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Research Article

Safety State Evaluation Method Based on Attribute Recognition Model for Ancient Timber Buildings

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To improve accuracy of safety state evaluation results for ancient timber buildings and to know the real state of the building, a safety grade evaluation model of ancient timber buildings is established based on attribute mathematic theory. From the perspective of macro, micro, qualitative, and quantitative, 22 factors may adversely affect the safety state of ancient timber building are considered in this model. First, evaluation system is established, and evaluation indexes are selected based on former study, seismic damage data, and Chinese current code about ancient timber buildings. In the evaluation system, whole building is divided into four parts, which are wood frame, enclosing wall, foundation, and plinth. Different parts contain different components. Every component has its own evaluation indexes. Second, based on the AHP and entropy method, the comprehensive empowering method is used to determine the weights of the indexes. Third, the attribute recognition model is established to identify the safety grade of components or units. Fourth, based on the evaluation results of components, safety grade of units is identified. Then, safety degree of the entire building is determined by the minimum safety grade of units. At last, the model is applied to the "Liben hall" in village Siping, Zhejiang province, China, and the assessment results are consistent with the results of damage identification.

1. Introduction

Ancient timber buildings play an important role in Chinese oriental culture and civilization. One-third of Chinese cultural relics sites consist of timber buildings [1]. Compared with various modern buildings, such as concrete structure, the bearing system of ancient timber buildings is quite different. Wood is an important load-bearing material for ancient timber buildings. The mechanical properties of wood are complex. Wood is anisotropic material, and different kinds of wood have different mechanical properties. And the mechanical properties of wood material change along with the environment, such as temperature, humidity, time, and so forth [2]. All of this make safety evaluation for ancient timber building becomes harder.

Different kinds of methods have been used to assess safety states of ancient timber buildings, such as finite element simulation, model test, theoretical analysis, stochastic and probabilistic analysis, and nondestructive detection and evaluation. Chen [3] analyzed the structural weakness of Yingxian wood pagoda. FEM models were constructed for the pagoda using ABAQUS. Li [4] built a model of Shang Youge by ANSYS software to study the structural characteristics and seismic performance of ancient wood structure. Xue et al. [5] put up with a seismic damage evaluation model for Chinese ancient timber building by theoretical and experimental methods. Huan et al. [6] proposed a vulnerability analysis method for ancient timber architecture based on probabilistic and Copulas. A shaking table test using a scale model of single-bay palace wood frame was carried out by Zhang [7] to study its dynamic characteristics. Shaking table tests and static lateral loading tests of full-scale traditional wood frame were carried out by Suzuki et al. [8] to study response characteristics of Japanese traditional wood buildings. A shaking table test of 1/5 scale wooden pagoda was carried out by Song et al. [9] to study its dynamic characteristics. Finite element simulation and the model experiment method can fully demonstrate the stress state of

ancient wooden structures. The limitations of these two methods make them difficult to apply in the building code. First, the complex structures and properties of wood frames of ancient timber buildings are difficult to simulate by finite element software. Deviation would be caused if the model was simplified. Second, the experimental method costs more money and time, and the deviation caused by the scale effect is hard to predict and estimate. Usually, the wood used in the experiment is nondamaged, which is different from the actual damaged state of the ancient buildings. So, whether the experiment and simulation results can demonstrate the real state of the building or not is hard to evaluate.

Nondestructive test and evaluation have been applied to safety assessment of ancient timber buildings. Three-dimensional stress wave test was carried out by Dai et al. [10] to detect the cavity area of wood components. Resistograph®3450-P/S was used by Huang et al. [11] to detect inside wood decay of ancient architecture, and the relationship between mechanical properties of wood materials and decay levels are analyzed. Typical assessment methods including observation, ruler measurement, nondestructive testing, three-dimensional laser imaging scanning, and finite element analysis were used by Zhou et al. [12] to evaluate the safety levels of Chinese ancient wood structures. Nondestructive testing is intuitionistic and convenient. Internal damage of timber components can be quickly detected. However, the comprehensive effects of all damages on the timber component need further study.

Research studies on mortise and mortise joint of ancient timber structures were conducted by many researchers. Chang et al. [13] studied the factors that affect the rational stiffness of timber joints, and an equation was established to estimate the initial rotational stiffness of timber joints. Column-girder joint specimens were tested by Han et al. [14] to study their mechanical properties. A series of 15 tests of traditional pegged mortise and tenon connections of green oak are conducted by Shanks and Walker [15]; the stiffness and ultimate strength of the tenon under tension, bending, and shear are investigated. King et al. [16] conducted an experiment on three naturally deteriorated joints of traditional Chinese wood frames. Low-cyclic reversal loading tests on damaged dovetail mortise-tenon joints were conducted by Xie et al. [17] to study the aseismic behaviors. Gao et al. [18] investigated the aseismic characteristics of corbel bracket. These studies focus on the joints of traditional wood structures. However, it is rare to find the research about how damage joints affect the safety state of the whole structure.

Chinese ancient timber buildings have been existing for hundreds years, and lots of factors, such as natural disasters, climate, and human activities, may affect their safety sates. In order to consider all the factors into consideration to improve the accuracy of evaluate results, an evaluation method based on attribute recognition theoretical model [19] is proposed in this paper. Attribute recognition theoretical model has been applied into civil engineering. Zhong [20] established a comprehensive evaluation model for existing RC structures based on attribute recognition theoretical theory to evaluate the durability of the structures. He et al. [21] evaluated the structure behavior of dam by attribute recognition theory. However, attribute recognition theoretical theory is rarely used in the field of timber structure and ancient buildings.

This paper purposed an evaluation method for ancient timber building based on attribute recognition theory. First, based on former research studies and seismic data, main parameters affecting the safety state of ancient timber buildings are selected, sorted, and analyzed. Second, evaluation system for ancient timber buildings is established. Third, evaluation model is established to identify the safety states of components by attribute recognition theory. Fourth, the safety states of the whole structure based on the evaluation results are evaluated.

2. Attribute Recognition Theory Model

Attribute recognition theory model includes 3 parts: single index attribute measure analysis, multiple index synthetic attribute measure analysis, and attribute recognition analysis.

Attribute recognition theory model could estimate the influence of various factors on the component at the same time. In the object space X, there are n components or units, which are $x_i\{i = 1, 2, \ldots, n\}$, which need to be evaluated. Each component or unit has m evaluate indexes, which are $I_j\{j = 1, 2, \ldots, m\}$. The measured series of values from a component or unit for index I_i is z_{ij}. Let F be some attribute space and $C_1, C_2, \ldots, C_K$ be an ordered series of safety grades in the attribute space F.

2.1. Calculation of Weights of Indexes. Weights are essential for accurate evaluation results. To take full advantage of subjective and objective opinions, combination weights are calculated based on subjective and objective weights. Analytic hierarchy process (AHP) [22] is used to calculate subjective weights of indexes, which is ω_{j1}. Entropy weight method (EWM) [23] is used to calculate objective weights of indexes, which is ω_{j2}. The combinatorial weights could be calculated by the following equation:

$$\omega_j = \frac{(\omega_{j1})^{\alpha}(\omega_{j2})^{\beta}}{\sum_{j=1}^{m}(\omega_{j1})^{\alpha}(\omega_{j2})^{\beta}}, \tag{1}$$

α and β are importance degree of subjective and objective weights, which can be calculated by the following equations:

$$\begin{aligned} T' &= \frac{2}{m}\left(1p_1' + 2p_2' + \cdots + mp_m'\right) - \frac{m+1}{m}, \\ \alpha &= \frac{m}{m-1}T', \\ \beta &= 1 - \alpha, \end{aligned} \tag{2}$$

where m is the number of evaluation indexes; $p_1', p_2', \ldots, p_m'$ are members of weight vector; and $p_1' < p_2' < \cdots < p_m'$.

2.2. Single Index Attribute Measure Analysis. The attribute measure $\mu_{xj}^{k} = \mu(z_{ij} \in C_k)$ of index value z_{ij}, which takes the

attribute levels from C_k. Suppose $a_{j0} < a_{j1} < \cdots < a_{jK}$ or $a_{j0} > a_{j1} > \cdots > a_{jK}$, then the standard grades of every index can be established, which is shown in Table 1.

Then,

$$b_{jk} = \frac{a_{jk-1} + a_{jk}}{2},$$
$$d_{jk} = \min\left\{\left|b_{jk} - a_{jk}\right|, \left|b_{jk+1} - a_{jk}\right|\right\}. \quad (3)$$

If $a_{j0} < a_{j1} < \cdots < a_{jK}$, single index attribute measure function $\mu_{ij}^{k}(t)$ could be

$$\mu_{xj}^{1}(t) = \begin{cases} 1, & t < a_{j1} - d_{j1}, \\ \dfrac{a_{j1} + d_{j1} - t}{2d_{j1}}, & a_{j1} - d_{j1} \le t \le a_{j1} + d_{j1}, \\ 0, & t > a_{j1} + d_{j1}, \end{cases} \quad (4)$$

$$\mu_{xj}^{k}(t) = \begin{cases} 0, & t < a_{jk-1} - d_{jk-1}, \\ \dfrac{t - a_{jk-1} + d_{jk-1}}{2d_{jk-1}}, & a_{jk-1} - d_{jk-1} \le t \le a_{jk-1} + d_{jk-1}, \\ 1, & a_{jk-1} + d_{jk-1} < t < a_{jk} - d_{jk}, \\ \dfrac{a_{jk} + d_{jk} - t}{2d_{jk}}, & a_{jk} - d_{jk} \le t \le a_{jk} + d_{jk}, \\ 0, & t > a_{jk} + d_{jk}, \end{cases} \quad (5)$$

$$\mu_{xj}^{K}(t) = \begin{cases} 0, & t < a_{jK-1} - d_{jK-1}, \\ \dfrac{t - a_{j1} + d_{j1}}{2d_{jK-1}}, & a_{jK-1} - d_{jK-1} \le t \le a_{jK-1} + d_{jK-1}, \\ 1, & t > a_{jK-1} + d_{jK-1}, \end{cases} \quad (6)$$

where $t = z_{ij}$, $k = 1, 2, \ldots, K-1$.

2.3. Multiple Index Synthetic Attribute Measure Analysis. Multiple index synthetic attribute measurements of a component or unit, which is v_{xk}, can be calculated by equation (7) that includes each attribute measure and combination weights.

$$v_{xk} = \sum_{j=1}^{m} \omega_j \mu_{xj}^{k}. \quad (7)$$

2.4. Attribute Recognition Analysis. Attribute recognition model could be built based on the weights and synthetic attribute measure of indexes. The model includes confidence criterion λ, and $0.5 \le \lambda \le 1$. Generally $\lambda = 0.6 \sim 0.7$ [24].

$$k_i = \min\left\{k: \sum_{s=1}^{k} v_{is}(C_i) \ge \lambda, \quad 1 \le k \le K\right\}. \quad (8)$$

Increase the value of k until equation (8) is satisfied, then the component or unit x_i belongs to safety grade C_{ki}.

Table 1: Standard grade of every index.

Evaluation indexes	Evaluation grades			
	C_1	C_2	$\cdots$	C_K
I_1	$a_{10} \sim a_{11}$	$a_{11} \sim a_{12}$	$\cdots$	$a_{1K-1} \sim a_{1K}$
I_2	$a_{20} \sim a_{21}$	$a_{21} \sim a_{22}$	$\cdots$	$a_{2K-1} \sim a_{2K}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
I_m	$a_{m0} \sim a_{m1}$	$a_{m1} \sim a_{m2}$	$\cdots$	$a_{mK-1} \sim a_{mK}$

3. Evaluation System and Classification Standards

3.1. Evaluation System. Based on historical seismic damage data [25], mechanical properties, and Chinese current national codes [26–29] of ancient timber buildings, appropriate evaluation indexes are selected. Divide an ancient timber building into four units, which are wood frame, enclosing walls, plinths of columns, and foundation. Units consist of many components. Different components have different evaluation indexes. Totally, 22 evaluation indexes are selected, and the evaluation system is shown in Figure 1.

3.2. Classification Standards of Indexes. Wood frames are the main load-bearing system of an ancient timber building. As service time of the building becomes longer and longer, mechanical property of wood would be decreased [30]. Wood frame of ancient timber building consists of beams, purlins, Fang, column, Dougong, and mortise-tenon joints.

Wood beams and Fang are the vertical structural members bearing the load on the roof and weight of roof. Fang is quite similar with beams, which is used to connect two columns in longitudinal direction of ancient timber building. Components that connect columns in transverse direction are named beams. The horizontal loads are transmitted by beams and Fang in ancient timber buildings. Based on references [2, 31, 32, 33], the deflection, lateral bending, decay area, insect-attacked area, and cracking degree are selected as the evaluation indexes of the beams, purlins, and Fang. According to the damage degree, the beams, purlins, and Fang of an ancient timber building are divided into four safety levels, C_1, C_2, C_3, and C_4; from C_1 to C_4, the damage degree gradually increases. These are listed in Table 2.

Wood columns are the vertical structural member transmitting axial compressive loads in ancient timber building. When earthquake occurs, wood columns also bear the horizontal shear force. With service time increasing, ancient timber buildings would be damaged by long-term load effect and biological and natural factors, such as wind, rain, corrosive gas, mould, and insect. Referring to references [2, 26, 31, 32], bending degree, decay area, insect-attacked area, and cracking degree are selected as evaluation indexes of a column, which is shown in Table 3.

In Table 3, x_3' is the semiqualitative and semiquantitative index. In order to improve accuracy of evaluation result, equation $t = \sum F_i d$ is used to quantify x_3'. F_i is the weight, and d is the depth of the crack. In order to get a reasonable

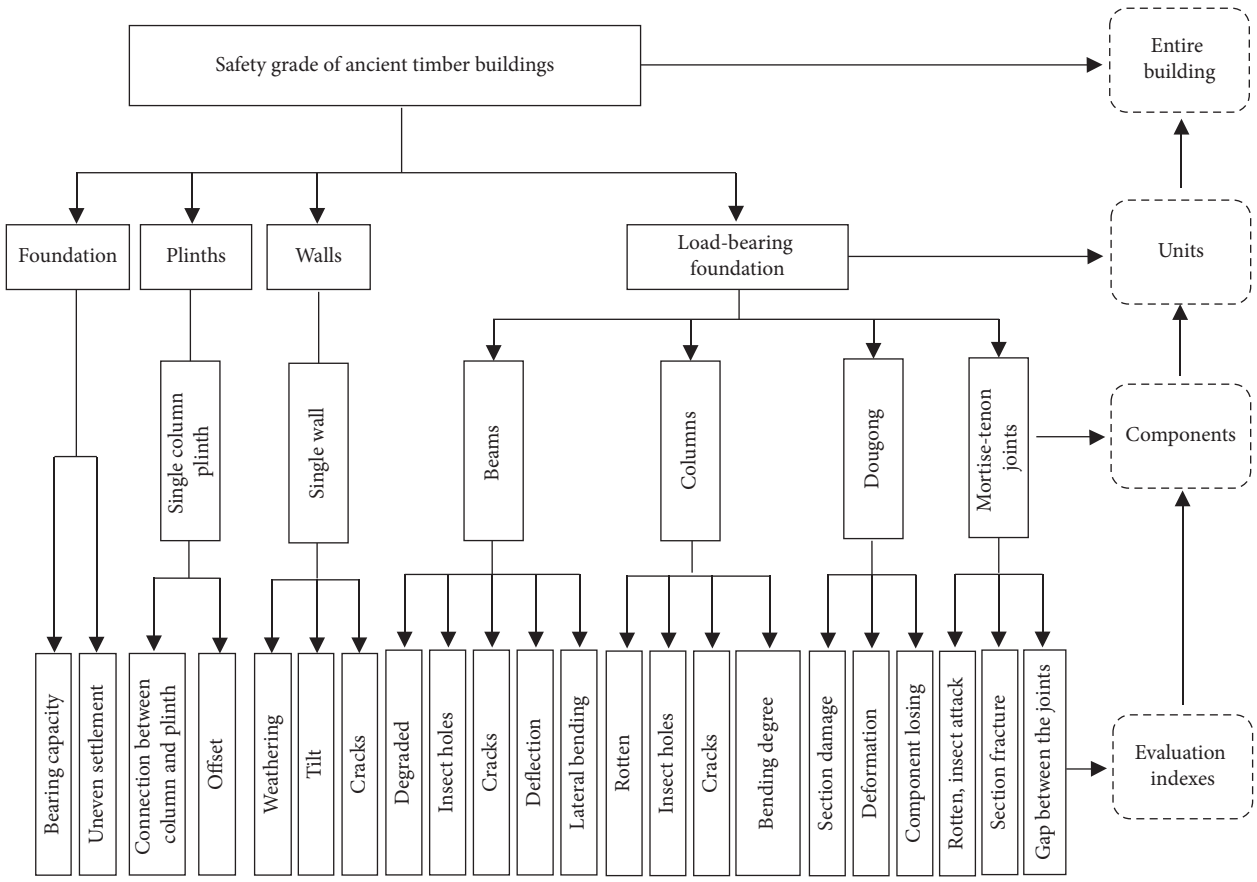


Figure 1: Safety grade evaluation system of ancient timber building.

Table 2: Safety grade classification for wood beam, Fang, and purlin.

Safety grade	Evaluation indexes				
	Decadent x_1	Insect attack x_2	Cracks x_3	Deflection x_4	Lateral bending x_5
C_1	$< 10\%$	No insect holes along the length, no hollowing sounds while knocking	$0 \sim 0.01$	$< l/300$	$< l/800$
C_2	$10\% \sim 20\%$	No obvious insect holes along the length, no hollowing sounds while knocking	$0.01 \sim 0.06$	$l/300 \sim l/200$	$l/800 \sim l/400$
C_3	$20\% \sim 30\%$	Has obvious insect holes along the length, no hollowing sounds while knocking	$0.06 \sim 0.12$	$l/200 \sim l/120$	$l/400 \sim l/200$
C_4	$\geq 30\%$	Has obvious insect holes along the length, hollowing sounds are heard while knocking	≥ 0.12	$\geq l/120$	$\geq l/200$

x_1 is the percentage of decayed area of cross section. x_3 is the sinusoidal value of angle between crack and longitudinal direction. l is the calculation span of beam, purlin, and Fang.

Table 3: Safety grade classification for wood column.

Safety grade	Evaluation indexes			
	Decay x_1'	Insect attack x_2'	Crack x_3'	Bending degree x_4'
C_1	$< 10\%$	No insect holes along the length, no hollowing sounds while knocking	No penetrating cracks along its longitudinal direction; maximum depth of crack $< 0.5R$	$< h/800$
C_2	$10\% \sim 20\%$	No obvious insect holes along the length, no hollowing sounds while knocking	No penetrating cracks along its longitudinal direction; maximum depth of crack between $0.5R$ and R	$h/800 \sim h/400$
C_3	$20\% \sim 30\%$	Has obvious insect holes along the length, no hollowing sounds while knocking	Penetrating cracks along its longitudinal direction exist; maximum depth of crack $< 0.5R$	$h/400 \sim h/200$
C_4	$\geq 30\%$	Has obvious insect holes along the length, hollowing sounds are heard while knocking	Penetrating cracks along its longitudinal direction exist; maximum depth of crack between $0.5R$ and R	$\geq h/200$

x_1' is the percentage of decayed area of cross section; R is the column diameter; h is the column height.

weight, advices from 2 professors, 1 doctor and 1 master, are adopted. Four couple of weights are obtained, which are [0.3,0.7], [0.4,0.6], [0.1,0.9], and [0.3,0.7]. Then, analytical hierarchy process is used to get the final criteria. Judgment matrix is

$$\begin{bmatrix} 1 & 1 & 2 & 3 \\ 1 & 1 & 2 & 3 \\ 1/2 & 1/2 & 1 & 2 \\ 1/3 & 1/3 & 1/3 & 1 \end{bmatrix}. \quad (9)$$

And the final weight is 0.3 and 0.7. Details are listed in Table 4.

A Dougong is formed by placing a large wooden block (Dou) on top of a column to provide a secure base for an interlocking pair of brackets (gong) above it. These then support subsequent Dou and Gong layers and ultimately a cross beam without glue or fasteners [34]. Dougong is usually used in large wood frame ancient timber buildings, which could support roof and provide a large space for palace at the same time. Usually Dougong is placed on column or beam. Dougong is an important part of ancient timber building for its exquisite shape and seismic capacity [35]. Figure 2 shows a Dougong of Liben hall. Layer of Dougong has good deformability, energy dissipation, and seismic capacity. References [31, 36] show main damages of Dougong are cracks of the components, obliqueness, decay, deterioration, and insect attacks on the wood. Decay, deterioration, and insect attacks on the wood are sorted as a same evaluation index, which is defined as section damage. The details are shown in Table 5.

Mortise and tenon joints are unique connection between columns and beams or Fang of ancient timber buildings. Semirigid characteristics make the joints have good energy dissipation capacity and seismic capacity. Based on references [36, 37], a classification standard for mortise and tenon joints' damage degree is established. This is shown in Table 6.

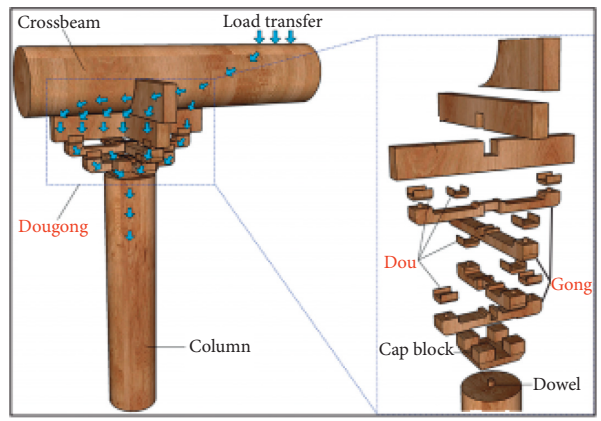
The foundations of ancient architecture have existed for at least hundreds of years. Thus, generally uneven settlement of the foundation does not occur. However, some natural disasters such as earthquakes, tsunamis, and mud-rock flows may rock the foundation and affect the safety state of the foundation. Based on the foundation design code of China [38, 39], a safety evaluation index of the foundation of ancient timber architecture is shown in Table 7.

Columns of ancient timber buildings are directly placed on the surface of pier stones. So, the contact area between column foot and plinth is very important for the safety of the whole building. Based on former study [31], a safety evaluation index for plinth in ancient timber architecture is shown in Table 8.

Enclosing walls of ancient timber buildings do not carry or transmit loads. According to Chinese codes [26] and reference [31], weathering degree, tilt angle, and cracks of every single wall are analyzed and chosen as evaluation indexes; the classification standard is shown in Table 9.

Table 4: Quantification for index x_3'.

Have penetrating crack or not	Weight	Depth of crack	
		$0\sim0.5R$	$0.5R\sim R$
No	0.3	C_1	C_2
Yes	0.7	C_3	C_4



(a)

(b)

Figure 2: Dougong. (a) Structure of Dougong. (b) Dougong of Liben hall.

3.3. Attribute Measure Function of Single Indexes. In the safety state evaluation process of an ancient timber building, the whole building is divided into different units. Units contain different components. 22 evaluation indexes are selected in this paper, which are shown in Figure 1. Attribute measure functions of single indexes can be built by equations (4)–(6). And x_2, x_2', y_3, d_2, and q_3 are

Table 5: Safety grade classification for Dougong.

Safety grade	Evaluation index		
	Section damage y_1	Deformation y_2	Components lost y_3
C_1	< 10%	0~0.02	No
C_2	10%~20%	0.02~0.04	—
C_3	20%~30%	0.04~0.07	—
C_4	≥30%	≥0.07	Yes

y_1 is the percentage of damage area on cross section; y_2 is the sinusoidal value of angle between central axis of Dougong and vertical direction (rad).

Table 6: Safety grade classification for mortise and tenon joints.

Safety grade	Evaluation indexes		
	Decay and insect attack s_1	Cracks s_2	Tenon out of mortise s_3
C_1	<5%	<0.01	$\leq l_2/8$
C_2	5%~15%	0.01~0.1	$l_2/8 \sim l_2/4$
C_3	15%~25%	0.1~0.2	$l_2/4 \sim l_2/2$
C_4	≥25%	≥0.2	$>l_2/2$

s_1 is the percentage of decay and insect attack area on cross section; s_2 is the percentage of crack area on cross section; l_2 is the length of tenon.

Table 7: Classification standards and evaluation index for foundation.

Grades	Evaluation indexes	
	Bearing capacity $d_1 = P_d/f_{sc}$ or $P_{d\,max}/(1.2f_{sc})$	Uneven settlement d_2
C_1	≥1.0	Uneven settlement is less than the allowable values in national code [37]; or no settlement cracks, deformations, and displacements
C_2	1.0~0.95	Uneven settlement is not greater than the allowable values in national code, and the settlement speed of the foundation is less than 2 mm/month in two months; or slightly cracks but no development sign
C_3	0.95~0.9	Uneven settlement is greater than the allowable values in national code; or the settlement speed of the foundation is more than 2 mm/month in two months; or the max width of cracks beyond 5 mm and no sign of stopping
C_4	<0.9	Uneven settlement is far greater than the allowable values in national code; or the settlement speed of the foundation is more than 2 mm/month in two months and tends to become faster; or the max width of cracks is beyond 10 mm and tends to become bigger

P_d is the design value of pressure at the bottom of foundation; f_{sc} is the design bearing capacity of foundation soil.

Table 8: Classification standards and evaluation indexes for plinth.

Safety grades	Evaluation indexes	
	Contact area j_1	Offset j_2
C_1	$\rho_c \geq 90\%$	$\rho_d < 4\%$
C_2	$75\% \leq \rho_c < 90\%$	$4\% \leq \rho_d < 8\%$
C_3	$60\% \leq \rho_c < 75\%$	$8\% \leq \rho_d < 12\%$
C_4	$\rho_c < 60\%$	$\rho_d > 12\%$

ρ_c is the ratio of contact area between column and plinth to cross section area of column; ρ_d is the ratio of offset distance to column diameter.

Table 9: Classification standards and evaluation index of wall.

Grades	Evaluation indexes		
	Weathering q_1	Tilt q_2	Cracks q_3
C_1	$<B/120$	$<H/300$	No cracks
C_2	$0 \sim B/12$	$H/300 \sim H/200$	No penetrating cracks
C_3	$B/12 \sim B/6$	$H/200 \sim H/150$	Has penetrating cracks that obviously affect mechanical properties
C_4	$>B/6$	$>H/150$	Has penetrating cracks that greatly affect mechanical properties

q_1 is the weathering depth; H is the height of the wall; B is the thickness of the wall.

qualitative indexes; attribute measure functions are shown in Table 10.

4. Study Case

4.1. Introduction of Liben Hall. Liben hall is located in Siping village, Jinhua city, Zhejiang Province, China. The village is provincial model village for its beautiful environment, distinct cultural characteristics, and history. And the village was named as "historically and culturally famous village of China" in 2010. History of the village can be dated to Ming Dynasty (1368–1644). Now only 8 ancient timber buildings are preserved. Liben hall is one of them. The hall was built in Kangxi period (1662–1722) of Qing Dynasty, which has been standing for hundred years. Long history and sophisticated structure made Liben hall become a famous heritage site in China. Liben hall is a 1 story building with 3 spans. Details are shown in Figures 2–4.

4.2. On-Site Damage Identification. Some damages are shown in Figure 5. Measuring tape was used to measure perimeters of columns, beams, purlins, and so on. Laser range finder was used to measure spacing and bending degree of columns, beams, Fang, and purlins. A stress wave testing instrument is used to detect the inner damage of components when damages cannot detect from appearance. Because of the imitate space, testing results of 2 columns (Z_1, Z_2) are shown in Figure 6. And testing results of beam L_1, column Z_1, and Dougong D_1 are listed as examples shown in Table 10.

4.3. Calculation of Weights of Evaluation Indexes. AHP is used to calculate subjective weights, and EWM is used to calculate objected weights. Combinatorial weights are

Table 10: Attribute measurement functions for single index.

Evaluation indexes	C_1	C_2	C_3	C_4
x_1 x_1' y_1	$\mu_{11} = \begin{cases} 1, & t < 0.05, \\ (0.15 - t)/0.1, & 0.05 \le t \le 0.15, \\ 0, & t > 0.15, \end{cases}$	$\mu_{12} = \begin{cases} 0, & t < 0.05, \\ (t - 0.05)/0.1, & 0.05 \le t \le 0.15, \\ (0.25 - t)/0.1, & 0.15 < t \le 0.25, \\ 0, & t > 0.25, \end{cases}$	$\mu_{13} = \begin{cases} 0, & t < 0.15, \\ (t - 0.15)/0.1, & 0.15 \le t \le 0.25, \\ (0.35 - t)/0.1, & 0.25 < t \le 0.35, \\ 0, & t > 0.35, \end{cases}$	$\mu_{14} = \begin{cases} 0, & t < 0.25, \\ (t - 0.25)/0.1, & 0.25 \le t \le 0.35, \\ 1, & t > 0.35, \end{cases}$
x_3	$\mu_{21} = \begin{cases} 1, & t < 0.005, \\ (0.015 - t)/0.01, & 0.005 \le t \le 0.015, \\ 0, & t > 0.015, \end{cases}$	$\mu_{22} = \begin{cases} 0, & t < 0.005, \\ (t - 0.005)/0.01, & 0.005 \le t \le 0.015, \\ 1, & 0.015 < t < 0.035, \\ (0.085 - t)/0.05, & 0.035 \le t \le 0.085, \\ 0, & t > 0.085, \end{cases}$	$\mu_{23} = \begin{cases} 0, & t < 0.0355, \\ (t - 0.035)/0.05, & 0.035 \le t \le 0.085, \\ 1, & 0.085 < t < 0.09, \\ (0.15 - t)/0.06, & 0.09 \le t \le 0.15, \\ 0, & t > 0.15, \end{cases}$	$\mu_{24} = \begin{cases} 0, & t < 0.09, \\ (t - 0.09)/0.06, & 0.009 \le t \le 0.15, \\ 0, & t > 0.15, \end{cases}$
x_4	$\mu_{31} = \begin{cases} 1, & t < l/400, \\ (l/240 - t)/(l/600), & l/400 \le t \le l/240, \\ 0, & t > l/240, \end{cases}$	$\mu_{32} = \begin{cases} 0, & t < l/400, \\ (t - l/400)/l/600, & l/400 \le t \le l/240, \\ (7l/1200 - t)/(l/600), & l/240 \le t \le 7l/1200, \\ 0, & t > 7l/1200, \end{cases}$	$\mu_{33} = \begin{cases} 0, & t < l/240, \\ (t - l/240)/l/600, & l/240 \le t \le 7l/1200, \\ 1, & 7l/1200 < t < l/150, \\ l/100 - t/l/300, & l/150 \le t \le l/100, \\ 0, & t > l/100, \end{cases}$	$\mu_{31} = \begin{cases} 0, & t < l/150, \\ (t - l/150)/(l/300), & l/150 \le t \le l/100, \\ 1, & t > l/100, \end{cases}$
$x_5 x_4'$	$\mu_{41} = \begin{cases} 1, & t < h/1600, \\ (3h/1600 - t)/h/800, & h/1600 \le t \le 3h/1600, \\ 0, & t > 3h/1600, \end{cases}$	$\mu_{42} = \begin{cases} 0, & t < h/1600, \\ (t - h/1600)/h/800, & h/1600 \le t \le 3h/1600, \\ (5h/1600 - t)/h/800, & 3h/1600 < t \le 5h/1600, \\ 0, & t > 5h/1600, \end{cases}$	$\mu_{33} = \begin{cases} 0, & t < 3h/1600, \\ (t - 3h/1600)/h/800, & 3h/1600 \le t \le 5h/1600, \\ 1, & 5h/1600 < t < 3h/800, \\ (h/160 - t)/h/400, & 3/800 \le t \le h/160, \\ 0, & t > h/160, \end{cases}$	$\mu_{41} = \begin{cases} 0, & t < 3h/800, \\ t - 3h/800/h/400, & 3h/800 \le t \le h/160, \\ 1, & t > h/160, \end{cases}$
x_3'	$\mu_{51} = \begin{cases} 1, & t < 0.075R, \\ 0.225R - t/0.15R, & 0.075R \le t \le 0.225R, \\ 0, & t > 0.225R, \end{cases}$	$\mu_{52} = \begin{cases} 0, & t < 0.075R, \\ t - 0.075R/0.15R, & 0.075R \le t \le 0.225R, \\ 1, & 0.225R < t < 0.275R, \\ 0.375R - t/0.05R, & 0.275R \le t \le 0.375R, \\ 0, & t > 0.375R, \end{cases}$	$\mu_{53} = \begin{cases} 0, & t < 0.225R, \\ t - 0.275R/0.05R, & 0.225R \le t \le 0.325R, \\ 0.375R - t/0.05R, & 0.325R < t \le 0.375R, \\ 0, & t > 0.375R, \end{cases}$	$\mu_{55} = \begin{cases} 0, & t < 0.325R, \\ t - 0.325R/0.05R, & 0.325R \le t \le 0.375R, \\ 1, & t > 0.375R, \end{cases}$
y_2	$\mu_{61} = \begin{cases} 1, & t < 0.01, \\ 0.03 - t/0.02, & 0.01 \le t \le 0.03, \\ 0, & t > 0.03, \end{cases}$	$\mu_{62} = \begin{cases} 0, & t < 0.01, \\ t - 0.01/0.02, & 0.01 \le t \le 0.03, \\ 0.05 - t/0.02, & 0.03 < t \le 0.05, \\ 0, & t > 0.05, \end{cases}$	$\mu_{63} = \begin{cases} 0, & t < 0.03, \\ t - 0.03/0.02, & 0.03 \le t \le 0.05, \\ 1, & 0.05 < t < 0.055, \\ 0.085 - t/0.03, & 0.055 \le t \le 0.085, \\ 0, & t > 0.085, \end{cases}$	$\mu_{64} = \begin{cases} 0, & t < 0.055, \\ t - 0.055/0.03, & 0.055 \le t \le 0.085, \\ 1, & t > 0.085, \end{cases}$
s_1	$\mu_{71} = \begin{cases} 1, & t < 0.025, \\ 0.075 - t/0.05, & 0.025 \le t \le 0.075, \\ 0, & t > 0.075, \end{cases}$	$\mu_{72} = \begin{cases} 0, & t < 0.025, \\ t - 0.025/0.05, & 0.025 \le t \le 0.075, \\ 1, & 0.075 < t < 0.01, \\ 0.2 - t/0.1, & 0.1 \le t \le 0.2, \\ 0, & t > 0.2, \end{cases}$	$\mu_{73} = \begin{cases} 0, & t < 0.1, \\ t - 0.1/0.1, & 0.1 \le t \le 0.2, \\ 0.3 - t/0.1, & 0.2 < t \le 0.3, \\ 0, & t > 0.3, \end{cases}$	$\mu_{74} = \begin{cases} 0, & t < 0.2, \\ t - 0.1/0.1, & 0.2 \le t \le 0.3, \\ 1, & t > 0.3, \end{cases}$
s_2	$\mu_{81} = \begin{cases} 1, & t < 0.005, \\ 0.015 - t/0.01, & 0.005 \le t \le 0.015, \\ 0, & t > 0.015, \end{cases}$	$\mu_{82} = \begin{cases} 0, & t < 0.005, \\ t - 0.005/0.01, & 0.005 \le t \le 0.015, \\ 1, & 0.015 < t < 0.055, \\ 0.145 - t/0.09, & 0.055 \le t \le 0.145, \\ 0, & t > 0.145, \end{cases}$	$\mu_{83} = \begin{cases} 0, & t < 0.055, \\ t - 0.055/0.09, & 0.055 \le t \le 0.145, \\ 1, & 0.145 < t < 0.15, \\ 0.25 - t/0.119, & 0.15 \le t \le 0.25, \\ 0, & t > 0.25, \end{cases}$	$\mu_{84} = \begin{cases} 0, & t < 0.15, \\ t - 0.15/0.1, & 0.15 \le t \le 0.25, \\ 1, & t > 0.25, \end{cases}$
s_3	$\mu_{91} = \begin{cases} 1, & t < l_2/8, \\ (3l_2/16 - t)/(l_2/8), & l_2/8 \le t \le 3l_2/16 \\ 0, & t > l_2/16, \end{cases}$	$\mu_{92} = \begin{cases} 0, & t < l_2/8, \\ (t - l_2/8)/l_2/8, & l_2/8 \le t \le 3l_2/16, \\ (5l_2/16 - t)/(l_2/8), & 3l_2/16 < t \le 5l_2/16, \\ 0, & t > 5l_2/16, \end{cases}$	$\mu_{93} = \begin{cases} 0, & t < 3l_2/16, \\ (t - 3l_2/16)/(l_2/8), & 3l_2/16 \le t \le 5l_2/16, \\ 1, & 5l_2/16 < t < 3l_2/8, \\ (5l_2/8 - t)/l_2/4, & 3l_2/8 \le t \le 5l_2/8, \\ 0, & t > 5l_2/8, \end{cases}$	$\mu_{94} = \begin{cases} 0, & t < 3l_2/8, \\ t - 3l_2/8/(l_2/4), & 3l_2/8 \le t \le 5l_2/8, \\ 1, & t > l5l_2/8, \end{cases}$

Table 10: Continued.

Evaluation indexes	C_1	C_2	C_3	C_4
d_1	$\mu_{101} = \begin{cases} 0, & t < 0.975, \\ t - 0.975/0.05, & 0.975 \le t \le 1.025, \\ 1, & t > 1.025, \end{cases}$	$\mu_{102} = \begin{cases} 0, & t < 0.925, \\ (t - 0.925)/0.05, & 0.925 \le t \le 0.975, \\ 1.025 - t/0.05, & 0.975 < t \le 1.025, \\ 0, & t > 1.025, \end{cases}$	$\mu_{103} = \begin{cases} 0, & t < 0.875, \\ t - 0.875/0.05, & 0.875 \le t \le 0.925, \\ 0.975 - t/0.05, & 0.925 < t \le 0.975, \\ 0, & t > 0.975, \end{cases}$	$\mu_{104} = \begin{cases} 1, & t < 0.875, \\ 0.925 - t/0.05, & 0.875 \le t \le 0.925, \\ 0, & t > 0.925, \end{cases}$
j_1	$\mu_{111} = \begin{cases} 0, & t < 0.825, \\ t - 0.825/0.05, & 0.825 \le t \le 0.975, \\ 1, & t > 0.975, \end{cases}$	$\mu_{112} = \begin{cases} 0, & t < 0.675 \\ t - 0.675/0.15, & 0.675 \le t \le 0.825, \\ 0.975 - t/0.15, & 0.825 < t \le 0.975, \\ 0, & t > 0.975 \end{cases}$	$\mu_{113} = \begin{cases} 0, & t < 0.525, \\ t - 0.525/0.15, & 0.525 \le t \le 0.675, \\ 0.825 - t/0.15, & 0.675 < t \le 0.825, \\ 0, & t > 0.825, \end{cases}$	$\mu_{114} = \begin{cases} 1, & t < 0.525, \\ 0.675 - t/0.15, & 0.525 \le t \le 0.675, \\ 0, & t > 0.675, \end{cases}$
j_2	$\mu_{121} = \begin{cases} 1, & t < 0.02, \\ 0.06 - t/0.04, & 0.02 \le t \le 0.06, \\ 0, & t > 0.06, \end{cases}$	$\mu_{122} = \begin{cases} 0, & t < 0.02, \\ t - 0.02/0.04, & 0.02 \le t \le 0.06, \\ 0.1 - t/0.04, & 0.06 < t \le 0.1, \\ 0, & t > 0.1, \end{cases}$	$\mu_{123} = \begin{cases} 0, & t < 0.06, \\ t - 0.06/0.04, & 0.06 \le t \le 0.1, \\ 0.22 - t/0.04, & 0.1 < t \le 0.22, \\ 0, & t > 0.22, \end{cases}$	$\mu_{124} = \begin{cases} 0, & t < 0.1, \\ t - 0.1/0.04, & 0.1 \le t \le 0.22, \\ 1, & t > 0.22, \end{cases}$
q_1	$\mu_{131} = \begin{cases} 1, & t < B/240, \\ (B/180 - t)/(B/120), & B/240 \le t \le B/80, \\ 0, & t > B/80, \end{cases}$	$\mu_{132} = \begin{cases} 0, & t < B/240, \\ (t - B/240)/(B/120), & B/240 \le t \le B/80, \\ 1, & B/80 < t < 11B/240, \\ (29B/240 - t)/(3B/40), & 11B/240 \le t \le 29B/240, \\ 0, & t > 29B/240, \end{cases}$	$\mu_{133} = \begin{cases} 0, & t < 11B/240, \\ (t - 11B/240)/(3B/40), & 11B/240 \le t \le 29B/240, \\ 1, & 29B/240 < t < B/8, \\ (5B/24 - t)/(B/12), & B/8 \le t \le 5B/24, \\ 0, & t > 5B/24, \end{cases}$	$\mu_{134} = \begin{cases} 0, & t < B/8, \\ (t - B/8)/(B/12), & B/8 \le t \le 5B/24, \\ 1, & t > 5B/24, \end{cases}$
q_2	$\mu_{141} = \begin{cases} 1, & t < H/400, \\ (H/240 - t)/(H/600), & H/400 \le t \le H/240, \\ 0, & t > H/240, \end{cases}$	$\mu_{142} = \begin{cases} 0, & t < H/400, \\ (t - H/400)/(H/600), & H/400 \le t \le H/240, \\ (7H/1200 - t)/(H/600), & H/240 < t \le 7H/1200, \\ 0, & t > 7H/1200, \end{cases}$	$\mu_{142} = \begin{cases} 0, & t < H/240, \\ (t - H/240)/(H/600), & H/240 \le t \le 7H/1200, \\ (3H/400 - t)/(H/600), & 7H/1200 < t \le 3H/400, \\ 0, & t > 3H/400, \end{cases}$	$\mu_{141} = \begin{cases} 0, & t < 7H/1200, \\ (t - 7H/1200)/(H/600), & 7H/1200 \le t \le 3H/400, \\ 1, & t > 3H/400. \end{cases}$

Figure 3: Elevation graph of Liben hall.

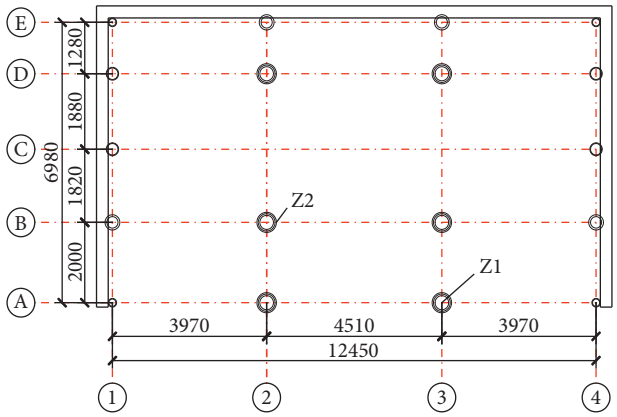


Figure 4: Plane graph of Liben hall (mm).

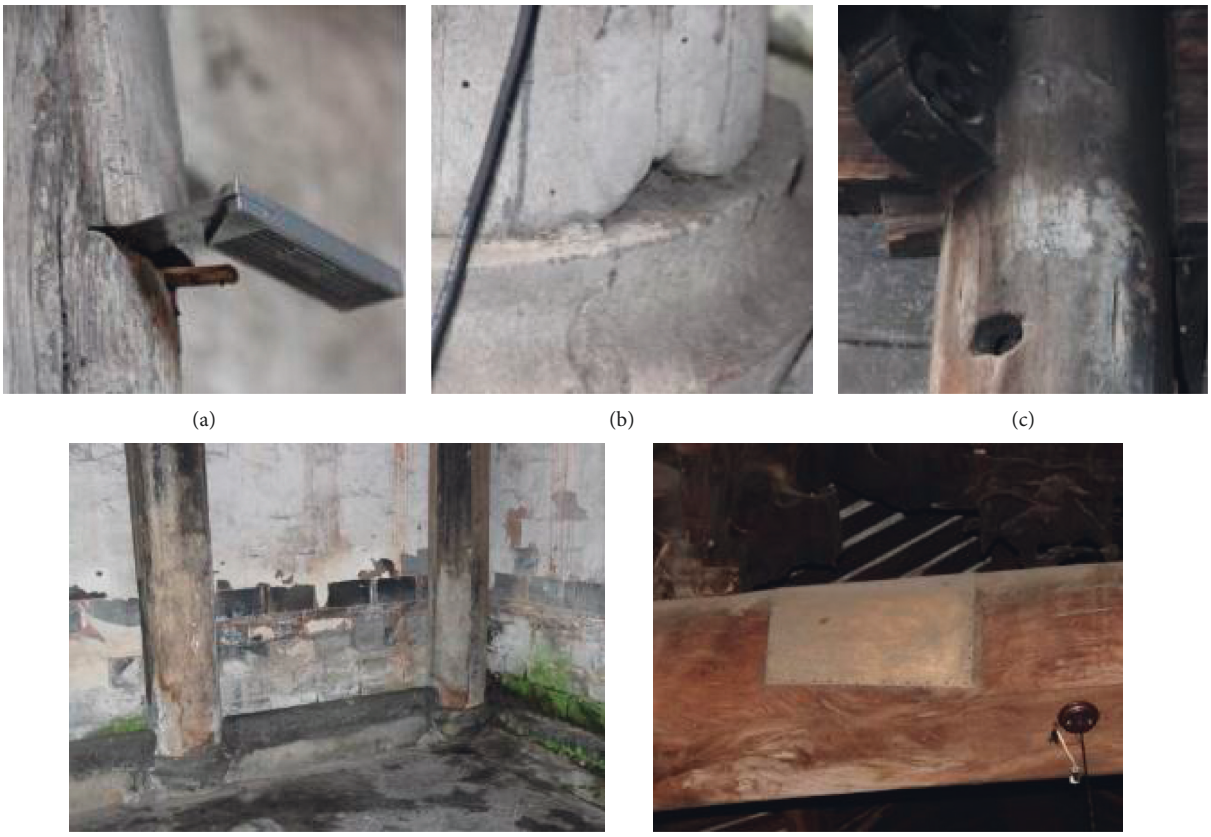


Figure 5: External damage of the building.

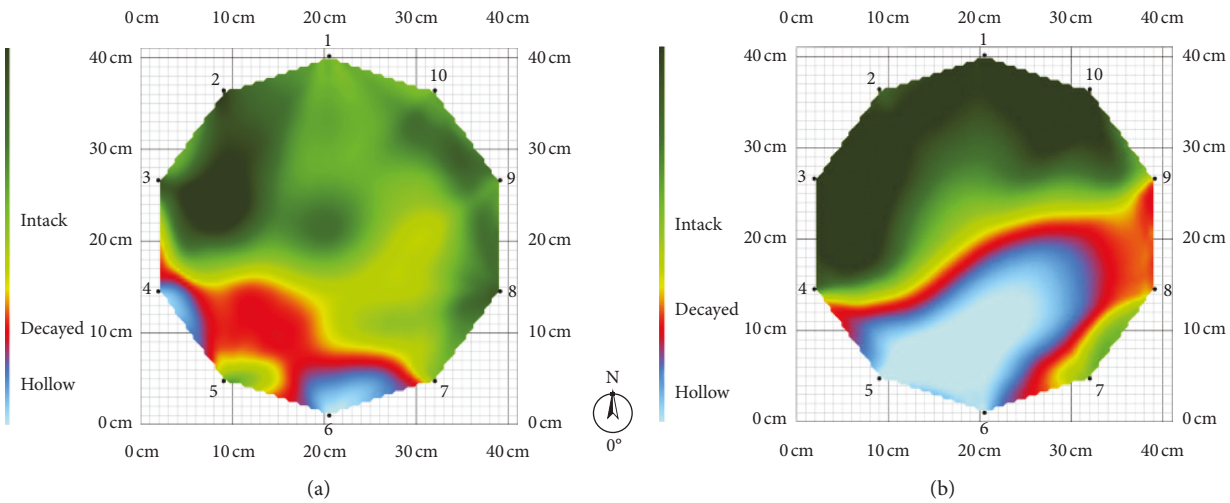


Figure 6: Internal damage of columns detected by stress wave testing instrument.

Table 11: Comparison matrix and indexes weight of L_1.

L_1	x_1	x_2	x_3	x_4	x_5	ω_{L11}	ω_{L12}	ω_{L1}
x_1	1	1	3	5	7	0.359	0.173	0.280
x_2	1	1	3	5	7	0.359	0.251	0.342
x_3	1/3	1/3	1	3	5	0.162	0.221	0.178
x_4	1/5	1/5	1/3	1	3	0.079	0.203	0.115
x_5	1/7	1/7	1/5	1/3	1	0.040	0.152	0.085
$\lambda_{\max} = 5.136$		CI = 0.034		CR = CI/RI = 0.030 < 0.1			Satisfy consistency test	

$\lambda_{\max}$ is the maximum eigenvalue; CI and RI are the general and average consistency indexes; CR is the random consistency ratio.

Table 12: Comparison matrix and indexes weight of Z_1.

Z_1	x_1'	x_2'	x_3'	x_4'	ω_{Z11}	ω_{Z12}	ω_{Z1}
x_1'	1	1	3	5	0.389	0.188	0.283
x_2'	1	1	3	5	0.389	0.366	0.423
x_3'	1/3	1/3	1	3	0.153	0.215	0.172
x_4'	1/5	1/5	1/3	1	0.069	0.231	0.122
$\lambda_{\max} = 4.044$		CI = 0.015		CR = CI/RI = 0.016 < 0.1		Satisfy consistency test	

Table 13: Comparison matrix and indexes weight of D_1.

D_1	y_1	y_2	y_3	ω_{D11}	ω_{D12}	ω_{D1}
y_1	1	1	1/5	0.158	0.317	0.522
y_2	1	1	1/3	0.187	0.194	0.290
y_3	5	3	1	0.655	0.489	0.188
$\lambda_{\max} = 3.029$		CI = 0.015		CR = CI/RI = 0.029 < 0.1	Satisfy consistency test	

calculated via equation (7). Judgment matrixes [39] and weights of examples are shown in Tables 11–13.

4.4. Calculation of Attribute Measure of Single Index. Based on the testing results and attribute measure functions, the calculation results of single index attribute measure are shown in Table 14.

4.5. Evaluation Results. Comprehensive attribute measures of evaluation indexes are calculated based on equation (7). Confidence criterion, $\lambda = 0.65$, is used to evaluate the safety state of components. The evaluation results are consistent with the damage identification results [31], which are shown in Table 15.

No uneven settlement was detected. Based on Table 7 and testing results, the evaluation results show that the safety

Table 14: Attribute measure of single index.

Components	Evaluation index	Testing results	Attribute measure			
			C_1	C_2	C_3	C_4
L_1	x_1	0.230	0	0.20	0.800	0
	x_2	C_3	0	0.00	1	0
	x_3	0.0943	0	0	0.950	0.050
	x_4	$21l/3700$	0	0.095	0.905	0
	x_5	$l/370$	0	0.338	0.662	0
Z_1	x_1'	0.310	0	0	0.400	0.600
	x_2'	C_4	0	0	0	1
	x_3'	0.114 R	0.740	0.260	0	0
	x_4'	$h/620$	0.210	0.790	0	0
D_1	y_1	0.137	0.130	0.870	0	0
	y_2	0.018	0.625	0.375	0	0
	y_3	C_2	0	1	0	0

Table 15: Safety evaluation results of components.

Component	Safety degree				Evaluation results
	C_1	C_2	C_3	C_4	Attribute recognition
L_1	0	0.095	0.898	0.007	C_3
Z_1	0.262	0.394	0.037	0.307	C_2
D_1	0.056	0.944	0	0	C_2

degree of foundation is C_1. Evaluation results of all the components are shown in Figure 6. Reference [31] provides a damage identification method for ancient timber architecture based on seismic construction identification of entire building and damage identification of every component. In order to validate the correctness of this evaluation results, the damage identification method provided by reference [31] is used to evaluate the safety state of Liben hall. Most of the results are consistent with the damage identification results [31] (Figure 7).

4.6. Safety State Evaluation of the Whole Building. As mention above, in this evaluation system, Liben hall is divided into four units. The four units are wood frame, enclosing walls, plinths of columns, and foundation. Figure 6 shows the safety degree of the wood components, and joints are concentrated in C_3 and C_4, and the proportion of several C_4 components are higher than 50%. Safety levels of units are determined by the distribution of components damage levels.

(1) As mentioned above, foundation of the building is in good condition, and safety grade is C_1.

(2) Evaluation results show that 5.56% of the plinths' safety state is C_1, 33.33% is C_2, 50% is C_3 and 11.11% is C_4. Half of the plinths' safety state is C_3, so the safety state of plinth is C_3.

(3) Figure 6 shows that 72.73% of walls' safety state is C_2 and 27.27% is C_3. So, the safety state of unit wall is C_2.

(4) Unit wood frame consists of columns, Dougong, mortise and tenon joints, beams, and Fang. Most components of wood frame attribute to C_3 safety state. 12.5% of Dougong components attribute to C_2, 56.25% attribute to C_3, and 31.25% attribute to C_3. 2.27% of beams, purlins, and Fang attribute to C_1, 31.82% attribute to C_2, 54.55% attribute to C_3, and 31.25% attribute to C_4. 26.14% of mortise and tenon joints attribute to C_2, 51.13% attribute to C_3, and 27.73% attribute to C_4. Columns are vertical load-bearing components, which are very important for wood frame. Figure 6 shows 66.67% of columns attribute to C_4 safety state. So, the safety state of wood frame unit is C_4.

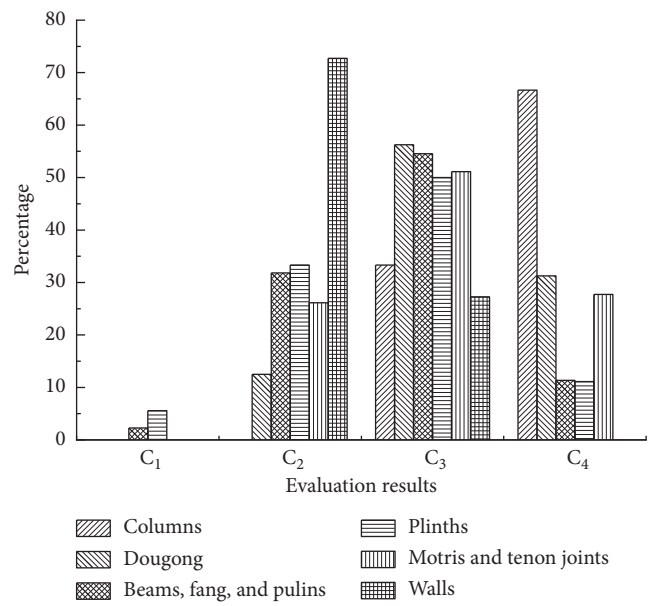


Figure 7: Evaluation results for components.

Overall, the safety level of entire building is determined by the lowest safety grade of the units. So, the safety grade of Liben hall is C_4.

5. Conclusion

(1) According to the structural characteristics of ancient timber building, seismic damage data, relevant Chinese codes, and researchers' study results, appropriate evaluation indexes that may influence the safety state of ancient timber building were selected. A safety degree evaluation model for ancient timber building based on the attribute recognition theory was built. This is a new method to assess the safety state of ancient timber architecture.

(2) To make sure the evaluation process and results are reasonable and reliable, both qualitative and quantitative indexes were selected to consider the negative effects caused by different components and joints of various damage degrees on the overall safety state of the building in this model. A combination of both subject weight and object weight was adopted in the model.

(3) This evaluation model was applied to evaluate the safety state of the Liben hall, which is a famous

ancient site in Zhejiang, China. The evaluation result is consistent with the damage identification result and actual situation of the architecture. This proved the correctness of this model.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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