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Research on the reliability assessment method of bridges incorporating transversely distributed damage information

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ABSTRACT

As the throat of transportation system, bridge structure is a lifeline project related to the coordinated development of society and economy. Based on fuzzy mathematical theory, this paper adopts Gaussian subordinate degree function to quantitatively characterize the damage detection information of articulation joints, combines Latin hypercubic sampling method and response surface method, and proposes a reliability assessment method for bridges integrating transversely distributed damage information, and analyzes the bridge of a certain structure as an engineering case, compares the failure probability corresponding to the model outputs and the real damage degree under different damage degrees, and analyzes the change of reliability indexes with the damage degree under articulation joint damage and main plate damage conditions, respectively. Under the conditions of articulation joint damage and main plate damage, the changes of reliability indexes with the damage degree are analyzed. The results show that the narrower the width of the damage interval is, the closer the failure probability is to the value corresponding to the real damage degree, and the reliability of the bridge decreases with the increase of the articulation damage and the main plate damage, which illustrates the objectivity and reasonableness of the method proposed in this paper.

Keywords: transverse distribution, affiliation function, response surface method, fuzzy mathematics, bridge reliability

1. Introduction

Bridges are an important part of the urban transportation infrastructure system and play a vital role in regional economic development. Under the action of external loads and environmental erosion

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and other factors, the resistance of bridges during the service period gradually decays, and local damage will occur in the components [1-2]. The early damage of bridges, if not recognized and repaired in time, may lead to further accumulation of local damage, affecting the normal use of the structure and even causing serious loss of life and property [3-4]. In order to ensure the safety of bridges, it is necessary to monitor and evaluate bridge performance in real time, identify localized damage to the structure in a timely manner, and update the health status of the bridge immediately after experiencing an event that may lead to the occurrence of damage to the structure [5-8].

As an important structure to ensure the overall stress of the structural system, the long-term action of external loads puts it in a three-dimensional stress space state, which is prone to damage during operation [9-11]. In order to ensure the safe operation of the bridge structure, it is necessary to make an accurate judgment of the state of the bridge to provide a reasonable basis for maintenance decisions [12-13]. However, the randomness of the constituent materials of bridge structures and the loads acting on them leads to a large amount of uncertainty in the bridge assessment process [14-15]. It is difficult for engineers and technicians to make quantitative judgment on the damage condition of transverse connection parts, and it is easy to get vague and uncertain interval test results [16]. Considering the importance of the influence of lateral distribution performance on the safety of the structural system, it is particularly important to integrate the lateral distribution detection information to analyze the reliability of bridge structures [17].

In the article, the reliability assessment methods of bridges are sorted out, and the assessment methods based on structural reliability are selected for research. Based on the fuzzy stochastic reliability theory, the Gaussian affiliation function is used to characterize the fuzzy detection information of the damage degree of the hinge joints, and the fuzzy information equivalent is randomized to convert the fuzzy variable of the damage degree of the hinge joints into a random variable, and the corresponding probability density function is obtained. Combining the Latin hypercubic sampling method and response surface method, the lateral distribution coefficient calculation method considering the fuzzy detection information of hinge damage is proposed, and the lateral distribution coefficient considering the fuzzy detection information is substituted into the standard value of the live load effect, so as to integrate the fuzzy detection information of the degree of damage of the hinges into the reliability assessment of the bridge components.

2. Reliability assessment methods for bridges

Bridge assessment is the process of using specific information to analyze the reliability of existing bridges and make sound engineering decisions. There are many existing bridge assessment methods, and the main assessment methods of bridge reliability are shown in Fig. 1, which can be roughly categorized into the following in practice: appearance survey assessment method, test assessment method, bridge expert assessment system, assessment method based on design specification, and method based on structural reliability theory.

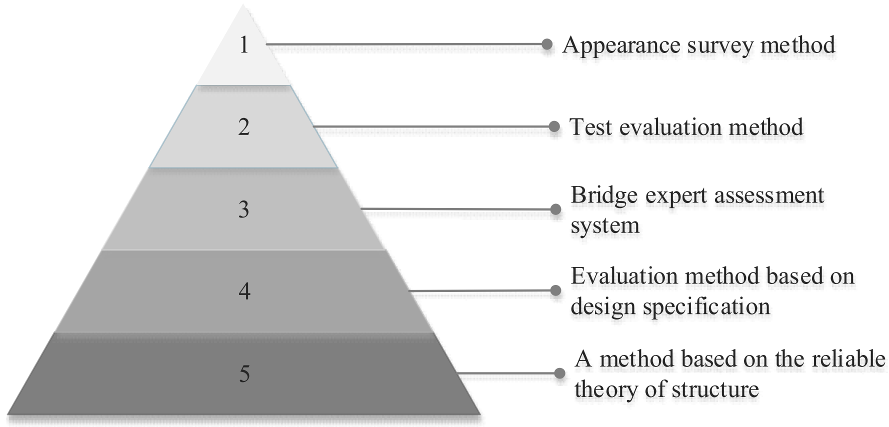


Fig. 1. The main evaluation method of bridge reliability

2.1. Appearance survey assessment methodology

During the use of highway bridges, under the action of vehicle loads, due to the changes and influences of design, construction, water flow state, climate conditions and other environmental factors, the bridges are likely to have damage, such as cracks as well as deformation. Excessive cracks and abnormal deformations make the normal serviceability and load carrying capacity of the bridge not satisfy the function required by the design. Appearance survey and evaluation method is to have experienced bridge technicians conduct a detailed inspection of the appearance of the old bridge, describe it into textual qualitative or quantitative test results, and determine the actual operational status of the bridge according to the evaluation criteria of the "Highway Bridge Maintenance Code" in the categories from one to five.

2.2. Test evaluation methods

Test assessment methods are methods of evaluating bridge structures by means of field tests. Depending on the nature of the loads acting on the bridge, the tests can be divided into static and dynamic tests. The main purpose of applying static load test to bridge assessment is to measure the structural response, such as deflection, strain, crack width, and compare it with the code allowable values, so as to deduce the corresponding load rating and load carrying capacity. However, it should be noted that when the test load is small, the extrapolated load capacity based on the structural response is not very credible. The application of dynamic load test to bridge assessment is mainly to analyze the operation condition of the bridge and determine a reasonable impact factor with the help of the determination of structural dynamic characteristics and response vibration period, amplitude, damping coefficient and impact factor. It should be emphasized that, although load tests are used from time to time in bridge assessment, they are not a substitute for conventional assessment methods, but can only be regarded as a means of obtaining information and a supplement to analysis methods, and the tests are expensive and difficult to popularize, which may cause serious structural damage and affect normal traffic.

2.3. Expert bridge assessment system

Expert assessment systems have the ability to process, express, utilize and reason about knowledge, which is particularly applicable to fuzzy processing of complex problems. The bridge expert assessment system is a method of comprehensive assessment of existing bridges by using computers to simulate the decision-making mechanism of experienced experts. It should be noted, however, that bridge expert assessment systems give qualitative conclusions on reliability estimates and are often auxiliary in their impact on assessment decisions.

2.4. Assessment methods based on design specifications

Bridge design codes are the standards guiding bridge design, based on engineering mechanics, structural tests and engineering experience, and are constantly being enriched and improved. Therefore, using the calculation theory of bridge codes to analyze the reliability of existing bridges has a solid theoretical foundation and is widely used.

However, it is inappropriate to directly apply the bridge gauge to bridge load carrying capacity assessment, which is due to the difference between design and assessment. For example, in the assessment phase, more specific information can be obtained than in the design phase. From the point of view of structural reliability theory, the uncertainty of loads and resistances in the assessment may be less than that considered in the design, so that the values of certain safety factors can be appropriately reduced in the assessment. However, using this approach to analyze the actual load carrying capacity of bridges tends to give conservative and rougher results.

2.5. Assessment methods based on structural reliability

The most prominent feature of the probability-based structural reliability theory is that it recognizes and reveals the existence of uncertainty in the properties of the structure, treats the various factors affecting the reliability of the structure as random variables, recovers the inherent natural characteristics, and obtains this objective variability through data. Based on the reliability theory adopts the method of reliability calculation, i.e., through actual measurement and statistics, using the mathematical theory of reliability, the probability of structural failure or reliability index is calculated to measure the safety level of the structure. Being based on probabilistic statistics, the theory can deal with the uncertainties of loads and resistances, and in particular with the effects of variations in these uncertainties on the reliability of the structure.

The first three methods can simply give the condition that the bridge is in, but they are all based on experience or too subjective, failing to assess the actual condition of the bridge in a fundamentally exact and objective way, so this paper proposes to combine the fifth method to quantitatively calculate the reliability of the concrete bridge system by taking into account the fuzzy detection information of the transversely distributed damage.

3. Reliability assessment methods incorporating horizontally distributed damage information

Combined with the structural reliability theory and based on the Gaussian affiliation function in fuzzy mathematical theory, a randomized processing method is proposed for the fuzzy detection information of transversely distributed damage to realize the quantitative characterization of the fuzzy detection information. Combining the Latin hypercube sampling method and the response surface method, the transverse distribution damage model is established to consider the different locations of the transverse links and the different degrees of damage. Based on the primary second-order moment method, a reliability assessment method is proposed to integrate the detection information of transversely distributed damage intervals.

3.1. Fuzzy reliability analysis

3.1.1. Fuzzy mathematical theory. Fuzzy sets are the promotion of classical sets, and fuzzy mathematics based on fuzzy sets is not to make the already-precise mathematics fuzzy, but to let mathematics enter the field of fuzzy phenomena.

1) Definition of fuzzy sets. Let the mapping μ be given on the thesis domain X, and define μ to have the following relations:

$$\mu : X \to [0,1] \tag{1}$$

Then μ determines a fuzzy set on X, denoted as $\underset{\sim}{A} \in \varpi(X)$, and μ is called the affiliation function of fuzzy event $\underset{\sim}{A}$ denoted as $\mu_A(x)$. For $x_0 \in X$, $\mu_A(x_0)$ is called the degree of affiliation of element x_0 with respect to $\underset{\sim}{A}$, which indicates the degree to which element x_0 belongs to fuzzy event $\underset{\sim}{A}$.

A fuzzy set is completely inscribed by its subordination function. The magnitude of $\mu_A(x)$ reflects the degree of subordination of x to the fuzzy set. The closer the value of $\mu_A(x)$ is to 1, the more subordinate x is to $\underset{\sim}{A}$. The closer the value of $\mu_A(x)$ is to 0, the lower the degree of affiliation of x to $\underset{\sim}{A}$.

2) Commonly used affiliation functions. In fuzzy mathematics, the degree of affiliation is the cornerstone of establishing fuzzy set theory, and the affiliation function is the key to describing fuzziness. Although the determination of the affiliation function has a great deal of subjectivity, the affiliation function still has a certain objective regularity. According to the empirical records, the commonly used affiliation functions are F-statistics, trichotomization, F-distribution, correlation, expert scoring, inference and binary comparison ranking. In this paper, Gaussian affiliation function is mainly used.

3.1.2. Fuzzy stochastic reliability. Probabilistic analysis is for the possibility of the occurrence of random events, the meaning of the event itself is clear and certain. However, when the meaning of the event itself is only fuzzy uncertainty, it is necessary to describe the likelihood of the occurrence of the event with the help of fuzzy rate analysis. The fuzzy probability reliability of structures is the application of fuzzy probability analysis to study the reliability of structures. As for the basic events, they may be discrete or continuous depending on their own situation.

A fuzzy event is a fuzzy set on the basic event space. If basic event X is discrete, its basic event space is:

$$X = \{X_1, X_2, \cdots, X_i, \cdots\} \tag{2}$$

Let its probability be $P(X_i)(i = 1, 2, \cdots\cdots)$ and the affiliation function of event X_i belonging to fuzzy event A be $\mu_A(X_i)$. The probability $P(\underset{\sim}{A})$ of fuzzy event $\underset{\sim}{A}$ is the expected value of its affiliation function, i.e:

$$P(\underset{\sim}{A}) = \sum_i \mu_A(X_i) P(X_i) \tag{3}$$

If the basic event X is continuous, the probability density function is known to be $P(X_i)$, and the affiliation function of fuzzy event A is $\mu_{\underset{\sim}{A}}(X_i)$, then the probability of fuzzy event $\underset{\sim}{A}$ is:

$$P(\underset{\sim}{A}) = \int_{-\infty}^{\infty} \mu_A(x) p(x) dx \tag{4}$$

The fuzzy stochastic reliability of structures is subdivided into three cases:

One is that the design parameters of the structure have only randomness without fuzziness, but the safety state (normal operating state) of the structure is fuzzy.

The second is that the safety state (normal operating state) of the structure is definite, but the design parameters have both randomness and fuzziness.

The third is that both the operating state and the design parameters of the structure are ambiguous.

3.2. Randomization of fuzzy detection information

In the reliability assessment of bridge components, if the detection information of lateral distribution condition can be combined, then the assessment results obtained will be more accurate and reasonable. To this end, the detection information of interval type needs to be randomized, and according to the characteristics of engineers and technicians detecting bridge hinge joints, Gaussian affiliation function is used to characterize the detection information.The expression of Gaussian affiliation function is shown in Equation (5):

$$u(\tilde{x}) = e^{-(\frac{x-i}{i})^2}, -\infty < x < +\infty \tag{5}$$

where μ and σ denote the mean and standard deviation of the Gaussian affiliation function, respectively. When the damage degree detection interval is [DL, DU], let $\mu = (L+U)/2, \sigma = (U-\mu)/k = (\mu - L)/k$, where k is a real number greater than 0.

In order to perform the bridge reliability assessment, the fuzzy detection information needs to be randomized, and according to Eq. (6), the Gaussian affiliation function shown in Eq. (5) is converted into a probability density function $f(x)$ and a distribution function $F(x)$ as shown in Eq. (7) and Eq. (8):

$$f(x) = \frac{\mu(\tilde{x})}{\int_{\tilde{x}U}^{\tilde{x}L} \mu(\tilde{x}) \tilde{d}x}, \tilde{x}_L < x < \tilde{x}_U \tag{6}$$

$$f(x) = \frac{\frac{2k}{M-L} e^{-(\frac{N-1}{M-L})^2}}{1.775\, erf\left(\frac{M-\inf}{M-L}k\right) - 1.775 erf\left(\frac{M+\inf}{M-L}k\right)} - \infty < x < +\infty \tag{7}$$

$$F(x) = \frac{1}{2} + \frac{\sqrt{\pi}\, erf\left(\frac{M-x}{M-L}k\right)}{1.775\, erf\left(\frac{M-\inf}{M-L}k\right) - 1.775\, erf\left(\frac{M+\inf}{M-L}k\right)} - \infty < x < +\infty \tag{8}$$

where: $erf(\cdot)$ - error function, $\inf$ - infinity. Where, $M = (L+U)/2$.

3.3. Probabilistic modeling of cross-sectional distribution coefficients

The transverse connection damage of multi-girder bridge girders directly affects the initial transverse distribution state of the bridge, in order to quantify the relationship between the transverse connection damage detection information and the transverse distribution coefficients, a probabilistic model of the transverse distribution coefficients is established based on the Latin Hypercube (LHS) sampling method and the response surface method with the following specific steps:

Step 1: Define the degree of damage of each hinge seam as a random variable x_i.

Step 2: Generate sample points of hinge damage using the LHS sampling method, and then calculate the transverse distribution coefficient of each plate using the modified articulated plate method.

Step 3: Establish the response surface function between the transverse distribution coefficient of each plate and the variable of the degree of hinge damage, determine the pending coefficients of the response surface function by using the least squares method, and substitute Eq. (7) into the response surface function as shown in Eq. (9) to obtain the probabilistic model of the transverse distribution coefficient:

$$mi = a + \sum_{j=1}^{n-1} b_j x_j + \sum_{j=1}^{n-1} c_j x_j{}^2 + \sum_{1 \le j \le k \le n-1} d_{jk} x_j x_k i = 1, 2 \cdots, n \tag{9}$$

where mi represents the transverse distribution coefficient of the fuzzy detection information of the hinge damage considered in beam No. i, x_i represents the random variable transformed from the fuzzy detection information of the hinge damage in No. i, and the rest of the parameters are coefficients to be determined.

Step 4: Verify the accuracy of the established response surface function and analyze the error between the response value and the theoretical value.

3.4. Reliability calculation methods

According to the calculation method of reliability index to determine the function function, for small and medium-span multi-girder bridge girders, flexural failure as the main failure mode of the main girder, the function function function expression is equation (10):

$$Z = R - S_{G1} - S_{G2} - S_Q \tag{10}$$

where, R, S_{G1}, S_{G2}, S_Q is a random variable that represents the resistance, one-phase constant load effect, two-phase constant load effect and live load effect, respectively. Where the standard value of live load effect is calculated as shown in Eq. (11):

$$S_Q = (1 + \mu) mi \, (q_k \Omega_k + p_k y_k) \tag{11}$$

where μ represents the impact coefficient, mi is the random variable of the lateral distribution coefficient as shown in Eq. (9), q_k, p_k represents the mean load and the concentrated load, respectively, and $y_k = \frac{L}{4}, \Omega_k = \frac{L^2}{8}$ and L represent the calculated span of the bridge.

Combining Eq. (10) and Eq. (11) and adopting the primary second-order method of moments (FOSM), the reliability indexes of each main girder considering lateral connection damage are calculated.

4. Case Studies

In order to illustrate the specific implementation process of the bridge reliability assessment method using the fuzzy detection information of the lateral distribution of damage proposed in this paper, the case bridge (BQ bridge) is selected as an example and the reliability of its components is assessed separately.

4.1. Probability of failure analysis

The bending limit state equations of the case bridge and the statistical parameters of the random variables are selected as the basis of reliability analysis. In this paper, four representative hinge damage conditions are selected, and the hinge damage conditions are shown in Table 1.

Table 1. Damage case of hinge joints

Case	Damaged hinge	Degree of damage
1	Hinge 1	0%, 20%, 40%, 60%, 80%, 100%
2	Hinge 1 and 2	
3	Hinge 1, 2 and 4	
4	Hinge 1, 2, 3 and 4	

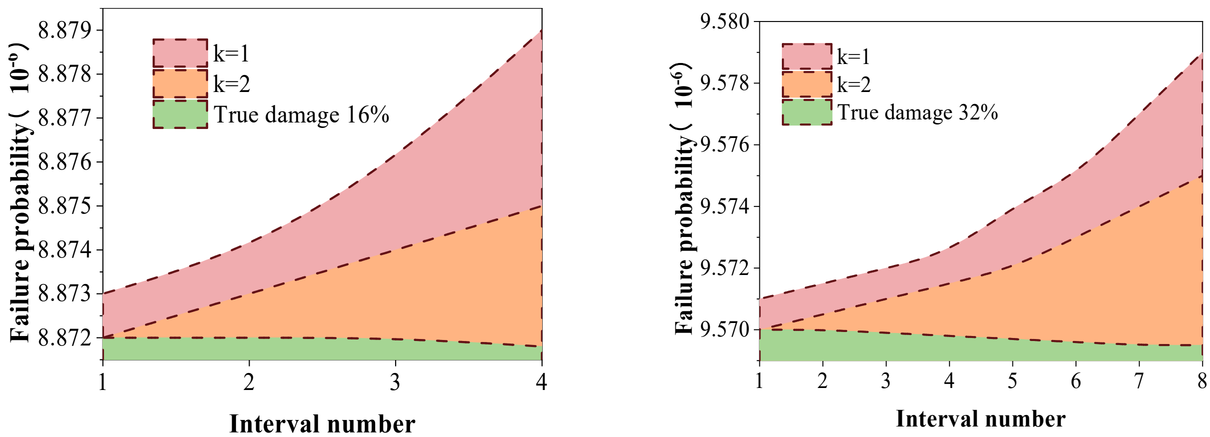
Different fuzzy detection intervals are obtained due to different confidence levels of engineers and technicians on the damage level of the hinge joints. If the confidence level is larger, then the fuzzy detection interval is narrower. In order to simulate the different confidence level of technicians on the damage of the hinge, the damage level of 16% and 32% as the real damage level, and the real damage level as the center, according to the 4% increment for the increment and decrement to generate the damage level intervals, different hinge damage level intervals as shown in Table 2.

Table 2. The different intervals of damage degree of hinge joints

True damage 20%		True damage 40%			
Interval number	Degree of damage	Interval number	Degree of damage	Interval number	Degree of damage
1	[12%,20%]	1	[28%,36%]	5	[12%,52%]
2	[8%,24%]	2	[24%,40%]	6	[8%,56%]
3	[4%,28%]	3	[20%,44%]	7	[4%,60%]
4	[0%,32%]	4	[16%,48%]	8	[0%,64%]

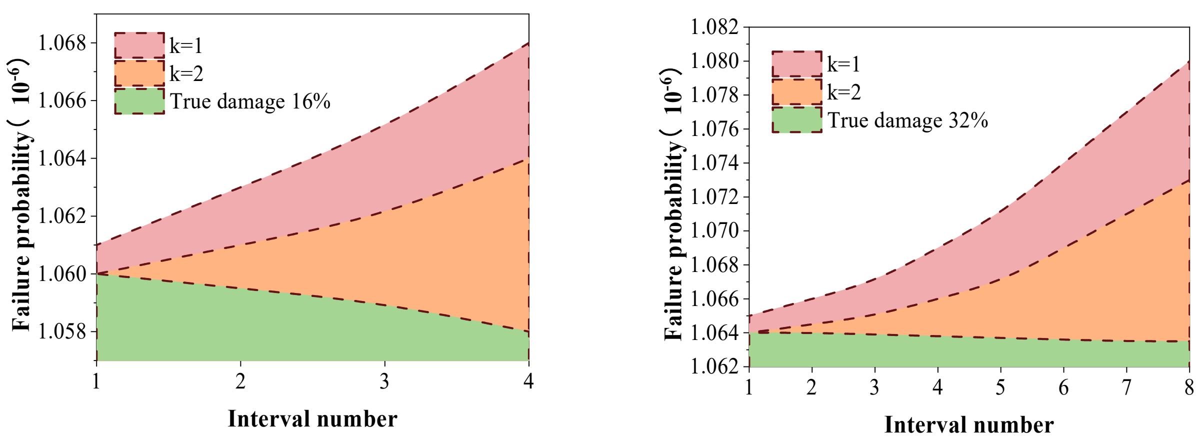
In order to verify the reasonableness of the proposed reliability assessment method for bridges considering the fuzzy detection information of transversely distributed damage, the failure probability of No.1 plate for different hinge damage intervals in Table 2 is calculated by taking hinge damage conditions 2 and 4 as an example. And compared with the failure probability corresponding to the real hinge damage degree, the results of the failure probability of different damage degree intervals under Case 2 and Case 4 are shown in Fig. 2 and Fig. 3. In the characterization of Gaussian affiliation function, two cases of k=1 and k=2 are considered.

With the increase of the width of the damage interval boundary, the failure probability of the No.1 plate shows an increasing trend when the Gaussian affiliation function is used to express the fuzzy detection information of the hinge seam damage, which is gradually far away from the failure probability corresponding to the real damage degree. The narrower the boundary width of the damage interval, the closer it is to the failure probability corresponding to the real damage level of the hinge. For example, in the case that the real damage degree of Case 2 is 16%, the failure probabilities of interval 1 are 8.873 (k=1) and 8.872 (k=2), the failure probabilities of interval 4 are 8.879 (k=1) and 8.875 (k=2), and the failure probability of the real damage degree is basically near 8.872. It shows that the bridge reliability assessment method proposed in this paper considering the fuzzy detection information of transversely distributed damage is in line with the objective law and verifies the rationality and accuracy of the method.



(a)True damage 16% of hinge joint (b)True damage 32% of hinge joint

Fig. 2. Failure probability of slab one in different damage intervals under the case 2



(a)True damage 16% of hinge joint (b)True damage 32% of hinge joint

Fig. 3. Failure probability of slab one in different damage intervals under the case 4

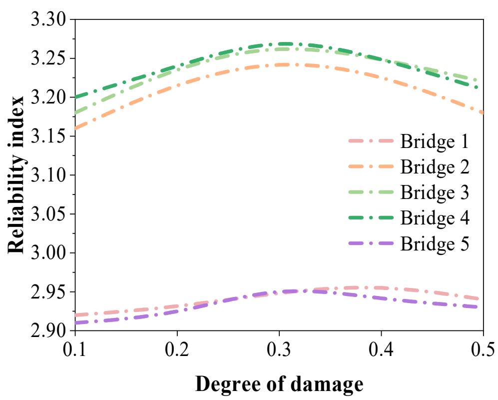
4.2. Analysis of reliability indicators

In this part, the damage to the articulation joints at different locations and the effect of the degree of damage on the time-varying reliability of the ultimate load carrying capacity of each plate are analyzed using the case bridge as an example.

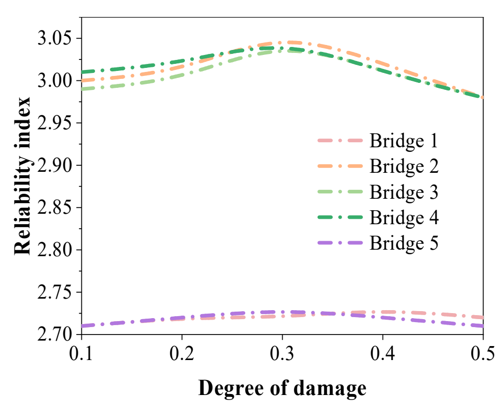
4.2.1. Damage to articulated joints. According to the reliability assessment method that integrates the transversely distributed damage information, the reliability indexes of six plates of the bridge were calculated under different hinge damage conditions, and the results of the calculation of the reliability indexes of the plates under different hinge damage conditions are shown in Fig. 4. Under different hinge damage conditions, the reliability index of each plate changes with the increase of hinge damage. The reliability indexes of plate No.1 and plate No.5 with 20 and 40 years of service are around 2.80~2.95 and 2.60~2.75, respectively, and the reliability indexes of plate No.2~4 are higher than those of plate No.1 and plate No.5 in the same case, and the reliability indexes of plate No.1 and plate No.5 with 20 and 40 years of service are around 3.10~3.20 and 2.80~3.08, respectively. This is due to the fact that plate 1 and plate 5 are located at the edge of the bridge and the reliability index results are in line with the actual situation.

In service for 20 years, from the figure (a) can be seen, the reliability index of each plate in case one with the articulation joint damage degree increase is first increase and then reduce the law of change, this is due to the damage of the articulation joint is located in the outermost in case one. From the figure (c) and (e) can be seen, working condition two and working condition three in the bridge reliability index law change rule is basically the same, with the articulation joint damage degree increases, the reliability index of each plate are the middle process for the nonlinear overall decline trend, and the change rule of each plate is not completely consistent. In working condition two, the change rule of the first board, two and five boards is basically the same, the rest of the two boards of the change trend is basically the same. In working condition three, the law of change of the first plate and the second plate is basically the same, and the law of change of the remaining three plates is basically the same, so it can be seen that the articulation joint damage to the plate in its vicinity affects the law of change is basically the same. From Fig. (g), it can be seen that the reliability index of each plate in Case IV is linearly decreasing with the increase of the damage degree of the articulation joint. It shows that compared with the damage of single articulation joint, when multiple articulation joints are damaged, the impact on the reliability index of each plate in the bridge span is more serious.

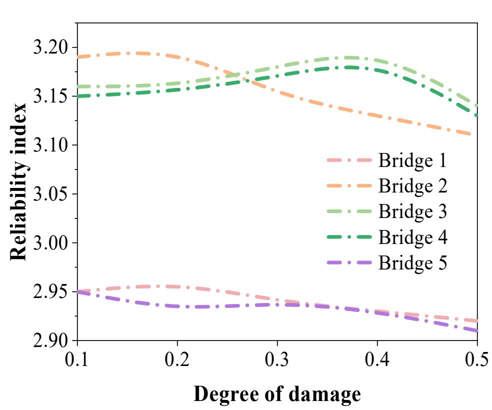
In 40 years of service, the pattern of change of reliability index of each plate under each articulation damage condition is basically the same as that in 20 years of service, and the trend of change of reliability index of each plate is basically the same, but the magnitude of change is slightly reduced compared with that in 20 years of service.



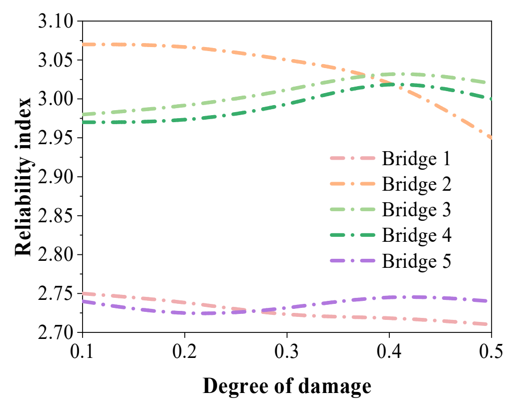
(a)Case 1(20 years)



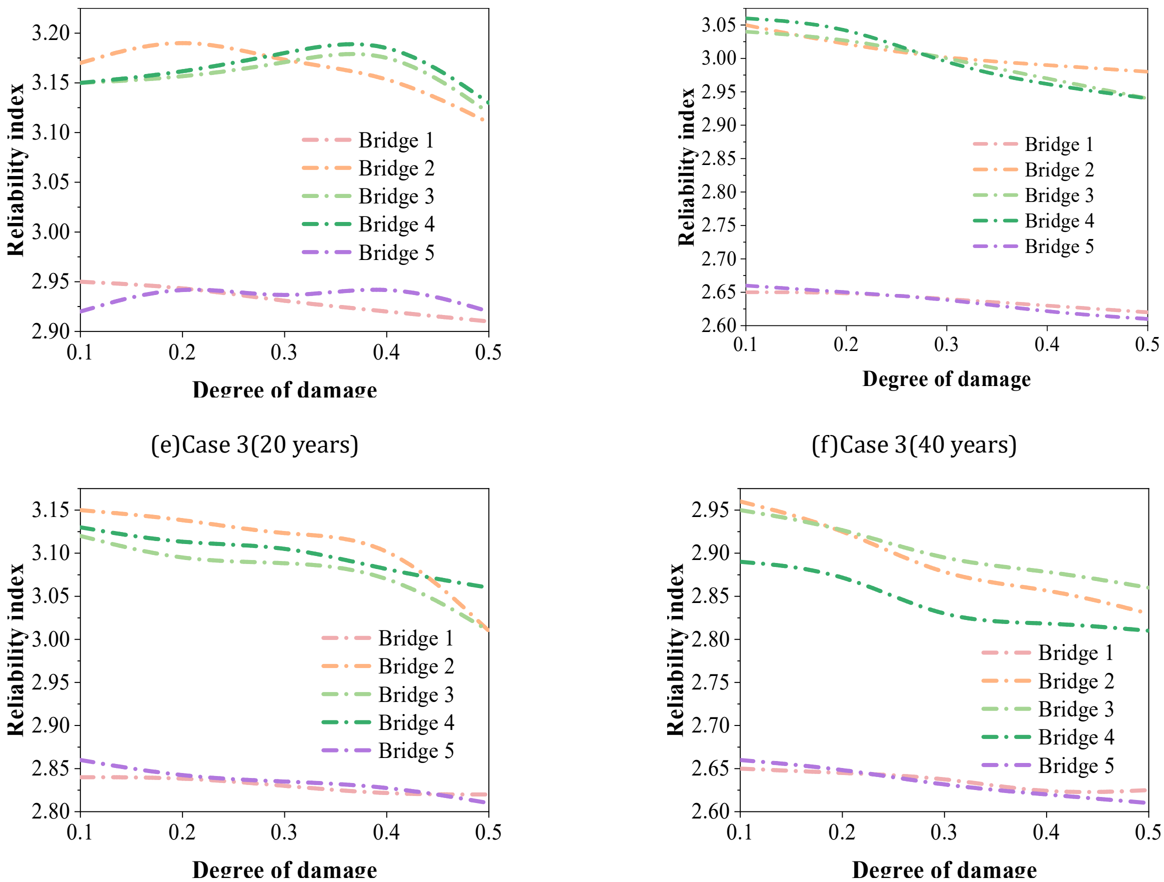
(b)Case 1(40 years)



(c)Case 2(20 years)



(d)Case 2(40 years)

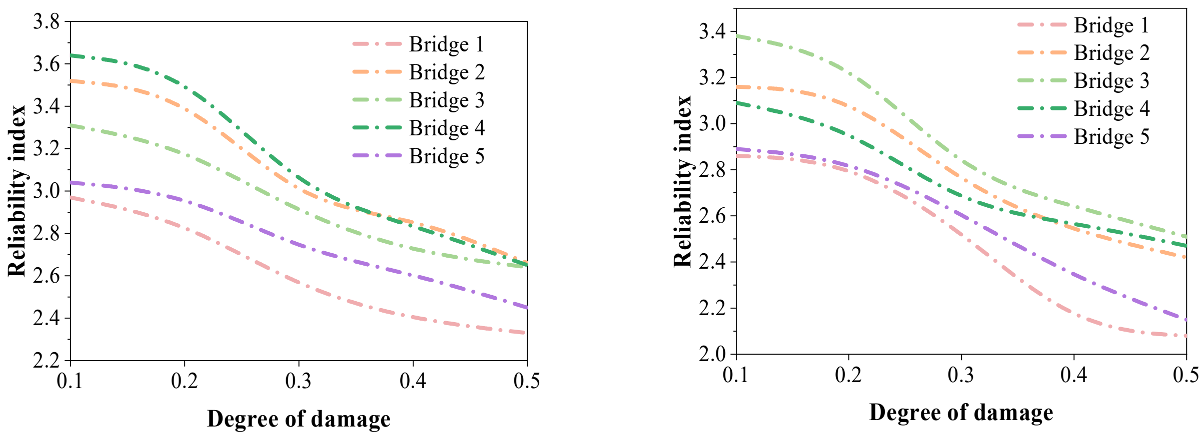


(e)Case 3(20 years) (f)Case 3(40 years)

(g)Case 4(20 years) (h)Case 4(40 years)

Fig. 4. Reliability index of slabs under different hinge joint damage cases

4.2.2. Main board damage. Analyze the case bridge main plate of different damage degree on the ultimate load carrying capacity of each plate time-varying reliability of the impact. Fig. 5 shows the change rule of reliability index with the damage degree of the main plate in the 20th and 40th year of service respectively. Each plate with the increase of the degree of damage are gradually reduced trend, in the degree of damage is 0.3, the rate of damage began to increase. Comparing the change of reliability index of each board, the change trend of two side boards is the same, and the change trend of three center boards is basically the same. And the change amplitude of the side plates is more obvious than that of the center plate under different damage degrees. The reliability indexes of the bridge main plate decreased by 22.75% and 24.38% as a whole in the case of 20 years of service and 40 years of service, respectively.



(a)20 years (b)40 years

Fig. 5. Reliability index of slabs under different slab damage cases

5. Conclusion

In recent years, the deterioration damage phenomenon of bridges has become more and more serious, this topic is based on the Gaussian affiliation function in the fuzzy mathematical theory, and proposes a bridge reliability assessment method that integrates the transversely distributed damage information. The BQ bridge is selected as a case for specific analysis, and the following main conclusions are obtained:

1) The failure probability corresponding to the Gaussian dependency function is closer to the failure probability corresponding to the real damage level of the hinge as the boundary width of the hinge damage level interval decreases. It shows that the bridge reliability assessment method proposed in this paper considering the fuzzy detection information of transversely distributed damage is in line with the objective law, which verifies the rationality and accuracy of the method.

2) Under different articulation damage conditions, the reliability indexes of each plate at different service times change with the increase of the damage degree of the articulation joint, and except for Case I, the reliability indexes of Case II, III and IV decrease with the increase of the damage degree of the articulation joint. However, in Case 4, the reliability index of each plate decreases more due to the larger number of damaged hinges. When the main plate is damaged, each plate shows a gradual decrease with the increase of damage degree, and the reliability indexes of the main plate of the bridge in service for 20 and 40 years decrease by 22.75% and 24.38%, respectively. The decrease of reliability indexes of side panels under different degrees of panel damage is more obvious than that of center panels.

In this paper, some work has been done and some research results have been obtained in the study of bridge reliability, however, due to the complexity of the influencing factors in the bridge condition assessment, there are still many problems to be solved, the bridge system reliability assessment method still needs to be further improved, and the system reliability assessment method of the failure credibility can be considered in the future.

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