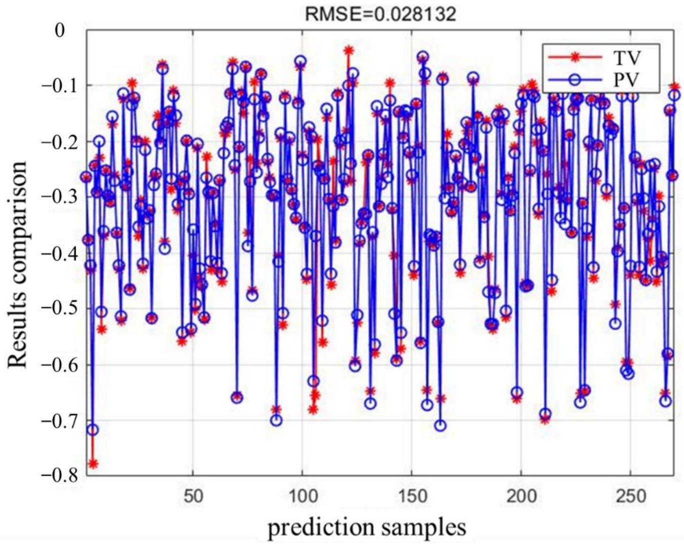
The structure contains fifteen stabilizing cables, with random errors in the length of the stabilizing cable arrangement in the finite element model. a, b, c, d, and e represents 1/2000, 1/2250, 1/2500, 1/2750, and 1/3000 of the span, respectively. They are used to obtain the maximum rates of decrease and increase in the cable force in the structure in the presence of errors.

Based on the cable force analysis process, predict the maximum rate of reduction of the cable force in the event of length errors in structures. The optimization parameters of the neural network are obtained by analyzing the drop rate of the cable force, ensuring the validity of the research method. As is shown in Figure 10, the neural network-based and finite element-based predictions of the maximum rate of drop in cable force have been compared. Especially when there are cable length errors. Due to space limitations,

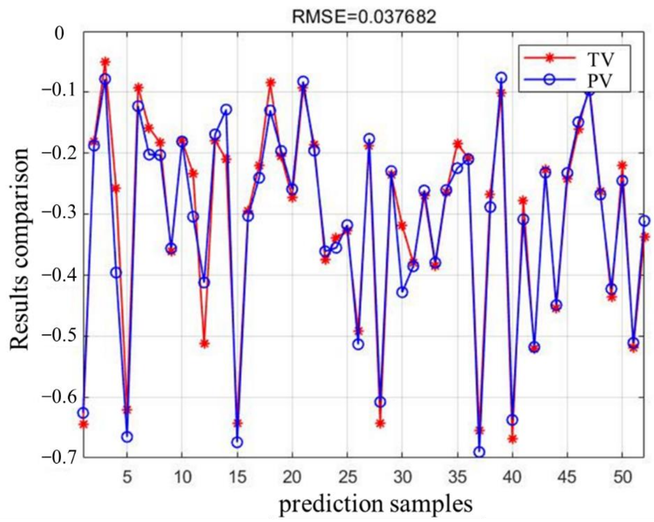
Figure 10 only shows a partial comparison of the working conditions. TV represents the true value, and PV represents the predicted value. This research is based on the root mean square error assessment method to evaluate the superiority of neural networks [34]. The mathematical language of the root mean square error is expressed in Equation (14).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(predicted_i - analytical_i)^2}{N}} \tag{14}$$

where $RMSE$ is the root mean square error, the range of which is [0, +∞). It equals 0 when the predicted value exactly matches the true value, which is called the perfect model. $predicted_i$ is the predicted value of the No.i sample, $analytical_i$ is the analytical value for the No.i sample, N is the amount of samples. By continuously optimizing the parameters of the neural network, the resulting predictive model has a high degree of robustness. For the training set, $RMSE$ is 0.02813. As for the testing set, $RMSE$ is 0.037682.



(**a**)



(**b**)

Figure 10. The prediction results of the maximum drop rate of cable force when different length errors occur in different cables. (**a**) Comparison of prediction results of some training samples. (**b**) Comparison of prediction results of some test samples.

Use a goodness of fit to assess the feasibility of neural networks in analyzing the changing rate of the cable force in a comprehensive way. In addition, the equation for calculating the goodness of fit is expressed as Equation (15).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(analytical_i - predicted_i)^2}{\sum_{i=1}^{N}\left(analytical_i - \overline{analytical_i}\right)^2} \quad (15)$$

where R^2 is the goodness of fit, $\overline{analytical_i}$ is the average value of the maximum rate of decline of the cable force in all samples. R^2 takes values on the closed interval from 0 to 1. The larger the value of R^2, the higher the degree to which the independent variable explains the dependent variable.. In addition, the more scattered points converge near the regression line. During the neural network analysis, R reached 0.97871 at the training phase, 0.99414 at the cross-validation phase, and 0.98904 at the testing phase. The neural network has high analytical accuracy throughout the whole process. The results of the fit of the neural network for the analysis of the falling rate of the cable forces are shown in Figure 11.

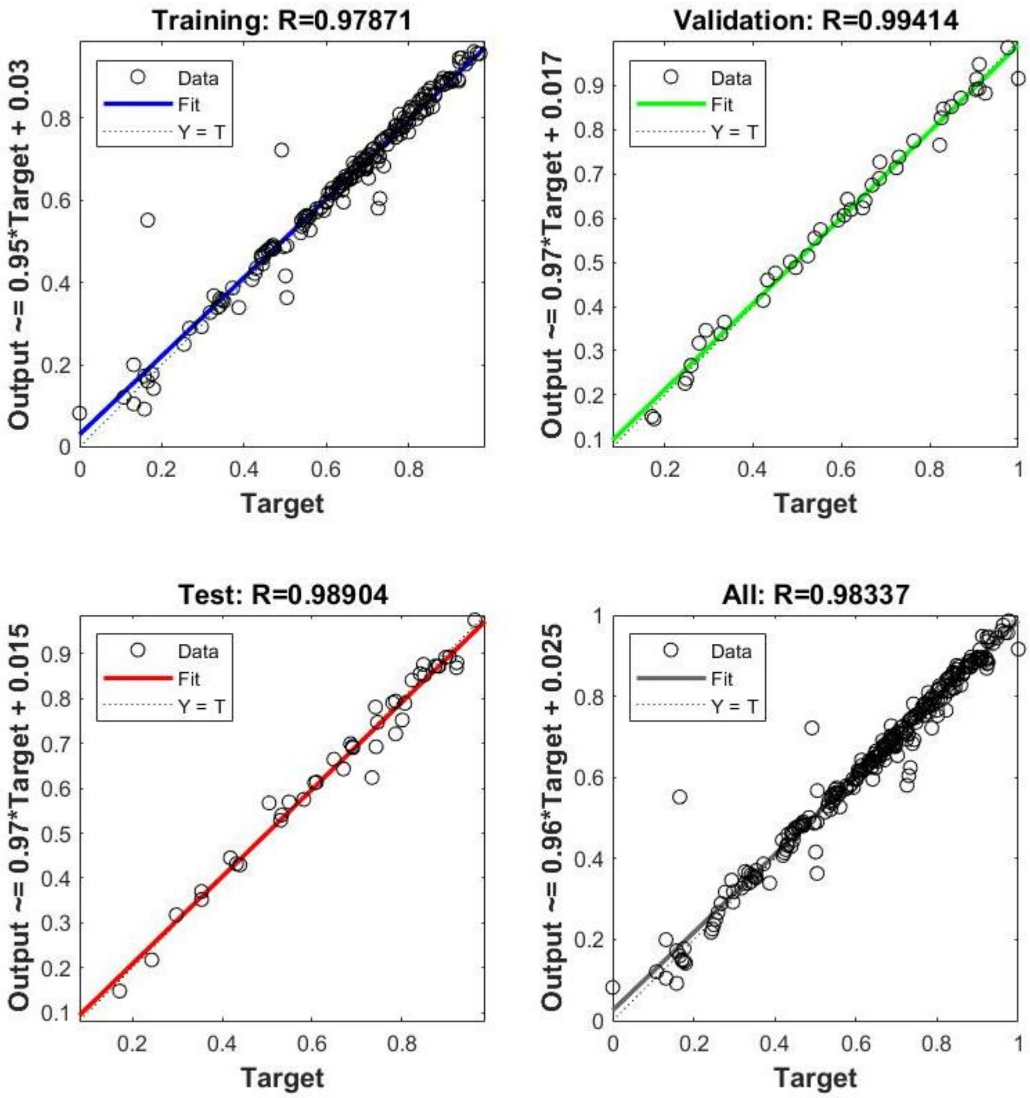


Figure 11. Fitting effect of neural network for cable force descent rate analysis.

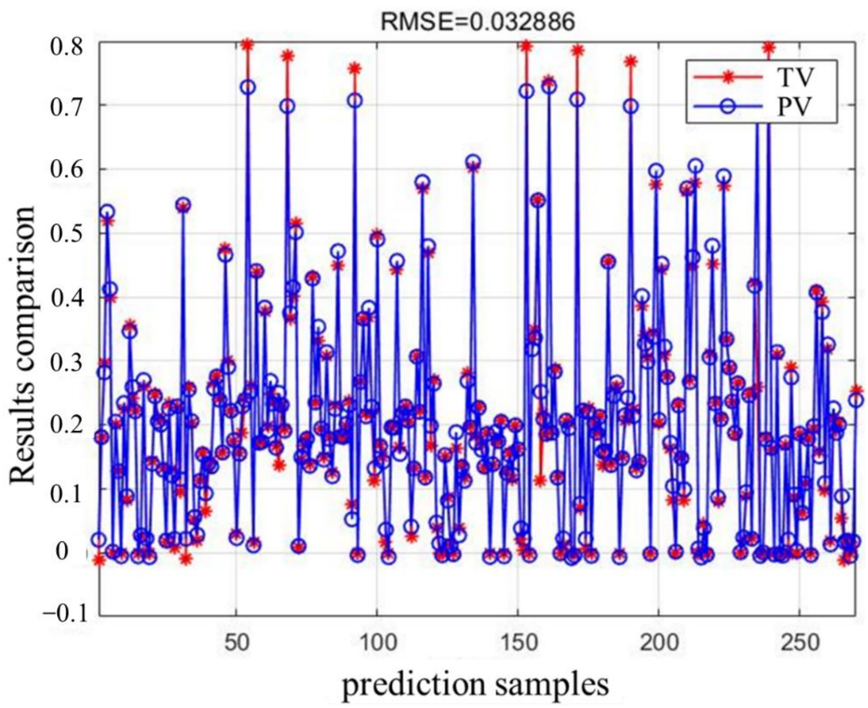
The use of genetic algorithms to optimize the weights and thresholds of the neural network improves the training capacity and prediction accuracy of the network. Although improving the shortcomings of the BP neural network, it is slow to converge and prone to fall into minimal values. However, it makes the prediction results more accurate and reliable. For the key parameters of the neural network, it can be obtained by analyzing the decreased rate of the cable force. The values of the key parameters in this study are shown in Table 3. According to Figures 10 and 11, it was found that the analysis model formed based on the principle of GA-BPNN can predict structural cable forces. In addition, the analysis process of the structural cable force can also accurately predict the trend of the structural cable force under different working conditions. This model guarantees the accuracy of the analysis while effectively improving the efficiency of the analysis at the same time.

Table 3. Values of key parameters of neural networks.

Parameter Type	Number of Hidden Layer Nodes	Maximum Number of Iterations	Learning Rate	Genetic Algebra	Population Size
specific value	10	1000	0.01	500	50

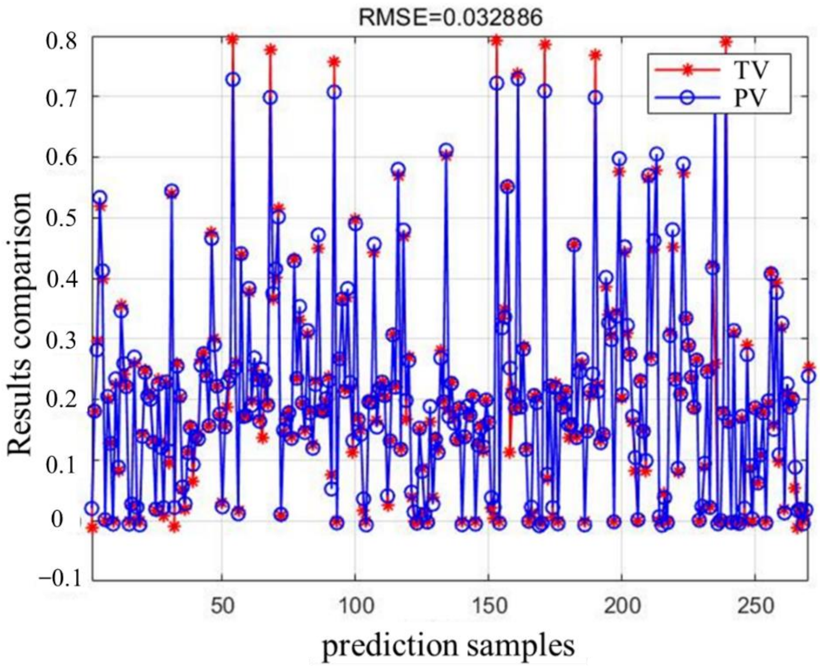
4.3. Neural Network-Based Analysis of the Effect of Construction Errors on the Maximum Rate of Cable Force Increase

The key parameters of the neural network are obtained in Section 4.2. In this section, the highly robust GA-BPNN obtained from training is applied to predict the elevation rate of the cable force under different operating conditions. As shown in Figure 12, the predicted and analyzed values of the maximum rate of increase in cable force are compared for different operating conditions. For the training set, *RMSE* is 0.02813. As for the testing set, *RMSE* is 0.037682.



(**a**)

Figure 12. *Cont.*



(**b**)

Figure 12. The prediction results of the maximum increase rate of cable force when different length errors occur in different cables. (**a**) Comparison of prediction results of some training samples. (**b**) Comparison of prediction results of some test samples.

The trained neural network was applied to predict the maximum rate of increase in cable force for different cable length errors. During the process of neural network analysis, R reached 0.97871 at the training phase, 0.99414 at the cross-validation phase, and 0.98904 at the testing phase. The neural network has a high analytical accuracy throughout the process. The results of the fit of the neural network for the analysis of the elevation rate of the cable force are shown in Figure 13.

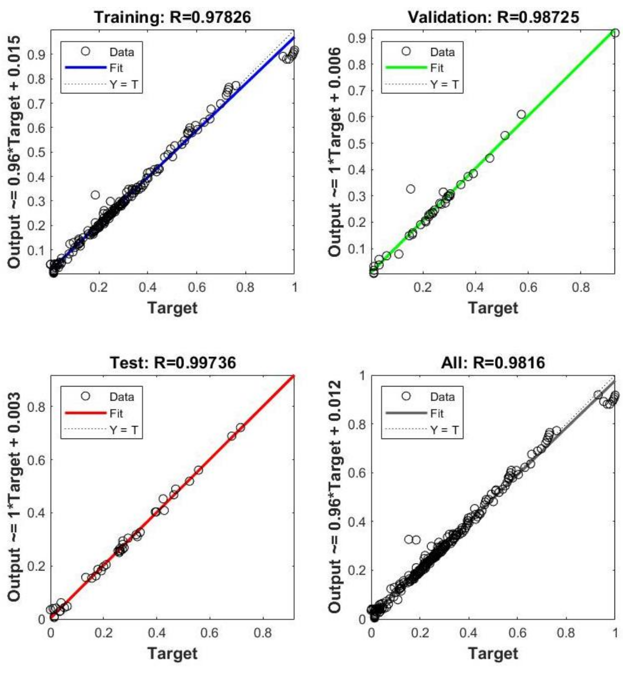


Figure 13. Fitting effect of neural network for analysis of cable force rise rate.

4.4. Discussion of Results

When analyzing the effects of different construction errors on structural rigging, the large number of structural elements results in a large volume of data [35]. In this research, GA-BPNN was applied to process a large amount of data. To be specific, take the error in the length of the different cables in the neural network as the input layer. The maximum rates of decrease and increase in the cable forces are the output layers. The layers are used to analyze the maximum decrease rate of the cable force and train the neural network.

Eventually, the specific values of the key parameters in the neural network can be obtained by calculating the error between the predicted and analyzed values. In practical engineering, the neural network is highly accurate in analyzing both the maximum rate of fall and rise of the cable force. To predict the influence of construction error on the rate of change of cable force, the key parameters of the neural network are determined. The number of hidden layer nodes is 10, the maximum number of iterations is 1000, the learning rate is 0.01, the genetic algebra is 500, and the population size is 50. As a result, the highly robust GA-BPNN is suitable for predicting the rate of rise of the cable force under different operating conditions. Meanwhile, the analysis results show that the neural network developed in this research has a high accuracy of analysis and a good capability of generalization. For the training set, $RMSE$ is 0.02813. As for the testing set, $RMSE$ is 0.037682. In terms of goodness of fit, during the process of neural network analysis, R reached 0.97871 at the training phase, 0.99414 at the cross-validation phase, 0.98904 at the testing phase, and in the entire sample set, R reached 0.9816.

Based on the GA-BPNN, this research enables an effective and accurate analysis of the effects of different types of construction errors on structural safety performance. The analysis of the maximum rates of decrease and increase in the cable force in a structure provides a holistic approach to force change. It can assess the safety status of a structure. According to the engineering specifications, the rate of reduction of the cable force after forming the structure cannot exceed 10%. In addition, the value of the cable stress cannot exceed 0.4 times the allowable stress. It is possible for GA-BPNN to provide a reliable basis for the safe maintenance of structures. Due to that, it can accurately analyze the effect of construction errors on structural rigging.

5. Conclusions and Future Works

In actual engineering, errors in the length of the cables during construction seriously affect the accuracy and efficiency of the structural safety analysis. The main reason is the large number of elements of large and complex cable network structures. This paper proposed a GA-BPNN-based method for analyzing the effect of construction errors on the cable forces of single-story orthogonal cable network structures. The roofing network in the speed skating stadium of the 2022 Winter Olympic Games can be used as an example of this research. It made the effect of construction errors on the cable forces of single-story orthogonal cable network structures be explored. In the course of the research, the following main conclusions were reached.

(1) The principles of analysis of construction errors have been clarified. For example, a range of member length errors is determined from engineering knowledge. Cable length errors are modeled in finite elements in terms of cell temperatures, and the structure mainly consists of load-bearing and stabilizing cables. The key force elements in this research were captured by arranging the length errors. The coupling between the maximum changing rate of the cable force and errors was obtained by setting different length errors in the critical force elements.

(2) Based on the GA-BPNN, it is possible to intelligently analyze the variation of cable forces when different errors occur simultaneously in multiple types of cables. The specific values corresponding to the key parameters in the neural network are obtained by analyzing the maximum descent rate of the cable force training. Furthermore, the trained neural network is highly robust and can accurately analyze the maximum rate of increase in the rope force.

This research has developed a method to intelligently analyze the variation of structural cable forces under the influence of construction errors. Based on the methodology developed in this research, the impact of construction errors on cable force response can be predicted effectively. On the one hand, this research method enables an overall assessment of the safety status of the structure. On the other hand, it provides a basis for the development of safety control measures for the structure during construction.

This study focuses on analyzing the influence of errors on the mechanical properties of the structure and obtains the key mechanical components. For the maintenance of the structure, the corresponding control measures and construction error control index have not been formed. In the future, forming accurate structural safety control measures for construction errors and obtaining the most unfavorable combination of construction errors and their control index will be the next research focus.

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