

## Research Article

# Analysis of Bridge Health Detection Based on Data Fusion

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By integrating rough set theory and neural network theory, this study combined their advantages. Drawing on the existing theoretical results for bridge influencing factors, a method for numerical simulation and data fusion was used in the application of multifactor data fusion for cable-stayed bridge safety evaluation. Based on studying existing bridge safety evaluation methods, a neural network and rough set theory were combined to perform a safety evaluation of PC cable-stayed bridge cables, which provided a new means for bridge safety evaluation. First, a cable-stayed bridge in Shenyang was used as the engineering background, the safety level of its cables was divided into five levels, and a safety evaluation database was established, clustered by a Kohonen neural network. This provided specific evaluation indicators corresponding to the five safety levels. A rough neural network algorithm integrating the rough set and neural network was applied to data fusion of the database, with the attribute-reduction function of the rough set used to reduce the input dimension of the neural network. *Conclusions.* The neural network was then trained and the resulting trained network was applied to the safety evaluation of the cables of the cable-stayed bridge. Four specific attribute index values, corresponding to the bridge cables, were directly input to obtain the safety status of the bridge and provide corresponding management suggestions.

## 1. Introduction

Artificial intelligence (AI) is a branch of computer science and a new research direction that has emerged in recent years. AI can solve many complex problems with strong nonlinearity and large uncertainty, which are difficult to solve by traditional methods, through simulation of the decision-making process of human thinking. Recently, AI tools represented by neural networks have been successfully applied to bridge evaluation [1, 2].

Scholars have also optimized the evaluation method, index system, evaluation standard, and other factors based on manual detection. Sun et al. [3] have provided the weights of each bridge component and realized the performance evaluation layer by layer according to fuzzy weighting and the weak segmentation method and have formulated different maintenance plans for structures with different ratings. Based on the Dempster-Shafer evidence theory and Yager combination rule, Bolar et al. [4] have proposed a hierarchical assessment method for bridge status, which

reduces the uncertainty of multisource index information. Based on field test data, Caglayan et al. [5] have carried out dynamic corrections to the model of a railway bridge, simulated testing of most of the dynamic indices of the whole bridge, and completed the safety assessment of damaged bridge components. Kim [6] has calculated 36 load combinations on steel box girder bridge models with different spans and predicted the load response distribution of the actual structure. Wang [7] has established a time-varying probability model of resistance as well as a probability model of vehicle loading based on the probability model of resistance parameters. The main failure modes and correlation coefficients of bridge structures were also derived through the principle of minimum load increment and a failure tree model. Wang [8] has defined the concept of “generalized post progress,” weighted the main load-bearing members of a steel truss-tied arch bridge, and completed a comprehensive evaluation of the safety of the whole bridge through the fuzzy comprehensive evaluation method. Yan et al. [9] have identified and extracted the structural response signals

under car load and crowd load and established a mathematical model for bridge safety monitoring and evaluation based on hesitant fuzzy set. Wang et al. [10] have proposed an influence line-based moving load test method for a rapid bridge capacity evaluation. Mohammad et al. [11] have used a comprehensive and coherent reliability approach to assess the safety of TSBG bridges after the complete fracture of one steel girder.

In recent years, security issues of bridges have received widespread attention from governments and communities around the world. Security research on the later stage of bridge operation has also become a hot research topic. Carrying out safety assessment of bridges can quickly and accurately obtain the current safety status of bridges. The actual bearing capacity of bridges is obtained, such that the actual working state of the bridge in service can be understood. Based on assessment conclusions, the corresponding measures are then taken in time to ensure that bridges remain in safe operational state.

Although the current bridge-evaluation field has been developing rapidly, there are still some problems to be solved in terms of data sources, indicator empowerment, and evaluation methods. Division of the scoring interval cannot be completely accurate and reasonable and the weights of indicators have a great influence on evaluation results. However, the current subjective weighting method is too arbitrary and the objective weighting results are easily inconsistent with human cognition.

This study was based on a current situation, in which a cable-stayed bridge is vulnerable and difficult to repair during its operation and takes detection, monitoring, and finite elements as the source of index data. Then, research on the comprehensive evaluation method for the reliability of the cable-stayed bridge box girder was performed and the applicability and effectiveness of the method were verified by taking the background engineering as an example. The main contributions were as follows:

- (1) Many relevant publications were consulted and the relevant overviews, necessity, and research status of bridge safety evaluation were summarized. The commonly used bridge structure safety-evaluation methods were proposed and the basic concept of multisource data fusion and the feasibility of its application in bridge evaluation were expounded.
- (2) Various existing data fusion algorithms and their practicality were comprehensively considered. A rough set and neural network were integrated to complement each other in constructing a rough neural algorithm. The accuracy of data fusion was further improved, reducing the time required for fusion.
- (3) On the basis of relevant literature, the existing study addressed and integrated stress amplitude, corrosion degree, sheath damage, and damping system influencing factors. A safety evaluation database of stay

cables was established and specific grading standards for safety evaluation grades were obtained by cluster analysis. A rough set was used to reduce the attribute index of the database. After simplification, a database is obtained and the designed neural network trained using this data.

- (4) The trained neural network was then applied to the evaluation of the selected Fumin Bridge. The safety level corresponding to the bridge was provided based on the prediction result produced by the neural network.

The research background of this study was the situation of the Fumin Bridge in Shenyang, described as follows.

The main bridge of Shenyang, Fumin Bridge, is a single-plane PC cable-stayed bridge with a length of 420 m and span arrangement of 89+242+89 m (see Figure 1). The material of the main girder is C50 concrete, with a nearly triangular section formed with good wind resistance, a single box with three rooms, and girder height of 3.414 m. The dimensions of each part of the midspan were the upper edge thickness of the two chambers at 25 cm, upper edge thickness of the middle chamber at 40 cm, lower edge thickness at 30 cm, side web thickness at 25 cm, and middle web thickness at 40 cm (see Figure 2). The thickness of each part of the side-span included the upper edge of both chambers at 40 cm, upper edge of the middle chamber at 50 cm, lower edge at 40 cm, middle web at 50 cm, and side web at 30 cm (see Figure 3). The main tower is cast with C50 concrete, with a box-shaped section, tower height above the bridge deck at 67.5 m, and folded angle of the main tower located 33.9 m above the bridge deck. The angle between the lower tower body and horizontal plane is  $75^\circ$  and the angle between the upper and lower tower bodies is  $7.5^\circ$ . The stay cables are made of galvanized high-strength steel wires, with four specifications of 301- $\Phi$ 7, 241- $\Phi$ 7, 211- $\Phi$ 7, and 151- $\Phi$ 7. They are arranged in a fan shape, with 15 pairs arranged on each main tower and a total of 120 cables in the whole bridge. The cable force of the bridge is 5500–9500 kN. The 4# pier is a fixed connection system of towers, girders, and piers and 5# pier is a tower-girder fixed connection and girder-pier separation system.

## 2. Safety Assessment Level

Cable-stayed cables are vulnerable force-transmitting components in cable-stayed bridges which also determine the performance of the entire bridge. It is necessary to evaluate the durability of cable-stayed cables to provide guidance for management and maintenance and to reduce life cycle costs.

*2.1. Stay Cables Reliability Risk Recognition.* Different risk types determine different risk factors. For example, the risk factors of bridge earthquakes and fires are totally different. It is necessary to recognize and confirm risk types before risk

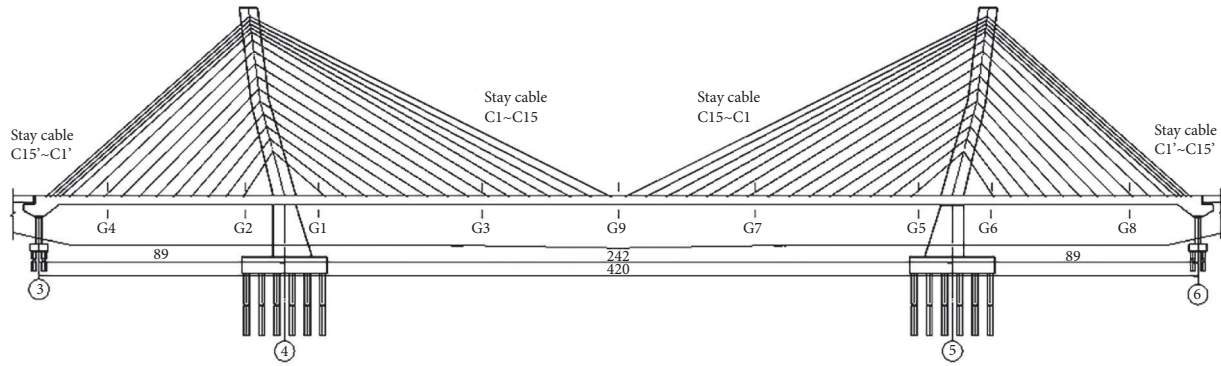


FIGURE 1: Arrangement of the main bridge (m).

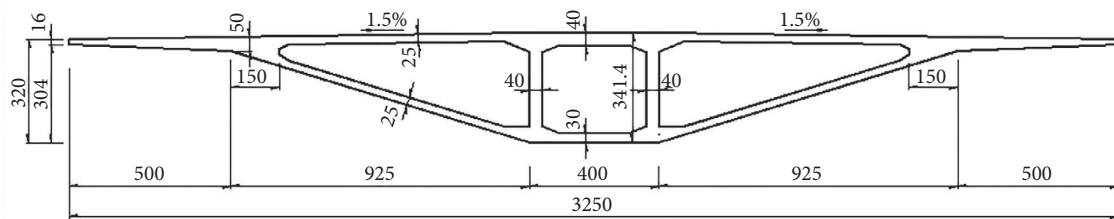


FIGURE 2: Cross section of midspan girder (cm).

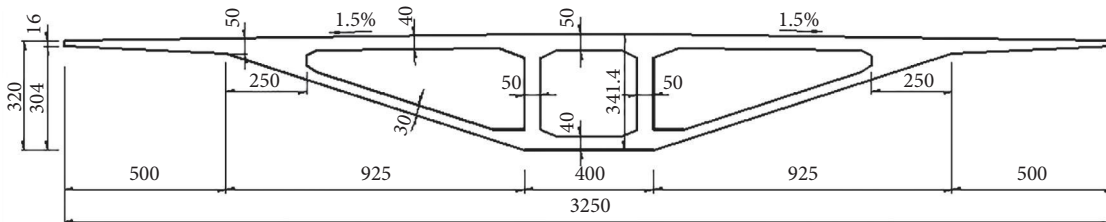


FIGURE 3: Cross section of side-span girder (cm).

assessment. The reliability of the project refers to the ability to complete the intended functionality within the intended environment and intended time, which mainly includes safety, applicability, and durability. Therefore, the reliability risk recognition of the cable must be carried out separately from these three aspects.

**2.1.1. Safety Risk.** The safety of structural components is closely related to the bearing capacity, which is controlled by strength, stiffness, or stability. For typical tensile members, such as stay cables, the problem of stability is generally not considered. High-strength steel wire materials have a high stiffness and low elongation rate, with deformation not controlling its failure. In fact, the safety risk of stay cables is the strength failure risk. Without considering the impact of durability degradation on the risk of cable breaking, the safety risks can be attributed to excessive tensile stress in stay cables.

**2.1.2. Adaptability Risk.** Applicability refers to the ability to maintain good functions in the normal use process, such as not producing excessive deformation which affects the normal use of components. As the regulating unit of the whole bridge mechanical state, good performance of stay cables is mainly reflected in ensuring the uniform and reasonable force of the beam and tower members. Therefore, the applicability risk can be attributed to increase and decrease of the cable force value under constant loading.

**2.1.3. Durability Risk.** Different scholars have different understandings of durability. The definitions of durability have been summarized in some references (see Table 1). Through comparison, the durability of existing structures is defined here as follows: the ability of the structure to maintain a minimum predetermined function under the conventional level of maintenance due to deterioration of the design, construction defects, use environment, material

TABLE 1: Definition of durability.

	Reference [12]	Reference [13]	Reference [14]	Reference [15]	Reference [16]
Duration	Design duration	Design duration	Intended duration	Design duration	Specified duration
Effect	Intended effect	Design environment effect	Deterioration effect	Use environment, material deterioration	Various adverse factors
Condition	Intended use maintenance	Design use maintenance	Intended use maintenance	Optimization funds	Normal use maintenance
Performance	Safety, applicability	Safety, applicability	Necessity	Safety, applicability	Intended function

TABLE 2: Durability risk factors of stay cables.

Environment	Material	Stress	Human Factor
Corrosion	Aging	Fatigue	Low construction quality
Vibration	Prestress relaxation Material defects	Sheath cracking	Not timely inspection

Note. Aging is the degradation of materials due to the decrease in molecular coalescence. Sheath cracking is the cracking caused by repeated cooperative deformation of sheath and steel wire under high stress state.

TABLE 3: Grading standard of risk indexes.

	Probability		Harmfulness		Premonitory	
	Quality	Quantity	Quality	Quantity	Quality	Quantity
1	Rare	$P \leq 0.003$	Insignificant	$Q \leq 0.125\%$	Common sense judgment	$t > 12$ h
2	Occasional	$0.003 < P \leq 0.03$	Sight	$0.125\% < Q \leq 1.25\%$	Infer with professional knowledge	$3 \text{ h} < t \leq 12 \text{ h}$
3	Possible	$0.03 < P \leq 0.3$	Serious	$1.25\% < Q \leq 12.5\%$	Professional tool calculation	$0.5 \text{ h} < t \leq 3 \text{ h}$
4	More possible	$P > 0.3$	Extremely serious	$Q > 12.5\%$	Unpredictable	$t \leq 0.5 \text{ h}$

properties, and other factors during the remaining service life of the structure. The main intended function of the stay-cable system is to deliver the bridge surface load. The risk of existing durability can be expressed as follows: During the remaining use phase, durability risk is a factor that has adverse effects on the performance of the cable force-transmission system (high-strength steel wire and anchorage system) at the level of normal pipe curing.

The harmfulness of the durability risk is reflected in the form of disease. Existing references list the main diseases of the cable system [17], and, on this basis, the durability risk identification of the cable is realized by combining retrieval experience and expert interviews. The durability risks of common stay cables were sorted out according to the environment, material, force, and human factors, and evaluations were made for these nine risks (see Table 2).

**2.2. Risk Matrix Expansion.** In [18], the indicators and standards suitable for engineering risk assessment have been proposed. The absolute value of direct economic losses is used as an assessment standard for harmfulness, which is not applicable to the risk assessment of small and medium structures with low cost. This study used relative economic losses as a harmfulness evaluation standard. The internal rate of return of engineering projects is generally 12%, with this standard conforming to national conditions.

Premonitory sign is a sign that occurs before an incident. The important manifestation of premonitory risk is the

advancement value of forecast time, which is of great significance to reduce risk losses, as discussed in [19]. The safe evacuation time for the risk population in a fire is stipulated in [20]. Different grades of premonitory indices have been roughly described, which yields it difficult to form normative standards, as discussed in [21]. At present, there are few studies of premonitory risk and few references have incorporated it into risk assessment.

The advancement value of forecast time “ $t$ ” is introduced as a quantitative standard for “premonitory.” Combined with the corresponding qualitative description, the risk matrix was extended to a three-dimensional (3D) risk space. The risk indices and grading standards are shown in Table 3 and 3D risk space is shown in Figure 4. Note. Risk sample corresponding to different risk areas (see Table 4).

**2.3. Evaluation Index System.** The durability of stay cables is mainly affected by fatigue and corrosion. Following the principles of effectiveness [22–26], measurability, comprehensiveness, and independence, a durability evaluation index system for stay cables was established (see Table 5).

**2.4. Durability Qualitative Description.** As the reduction of the performance of structural components must be manifested in the form of external diseases, the formulation of durability standards can be considered from the perspective of disease conditions and service performance [27, 28]. The qualitative criteria of evaluation indicators and evaluation

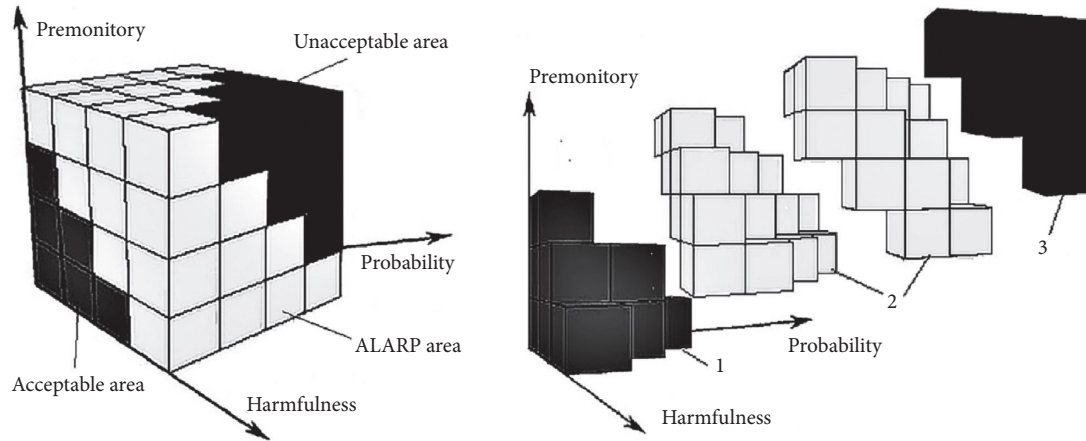


FIGURE 4: Three-dimensional risk space.

TABLE 4: Combination of risk factors.

Risk grade	Risk sample
Acceptable	Aa1, Aa2, Aa3, Ab1, Bb1, Ab2, Ac1, Ba1, Ba2, Ca1, Bb2
ALARP	Aa4, Ba4, Ba3, Ca3, Ca2, Da2, Da1, Db1, Ab4, Ab3, Ac3, Ac2, Ad2, Ad1, Bd1, Bb3, Cb2, Bc2, Cb1, Bc1, Cc1, Dd1, Dc1, Dc2, Db2, Db3, Da3, Da4, Ca4, Cb4, Bb4, Bc4, Ac4, Ad4, Cd1, Cd2, Bd2, Bd3, Ad3, Cc2, Cb3, Bc3
Unacceptable	Dd4, Dd3, Dd2, Dc3, Cd3, Dc4, Cd4, Db4, Bd4, Cc4, Cc3

Note. A-D, a-d, and 1-4 represent probability, harmfulness, and premonitory indicators 1-4.

TABLE 5: Durability index system of stay cables.

Index	Upper limit	Lower limit	Weights
Stress amplitude	250 MPa	110 MPa	0.3
Corrosion degree	Quantitative	Quantitative	0.3
Sheath damage	Qualitative	Qualitative	0.2
Damping system	Quantitative	Quantitative	0.2

Note. Weights are not the focus of this study. Stress amplitude is the difference between maximum tensile stress and minimum tensile stress in each stress cycle. Corrosion degree is divided into four grades: serious corrosion, medium corrosion, weak corrosion, and no corrosion. Sheath damage is mainly affected by aging and fatigue.

results might be inconsistent, but the focus here was on verification of method applicability. The qualitative scale of indicators and evaluation results are shown in Table 6.

2.5. *Safety Assessment Level.* According to the approximate derivation results of the bridge structure evaluation grade, the evaluation grade standard of a stay cable is shown in Table 7.

For the evaluation standard of safety level, 20 experts and scholars were determined by asking for advice using distributed questionnaires. Statistical results of the questionnaires are shown in Table 8.

This study used Clementine 12.0 [7] as a data mining tool to establish a Kohonen neural network for clustering and analyzing the database data flow. Training of the Kohonen neural network entailed the expert mode, with the width at 5, length 1, and number of neurons in the output layer 5, and the network clustered the samples into 5 classes. After cluster

TABLE 6: Qualitative description of durability rating.

Level	Qualitative description
1	Excellent performance, no disease, completely normal use
2	General performance, weak disease, partially affecting use
3	Performance degradation, moderate disease, affecting normal use
4	Performance deviation, serious disease, difficult to use normally
5	Poor performance, badly ill, barely useable

analysis, the entire evaluation database was clustered into five categories, with the specific evaluation standards shown in Table 9.

The evaluation standard obtained by the Kohonen neural network was seen to be very close to the recommended evaluation standard given by most experts, indicating that it possessed high reliability. It was thus determined as the safety level evaluation standard for the main girder of the bridge.

### 3. Processing of Evaluation Data

3.1. *Calculation of Sample Data.* Taking the case of bridge operation as an example, the calculation process of one sample of data was considered and the method for obtaining other sample data was the same as this example. When the bridge was built and operated for the 5th year, the corrosion degree did not reach the critical maximum corrosion degree. Therefore, it was considered that the prestressed steel bars in the bridge stay cables were not corroded and the prestress condition was not lost, such that the prestress was taken as

TABLE 7: Rating standards for stay cables.

Type of structure or member	a	b	c	d
Safety identification factor $K$	$K \geq 1.0$	$0.95 \leq K < 1.0$	$0.86 \leq K < 0.95$	$K < 0.86$

TABLE 8: Statistical table of questionnaire survey results.

Supporters (%)	Plan	Evaluation standards				
		Level 1	Level 2	Level 3	Level 4	Level 5
35	Plan 1	$K \geq 1.30$	$1.20 \leq K < 1.30$	$1.10 \leq K < 1.20$	$1.00 \leq K < 1.10$	$K \leq 1.00$
40	Plan 2	$K \geq 1.20$	$1.10 \leq K < 1.20$	$1.00 \leq K < 1.10$	$0.90 \leq K < 1.10$	$K \leq 0.90$
25	Plan 3	$K \geq 1.25$	$1.15 \leq K < 1.25$	$1.00 \leq K < 1.15$	$0.95 \leq K < 1.00$	$K \leq 0.95$

TABLE 9: Safety rating standard table.

Evaluation standards				
Level 1	Level 2	Level 3	Level 4	Level 5
$K \geq 1.20$	$1.00 \leq K < 1.20$	$0.95 \leq K < 1.00$	$0.90 \leq K < 0.95$	$K \leq 0.90$

1.00. The bridge had endured a 5-year operation period, which meant that the elastic modulus should have been reduced to a certain extent. According to the time-varying formula of steel strength, the reduction coefficient was 0.832. After 5 years of operation, the bridge should appear to be damaged and the apparent score thus decreased with operation time, such that there was great uncertainty. Therefore, by randomly generating a set of values between 0 and 1 to simulate the visual inspection (sheath damage) score, the resulting score was 0.9437. At this point, the sample data corresponding to the 5th year of bridge operation had been obtained.

**3.2. Rough Set Attribute Reduction.** Before performing rough set attribute reduction on the data, the data needed to be processed. Because the data in the information table was complete and some value ranges of the condition and decision attributes were continuous, it was not necessary to complete them and only the information table needed to be discretized. With Clementine 12.0 as a data mining tool, the data flow for the sample data was discretized using mean-standard deviation grouping (see Figure 5).

Using the sufficiency theory of rough set knowledge to simplify the sample data, processing was divided into two steps, one to simplify summation of the conditional attribute set of the decision table and the other to simplify the conditional attribute value. Using rough set theory for data preprocessing, no additional information needed to be known in advance and the reduction algorithm simple was beneficial for realizing automatic operation with the help of a computer or software [29–31].

#### 4. Neural Network Training and Prediction

The performance and correctness of the training model based on the rough neural network were tested by extracting 545 sets of data samples from the reduced database as the

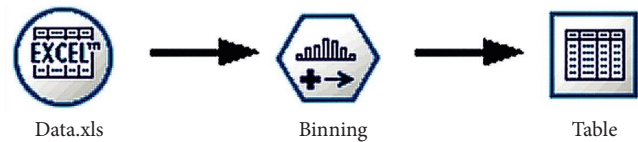


FIGURE 5: Data flow diagram for data discretization.

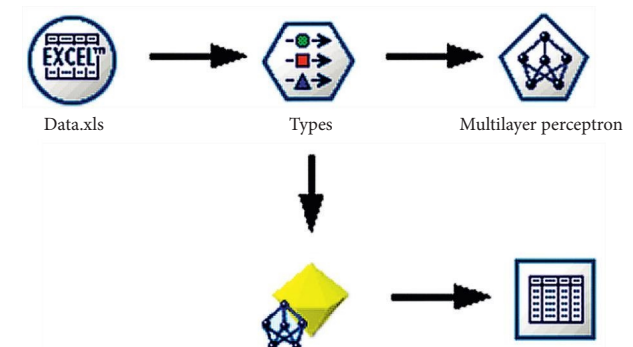


FIGURE 6: Data flow diagram for training a neural network.

training set, with inputting to the neural network for training the neural network. The remaining 120 sets of data samples were used as verification data to test the prediction accuracy of the network [32, 33]. The neural network was created and trained through the neural network node. The data flow diagram is shown in Figure 6.

Neural networks were created and trained through neural network nodes and used to simulate the work of a large number of interconnected processing units arranged in layers. Neural networks often consist of 3 parts: First is the input layer, whose units represent the input fields. Second, one or more layers are hidden layers. Third, one is the output layer, whose units represent output fields. Units are connected by changing connection strengths or weights. Clementine provides 6 training modes to train neural network models: fast, dynamic, multiple, pruned, radial basis function network (RBFN), and thorough pruning.

The training method selected in this study was the fast method, with the number of neurons in the input layer being  $n = 7$  and the number of neurons in the output layer being  $m = 1$ . The neural network had 3 hidden layers, with the

FIGURE 7: The parameter settings of neural network.

number of neurons in the first, second, and third layers being  $l = 20, 15,$  and  $10,$  respectively, and the number of continuations was set to 200 times. The accuracy of the neural network training error was set to  $k = 0.0001$  and the correct rate of the neural network was  $>95\%$ . The learning efficiency of the neural network was set as follows: Alpha = 0.3, initial Eta = 0.3, Eta decay = 30, high Eta = 0.1, and low Eta = 0.01. The parameter settings are shown in Figure 7.

The prediction accuracy of the categorical output variable is the proportion of the model's correctly predicted samples to the total samples. For a numeric output variable, the prediction accuracy was calculated as follows:

$$\frac{1 - |Y_i - Y'_i|}{Y_{\max} - Y_{\min}} \times 100\%, \quad (1)$$

where  $|Y_i - Y'_i|$  is the absolute error between the  $i$ th actual observed and model predicted values and  $Y_{\max}$  and  $Y_{\min}$  are the actual maximum and minimum values of the output variable, respectively. Note that the values refer to values after normalization. The prediction accuracy needed to be calculated for each observation and the average value was the total prediction accuracy of the model.

After the neural network training was completed [34, 35], 120 sets of verification data were input into the neural network to obtain a predicted value based on the coarse neural network algorithm. The data flow diagram predicted by the neural network is shown in Figure 8.

The  $K$  value of the 120 groups of data in the original safety assessment database was taken as the theoretical value and the value output by the neural network was taken as the predicted value. The relative sizes of the two data groups were compared and used as the basis for evaluating the prediction accuracy of the neural network model. The network prediction error curve is shown in Figure 9.

The neural network was seen to have high accuracy, with the relative error not exceeding 3%. This completely met the

needs of the actual situation and thus could be applied to practical projects.

## 5. Example Verification

**5.1. Testing Results of Single-Plane Cable-Stayed Bridges.** A cable-stayed bridge in Shenyang is located 2 km downstream of the Changqing Bridge on the Hunhe River in the south of Shenyang City. The bridge was built in 2003 and belongs to urban class I bridges. The bridge is China's first double-tower single-plane prestressed-concrete cable-stayed bridge in the shape of a broken line. The bridge shape is partially unbalanced to form an overall balance, which is in line with traditional Chinese architectural aesthetics. The overall combination of bridges has a sense of rhythm, reflecting the perfect combination of strength and beauty. Its unique polyline-shaped tower shape and its special location in Hunhe Park make it a landmark building in Shenyang City and Hunnan New District. In April 2011, the Transportation Experiment Center of Harbin Institute of Technology carried out dynamic and static load testing as well as appearance inspections of the bridge. The test (Figure 10) results were as follows:

- (1) During inspection of the appearance, it was found that the PE sheath of the stay cable in the midspan part of the main span was broken. There were cracks in the main and diaphragm girders, most of the crack widths were stable, and individual crack widths tended to increase. Although these cracks were not enough to cause cable damage, this affected the aesthetic of this bridge. The aesthetic characteristics of the bridge building determined that, with its entire exposed structure and clear image of each component's function, a harmonious landscape aesthetic effect had been formed in synergy. The cracks of the cable-stayed sheath and main girder of the bridge first had an intuitive deterioration effect on the aesthetic expression of the bridge building itself and the quality of the environmental landscape. Appearances observations are shown in Figure 10.
- (2) When the bridge was completed in November 2003; the actual measured bridge deck elevation in the middle of the main span was 18 mm lower than the design elevation. After seven years of operation, the theoretically calculated value of the lower deflection in the middle of the main span was 59 mm, but the measured value of the lower deflection in the middle of the main span was 87 mm, which was an actual 28 mm lower deflection than the theoretical lower deflection. When the bridge was completed in 2003, the measured elevation of the main span should have been higher than the design value. The higher part should have been equal to the 10-year shrinkage creep value plus 0.5 times the deflection value generated by the live-car load. In fact, the measured elevation of the main span was 56.743 m, which was 18 mm lower than the designed elevation of

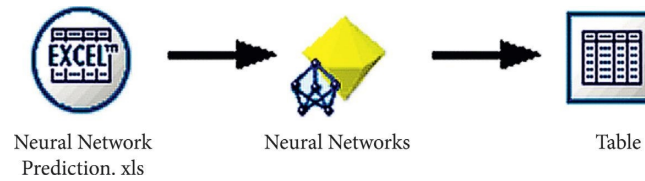


FIGURE 8: Data flow diagram of neural network prediction.

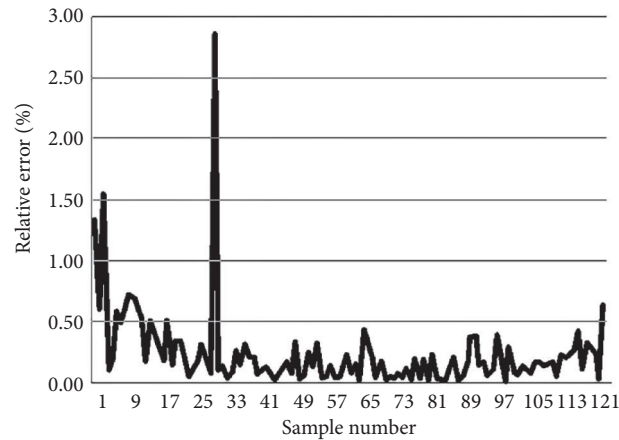


FIGURE 9: Network prediction error curve.



FIGURE 10: Appearance images.

56.761 m. Clearly, the bridge deck alignment of the main span was significantly lower than the design value. This was known from comprehensive test results and theoretical results of the whole bridge cable force and linear shape. Seven years after the bridge was opened to traffic, the change range of the cable force-line shape was within a small range and the line-shape change value was basically consistent with the theoretical value. Change in the cable force was not large, but there was a slight difference from the theoretical value in the specific change trend. At the same time, there was a large deviation between the current actual and designed alignments. The actual measurements of the bridge deck alignment are shown in Figure 11.

Based on the above two inspection contents, according to the ratio of bridge deflection change

and the influence of sheath rupture on the galvanized high-strength (Figure 11) steel wire of the inner stay cable, the safety evaluation index from the appearance inspection was given as  $P1 = 0.8764$ .

- (3) In the state of no vehicle load on the bridge deck, data collection was performed on the permanent strain detection points embedded in the stay cables. Comparison results showed that there was no clear tensile strain at each measuring point during monitoring. Therefore, it was considered that there has been no prestress loss in the stay cable and the stress state of the stay cable had not changed significantly. The bridge safety assessment index for the stay cable was given as  $P3 = 0.9544$ .
- (4) During monitoring, the natural frequency of the bridge was observed and the data analyzed in the frequency domain of a sports car, thus establishing a



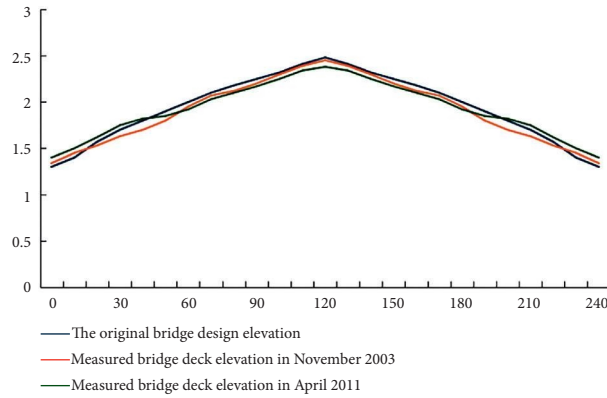


FIGURE 11: Alignment of main girder monitoring summary.

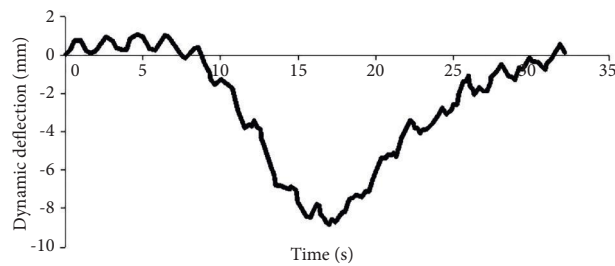


FIGURE 12: Time-history of the midspan dynamic deflection of the main span.

TABLE 10: Summary of security assessment indicators.

Indicator name	Stress amplitude	Corrosion degree	Sheath damage	Damping system
Value	0.9544	0.9821	1.10	1.20

dynamic model of the bridge. At measuring points in the middle of the main span, the frequencies of grades 1–8 were 0.51, 1.37, 2.85, 2.95, 3.09, 3.24, 3.38, and 5 Hz, respectively. The time-history of the midspan dynamic deflection of the main span was then plotted (see Figure 12).

Through the above dynamic testing and theoretical calculations, the first-order symmetrical vertical bending of the midspan was found to be 0.490106 Hz with the test value being 0.51 Hz. The first-order antisymmetric vertical bending of (Figure 12) the midspan was 0.759268 Hz and the test value was 0.86 Hz. The measured value of the bridge frequency was seen to be greater than the theoretical value (but the difference was small), which indicated that the bridge’s dynamic stiffness met the design requirements. At the same time, it should be noted that the two most important frequencies were basically the same as the test values of the completion test in November 2003, with the difference also being very small. This showed that the dynamic characteristics of the bridge’s structure corresponding to the second-order frequency did not change and the stay-cable damping system was intact.

5.2. *Safety Evaluation Index of Single-Plane Cable-Stayed Bridge.* Combined with previous theoretical research, the bridge safety assessment indicators were determined (see Table 10).

## 6. Conclusions

By considering various existing data fusion algorithms and their practicality, this study integrated rough sets and neural networks, which learned from each other’s strengths and complemented each other. From this, a rough neural algorithm was constructed, which was then applied to bridge safety evaluation. Four indicators were input into the trained neural network model, yielding a predicted value of 1.041 (see Table 10). According to the safety level evaluation standard, the safety level of the bridge was seen to be Class II (see Table 9). The safety reserve of the bridge met the current use requirements, which was consistent with the direct detection conclusion. The validity and accuracy of the evaluation model were demonstrated and the specific conclusions are as follows:

- (1) The Kohonen neural network was applied to the safety evaluation of a cable-stayed bridge with reference to the building structure appraisal and rating method. The evaluation database was clustered and the evaluation labels corresponding to the five types of safety levels were obtained, which provided a corresponding reference for the safety evaluation of similar bridge types.
- (2) Combined with bridge safety evaluation data, four indices of stress amplitude, corrosion degree, sheath damage, and damping system were selected as attribute indices. Taking the bridge structure safety appraisal coefficient  $K$  as the decision-making index, the safety evaluation database of Fumin Bridge was established.
- (3) The training time of the simplified neural network was shortened and the training speed improved. Also, the neural network model possessed high simulation accuracy and the absolute error value between the predicted and theoretical values did not exceed 3%. This showed that the coarse neural network data fusion method could be used for bridge safety evaluation.
- (4) During the safety evaluation of a cable-stayed bridge, entering the four specific attribute indices of the bridge directly, the current safety status of the bridge was quickly determined to be Class II. That is to say, the safety reserve of the bridge met the current use requirements and was consistent with the results of the testing unit. This showed that these evaluation results of this method were objective and could thus improve bridge evaluation work efficiency.

## 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 there are no conflicts of interest regarding the publication of this paper.

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