



Challenge Journal of STRUCTURAL MECHANICS

Research Article

Experimental investigation of material and joint influence on timber I-beam performance

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ABSTRACT

This study experimentally investigates the influence of web material and joint configuration on the flexural performance of timber I-beam configurations. A total of 27 specimens representing nine beam types were tested, including oriented strand board (OSB), laminated timber, and plywood-web beams produced as continuous, web-joined, and flange-joined members. Three-point bending tests were conducted over a clear support span of 1000 mm, and the load–displacement response, maximum load capacity, stiffness, energy absorption, strength-to-weight ratio, and failure modes were evaluated. The results showed that continuous specimens generally achieved higher load-bearing capacities than their joined counterparts, indicating the importance of uninterrupted load transfer. Among the tested configurations, the continuous plywood-web beam exhibited the highest mean maximum load of 28.569 kN and the highest strength-to-weight ratio of 6.93 kN/kg. OSB-web beams showed lower absolute load capacity but a competitive strength-to-weight ratio of 5.45 kN/kg, suggesting potential for lightweight applications. Web-joined specimens generally performed better than flange-joined specimens because flange continuity provided more effective resistance to bending-induced tensile and compressive stresses. Failure observations indicated that joint location influenced damage initiation, web-flange separation, adhesive debonding, and post-peak behavior. Since the specimens represented practical beam configurations incorporating locally available, unused, or previously used wood-based components, the findings should be interpreted at the configuration level rather than as isolated material-property comparisons. Overall, the study provides practical insight into material selection and joint detailing for sustainable timber I-beam applications.

Citation: Gürbüz M (2026). Experimental investigation of material and joint influence on timber I-beam performance. *Challenge Journal of Structural Mechanics*, 12(3), 178–193.

ARTICLE INFO

Article history:

Received – April 7, 2026
Revision requested – April 27, 2026
Revision received – May 4, 2026
Accepted – May 16, 2026

Keywords:

Timber I-beams
Oriented strand board
Laminated timber
Plywood
Joint configuration
Sustainable construction



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1. Introduction

Timber structures, particularly timber I-beams, have gained significant attention in the construction industry due to their sustainability and favorable mechanical properties, while efficient use of alternative and waste-derived resources has similarly become an important strategy in sustainable construction-material development (Mohamad et al. 2025; Wee Chit et al. 2025). As the demand for efficient and sustainable building materials

grows, researchers have been exploring various ways to enhance the performance of timber beams. This study aims to contribute to this field by investigating the flexural behavior of different types of timber I-beams, including those made with oriented strand board (OSB), laminated timber, and plywood, with and without joints in the web and flange regions.

Recent research in timber beam performance has made significant strides in various aspects of design, reinforcement, and application. Several studies have fo-

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cused on reinforcing timber beams using various materials and methods. Studies (Ling et al. 2020; Shekarchi et al. 2020; Chen et al. 2021; Yeboah and Gkantou 2021; Zhang et al. 2022; Wdowiak-Postulak 2023) investigated the use of fiber-reinforced polymers (FRP), steel bars, basalt, glass, and even bamboo for strengthening timber beams. These studies generally found that reinforcement significantly improved the load-bearing capacity, stiffness, and flexural performance of timber beams. More broadly, the beneficial effect of waste-derived composite laminates on beam flexural performance has also been experimentally demonstrated (Çelik et al. 2024). The study by Yeboah and Gkantou (2021) showed that near-surface mounted (NSM) basalt and glass FRP bars enhanced the moment resistance of timber beams under bending.

Research has also explored the potential of composite and hybrid beam designs. Previous studies (Ghanbari-Ghazijahani et al. 2020; Müller et al. 2021; Jurkiewicz et al. 2022; Chen et al. 2022a; Zhao et al. 2023; Zhang et al. 2023; Wen and Xiao 2023) examined various combinations of timber with other materials such as concrete, steel, and bamboo. These studies demonstrated that composite designs often result in improved mechanical properties compared to traditional timber beams. Jurkiewicz et al. (2022) concluded that hybrid steel-timber beams offered advantages in terms of stiffness, strength, and ductility compared to conventional all-wood or all-steel beams.

Several studies focused on developing and analyzing new connection methods for timber structures. Numerous studies (Sotayo et al. 2020; Müller et al. 2021; Karimi-Nobandegani and Valipour 2022; Zhao et al. 2023) investigated various connection techniques, including micro-notches for timber-concrete composites and self-tapping screws for cross-laminated timber panels. These studies aimed to simplify assembly processes and improve the overall performance of composite structures.

A significant portion of the research was dedicated to understanding and modeling the structural behavior of timber beams. Several studies employed analytical and numerical methods to predict the performance of timber beams under different loading conditions (Karimi-Nobandegani and Valipour 2021; Dönmez et al. 2022; Hammad et al. 2022; Goodwin et al. 2022; Patalas et al. 2022; Patalas et al. 2023). For example, Dönmez et al. (2022) investigated the performance of timber formwork beams under static, fatigue, and sudden dynamic impact loads, providing valuable insights into their behavior in construction applications. The study found that the stiffness of timber formwork beams decreases with an increase in load repetition number, and their energy dissipation capacity decreases with an increase in the number of impact loads.

Several studies compared the performance of different engineered wood products. Researchers (Li et al. 2022; Sciomenta et al. 2022; Wen and Xiao 2023) examined the mechanical properties of various timber products such as glued laminated timber, cross-laminated timber, and laminated bamboo-timber composites. These comparisons help in selecting the most appropriate materials for specific structural applications.

Application-oriented studies have investigated several specific topics in timber construction, including

curved laminated bamboo-timber composites, timber beams with openings, cross-laminated timber walls, and timber formwork beams under different loading conditions (Karimi-Nobandegani and Valipour 2021; Dönmez et al. 2022; Li et al. 2022; Chen et al. 2022b). These studies provide useful insights into the broader application of timber-based structural systems. Recent studies have also continued to investigate the flexural behavior and structural performance of I-shaped timber and wood-based members, including I-joists with alternative web configurations, OSB-based I-beams, and I-shaped laminated bamboo composite beams (Li et al. 2024; Jiloul et al. 2024; Denisiewicz et al. 2025).

Although previous studies have provided important insights into reinforced, hybrid, and composite timber beam systems, limited comparative experimental evidence is available on the flexural performance of timber I-beams produced with different web materials and joint configurations. In particular, the influence of joint location in critical regions, such as the web and flanges, remains insufficiently clarified, although such joints may be unavoidable in practical large-span applications due to manufacturing and transportation constraints. Therefore, this study addresses this gap by experimentally investigating OSB, laminated timber, and plywood I-beams produced as continuous, web-joined, and flange-joined members under identical testing conditions.

This study focuses on a unique set of timber I-beams, designed to address practical considerations and explore the potential of various materials, including those typically considered as waste or byproducts. The beam configurations used in this study are illustrated in Fig. 1, showcasing different types of I-beams made from OSB, laminated timber, and plywood, with variations in joint placement. The joint placement and the fabrication process of the beams are explained in the following sections.

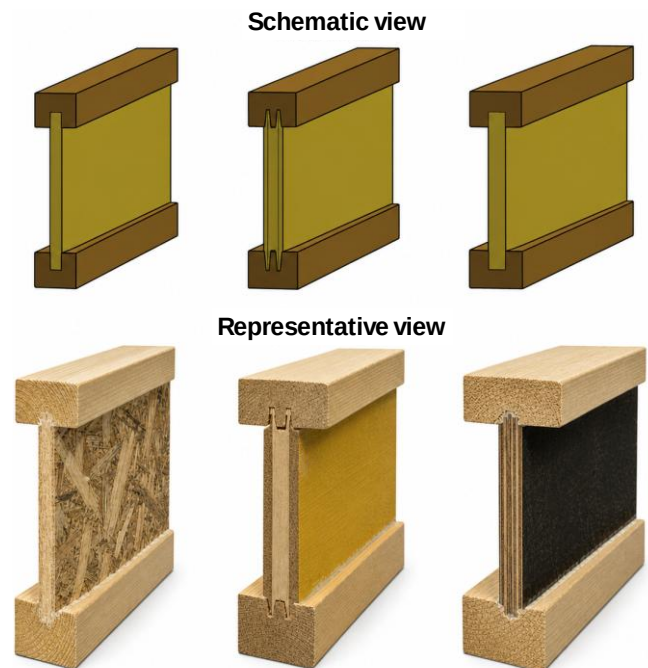


Fig. 1. Schematic and representative views: (a) Oriented strand board; (b) Laminated beams; (c) Plywood beams.

The contribution of this study lies in its comparative evaluation of material type and joint location in timber I-beams under identical experimental conditions. By testing continuous, web-joined, and flange-joined specimens made with OSB, laminated timber, and plywood webs, the study provides practical insight into how joint placement affects load-bearing capacity, stiffness, energy absorption, and failure behavior. In addition, the use of locally available materials, including unused timber pieces and previously used plywood, highlights the potential of resource-efficient and sustainable material utilization in engineered timber beam production, consistent with broader construction-material research linking waste reuse with resource conservation and circular-economy goals (Çelik et al. 2024; Mahmud et al. 2025; Tanash et al. 2025; Ünal and Canbaz 2025, 2026). Therefore, the findings are expected to support more informed material selection and joint-detailing decisions in practical timber I-beam applications.

2. Materials and Methods

2.1. Specimen preparation

In this study, a total of 27 timber I-beam specimens were tested. Unlike laboratory-produced samples, these specimens were sourced randomly from local manufacturers in the market to reflect real-world conditions and assess the performance of commercially available timber I-beams. These specimens represented 9 different beam types, with 3 replicates for each type. The beams were 1.2 m in length and were categorized based on their material composition and joint configuration.

The I-beam specimens were fabricated using a combination of web and flange materials. The web material varied according to the specimen group and consisted of OSB, laminated timber, or plywood. In all configurations, the web acted as the central vertical component of the I-section, while the upper and lower flanges provided the main resistance to bending stresses. All specimens featured solid timber flanges made from Ardanuç spruce (*Picea orientalis*), a species native to the Black Sea region of Türkiye. This material was selected because of its structural suitability, local availability, and practical use in timber products.

The OSB and plywood specimens had a similar general I-beam layout, consisting of a flat web panel bonded to solid timber flanges at the top and bottom. In these specimens, the web-flange connection was formed through continuous adhesive-bonded contact surfaces along the beam length. In contrast, the laminated timber specimens had a different web configuration, in which unused or waste Ardanuç spruce pieces were arranged in an interlocking pattern within the web region. This configuration was intended to improve material utilization while maintaining the overall I-beam geometry. Thus, although all specimens shared the same basic I-section concept, they differed in terms of web material, web configuration, and joint location. The specimens were coded as shown in Table 1, where the first letter indicates the beam material (O: OSB, L: Laminated, P: Plywood), and the following letters indicate the joint

type (WJ: Web Joined, FJ: Flange Joined) or continuous beams without joints.

Table 1. Specimen coding.

Type	OSB	Laminated	Plywood
Web Joined	OWJ	LWJ	PWJ
Flange Joined	OFJ	LFJ	PFJ
Continuous	O	L	P

Note: OSB = oriented strand board; WJ = web-joined; FJ = flange-joined; O = OSB-web beam; L = laminated-web beam; P = plywood-web beam.

OSB beam consists of an oriented strand board web with solid timber flanges at the top and bottom. The OSB web provides good shear resistance, while the solid timber flanges offer strength in tension and compression. The OSB web was connected to the upper and lower solid timber flanges through continuous flat adhesive-bonded interfaces along the beam length. Polyurethane adhesive was applied to the full web-flange contact surfaces, and no toothed or interlocking profile was used at this interface.

The laminated-web beam differs from the OSB- and plywood-web beams in terms of its web configuration. Its web consists of laminated timber elements, while the flanges are solid Ardanuç spruce members, as described above. The toothed connection structure of the laminated beam is a significant feature that distinguishes this type from the others. This design may provide a stronger connection and more effective load transfer between the web and flanges. The laminated beam web design shows an innovative approach to timber engineering. It features a continuous outer siding for structural integrity, while the interior utilizes unused or waste Ardanuç spruce in an interlocking pattern as seen in Fig. 2. This design maximizes material efficiency by incorporating otherwise discarded wood, enhancing sustainability. The interlocking structure likely improves the beam's shear strength and stability. This approach balances structural performance with eco-friendly practices, demonstrating a creative solution for efficient resource use in timber construction.

Similar in overall shape to the OSB beam, this design uses a plywood web with solid timber flanges. Plywood, made from thin layers of wood veneer, offers good strength and dimensional stability. The plywood web was connected to the solid timber flanges through continuous flat adhesive-bonded web-flange interfaces, similar to the OSB-web specimens.

All three beam types share the I-beam geometry, which is efficient in resisting bending and shear forces. The different web materials (OSB, laminated timber, and plywood) each bring unique properties to the beam's overall performance. The solid timber flanges in all designs provide the primary resistance to bending stresses. All specimens were tested over a support span of 1000 mm. The nominal cross-sectional dimensions of the specimens, including the overall beam depth, flange dimensions, and web thickness, are provided in Fig. 3.

These beams represent different approaches to engineered wood products, each balancing factors such as

material availability, manufacturing processes, and desired structural properties. The specific choice between

these types would depend on the intended application, load requirements, and economic considerations.

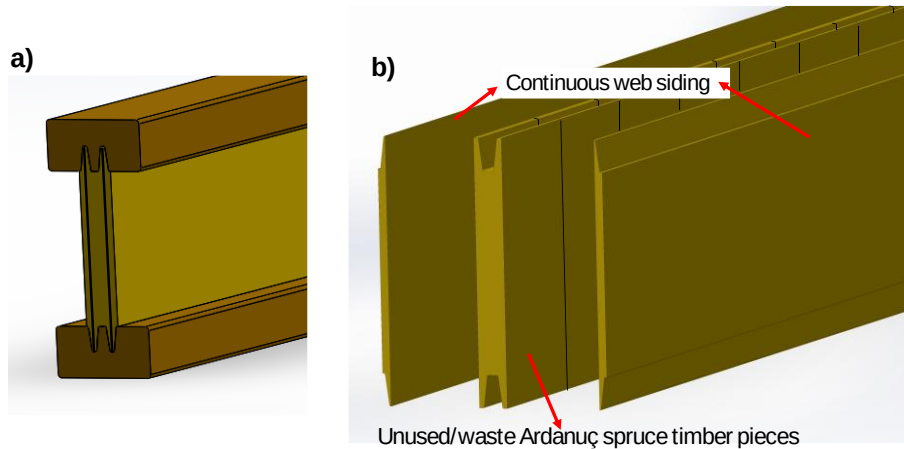


Fig. 2. (a) Perspective view of the laminated timber I-beam; (b) Detailed view of the laminated web configuration.

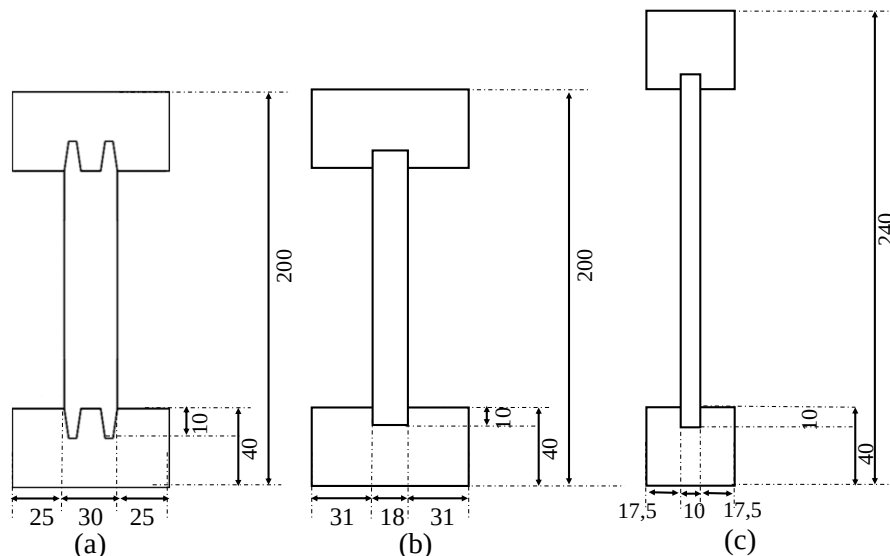


Fig. 3. Dimensions of the specimens (mm): (a) Laminated beam; (b) Plywood beam; (c) OSB beam.

2.1.1. Materials

OSB is an engineered wood product made of wood strands or flakes compressed and bonded with resin under high pressure and temperature. It is widely used in construction due to its strength, durability, and cost-effectiveness. While specific properties of the OSB used in this study were not measured, typical OSB panels have a density ranging from 600 to 680 kg/m³, and modulus of elasticity (MOE) between 3500 and 4800 N/mm². The exact properties can vary based on the manufacturing process and wood species used. The measured density and costs of the materials are provided in Table 2. In this study, the OSB used for the web had a density of 670.76 kg/m³ and cost \$444.61 \$/m³.

The laminated timber used in this study was made from Ardanuç spruce (*Picea orientalis*) as mentioned earlier. Laminated timber, also known as glued laminated timber or glulam, is an engineered wood product made by bonding together individual wood laminations

with durable, moisture-resistant adhesives. The laminated timber used for the web had a density of 431.20 kg/m³ and approximately cost 294.12 \$/m³.

The Ardanuç spruce used for the flanges and laminated beams exhibits notable physical and mechanical properties. The air-dry density of the wood is 0.448 g/cm³, indicating a moderate weight suitable for structural applications. The wood demonstrates varying shrinkage rates: 4.56% radially (β_g), 8.13% tangentially (β_k), 0.23% longitudinally (β_l), and a volumetric shrinkage (β_v) of 12.93% (Keskin et al. 2009). These shrinkage characteristics are important for understanding the dimensional stability of the material under changing moisture conditions.

In terms of mechanical properties, the Ardanuç spruce shows considerable strength. It has a bending strength (N/mm²) of 72.88, which is crucial for its performance in beam applications. The elasticity modulus (N/mm²) is 10070.09, indicating good stiffness and resistance to deformation under load. The compression

strength (N/mm^2) of 40.92 demonstrates the wood's ability to withstand compressive forces along the grain (Keskin et al. 2009). Additionally, the shear strength (N/mm^2) of 6.28 is important for its resistance to shearing forces (Keskin et al. 2009), particularly relevant in beam design where shear stresses can be significant. These properties make Ardanuç spruce a suitable choice for the flanges and laminated beams in this study, offering a balance of strength, stiffness, and dimensional stability. Although all flanges were produced from the same wood species, the flange materials used in the OSB-web beams and those used in the laminated- and plywood-

web beams were obtained from different commercial batches. Therefore, their measured density and cost values are reported separately in Table 2.

Plywood is a panel product made from thin layers of wood veneer, called plies, which are glued together with adjacent layers having their wood grain rotated up to 90 degrees from the adjacent layer. This cross-graining improves the panel's strength and dimensional stability. Although the specific properties of the plywood used in this study were not measured, the modulus of elasticity of plywood generally ranges from 6000 to 10000 N/mm^2 , depending on the specific type and grade of plywood.

Table 2. Material density and cost values.

Material Type	Density (kg/m^3)	Cost ($\$/\text{m}^3$)	Cost ($\$/\text{kg}$)
OSB web	670.76	444.61	0.66
Laminated timber web	431.20	294.12	0.68
Plywood web	663.48	915.03	1.38
Ardanuç spruce flange for laminated- and plywood-web beams	382.43	337.44	0.88
Ardanuç spruce flange for OSB-web beams	331.75	441.18	1.33

Note: OSB = oriented strand board.

It should be noted that the density values reported in Table 2 were directly measured for the materials used in this study, whereas some mechanical properties of OSB and plywood, such as typical modulus of elasticity ranges, were taken from literature or manufacturer-based reference ranges rather than being measured separately for each material batch. Therefore, these values are provided only to describe the general material characteristics and should not be interpreted as direct material test results. The experimental comparison in this study focuses on the flexural performance of the complete I-beam configurations under identical testing conditions, rather than on the isolated mechanical characterization of the individual web materials.

For all these materials, it's important to note that their performance in the I-beam configuration may differ from their individual properties due to the composite nature of the beams and the specific manufacturing processes used by the local producers. The experimental results from this study will provide valuable insights into how these materials perform in real-world, commercially produced I-beam configurations.

Polyurethane adhesive was used for bonding in the web-flange connections and at the joints. In addition to the adhesive, simple staples were used in both web and flange joints for added strength.

The cost analysis for 1 m I-beams showed that OSB beams cost \$3.62 (flange: \$2.82, web: \$0.80), laminated beams cost \$3.31 (flange: \$2.16, web: \$1.15), and plywood beams cost \$4.47 (flange: \$2.16, web: \$2.31).

It's important to note that the prices mentioned in this study are local market prices in Türkiye as of [09/2024] and may vary in different regions or countries. These costs are provided to give a general idea of the relative expenses associated with each material and beam type, but readers should be aware that prices can fluctuate based on local market conditions, availability, and economic factors.

2.1.2. Joint configuration

In this study, two distinct joint configurations were investigated: web-joined (WJ) and flange-joined (FJ) specimens. Continuous specimens without web or flange joints were also tested as reference specimens to evaluate the influence of joint location on flexural performance. The joint regions are shown in Fig. 4, where enlarged details are provided to emphasize the web and flange joint locations.

In the web-joined (WJ) configuration, the web panel was produced from two separate web segments, and the joint was located at the midspan of the beam. The upper and lower flanges remained continuous along the beam length. This configuration was selected to evaluate the influence of discontinuity in the web region while maintaining flange continuity, which is important for bending resistance.

In the flange-joined (FJ) configuration, the upper and lower flanges were each produced from two separate flange segments, and the joints were also located at the midspan of the beam. In this configuration, the web panel remained continuous, while the discontinuities were introduced in the flange members. Since the flanges carry the dominant tensile and compressive stresses under bending, this configuration was used to evaluate the effect of flange discontinuity on flexural performance and failure behavior.

For both jointed configurations, the mating surfaces were carefully aligned before bonding. Polyurethane adhesive was applied uniformly to the contact surfaces of the joint region and to the web-flange interfaces. Simple staples were additionally used in the jointed regions to assist mechanical fixing during assembly and to provide supplementary resistance against local separation. All joints were located at the beam midspan so that the effect of joint type could be evaluated under the same three-point bending configuration.

During specimen procurement, beams with visible manufacturing or material defects were not accepted from the manufacturer. Only visually sound specimens,

without apparent cracks, excessive warping, delamination, or major surface damage, were selected for testing.

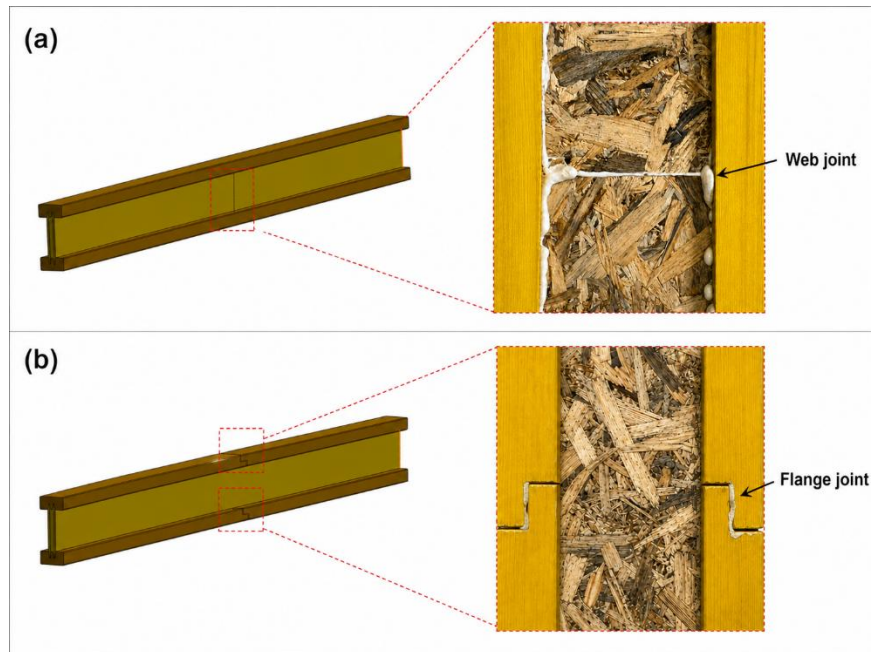


Fig. 4. Joint configurations of the tested timber I-beam specimens: (a) Web-jointed specimen with an enlarged detail of the web joint region; (b) Flange-jointed specimen with an enlarged detail of the flange joint region.

2.2. Experimental setup and procedure

The static bending tests were conducted using a three-point bending setup adapted from the general principles of ASTM D198 for structural-size wood and wood-based members. The experimental program was designed as a comparative flexural performance assessment rather than as a formal certification test for establishing standardized design values. Therefore, the same loading arrangement, boundary conditions, loading rate, and measurement procedure were used for all specimens to ensure a consistent comparison among the different material and joint configurations.

The tests were carried out using a BCO-FC fully automatic Sematron touch-controlled servo-hydraulic bending test machine (BESMAK, column-type frame). The machine is designed for three- and four-point bending tests and is equipped with a servo-hydraulic loading system,

adjustable bending supports, a hydraulic piston/loading head, and a computer-controlled Sematron Touch data acquisition system. The control unit supports load cell, LVDT, strain gauge, and pressure sensor inputs and has a data acquisition rate of up to 1 kHz. In the present study, the applied load was measured using the load cell of the testing machine, and the corresponding displacement was recorded from the crosshead displacement.

The specimens were placed on two roller supports and tested under simply supported boundary conditions. The clear span between the supports was 1000 mm, and the vertical load was applied at midspan through a single loading nose, as illustrated in Fig. 5. Prior to testing, each specimen was carefully measured, marked, and positioned symmetrically on the supports. The loading nose was aligned with the midspan to minimize eccentric loading and local stress concentrations.

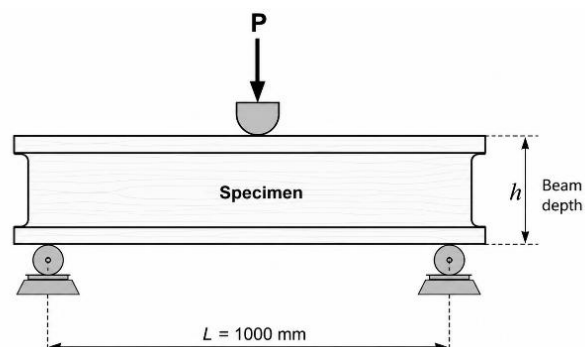


Fig. 5. Three-point bending test setup showing the midspan load, simply supported boundary conditions, clear support span ($L = 1000 \text{ mm}$), and beam depth (h).

The tests were performed under displacement control at a constant crosshead displacement rate of 1 mm/s, equivalent to 60 mm/min. Load and displacement data were continuously recorded throughout the test using the computer-based data acquisition system. The collected data were used to determine the load–displacement response, maximum load capacity, displacement at maximum load, maximum displacement, initial stiffness, post-peak behavior, failure mode, and energy absorption capacity of each specimen.

For each specimen, the cleaned load–displacement signal recorded by the testing machine was used without additional smoothing. The maximum load $P_{\max}$ was taken as the maximum value of the load array, and $\delta P_{\max}$ was defined as the displacement corresponding to $P_{\max}$. The maximum displacement $\delta_{\max}$ was defined as the largest displacement recorded before the end of the test. The initial stiffness K was calculated as the slope of an ordinary least-squares linear regression fitted to the loading branch between 10% and 40% of $P_{\max}$. Energy absorption was calculated by trapezoidal numerical integration of the load–displacement curve and is reported in

kN·mm. For each beam group, the mean, sample standard deviation, and coefficient of variation were calculated from the three replicate specimens.

3. Results and Discussion

This section presents the experimental results obtained from the flexural tests conducted on the nine different types of timber I-beams. The results are analyzed in terms of load-displacement behavior, maximum load capacity, stiffness, and energy absorption. Additionally, the failure modes observed during the tests are described and illustrated. Load-displacement graphs for all tested specimens are given in Fig. 6. This comprehensive figure presents the results of all test specimens together, allowing for the observation of general trends and comparisons. However, to conduct more detailed and specific analyses, the specimen results have been categorized and examined separately in subsequent sections. This approach enables a more in-depth evaluation of the unique performance characteristics and behaviors of each configuration.

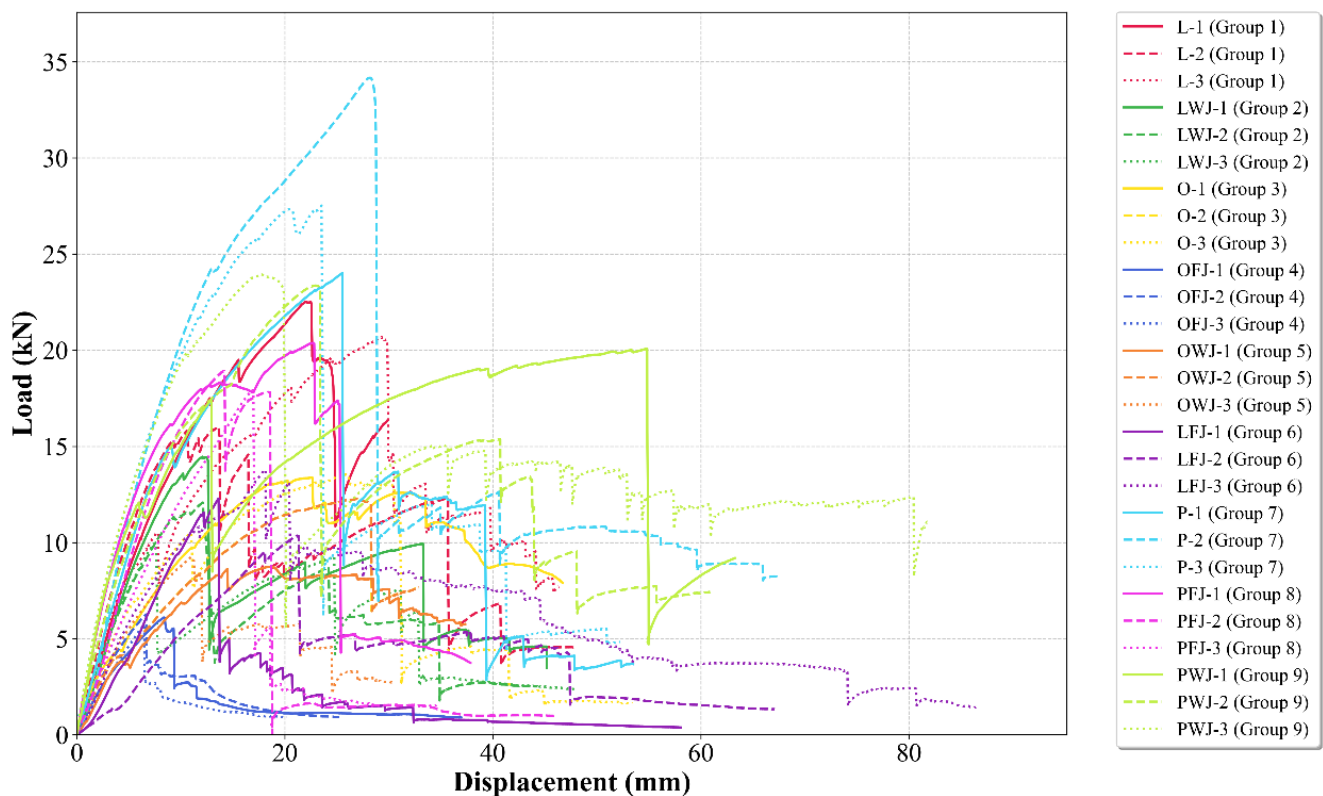


Fig. 6. Load displacement curves for all specimens.

The peak points of the curves represent the maximum load-bearing capacities of the individual specimens, while the post-peak branches reflect the progression of damage and the residual deformation capacity after peak load. Some specimens showed abrupt post-peak load reduction, indicating relatively brittle failure, whereas others maintained residual load over larger displacements, indicating progressive damage development and higher deformation capacity. Since Fig. 6 includes all individual specimens, the curves appear dense and overlapping;

therefore, the grouped mean curves in Fig. 7 and the numerical summary in Table 3 are used for clearer quantitative comparison among beam types and joint configurations.

The performance of each beam type is evaluated, with particular attention given to the effects of different materials (OSB, laminated timber, and plywood) and joint configurations (web-joined, flange-joined, and continuous). The data presented here forms the basis for the subsequent discussion on the comparative performance

of these engineered timber I-beams. To provide a clearer quantitative comparison of the experimental results, the main mechanical parameters obtained from all specimens are summarized in Table 3. The table includes the maximum load ($P_{\max}$), displacement at maximum load ($\delta P_{\max}$), maximum recorded displacement ($\delta_{\max}$), initial

stiffness (K), and energy absorption capacity of each specimen. For each beam group, the mean value, sample standard deviation (SD), and coefficient of variation (CoV) were calculated based on the three replicate specimens to evaluate the variability and repeatability of the test results.

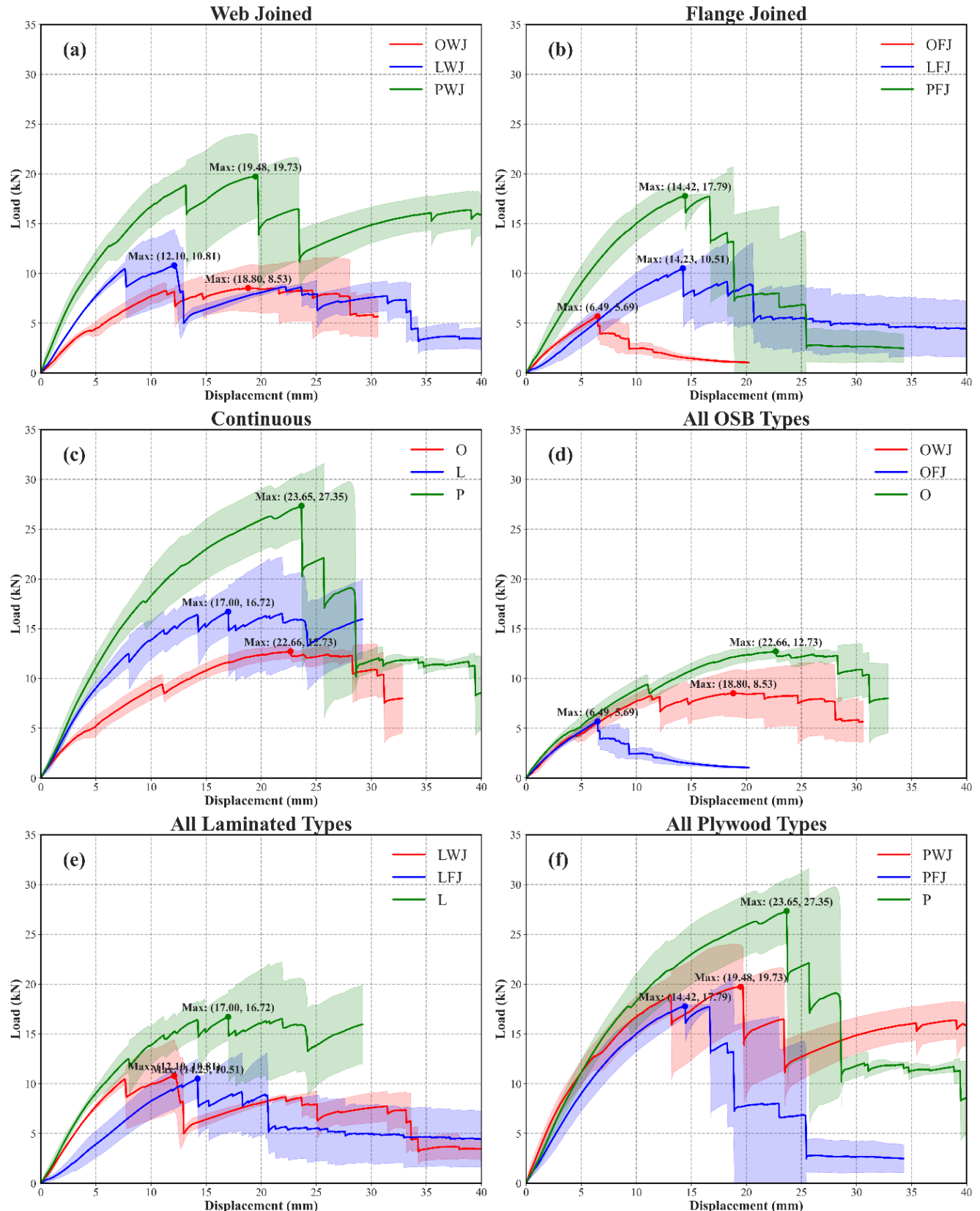


Fig. 7. Average load–displacement curves for specified groups of specimens.

Table 3. Comprehensive experimental results of timber I-beam specimens.

Beam group	Specimen ID	$P_{\max}$ (kN)	$\delta P_{\max}$ (mm)	$\delta_{\max}$ (mm)	K (kN/mm)	Energy absorption (kN·mm)
O	O-1	13.368	35.096	59.276	0.7735	460.62
O	O-2	12.282	41.144	46.952	0.6441	275.36
O	O-3	13.557	35.924	63.363	1.3687	380.57
O	Mean	13.069	37.388	56.53	0.9288	372.19
O	SD	0.688	3.279	8.543	0.3865	92.91
O	CoV (%)	5.265	8.77	15.112	41.6101	24.96
OWJ	OWJ-1	8.735	31.674	50.455	1.0304	249.31
OWJ	OWJ-2	9.125	28.144	48.452	1.1421	215.36
OWJ	OWJ-3	9.243	24.885	44.314	1.2935	155.48
OWJ	Mean	8.989	28.279	47.385	1.1619	202.39
OWJ	SD	0.359	4.801	4.342	0.186	66.35
OWJ	CoV (%)	3.998	16.975	9.164	16.012	32.78
OFJ	OFJ-1	6.1	74.989	103.569	1.0706	91.26
OFJ	OFJ-2	6.257	21.502	40.092	1.1812	65.2
OFJ	OFJ-3	5.742	20.383	34.114	0.9464	44.47
OFJ	Mean	6.033	38.958	59.258	1.0661	66.98
OFJ	SD	0.264	31.209	38.49	0.1175	23.44
OFJ	CoV (%)	4.373	80.109	64.954	11.0191	35.0
L	L-1	22.523	30.955	38.333	1.7685	437.32
L	L-2	15.956	23.123	57.231	2.3345	450.14
L	L-3	20.687	49.733	66.814	1.0502	590.97
L	Mean	19.722	34.604	54.126	1.7177	492.81
L	SD	3.388	13.675	14.492	0.6437	85.25
L	CoV (%)	17.18	39.519	26.775	37.4727	17.3
LWJ	LWJ-1	14.459	30.305	63.401	1.7083	346.31
LWJ	LWJ-2	12.078	31.386	63.595	1.7036	270.76
LWJ	LWJ-3	9.976	22.275	62.684	1.8338	263.77
LWJ	Mean	12.171	27.989	63.227	1.7485	293.61
LWJ	SD	2.243	4.978	0.48	0.0739	45.77
LWJ	CoV (%)	18.43	17.784	0.759	4.2237	15.59
LFJ	LFJ-1	12.283	13.632	58.082	0.9591	145.76
LFJ	LFJ-2	10.359	21.191	67.102	0.5905	273.4
LFJ	LFJ-3	13.794	18.084	86.534	1.3065	523.39
LFJ	Mean	12.145	17.636	70.573	0.9521	314.18
LFJ	SD	1.722	3.799	14.54	0.358	192.09
LFJ	CoV (%)	14.176	21.544	20.603	37.6067	61.14
P	P-1	24.018	25.544	53.483	1.8946	629.02
P	P-2	34.168	28.194	67.444	2.5441	1037.57
P	P-3	27.522	23.543	52.273	2.3603	697.96
P	Mean	28.569	25.76	57.733	2.2663	788.18
P	SD	5.155	2.333	8.431	0.3348	218.71
P	CoV (%)	18.045	9.057	14.604	14.7715	27.75
PWJ	PWJ-1	20.084	54.826	63.285	2.7511	926.04
PWJ	PWJ-2	23.363	22.966	60.897	1.8751	766.08
PWJ	PWJ-3	23.93	17.824	81.863	2.5898	1120.9
PWJ	Mean	22.459	31.872	68.682	2.4053	937.67
PWJ	SD	2.076	20.044	11.478	0.4662	177.7
PWJ	CoV (%)	9.246	62.89	16.711	19.3818	18.95
PFJ	PFJ-1	20.383	51.963	67.062	2.6281	444.76
PFJ	PFJ-2	18.915	14.174	46.173	1.9702	269.37
PFJ	PFJ-3	17.914	16.908	34.606	1.3423	209.48
PFJ	Mean	19.07	27.682	49.28	1.9802	307.87
PFJ	SD	1.242	21.073	16.45	0.6429	122.27
PFJ	CoV (%)	6.51	76.125	33.38	32.4682	39.72

Note: $P_{\max}$ = maximum recorded load; $\delta P_{\max}$ = displacement at $P_{\max}$; $\delta_{\max}$ = maximum recorded displacement before end of test; K = slope of OLS linear regression of P vs δ over the 10-40 % $P_{\max}$ window of the loading branch (fallback 20-50 % $P_{\max}$); Energy absorption = trapezoidal integration of P - δ over the cleaned load-displacement curve. Mean = arithmetic mean of valid replicates; SD = sample standard deviation (divisor $n - 1$); CoV (%) = SD / Mean x 100.

3.1. Load-displacement behavior

Fig. 7 illustrates the grouped load-displacement curves for various timber I-beam configurations. The curves represent the mean values calculated from three specimens for each beam type. The shaded areas around these mean curves represent the standard deviation of the measurements, providing a visual representation of the variability within each beam type.

This visualization method, combining mean curves with standard deviation bands, offers a comprehensive view of the structural performance and inherent variability in each beam configuration. It allows for a nuanced understanding of not only the average performance but also the consistency and reliability of different beam types under load.

The comparative analysis of different beam types shown in Fig. 7 reveals various structural performance characteristics and sustainability approaches. Continuous beams consistently demonstrated superior load-bearing capacities compared to their joined counterparts across all subplots Figs. 7(d-f). This highlights the significant impact of joints on overall structural integrity. The superior performance of continuous beams is attributed to the continuity in load distribution and the absence of stress concentrations.

The effect of material properties on load-bearing capacity is evident. As seen in Fig. 7(f), plywood (P) beams exhibited the highest peak loads, followed by laminated (L) and OSB beams. This ranking is explained by the high strength and stability provided by the cross-layered structure of plywood. Notably, the webs of the plywood beams were produced from plywood panels previously used as formwork. This demonstrates that waste materials can be transformed into high-performance structural elements.

The performance of laminated beams (L) is particularly noteworthy from a sustainability perspective. The web portion of these beams is made from timber pieces typically considered waste or unused. This innovative design ensures efficient resource utilization while providing satisfactory structural performance.

The effect of joint types on performance is clearly visible in Figs. 7(a) and (b). Generally, web-joined (WJ) beams exhibited higher maximum load capacities compared to flange-joined (FJ) beams. This indicates that the

position of the joint in the beam cross-section has a significant impact on load-bearing capacity. The superior performance of web-joined specimens is attributed to two key factors. First, the continuity of the flanges provides more effective resistance to bending moments. Second, and crucially, the continuous flanges in web-joined beams prevent premature failure by maintaining the integrity of the flange-web connection under shear stresses. In web-joined specimens, failure does not occur until either the continuous flange fails or the adhesive bond between the flange and web fails under shear stress. This mechanism allows web-joined beams to sustain higher loads and exhibit more ductile behavior compared to flange-joined beams, where the discontinuity in the flanges can lead to earlier failure initiation.

Performance variability, represented by the shaded areas in the graphs, differs among beam types. For example, in Fig. 7(a), PWJ beams show a wider range of variability compared to OWJ and LWJ beams. This variability is more pronounced in beams made from recycled or waste materials, as the properties of these materials can show greater variation.

Maximum load points are marked for each beam type in the graphs. These points allow us to compare the load-bearing capacities of different beam types and the displacement values at which they reach this capacity.

An important consideration in structural design is the strength-to-weight ratio of materials. Analysis of 1-meter beam sections reveals significant differences among the tested materials. OSB beams weigh 2.40 kg, substantially less than laminated beams at 4.13 kg and plywood beams at 4.12 kg. When considering the maximum load capacity in relation to weight, plywood beams demonstrate the highest strength-to-weight ratio of 6.93 kN/kg, followed by OSB beams at 5.45 kN/kg, while laminated beams show a ratio of 4.78 kN/kg. This analysis reveals that plywood beams offer both the highest absolute load-bearing capacity and the best strength-to-weight ratio. Interestingly, OSB beams, despite their lower absolute strength, provide a competitive strength-to-weight ratio that significantly outperforms laminated beams. Such characteristics make OSB an attractive option for applications where balancing weight and strength is crucial, such as in renovations of existing buildings or in designs where foundation loads need to be minimized.

Table 4. Strength-to-weight comparison of continuous timber I-beam specimens.

Type	Weight (kg)	Max load (kN)	Strength-to-weight ratio (kN/kg)
OSB Beam	2.40	13.069	5.45
Laminated Beam	4.13	19.722	4.78
Plywood Beam	4.12	28.569	6.93

Overall, this comprehensive analysis details the effects of different beam types, materials, and joining methods on structural performance. It is particularly important in demonstrating that waste or used materials can be transformed into high-performance structural el-

ements. This approach makes a significant contribution to sustainable construction practices and circular economy principles. At the same time, understanding the impact of joint locations on beam performance is critical, especially in large-span applications. This information

will serve as a valuable guide in selecting the most appropriate beam configuration for specific applications and in sustainable structural design.

3.2. Energy absorption

Fig. 8 presents the energy absorption capacities of different timber I-beam types. These results provide experimental evidence for comparing the flexural response of timber I-beams with different web materials and joint configurations.

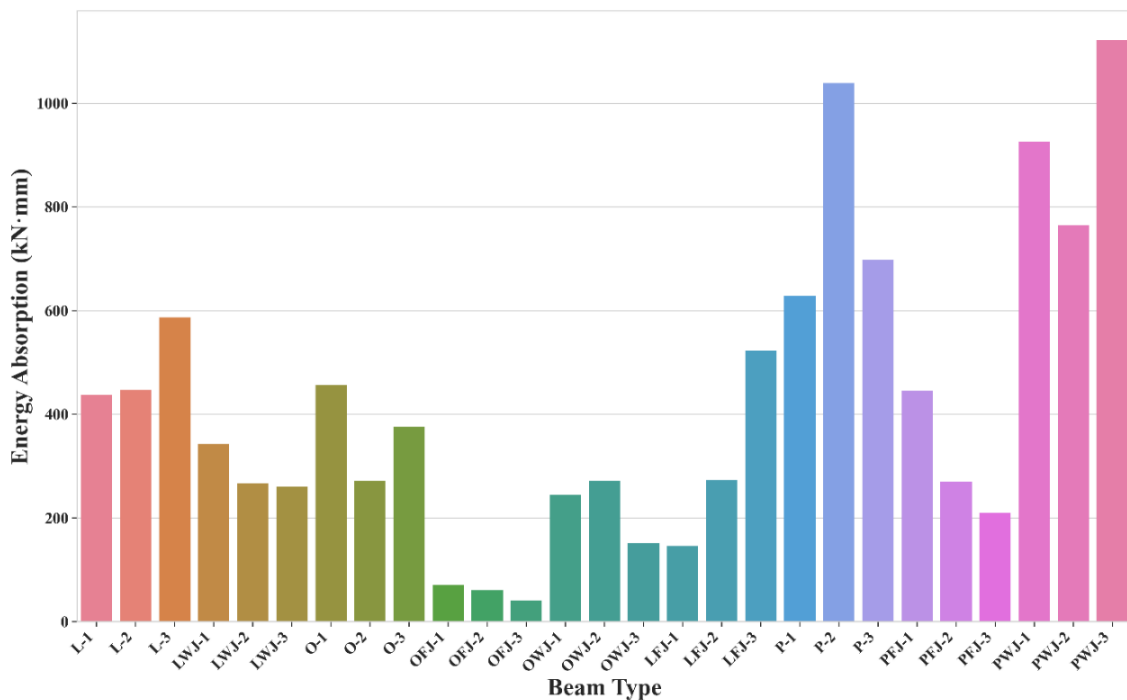


Fig. 8. The comparison of energy absorption capacity of the specimens.

It should be emphasized that the energy absorption values reported in this study were obtained from monotonic three-point bending tests and were calculated as the area under the load–displacement curves. Therefore, these values represent the absorbed energy under monotonic loading and should be interpreted as a comparative indicator of deformation capacity and post-peak response among the tested configurations. They should not be directly interpreted as cyclic energy dissipation capacity. Under cyclic loading, stiffness degradation, damage accumulation, adhesive debonding, and progressive joint deterioration may influence the hysteretic response and energy dissipation behavior. Therefore, future studies should include cyclic or repeated loading tests to evaluate the dissipative performance of these timber I-beam configurations more comprehensively.

3.3. Maximum load capacity

Fig. 9 presents the maximum load capacity of each beam type. Load capacity is vital for determining safety factors and load limits in structural design. P-series beams consistently demonstrated the highest maximum load capacities, suggesting superior performance in applications requiring high strength-to-weight ratios.

PWJ beams, particularly PWJ-3, demonstrated exceptional energy absorption capacity, suggesting potential applications in structures requiring high ductility. Energy absorption generally decreased in several joined configurations; however, some specimens, particularly in the PWJ group, exhibited higher energy absorption due to their larger deformation capacity. OSB beams showed the lowest energy absorption among the tested configurations, indicating limitations in their use for applications requiring high energy dissipation.

Joined beams, particularly flange-joined types, exhibited lower maximum load capacities compared to continuous beams, highlighting the need for careful consideration of joint placement in design. Within each material category (OSB, laminated, plywood), continuous beams outperformed joined beams in terms of maximum load capacity, emphasizing the structural advantages of uninterrupted beam sections.

3.4. Stiffness analysis

Fig. 10 presents the stiffness values for different timber I-beam types. Stiffness, calculated as the slope of the linear portion of the load–displacement curve, indicates the beam's resistance to deformation under load - a critical factor in serviceability limit state design.

P-series beams, especially the continuous ones, demonstrated the highest stiffness values, suggesting their suitability for applications where minimal deflection is crucial. OSB beams generally showed lower stiffness compared to laminated and plywood beams, indicating potential limitations in their use for long-span or heavily loaded structures. The effect of joints on stiffness was configuration-dependent; however, flange-joined specimens generally showed a less favorable stiffness response in the laminated and plywood groups.

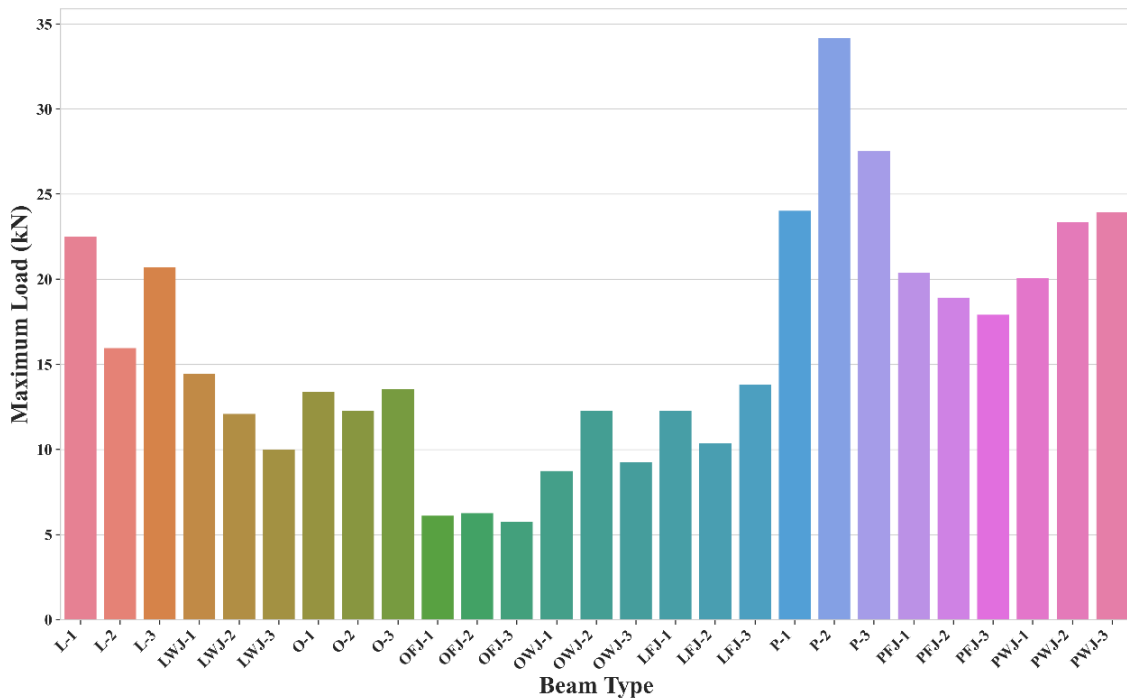


Fig. 9. Maximum load capacity of each specimen.

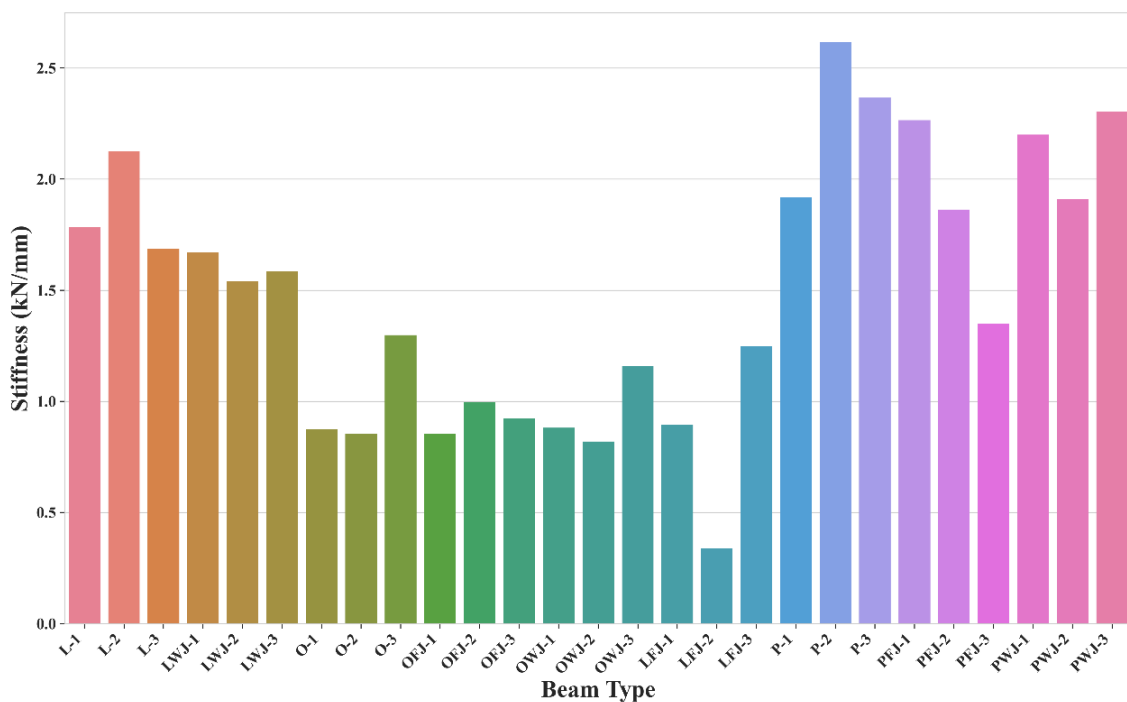


Fig. 10. Stiffness comparison of the specimens.

3.5. Failure modes

In the three-point bending configuration, the specimens were subjected to a combination of bending moment and shear force. While the flanges primarily resisted the tensile and compressive stresses generated by bending, the web and the web-flange adhesive interfaces were mainly responsible for shear transfer. Therefore, shear effects played an important role in the initiation and progression of several observed failure modes, particularly web cracking, web tearing, web-flange sep-

aration, adhesive bond failure, and damage around the jointed regions.

The observed failure modes provide valuable insights into the structural behavior and weak points of different beam configurations. These observations offer critical information for refining design methodologies and improving structural resilience.

Laminated timber beams exhibited distinct failure patterns depending on their joint configuration. In web-joined (LWJ) beams, failure typically initiated in the web, often near the stapled joint area. This initial web failure

was followed by progressive failure of the flanges, with the bottom flange usually failing before the top flange (Fig. 11(a)). On the other hand, flange-joined (LFJ) beams highlighted the critical nature of the flange joint, with failure often initiating as cracking or delamination at the bottom flange joint, followed by web separation and potential progression to the top flange (Fig. 11(b)).

Continuous laminated timber (L) beams demonstrated more varied failure modes. Some specimens experienced initial crushing or breaking of the top flange due to load-induced slippage, while others exhibited web failure followed by bottom flange separation from the web and upward crack propagation (Fig. 11(c)).

OSB beams also showed distinct failure characteristics based on their joint configuration. Web-joined (OWJ) beams exhibited more varied failure modes compared to their flange-joined (OFJ) counterparts. In OWJ beams, delamination between the web and flange was more pronounced, especially under high loads, potentially leading to ultimate failure (Fig. 11(d)). In contrast, OFJ beams consistently demonstrated a characteristic failure pattern, with cracks initiating at the bottom flange joint and propagating upwards through the web (Fig. 11(e)). This consistent behavior across OFJ specimens highlights the critical nature of the flange joint in OSB beams.

Continuous OSB (O) beams typically failed in a sequence starting with the top flange, followed by the bot-

tom flange, and finally the web. However, some variations were observed, such as initial top flange crushing followed by web cracking and bottom flange failure (Fig. 11(f)).

Plywood beams exhibited failure modes that were influenced by both joint configuration and the brittle nature of the material. Web-joined (PWJ) beams typically failed through web separation at the joint, followed by flange failure (Fig. 11(g)). The failure often initiated with the bottom flange sliding relative to the web, accompanied by progressive web tearing. Similarly, flange-joined (PFJ) beams exhibited bottom flange slippage occurring simultaneously with web failure initiation (Fig. 11(h)).

Continuous plywood (P) beams often showed a distinct failure sequence, with initial failure in the top flange, followed by brittle web failure and subsequent bottom flange separation. The brittle web failure was a notable characteristic of plywood beams, setting them apart from the other materials tested (Fig. 11(i)).

The diverse failure modes observed across different beam types and joint configurations underscore the complex interplay between material properties, joint design, and load distribution mechanisms. Understanding these failure mechanisms is crucial for optimizing beam design and improving overall structural performance. By carefully considering the strengths and weaknesses of each configuration, engineers can develop more resilient and efficient structural solutions.

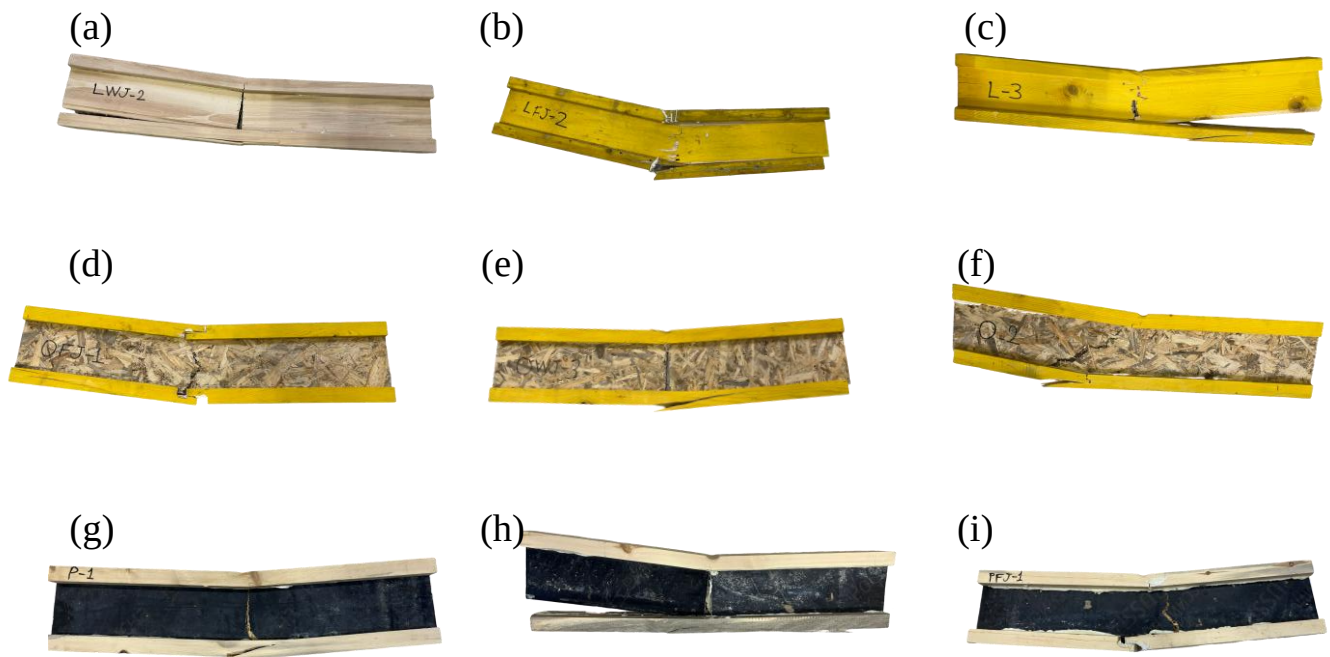


Fig. 11. Representative failure modes observed in the tested timber I-beam specimens:

(a) LWJ specimen; (b) LFJ specimen; (c) Continuous laminated specimen; (d) OWJ specimen; (e) OFJ specimen; (f) Continuous OSB specimen; (g) PWJ specimen; (h) PFJ specimen; (i) Continuous plywood specimen.

3.6. Joint performance analysis

A comparative analysis of joined beams (WJ and FJ) with continuous beams reveals the significant impact of joints on structural performance. Joined beams consistently showed lower maximum load capacities compared to continuous beams of the same material, with reductions ranging from 15% to 30%. Compared with the cor-

responding continuous beams, the joined specimens generally exhibited lower maximum load capacities. The retained load capacity varied depending on both material type and joint location. Web-joined specimens retained approximately 62–79% of the continuous beam capacity, whereas flange-joined specimens retained approximately 46–67%. This confirms that joint location has a pronounced influence on ultimate load capacity,

with flange joints generally producing a more detrimental effect.

Energy absorption showed a more configuration-dependent trend than maximum load capacity. While most joined specimens exhibited lower energy absorption than the corresponding continuous beams, the PWJ group showed higher energy absorption due to its larger deformation capacity. This indicates that energy absorption is governed not only by peak load but also by post-peak deformation behavior and failure progression (Ozdemir 2025).

The effect of joints on stiffness was less uniform than their effect on maximum load capacity. While flange-joined specimens generally showed lower stiffness in the laminated and plywood groups, some web-joined specimens exhibited comparable or slightly higher initial stiffness than their continuous counterparts. This indicates that the presence of a joint does not necessarily reduce the initial elastic stiffness, although it generally affects load-bearing capacity, post-peak response, and failure mode.

Joints often served as initiation points for failure, particularly in flange-joined beams, suggesting that joint design and placement are critical factors in overall beam performance, as interfacial bond quality directly affects stress-transfer efficiency (Tarhan et al. 2025). It should be noted that the tested beam types were compared as commercially available I-beam configurations rather than as geometrically identical laboratory-manufactured specimens. Therefore, the observed differences in maximum load, stiffness, and energy absorption are influenced not only by the web material and joint configuration, but also by differences in cross-sectional geometry and the corresponding sectional properties, such as the moment of inertia. For this reason, the results should be interpreted as a comparative assessment of practical beam configurations under identical testing conditions, rather than as an isolated comparison of material properties alone.

The influence of shear forces was particularly evident in the joined specimens. In web-joined beams, the web joint was located in the component responsible for shear transfer, and this promoted local web damage, adhesive debonding, or progressive web tearing depending on the material type. In flange-joined beams, although the joint was located in the flexural stress-carrying component, shear transfer through the web-flange interface also contributed to local separation and crack propagation near the joint region. Thus, the observed failures should be interpreted as the result of combined bending and shear actions rather than pure flexural failure alone.

Overall, this comprehensive analysis of various timber I-beam configurations provides valuable insights into the complex interplay between material properties, joint design, and overall structural performance. These findings not only contribute to our understanding of engineered timber structures but also offer practical guidance for optimizing beam design in real-world applications. Future research should focus on developing material-specific joint designs that address the observed failure modes, potentially incorporating local reinforcement at critical points identified through this analysis.

4. Conclusions

The extensive investigation into the structural behavior of various engineered wood I-beams has yielded significant insights into the performance characteristics of different materials and joint configurations. Our study, encompassing OSB, laminated timber, and plywood beams with various joining methods, has revealed complex interactions between material properties, joint designs, and load distribution mechanisms that profoundly influence beam performance.

The plywood-web I-beam configuration exhibited the highest load-bearing capacity and stiffness among the tested beam configurations. However, the unexpected competitiveness of OSB beams in terms of strength-to-weight ratio highlights the potential for utilizing this more cost-effective material in applications where weight reduction is crucial. The varied performance of laminated timber beams across different configurations emphasizes the critical role of manufacturing processes and joint designs in determining overall structural integrity.

The observed variations in stiffness and failure modes between continuous beams and their joined counterparts highlight both the challenges and opportunities in joint design. While joined beams generally exhibited lower stiffness and more complex failure mechanisms, the potential for optimizing joint configurations to enhance performance is evident. This opens avenues for developing more efficient and resilient structural elements that balance performance with material economy.

Furthermore, our study demonstrates the viability of incorporating recycled or repurposed materials, such as construction site plywood and typically unused timber pieces, into high-performance structural elements. This approach not only contributes to sustainable construction practices but also aligns with circular economy principles, offering a pathway to reduce waste and enhance resource efficiency in the construction industry. Since the tested specimens represent practical beam configurations with possible differences in cross-sectional geometry, the conclusions should be interpreted in terms of overall beam configuration performance. A further limitation of this study is that analytical load-carrying capacity predictions were not developed, because the tested beams were not laboratory-manufactured specimens produced under fully controlled and standardized material and bonding conditions. The novelty of the study is based on the comparative experimental evaluation of practical timber I-beam configurations incorporating locally available, unused, and previously used wood-based components. Although nominal adhesive properties may be available, the actual web-flange and joint-interface behavior depends on several application-dependent factors, including surface condition, adhesive thickness, bonding pressure, curing conditions, moisture state, and the previous service history of reused materials. These parameters were not independently characterized in the present study. Therefore, a simplified analytical capacity model would require assumptions that may not reliably represent the actual behavior of the tested beams. For this reason, the results are presented

as an experimental comparison of practical beam configurations under identical testing conditions. Future studies should develop analytical or numerical models calibrated with directly measured material properties, adhesive bond characteristics, and joint-interface parameters.

Overall, this study provides practical insight into the flexural performance of timber I-beam configurations produced with different web materials and joint details. The results show that joint location significantly affects load-bearing capacity, deformation behavior, and failure mechanisms, particularly when discontinuities are introduced in the flange region. Since the tested specimens represent practical beam configurations rather than laboratory-manufactured members with fully controlled material and bonding properties, the findings should be interpreted at the configuration level. Future studies should focus on developing analytical and numerical models calibrated with directly measured material properties, adhesive bond characteristics, and joint-interface parameters.

Acknowledgements

The author would like to express their gratitude to Balsa Timber Ltd. Co. for generously donating the timber beams used in this study.

Funding

The author received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

During the preparation of this manuscript, Google Gemini was used exclusively for language editing and stylistic refinement. The authors take full responsibility for the content, interpretation, and conclusions of the published article.

Author Contributions

The author declares sole responsibility for all aspects of the study, including conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing of the original draft, and writing, review, and editing of the manuscript.

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