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Quantitative safety evaluation of ancient Chinese timber arch lounge bridges

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Abstract

The timber arch lounge bridge is a special type of Chinese architectural heritage that is widely distributed in the southern Zhejiang Province and the northern Fujian Province. The precondition of planning the preventive conservation of built cultural heritage is the reliable evaluation of the structure safety, which enables the planners or decision-makers to comprehensively understand the complex damaged situation of the bridge and figure out a grading system for the bridge safety state. This paper puts forward a universal safety evaluation method for ancient Chinese timber arch lounge bridges. Special stress is given to the weight assignments during the procedure. Moreover, following the proposed evaluation method a case study of Wenxing Bridge is conducted, which could give a better insight into the evaluating process. This study contributes to a step forward, from the qualitative cognition to the quantitative assessment, on the way of evaluating the structure safety condition of ancient Chinese timber arch lounge bridges.

Keywords: Timber arch lounge bridge, Set pair analysis, Component importance analysis, Structural safety evaluation

Introduction

The timber arch lounge bridge, one type of China's national cultural heritage, refers to the type of bridge with a covered timber lounge house or corridor built on the timber member-weaving arch system. This special type of timber bridges in China originating in the Northern Song Dynasty (960–1127A.D.) and now mainly distributed in the southern Zhejiang Province and northern Fujian Province along China's south east coast. The construction of these bridges relies on the skilled craftsmanship with a woodworking master directing the carpentry of a team of woodworkers, since the bridges were entirely constructed by hand. This craftsmanship has been passed on down the years from one generation to another by masters teaching apprentices or relatives within a clan following strict procedures. The clans then play a vital role in the building, maintenance and protection of the bridges, while the diminishing of the craftsmanship and technique caused by urbanization is becoming even more serious these years. The construction techniques were ascribed by UNESCO to the Intangible Cultural Heritage in Need of Urgent Safeguarding in 2009 [1]. Many of the existing ancient timber arch lounge bridges have entered the list of China National Key Cultural Relics [2]. At present, there are totally around a hundred of the bridges existing in China, but not all of them are in a good structural health condition. As more and more ancient timber arch lounge bridges were destroyed in the past two decades due to material deterioration, natural disasters, anthropogenic influence, and the losing of the craftsmanship as well, the structural vulnerability and preventive conservation of the bridges are consequently receiving significant attention in recent years in China [3–7]. Therefore, a thorough and scientific structural evaluation of these historic bridges is a necessary and urgent task so as to carry out the possible preventive protection or refurbishment.

This study contains two aspects, one is to work out a proper quantitative evaluation method and the other is to determine the importance weight of different structural components so as to give a possible suggestion on the repair or maintenance priority of the members. Most of the present studies on the traditional arch lounge bridge

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are focused on the evolution of this bridge structure type [8] and the construction technology and philosophy [3, 5, 6]. Only a few studies are carried out from the perspective of structural performance, while much attention is only paid to the bridge arch system [9, 10] rather than the entire structure including the covered house. The structure of the covered house is formed of a sequence of single frames of the traditional Chinese timber buildings, of which the mechanical behavior has been researched relatively more sufficient [11–14].

Regarding the quantitative evaluation, the crux is to find out a procedure integrating all the members' safety conditions to give an overall result for the entire structure. Solving this kind of problems is often called the multicriteria decision-making procedure. There are many studies focusing on the method to perform the procedure. Risk-UE methodology [15, 16] suggested a procedure that assesses the seismic vulnerability of a building with index method, which is based on evaluating the main parameters that configure a specific building typology to establish the damage index. Some detailed evaluation procedures on the basis of the Analytic Hierarchy Process (AHP) method and the Delphi model, a qualitative model used to assign weights through interviewing a panel of experts on the field, are realized by jointly applying the Leopold matrix method [17]. Those principles are used in many studies [18–23] related to the evaluation of built heritage, nevertheless the assessment procedures in these studies are not limited to the structural assessment of a single building, but also involving the esthetic or cultural-symbolic significance to the priorities of renovation actions of aggregated built heritage. No matter what factors or significances are considered in an assessment procedure, the crux is to establish a suitable and reliable multicriteria decision-making system where the criteria are defined on the basis of certain guidelines or standards by allocating seemingly stochastic but interrelated and contextualized values to various parameters. The structure safety evaluation is the result of an integrated consideration of different structural variables linked to the different components in which a structure can be organized [15].

Distinguished from the previous methods of the structural safety evaluation for traditional Chinese timber buildings, including the widely used AHP with Delphi model [22, 23] and attribute recognition [24], this study proposed a method based on Set Pair Analysis (SPA), by which a set of connection number formula is established so as to take full advantage of the collective information from the structure to be evaluated. Using Delphi model to assign weights is a subjective process, which is highly dependent on the empirical knowledge of the experts. In view of that, the weight assignments in this study are scientifically and objectively realized on the basis of component importance analysis (CIA) using the "strain energy method". The overall aim of the present research is solve the quantitative problems in the procedure of the structural safety evaluation of ancient Chinese timber arch lounge bridges and demonstrate how the decision-maker perform the procedure through the case of Wenxing Bridge.

Methodology

As shown in Fig. 1 there are four stages constituting the methodology of the safety condition assessment of ancient Chinese timber lounge bridges. In stage I, the typology and configuration of the lounge bridge to be assessed are determined based on the on-site inspection, and the deterioration is detected and measured for the following calculation. Stage II defines the structural hierarchy, which from the lower to higher levels are member, member assembly, structural system, and the entire structure. The safety condition of the ancient bridge is successively evaluated from the assembly level to the entire structure level. The evaluation will finally give a result from grade 1 to 5 indicating good to bad. The assessing criterion of the member assembly are established in this stage according to some related guidelines and standards. Once the safety conditions of all the member assemblies are determined by the criterion, the grade result of the entire structure will be achieved through the steps that will be introduced in next stage. Stage III includes two core steps. The first is the assignment of importance weight for different structural assemblies based on the CIA method. The second is the SPA-based decision-making procedure, which refers to the process of comprehensively considering the safety condition of each member assembly and its importance weight to

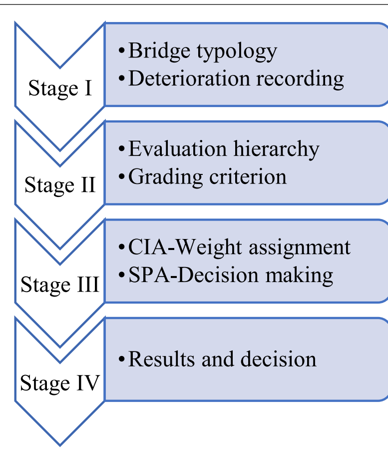

Fig. 1 Methodological scheme of structural safety evaluation

make a final grade decision. Once the result has been generated, the opportune decision may be taken in Stage IV.

Stage I: definition of typology and deterioration recording

Traditional Chinese timber bridge derived from the humpbacked bridge built in the twelfth century, during the hegemony of Song Dynasty, called Rainbow Bridge due to its arched shape. It is known by people because of its reproduction in the famous painting scroll Chhing-Ming Shang Ho Thu (Going up the river at spring festival), ascribed to Chang Tse-Tuan and taken in the Silk Museum of Beijing. The woven bracing beam systems constitute the stable force-bearing arch of the Rainbow Bridge [25]. The Rainbow Bridge is regarded as the earliest typology of timber arch bridge in Chinese bridge history, while none of the them is survived now. This bridge construction technique was believed to be lost after that until the twentieth century when many traditional timber arch lounge bridges located near the border between Zhejiang and Fujian provinces were found, as shown in Fig. 2. The arch lounge bridge has the covered house atop, which is the largest difference from the Rainbow Bridge, but holds the same construction philosophy of the arch under-deck systems as the Rainbow Bridge. Different from the simple arch of the Rainbow Bridge, the lounge bridge has a unique arch frame which consists of the tri-segment member system (TSMS) and penta-segment member system (PSMS). This combination of TSMS and PSMS can be seen in almost all the existing ancient timber lounge bridges in China. As shown in Fig. 3, all other structural components are configured based on them. The structure of a typical timber arch lounge bridge is composed of six systems, including covered house, deck system, column system, X-bracing system, PSMS, and TSMS. Each system can be deconstructed into several

Fig. 2 Some existing ancient timber arch lounge bridges: **a** Beijian Bridge, **b** Huangshui Bridge, **c** Santiao Bridge, and **d** Xianju Bridge

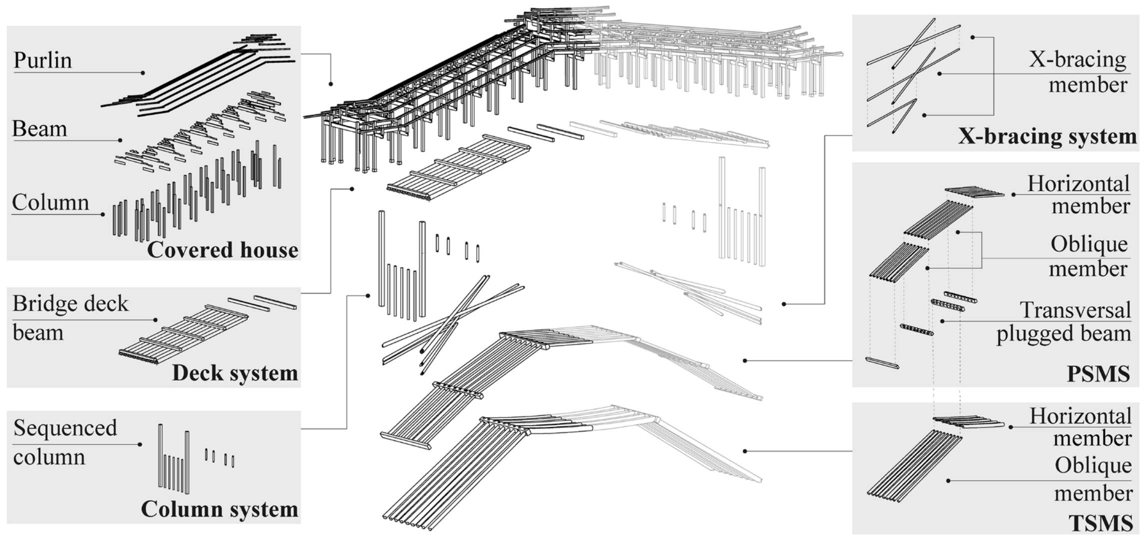

Fig. 3 Structural components of a typical timber arch lounge bridge

member assemblies, and there are totally ten member assemblies in a lounge bridge structure. In this first stage, besides the basic typology of the timber lounge bridge defined, other general information, including its physical dimensions, timber material and deterioration, of the bridge to be assessed should be gathered with inspectors knowing the evaluation criterion that will be introduced in the next stage.

Stage II: evaluation hierarchy and grading criterion

The safety evaluation of the entire bridge structure should be hierarchically carried out from the member assembly to the entire structural. The condition of the most damaged member in an assembly represents the condition of its member assembly.

Since there is no standard evaluation criteria in China targeted at the ancient bridge structures, in this study the evaluation criteria of the structural member are determined according to some related guidelines for historical timber buildings [20, 21, 26], as well as the empirical knowledge from the inspection in field work. Under the external loads, some of the bridge members bear the action of bending. Some members are under the compression-bending action. How a member will be evaluated depends on its load-bearing state. Therefore, as shown in Fig. 4, each of the ten assemblies labeled A1–A10 is grouped as 'Bending component' or 'Compression-bending component'. The bending components, which normally are beam members or horizontal members, should be assessed by six factors, b1–b6. The compression-bending components, which normally are column members or vertical members, should be assessed by nine factors, c1–c9. It should be noted that, regarding the compression-bending components, only c1–c7 are available for the members of which the foot end is not placed on the ground or plinth. The grading scales of bending and compression-bending components are listed in Tables 1 and 2, respectively.

In Tables 1 and 2, ρ represents the ratio of the maximum area of timber decay or insect attack and the area of cross-section of the member. k denotes the value of $\tan\theta$, where θ is the angle between the cracking and the direction along the timber grain. t refers to the maximum cracking depth, and b is dimension of the cross-section along the cracking direction.h is the height of the cross-section. l is the length of the member. w is the maximum value of the deflection. δ is the translocation distance of the member top. R is the structural resistance capacity, and S is the acting effects, which can be calculated with finite element (FE) method. $\gamma_0 = 1.2$ is the structure importance factor. Δt is the length of the part that is pulled out from the mortise in a tenon, of which the overall length is T. λ represents the slenderness ratio of the compression-bending member. ρ_c is the ratio of effective contact area between the column and the plinth to the cross-section area. ρ_d is the ratio of offset distance to the dimension of the cross-section along the offset direction, which is the cross-section diameter for the circular column.

Until here, the safety condition of all the member assemblies can be known, then the safety grade of the bridge will be consequently determined through

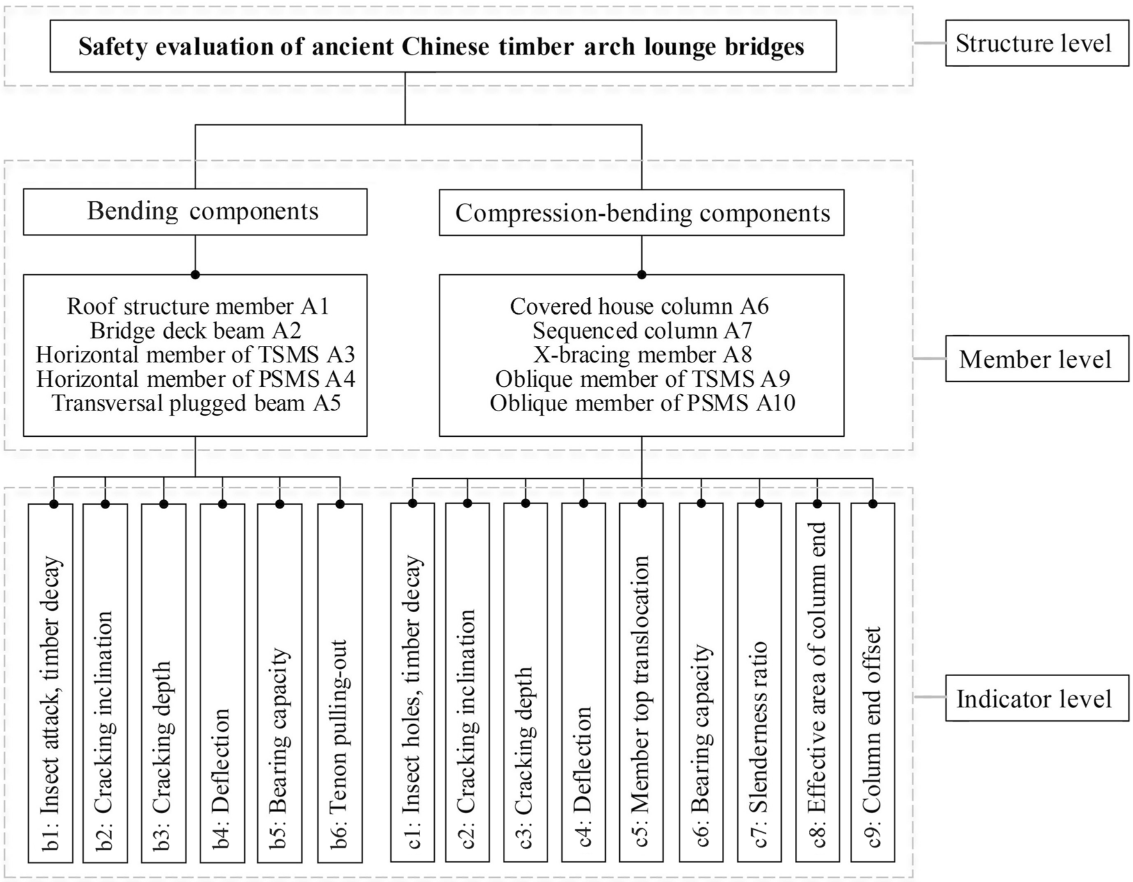

Fig. 4 Structure safety evaluation system of the timber lounge bridge

Table 1 Assessing indicators and grading criteria for bending components

Factor	b1	b2	b3	b4					b5	b6
				For beam member		For purlin member		Deck member		
Assessing indicator	ρ	k	$\frac{t}{b}$	$\frac{h}{l}>1/14$	$\frac{h}{l}\leq 1/14$	$l\leq 4.5$ m	$l>4.5$ m	$50\frac{w}{l}$	$1.1-\frac{R}{\gamma_0 S}$	$\frac{\Delta t}{T}$
				$50\frac{w}{l}$	$500\frac{wh}{l^2}$	$25\frac{w}{l}$	$30\frac{w}{l}$			
Grade 1	0–0.03	0–0.05	0–0.03	0–0.11	0–0.08	0–0.09	0–0.06	0–0.09	0–0.1	0–0.05
Grade 2	0.03–0.07	0.05–0.10	0.03–0.06	0.11–0.17	0.08–0.12	0.09–0.14	0.06–0.12	0.09–0.14	0.1–0.15	0.05–0.125
Grade 3	0.07–0.125	0.10–0.15	0.06–0.1	0.17–0.33	0.12–0.24	0.14–0.28	0.12–0.24	0.14–0.28	0.15–0.20	0.125–0.25
Grade 4	0.125–0.15	0.15–0.20	0.1–0.25	0.33–0.45	0.24–0.40	0.28–0.40	0.24–0.40	0.28–0.40	0.20–0.25	0.25–0.50
Grade 5	>0.15	>0.20	>0.25	>0.45	>0.40	>0.40	>0.40	>0.40	>0.25	>0.50

synthesizing the conditions of all assemblies. The grade levels of the entire structure and corresponding recommended interventions are presented in Table 3. Whereas different member assemblies have different functions, so they have different importance weights for a structure. That is a tough task, dealing with the data of all member assemblies to give an overall grade decision. These two problems, weight assignment and decision-making, will be solved in the next stage.

Table 2 Assessing indicators and grading criteria for compression-bending components

Factor	c1	c2	c3	c4	c5	c6	c7	c8	c9
Assessing indicator	ρ	k	$\frac{t}{b}$	$50\frac{w}{l}$	$30\frac{\delta}{l}$	$1.1-\frac{R}{\gamma_0 S}$	$\frac{\lambda}{200}-0.1$	$1-\rho_c$	$bf\,\rho_d$
Grade 1	0–0.05	0–0.05	0–0.05	0–0.11	0–0.11	0–0.1	0–0.6	0–0.05	0–0.05
Grade 2	0.05–0.10	0.05–0.10	0.05–0.10	0.11–0.17	0.11–0.17	0.1–0.15	0.6–0.65	0.05–0.30	0.05–0.10
Grade 3	0.10–0.20	0.10–0.15	0.10–0.20	0.17–0.33	0.17–0.33	0.15–0.20	0.65–0.75	0.30–0.40	0.10–0.17
Grade 4	0.20–0.25	0.15–0.20	0.20–0.25	0.33–0.45	0.33–0.45	0.20–0.25	0.75–0.90	0.40–0.50	0.17–0.30
Grade 5	> 0.25	> 0.20	> 0.25	> 0.45	> 0.45	> 0.25	> 0.90	> 0.50	> 0.30

Table 3 Safety grading of ancient Chinese timber arch lounge bridges

Grades	1	2	3	4	5
Structure state	Basically intact	Slightly damaged	Moderately damaged	Severely damaged	Nearly collapsed
Intervention	Periodical inspection	Minor maintenance	Moderate maintenance	Major maintenance	Emergency repair

Stage III: weight assignment and decision-making

Weight assignment based on CIA with strain energy method

Introduction of CIA The concept of component importance analysis (CIA) was first proposed by Ye et al. [27]. They use I in Eq. (1) to represent the importance of a certain component in a structure. In the equation, U_0 denotes the strain energy of an intact structure under certain external loads, and U represents the strain energy of this structure under the same loads when a certain component is ineffective. The equation expresses that how important a certain component is to a structure is reflected by how much influence the structure will get if this component is lost:

$$I = 1 - \frac{U_0}{U}. \tag{1}$$

Realization by FE calculation In this study, in order to take advantage of Eq. (1) to realize the calculation of the importance of each member assembly, FE method is adopted in ANSYS 16.0 with secondary development using APDL (ANSYS Parametric Design Language, a powerful scripting language in ANSYS). The ineffective component is achieved by reducing its elastic modulus to only 0.01%. Out of conservative consideration the importance is calculated on the member level in FE simulation, i.e., elastic modulus is reduced on a member-by-member basis, and the averaged value of all the members of an assembly represents the importance of this assembly. Supposing I_i represents the importance of the assembly $A_i, i \in [1, 10]$. The importance weight w_i applied in the later procedure of the safety evaluation is assigned by the normalized value as expressed in Eq. (2):

$$w_i = \frac{I_i}{\sum_{i=1}^{10} I_i}. \tag{2}$$

Decision-making based on SPA

Introduction of SPA Making the final grade decision of the entire structure is based on the set pair analysis (SPA) theory. The SPA theory is first put forward by Zhao [28] for dealing with the uncertainty problem. The theory handles the given problem involving set A and set B by regarding it as a system or a set pair (as its name implies). The SPA is analyzing the feature of sets A and B so as to figure out the relation or connection between them, and then find a way to quantify the connection degree. The connection degree between two sets can be characterized by three aspects, "identity", "discrepancy", and "contrary", which are denoted by α, β, and η, respectively. Supposing N represents the total number of the set pair features, and I and C represent the number of identical and contrary features, respectively, then $\alpha = I/N, \eta = C/N$, and $\beta = (N - I - C)/N$. The connection number, μ, can be expressed by $\mu = \alpha + \beta c_{\text{dis}} + \eta c_{\text{con}}$, where $c_{\text{dis}} \in [-1, 1]$ and $c_{\text{con}} = -1$, and they refer to the discrepancy and contrary coefficients, respectively. By this equation, the dialectical cognition of the uncertainty problem is transformed into the quantitative expression.

The crux of bridge safety evaluation in this study is the decision-making procedure. Using the SPA theory, the procedure is to find out first the connection between assessing indicators and five grades, and second the connection between member assemblies and five grades. The most connected grade among five grades is the final structural safety grade.

Realization by formula construction

Step 1: Set Pair I—connection between assessing indicators and five grades,

This problem involves two sets, A: the assessing indicator denoted by i, and B: the rating grade denoted by j. Here a set of formulas is constructed so as to give five numbers μ_{i1} to μ_{i5}, which are for denoting the connection degrees and called connection numbers. If i is right in the grade j, the connection number, μ_{ij}, is assigned as 1, i.e., they are considered identical. $\mu_{ij} = -1$, i.e., they are considered contrary, on the condition that i is in the grade of $j + m$, where $m > 1$. If i is in the adjacent grade of j, say $j + 1$ or $j - 1$, they are redarged discrepant, so $\mu_{ij} \in [-1, 1]$. As i is approaching to the grade j or $j \pm 1$, μ_{ij} is closer to 1 or -1. For the condition of "identity" and "contrary", the value μ_{ij} is ascertained, while the difficulty lies in figuring out the connection number of "discrepancy". Supposing that $j \in [1, 5]$, the formulas of the connection number are listed as follows:

$$\mu_{i1}\begin{cases} 1, x_i \in [0, S_{i1}] \\ 1 + \frac{2(x_i - S_{i1})}{S_{i1} - S_{i2}},\ x_i \in [S_{i1}, S_{i2}] \\ -1, x_i \in [S_{i2}, S_{i5}] \end{cases}, \tag{3}$$

$$\mu_{i2}\begin{cases} 1, x_i \in [S_{i1}, S_{i2}] \\ 1 + \frac{2(x_i - S_{i2})}{S_{i2} - S_{i3}},\ x_i \in [S_{i2}, S_{i3}] \\ -1,\ x_i \in [S_{i3}, S_{i5}] \\ -1 + \frac{2x_i}{S_{i1}},\ x_i \in [0, S_{i1}] \end{cases}, \tag{4}$$

$$\mu_{i3}\begin{cases} 1,\ x_i \in [S_{i2}, S_{i3}] \\ 1 + \frac{2(x_i - S_{i3})}{S_{i3} - S_{i4}},\ x_i \in [S_{i3}, S_{i4}] \\ 1 + \frac{2(x_i - S_{i2})}{S_{i2} - S_{i1}},\ x_i \in [S_{i1}, S_{i2}] \\ -1,\ x_i \in [0, S_{i2}] \text{ or } x_i \in [S_{i3}, S_{i5}] \end{cases}, \tag{5}$$

$$\mu_{i4}\begin{cases} 1,\ x_i \in [S_{i3}, S_{i4}] \\ 1 + \frac{2(x_i - S_{i4})}{S_{i4} - S_{i5}},\ x_i \in [S_{i4}, S_{i5}] \\ 1 + \frac{2(x_i - S_{i3})}{S_{i3} - S_{i2}},\ x_i \in [S_{i2}, S_{i3}] \\ -1,\ x_i \in [0, S_{i2}] \end{cases}, \tag{6}$$

$$\mu_{i5}\begin{cases} 1,\ x_i \in [S_{i4}, S_{i5}] \\ 1 + \frac{2(x_i - S_{i4})}{S_{i4} - S_{i3}},\ x_i \in [S_{i3}, S_{i4}] \\ -1,\ x_i \in [0, S_{i3}] \end{cases}, \tag{7}$$

where S_{ij} is the top limit value of assessing indicator i in grade j, and x_i is the actual sample value of i obtained from the on-site inspection or calculation.

Supposing that the total number of assessing indicators is n, then, μ_j, the average connection number of all those indicators with grade j, can be calculated as:

$$\mu_j = \sum_{i=1}^{n} w_{ij}\mu_{ij}, \tag{8}$$

where w_{ij} is the weight value of the factor i in grade j. Now the problem is how to deal with the w_{ij}. Regarding the Set Pair I, the factor weights are not constant values. The weight value of the same factor could vary in different grades. The weight of a certain factor in a certain grade is measured according to the actual state of the component, namely the sample value of the corresponding indicator. This measurement is achieved by ratio of the sample value to each top limit value of the five grades. The larger the ratio is in some grade, the larger weight value this factor has in this grade. The final weight value can be obtained after normalization, which is expressed as:

$$w_{ij} = \frac{x_i/S_{ij}}{\sum_{i=1}^{n}\left(x_i/S_{ij}\right)}. \tag{9}$$

Step 2: Set Pair II—connection between member assemblies and five grades.

Each member assembly will get five average connection numbers regarding five grades in step 1. In this step, the average connection number (μ_{rj}) between each member assembly ($A_r, r \in [1, 10]$) and

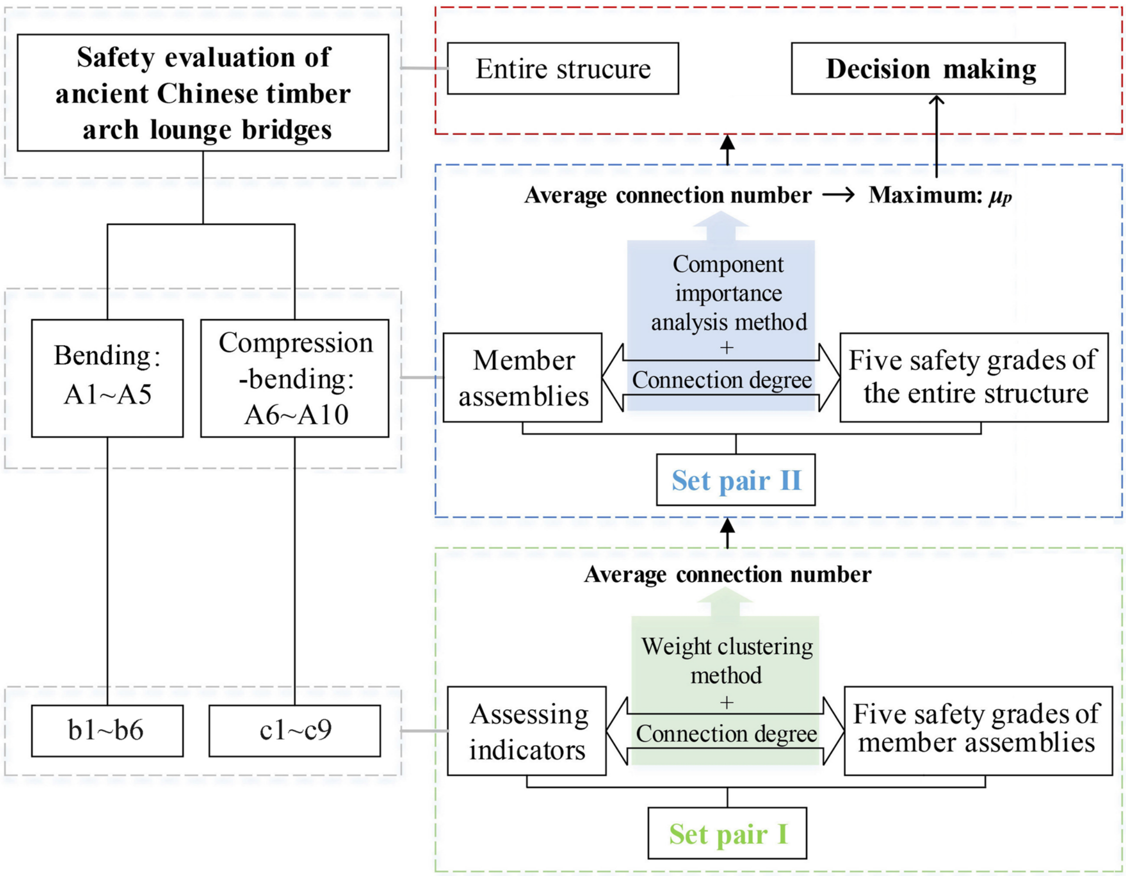

Fig. 5 Roadmap of performing the safety evaluation procedure

Fig. 6 The Wenxing Bridge

five grades of the entire structure (j, $j \in [1, 5]$) can be calculated with the weight assignment of each assembly (w_{rj}) that was calculated in "Weight assignment based on CIA with strain energy method" section by the strain energy method.

Stage IV: results and decision

The Fig. 5 presents the roadmap for performing the safety evaluation procedure. With Eq. (9), a set of connection number μ_j between the structural safety and five grades is finally obtained. If the maximum value of μ_j is μ_p, the assessed system has the closest connection with the grade p. Therefore, the safety condition of the lounge bridge is regarded as grade p.

Case study of Wenxing Bridge

Description of the bridge

The Wenxing Bridge, built in 1857 (Qing Dynasty) and located in Taishun county, Zhejiang Province, is a typical ancient Chinese timber lounge bridge with representative covered house and under-deck arch system. The bridge entered the list of China National Key Cultural Relics in 2006. The length of the bridge is 30 m. There are 27 tri-segment members, 40 penta-segment members, 6 transversal plugged beams and 6 sets of X-shape scissor bracing members in the under-deck arched part. The framework of the covered house is the typical Chinese style of "tie-and-column construction" with double-eave roof in the middle and single-eave roof in two sides, as shown in Fig. 6, which presents the bridge before the renovation in 2018. The timber used in transversal plugged beams is Chinese pine and all other members are Chinese fir.

Deterioration of the bridge

According to the on-site inspection, the transversal plugged beam members in a half side of the Wenxing Bridge (left side in Fig. 6) has sunk to a great extent, leading to the deflection and cracking of members in PSMS and TSMS and the severely asymmetric deformation of the whole structure. The altitude difference of transversal plugged beams between the two sides is 0.84 m. The impact of this deformation on the safety of the bridge can reflected by the assessing indicator c5. A noticeable deformation is found on the roof of covered house, which is caused by the purlin deflection, and much cracking takes place on the house roof structure members. Tenons of many PSMS and TSMS members are pulled out seriously. The transversal plugged beam members are also the most badly damaged part in the bridge as a result of their nature of being mortised and plugged by PSMS and TSMS members. Another serious problem is the reduced effective area of the member cross-section caused by the insect attack and timber decay. The member deformation was detected by a 3D laser scanner (Leica ScanStation P16). The crack depth was detected by HC-CS202 crack depth meter from Beijing Hichance Technology Co., Ltd. When the depth of insect attack and timber decay was less than 40 mm, the Pilodyn test method was used to determine the depth. The Resistograph test method was adopted for the insect attack and decay, which the depth of was larger than 40 mm. Some other lengths, including the length of tenon pulling-out and the distance of column end offset, were tape-measured. The typical deterioration is presented in Fig. 7.

Weight assignment

The CIA of the Wenxing Bridge is conducted with the FE software ANSYS. The timber grades and material constants of Chinese fir and Chinese pine were obtained from another relative study by Chun [4]. Since the bridge has been in service for more than 100 years, according to the code [26], material constants need to be reduced to a certain extent. The reduction factor of the compressive strength parallel to grain was 0.95. The reduction factors of both the bending strength and the shear strength parallel to grain were 0.90. The reduction factor of the elastic modulus was 0.90. In the reference [4], the mechanical properties of timber material are determined by timber sample testing. For Chinese fir, the material properties are as follows: 6.3 MPa for the tensile strength parallel to grain, 9.5 MPa for the compressive strength parallel to grain, 1.08 MPa shear strength parallel to grain, and 8100 MPa for the longitudinal elastic modulus. The weight density is 4 kN/m^3. The mechanical properties of Chinese pine are as follows: 8.55 MPa for the tensile strength parallel to grain, 14.25 MPa for the compressive strength parallel to grain, 1.44 MPa for the shear strength parallel to grain, and 9000 MPa for the longitudinal elastic modulus. The weight density is 5 kN/m^3. Since timber is the orthotropic material with nine constants in three directions, combining the proposed ratio values for timber elastic constants in the reference [29], the material constants of Chinese fir and Chinese pine can be determined as shown in Table 4.

The tile dead load and roof live load are 1.0 kN/m^2 and 0.7 kN/m^2, respectively. The deck live load is assigned as 3.5 kN/m^2. Since both the bridge structure and the external loads are symmetric, the present study only analyzes a half of the bridge structure, and the averaged assembly importance index of the bridge is presented in Fig. 8. The hierarchical order of the assembly importance is list as follows with the normalized values w_i in brackets: Oblique member of PSMS A10 (0.2031) > Oblique

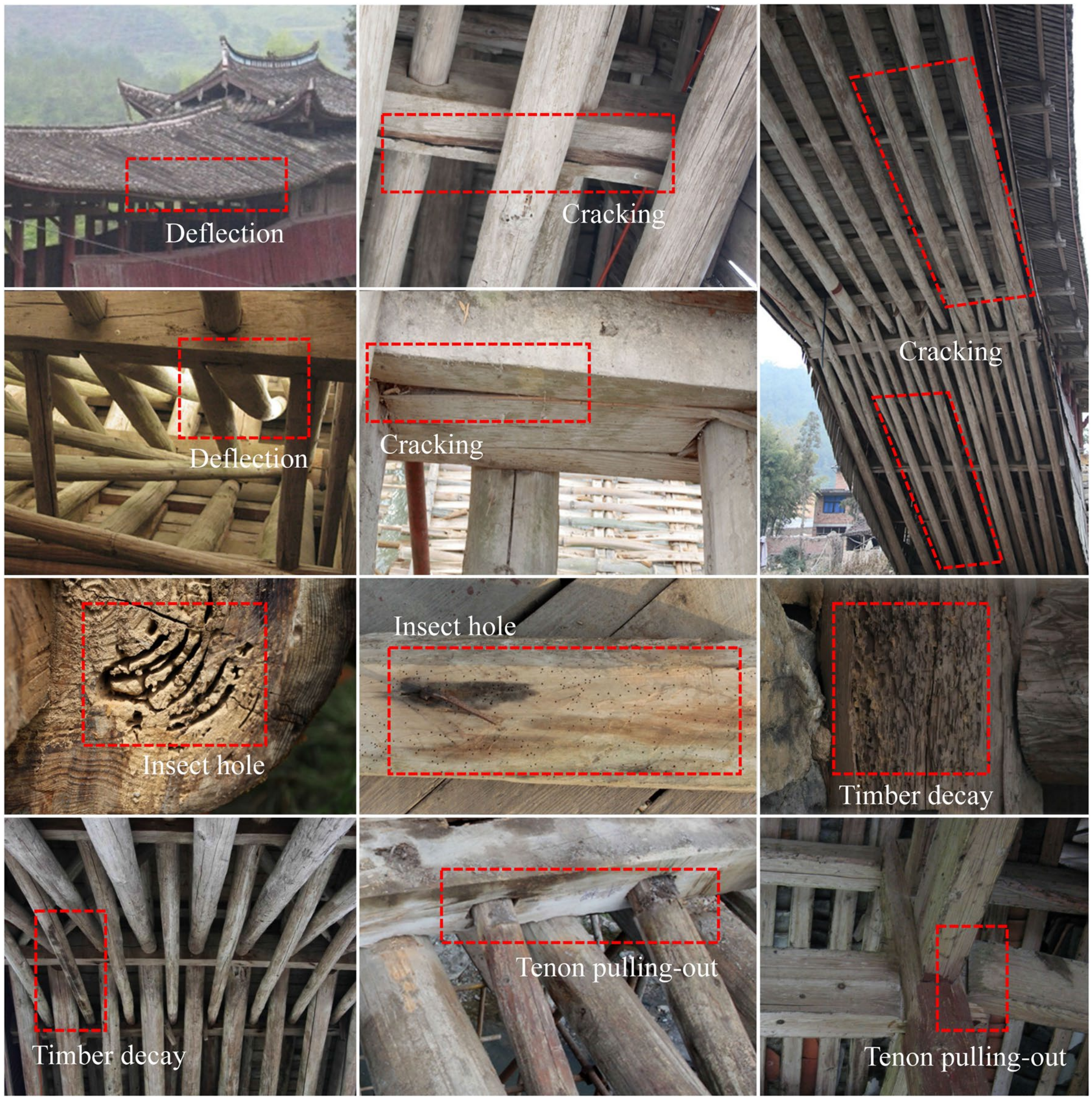

Fig. 7 Typical deteriorations of Wenxing Bridge

Table 4 Material constants of Chinese fir and Chinese pine

	E_L/GPa	E_R/GPa	E_T/GPa	v_{LT}	v_{LR}	v_{RT}	G_{LT}/GPa	G_{LR}/GPa	G_{RT}/GPa
Chinese fir	8.1	0.81	0.41	0.1	0.1	0.35	0.49	0.61	0.15
Chinese pine	9.0	0.9	0.45	0.1	0.1	0.35	0.54	0.68	0.17

E denotes elasticity modulus, *v* denotes Poisson ratio, and *G* denotes tangential modulus. The subscript: L-longitudinal, R-radial, and T-tangential

member of TSMS A9 (0.1467) > transversal plugged beam A5 (0.1431) > sequenced column A7 (0.1348) > horizontal member of PSMS A4 (0.1098) > horizontal member of TSMS A3 (0.0943) > X-bracing member A8 (0.0851) > covered house column A6 (0.0360) > roof structure member A1 (0.0276) > bridge deck member A2 (0.0194).

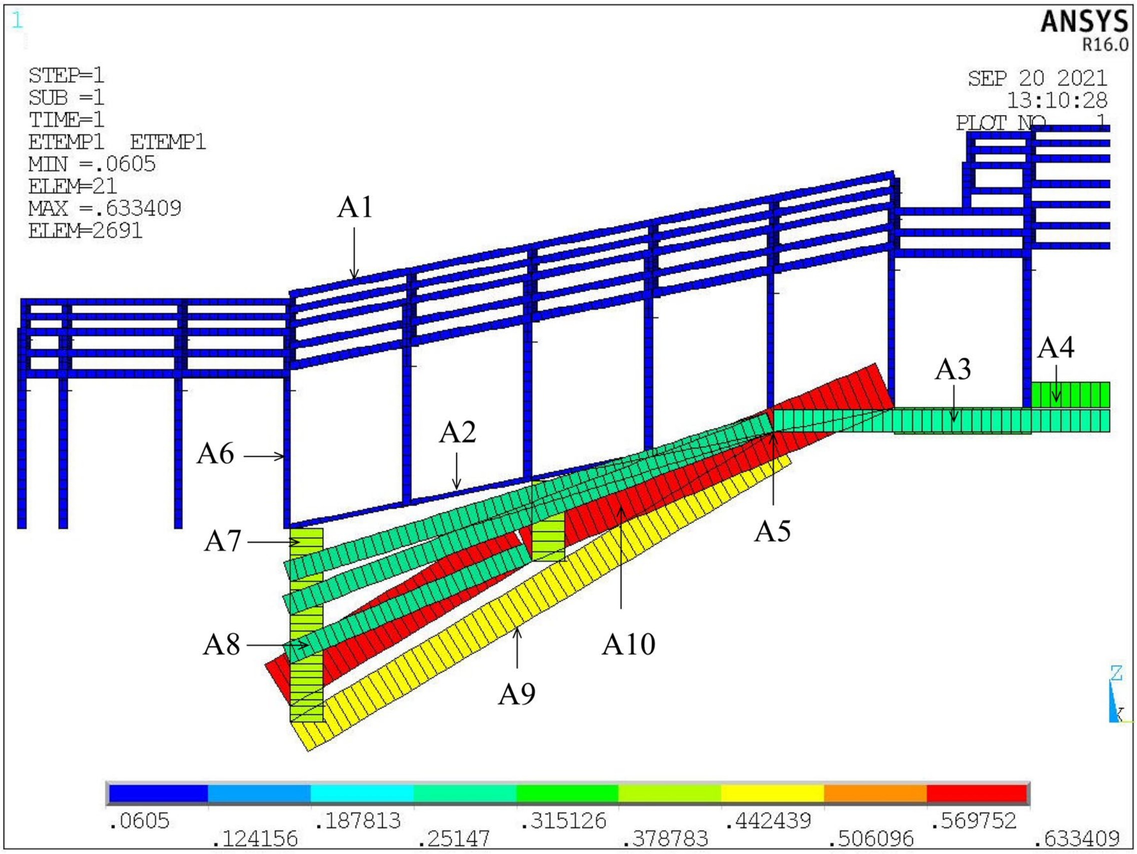

Fig. 8 Assembly importance result of the half structure

Decision-making

The sample values for assessing factors are collected from the on-site inspection, measurement, and FE simulation results. Here, four member assemblies, of which two are bending components: "roof structure member A1" and "bridge deck beam A2", and the other two are compressive-bending components: "covered house column A6" and "sequenced column A7", are taken as examples to perform the calculation procedure of the connection numbers.

1. Calculation procedures for A1 and A2

   The sample values are taken from the most seriously deteriorated places in all the assemblies of the bridge, and the sample values for the six assessing factors of A1 are determined as follows: $\rho = 0.067$, $k = 0.17$, $\frac{t}{b} = 0.70$, $500\frac{wh}{l^2} = 0.36$, $1.1 - \frac{R}{\gamma_0 S} = 0.28$, and $\frac{\Delta t}{T} = 0.48$. The sample values for the six assessing factors of A2 are as follows: $\rho = 0.10$, $k = 0.18$, $\frac{t}{b} = 0.70$, $500\frac{wh}{l^2} = 0.50$, $1.1 - \frac{R}{\gamma_0 S} = 0.30$, and $\frac{\Delta t}{T} = 0.48$. According to Eqs. (3)–(7), the connection number μ_{ij} between the six assessing factors and five grades are calculated. The normalized weight values of the assessing factors in all five grades w_{ij} are obtained based on Eq. (9). and the average connection numbers μ_j (SUM values in the last row) achieved by Eq. (8).

   The Table 5 presents the μ_{ij}, w_{ij} (in brackets) and the average connection numbers μ_j (SUM values in the last row) achieved by Eq. (8).

2. Calculation procedure for A6 and A7

   The sample values of A6 are as follows: $\rho = 0.24$, $k = 0.23$, $\frac{t}{b} = 0.34$, $50\frac{h}{l} = 0.18$, $30\frac{\delta}{l} = 0.13$, $1.1 - \frac{R}{\gamma_0 S} = 0.14$, and $\frac{\lambda}{200} - 0.1 = 0.18$. The sample values of A7 are determined as follows: $\rho = 0.083$, $k = 0.23$, $\frac{t}{b} = 0.75$, $50\frac{h}{l} = 0.24$, $30\frac{\delta}{l} = 0.15$, $1.1 - \frac{R}{\gamma_0 S} = 0.33$, $\frac{\lambda}{200} - 0.1 = 0.43$, $1 - \rho_c = 0.03$, and $\rho_d = 0.01$. According to Eqs. (3)–(7), the connection number μ_{ij} between assessing factors and five grades are calculated. The normalized weight values

Table 5 Calculation of connection numbers for A1 and A2

	Grade 1		**Grade 2**		**Grade 3**		**Grade 4**		**Grade 5**	
	$\mu_{i1}(w_{i1})$	$\mu_{i1}\times w_{i1}$	$\mu_{i2}(w_{i2})$	$\mu_{i2}\times w_{i2}$	$\mu_{i3}(w_{i3})$	$\mu_{i3}\times w_{i3}$	$\mu_{i4}(w_{i4})$	$\mu_{i4}\times w_{i4}$	$\mu_{i5}(w_{i5})$	$\mu_{i5}\times w_{i5}$
A1										
b1	− 0.85 (0.049)	− 0.041	1.00 (0.042)	0.042	0.85 (0.040)	0.034	− 1.00 (0.063)	− 0.063	− 1.00 (0.033)	− 0.033
b2	− 1.00 (0.074)	− 0.074	− 1.00 (0.074)	− 0.074	0.2 (0.084)	0.017	1.00 (0.120)	0.12	− 0.2 (0.083)	− 0.017
b3	− 1.00 (0.509)	− 0.509	− 1.00 (0.507)	− 0.507	− 1.00 (0.519)	− 0.519	− 0.20 (0.396)	− 0.079	1.00 (0.340)	0.34
b4	− 1.00 (0.098)	− 0.098	− 1.00 (0.130)	− 0.13	− 0.50 (0.111)	− 0.056	1.00 (0.127)	0.127	0.50 (0.175)	0.088
b5	− 1.00 (0.061)	− 0.061	− 1.00 (0.081)	− 0.081	− 1.00 (0.104)	− 0.104	0.92 (0.158)	0.146	1.00 (0.136)	0.136
b6	− 1.00 (0.209)	− 0.209	− 1.00 (0.166)	− 0.167	− 0.84 (0.142)	− 0.12	1.00 (0.136)	0.136	0.84 (0.233)	0.196
SUM	–	− 0.993	–	− 0.917	–	− 0.747	–	0.386	–	0.711
A2										
b1	− 1.00 (0.068)	− 0.068	− 0.09 (0.057)	− 0.005	1.00 (0.055)	0.055	0.09 (0.086)	0.008	− 1.00 (0.044)	− 0.044
b2	− 1.00 (0.073)	− 0.073	− 1.00 (0.072)	− 0.072	− 0.20 (0.083)	− 0.017	1.00 (0.116)	0.116	0.20 (0.080)	0.016
b3	− 1.00 (0.475)	− 0.475	− 1.00 (0.469)	− 0.469	− 1.00 (0.483)	− 0.483	− 0.20 (0.360)	− 0.072	1.00 (0.310)	0.310
b4	− 1.00 (0.127)	− 0.127	− 1.00 (0.167)	− 0.167	− 1.00 (0.144)	− 0.144	0.67 (0.161)	0.107	1.00 (0.221)	0.221
b5	− 1.00 (0.061)	− 0.061	− 1.00 (0.080)	− 0.080	− 1.00 (0.103)	− 0.103	0.87 (0.154)	0.134	1.00 (0.133)	0.133
b6	− 1.00 (0.196)	− 0.196	− 1.00 (0.154)	− 0.154	− 0.84 (0.132)	− 0.111	1.00 (0.123)	0.123	0.84 (0.212)	0.178
SUM	–	− 1.000	–	− 0.948	–	− 0.802	–	0.416	–	0.814

Table 6 Calculation of connection numbers for A6 and A7

	Grade 1		**Grade 2**		**Grade 3**		**Grade 4**		**Grade 5**	
	$\mu_{i1}(w_{i1})$	$\mu_{i1}\times w_{i1}$	$\mu_{i2}(w_{i2})$	$\mu_{i2}\times w_{i2}$	$\mu_{i3}(w_{i3})$	$\mu_{i3}\times w_{i3}$	$\mu_{i4}(w_{i4})$	$\mu_{i4}\times w_{i4}$	$\mu_{i5}(w_{i5})$	$\mu_{i5}\times w_{i5}$
A6										
c1	− 1.00 (0.234)	− 0.234	− 1.00 (0.218)	− 0.218	− 0.60 (0.192)	− 0.115	1.00 (0.197)	0.197	0.60 (0.168)	0.101
c2	− 1.00 (0.214)	− 0.214	− 1.00 (0.199)	− 0.199	− 1.00 (0.235)	− 0.235	0.95 (0.226)	0.215	1.00 (0.154)	0.154
c3	− 1.00 (0.331)	− 0.331	− 1.00 (0.308)	− 0.308	− 1.00 (0.272)	− 0.272	0.76 (0.279)	0.212	1.00 (0.238)	0.238
c4	− 1.00 (0.080)	− 0.080	0.88 (0.096)	0.084	1.00 (0.087)	0.087	− 0.88 (0.082)	− 0.072	− 1.00 (0.126)	− 0.126
c5	− 0.20 (0.058)	− 0.012	1.00 (0.069)	0.069	0.20 (0.063)	0.013	− 1.00 (0.059)	− 0.059	− 1.00 (0.091)	− 0.091
c6	− 0.60 (0.068)	− 0.041	1.00 (0.085)	0.085	0.60 (0.112)	0.067	− 1.00 (0.115)	− 0.115	− 1.00 (0.098)	− 0.098
c7	1.00 (0.015)	0.015	− 0.40 (0.025)	− 0.01	− 1.00 (0.038)	− 0.038	− 1.00 (0.041)	− 0.041	− 1.00 (0.126)	− 0.126
c8	1.00 (0.000)	0.000	− 1.00 (0.000)	0.000	− 1.00 (0.000)	0.000	− 1.00 (0.000)	0.000	− 1.00 (0.000)	0.000
c9	1.00 (0.000)	0.000	− 1.00 (0.000)	0.000	− 1.00 (0.000)	0.000	− 1.00 (0.000)	0.000	− 1.00 (0.000)	0.000
SUM	–	− 0.896	–	− 0.497	–	− 0.493	–	0.337	–	0.052
A7										
c1	− 0.32 (0.056)	− 0.018	1.00 (0.052)	0.052	0.32 (0.045)	0.014	− 1.00 (0.046)	− 0.046	− 1.00 (0.037)	− 0.037
c2	− 1.00 (0.155)	− 0.155	− 1.00 (0.144)	− 0.144	− 1.00 (0.166)	− 0.166	0.93 (0.159)	0.148	1.00 (0.102)	0.102
c3	− 1.00 (0.506)	− 0.506	− 1.00 (0.469)	− 0.469	− 1.00 (0.406)	− 0.406	− 0.33 (0.414)	− 0.137	1.00 (0.333)	0.333
c4	− 1.00 (0.074)	− 0.074	0.13 (0.088)	0.011	1.00 (0.079)	0.079	− 0.13 (0.074)	− 0.010	− 1.00 (0.107)	− 0.107
c5	− 0.33 (0.046)	− 0.015	1.00 (0.055)	0.055	0.33 (0.049)	0.016	− 1.00 (0.046)	− 0.046	− 1.00 (0.067)	− 0.067
c6	− 1.00 (0.111)	− 0.111	− 1.00 (0.138)	− 0.138	− 1.00 (0.179)	− 0.179	0.79 (0.182)	0.144	1.00 (0.146)	0.146
c7	1.00 (0.024)	0.024	0.43 (0.041)	0.018	− 1.00 (0.062)	− 0.062	− 1.00 (0.066)	− 0.066	− 1.00 (0.191)	− 0.191
c8	1.00 (0.020)	0.020	0.20 (0.006)	0.001	− 1.00 (0.008)	− 0.008	− 1.00 (0.008)	− 0.008	− 1.00 (0.013)	− 0.013
c9	1.00 (0.007)	0.007	− 0.60 (0.006)	− 0.004	− 1.00 (0.006)	− 0.006	− 1.00 (0.005)	− 0.005	− 1.00 (0.004)	− 0.004
SUM	–	− 0.828	–	− 0.617	–	− 0.717	–	− 0.026	–	0.162

Table 7 Calculation of average connection numbers for all member assemblies

	Grade 1		Grade 2		Grade 3		Grade 4		Grade 5	
	$\mu_{m1}(w_{m1})$	$\mu_{m1}\times w_{m1}$	$\mu_{m2}(w_{m2})$	$\mu_{m2}\times w_{m2}$	$\mu_{m3}(w_{m3})$	$\mu_{m3}\times w_{m3}$	$\mu_{m4}(w_{m4})$	$\mu_{m4}\times w_{m4}$	$\mu_{m5}(w_{m5})$	$\mu_{m5}\times w_{m5}$
A1	−0.99 (0.028)	−0.028	−0.92 (0.028)	−0.026	−0.75 (0.028)	−0.021	0.39 (0.028)	0.011	0.71 (0.028)	0.020
A2	−1.00 (0.019)	−0.019	−0.95 (0.019)	−0.018	−0.80 (0.019)	−0.016	0.42 (0.019)	0.008	0.81 (0.019)	0.016
A3	−1.00 (0.094)	−0.094	−1.00 (0.094)	−0.094	−0.98 (0.094)	−0.093	0.50 (0.094)	0.047	0.97 (0.094)	0.091
A4	−1.00 (0.110)	−0.11	−0.90 (0.110)	−0.099	−0.49 (0.110)	−0.054	0.52 (0.110)	0.057	0.36 (0.110)	0.04
A5	−0.80 (0.143)	−0.115	−0.62 (0.143)	−0.089	−0.41 (0.143)	−0.059	0.58 (0.143)	0.082	0.24 (0.143)	0.035
A6	−0.90 (0.036)	−0.032	−0.50 (0.036)	−0.018	−0.49 (0.036)	−0.018	0.34 (0.036)	0.012	0.05 (0.036)	0.002
A7	−0.83 (0.135)	−0.112	−0.62 (0.135)	−0.083	−0.72 (0.135)	−0.097	−0.03 (0.135)	−0.004	0.16 (0.135)	0.022
A8	−0.95 (0.085)	−0.081	−0.84 (0.085)	−0.072	−0.03 (0.085)	−0.003	0.72 (0.085)	0.061	−0.11 (0.085)	−0.01
A9	−0.97 (0.147)	−0.142	−0.93 (0.147)	−0.136	−0.63 (0.147)	−0.092	−0.08 (0.147)	−0.012	0.31 (0.147)	0.046
A10	−0.95 (0.203)	−0.193	−0.99 (0.203)	−0.202	−0.63 (0.203)	−0.128	0.12 (0.203)	0.024	0.24 (0.203)	0.048
SUM	–	−0.926	–	−0.837	–	−0.580	–	0.287	–	0.310

of the assessing factors in all five grades w_{ij} are obtained based on Eq. (9). Table 6 presents the μ_{ij}, w_{ij} (in brackets), and the average connection numbers μ_j (SUM values in the last row) achieved by Eq. (8).

3. Average connection numbers

   The calculation procedures of all the bending and compression-bending member assemblies are the same as A1/A2 and A6/A7, respectively. Due to the space limit, this paper will not present the detailed calculation procedures of all the ten assemblies. The resulted average connection numbers between A1 and A10 and five safety grades are summarized in Table 7. The assembly weight values are obtained in "Weight assignment" section and here listed in Table 7 with brackets.

Results and discussion

The real status of the most damaged members in all the assemblies are referred when the connection numbers are calculated. Compared to the traditional evaluation methods, this procedure could reflect the real safety condition as much as possible. As the numbers in the final row shown in Table 7, the maximum connection number is 0.31 in grade 5. The Wenxing Bridge has the closest connection with the grade 5. Therefore, the safety grade of the bridge can be assessed as Five, which implies the bridge structure is "Nearly collapsed" and needs "Emergency repair". The result could reflect the real safety status of the Wenxing Bridge. The data in Table 7 could also give some suggestion on the repair priority of member assemblies. Integrating the connection number and the importance weight of each member assembly, the bold typeface number on each row of Table 7 could reflect the closet connection to some grade, which is the safety grade of this assembly. The repair should start from the member assemblies that are in Grade 5 and then to the Grade 4. For those in Grade 5, the priority is A3(0.091) > A10 (0.48) > A9(0.046) > A7(0.022) > A1(0.020) > A2(0.016). For those in Grade 4, the priority is A5 (0.082) > A8(0.061) > A4(0.057) > A6(0.012).

Conclusion

Ancient timber arch lounge bridges are a unique structural type, and they are an important part of cultural heritage in China. Due to the various deterioration and long-term service, the number of these remaining bridges is decreasing year after year. A correct method for structural evaluation of these bridges is urgently needed.

This paper presents a method for quantitative evaluation of structural safety of ancient timber lounge bridges. The whole evaluation procedure consists of two steps. Step 1 is to figure out the connection numbers between assessing factors and five grades. In this step, a set of connection number formula (3)–(7) was constructed. The changing weights of assessing factors with the sample values were also considered. In step 2, the connection numbers between member assemblies and five grades were calculated. During this step, the problem of weight assignments of different member assemblies was solved by FE structural calculation with strain energy method. That is critical for the accurate decision-making, and also helps in establishing an order of priority for protective interventions through understanding the importance hierarchy of different structural members.

The evaluation method proposed in this study contributes to a step forward from the qualitative cognition to the quantitative evaluation on the way of assessing the structure safety condition of ancient Chinese timber arch lounge bridges.

Abbreviations
AHP: Analytic Hierarchy Process; SPA: Set pair analysis; CIA: Component importance analysis; PSMS: Penta-segment member system; TSMS: Tri-segment member system; FE: Finite element.

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Authors' contributions
YH contributed to the methodology, simulation, results analysis and original draft of this manuscript. QC contributed to the methodology and review of this manuscript. All authors contributed to the on-site investigation of the Wenxing Bridge. All authors read and approved the final manuscript.

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All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests
The authors declare that they have no competing interests.

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