

Research Article

Digital Twin-based Safety Evaluation of Prestressed Steel Structure

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The safety of prestressed steel structures in service has been studied widely. However, traditional safety assessment methods for prestressed steel structures involve few sample points, do not provide accurate predictions, and consume substantial human and material resources. The digital twin technology can be used to monitor the structural behavior, state, and activity of a steel structure throughout its life cycle, which is equivalent to performing a safety assessment of the structure. The purpose of this study is to establish a digital twin multidimensional model of prestressed steel structures. Based on this model, the support vector machine and prediction model are trained using the relevant structural history data, and the safety risk level of the structure is then predicted based on the measured data. Finally, a proportional reduction model of the wheel-spoke cable truss structure is used to verify the feasibility of the proposed method. The results show that digital twin technology can achieve real-time monitoring of prestressed steel structures in use and can provide timely predictions of the safety level. This represents a new method for the safety risk assessment of prestressed steel structures.

1. Introduction

The prestressed space steel structure has a unique shape and simple appearance and can improve the structural force, stiffness, and stability of engineering structures; this ensures structural safety as well as a visually pleasing design. Therefore, prestressed space structures have been widely used in large stadiums in recent years. However, the longer a structure is in service, the more it is affected by various uncertain factors, such as component failure, temperature effects, loss of prestress, and bar construction error; this adversely affects the structural safety; therefore, the mechanical performance and reliability of prestressed structures are very important.

In general, the safety assessment process of prestressed steel structures in service is to determine the change rule of the structure under various damage conditions according to the actual principle of the structure, provide the degree of influence of each damage condition on each member of the prestressed steel structure, and finally determine the sensitivity and curve change of variables such as prestress

loss to the structure and the structural material. Scholars worldwide have studied the methods to realize structural safety assessment [1]. Qiang et al. studied the reliability of steel structural roof members under snow loads, based on ground snow load samples simulated using the snow melting model [2]. A semianalytical simulation method combined with numerical simulation was proposed by Li and Li to study the reliability of the structural assessment system [3]. Jiang et al. analyzed the reliability of high strength steel (HSS) built-up box column under different welding processes [4, 5]. Deng et al. used the secondary development of Revit to build a construction hazard source safety management system [6]. In conclusion, although the existing research methods can achieve safety assessment to a certain extent, analysis software such as ABAQUS and ANSYS are usually used for analysis and calculation, but it is difficult to determine the boundary conditions of the study, and in service, it is even more complicated, with fewer sample points and lack of prediction; hence, it may not be ideal for safety assessment of the prestressed steel structures in service.

With the advent of the “Industry 4.0” era, digital twin technology has become a feasible and effective method to achieve intelligent construction. The concept of digital twin was first proposed by Professor Grieves. The digital twin system includes physical space, virtual space, and mutual data interaction. In 2012, NASA applied digital twins to aircraft maintenance and quality monitoring. Concurrently, it provided a clear definition of digital twin: “digital twin” is a multidisciplinary, multiphysical, multiscale, and multidimensional simulation process that makes full use of the entity model, perceptron, and real-time data. It mirrors the physical entity in virtual digital space reflecting the entire life cycle process of the physical entity’s behavior, state, or activity [7, 8]. In recent years, digital twin technology has developed rapidly and has been increasingly used in the design, construction, operation, and maintenance of buildings. Lu and Brilakis realized digital twin automation of reinforced concrete bridges using a slicing-based object fitting method [9]. Shim et al. proposed a new generation bridge maintenance system based on the concept of the digital twin model [10]. In general, digital twin technology can realize the interactive fusion of the physical space and information space of the prestressed steel structure in service. Users can collect real-time information of the physical structure through the virtual structure and use neural networks to extract the correlation features of the data, and the safety assessment is then conducted on this basis. Corresponding maintenance measures can be applied to the physical structure based on the assessment results of the virtual structure to ensure the safe service of the building, which is in line with the basic concept of analysis, evaluation, and application of the data during the safety assessment process of the prestressed steel structure during service. Therefore, digital twin technology provides new method for the safety assessment of prestressed steel structures.

2. Safety Assessment Method Based on Digital Twins

2.1. Framework Structural Safety Assessment. According to the structural characteristics and safety requirements of prestressed steel structures, guidelines for the structural safety assessment are proposed, as shown in Figure 1. Firstly, a virtual model of the prestressed steel structure is built according to the physical building, and sensors are arranged on the physical building to collect the cable force, displacement, and other data during the service of the structure. The data are then transmitted to the master computer through the serial communications in order to realize the collection and interaction of the data related to the service process of the prestressed steel structure. Before using the structure, a sensor is installed on it to collect and store the structural data. The data of structural displacement or cable force change in the physical layer can be mapped to the virtual layer in real time. Structure-related data are stored in the twin data service system. Based on these data, the structure is evaluated for safety. In addition, the measured data, digital model, and evaluation results of the structure can be viewed in real time on the web page; thus, visual

management is achieved. This study focuses on the structural safety risk assessment method based on the digital twin multidimensional model under the above framework.

2.2. Digital Twin Multidimensional Evaluation Model.

The definition of safety risk assessment is, from a risk management perspective, using scientific methods to systematically analyze the threats and vulnerabilities, then assess the degree of damage if a damage should occur, and finally propose targeted protective countermeasures and corrective measures against threats [11–13]. Subsequently, safety risk assessment is conducted based on digital twins. In combination with the safety risk assessment framework and the five-dimensional model of digital twins [14, 15], a multidimensional model for the safety risk assessment is proposed in this study, as shown in the following equation:

$$M_{SDT} = (B_{PE}, B_{VE}, S_S, DD, OA, CN). \quad (1)$$

where M_{SDT} represents the multidimensional model of security risk assessment; B_{PE} represents the building physical structure; B_{VE} represents the building virtual structure; S_S represents the security risk assessment service for structures; DD represents the data related to security risk assessment; OA represents a risk assessment algorithm for processing data; and CN represents the connection between the various components. The security risk assessment process based on digital twins is shown in Figure 2.

In the aforementioned evaluation model, B_{VE} is composed of the geometric model (B_{GVE}), physical model (B_{PVE}), behavior model (B_{BVE}), and rule model (B_{RVE}). B_{GVE} is established using three-dimensional (3D) laser scanning technology for 3D modeling. B_{GVE} needs to be characterized by the dimensions, installation position relationship, and other information for each member of B_{PE} . Finite element analysis software is used to simulate and analyze the 3D model and build B_{PVE} . B_{BVE} describes the real-time variation of the structure under the action of different factors. B_{RVE} refers to the classification of the safety level of the structure based on relevant norms and expert experience. DD includes the measured data (DD_1) obtained by arranging the sensors and historical related data (DD_2). OA represents the processing of DD , from which an algorithm to predict the structure security level is obtained.

2.3. Support Vector Machine Model. A support vector machine (SVM) is a small-sample training method, which can produce better training results with fewer samples of data and can thus eliminate the requirement of collecting data samples of prestressed steel structures [16]. The SVM model consists of training and recognition stages. In the first stage, input and output samples are selected according to the actual problem, and the SVM is trained using existing data to obtain the maximum margin hyperplane. In the second stage, the input data are from unknown samples and output data are those recognized by the SVM [17].

The SVM model is built using the LIBSVM software package [18] developed by Professor Lin Chin-Jen of Taiwan

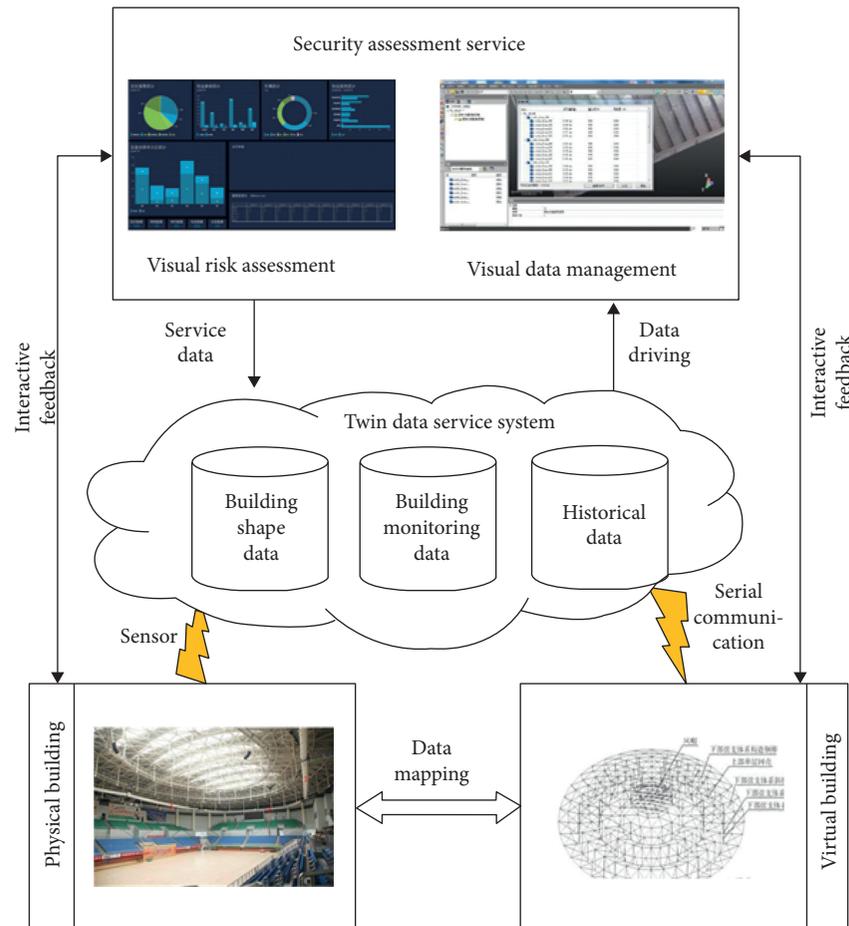


FIGURE 1: Framework of structural safety assessment.

University. LIBSVM not only contains the source code but also provides the executable file, which is user-friendly and easy to operate. LIBSVM is widely used for classification regression and distribution estimation [19]. The general steps for using LIBSVM are as follows:

- (1) Select the sample set according to the format requirements of the LIBSVM software package
- (2) Process the sample set
- (3) Choose an appropriate kernel function
- (4) Choose the optimal combination of parameters penalty coefficient C and kernel function parameter g
- (5) Train the entire training set with the optimal parameter combination to obtain the SVM model
- (6) Use the obtained training model to predict the test sample

2.4. Security Evaluation Method Based on Digital Twin and SVM. Combining the multidimensional model based on digital twin proposed in 1.2 and the SVM model proposed in 2.1, the safety risk assessment method of the prestressed steel structure based on digital twins and SVM is proposed. The required steps include establishing the digital twin

multidimensional model and training the SVM using the collected data to obtain the structural safety risk assessment model.

The specific steps of the SVM method are as follows:

- (1) Select and process the data: the sample data are derived from the monitoring data during service (DD_1) and the related historical data (DD_2) of B_{VE} . To avoid overfitting, at least 80% of the data are selected as input for SVM model training. The remainder is used to test the accuracy of the model, and the sample data need to be randomly scrambled. The training sample set is $\{x_i, y_i\}, i = 1, 2, \dots, n$, where feature vectors of x_i are different factors affecting the B_{PE} structure safety.
- (2) Choose the kernel function: in the safety evaluation algorithm (OA), selecting the appropriate kernel function is an important step. Polynomial and radial basis kernel functions are relatively common types of kernel function; the latter is superior in terms of calculation accuracy and other performance criteria. Therefore, this study selects radial basis as the preferred kernel function.
- (3) Select the optimal parameter combination of C and g : in this study, a cross-validation method is

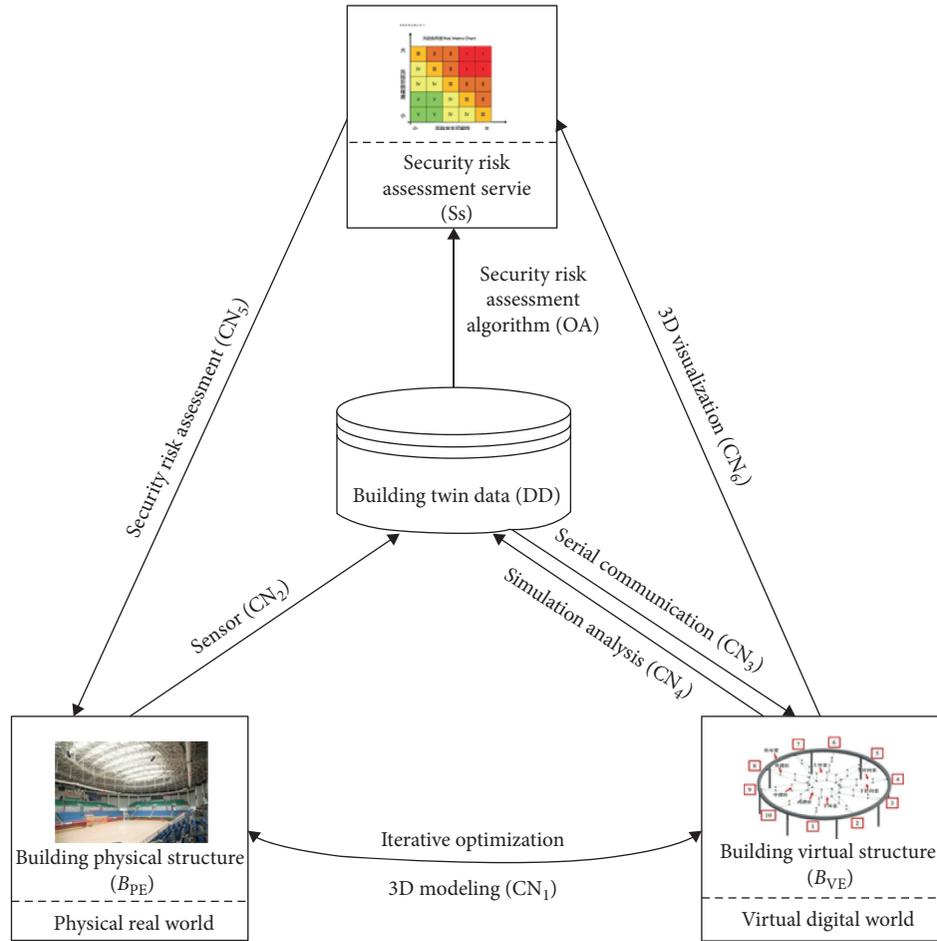


FIGURE 2: Digital twin-based security risk assessment process.

used to search for the optimal combination of C and g .

- (4) Train and test the model: in the entire security assessment service process (S_s), model training and testing are the core elements. Input the training samples selected in (1) and output the structural security level to train the network. The remaining samples are used for testing; thereby, a security risk assessment SVM model of B_{PE} is established. The structural safety risk level obtained by the training test sample is compared with the actual risk level. The higher the accuracy of the model, the stronger its predictive ability [20].
- (5) Predict the security level: the test samples are selected from DD_1 . Input the test sample and output the structural security level. The security risk level of B_{PE} is predicted; thus, the security risk assessment service of B_{PE} (S_s) is implemented. The process is shown in Figure 3.

3. Case Study

3.1. Model Description. The wheel-spoke cable truss is an important form of the prestressed steel structure. Its shape is similar to that of a bicycle wheel. It is commonly used in

large exhibition halls and Ferris wheels [21]. In the process of using the wheel-spoke cable truss, due to influences such as temperature changes [22], material corrosion, complex loads, and prestress loss, the overall structure or local components show different degrees of damage, resulting in the shortening of its life cycle and adverse impact on human life and property safety. Therefore, it is particularly important to evaluate the safety of wheel-spoke cable trusses in service. In this study, a proportional reduction model of the wheel-spoke cable truss structure is taken as an example.

The experimental model built in this study is a reduced scale test model based on a certain wheel-spoke cable truss project. Compared with the actual project, the scale ratio of the test model is 1:10, the cross-sectional area ratio of the cable is 1:100, and the materials are identical. The structure span of the test model is 6 m and consists of 10 radial cables, ring cables, braces, nodes, outer ring beams, and steel columns. The radial cables include upper radial and lower radial cables, and the ring cables include upper ring and lower ring cables. The struts include outer, middle, and inner struts, as shown in Figure 4. The installation and construction process of this test model are as follows:

- (1) Installation of the steel columns and outer ring beam: the steel columns in the lower part are positioned and installed for the complete unit, and then the

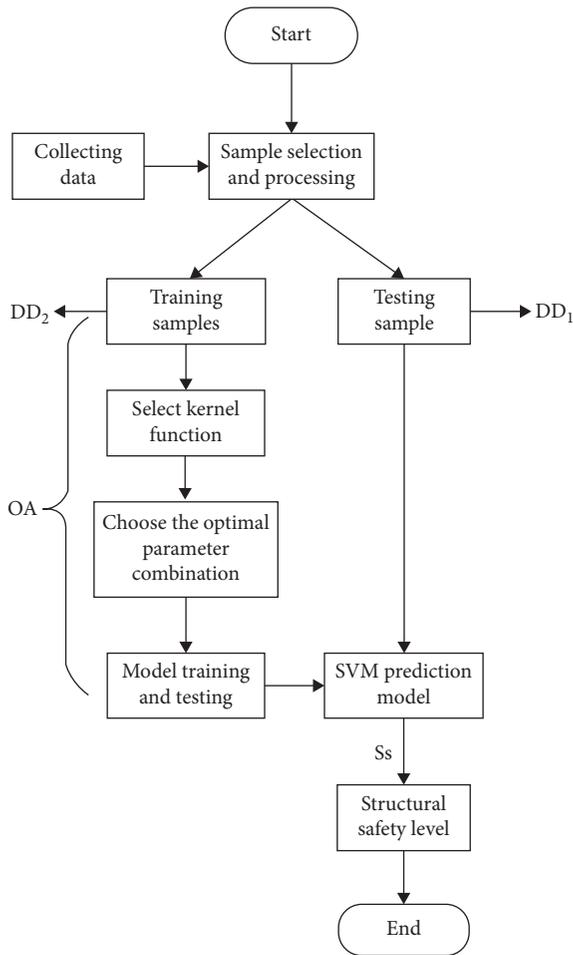


FIGURE 3: Digital twin and SVM-based security evaluation model.

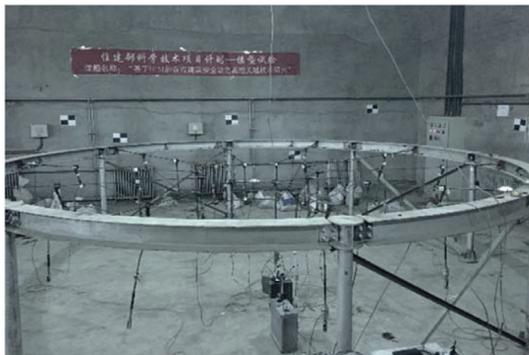


FIGURE 4: Test model.

outer ring beam and steel columns are connected by bolts.

- (2) Installation of the upper ring cable and the upper radial cable: assemble the upper radial cable and the upper ring cable on the ground. Connect the 10 upper radial cables and upper ring cable in radial form according to the coordinates. Install the upper ring cable and upper radial cable clip after completion of the connection.

- (3) Tensioning of the upper radial cable: use the guide chain to tension the upper radial cable. When the upper radial cable is sufficiently high above the ground to install the struts, install the inner, middle, and outer struts, and the lower ring and lower radial cables. The guide chain is used to tension the upper radial cable. After the upper radial cable is tensioned in place, the upper radial cable head and the ear plate of the outer ring beam are connected using a pin.
- (4) Tensioning of the lower radial cable: adjust the sleeve to adjust the length of the lower radial cable to the structure forming state and finally install the lower radial cable.

3.2. Application Framework of Safety Assessment Method.

Based on the method proposed above, this study proposes the safety risk assessment theory, as shown in Figure 5. Firstly, a virtual model (B_{VE}) is built according to the structure entity (B_{PE}); then, sensors (CN_2) are suitably arranged on B_{PE} to collect and store the internal force data. There is a change in the cable force of B_{PE} while operational will synchronously reflect on B_{VE} , thus realizing the dynamic synchronization of physical space and virtual space. The data (DD_2) collected by the experimental model are used to train the model. Based on the monitoring data (DD_1), the trained SVM model is used to perform the security assessment of the physical structure in the physical layer; thus, the risk prediction for the structure (S_s) is achieved. In addition, B_{VE} and DD collected by the sensor can be displayed in real time on the web page, where the relevant personnel can also view the final structural safety level. This study explored these functions.

Based on the method proposed above, this study proposes a set of safety risk assessment theory, as shown in Figure 5. Firstly, a virtual model (B_{VE}) is built according to the structure entity (B_{PE}), and then sensors (CN_2) are reasonably arranged on B_{PE} to collect and store the internal force data. The change of cable force of B_{PE} in the process of use will be reflected on B_{VE} in synchronously, which realizes the dynamic synchronization of physical space and virtual space. The data (DD_2) collected by the experimental model is used to train the model. Based on the monitoring data (DD_1), the trained SVM model is used to carry out security assessment for the physical structure in the physical layer, realizing the risk prediction service of the structure (S_s). In addition, B_{VE} and DD collected by the sensor can be displayed in real time on the web page, and the relevant personnel can also view the final structural safety level on the web page. This study explored these functions.

3.3. Application Based on Digital Twin Model Security Assessment.

The B_{VE} of the wheel-spoke cable truss should reflect the structure entity in the physical space accurately and in real time. Digital twin models include geometric models (B_{GVE}), physical models (B_{PVE}), behavior models (B_{BVE}), and rule models (B_{RVE}). The establishment of the 3D model of B_{GVE} is based on 3D laser scanning technology;

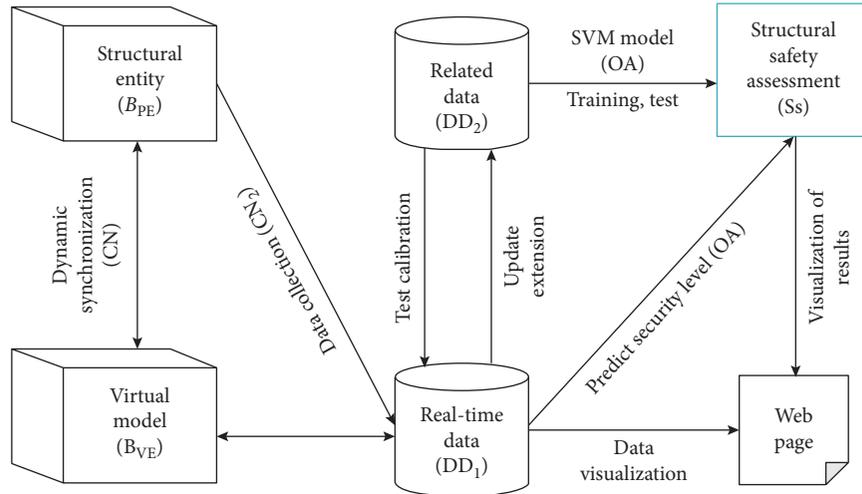


FIGURE 5: Safety evaluation system framework.

ANSYS is used to conduct the static analysis of the 3D model and establish B_{PVE} ; B_{BVE} depicts the real-time changes of the structural cable forces under the different factors; by querying the relevant specifications and soliciting the experts' experience, the safety level of the cable under different influences is divided to obtain B_{RVE} :

- (1) Geometric models (B_{GVE}): the process of establishing the B_{GVE} is shown in Figure 6. A theoretical building information model (BIM) model is established during the component design process. The drawing and processing of the components are performed according to this model. Simultaneously, the coordinates of key points are extracted from the BIM model to establish a theoretical finite element analysis model. According to the analysis results, the wheel-spoke cable truss is tensioned to the test model. To consider the influence of time on the spatial coordinates of the structure, 3D laser scanning technology is introduced, which is also known as "real scene replication" technology [23]. After being built, the test model is scanned using a 3D laser scanner to obtain the actual measured model of the structure. The point cloud data include many outliers due to inherent machine errors, human factors, and external environment. It is necessary to further denoise the point cloud data. The processed data are then imported into the BIM software, and the key points of the cable truss are extracted. The modified BIM model is established by correcting the coordinates of the theoretical BIM model, as shown in Figure 7. The key node coordinates are extracted from the modified BIM model to modify the theoretical finite element analysis model. Finally, the modified finite element analysis model considering the time dimension is obtained to ensure the accuracy of the simulation analysis.
- (2) Physical models (B_{PVE}): the process of establishing the B_{PVE} of the wheel-spoke cable truss is shown in Figure 8. The multicondition static test is performed

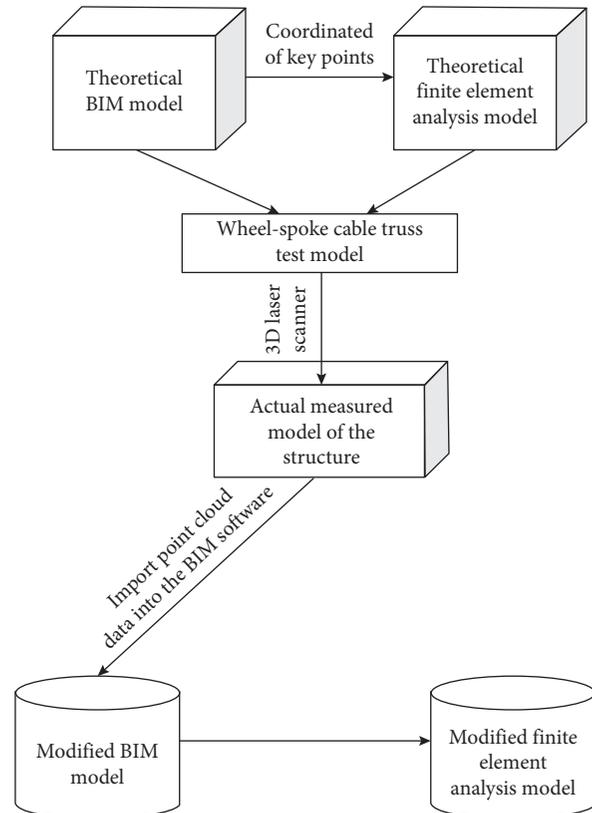


FIGURE 6: Geometric model building process.

to study the static performance of the wheel-spoke cable truss. In this study, the static load of the structure is investigated by gravity loading. The specific method of force application is loading sandbags. According to the "Code for Design of Building Structural Loads (GB50009-2012)," the live load is 0.5 kN/m^2 . The area load is converted into the equivalent node load, in which the node load on the inner strut is 154 N , while that on the middle and outer struts is 476 N and 714 N , respectively. The

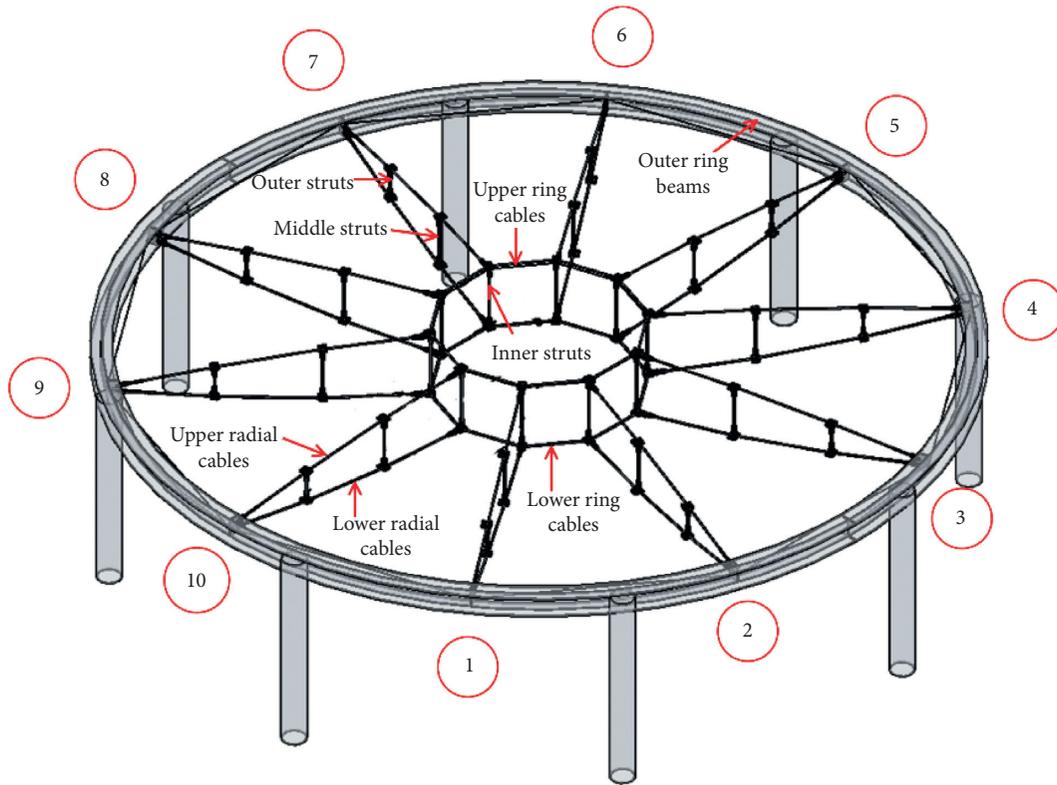


FIGURE 7: The BIM model of structure.

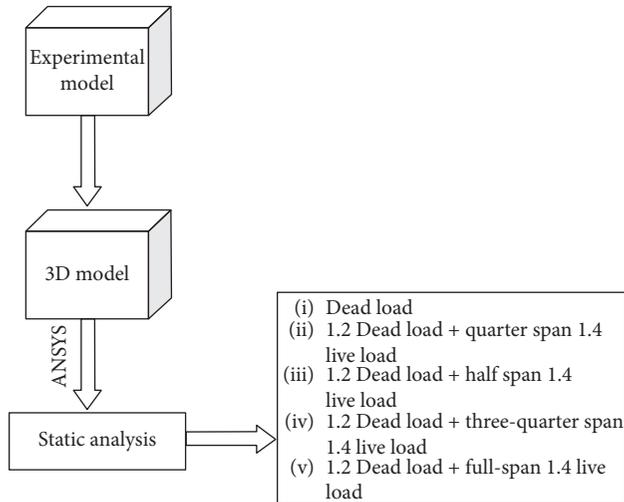


FIGURE 8: Physical model building process.

simulated and experimental values of the cable force under self-weight load are shown in Table 1. From the data in the table, the error between the simulated and experimental values is small; therefore, B_{PVE} can be used effectively for the safety assessment of the structure.

(3) Behavior models (B_{BVE}): when the wheel-spoke cable truss structure is in use, the cable force varies owing to temperature change, material corrosion, complex loads, and loss of prestress. B_{BVE} depicts

TABLE 1: Comparison of cable force value.

Component number	Simulated value	Test value	Error (%)
Upper radial cable 1	4695	4726	-1
Upper radial cable 3	5629	5821	-3
Upper radial cable 5	5017	5126	-2
Upper radial cable 7	5699	5592	2
Upper radial cable 9	5074	5034	1
Lower radial cable 1	5447	5545	-2
Lower radial cable 3	6353	6375	0
Lower radial cable 5	5283	5170	2
Lower radial cable 7	5966	5722	4
Lower radial cable 9	5623	5463	3
Upper ring cable	8580	8537	1
Lower ring cable	9037	8846	2

the real-time changes in the cable force of the structure under the action of different factors and provides dynamic synchronization with the physical structure. Tables 2–4 show the changes of the upper radial cable force when the structure temperature changes and the lower ring cable relaxes and has a length error. Furthermore, the three influencing factors—temperature change, cable relaxation, and rod error—are used as the main evaluation indexes for the subsequent training of the SVM model.

(4) Rule models (B_{RVE}): B_{RVE} refers to the classification of the safety level of the structure based on relevant codes and expert experience. According to the

TABLE 2: Upper radial cable force (N).

Temperature change	1	3	5	7	9
-55	6118	6102	6081	6125	6135
-25	4956	4943	4930	4961	4968
0	3996	3986	3978	3999	4005
25	3052	3046	3041	3054	3058
55	1962	1958	1956	1963	1965

TABLE 3: Upper radial cable force (N).

Degree of relaxation	1	3	5	7	9
0	3996	3986	3978	3999	4005
10%	3965	3956	3948	3969	3974
40%	3875	3866	3858	3878	3883
70%	3784	3776	3768	3787	3792

TABLE 4: Upper radial cable force (N).

Length error	1	3	5	7	9
1/400	3387	3368	3351	3385	3396
1/700	3630	3616	3602	3630	3639
1/1000	3730	3717	3705	3731	3738
0	3996	3986	3978	3999	4005
-1/1000	4210	4200	4195	4212	4215
-1/700	4310	4306	4303	4317	4319
-1/400	4570	4573	4574	4583	4583

content involved in the safety assessment index system of the wheel-spoke cable truss, the assessment levels are divided into four categories. The safety levels from high to low are *a*, *b*, *c*, and *d*. In this study, a cable is used as an example, and the quantitative evaluation criteria of the cable force are shown in Table 5.

3.4. Twin Data (DD) Collection. An important way to use the digital twin model to evaluate the safety risk of the in-service wheel-spoke cable truss is to store the collected data, analyze the reliability of the virtual structure, and then implement the corresponding remedial measures. In this study, the cable force of the structure is recorded using a pressure transducer after applying a column tension. The different rods of the wheel-spoke cable truss perform different functions; therefore, the collection methods of DD should not be identical. For the cable force, a total of 12 monitoring points are present: 2 monitoring points are arranged for each of the upper and lower ring cables and 10 monitoring points for 1, 3, 5, 7, and 9 of the upper and lower radial cables. The location of the monitoring points is shown in Figure 9.

3.5. Application Based on SVM Algorithm Security Level Prediction. In this study, the change in the cable force of the wheel-spoke cable truss is used as an example. First, the digital twin multidimensional model of the structure is built. The SVM evaluation model is then established using the safety evaluation method based on the digital twin and

TABLE 5: Forced evaluation standards.

Structure type	Component category	Ratio of measured value to design			
		<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>
Cable	Important secondary components	≥ 1.00	≥ 0.93	≥ 0.90	< 0.85
	General components	≥ 1.00	≥ 0.91	≥ 0.86	< 0.81

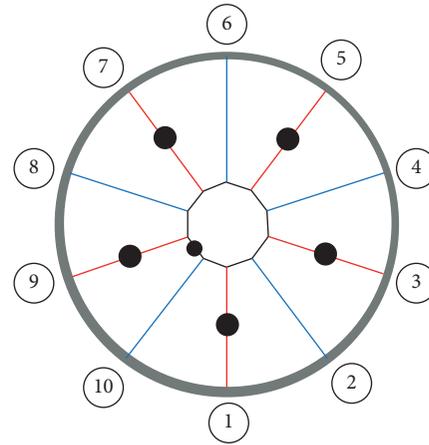


FIGURE 9: Cable monitoring point.

TABLE 6: Comparison of actual and predicted structural risk levels.

Inspection sample number	Actual risk level	Predicted risk level	Inspection sample number	Actual risk level	Predicted risk level
1	<i>a</i>	<i>a</i>	11	<i>c</i>	<i>c</i>
2	<i>a*</i>	<i>b*</i>	12	<i>b</i>	<i>b</i>
3	<i>b</i>	<i>b</i>	13	<i>a</i>	<i>a</i>
4	<i>b</i>	<i>b</i>	14	<i>a</i>	<i>a</i>
5	<i>c</i>	<i>c</i>	15	<i>b*</i>	<i>a*</i>
6	<i>b*</i>	<i>c*</i>	16	<i>a</i>	<i>a</i>
7	<i>a</i>	<i>a</i>	17	<i>b</i>	<i>b</i>
8	<i>a</i>	<i>a</i>	18	<i>c</i>	<i>c</i>
9	<i>b</i>	<i>b</i>	19	<i>b</i>	<i>b</i>
10	<i>a</i>	<i>a</i>	20	<i>a</i>	<i>a</i>

support vector machines described in Section 2. Finally, the accuracy of the model is tested.

The main factors that affect the change in the structural cable force include temperature change, prestress losses, and rod length errors. In this study, as SVM input, 200 sets of sample data of the three aforementioned factors are selected from the experimental data. The cable force safety assessment level described in Section 3.2 is used as the expected output to train the model. A total of 20 groups of evaluation values and cable force evaluation levels are selected as the test samples to establish the SVM safety evaluation model. The test results are shown in Table 6. It shows that, compared with the actual safety level, the accuracy of the SVM model is 85%. In the sample with error, the corresponding safety level interval is no more than one safety level. Therefore, the SVM evaluation model can accurately predict the structural safety level of the wheel-spoke cable in service. The input and

output values of the trained SVM evaluation model are available for users to view in real time on the website.

4. Conclusion

This study investigates the safety assessment method of prestressed steel structures in service based on digital twins. Based on the structural safety assessment framework, a digital twin multidimensional model of the structure is established. The SVM algorithm is used to predict the structural safety level. Finally, the risk assessment of the structure is performed. Taking a wheel-spoke cable truss as an example, the geometric, physical, behavior, and rule models are built. A structural safety risk prediction and evaluation system is constructed based on the SVM theory and related data. The advantages of using digital twin technology in the safety risk assessment of prestressed steel structures can be summarized as follows:

- (1) The digital twin can realize the self-awareness, self-prediction, and self-evaluation of the structure, thus creating a more intelligent and safer structure while operational
- (2) The virtual model of the structure can be dynamically synchronized with the physical structure on the web page, and the relevant data and security levels of the structure can also be viewed; this makes the entire evaluation process more intuitive and concise
- (3) The digital twin-dimensional model integrates the entity structure, physical structure, relevant data, evaluation algorithm, and evaluation service, which is conducive to the rapid evaluation, prediction, and maintenance of the structure and provides a new method for the safety evaluation of the structure

5. Discussion

Digital twin technology has good research value in the safety assessment of prestressed steel structures; however, the research in this study is only a preliminary exploration of digital twin technology in structural risk assessment. The research object is the prestressed steel structure during the service period only and the study omitted to consider the safety risk in the construction process. The proposed method has not yet considered the subsequent maintenance of the structure.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] F. Biondini and D. M. Frangopol, "Life-cycle performance of deteriorating structural systems under uncertainty: review," *Journal of Structural Engineering*, vol. 142, no. 9, 2016.
- [2] S. Qiang, X. Zhou, and M. Gu, "Research on reliability of steel roof structures subjected to snow loads at representative sites in China," *Cold Regions Science and Technology*, vol. 150, pp. 62–69, 2018.
- [3] G.-Q. Li and J.-J. Li, "A semi-analytical simulation method for reliability assessments of structural systems," *Reliability Engineering & System Safety*, vol. 78, no. 3, pp. 275–281, 2002.
- [4] J. Jiang, S. P. Chiew, C. K. Lee, and P. L. Y. Tiong, "A numerical study on residual stress of high strength steel box column," *Journal of Constructional Steel Research*, vol. 128, pp. 440–450, 2017.
- [5] J. Jiang, S. P. Chiew, C. K. Lee, and P. L. Y. Tiong, "An experimental study on residual stresses of high strength steel box columns," *Journal of Constructional Steel Research*, vol. 130, pp. 12–21, 2017.
- [6] L. Deng, M. Zhong, L. Liao, L. Peng, and S. Lai, "Research on safety management application of dangerous sources in engineering construction based on BIM technology," *Advances in Civil Engineering*, vol. 2019, pp. 1–10, 2019.
- [7] E. J. Tuegel, A. R. Ingraffea, T. G. Eason, and S. M. Spottswood, "Reengineering aircraft structural life prediction using a digital twin," *International Journal of Aerospace Engineering*, vol. 2011, pp. 1–14, 2011.
- [8] E. M. Kraft, "The US air force digital thread/digital twin–life cycle integration and use of computational and experimental knowledge," *Procedia Computer Science*, vol. 114, pp. 47–56, 2017.
- [9] R. D. Lu and I. Brilakis, "Digital twinning of existing reinforced concrete bridges from labelled point clusters," *Automation in Construction*, vol. 105, Article ID 102837, 2019.
- [10] C.-S. Shim, N.-S. Dang, S. Lon, and C.-H. Jeon, "Development of a bridge maintenance system for prestressed concrete bridges using 3D digital twin model," *Structure and Infrastructure Engineering*, vol. 15, no. 10, pp. 1319–1332, 2019.
- [11] W. Tian, H. M. Li, R. Q. Yan, and Y. X. Hu, "Safety risk assessment of highway special maintenance project based on BP neural network," *Advanced Materials Research*, vol. 373, pp. 3175–3179, 2011.
- [12] G. Macdonald, "Risk perception and construction safety," *Civil Engineering*, vol. 6, no. 159, pp. 51–56, 2006.
- [13] H.-S. Lee, H. Kim, M. Park, E. Ai Lin Teo, and K.-P. Lee, "Construction risk assessment using site influence factors," *Journal of Computing in Civil Engineering*, vol. 26, no. 3, pp. 319–330, 2012.
- [14] F. Tao, W. R. Liu, and M. Zhang, "Five-dimension digital twin model and its ten applications," *Computer integrated manufacturing systems*, vol. 25, no. 1, pp. 1–18, 2019.
- [15] Z. Liu, A. S. Zhang, and W. S. Wang, "Dynamic fire evacuation guidance method for winter olympic venues based on digital twin-driven model," *Journal of Tongji University(Natural Science)*, vol. 48, no. 7, pp. 962–971, 2020.
- [16] Q. Yang, Y. X. Jiang, and A. D. Xu, "A model divides the mobile security level based on SVM," in *Proceedings of the 2017 IEEE Conference on Communications and Network Security (CNS)*, pp. 370–371, Las Vegas, NV, USA, October 2017.

- [17] H. F. Wang and D. J. Hu, "Comparison of SVM and LS-SVM for regression," in *Proceedings of the 2005 International Conference on Neural Networks and Brain*, vol. 1, pp. 279–283, Beijing, China, October 2005.
- [18] C.-C. Chang and C.-J. Lin, "LIBSVM: A library for support vector machines," *ACM Transactions on Intelligent Systems and Technology*, vol. 2, no. 3, pp. 1–27, 2011.
- [19] S. Soleimani, O. Bozorg-Haddad, and M. Saadatpour, "Optimal selective withdrawal rules using a coupled data mining model and genetic algorithm," *Journal of Water Resources Planning and Management*, vol. 142, no. 12, Article ID 4016064, 2016.
- [20] C.-L. Huang and C.-J. Wang, "A GA-based feature selection and parameters optimization for support vector machines," *Expert Systems with Applications*, vol. 31, no. 2, pp. 231–240, 2006.
- [21] Z. S. Liu, Z. B. Han, and J. He, "Sensitive test on relaxation of cable and reliability assessment of spoke cable-truss structure," *Journal of Tongji University (Natural Science)*, vol. 47, no. 7, pp. 946–956, 2019.
- [22] J. Jiang, W. Bao, and Z. Y. Peng, "Creep property of TMCP high strength steel Q690CFD at elevated temperatures," *Journal of Materials in Civil Engineering*, vol. 32, no. 2, Article ID 4019364, 2020.
- [23] D. Zhang, T. Huang, and J. C. Song, "CAD model reconstruction using 3D laser scanning," *Applied Mechanics and Materials*, vol. 78, pp. 3485–3488, 2011.