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Research Article

Health Monitoring of Bolt Looseness in Timber Structures Using PZT-Enabled Time-Reversal Method

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A prestressed bolt connection is one of the crucial connection types in timber structures. The daily checking and maintenance of bolt connections have to be carried out in order to avoid the collapse of timber structures due to bolt looseness. Real-time health monitoring of bolt connections can not only reduce the daily maintenance cost of timber structures, but it can also avoid property loss and casualties by giving early warning if the bolt connection is loosened in timber structures. This paper proposes a method of prestress monitoring of bolt joints in timber structures by pasting lead zirconate titanate (PZT) patches on the surface of timber structures, and the time-reversal method is applied to denote the connection status of bolts in timber structures. The prestress loss index of timber structural bolts based on wavelet analysis is designed to quantify the bolt looseness of the timber structure. The experimental timber specimen was fabricated consisting of two timber panels, one bolt, and two PZT patches. One of the PZT patches acted as an actuator to emit the stress waves, and another one acted as a sensor to receive the stress wave propagating through the connection interface. The experimental results showed that the amplitude of the focused signal increases significantly with the increase of the prestress value of the bolts, which verify that the proposed method can be utilized to monitor the looseness of bolts in timber structures. The analysis results of the focused signal is proof that the prestress loss index of timber structural bolts designed based on wavelet analysis can reflect the looseness of timber structural bolts.

1. Introduction

The timber structure has traditionally been a symbol of ancient architecture, which has a long history of evolution. From the palaces and temples of monarchs to the houses and pavilions of people, there are many timber structures that still survive and are widespread. With the advancement of social science and technology, the timber structure has joined the elements of industry and has become a collection of traditional structural systems with modern science and technology [1, 2]. With the continuous optimization of timber structure design, the use of metal material connectors in the design of contemporary timber structures has gradually increased, and it has been extensively used in the design of connection nodes. Acting in accordance with relevant research, nearly 80% of damaged timber structures failed because of the destruction of node connections [3]. In order to reduce or even avoid the economic losses caused by the looseness of the bolts of a timber structure, it is of great significance to find an effective method to monitor the looseness of the bolts of a timber structure in real time, and give an early warning of the bolt prestress loss.

Recently, structural health monitoring (SHM) and nondestructive testing (NDT) have attracted the attention of numerous scholars. Zhang et al. proposed a feasibility research on timber damage detection and calculated wavelet packet-based energy to account for timber damage [4]. Annamdas utilized impedance-based technology to monitor the health of a timber structure [5]. Fredriksson et al. reviewed the moisture content of timber by identifying the change of electrical resistance [6]. Sanabria et al. proposed an accurate and reproducible method for the health assessment of glued timber [7]. Sanabria et al. also investigated individual bonding planes of structural multilayered glued timber laminates using a novel ultrasound method [8]. Klapálek et al. gave a pulse method for nondestructive evaluation of glued laminated timber beams [9].

In addition to medical imaging, vibration control, and nondestructive testing (NDT), piezoelectric materials have been broadly used in SHM [10]. Among the many types of piezoelectric materials, lead zirconate titanate (PZT) is favored by researchers because of its low cost, light weight, simple structure, moldability, and ease of construction. PZT sensors are also widely used because of their ability to collect energy [11]. Huo et al. proposed the PZT-based "smart washer" to monitor the looseness of the bolt, and utilized the bolt prestress loss index to reflect the health status of the bolt connection [12]. Huo et al. also proposed the impedance-based bolt prestress loss monitoring using "smart washers" [13]. Fan et al. developed the mechanical impedance to monitor the looseness of the pin connection [14]. An and Sohn proposed the impedance-based bolt loosening monitoring method [15]. Nguyen et al. presented a method by using multichannel wireless impedance sensors and multiple PZT interfaces to monitor the bolt connection [16]. Ritdumrongkul et al. used piezoceramic actuator-sensor quantitative health monitoring of bolted joints [17]. Peairs et al. examined the self-inductance and self-repair of bolted joints, which enriches the practicality of bolted joint self-repair [18]. Although many studies have been conducted to monitor the bolt connection, most of them focused on the bolts in steel or concrete structures.

This paper proposes a method to monitor bolt loosening in timber structures by combining the active sensing technology of piezoelectric ceramics and the time-reversal method. Two PZT patches are attached to the surface of the timber structures to realize the proposed method, as shown in Figure 1, in which one PZT is used as an actuator to generate stress waves and another one is used to receive the stress wave propagating through the connection interface. From the microscopic scale, the surfaces of two timber blocks cannot be fully contacted, as shown in Figure 1. There is a positive correlation between the peak amplitude of the focused signal and the actual contact area in the time domain [19]. Physically, as the prestress of the bolt increases, the actual contact area between the two boards increases and more energy can be propagated through the contact surface, and the peak of the focused signal obtained by the time-reversal method increases. Based on this understanding, this paper uses the peak value of the focused signal obtained in the time domain to monitor the prestress value of the timber structural bolts in real time and proposes the prestress loss index of the timber structural bolts to quantify the prestress loss of the bolt.

2. Principle of the Proposed Method

2.1. Time-Reversal Method. The time-reversal method has been used in imaging and signal processing. Regarding the theory of the time domain method, Wu et al. had conducted a large number of theoretical and experimental studies [20]. The time-reversal method has better antinoise performance, and the properties of temporal compression in the time domain and spatial focusing in the spatial domain were also better [21]. According to Huo et al.'s research, PZT sensors are very suitable as a time-reversal mirror in the time-reversal process [12]. Therefore, PZT sensors are invoked as actuators and sensors for bolt looseness monitoring. As shown in Figure 2, the excitation signal emitted by the PZT A patch is generated by the data acquisition system. After amplification by the power amplifier, the signal propagates along the board and passes through the contact interface between the two boards. PZT B receives the excitation signal sent from PZT A through the contact interface between the two boards. The signal received by the PZT B is reversed in the time domain, and then the reversed signal is retransmitted by the PZT B (the first signal received by the PZT B will be transmitted last and the last received signal would be transmitted first). PZT A eventually receives the focused signal [22]. The mathematical expression is presented in equation (1) [23, 24].

When a pulse signal $V_A(\omega)$ having a center frequency of ω applies to the PZT A, the PZT A generates a wave signal:

$$E_A(\omega) = k(\omega) V_A(\omega), \tag{1}$$

where $E_A(\omega)$ is the wave energy and $k(\omega)$ is the electromechanical coefficient.

The response signal of PZT A in the time domain can be defined by

$$V_A(t) = \frac{1}{2\pi} \int_{+\infty}^{-\infty} V_A(\omega) e^{i\omega t} d\omega. \tag{2}$$

The wave energy of PZT B is defined by

$$E_B(\omega) = G(\omega) k_A(\omega) V_A(\omega), \tag{3}$$

where $G(\omega)$ is the transfer function that relates the wave energy at PZT B to the input voltage at PZT A.

The wave signal received by PZT B can be defined by

$$V_B(\omega) = k(\omega)^{-1} G(\omega) k(\omega) V_A(\omega). \tag{4}$$

Then, the simplified equation (4) can receive

$$V_B(\omega) = G(\omega) V_A(\omega). \tag{5}$$

When V_B is reversed and applied to PZT B, the wave signal obtained by PZT A is defined by

$$V'_A(\omega) = G(\omega) V_B(\omega). \tag{6}$$

Substituting the value of V_B in equation (5) into equation (6) results in

$$V'_A(\omega) = G^2(\omega) V_A(\omega). \tag{7}$$

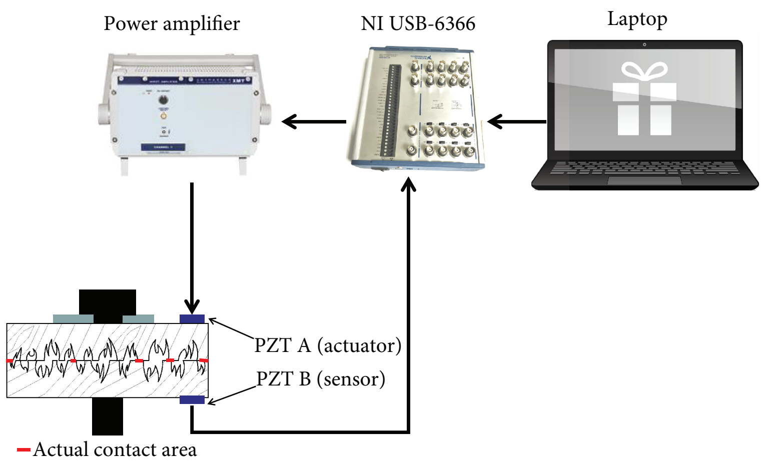


Figure 1: Schematic diagram.

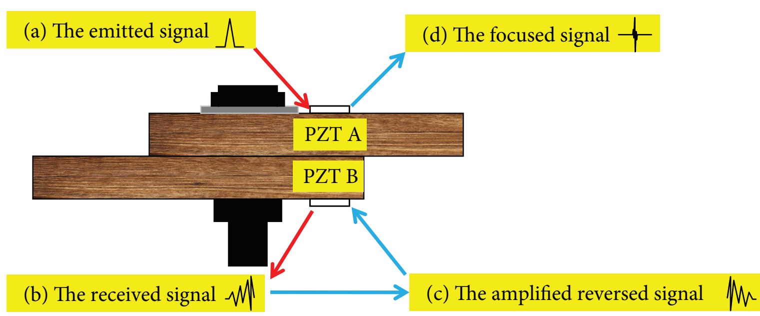


Figure 2: The time-reversal prestress monitoring in timber.

Thus, the reconstructed time domain response signal of PZTA is defined by

$$V'_A(t) = \frac{1}{2\pi}\int_{+\infty}^{-\infty} V'_A(\omega)e^{i\omega t}d\omega,$$
$$V'_A(t) = \frac{1}{2\pi}\int_{+\infty}^{-\infty} G^2(\omega)V_A(\omega)e^{i\omega t}d\omega. \quad (8)$$

2.2. The Loss Index of the Preload of Bolts Based on Wavelet Analysis. In this section, wavelet analysis helps to quantify the energy of the signals. The bolt looseness index is designed based on wavelet analysis to directly compare the change of the focused signal energy under the bolt looseness-induced damage. The variation of the prestress applied on the timber structural bolts can change the actual contact area between the two surfaces of the timber structures, and the stress wave energy received by the sensor through the contact surface will be increased with the increase of the prestress.

The focused signal received by the PZT A sensor can be decomposed by the n-level wavelet. The decomposed signal is used to access bolt looseness. Figure 3 illustrates the wavelet decomposition at level 4. The specimens in each signal set can be represented by X_{ij}, as follows [12]:

$$X_{ij} = [X_{i1}, X_{i2}, X_{i3}, \ldots, X_{im}], \quad (9)$$

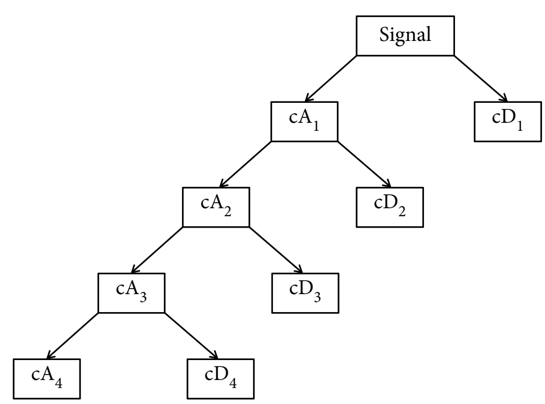


Figure 3: Wavelet decomposition at level 4.

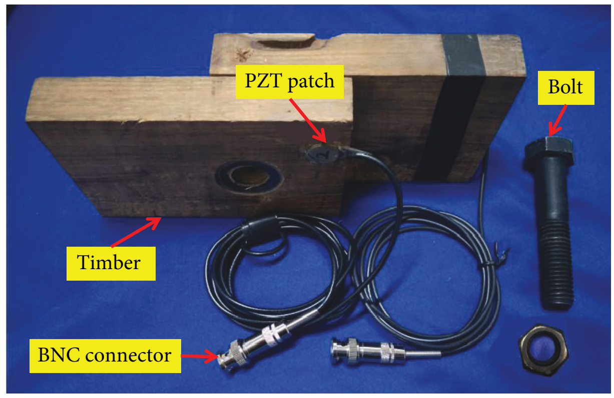
where $i = 1, 2, \ldots, 5$, $j = 1, 2, \ldots, m$, and m is the number of specimens in each signal set.

The energy of each signal set can be calculated by

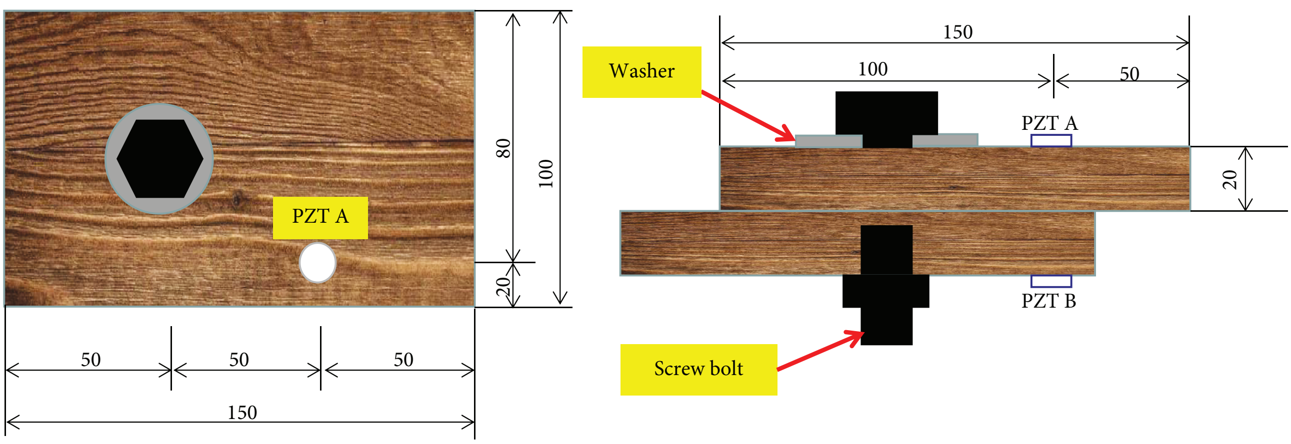
$$E_i^k = \sum_{j=1}^{m} |X_{ij}|^2, \quad (10)$$

where k is the serial number of the test.

E_i^k represents the energy of the ith set under test group k th test conditions.



(a) Timberwork specimen



(b) Detailed dimensions of timberwork specimen

Figure 4: Timber test specimen (unit: mm).

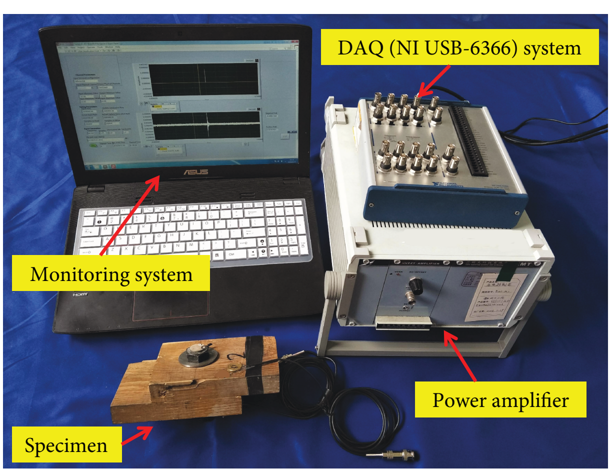


Figure 5: Experimental device.

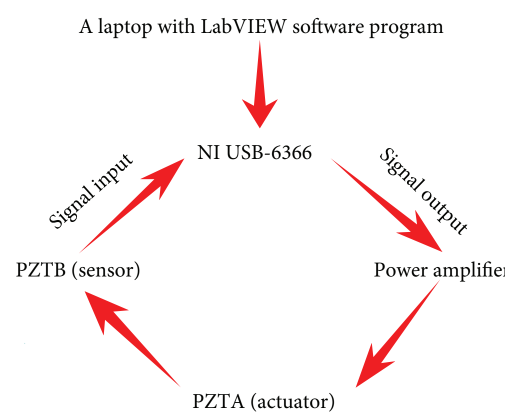


Figure 6: Signal propagation path.

Table 1: Experimental sequence number and preload information of the eight cases.

Sequence number	1st	2nd	3rd	4th	5th	6th	7th	8th
Preload (N·m)	0	10	20	30	40	50	60	65

The wavelet energy ratio for each discomposed coefficient set can be obtained:

$$W_i^k = \frac{E_i^k}{\sum_{i=1}^{n+1} E_i^k}. \tag{11}$$

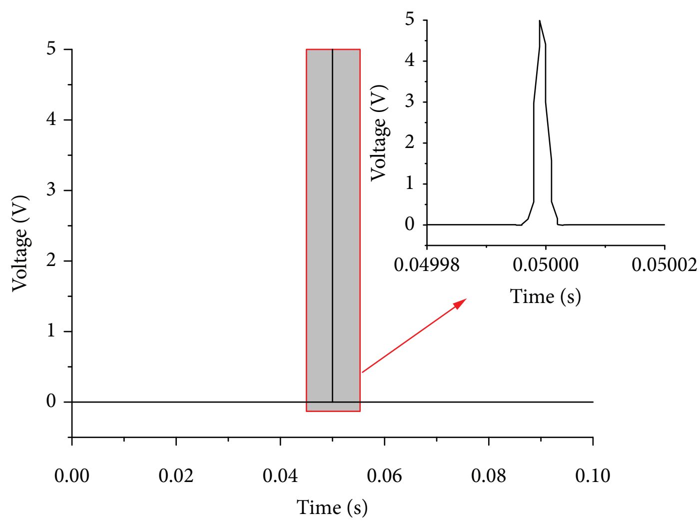


Figure 7: The emitted signal.

In order to quantify the prestress loss of the bolt connection in the timber structure, the bolt looseness index of timber structures is proposed as follows:

$$I_i^k = \frac{W_i^b - W_i^k}{W_i^b - W_i^t}, \tag{12}$$

where I_i^k represents the looseness index of the bolts under the kth group test conditions, W_i^b is the ith set t wavelet energy ratio under no bolt loosening, and W_i^t is the ith set wavelet energy ratio under an entirely loose condition. W_i^k is the ith set wavelet energy ratio under the kth group test conditions. When the bolt is not loose, the bolt prestress loss index is always 0. When the bolt is completely slack, the bolt prestress loss index has a maximum value of 1. With the change of the bolt prestress, the loss index of the preload of bolts will change, which can reflect the degree of looseness of the bolt connection in the timber structures.

3. Experimental Setup

3.1. Timber Structure Specimens and Two PZT Patches. In this experiment, two slabs of timber, one high-strength bolt of M20 × 100 (diameter × length), and two PZT patches were used. The type of PZT patches was PZT-P5H, which was attached to the surface of the timber by using epoxy to detect the health condition of the bolt. Detailed dimensions of the timber structure specimens are shown in Figure 4.

3.2. Instrumentation. Figure 5 shows the experimental setup for monitoring the timber bolt connection. The data acquisition system consisted of an NI USB-6366 data acquisition device with a maximum sampling rate of 2 MHz and a laptop with a LabVIEW software program. The bolt prestress was applied by a torque wrench designed specifically for measuring torque.

Figure 6 shows the propagation path of the signal in the experiment, where the data acquisition device (NI USB-6366) was used to generate and receive signals. Table 1 provides the prestressing force applied by the open-type torque wrench in the timber structure. Due to the hardness of the timber specimen and the limit of the open-type torque wrench, the bending moment value was up to 65 N·m.

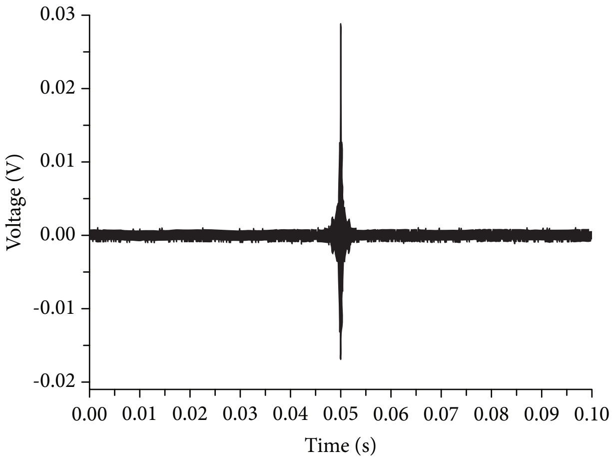
Table 2: The detailed information of the emitted signal.

Frequency (kHz)	Amplitude (V)	Attenuation (dB)	Bandwidth (Hz)
80	5	0.8	1.5

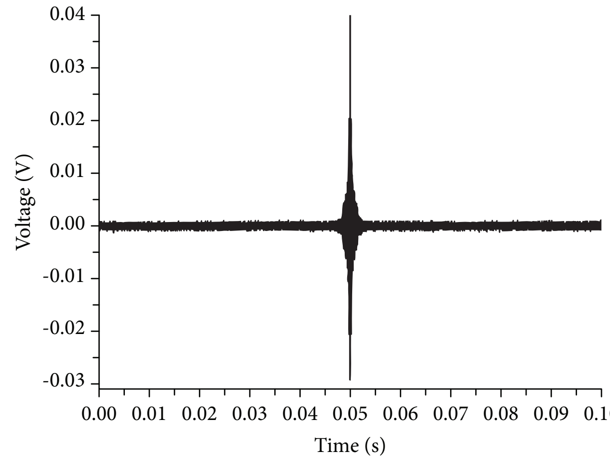
4. Experimental Results

4.1. Time Domain Analysis Results. In the experiment, the prestress of the bolt in the timber structure was controlled by a torque wrench. Prestressing was applied to the timber structural bolts according to the torque values given in Table 1. Figure 7 shows the emitted signal, and more detailed information of the emitted signal is given in Table 2. Figure 8 shows the focused signal when the bending moments are 10 N·m, 20 N·m, 30 N·m, and 40 N·m. Figure 9 shows the reversed signal and the focused signal at a bending moment of 50 N·m. Comparing Figures 8 and 9, it can be clearly seen that the bolt prestress is worth increasing and the peak value of the focused signal is significantly increased.

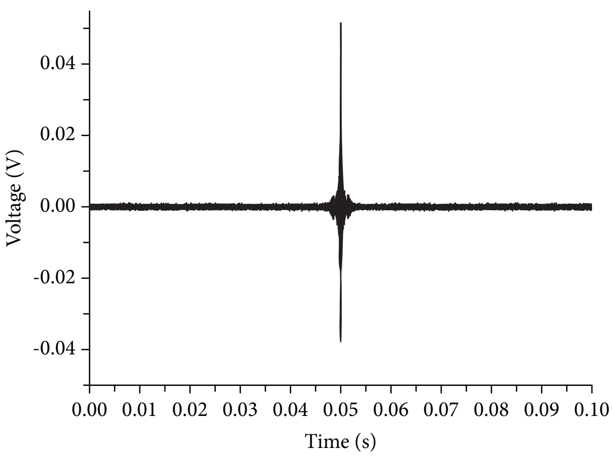
In this study, the reversed signal in Figure 9 was obtained by reversing and amplifying the received signal 200 times in the time domain. Five sets of experiments were carried out on the pretightening force of timber structural bolts. Figure 10 shows the peak change trend of the focused signal of the timber structural bolts under eight different prestress values. It can be seen from Figure 10 that as the prestress value of the timber structural bolt increases, the amplitude of the focused signal increases significantly, which proves that the looseness of the bolt in the timber structure can be reflected according to the amplitude change of the focused signal in the time domain. It is worth noting that when the



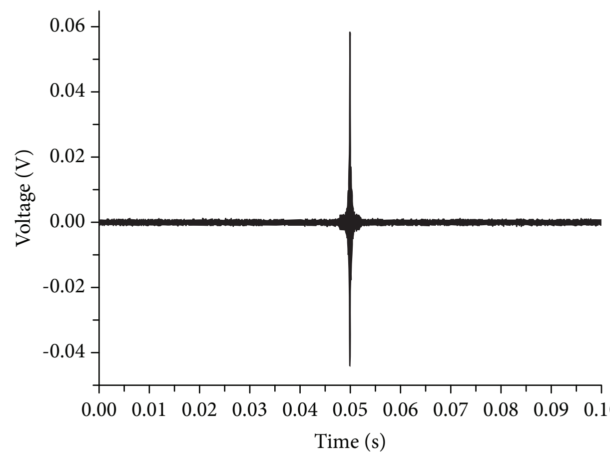
(a) The focused signal in 10 N·m



(b) The focused signal in 20 N·m

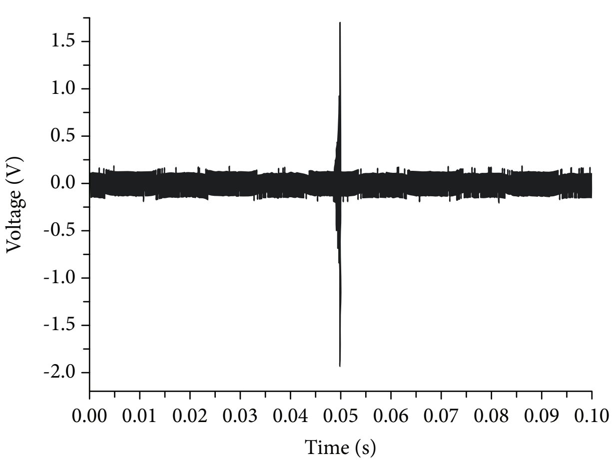


(c) The focused signal in 30 N·m

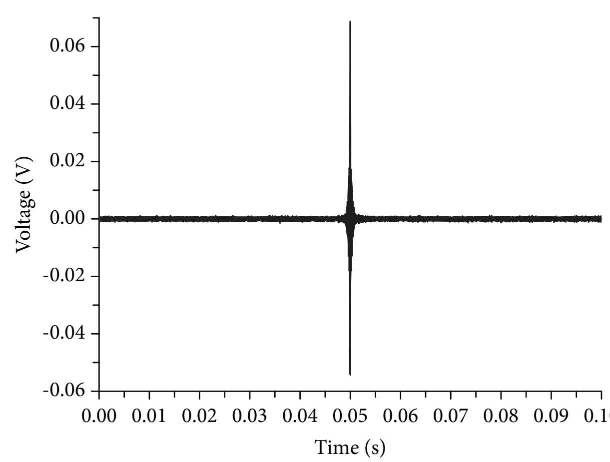


(d) The focused signal in 40 N·m

Figure 8: The focused signal with a preload of 10–40 N·m.



(a) The reversed signal in 50 N·m



(b) The focused signal in 50 N·m

Figure 9: Two signals in the time-reversal method at 50 N·m.

prestress value of the timber structural bolt exceeds 40 N·m, the peak value of the focused signal is close to saturation, which means that increasing the bolt prestress value has almost no effect on the actual contact area between the two boards. It hardly increases the propagation of stress waves between the two plates, for the reason that the two surfaces of the timber structure may have been in full contact with the torque moment at over 40 N·m.

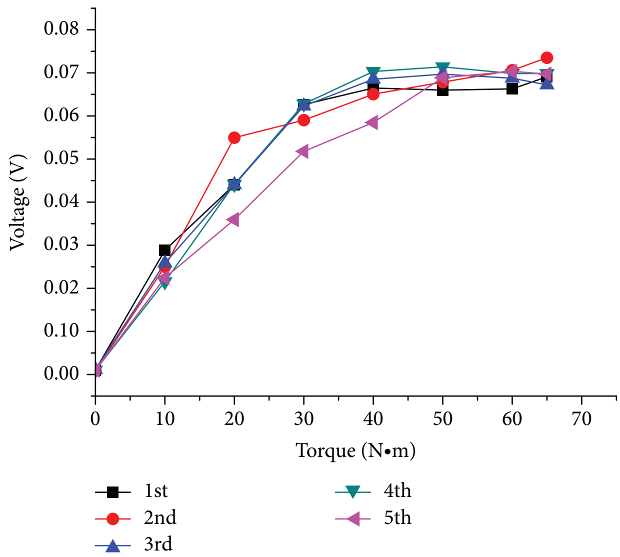


FIGURE 10: Peak values of the different bolt preload conditions in timber.

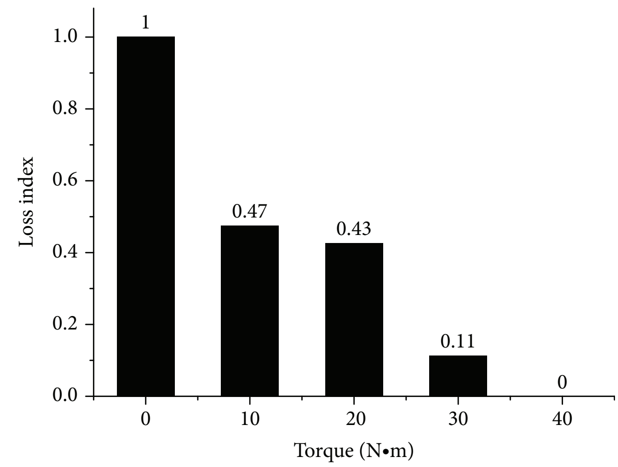


FIGURE 11: Loss index values of the different bolt preload conditions in timber.

4.2. Bolt Prestress Loss Index Based on Wavelet Analysis. In order to quantitatively analyze the prestress loss of timber structural bolts, the focused signal is processed according to the wavelet analysis method proposed in Section 2.2. In this experiment, eight focused signals are decomposed using a four-level wavelet. According to the related research, when the energy of the stress wave is calculated on the basis of wavelet analysis, the wavelet energy ratio of the low-frequency coefficient set can assess the loss of bolt prestress. In this article, the wavelet energy ratio of low-frequency coefficients is used to measure the loss of bolt prestress. The wavelet energy ratio W of the low-frequency coefficient set under different prestress values is substituted into equation (12), and the bolt prestress loss index under different prestress values is obtained.

As shown in Figure 11, when the timber structural bolt is completely loose, the prestress loss index is 1; when the timber structural bolts are not loose, the prestress loss index is 0. With the increase of the prestress of timber structural bolts, the prestress loss index of timber structural bolts gradually decreases, indicating that there is a relationship between the prestress loss index of the timber structural bolt and the bolt prestress, and the prestressing loss index of the timber structural bolt can be used to reflect the looseness of the timber structural bolt.

5. Conclusions

This paper proposes a health monitoring method for the bolt connection in timber structures based on PZT transducers. The PZT patches were pasted on the surface of the timber structure specimen, combining with the piezoelectric ceramic active sensing technology and the time-reversal method to monitor the looseness of the bolts of the timber structure in real time. The prestress loss index of timber structural bolts based on wavelet analysis is designed to reflect the looseness of timber structural bolts. The experimental results show that the prestress of the timber structural bolt will affect the actual contact area between the two boards, which will affect the peak value of the focused signal. It has been proven that the peak value of the focused signal can reflect the loss of the prestress of the timber structural bolt. The bolt prestress loss index based on wavelet analysis is gradually reduced with the prestress of bolts, which indicates that the proposed prestress loss index of timber structural bolts can be used to reflect the looseness of timber structural bolts. So far, the PZT-enabled time-reversal method set out in the present paper can effectively monitor the looseness of the bolts in timber structures in real time. To further develop this novel monitoring method, the influences of some variables, such as the different stiffness and anisotropy, will be considered and investigated comprehensively in the future.

Data Availability

The PZT-enabled time-reversal method content data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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