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Experimental Study on Influencing Factors of Fatigue Performance of Larch Plywood Beam

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Abstract

To investigate the fatigue performance of larch plywood beams under cyclic loading, this study systematically examined the effects of three key factors—loading frequency, loading waveform, and span-to-height ratio—on fatigue life, failure modes, and stiffness degradation through static and fatigue tests. Three plywood beams were first subjected to static tests, yielding a maximum load capacity of approximately 88 kN, with failure primarily occurring due to fiber fracture in the tension zone. Subsequent fatigue tests were conducted under varying loading frequencies (1 Hz, 3 Hz, 5 Hz), waveforms (sine, triangular, square), and span-to-height ratios (12,15,18). Results demonstrated that higher loading frequencies extended fatigue life, though the gain effect diminished beyond 3 Hz. The loading waveform significantly influenced fatigue life, with square wave loads causing maximum damage at equivalent stress levels compared to triangular wave loads. Increased span-to-height ratios reduced fatigue life, while smaller ratios exhibited more pronounced shear stress-dependent failure. A fatigue damage evolution model based on stiffness degradation theory was established, showing good agreement with experimental predictions. This research provides theoretical foundations for fatigue design of timber-structured bridges.

Keywords

Larch; glued laminated timber beam; fatigue performance; load frequency; load-ing waveform; span-to-height ratio; stiffness degradation

1. Introduction

With the deepening implementation of China's "dual carbon" strategy, green, eco-friendly, and low-carbon modern timber structures have garnered significant attention in the engineering sector. As a key application of timber construction, modern timber bridges have been widely adopted in Europe and North America. Statistics indicate that the United States currently has 75,000 timber bridges, accounting for approximately 15% of all highway bridges, with most exceeding 50 years of service. In Northern Europe, timber bridges have become a common bridge type [1]. However, China's research on modern timber bridges started relatively late, and its design and construction technologies remain relatively underdeveloped, which has hindered their widespread adoption.

In modern timber bridge structures, structural components endure cyclic loads from vehicles over extended periods. The loads they bear during fatigue failure often fall far below their ultimate load capacity. Consequently, the fatigue resistance of timber has become a critical scientific challenge requiring breakthroughs in modern timber bridge engineering [2]. Larch, a vital forest resource in China, boasts abundant reserves and exhibits exceptional hardness, strength, and corrosion resistance, making it an ideal building material [3]. As a novel green material, plywood effectively utilizes small-diameter timber to produce large-section components through bonding processes, and is increasingly being adopted in large-span and high-rise structures [4].

Current research on glued laminated timber beams (GLT) by scholars worldwide primarily focuses on static performance, including bending capacity, reinforcement measures, and long-term creep [5-7], while fatigue performance studies remain insufficient. Jianong Cai [8] discovered through fatigue tests on larch GLT beams that the beam's bending stiffness decreases with increasing cycle counts, with stiffer load values causing faster stiffness reduction. Lei Cao [9] conducted fatigue tests on six Xing' an larch GLT beams, obtaining their S-N curves. Foreign scholar Clorius [10] investigated fatigue performance of small-sized timber components under varying humidity conditions and proposed the DVM damage model. However, systematic research on critical influencing factors such as load frequency, loading waveform, and span-to-height ratio remains inadequate, as these factors directly affect the fatigue life assessment of timber bridges under actual service conditions.

Therefore, this paper takes the larch glued laminated timber beam as the research object, and determines its basic mechanical properties by static load test. Then, it carries out the fatigue test with different load frequency, loading waveform and span-to-height ratio, and analyzes the influence of each factor on the fatigue life, failure mode and stiffness degradation. Finally, it establishes the fatigue damage evolution model based on stiffness degradation, which provides the theoretical basis for the fatigue design of the glued laminated timber beam.

2. Overview of the Trial

2.1. Specimen Design and Fabrication

The test beams, fabricated from Northeastern larch (Larix kaempferi) in compliance with the "Standard for Experimental Methods of Timber Structures" (GB/T 50329-2012), comprise three static load test beams (P-1 to P-3) measuring 4000 mm × 100 mm × 200 mm (length × width × height) with a calculated span of 3600 mm and a span-to-height ratio of 18, where shear effects are negligible. The fatigue test beams are divided into three groups: different load frequency groups

(F-1 to F-3), different loading waveforms groups (W-1 to W-3), and different span-to-height ratio groups (S-1 to S-3), each containing three beams for a total of twelve. The span-to-height ratio groups feature beam heights of 200 mm, 240 mm, and 300 mm corresponding to ratios of 18,15, and 12, respectively, with beam widths maintained at 100 mm and lengths adjusted accordingly.

The plywood was manufactured in strict compliance with the "Code for Design of Timber Structures" (GB 50005-2017), using resorcinol resin adhesive with a bonding unit pressure of 1.0 MPa and a coating amount of approximately 250 g/m^2. After pressing, the plywood underwent a 3-day curing period.

2.2. Material Properties

The mechanical properties of the larch wood are as follows: the tensile strength in the grain direction is f_t=100 MPa, the compressive strength in the grain direction is f_c=43 MPa, the elastic modulus is E=12.5 GPa, the Poisson's ratio is ε =0.3, and the density is ρ =0.65 g/cm^3.

2.3. Loading Scheme and Measurement Point Layout

The static load test employed a four-point bending configuration, with jack loads transmitted through a distribution beam to the beam's 1/3 and 2/3 points. The loading protocol was implemented as follows: 5 kN increments before 50 kN, followed by 2 kN increments thereafter, with each load maintained for 2 minutes during data collection. The fatigue test utilized an electro-hydraulic servo fatigue testing machine, applying a load limit of 60% of the static load's ultimate bearing capacity at a stress ratio (R) of 0.1. Loading frequencies for different frequency groups were 1 Hz, 3 Hz, and 5 Hz respectively, with sine wave patterns. For waveform groups, sine wave, triangular wave, and square wave patterns were employed at a fixed frequency of 3 Hz. Span-to-height ratios of 12,15, and 18 were tested at a frequency of 3 Hz with sine wave loading.

Measurement points layout: A dial gauge is installed at the mid-span and third-point positions to measure deflection. Seven strain gauges (Y1~Y7) are evenly distributed along the mid-span section at 48 mm intervals to monitor strain distribution. Data is collected using a DH3831 static strain gauge.

3. Experimental Results and Analysis

3.1. Static Load Test Results

The three static load test beams exhibited ultimate bearing capacities of 86.5 KN, 89.2 KN, and 88.3 KN respectively, with an average of 88.0 KN. These values were 14.7% higher than the theoretical calculation of 76.7 KN, primarily due to conservative material parameter values in the theoretical analysis. The failure modes were as follows: The P-1 beam experienced wood fiber fracture in the tension zone at one-third span; the P-2 beam suffered stress concentration failure at the wood knot near the bottom; and the P-3 beam developed cracks near the support's wood knot, which progressed toward the mid-span before failure. These results demonstrate that natural wood defects significantly influence failure modes.

The load-deflection curve shows that the beam is in the linear elastic stage at the beginning of loading, the deflection rate increases rapidly when the beam is near the ultimate load, and there is a short plastic stage before the failure. The maximum deflection at the mid-span is 70 mm, which is about 1/51 of the span, indicating that the glued wood has a good deformation capacity.

3.2. Fatigue Test Results

3.2.1. Impact of Load Frequency

The fatigue life of the test beam at different frequencies is shown in Table 1. The average fatigue life at frequencies of 1 Hz, 3 Hz, and 5 Hz is 12.6×10^4cycles, 21.8×10^4cycles, and 25.3×10^4cycles, respectively. While fatigue life increases with higher frequencies, the gain in life decreases when the frequency rises from 3 Hz to 5 Hz. This occurs because low-frequency loads allow longer load-bearing time per cycle, leading to more pronounced viscoelastic deformation accumulation in wood and exacerbating creep-fatigue coupled damage. In contrast, high-frequency loads accelerate internal heat generation in the material. However, due to larch's poor thermal conductivity, heat accumulation may instead accelerate the aging of the adhesive layer.

Table 1. Fatigue Test Results at Different Frequencies

Beam Number	Frequency / Hz	Fatigue Life $/ * 10^4$ cycles	Failure Mode
F-1	1	12.6	Tensile Zone Fracture
F-2	3	21.8	Tensional Zone Fracture
F-3	5	25.3	Tensional Zone Fracture

3.2.2. Effects of Load Waveform

Table 2 presents the fatigue life of test beams under different waveforms. Under identical stress levels and frequencies, the square wave loading demonstrated the shortest fatigue life (9.8×10^4 cycles), while the triangular wave showed the longest (28.6×10^4 cycles), with the sine wave falling in between (21.8×10^4 cycles). The square wave's abrupt loading and holding phases create an impact effect during loading, while the holding phase accelerates viscoelastic flow in the adhesive layer and microcrack propagation. The triangular wave, with its constant rise/fall rates and absence of holding phases, exhibits the slowest damage accumulation. The sine wave's gradual loading results in intermediate damage severity. Fracture analysis reveals that square wave specimens show severe fiber tearing and obvious adhesive delamination, whereas triangular wave specimens exhibit smoother fractures with distinct fatigue bands.

Table 2. Fatigue Test Results under Different Waveforms

Beam Number	Waveform	Fatigue Life /* 10^4 cycles	Failure Mode
W-1	Sine Wave	21.8	Tension Zone Fracture
W-2	Triangle Wave	28.6	Tension Zone Fracture
W-3	Square Wave	9.8	Adhesive delamination + fiber breakage

3.2.3. Effects of the Span-to-Height Ratio

The fatigue life of test beams under different span-to-height ratios is presented in Table 3. For span-to-height ratios of 12,15, and 18, the fatigue life values are 32.4×10^4cycles, 24.7×10^4cycles, and 21.8×10^4cycles, respectively. A reduction in span-to-height ratio (increasing beam height) results in an increase in fatigue life. The beam with a span-to-height ratio of 12 fails in the shear zone near the support, where cracks propagate along the adhesive layer, demonstrating shear-compression failure. In contrast, the beam with a span-to-height ratio of 18 fails in the tension zone at the mid-span, exhibiting typical bending fatigue failure. This indicates that in beams with smaller span-to-height ratios, shear stress accounts for a larger proportion, making shear fatigue of the adhesive layer the dominant failure mode.

Table 3. Fatigue Test Results for Different Cross-Height Ratios

Beam Number	Span-to-Height Ratio	Fatigue Life /* 10^4 cycles	Failure Mode
S-1	18	12.6	Bending Fatigue Failure
S-2	15	24.7	Shear-bending failure
S-3	12	32.1	Shear failure

3.3. Stiffness Degradation Analysis

The damage accumulation process is characterized by the cross-center deflection-based inverse calculation of bending stiffness degradation rate $D=1-E_N/E_0$ (where E_N denotes the stiffness after N cycles and E_0 the initial stiffness). Figure 1 presents the stiffness degradation curve of a typical specimen, exhibiting three distinct phases: The initial phase (cycling <20% of life) shows a rapid 5%-8% decline in stiffness, primarily caused by microcrack initiation and material adjustment. The stable phase (20%-80% of life) features linear, gradual stiffness degradation with steady damage accumulation. The failure phase (>80% of life) demonstrates accelerated stiffness decline until ultimate failure.

The influence of different factors on the stiffness degradation rate is significant: the lower the frequency, the faster the degradation rate in the stable stage; the slope of the square wave loading is the largest in the stable stage, and the smallest in the triangular wave; the smaller the span-to-height ratio, the greater the initial stage stiffness reduction, but the slower the degradation rate in the stable stage.

3.4. Fatigue Life Prediction Model

Based on the stiffness degradation theory, a fatigue damage evolution model is established:

$$D = 1 - \frac{E_N}{E_0} = \alpha \left(\frac{N}{N_f}\right)^{\beta}$$

In the formula, N_f is the fatigue life, while α and β are parameters related to loading conditions, determined through experimental data fitting.

The regression analysis of the test data under different loading conditions is carried out, and the values of α and β are obtained (Table 4). The relative error between the predicted fatigue life and the experimental values is within ±15%, indicating that the damage model based on stiffness degradation can well describe the fatigue damage evolution process of larch plywood beams.

Table 4. Parameters of the injury model under different conditions

Factor	Condition	α	β	correlation coefficent
Frequency	1Hz	0.12	0.43	0.92
Frequency	2Hz	0.10	0.38	0.94
Frequency	3Hz	0.09	0.35	0.93
Waveform	Sine Wave	0.10	0.38	0.94
Waveform	Triangle Wave	0.08	0.32	0.91
Waveform	Square Wave	0.15	0.48	0.90
Span Ratio	18	0.10	0.38	0.94
Span Ratio	15	0.11	0.35	0.92
Span Ratio	12	0.13	0.30	0.91

4. Conclusion

1) The average static load capacity of larch plywood beams is 88 kN. The failure mode is significantly affected by natural defects of wood, such as knots and grain defects, which are easy to become the crack initiation points. Plywood has good deformation capacity and obvious signs before failure.

2) The fatigue life of the glued laminated timber beams is significantly affected by the load frequency. When the frequency increases from 1 Hz to 5 Hz, the fatigue life is approximately doubled. However, the gain decreases after the frequency exceeds 3 Hz. Under low-frequency loads, the creep-fatigue coupling effect exacerbates damage accumulation.

3) The loading waveform has a significant effect on the fatigue life. Under the same conditions, the triangular wave has the longest fatigue life, followed by the sine wave, and the square wave has the shortest. The sudden loading and holding stage of the square wave accelerate the delamination of the adhesive layer and fiber fracture. The impact load should be avoided in the design.

4) Reduced span-to-height ratio (increased beam height) enhances fatigue life. For beams with low span-to-height ratio, failure is shear-stress controlled, where adhesive layer shear fatigue becomes critical; whereas for high span-to-height ratio beams, bending fatigue predominates. Fatigue design of glued laminated timber beams should select appropriate control indices based on the span-to-height ratio.
5) The damage evolution model based on stiffness degradation can describe the fatigue damage process of the glued laminated timber beam well, and the predicted values of the model are in good agreement with the experimental results, which can provide a theoretical basis for the fatigue life assessment of the glued laminated timber beam.

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