

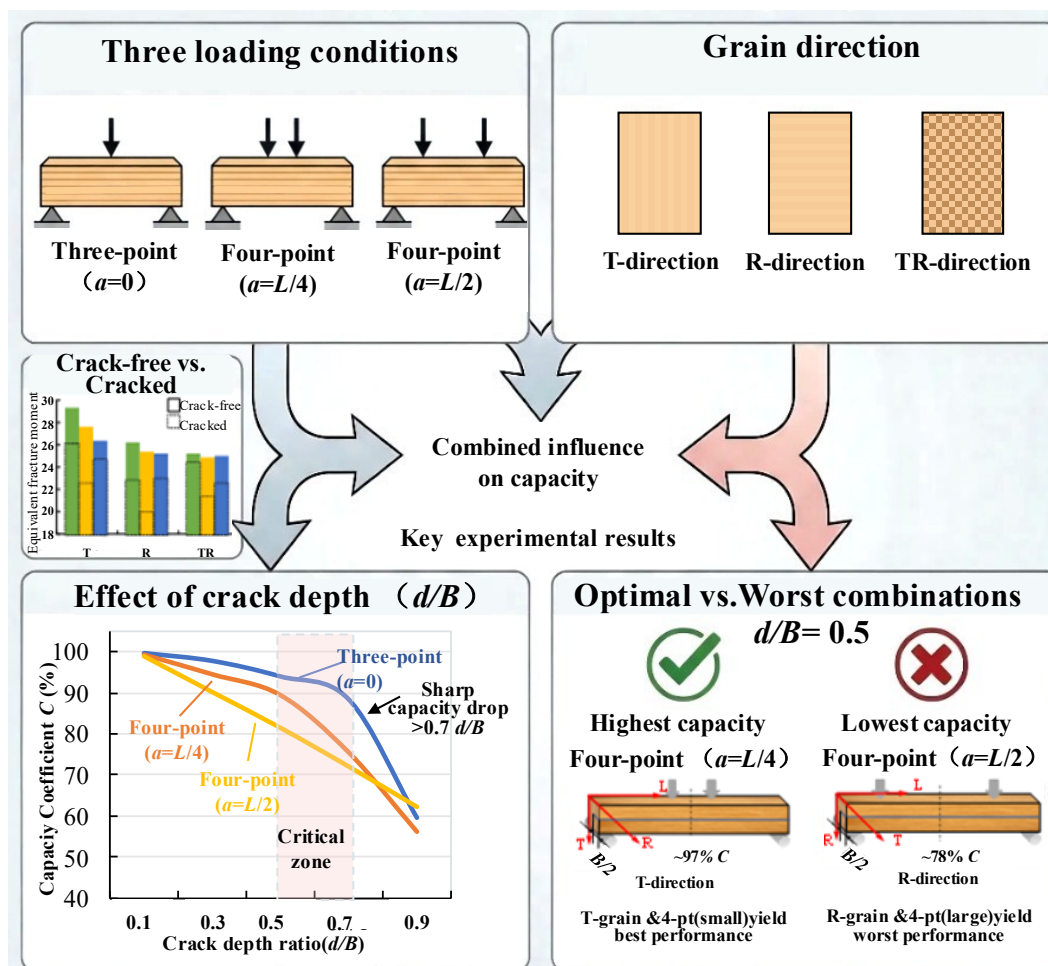
Load-bearing Capacity of Longitudinally Cracked Timber Beams Under Different Loading Conditions: Investigation of Three Different Loading Point Distances and Three Different Grain Directions

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GRAPHICAL ABSTRACT



Load-bearing Capacity of Longitudinally Cracked Timber Beams Under Different Loading Conditions: Investigation of Three Different Loading Point Distances and Three Different Grain Directions

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This study investigated the effects of loading point distance, grain direction, and crack depth ratio on the load-bearing capacity of longitudinally cracked timber beams. *Pinus sylvestris* var. *mongolica* was selected for specimen preparation, and fracture tests were conducted under three loading configurations: three-point bending, four-point bending with a large loading-point distance, and four-point bending with a small loading-point distance. Specimens with grain directions of T(tangential), R(radial), and TR(tangential-radial) in crosssection were used. A total of 720 defect-free specimens and 1,200 specimens containing a longitudinal crack at the middle-height layer were tested. Three coefficients, namely load-bearing capacity coefficient, load-bearing capacity degradation coefficient, and crack hazard effect coefficient, were defined to quantify the crack influence. The results showed that T-specimens had the highest load-bearing capacity, followed by R-specimens, and TR-specimens were the lowest. The increase of loading-point distance in four-point bending aggravates the degradation of load-bearing capacity. There exists a critical crack depth, and the load-bearing capacity decreases significantly only when the crack depth exceeds the critical value; the larger the loading point distance, the smaller the critical crack depth. These findings offer a scientific basis for damage assessment and safety control of timber structures with longitudinal cracks.

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Keywords: Load-bearing capacity; Timber beam; Longitudinal crack; Loading point distance; Grain direction

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Nomenclature

C	Load-bearing capacity coefficient	L	Total length of timber beam
D	Load-bearing capacity degradation coefficient	l_0	Standard calculated span of the timber beam
Λ	Crack hazard effect coefficient	l	Length of the longitudinal crack
T	Tangential grain direction	p	Significance level
R	Radial grain direction	a	Loading point distance
TR	Tangential-radial grain direction	d/B	Crack depth ratio
ρ	Air-dry density of wood	CV	Coefficient of variation
H	Actual measured cross-section height of the specimen	P/P'	Peak fracture load (defect-free/cracked)
H_0	Standard cross-section height of the specimen	M_e/M_e'	Equivalent fracture moment (defect-free/cracked)
C_p	Density influence coefficient	ANOVA	One-way Analysis of Variance
C_w	Cross-sectional size influence coefficient	Tukey HSD	Tukey's post-hoc test

INTRODUCTION

Crack damage is a common defect in timber structures. As a natural anisotropic material, wood is prone to generate longitudinal cracks along the grain direction during growth, drying and service processes, which is an inherent characteristic of wood (Villegas *et al.* 2025). After felling, the moisture evaporation in wood leads to uneven shrinkage between surface and inner layers, resulting in tensile stress. When the tensile stress exceeds the intercellular bonding strength, longitudinal shrinkage cracks will form and propagate along the wood fiber (Chi *et al.* 2023; Jerzy and Maciej 2023). Due to the fibrous structure and anisotropic nature, cracks tend to propagate along the wood fiber direction, sometimes developing into large longitudinal cracks that run the entire length of a timber beam's side (Zhang *et al.* 2025).

Longitudinal cracks, especially those located at the mid-height neutral layer, can induce stress concentration, reduce effective bearing section, and significantly degrade the bending resistance and structural stability of beams under service loads. Therefore, model experiments are required to estimate fracture risks and prevent fracture accidents.

Extensive studies have focused on the effects of cracks on the bending performance of timber beams. Shqipron and Waisman (2024) developed gradient damage models for anisotropic wood materials, providing a theoretical basis for analyzing crack propagation and mechanical degradation in timber beams under bending. Marija *et al.* (2022) experimentally examined the flexural behavior of cracked glulam beams *via* four-point bending tests and verified the effectiveness of GFRP reinforcement in suppressing crack growth. Huang *et al.* (2022) proposed a non-destructive method to evaluate mechanical properties of wood with longitudinal surface cracks. Chen *et al.* (2022) revealed the anisotropic mechanism of directional crack initiation in wood under tension. Shqipron and Waisman (2025) further refined the gradient damage model for anisotropic materials and applied it to timber mechanics analysis, achieving detailed simulation of longitudinal crack evolution to overall failure under loading by integrating wood microstructure and macroscopic mechanical characteristics.

The analysis of existing research indicates that current studies predominantly focus on the impact of specific crack patterns on load-bearing capacity of timber beams, with some emphasizing crack formation mechanisms. Most experiments employ single loading methods for beam performance evaluation, where cross-sectional grain orientation typically follows either fixed patterns (Sun *et al.* 2022) or random distributions (Yu *et al.* 2023). However, systematic comparative studies remain insufficient with regard to the load-bearing performance of longitudinally cracked timber beams under three typical bending configurations (three-point bending, four-point bending with small loading-point distance, and four-point bending with large loading-point distance). Similarly, few studies have quantitatively examined the coupled effects of cross-sectional grain orientations (T, R, TR) and crack depth ratio on the bearing degradation and failure behavior of cracked timber beams. Accordingly, this study aimed to quantitatively investigate the effects of loading configuration, cross-sectional grain direction, and crack depth ratio on the flexural load-bearing capacity of timber beams with mid-height longitudinal cracks. Three key indicators are defined to characterize crack-induced bearing degradation, and the failure mechanism and critical crack depth are further revealed.

This study systematically clarifies the degradation mechanism of longitudinal cracks on the flexural performance of timber beams under multiple loading conditions and grain orientations. The results provide specific experimental support and a theoretical

reference for damage evaluation, safety assessment, and engineering application of cracked timber structural members.

EXPERIMENTAL

Wood Selection

Pinus sylvestris var. *mongolica* was obtained from the Krasnoyarsk Krai region in Russia and used as the experimental material in this study. This wood species has a standard air-dry density of $\rho_0=480 \text{ kg/m}^3$. It offers advantages such as moderate strength, good durability, ease of processing, and relatively low cost, making it a commonly used material for timber beams in structures (Li *et al.* 2024; Peng *et al.* 2025). To minimize the uncertainty in experimental results caused by variations among individual specimens, a large sample size was tested for each experimental group, resulting in a total sample size of 1920.

Considering the large sample size in this experimental program, small-scale specimens were employed to minimize wood consumption. It should be noted that wood exhibits a hierarchical microstructure across multiple scales, and the use of small-scale specimens introduces size effects, resulting in deviations from the actual behavior of full-scale timber beams. Consequently, the experimental results are not directly applicable to assessing the load-bearing capacity of large-scale timber beams. The unique contribution of this study lies in its comparative analysis of the effects of wood grain direction and loading configuration on beam load-bearing capacity. The findings provide a basis for the subsequent design of experiments on full-scale timber beams.

Load-bearing Capacity Testing Method and Method for Correcting Experimental Results

The loading method, geometric parameters, fracture moment calculation method, and crack machining method of the timber beam are shown in Fig. 1. The parameters L and l represent the length of the beam and the length of the crack, respectively.

Considering that longitudinal cracks occurring precisely at the neutral layer position of timber beams have the most severe impact on their load-bearing capacity (Toivanen *et al.* 2025), and that shrinkage cracks are most likely to form near the neutral layer (Zhou *et al.* 2026), this study focused solely on analyzing the influence of longitudinal cracks at the neutral layer on beam performance. The fiber structure of wood results in its tensile elastic modulus being slightly higher than compressive elastic modulus, causing the neutral layer to be positioned slightly above the middle height layer of timber beams (Davis *et al.* 2012). This assumption that the neutral layer coincides with the mid-height is fully consistent with Section 3.3.2.2 of ANSI/AWC NDS (2018), which specifies that the neutral axis is taken at the center of the depth for solid rectangular wood bending members. The offset is very small relative to the section height and thus is expected to have negligible influence on the load-bearing capacity degradation law, failure mechanism, and conclusions of this study. Given the minimal displacement of the neutral layer due to these factors, and considering that such displacement would complicate both specimen processing and theoretical analysis, this study maintained the assumption that the neutral layer coincides with the middle height layer. All processed specimens exhibited longitudinal cracks located at the middle height layer.

To facilitate comparison of experimental results across different timber beams and to minimize uncertainties caused by variations in specimen dimensions and density, this study standardized the timberbeam span-to-height ratio at 1:10 and employed uniformly sized specimens ($l_0 = 150$ mm, $H_0 = 15$ mm, $B_0 = 10$ mm, $L_0 = 160$ mm). Three loading conditions were investigated: (1) three-point bending with $a=0$; (2) four-point bending with small loading point distance at $a=L/4$ (a denotes the loading point distance); (3) four-point bending with large loading point distance $a=L/2$.

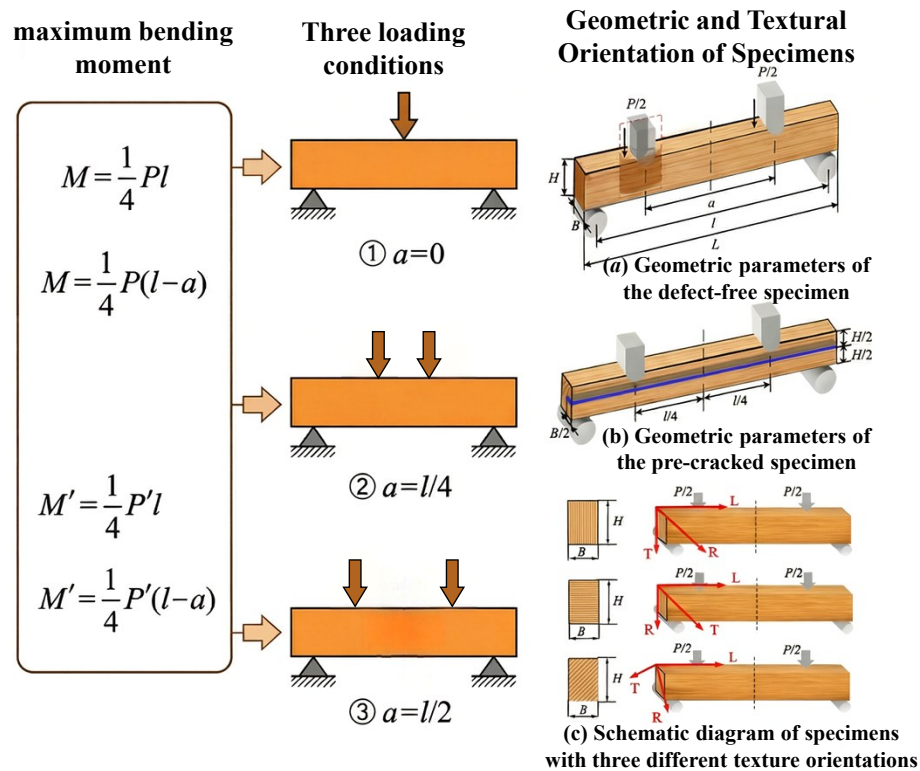


Fig. 1. Schematic diagram of the geometric dimensions, grain direction, and loading direction of specimens

Before the experiment began, 720 defect-free specimens and 1200 specimens with longitudinal cracks of different parameters were processed. The overall condition of the specimens is shown in Table 1.

Table 1. Number of Specimens in Each Experimental Control Group

Loading case	Loading method $a=L/2$	Loading method $a=L/4$	Loading method $a=0$	Total number of specimens
Defect-free	80(T), 80(R), 80(TR)	80(T), 80(R), 80(TR)	80(T), 80(R), 80(TR)	$80 \times 3 \times 3 = 720$
Longitudinal crack ($d=B/2$)	80(T), 80(R), 80(TR)	80(T), 80(R), 80(TR)	80(T), 80(R), 80(TR)	$80 \times 3 \times 3 = 720$
Longitudinal crack: $d/B=(0.1, 0.3, 0.7, 0.9)$	40(T)	40(T)	40(T)	$40 \times 3 \times 4 = 480$

Note: The numbers 80 or 40 in the table indicate the number of specimens per loading case, while the T, R, and TR in parentheses denote the grain direction of specimens.

During specimen preparation, an ultra-thin small-diameter saw blade with a thickness of only 0.5 mm was used to cut the cracks. Although the artificially prefabricated cracks differed in morphology from naturally formed cracks in timber beams, this method enables precise control over the crack geometry parameters, thereby facilitating repeatable experiments with a large sample size. Specifically, artificially cut cracks possess regular shapes and consistent expansion paths, which differ from the irregular morphology and random distribution characteristics of natural cracks. Nevertheless, standardized prefabricated cracks can eliminate the interference of crack uncertainty on test results and highlight the quantitative influence of crack depth and loading conditions. In contrast, natural cracks are affected by growth stress and environmental drying, with highly variable geometric features, making it difficult to establish a unified control variable for mechanical analysis (Jiang *et al.* 2015). In contrast, using specimens with naturally formed cracks makes it difficult to control the crack geometry and location, rendering such an approach unsuitable for large-sample-size experiments.

Prior to testing, the prepared specimens were stored in a drying oven to stabilize the moisture content at 12% (with a tolerance of $\pm 1.5\%$). After removal from the drying oven, all tests were completed within two hours to prevent significant changes in moisture content. Subsequently, the geometric dimensions (length, width, and height) of the specimens were measured with an accuracy of ± 0.1 mm, and the mass was measured with an accuracy of ± 0.01 g. These measurements were used for subsequent correction of the experimental results.

During the experiment stage, specimens were placed on a dedicated metal hinge support with a span of $l=150$ mm, and subjected to fracture and failure loading using a universal mechanical testing machine, PUYAN980 (Yaofeng Electronic Equipment Co., Ltd., Dongguan, China), with a maximum load 20 kN, load measurement resolution 0.01 N and combined with a three-point bending special pressure head or a four-point bending pressure head with adjustable loading point distance for fracture failure loading.

The tests were conducted in accordance with GB/T 1927.10-2021 (Test methods for physical and mechanical properties of small clear wood specimens).

Pre-loading: A pre-load of approximately 10% of the expected maximum load was applied to the specimen to eliminate potential loose contact between the specimen and the distribution steel beam and to verify the functionality of displacement measurement sensors. The load was applied under displacement control mode at a loading rate of 2 mm/min.

Standard loading: Vertical displacement was continuously applied at a rate of 2 mm/min until the specimen completely fractured.

Under each loading condition, the defect-free specimen was tested first, followed by the specimen with cracks. Failure is defined as the complete fracture of the specimen, and the maximum load refers to the peak load recorded immediately before fracture occurs. During the experiment, the maximum load before fracture failure was recorded for each specimen (P for the defect-free specimen and P' for the cracked specimen). After the experiment, the measured fracture load values were converted into fracture moment values (M and M') using the formula in Fig. 1.

To reduce the uncertainty of experimental results caused by the differences in timberbeam size and density, the directly measured fracture moment values (M , M') need to be converted into equivalent values (M_e , M_e'). The conversion formulas are as follows,

$$M_e = M \cdot C_p \cdot C_W \quad (1)$$

$$M_e' = M' \cdot C_\rho \cdot C_W \quad (2)$$

where M and M_e represent the measured and equivalent fracture moment values of a defect-free timber beam, while M' and M_e' denote the corresponding values for a cracked beam. C_ρ is the density influence coefficient, which corrects for density variations affecting experimental results (Shao *et al.* 2012; Yin *et al.* 2020), and C_W is the cross-sectional size influence coefficient, which corrects for dimensional differences. The equivalent fracture moment value physically corresponds to the fracture moment of a timber beam with standard density and identical cross-sectional dimensions, calculated under the assumption that the beam's load-bearing capacity is directly proportional to its density (Górska *et al.* 2025).

The calculation formula for the density influence coefficient C_ρ is as follows,

$$C_\rho = \rho_0 / \rho \quad (3)$$

where ρ_0 is the standard air-dry density of *Pinus sylvestris* var. *mongolica* wood (taken as 480 kg/m³); and ρ is the actual air-dry density of the specimen. For defect-free specimens and those with pre-cracks, the specific calculation formula for ρ can be calculated separately through formulas (4) and (5). By subtracting the crack volume from the total specimen volume in the denominator of Eq. 5, the proposed formula effectively compensates for the geometric weakening effect induced by artificial cracks. This correction eliminates the underestimation of actual density caused by ignoring crack volume, and realizes more reasonable and refined density characterization for cracked wood beams (Hu *et al.* 2026).

$$\rho_{(\text{defect-free-beam})} = m / (BHL) \quad (4)$$

$$\rho_{(\text{cracked-beam})} = m / (BHL - d\delta L) \quad (5)$$

where B , H , L and m are the width, height, length and the static mass of specimens, respectively, δ is the width of the prefabricated crack (the volume of the prefabricated crack is δdL and in calculating, take $\delta = 0.5$ mm). It can be seen that the calculation formula takes into account the volume of wood removed due to fabricating cracks, making the calculated density more accurate. In addition, when measuring the static mass of specimens, based on the condition of a moisture content of 12.0%±1.5%, it is ensured that the calculated ρ is the actual air dry density of the specimens.

The calculation method for the influence coefficient C_W of cross-sectional dimensions is shown in Eq. 6,

$$C_W = B_0 H_0^2 / (BH^2) \quad (6)$$

where B_0 and H_0 are the standard width and height of the specimen ($B_0 = 10.0$ mm, $H_0 = 15.0$ mm), respectively; B and H are the actual cross-sectional width and height of the specimen measured by a vernier caliper (accuracy 0.1 mm). According to Euler-Bernoulli beam theory, the flexural capacity of a rectangular section is proportional to its section modulus $W = BH^2/6$. Therefore, Eq. 6 normalizes the measured fracture load to the standard dimensions through the inverse ratio of section moduli, eliminating geometric bias caused by dimensional variations. By introducing density influence coefficient and cross-sectional influence coefficient to adjust the experimental results, the influence of density differences between specimens and processing errors in specimen size on the experimental results can be significantly reduced. Examples of the fracture load adjustment in this study are shown in Table 2.

Table 2. Example of Adjustment of Fracture Load and Correction of Fracture Moment for Specimens under Three Loading Conditions

Loading method	$m/(g)$	$L/(mm)$	$B/(mm)$	$H/(mm)$	I	$\rho_1/(kg \cdot m^{-3})$	$\rho/(kg \cdot m^{-3})$	C_p	C_w	$P'/(N)$	$M'/(N \cdot m)$	$M_e'/(N \cdot m)$
Three-point bending ($a=0$)	10.21	159.9	9.9	14.9	$L/3$	433	438	1.089	1.024	606	22.7	25.3
Four-point bending ($a=L/4$)	11.30	160.0	10.0	15.0	$L/2$	471	479	0.996	1.000	946	26.5	26.4
Four-point bending($a=L/2$)	12.32	160.1	10.1	15.2	$2L/3$	501	512	0.932	0.964	1502	28.2	25.3

From the process of adjusting the fracture load in the table, it can be seen that if the cross-sectional size and density of the timber beam are below the standard value, the adjusted fracture load value will increase compared to the actual measured value. If the cross-sectional size and density of the timber beam are exceeding the standard value, the adjusted fracture load value will decrease compared to the actual measured value. By using this method for adjustments, the influence of size and density differences between specimens on experimental results can be reduced, making the experimental results more credible.

Correlation Coefficient and Calculation Formula of Crack Influence

To quantify the impact of cracks on load-bearing capacity of timber beams, three coefficients are defined in this study: the “load-bearing capacity coefficient (C)”, the “load-bearing capacity degradation coefficient (D)”, and the “crack hazard effect coefficient (A)”. The first two coefficients are expressed as percentages. The physical meaning of the load-bearing capacity coefficient is the ratio of the fracture bending moment of a cracked timber beam to that of a defect-free timber beam under identical conditions, calculated as follows,

$$C = \frac{M_e'}{M_e} \times 100\% \quad (7)$$

where M_e' represents the equivalent fracture moment of the cracked timber beam and M_e is the equivalent fracture moment of the defect-free timber beam under the same loading conditions. Because the fracture bending moment of a cracked timber beam is generally lower than that of a defect-free timber beam, the value of C is typically less than 1. Mechanically, this phenomenon stems from section weakening and stress concentration induced by internal cracks. In engineering assessments, the C value can be directly used to evaluate the safety margin of a structural member.

Basic test data in Table 2 provides reliable parametric support for the quantitative calculation of the above three characteristic coefficients.

The physical meaning of the load-bearing capacity degradation coefficient (D) is the rate of reduction in the load-bearing capacity of the timber beam caused by the crack. Its calculation formula is,

$$D = (1 - C) \times 100\% \quad (8)$$

where C is the load-bearing capacity coefficient of the cracked timber beam.

The load-bearing capacity degradation coefficient (D) is the complement of load-bearing capacity coefficient (C), representing the percentage of load-bearing capacity loss due to the presence of cracks. In structural repair decision-making, the D value helps quantify the “extent of damage.” Different from the overall residual performance reflected by coefficient C , D focuses on describing the damage severity of cracked beams. A higher D value indicates that cracks have caused significant strength loss, necessitating prioritized reinforcement measures.

The physical meaning of the crack hazard effect coefficient (A) is defined to establish a correlation between load-bearing capacity degradation and crack geometric characteristics, reflecting the ratio of the load-bearing capacity degradation rate to the relative crack depth ratio. Its calculation formula is,

$$A = \frac{D}{(d/B)} \quad (9)$$

where D is the load-bearing capacity degradation coefficient of the timber beam d/B is the ratio of crack depth to timber beam width, where d denotes crack depth and B represents timber beam cross-sectional width. The crack hazard effect coefficient (A) is designed to comprehensively assess the “weakening efficiency” of a crack, characterizing its equivalent level of danger.

Physically, A quantifies the degree of load-bearing capacity degradation induced by per unit relative crack depth, which effectively distinguishes the differential hazards of cracks with different sizes. Thus, A can serve as an effective engineering tool for identifying and quantifying “high-risk cracks”. In the “Results and discussion” section (specifically in the analysis of specimens with different crack depths), the influence patterns and mechanisms of cracks on the load-bearing capacity of timber beams are analyzed using the load-bearing capacity coefficient curves and the crack hazard effect coefficient curves.

Data Analysis

For the input, organization, calculation, and analysis of key experimental data, including beam dimensions (L, B, H), mass (m), density (ρ), density influence coefficient (C_ρ), cross-sectional dimension influence coefficient (C_w), fracture load (P, P'), and fracture bending moment (M, M', M_e') (encompassing maximum, minimum, average values, and the CV value), a custom-built mini-program developed by the research group was employed in conjunction with Excel. Experimental specimens were grouped by crack depth, grain orientation, and loading configuration, with replicate specimens in each group to ensure statistical reliability. Statistics included ANOVA and Tukey HSD. This approach enhanced the automation level of data analysis, accelerated the processing speed, and reduced the manual workload involved in data analysis. The software Origin2024 and Visio2023 were utilized to generate the curves for the load-bearing capacity coefficient and the crack hazard effect coefficient, as well as to create relevant schematic diagrams for mechanistic analysis.

RESULTS AND DISCUSSION

Experimental Data and Analysis of Defect-free Specimens

Table 3 presents comparative fracture test data for defect-free specimens under three loading conditions. The data revealed significant variations in fracture loads under different load conditions: the three-point bending exhibited the lowest fracture load, while the four-point bending with large loading point distance demonstrated the highest fracture load (approximately twice that of the former).

When converted to equivalent bending moment values, the maximum deviation between experimental measurements across conditions was reduced to merely 10%. These comparative results demonstrate that fracture moment values objectively reflect the load-bearing capacity of timber beams with reduced sensitivity to loading conditions, facilitating the comparison across different loading scenarios. Consequently, equivalent fracture moment values will be adopted for subsequent analysis and discussion.

Table 3. Comparison of Data from Fracture Experiments of Defect-Free Specimens under Three Loading Conditions

Loading method	Grain direction	Sample size	Average fracture load/(N)	Equivalent Fracture Moment (N·m)				Tukey HSD
				Average (N·m)	Max (N·m)	Min (N·m)	CV (%)	
Three-point bending ($a=0$)	T	80	726	26.4	35.5	16.9	14.7	C
	R	80	677	25.3	35.7	16.8	16.9	C
	TR	80	644	24.8	35.4	15.3	14.5	C
Four-point bending ($a=L/4$)	T	80	1061	29.3	42.5	16.1	18.8	A
	R	80	917	26.3	39.9	16.2	18.1	BC
	TR	80	878	25.2	33.7	17.3	14.6	C
Four-point bending ($a=L/2$)	T	80	1443	27.6	40.5	16.6	18.1	AB
	R	80	1276	25.4	36.2	16.1	16.6	C
	TR	80	1298	24.7	35.6	7.0	20.2	C

Note: A, B, and C represent different groups. Groups with the same letter show no significant difference ($p > 0.05$), while groups with different letters show a significant difference ($p < 0.05$). CV in the table stands for coefficient of variation. The same applies to subsequent data tables.

One-way ANOVA showed that the combination of loading method and grain direction had an extremely significant effect on equivalent fracture moments ($F(8,711)=9.338$, $p<0.001$). Tukey's post-hoc multiple comparisons revealed that the four-point bending ($a=L/4$)-T group exhibited the highest equivalent fracture moment (Group A), with a statistically significant advantage over all other groups. For defect-free specimens, the equivalent fracture moment was significantly affected by loading method: based on Tukey's HSD results, four-point bending ($a=L/4$)-T group (Group A) demonstrated the most favorable flexural performance in terms of equivalent fracture moment, followed by four-point bending ($a=L/2$)-T group (Group AB, 27.6 N·m), while three-point bending ($a=0$) group (Group C, 24.8-26.4 N·m) exhibited relatively lower flexural behavior. The influence of grain direction on timber beam performance was particularly evident under loading configurations with higher load-bearing potential (four-point bending with large loading point distance).

The box plots further intuitively demonstrate the distribution characteristics of each group of data: The box of the four-point bending ($a=L/4$)-T group is located at the highest position with no outliers; the four-point bending ($a=L/2$)-TR group has the lowest median value, accompanied by low outliers, and exhibits the largest data dispersion, which is consistent with the conclusions of the statistical analysis.

By comparing the coefficients of variation (CV) of the equivalent fracture moment of specimens under three loading conditions in the table, it can be seen that the CV of the equivalent fracture moment tended to increase as the loading point distance increased: as the loading condition changed from three-point bending ($a=0$, the minimum loading point spacing) to four-point bending ($a=L/2$, the maximum loading point spacing), the CV of T grain specimens rose from 14.7% to 18.1%, R grain specimens from 16.9% to 16.6%, and TR grain specimens from 14.5% to 20.2%, with all groups maintaining a higher CV level under four-point bending than three-point bending. This is because, with the increase in loading point distance, the length of the pure bending segment (the region of maximum normal stress) of the specimen increases, and according to Weibull's weakest link theory (Weibull 1951), a longer pure bending segment significantly increases the probability of

initial critical micro-defects (which dominate fracture initiation) occurring within the high-stress region, thereby inherently increasing the dispersion of fracture strength, while the maximum shear stress in the transverse bending segment also increases accordingly. The combined effect of the above changes increases the randomness of failure caused by internal micro-defects in the specimen, which is macroscopically manifested as an increase in the *CV* of the fracture moment of the specimen.

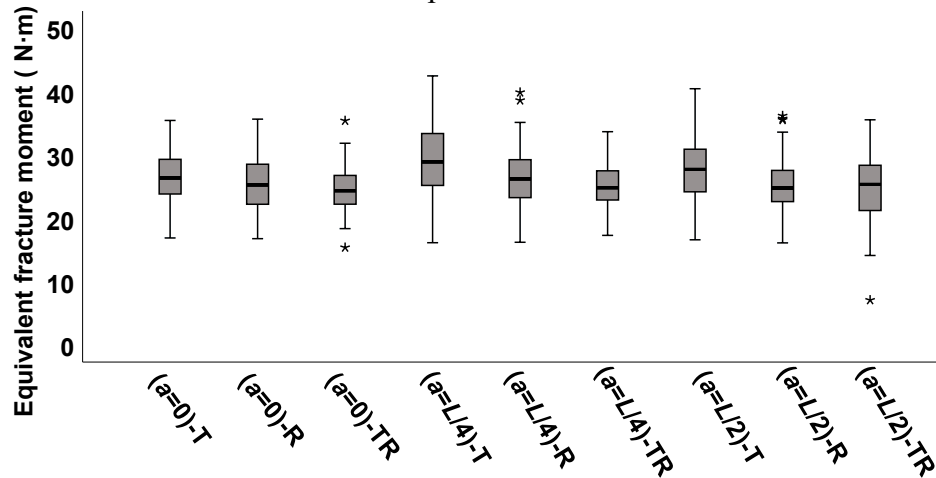


Fig. 2. Box plots of equivalent fracture moment of defect-free timber beams with three grain orientations

From the comparative data of different grain directions in the table, it can be observed that across all three loading conditions, the average equivalent fracture moment of T-specimens was consistently the highest among the three grain directions. It was 4.35%, 11.41%, and 8.66% higher than that of R-specimens, respectively. Compared with the TR-specimens, the average values were 6.45%, 16.27%, and 11.74% higher, respectively.

Figure 3 compares the annual ring distributions on the cross section between a T-specimen and two R-specimens. It can be seen from the figure that the range of variation in the early wood and latewood content of the T-specimen in high-stress regions was relatively limited, whereas the earlywood and latewood content of the R-specimens in high-stress regions may show more pronounced variation: R-specimen 1 in the figure contains much more earlywood than R-specimen 2 in high-stress regions. In wood annual rings, the strength of latewood can reach 2 to 4 times that of earlywood. Accordingly, this difference in wood tissue composition may lead to notable differences in the load-bearing capacity between R-specimen 1 and R-specimen 2. Since specimens with a higher proportion of earlywood in the high-stress zone tend to exhibit reduced overall load-bearing capacity, the average load-bearing capacity of R-specimens was consistently lower than that of T-specimens in this test. In addition, as the stress gradient of timber beams is distributed along the height direction, R-specimens are more likely to experience interlaminar shear failure between earlywood and latewood layers, whereas this phenomenon is less likely to occur in T-specimens.

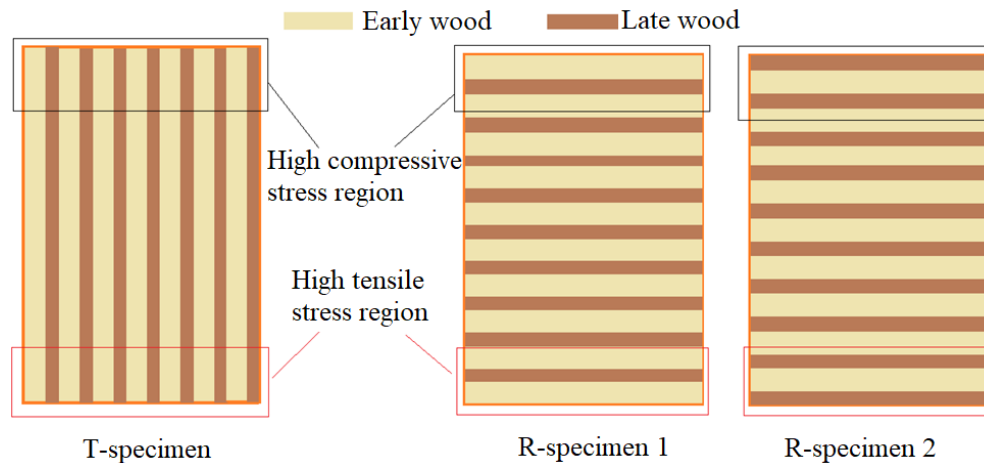


Fig. 3. Comparison of annual ring distribution in T-specimen and R-specimens

Among the specimens with three grain directions, TR-specimens exhibited the lowest average load-bearing capacity among the three groups in this test, and it was observed that TR-specimens were more likely to experience sudden brittle fracture, with the fracture surface predominantly observed near the loading points or support points. The stress along the beam height direction at each loading point is primarily dominated by compressive stress and the shear stress reaches its maximum in the plane oriented at 45° to the beam height direction. This plane may align closely with the interface between earlywood and latewood in the annual rings of the TR-specimens. On this basis, in TR-specimens, the stress field near the loading and support points is more likely to trigger shear failure. This matches the failure phenomena observed in the experiments.

Figure 4 shows photographs of the failure morphology of longitudinally cracked specimens with three different grain directions. It can be seen that, regardless of whether the specimens were T, R or TR, cracks generally propagated along the direction of the annual ring interfaces during fracture (the shear strength parallel to the annual ring interfaces is lower than that in other directions).

However, the critical loads for shear crack propagation varied among specimens with different grain directions: R-specimens exhibited the lowest critical load, while TR-specimens exhibit the highest critical load.

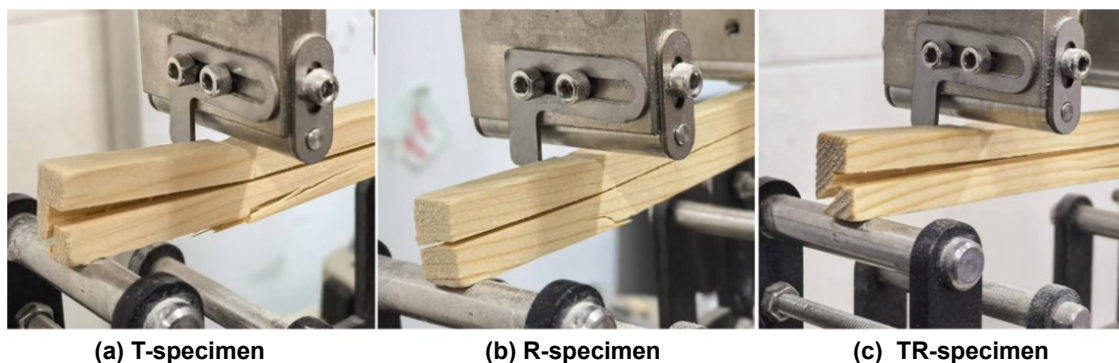


Fig. 4. Failure morphology photos of specimens with longitudinal cracks in three different grain directions

Comparative Study of Cracked Specimens with $d/B=0.5$

Table 4 presents a comparison of the fracture test data of cracked timber beams under three loading conditions. First, the statistical trends observed from this test are summarized as follows: It can be seen from the data in the table that load-bearing capacity coefficient of specimens with a large loading-point distance was consistently significantly lower than that of specimens under the other two loading conditions: as the loading-point distance increased, the value of C showed a significant downward trend. The C value of T-specimens was higher than that of R-specimens across all three loading conditions. One-way analysis of variance (ANOVA) showed that the interaction between loading method and grain direction had an extremely significant effect on the equivalent fracture moment ($F(8,711)=20.953$, $p<0.001$). The results of Tukey's post-hoc test indicated that the effect of the interaction between loading method and grain orientation exhibited an obvious gradient characteristic in this test: the four-point bending ($a=L/4$)-T group had the highest equivalent fracture moment (Group A); with the changes of loading method and grain direction, the equivalent fracture moment of the three-point bending ($a=0$)-T, four-point bending ($a=L/4$)-R, four-point bending ($a=L/2$)-T, three-point bending ($a=0$)-R, three-point bending ($a=0$)-TR, four-point bending ($a=L/4$)-TR, and four-point bending ($a=L/2$)-TR groups decreased in turn; the four-point bending ($a=L/2$)-R group had the lowest equivalent fracture moment (Group D).

Based on the above statistical trends, the following inferences and broader engineering implications can be drawn:

1. The consistent decrease of coefficient C with increasing loading point distance shows that larger loading point spacing both weakened the fracture performance of cracked timber beams in this test and enlarged the mechanical response difference caused by grain direction variation.

2. T-specimens had consistently higher C values than R-specimens under all loading conditions, verifying grain direction as a key factor for the load-bearing performance of cracked timber beams. The extremely significant interaction between loading method and grain direction ($p<0.001$) confirms that the effect of grain direction on fracture performance was strongly dependent on loading configuration.

3. Specimens showed the minimum load-bearing capacity under the most unfavorable combination (four-point loading, $a=L/2$ -R grain direction), with the largest performance difference from the optimal combination (four-point loading, $a=L/4$ -T grain direction). This interaction highlights the necessity of considering both loading configuration and material anisotropy in practical timber structure design and safety evaluation.

The error bars represent the 95% confidence interval. Within the scope of this test, a crack depth with $d/B=0.5$ exhibited a significant weakening effect on the load-bearing capacity of the tested timber beams, and this effect was found to be more pronounced under the condition of a large loading point distance, while it was relatively milder under three-point bending, which also corresponded to a lower degree of data dispersion for this loading condition.

The Load-bearing capacity of T-specimens was consistently significantly higher than that of TR-specimens across all tested loading conditions, which aligns with the well-documented anisotropic characteristics of wood. The magnitude of load-bearing capacity reduction caused by different loading point distance conditions showed notable differences among the three grain directions in this test.

It was observed that in the T grain direction and TR grain direction, the equivalent fracture moment of four-point bending with $a=L/4$ was higher than that of the $a=L/2$ condition, and the performance in the T grain direction was found to approach or even slightly exceed that of three-point bending; by contrast, no obvious advantage of this loading configuration was observed in the R grain direction, and the weakening effect of cracks on load-bearing capacity was significantly lower than that under three-point bending, which may be attributed to the difference in stress distribution under different loading methods.

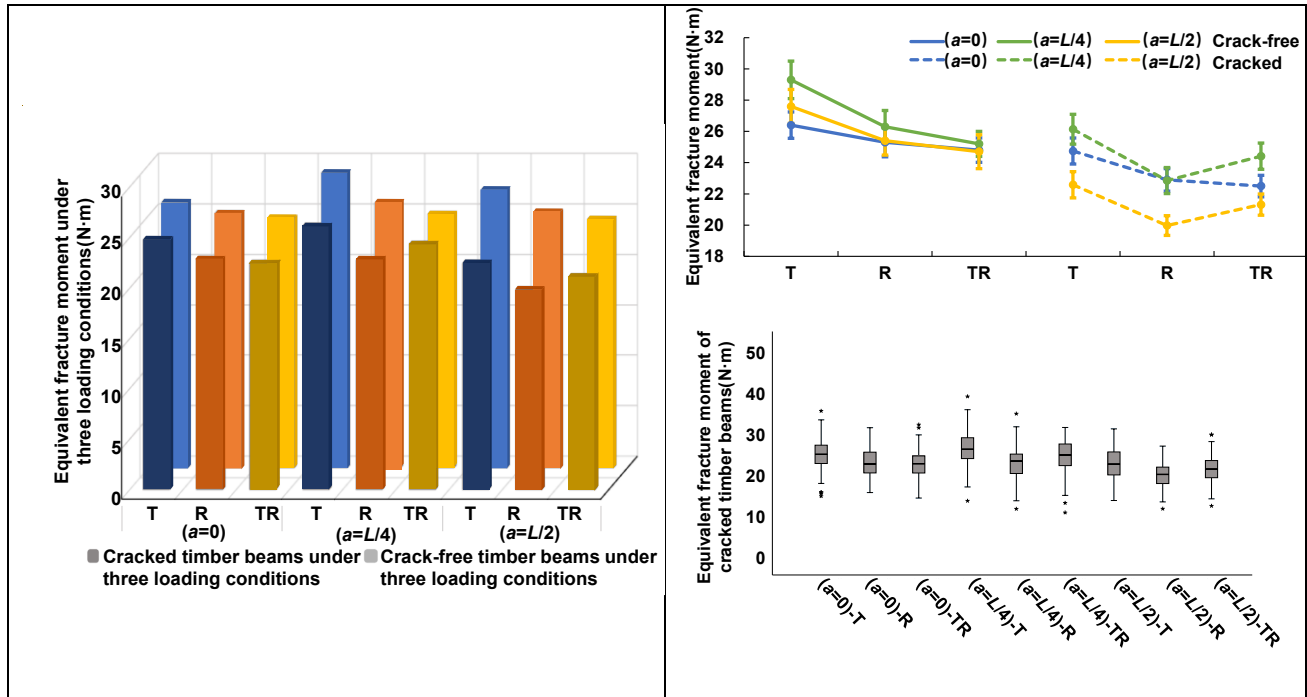


Fig. 5. Diagram of the equivalent fracture moment of timber beams with and without cracks under three loading conditions

Table 4. Comparison of Data from Fracture Experiments of $d/B=0.5$ Cracked Specimens under Three Loading Conditions

Loading	Grain direction	Sample size	Equivalent Fracture Moment		C	D	TukeyHSD
			Average, max, min/(N·m)	CV/%			
Three-point bending ($a=0$)	T	80	24.8, 34.7, 15.2	15.5	93.9	6.1	A
	R	80	22.9, 30.8, 16.01	14.5	90.5	9.5	BC
	TR	80	22.5, 31.5, 14.8	14.1	90.7	9.3	C
Four-point bending ($a=L/4$)	T	80	26.2, 37.9, 14.1	16.8	89.4	10.6	A
	R	80	22.8, 34.0, 12.3	16.8	86.7	13.3	BC
	TR	80	24.4, 30.1, 11.5	15.8	96.8	3.2	AB
Four-point bending ($a=L/2$)	T	80	22.5, 30.6, 14.2	16.7	81.5	18.5	C
	R	80	19.9, 26.6, 12.3	14.2	78.3	21.7	D
	TR	80	21.2, 29.2, 13.0	14.1	85.8	14.2	CD

Table 5. Comparison of Experimental Data on Specimens with Different Crack Depth

Loading	Crack depth ratio d/B	Sample size	Equivalent Fracture Moment		C	D	Δ	Tukey HSD
			Average, max, min/(N·m)	CV/ %				
Three-point bending ($a=0$)	0.1	40	26.3, 32.5, 19.7	12.8	99.6	0.4	4.0	BC
	0.3	40	25.8, 35.1, 15.0	15.0	97.7	2.3	7.7	BCD
	0.5	80	24.8, 34.7, 15.2	15.5	93.9	6.1	12.2	CDE
	0.7	40	23.3, 30.2, 15.4	12.0	88.3	11.7	16.7	DE
	0.9	40	15.7, 23.1, 10.9	16.5	59.4	40.6	45.1	H
Four-point bending ($a=L/4$)	0.1	40	29.1, 38.6, 14.1	18.8	99.3	0.7	7.0	A
	0.3	40	27.7, 37.5, 14.2	17.7	94.5	5.5	18.3	AB
	0.5	80	26.2, 37.9, 14.1	16.8	89.4	10.6	21.2	BC
	0.7	40	22.1, 26.9, 15.4	11.8	75.4	24.6	35.1	EF
	0.9	40	16.4, 26.8, 7.3	24.9	56.0	24.0	26.7	H
Four-point bending ($a=L/2$)	0.1	40	27.3, 36.5, 19.1	14.7	98.9	1.1	11.0	ABC
	0.3	40	24.9, 33.9, 18.4	13.3	90.2	9.8	32.7	CDE
	0.5	80	22.5, 30.6, 14.2	16.7	81.5	18.5	37.0	EF
	0.7	40	19.9, 26.8, 15.1	14.2	72.1	27.9	39.9	FG
	0.9	40	17.2, 22.2, 10.8	17.4	62.3	37.7	41.9	GH

In summary, the test results showed that the presence of cracks not only markedly reduced the load-bearing capacity of the tested specimens, but it also amplified the combined effect of loading method and grain direction on fracture performance.

Within the range of parameters tested in this study, the four-point bending $a=L/4$ -T group exhibited the best overall performance under both defect-free and $d/B=0.5$ crack conditions, as it maintained both high load-bearing capacity in the defect-free state and strong anti-degradation performance in the cracked state, which may be considered as a preferred configuration for practical timber structures under normal and crack-damaged conditions similar to the test scenarios. In contrast, the four-point bending $a=L/2$ -R group exhibited poor overall performance under both conditions and showed high sensitivity to crack damage, thus this configuration should be used with sufficient caution in practical engineering design.

Specimens with Cracks at Different Depths

Table 5 shows a comparison of fracture experimental data for cracked specimens under three loading conditions. Considering that timber beams in buildings mainly adopt the T-direction grain, this study also focuses on specimens with this grain direction. It can be seen from the data in the table that under the three loading conditions, the average equivalent fracture moment showed a gradual decreasing trend as the crack depth ratio (d/B) increased from 0.1 to 0.9. This indicates that the increase in crack depth significantly reduced the load-bearing capacity of specimens. When the crack depth ratio increased from 0.1 to 0.5, the reduction range of the fracture bending moment was relatively gentle; whereas when it increased from 0.7 to 0.9, the reduction range increased significantly. In particular, under three-point bending and four-point bending $a=L/4$ conditions, the bending moment value at a depth ratio of 0.9 decreased by more than 25% compared with that at 0.7. When $d/B > 0.7$, the decline rate of C accelerated, indicating that the structural safety reserve decreased sharply when the crack depth exceeded 70% of the specimen width. This critical depth effect can be explained by two core mechanisms: stress-wise, cracks with

$d/B > 0.7$ extend from the neutral shear zone to the tensile section edge, causing a sharp drop in effective section modulus and intensified crack tip stress (Toivanen *et al.* 2025); microstructurally, high stress at deep crack tips penetrates weak earlywood-latewood interfaces, inducing unstable crack propagation (Villegas *et al.* 2025). This demonstrates that crack depth is a key factor affecting the fracture performance of timber beams. Especially under deep crack conditions, the load-bearing capacity of specimens decreases significantly and the discreteness increases.

One-way ANOVA showed that crack depth had an extremely significant effect on the C value ($F(14,705)=52.133$, $p < 0.001$). Tukey's post-hoc test revealed that the load-bearing capacity of three-point bending ($a=0$) with $d/B=0.9$ (Group H) was significantly lower than that of the other groups. Differences among the other three-point bending groups were not fully significant. For four-point bending ($a=L/4$), the group with $d/B=0.1$ (Group A) exhibited the highest load-bearing capacity, which was significantly different from the groups with $d/B=0.7$ (Group EF) and $d/B=0.9$ (Group H). Load-bearing capacity decreased significantly in the high crack depth ratio groups. For four-point bending ($a=L/2$), the group with $d/B=0.1$ (Group ABC) had the highest load-bearing capacity, which was significantly different from the groups with $d/B=0.7$ (Group FG) and $d/B=0.9$ (Group GH). The load-bearing capacity decreased significantly when $d/B > 0.5$.

With an increase in crack depth ratio (d/B), the equivalent fracture moment showed an overall significant downward trend. In three-point bending, load-bearing capacity of the $d/B=0.9$ group was significantly lower than that of the other groups. In four-point bending ($a=L/4$ and $a=L/2$), significant differences in load-bearing capacity were observed between the high crack depth ratio groups ($d/B > 0.5$) and the low crack depth ratio groups, indicating that the influence of crack depth on load-bearing capacity is more pronounced under high crack depth ratios.

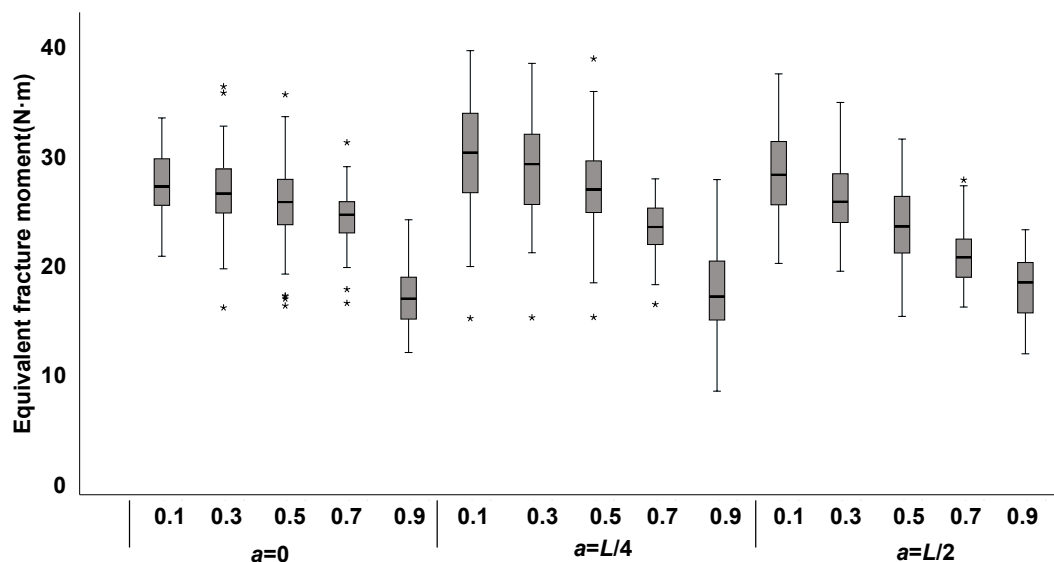


Fig. 6. Box plots of equivalent fracture moment for timber beams with different crack depths under three loading conditions

Figure 6 shows box plots of the equivalent fracture moment of specimens with different crack depths under three loading conditions. As can be seen from the figure, high outliers appear in several groups, especially the shallow crack groups under $a=0$ and $a=L/4$

loading condition, reflecting the performance fluctuation of the material under low damage conditions. In contrast, low outliers are more prominent under the combination of deep cracks ($d/B=0.7, 0.9$) and four-point bending ($a=L/2$), indicating a higher risk of failure. Crack depth and loading condition have a significant interactive effect on load-bearing performance: four-point bending ($a=L/4$) exhibits the optimal crack resistance at all crack depths, while four-point bending ($a=L/2$) is the most sensitive to crack propagation and shows the most severe performance degradation.

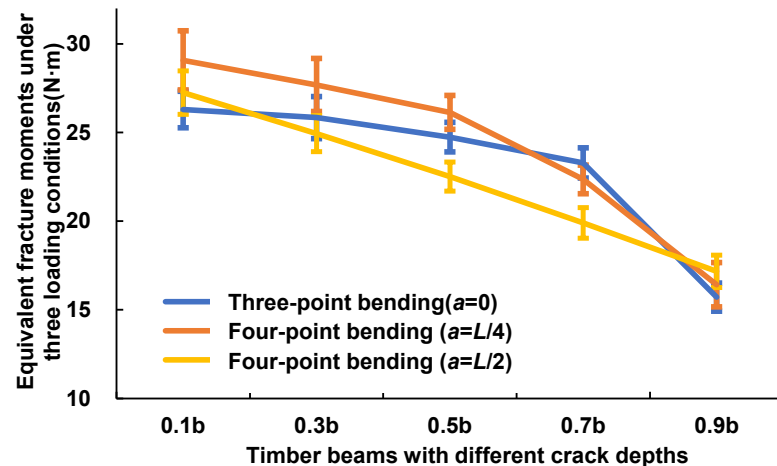


Fig. 7. Equivalent fracture moment diagrams for different crack depths under three loading conditions

Figure 7 shows the equivalent fracture moment diagrams for different crack depths under three loading conditions. Error bars represent 95% confidence intervals. The crack hazard effect coefficient D increases significantly with the increase of d/B , indicating that the deeper the crack depth, the more severe the damage effect. The growth rate of D accelerates obviously when $d/B > 0.5$, suggesting that the damage enters an accelerated stage when the crack extends to more than half of the specimen width.

Figure 8 presents the load-bearing capacity coefficient (C) and crack hazard effect coefficient (A) curves for specimens with varying crack depth ratios (d/B) under three loading conditions.

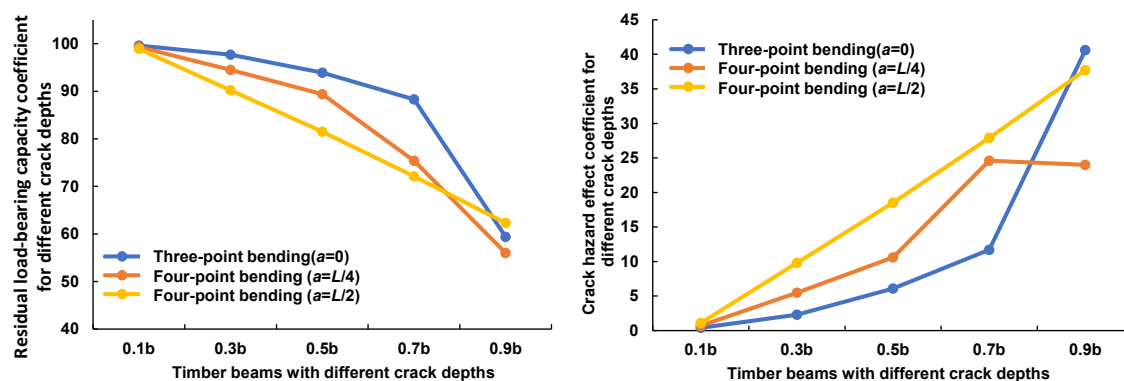


Fig. 8. Curves of load-bearing capacity coefficient and crack hazard effect coefficient for different crack depths under three loading conditions

These curves systematically illustrate the influence patterns of crack depth on the load-bearing performance of timber beams. The load-bearing capacity coefficient C decreases with increasing d/B , while the crack hazard effect coefficient A reveals the nonlinear amplification of crack damage. Through these curves, the underlying mechanisms governing crack-induced degradation in timber beams can be quantitatively analyzed.

Crack depth ratio d/B is a key factor affecting load-bearing capacity and damage degree of specimens. When d/B exceeds 0.7, structural safety risk increases significantly. Loading conditions significantly influence the hazard effect of cracks. Under the loading condition of three-point bending, load-bearing capacity of timber beams decreases the fastest, while the crack hazard effect coefficient increases most severely under four-point bending ($a=L/2$) condition. Therefore, targeted evaluation of crack risks under different stress scenarios is required in engineering design. These curves can provide experimental evidence for determining the safety threshold of timber structures.

Validity and Limitations of the Study

This study is based on small-sized specimens with artificial prefabricated cracks, while through large sample size experiments to enhance statistical accuracy, it only improves the precision of the experiment and cannot fully substitute for tests on full-size timber beams. Due to the size effect, the reduction in load-bearing capacity derived from small-scale specimens may not equivalent to that of full-size timber beams.

In this study, cracks were artificially prefabricated in the specimens, resulting in highly consistent crack geometries (e.g., 80 specimens with identical crack length and depth), which ensures high reproducibility of the experiment. However, it should be noted that cracks in actual timber beams exhibit complex morphologies, with varying lengths and depths in each beam. Therefore, this study can only provide an overall pattern of the decrease in load-bearing capacity of timber beams with increasing crack depth, but the experimental results cannot accurately represent the true rate of decrease in load-bearing capacity of full-size timber beams.

CONCLUSIONS

1. Within the range of loading configurations tested in this study, increasing the loading point distance was found to increase the CV of specimens' equivalent fracture moment and increase failure randomness. Larger loading-point distances also significantly aggravated crack-induced bearing capacity degradation.
2. Grain direction was verified as a key factor affecting load-bearing performance of timber beams under the tested conditions. Across all three loading conditions, the equivalent fracture moment was consistently the highest for T-specimens, followed by R-specimens, and the lowest for TR-specimens. The superior load-bearing performance of T-specimens relative to R-specimens may be primarily attributed to their more uniform annual ring distribution in the high-stress zone and lower susceptibility to interlayer shear failure between earlywood and latewood. The TR-specimens exhibited the lowest load-bearing capacity and the highest tendency for sudden brittle shear failure in this test, which is likely associated with the coincidence between the 45° shear

stress plane and the annual ring interface.

3. The weakening effect of longitudinal cracks on timber beams was found to intensify with the increase of loading point distance in this study. Loading configuration and grain direction were found to interact significantly ($p < 0.001$). Four-point bending ($a=L/2$)-R group was the most unfavorable. The four-point bending ($a=L/4$)-T group was the optimal combination. For T-grain timber beams most commonly used in ancient architectures, their load-bearing capacity exhibited a continuous downward trend with the increase of the crack depth ratio, and exhibited a critical depth effect observed in this test: when $d/B \leq 0.5$, load-bearing capacity decreased gently. However, when $d/B > 0.7$, the descending rate of load-bearing capacity accelerated sharply, the structural safety reserve was greatly reduced, and the crack hazard effect coefficient increased significantly. For the maintenance and safety assessment of in-service timber beams, it is recommended to establish a “critical crack depth” evaluation framework, which can provide targeted guidance for structural safety inspection and maintenance decision-making.
4. The findings provide targeted guidance for timber structure engineering: prioritizing T-grain components in flexural member design, focusing inspection on R-grain members under large loading point distances, and adopting the critical crack depth framework for daily maintenance of in-service and ancient timber structures.

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