Article

Intelligent Analysis for Safety-Influencing Factors of Prestressed Steel Structures Based on Digital Twins and Random Forest

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Abstract: The structure of a prestressed steel structure is complex, which can result in insufficient control accuracy and the low efficiency of the structural safety. The traditional analysis method only obtains the mechanical parameters of the structure and it cannot obtain the key factors that affect the structural safety. In order to improve the intelligence level of the structural safety performance analysis, this study proposes an intelligent analysis for the safety-influencing factors of prestressed steel structures that is based on digital twins (DTs) and random forest (RF). Firstly, the high-precision twin modeling is carried out by the weighted average method. The design parameters and the mechanical parameters of the structure are extracted in real time in the twin model, and the parameters are classified by the RF. The fusion mechanism of the DTs and RF is formed, and the intelligent analysis model of the structural safety factors is established. Driven by the analysis model, the correlation mechanism between the design parameters and the mechanical parameters is formed. The safety state of the structure is judged by the mechanical parameters, and the key design parameters that affect the various mechanical parameters are analyzed. Through the integration of the design parameters and mechanical parameters, the intelligent analysis process of the safety-influencing factors of prestressed steel structures is formed. Finally, an intelligent analysis of the importance of the safety-influencing factors is carried out with the string-supported beam structure as the test object. Driven by the integration of DTs and RF, the key design parameters that affect the various mechanical parameters are accurately obtained, which provides a basis for the intelligent control of the structural safety.

Keywords: digital twin; random forest; prestressed steel structure; influencing factors; intelligent analysis

1. Introduction

Prestressed steel structures have the advantages of strong spanning capacities, beautiful shapes, light weights and short construction periods, and they are used in public buildings, such as in large stadiums [1]. At present, prestressed steel structures mainly include the cable dome structure [2]; the wheel spoke structure [3]; the cable truss structure, without the inner ring space [4]; the cable net structure [5]; the cable net shell structure [6] and so on. Prestressed steel cable is widely used in cable dome structures, and the compression rod is less and shorter, so that it can give full play to the tensile strength of the steel, and the structural efficiency is very high. The cable dome structure was applied to the gymnastics hall of the Seoul Olympic Games in South Korea. Radiated cable truss is mainly composed of an external pressure ring, cable truss and an inner pull ring. The Jabir Ahmed Stadium in Kuwait is a single-layer spoke cable truss. The ringless prestressed cable-supported structure system includes two categories: the ringless prestressed cable-supported structure system, and the ringless prestressed string-supported structure system. The Beijing Olympic Badminton Pavilion applies a cableless dome structure. The Beijing Winter Olympic Speed Skating Hall is the largest single-layer orthogonal cable-net structure in the world. The accurate safety maintenance of long-span spatial structures is also an
important standard for the measurement of the national construction technology and level. The mechanical properties of the components directly determine the safety performance of the structure [7]. In the structure, different design parameters have also become important factors that affect the structural safety state. Since large-span spatial structures are mostly used in buildings of high importance, the safety performance of the structures is strictly required [8–10].

Guo et al. [11] investigated the effect of the initial cable length error in the prestressing state on the sensitivity of prestressed cables to the length error. By controlling the length error, the prestress level during the cable tensioning was effectively improved. In order to ensure the stability of the construction process of cable dome structures, Zhang et al. [12] propose a joint-square double-strut cable dome structure. This structure effectively improves the safety control accuracy of the structure. Wang et al. [13] analyzed the most active parameters (e.g., the cable force) in the construction process of spatial-structure prestressed cables in the whole process of prestressed cable tension. The safety of the construction process structure is ensured by analyzing the cable force. Arezki et al. [14] investigated the effect of temperature variation on the safety performance of cable truss structures and cables. Basta et al. [15] studied the quantitative evaluation of the decomposability of the cable-net structure on the basis of building information modeling (BIM).

By analyzing the research of the abovementioned scholars, new structural forms and efficient technical methods are studied for the safety maintenance of prestressed steel structures. With the development of a new generation of information technology and the promotion of industrial information systems, the application of intelligent technology to engineering construction has become a research hotspot. The application of DTs and intelligent algorithms in engineering practice can significantly improve the accuracy and intelligence of the structural performance analysis [16,17]. The integration of DTs and intelligent algorithms can realize the virtual simulation of the safety state of prestressed steel structures, and it can form the association mining between the design parameters and the mechanical parameters. Finally, the key factors that affect the structural safety performance were obtained in order to achieve the precise maintenance of structural safety.

DTs simulate and depict the state and the behavior of physical entities with a dynamic virtual model with high fidelity. As a link between the real physical world and the virtual digital space, it is the key enabling technology for the realization of intelligent construction [18,19]. Artificial intelligence has been applied in many disciplines and has formed a variety of intelligent algorithms [20], which can extract high-level features from the original data for perceptual decision making, and can improve the objectivity and accuracy of the information evaluation [21]. Liu et al. [22] propose a DT-driven dynamic guidance method for fire evacuation. The method integrates the Dijkstra algorithm to realize the real-time acquisition of environmental information, the three-dimensional visualization of the indoor layout and evacuation path planning. Lu et al. [23] integrated DTs, machine learning and data analysis to create a simulation model that represents and predicts the current and future conditions of physical counterparts. The integration of technology promotes the implementation and development of smart cities. Acharya et al. [24] propose a visual positioning method to achieve the real-time and accurate positioning of indoor buildings. The 3D indoor model is used to eliminate the image-based indoor environment reconstruction requirements, and the deep convolution neural network is fused to fine-tune the image. Random forest (RF) has strong advantages in data processing, especially data classification. Bhuiyan et al. [25] conducted a comprehensive assessment of 17 developed economies by using RF methods, a fuzzy decision-making test and assessment laboratory methods. For a structural health monitoring and reliability analysis, Liu et al. [26] studied an uncertain dynamic load identification strategy combined with the Kalman filter algorithm and the RF model. Soleimani [27] propose a machine learning algorithm (the RF ensemble learning method) to evaluate the importance of the modeling parameters for estimating the seismic demand. The results of the RF analysis are helpful to better understand the seismic performances of bridges. Therefore, the integration of
DTs and intelligent algorithms provides new ideas and methods for the intelligent transformation and upgrading of the construction industry. Driven by DTs, the high-fidelity twin model of the structure is established. By extracting the structural safety indicators and their corresponding influencing factors in the twin model, the importance of various factors is analyzed by RF, which provides a reliable basis for structural safety control and maintenance.

In view of the demand for the intelligent analysis of the construction safety of prestressed steel structures, the advantages of DTs and intelligent algorithms are combined. Prestressed steel structures are mostly used in large public buildings, and their dynamic behavior needs real-time simulation. Therefore, building a high-fidelity simulation model based on DTs is a key step. In this study, an intelligent analysis method for the safety-influencing factors of prestressed steel structures that is based on DTs and random forest (RF) is proposed. Firstly, the construction method of the high-precision twinning model of the structure is formed on the basis of the weighted average method. By analyzing the fusion mechanism of DTs and RF, an intelligent analysis model of the structural-safety-influencing factors is formed from five dimensions. Driven by the analysis model, the correlation mechanism between the design parameters and the mechanical parameters is established. Design parameters are the influencing factors of the structural safety. The safety performance of the structure is reflected according to the mechanical parameters. The key design parameters that affect the structural safety performance are obtained by the classification of the mechanical parameters. When the structural mechanical parameters exceed the limit, the key design parameters can be corrected to accurately formulate the safety maintenance measures. The resulting theoretical method is applied to the analysis of the influencing factors of the safety performance of beam string structures. By analyzing the influence of the change in the design parameters on the mechanical parameters in the test structure, the correction of the key influencing factors can significantly improve the safety performance of the structure. This study provides a reliable basis for structural health monitoring by analyzing the key factors that affect the structural safety performance.

2. Construction of Structural Twin Model Based on Weighted Average Method

In the process of the intelligent analysis of the safety-influencing factors of prestressed steel structures, the establishment of a high-precision twin model is the first step. Firstly, the finite element model of the structure is established, which can simulate the mechanical properties in real time. In order to strengthen the simulation ability of the finite element model, it is necessary to modify the virtual twin model of the structural construction process. The average weighting method corrected the virtual model by combining the monitoring data of the real structure and the simulation data of the finite element model. The basic principle involves the selection of different weights for different location sensitivity indicators to achieve the goal of minimizing the sum of the squared Euclidean distances between the fusion results and each sensitivity indicator.

Assuming that the actual monitoring value of a certain mechanical parameter of each node of a cable in a prestressed steel structure under a certain working condition is $x_1, x_2, \ldots, x_n$, then the average value ($\bar{x}$) of the actual monitoring value is expressed as Equation (1):

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i$$

Then, the weight ($\omega_i$) of each mechanical parameter is expressed by Equation (2), which is expressed as:

$$\omega_i = \frac{1/d_i}{\sum_{i=1}^{n} (1/d_i)}$$

In the equation, $d_i$ is the Euclidean distance between the mechanical parameters and the average value of the mechanical parameters, which is expressed as Equation (3):

$$d_i = \|\bar{x} - x_i\|$$
Combined with the data of each node, the weighted average of the monitoring value of the mechanical parameters ($\hat{x}$) of the whole cable can be calculated, which is expressed as Equation (4):

$$\hat{x} = \sum_{i=1}^{n} \omega_i d_i$$  

(4)

According to the weighted average of the monitoring values of the mechanical parameters of each cable, the overall monitoring value ($D$) of the structure can be calculated, which is expressed as Equation (5):

$$D = \mu + \alpha_c \sigma$$  

(5)

where $\alpha_c$ is the confidence level of the mechanical parameter analysis, which is 1.5 in this study. $\mu$ and $\sigma$ denote the mean and the standard deviation of the weighted average of the monitored values of the mechanical parameters ($\hat{x}$) for each cable, respectively.

Similarly, by using the above steps, the simulation values ($D^*$) of the mechanical parameters in the finite element model can be calculated. By using Equation (6) to judge the fidelity of the simulation model, the correction of the virtual model is completed, which ensures that the simulation data effectively represent the mechanical properties of the real structure:

$$E_D = \frac{|D^* - D|}{D} \times 100\%$$  

(6)

In Equation (6), $E_D$ is a metric for determining the fidelity of the twin model.

3. Analysis Framework of Influencing Factors Driven by Fusion of DTs and RF

DTs provide an important theoretical basis and technical support for the bidirectional connection and real-time interaction between virtual space and physical space. DTs use digital technology and virtual model simulation technology to explore and predict the running state of physical space. DTs are a link to realize the interaction and seamless connection between physical space and virtual space, and they provide more real-time, efficient and intelligent services. The strong nonlinear fitting ability of artificial intelligence is suitable for analyzing complex mapping relations, and its generalization ability, reliability and robustness have breakthrough advantages over performance prediction methods. Artificial intelligence can dispense with the dependence on a large number of signal-processing technologies and diagnostic experience, and can complete the adaptive feature extraction and security state analysis. The high-fidelity behavior simulation of the structure state that is driven by online data is completed by DT technology, and the real-time-state visualization of the structure is realized. On the basis of the intelligent algorithm, the analysis of the structural safety performance data is realized. The integration of DTs and the intelligent algorithm provides a theoretical basis for the intelligent analysis of the influencing factors of the structural safety performance.

3.1. Fusion Mechanism of DTs and RF

By combining DTs with RF [29], a highly robust analysis model with good performance can be obtained. By combining the data characteristics that are required for training the RF and the historical data structure in the DT model, the rules for RF to obtain twin data information can be obtained. On the basis of the prediction results of the DTs, the adjustment suggestions for the structural safety maintenance are provided. The collaborative interaction mechanism between the DT model and the RF model is formed so as to establish the fusion mechanism of the structural-safety-influencing factors on the basis of the DT model and the RF (DTs-RF).

The integration of DTs and RF forms an intelligent analysis system for the structural-safety-influencing factors. Its essence is as follows: Through the twin model of the virtual space to realize the real physical space structure to the virtual space synchronous mapping, realize the visualization and digitization of all of the elements of the structural safety maintenance. Through the virtual model to simulate the reality, the collaborative feedback
makes it run synchronously with the physical construction, and it realizes the virtual mapping and virtual control. By integrating the data analysis method of RF, the intelligent analysis of the data-driven structural-safety-influencing factors is realized. Finally, the collaborative manipulation and interactive feedback of the physical dimension of the real maintenance system and the information dimension of the virtual maintenance system are formed. A new structural safety analysis and maintenance mode with iterative optimization and intelligent analysis is constructed.

As is shown in Figure 1, the fusion mechanism of DTs and RF is built. The basis of this fusion mechanism is the intelligent collection and dynamic perception of real structural safety information. In this study, intelligent sensing devices, such as 3D laser scanners and sensors, are used to intelligently collect and dynamically perceive the environmental and mechanical properties of the structure [30], thereby providing a basis for the establishment of the structural twin model and the intelligent analysis. Information management and the control platform, which are based on multisource heterogeneous data, are the core of the fusion of DTs and RF, which can analyze and predict the safety performance of the structure in real time. Finally, the unsafe state of the structure is corrected, and the feasibility of the correction is analyzed in the twin model so as to accurately guide and control the safety state of the structure over the whole life cycle.

![Figure 1. Fusion mechanism of DTs and RF.](image)

Through the analysis of the fusion mechanism of DTs and RF, it can be concluded that the intelligent analysis of the structural-safety-influencing factors that are driven by the fusion of the two has the following characteristics:

1. **Real-time perception reflects reality by virtuality.** Through the information collection of the physical construction system, and the establishment of the virtual model for the whole life cycle of the structure, the visual monitoring of the whole process of the safety-state change is realized. The whole process of the full-factor multidimensional and multiscale information fusion is realized, which provides a synchronous operation model for the construction structure site;

2. **Data-driven intelligent diagnosis.** Through the information management and control platform, the DT model is combined with the RF so that the system can make full use of historical data, real-time data collection, simulation data and other multiple-construction information. The system excavates and analyzes all kinds of data, in-
telligently diagnoses the structural safety over the whole life period and avoids the construction risk in time;

3. Scientific prediction with virtual control. The data model and the intelligent scheme established by RF and other means. Through the simulation of the twin model, the maintenance measures are finally fed back into the actual maintenance process to realize the intelligent safety control of the real structure over the whole life cycle.

3.2. Intelligent Analysis Model of Structural Safety Factors

In the intelligent analysis method for the safety-influencing factors of prestressed steel structures, finding the key design parameters that affect the various mechanical parameters of the structure is the core step. Driven by DTs, a multidimensional model is formed. Under the interaction and cooperation of the various levels of the multidimensional model, the intelligent analysis of the structural safety factors is realized. In the physical space, the effect of the sensor on the structure and the mechanical parameters of the structure are collected in real time. At the same time, the virtual model of the solid structure is created in the process of the finite element analysis. The corresponding working conditions are set in the model so as to simulate the twin data of the role of the structure and the mechanical properties of the structure. Thus, the twin simulation of the real structure is realized. The model foundation is established for the intelligent analysis of the safety-influencing factors of prestressed steel structures driven by DTs, which provides a basis for the structural safety performance maintenance. The multidimensional model for the intelligent analysis of the structural-safety-influencing factors is established by Equation (7). The twin simulation model consists of five dimensions:

\[
DT_M = (S_{pr}, S_{vm}, P_{td}, L_{fa}, C_n)
\]  

where \(DT_M\) is a multidimensional model for the analysis of the influencing factors of the structural safety; \(S_{pr}\) denotes a physical structure entity; \(S_{vm}\) refers to the virtual structure model; \(P_{td}\) is the twin data processing layer; \(L_{fa}\) equals the functional application layer; and \(C_n\) is a connection between the components. The twin model can realize the simulation mapping of the real structure, and it can process the structural parameters of real monitoring and virtual simulation. In the structure, the influence degrees of various design parameters are obtained by analyzing the change in the mechanical parameters. Thus, the design parameters of the structure can be modified when a mechanical parameter of the structure changes. Finally, the intelligent maintenance of the structure is realized. The multidimensional model for the analysis of the influencing factors of structural safety is shown in Figure 2. In the multidimensional model, the virtual–real interaction and the spatiotemporal evolution of the structural-safety-state changes are fully considered. In the perspective of the virtual–real interaction, the virtual structure model is established according to the physical structure entity to realize the real mapping of the security state, and it can provide feasibility verification for the final maintenance measures. From the perspective of the spatiotemporal evolution, with the change in the structural state, the design parameters and the mechanical parameters are constantly changing. Finally, the influencing factors of the safety performance are analyzed by analyzing the relationship between the mechanical parameters and the design parameters. Driven by DTs and RF, the real-time feedback of the structural safety state and the closed-loop control of the safety risk are realized.
4. Importance Analysis of Structural-Safety-Influencing Factors under Multisource-Parameter Fusion

Driven by the multidimensional model for the structural safety factor analysis, the correlation mechanism between the structural design parameters and the mechanical parameters is first clarified by the twin model. By classifying the mechanical parameters, the key design parameters that affect the structural mechanical parameters are obtained under the driving force of the RF. Therefore, when a certain mechanical parameter of the structure exceeds the limit, the key mechanical parameters are corrected to realize the safety control of the structure.

4.1. Correlation Mechanism between Design Parameters and Mechanical Parameters

The structures of long-span prestressed steel structures are complex, and the safety state changes in real time. The structural safety risk involves multiple factors, such as the cable prestress, the component stress, the configuration, the tensioning machine, the construction parameters, the environmental change and the safety management level. The corresponding data and risk prediction control are often out of state, which also affects the efficiency of the structural safety risk state judgment and the control decision.

In the process of structural construction safety prediction, the corresponding relationship between the design parameters and the mechanical parameters is extracted according to the simulation results. With the help of the intelligent algorithm, association rules between the data are mined. According to the characteristics of prestressed steel structures, the correlation mechanism between the design parameters and the mechanical parameters is formed during the construction and maintenance stages of the structure, which is expressed as Equation (8):

\[
 f(a_1, a_2, \ldots, a_m) \rightarrow g(b_1, b_2, \ldots, b_n) \quad (8)
\]
In the equation, \( f(a_1, a_2, \ldots, a_m) \) denotes the set of design parameters. \( a_1, a_2, \ldots, a_m \) denote the specific design parameters, such as the size of the member, the initial tension of the cable, the number of the structural pieces, etc.; and \( g(b_1, b_2, \ldots, b_n) \) represents the aggregate of the mechanical parameters. \( b_1, b_2, \ldots, b_n \), respectively, equal the specific mechanical parameters, such as the cable force, the stress and the vertical displacement of the structure. \( R \leftrightarrow \) denotes the corresponding relationship between the different design parameters and the mechanical parameters according to the technical standards and the data association rules of the structures. Driven by the association rules, the intelligent analysis of the influencing factors of the structural safety can be realized. The mechanical parameters of the structure are obtained by changing the design parameters, and the data set is formed to judge the key design parameters that are driven by RF.

4.2. Analysis Process of the Importance of Structural Safety Factors

By establishing the correlation mechanism between the design parameters and the mechanical parameters, the analysis set of the safety-influencing factors is formed. In the process of analysis, the mechanical parameters are classified, and the key factors are analyzed by RF. By constructing different sample training sets, the RF expands the differences among the classification models of the decision tree so as to improve the extrapolation prediction ability of the combined classification model [31–33]. A classification model sequence \( ([h_1(x), h_2(x), \ldots, h_K(x)]) \) is obtained through K-round training. At this time, a multiclassification model system is formed. The final classification result is obtained by using a simple majority voting decision, and the final classification decision is expressed as Equation (9):

\[
H(x) = \arg \max_Y \sum_{i=1}^{K} I(h_i(x) = Y)
\]  

(9)

In the formula, \( H(x) \) represents the combined classification model; \( h_i \) refers to the single decision tree classification model; \( Y \) denotes the output variable; and \( I(\cdot) \) is the indicative function. In the process of constructing the RF classification algorithm, it is necessary to set the number of decision trees and to ensure the maximum number of features when the model is optimal.

According to the correlation mechanism between the design parameters and the mechanical parameters and the classification of the mechanical parameters, the data samples of the mechanical analysis are formed. In the sample, the design parameters are used as the input elements, and the security level is used as the output element. A sample acquisition can be expressed as Equation (10):

\[
DP \xrightarrow{MP} \left\{ \begin{array}{l}
\overset{D_v}{\rightarrow} (A, B, C, D) \\
\overset{S_c}{\rightarrow} (A, B, C, D)
\end{array} \right.
\]

(10)

In the formula, \( DP \) represents the design parameters of the structure, and \( MP \) represents the mechanical parameters of the structure. The safety performance is characterized by the mechanical parameters of the structure. There are mainly two types of mechanical parameters in the prestressed steel structure: the vertical displacement (\( D_v \)) and the stress of the cable (\( S_c \)). The two types of mechanical parameters are classified into four grades \( (A, B, C, D) \). On the basis of the obtained samples, the training set and the test set of the analysis model are divided. Driven by RF, a high-precision mechanical property analysis model is established by adjusting the super-parameters. The grades of the various mechanical parameters can be judged by the designing parameters, and the key factors that affect the changes in the various mechanical parameters can be obtained. The key influencing factors of the mechanical parameters are the corresponding design parameters. The importance analysis process of the safety-influencing factors of prestressed steel structures is shown in Figure 3.
5. Analysis of Safety Factors of Beam String Structures

The data association mechanism of DT modeling is applied to RF to form an intelligent analysis method for the structural safety factors. The theoretical method is applied to the safety assessment of a beam string structure. The correlation mechanism between the design parameters and the mechanical parameters is established. Driven by this research method, the key design parameters are obtained through the classification of the structural mechanical parameters, and the intelligent analysis of the structural-safety-influencing factors is realized.

5.1. Test Structure Model

Taking the chord beam roof of a convention and exhibition center as the research object, one of the plane string structures is selected as the calculation model. One of the design parameters is taken in this study, and the model construction is shown in Figure 4. The span of the structure is \( L = 48 \text{ m} \), the rise height is \( 0 \text{ m} \), the sag is \( 3.5 \text{ m} \), and the number of struts is 9. The upper chord beam adopts H-shaped steel (Q345B). The pole adopts a round steel tube (Q235B). The lower chord cable adopts two types of 55 light-circle stress-relief steel wires.

In the process of the structural construction safety analysis, the size of the abovementioned chord beam, the size of the strut, the diameter of the lower chord cable, the number of struts, the arc of the lower chord cable and the initial tension of the lower chord cable are taken as the structural design parameters. The arc of the lower chord cable is used to reflect the length of each strut. In this test structure, the tangent value \((\tan \alpha)\) of the radian is expressed by Equation (11):

\[
\tan \alpha = \frac{h_s}{l_c}
\]  

(11)

In the equation, \( h_s \) represents the length of the mid-span brace, and \( l_c \) refers to the distance from the starting point of the lower chord cable to the midspan.
According to the design parameters, the mechanical parameters of the structure can be generated by setting the construction conditions in the finite element software. The main mechanical parameters that are analyzed in this study are the vertical displacement and the stress of the lower chord cable. The working condition that is considered in the construction process is: 0.9 × constant load + 1.5 × wind load.

5.2. Relationship between Design Parameters and Mechanical Parameters

In the analysis process of this structure, in order to accurately determine the mechanical parameters, two analysis models of the vertical displacement that correspond to the design parameters and the stress of the lower chord cable, respectively, are established. The values of the six design parameters, according to engineering experience, are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter Type</th>
<th>Taking Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of upper chord beam (mm)</td>
<td>H700 × 250 × 20 × 36, H700 × 250 × 16 × 20</td>
</tr>
<tr>
<td>Size of strut (mm)</td>
<td>φ150 × 8, φ160 × 8, φ170 × 8</td>
</tr>
<tr>
<td>Diameter of lower chord cable (mm)</td>
<td>50, 55, 60, 65, 70</td>
</tr>
<tr>
<td>Number of struts</td>
<td>7, 9, 11</td>
</tr>
<tr>
<td>Arc of lower chord cable (°)</td>
<td>8, 9, 10</td>
</tr>
<tr>
<td>Initial tension of the lower chord cable (KN)</td>
<td>600, 700, 800, 900, 1000</td>
</tr>
</tbody>
</table>

A high-precision finite element twin model is established by the weighted average method. Taking the combination of one of the design parameters as an example, the specific parameters are shown in Table 2. Among them, there are nine struts, the radian of the lower chord cable is 8° and the initial tension is 700 kN. The twin model of the structure is established under the correction of the weighted average method. Under the condition of self-weight, the accuracy of the twin model is verified by comparing the internal forces of each component in the experimental model to the twin structure. In the test, the internal force of each component is collected by the column tension-and-compression sensor. The comparison between the simulation value of the internal force in the twin model and the acquisition value of the internal force in the test structure is shown in Table 3. The internal force error of the component is within 3%, which realizes the high-fidelity mapping of the test structure. The test structure is symmetrical. Therefore, under the condition of self-weight, the internal force of half of the components in the structure is compared. The numbers of the components are shown in Figure 5.
The mechanical parameters of the twin model structure are shown in Figure 6. By comparing them with the parameters in the real structure, the high fidelity of the twin model is ensured. The structure forms that correspond to the other design parameters in 30 structural types. Limited to the length of the article, Table 4 shows the combinations of design parameters. Therefore, Table 5 shows the high fidelity of the twin model structure.

### Table 2. Sectional dimensions of components.

<table>
<thead>
<tr>
<th>Component Number</th>
<th>Size of Strut</th>
<th>Cable Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Section (mm)</td>
<td>Midportion (mm)</td>
<td>Right Section (mm)</td>
</tr>
<tr>
<td>H700 × 250 × 20 × 36</td>
<td>H700 × 250 × 16 × 20</td>
<td>H700 × 250 × 20 × 36</td>
</tr>
</tbody>
</table>

### Table 3. Comparison of internal force simulation values and acquisition values.

<table>
<thead>
<tr>
<th>Component Number</th>
<th>Simulation Value (N)</th>
<th>Acquisition Value (N)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140,377</td>
<td>140,253</td>
<td>0.088%</td>
</tr>
<tr>
<td>2</td>
<td>−6435</td>
<td>−6447</td>
<td>−0.186%</td>
</tr>
<tr>
<td>3</td>
<td>−6853</td>
<td>−6842</td>
<td>0.161%</td>
</tr>
<tr>
<td>4</td>
<td>−6907</td>
<td>−6893</td>
<td>0.203%</td>
</tr>
<tr>
<td>5</td>
<td>−6939</td>
<td>−6947</td>
<td>−0.115%</td>
</tr>
<tr>
<td>6</td>
<td>−6949</td>
<td>−6962</td>
<td>−0.187%</td>
</tr>
</tbody>
</table>

### Figure 5. Numbering of components.

5.3. Analysis of Structural Safety Factors

Driven by the correlation mechanism between the design parameters and the mechanical parameters, the mechanical properties of the structure are analyzed by integrating random forests. The mechanical properties of the structure are analyzed under the action of: 0.9 × constant load + 1.5 × wind load. In the high-fidelity twin model, the design parameters of the structure are set. The combination of the design parameters is selected according to Table 1. In this study, a total of 560 structural analyses were carried out in the combination of design parameters. Limited to the length of the article, Table 4 shows the design parameters and their corresponding mechanical parameters in 30 structural types. In the analysis process, the correlation between the design parameters and the mechanical parameters was established through 560 sample sets. The vertical displacement of the structure and the stress of the cable are important indexes to measure the safety performance of the structure. According to the analysis process in Section 4.2, various mechanical parameters are classified first, as shown in Table 5.
Table 4. Correspondence between different design parameters and mechanical parameters.

<table>
<thead>
<tr>
<th>Size of Upper Chord Beam (mm)</th>
<th>Size of Strut (mm)</th>
<th>Diameter of Lower Chord Cable (mm)</th>
<th>Number of Struts</th>
<th>Arc of Lower Chord Cable (°)</th>
<th>Initial Tension of the Lower Chord Cable (kN)</th>
<th>Vertical Displacement (mm)</th>
<th>Cable Stress (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H700 × 250 × 20 × 36</td>
<td>150×8</td>
<td>50</td>
<td>7</td>
<td>8</td>
<td>600</td>
<td>−21.8549</td>
<td>292.9</td>
</tr>
<tr>
<td>H700 × 250 × 20 × 36</td>
<td>160×8</td>
<td>55</td>
<td>7</td>
<td>8</td>
<td>700</td>
<td>−20.7268</td>
<td>269</td>
</tr>
<tr>
<td>H700 × 250 × 20 × 36</td>
<td>170×8</td>
<td>60</td>
<td>7</td>
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Table 5. Classification of various mechanical parameters.

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<th>Parameter Type</th>
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<td>Vertical displacement</td>
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<td></td>
<td>B</td>
<td>[−20 mm, −10 mm)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>[−30 mm, −20 mm)</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>[−40 mm, −30 mm)</td>
</tr>
<tr>
<td>Cable stress</td>
<td>A</td>
<td>[100 Mpa, 175 Mpa)</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>[175 Mpa, 250 Mpa)</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>[250 Mpa, 325 Mpa)</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>[325 Mpa, 400 Mpa)</td>
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In the process of the mechanical property analysis, vertical displacement and cable stress analysis models are established. Driven by random forests, the levels of the design parameters and of the mechanical parameters are taken as the input and output layers of the model, respectively. Through the analysis of the model, the key factors that affect the changes in the various mechanical parameters are found, as shown in Figure 7.

It can be seen from Figure 7 that the key factors that affect the vertical displacement and the cable stress in this structure are the number of struts and the radius of the lower chord cable, respectively. Therefore, when the safety performance of the structure exceeds the specification limit, the structural maintenance can be accurately carried out by adjusting the corresponding design parameters. In order to intuitively represent the influence of the key factors on the structural mechanical parameters, two types of design parameters, and their corresponding mechanical parameters, are extracted from the correlation mechanism of the design parameters and the mechanical parameters. The relationship between the key design parameters and the mechanical parameters is shown in Figure 8. In the string-supported beam structure, the greater the number of struts, the greater the initial tension of the lower chord cable, and the vertical displacement of the structure is relatively small. When the arc of the lower chord cable is smaller and the number of struts is greater, the corresponding
cable stress is relatively large. Therefore, when the mechanical parameters of the structure exceed the limit, the safety maintenance measures can be accurately formulated.

The limit values of the structural mechanical parameters are shown in Table 6. During the test, the mechanical parameters that correspond to different design parameters are compared and analyzed by setting the load conditions. At the same time, the change in the mechanical parameters is investigated by changing the key factors that affect the structural safety. In the process of the experimental verification, it was proven that the number of struts and the arc of the lower chord cable have the greatest influence on the vertical displacement and the cable stress of the structure. The experimental verification of the structural-safety-influencing factor analysis is shown in Figure 9. The intelligent analysis method for the safety-influencing factors of prestressed steel structures based on digital twinning and random forest that was formed in this study provides a basis for the safety maintenance of the structure.

Figure 6. Mechanical parameters of twin model structure: (a) vertical displacement; and (b) cable stress.
The influence of various design parameters on various mechanical parameters is shown in Figure 7. The parameters include size of upper chord beam, size of strut, diameter of lower chord cable, number of the strut, arc of lower chord cable, initial tension of the lower chord cable, etc. The importance of these parameters is shown in the bar chart. For vertical displacement, the parameters are arranged in order of importance, with size of upper chord beam being the most important, followed by size of strut, diameter of lower chord cable, number of the strut, arc of lower chord cable, initial tension of the lower chord cable, etc. For cable stress, the parameters are arranged in order of importance, with size of upper chord beam being the most important, followed by size of strut, diameter of lower chord cable, number of the strut, arc of lower chord cable, initial tension of the lower chord cable, etc.

In Figure 8, the relationship between key design parameters and mechanical parameters is shown. Figure 8a shows the relationship between number of the strut and vertical displacement. The vertical displacement increases with the number of the strut. Figure 8b shows the relationship between number of the strut and cable stress. The cable stress decreases with the number of the strut.

Figure 7. Influence of various design parameters on various mechanical parameters.

Figure 8. Relationship between key design parameters and mechanical parameters: (a) relationship between key design parameters and vertical displacement; (b) relationship between key design parameters and cable stress.
At the same time, RF is an important tool for data classification and analysis. Therefore, the establishment of a twin model can accurately reflect the state of the structure. This study, which is based on DTs, can effectively map the state of the test structure. On the same basis of the two improves the intelligence level of the structural analysis. The traditional analysis method only simulates the mechanical properties of the structure by setting the load conditions. In this study, taking the chord-supported beam roof of a convention and exhibition center as the research object, the effectiveness of this method is verified. Firstly, the twin model of the structure is established on the basis of the weighted average method. By comparing the simulation value and the collected value of the internal force of the component, it is verified that the twin model has high fidelity. The analysis model that is established in this study, which is based on DTs, can effectively map the state of the test structure. On the basis of the twin model, the mechanical parameters of the structure are obtained by adjusting the different design parameters under load conditions. In the research process, the correlation mechanism between the design parameters and the mechanical parameters was established. The vertical displacement of the structure and the stress of the cable are important indexes for measuring the safety performance of the structure. Driven by RF, the key design factors that affect the two types of mechanical parameters are obtained. Therefore, the intelligent analysis method that is formed in this study can provide a reliable basis for the safety maintenance of the structure. At the same time, large-span spatial structures are mostly used for buildings of high importance, such as large public buildings. In the construction and operation of the structure, it is necessary to strictly ensure safety and reliability. Therefore, the analysis of the structural safety factors is very necessary. The establishment of a twin model can accurately reflect the state of the structure. This method can predict the mechanical properties of the structure by setting the load conditions. At the same time, RF is an important tool for data classification and analysis. Therefore, the combination of the two improves the intelligence level of the structural analysis. The combination of DTs and RF can accurately obtain the key factors, on the one hand, and can accurately reflect the safety state of the structure, on the other hand. This research method can assist with the formulation of structural safety maintenance measures.

Table 6. Limits of mechanical parameters of structures.

<table>
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<tr>
<th>Mechanical Parameter</th>
<th>Specific Limits</th>
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<tr>
<td>Perpendicular displacement</td>
<td>Less than 1/250 of structural span</td>
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<tr>
<td>Cable stress</td>
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</table>

Figure 9. Experimental verification of structural safety influence factor analysis.

5.4. Results Analysis

How to realize an intelligent safety performance analysis of long-span spatial structures is an important research direction. The traditional analysis method only simulates the mechanical properties by the finite element method, which cannot accurately and efficiently obtain the key factors that affect the structural safety performance. In this study, and on the basis of the previous research and the application of DTs and RF, the intelligent analysis of the safety-influencing factors of prestressed steel structures based on DTs and RF is proposed. Taking the chord-supported beam roof of a convention and exhibition center as the research object, the effectiveness of this method is verified. Firstly, the twin model of the structure is established on the basis of the weighted average method. By comparing the simulation value and the collected value of the internal force of the component, it is verified that the twin model has high fidelity. The analysis model that is established in this study, which is based on DTs, can effectively map the state of the test structure. On the basis of the twin model, the mechanical parameters of the structure are obtained by adjusting the different design parameters under load conditions. In the research process, the correlation mechanism between the design parameters and the mechanical parameters was established. The vertical displacement of the structure and the stress of the cable are important indexes for measuring the safety performance of the structure. Driven by RF, the key design factors that affect the two types of mechanical parameters are obtained. Therefore, the intelligent analysis method that is formed in this study can provide a reliable basis for the safety maintenance of the structure. At the same time, large-span spatial structures are mostly used for buildings of high importance, such as large public buildings. In the construction and operation of the structure, it is necessary to strictly ensure safety and reliability. Therefore, the analysis of the structural safety factors is very necessary. The establishment of a twin model can accurately reflect the state of the structure. This method can predict the mechanical properties of the structure by setting the load conditions. At the same time, RF is an important tool for data classification and analysis. Therefore, the combination of the two improves the intelligence level of the structural analysis. The combination of DTs and RF can accurately obtain the key factors, on the one hand, and can accurately reflect the safety state of the structure, on the other hand. This research method can assist with the formulation of structural safety maintenance measures.

6. Discussion and Conclusions

In this study, an intelligent analysis method for the safety-influencing factors of prestressed steel structures based on DTs and RF is proposed. This method effectively improves
the maintenance accuracy and efficiency of the structural safety state. The dynamic simulation of the structural safety state is realized by DTs, and the design parameters and mechanical parameters of the structure are obtained. The importance analysis of the influencing factors of the structural safety is realized by RF. The intelligent analysis of the influencing factors of the structural safety performance formed by the integration of RF and RF was applied to the beam string structure, and the effectiveness of this research method is verified. By analyzing the key factors that affect the structural mechanical parameters, a reliable basis is provided for the safety maintenance of the structure. The main conclusions are as follows:

1. In the process of the safety intelligent analysis of prestressed steel structures, the establishment of a high-precision twin model is the first step. The high-fidelity mapping of the finite element model to the real structure can be realized by the weighted average method. The resulting high-fidelity twin model can directly extract the structural design parameters and their corresponding mechanical parameters;

2. The twin model obtains the structural parameters. Driven by RF, an intelligent analysis model of the structural-safety-influencing factors can be formed. The model is divided into five modules, with full consideration to the virtual–real interaction and the spatiotemporal evolution of the structural-safety-state changes;

3. Driven by the intelligent analysis model, the correlation mechanism between the design parameters and the mechanical parameters of the structure is formed. The design parameters are the influencing factors of the structural safety. The safety performance of the structure is reflected according to the mechanical parameters. The key factors that affect the safety performance of the structure are obtained as the basis for the formulation of safety maintenance measures.

In the process of the experimental verification of a beam string structure, it was proven that the number of struts and the arc of the lower chord cable have the greatest influence on the vertical displacement and the cable stress of the structure. Therefore, when the mechanical parameters of the structure exceed the limit, the key factors can be corrected to improve the safety performance of the structure. The research method provides a basis for the safety, high precision and high efficiency maintenance of the structure. In the future, the intelligence level of the structural safety maintenance will be improved through the consideration of more realistic conditions. Under various load conditions, the relationship between the design parameters and the mechanical parameters can be quantitatively determined by correcting the key factors and by formulating efficient safety maintenance measures.

**Author Contributions:** Conceptualization, H.Z.; methodology, H.Z.; software, H.Z.; validation, H.Z. and Y.W.; writing—original draft preparation, H.Z.; writing—review and editing, H.Z.; project administration, H.Z.; funding acquisition, H.Z. All authors have read and agreed to the published version of the manuscript.

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References


33. Tan, J.; Xie, X.; Zuo, J.; Xing, X.; Liu, B.; Xia, Q.; Zhang, Y. Coupling Random Forest and Inverse Distance Weighting to Generate Climate Surfaces of Precipitation and Temperature with Multiple-Covariates. *J. Hydrol.* 2021, 598, 126270. [CrossRef]