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INFLUENCE OF RECTANGULAR WEB OPENINGS ON LOAD-CARRYING CAPACITY OF TIMBER I-JOISTS

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ABSTRACT: This paper presents test results of experimental work conducted to evaluate the influence of rectangular web openings on the structural performance of timber I-joists fabricated from solid wood flanges and oriented-strand board web. Four-point bending tests were conducted on specimens with and without openings. The test sample span was equal to 9 times the joist depth with openings located at various locations relative to the joist depth (D). Effects of the size and opening locations on the load-carrying capacity of the I-joists were determined. Test results revealed that an increase in the height and width of the openings significantly reduced the load-carrying capacity when openings were placed outside pure bending areas (i.e., a reduction of up to 58% for I-joists with the largest opening tested) and changed the failure mode of I-joist. In contrast, openings within the pure bending area had a negligible influence on the capacity.

KEYWORDS: Wood I-joist, Load-carrying capacity, Opening, Four-point bending, Load-deflection curve

1 – INTRODUCTION

Engineered wood products (EWPs) are manufactured building materials created by bonding together wood strands, fibres, or veneers using adhesives, heat, or pressure. Unlike traditional solid timber, EWPs are designed to optimise structural performance, overcome natural wood limitations (e.g., knots, warping), and use resources more efficiently. They are engineered for specific applications, offering enhanced strength, dimensional stability, and uniformity. Common examples include laminated veneer lumber (LVL), oriented strand board (OSB), glued-laminated timber (glulam), and cross-laminated timber (CLT). By utilising fast-growing species, recycled wood, or smaller-diameter trees, EWPs also promote sustainable construction practices [1].

Wood I-joists are EWPs designed for greater strength, dimensional stability, and longer spans in timber floors and roofs compared to traditional solid timber beams. The high strength-to-weight ratio and ability to support larger spans make I-joists a popular choice for both residential and commercial construction in North America and Europe. The widespread use of I-joists began in the 1960s, with mass production commencing in 1969 [2]. A wood I-joist consists of two horizontal flanges connected by a vertical web using adhesives, creating the I-shaped cross-section. The flanges are typically made from LVL or LSL. The web is usually made from wood-based sheathing materials like hardboard, plywood, or OSB. Before the 1990s, plywood was the primary web material. However, OSB has since become the preferred choice due to its excellent mechanical properties. Manufactured by bonding fully dried, cross-layered wood strands with waterproof resin, OSB is a high-strength, lightweight, cost-effective, and environmentally friendly option for web panels [2].

In residential construction, it is common practice to cut openings in the webs of I-joists onsite to accommodate utilities such as plumbing, electrical wiring, heating and air-conditioning ducts [1,3]. However, the presence of web openings may adversely affect the structural performance of I-joist, potentially reducing the overall

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load-carrying capacity and inducing premature failure [3]. It is widely accepted that web openings primarily affect the shear capacity of I-joists, as the web and flange are designed to resist shear and bending stresses, respectively.

Though widely used in timber frame construction, I-joists lack comprehensive industry standards for designing web openings. Leichti et al. [2] conducted a review on I-joists, revealing that manufacturers have developed individualized design guidelines to ensure the safe integration of openings. These guidelines specify acceptable shapes, sizes, and locations to minimise structural risks. Notably, circular openings with diameters less than 38 mm are generally permitted in any location along the span owing to their negligible structural impact. In contrast, square or rectangular openings are subject to stricter limitations due to the stress concentration at the corners and are typically restricted to areas away from supports, where shear forces are lower. Especially for large rectangular openings, which are only allowed at distances of 3 to 5 times of I-joist depth (D) from the supports. Despite these specific recommendations by manufacturers, the industry lacks broadly accepted standards for introducing openings in I-joists. To address this gap, the Wood I-joist Manufacturer Association (WIJMA) [4] published a test method and procedure to evaluate the shear capacity of I-joists with web openings, providing a foundational framework for assessment. While the I-joist industry has applied this method to develop proprietary criteria [5], it has not been widely adopted as a standardised approach, partly due to its limitation on the opening diameter within 75% of web depth as well as the restrictions on opening locations. Other existing standards also present challenges. Eurocode 5 [6], for instance, lacks explicit recommendations for web openings in I-joists. ASTM 5055 [7] outlined a procedure for shear capacity evaluation but relies on complex empirical formulas derived from extensive testing, which has hindered its adoption in conventional practice due to practicality concerns. These gaps highlight the need for a comprehensive, standardised approach that balances practicality and technical rigor.

To address the limitations, Wang and Cheng [8] conducted experimental research to develop shear design criteria for OSB-webbed I-joists with web openings. Recognising that rectangular openings induce greater stress concentrations at the corners compared to circular ones, the researchers focused on the rectangular-shaped opening to assess its impact on the shear strength of I-joist. They tested 24 I-joists with spans ranging from 2.7 m to 3.6 m, incorporating single rectangular openings sized between 33% and 100% of the web height, positioned 2.5×D from the supports. The results highlighted a severe reduction in shear capacity: openings matching the full web height caused a 70–80% decrease, with cracks predominantly initiating at the corners. Smaller openings (33–66% of the web height) had less effect, though failures shifted to mechanisms like web buckling or flange compression rather than localised corner failures. Notably, variations in opening width, shear span length, and corner radii showed less influence on shear performance. Based on these findings, Wang and Cheng [8] proposed a calculation method based on Vierendeel truss mechanics to predict shear strength in I-joists with openings

In a large-scale experimental study, Gudmundsson [9] investigated the influence of square openings on the shear strength of I-joists. The research tested approximately 150 I-joists with depths ranging from 195 mm to 450 mm and varying flange sizes under three-point bending loading conditions. These specimens incorporated single square openings, sized incrementally from 15% to 100% of the web depth in 15% increments. The openings were positioned between the loading point and the end support to reduce the shear stress effects. It was found that for shallow I-joists (≤195 mm in depth), openings up to 50% of the web height caused a pronounced reduction in shear capacity, far exceeding the impact observed in deeper joists. Larger openings (50 – 100% of the web height) reduced shear strength similarly in both shallow and deep joists. However, the adverse effect diminished when increasing the hole size beyond 50%, with incremental strength reductions becoming less significant compared to the decline observed within the 0–50% range. These findings highlight that shallow I-joists are more susceptible to smaller openings and emphasise the non-linear relationship between opening size and degradation in shear capacity.

An extensive experimental study was conducted by Afzal et al. [10] to examine the effects of web openings on I-joists, focusing on opening shape, opening size, and interactions between adjacent openings. The study tested 302 mm and 406 mm deep joists with circular and square openings, incrementally sized from 25%–100% and 20%–100% of the web height, respectively. Results showed that square openings significantly reduced load-carrying capacity by up to 85% when the opening height matched the web depth. In contrast, circular openings exhibited a lesser impact, reducing capacity to 70% compared to square openings of the same size. The strength reduction for circular openings followed a linear trend with increasing size, while square openings showed a sharp decline up to 60% of the web height, transitioning to gradual degradation thereafter. A comparison of the

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reductions in load-carrying capacities caused by circular and square openings revealed that a square opening has a similar effect to a circular opening that circumscribes it (i.e., a circle encompassing the square's corners). The researcher also recommended incorporating the bending moment effect into the design process to ensure safe positioning of web openings. Based on these findings, the researchers suggested maintaining a minimum spacing of twice the diameter between adjacent circular openings to avoid interaction effects.

Building on the prior research, Pirzada et al. [3] extended the investigation by proposing a fracture mechanics-based model to predict the failure load of I-joists containing single circular openings. The methodology integrated two key approaches: curved beam analysis to map stress distribution around the hole and the finite area method, which incorporated these stress values to estimate fracture load. When validated against experimental data from Afzal et al. [10], the model demonstrated strong alignment with test results within 75%-92% of the relative failure load. The authors attributed this underestimation to oversimplified assumptions about OSB material properties in the analysis. They emphasised that refining the model's accuracy would require a deeper characterisation of OSB's mechanical behaviour, particularly its anisotropic and nonlinear characteristic. This work indicated the potential of fracture mechanics in joist design.

Instead of incorporating a single opening, Morrissey et al. [5] evaluated the structural impact of multiple web openings on I-joists under realistic uniformly distributed loads (UDLs). Following the *AllJoist Specifier Guide* [11], their study categorised a 4.27 m long I-joist with multiple openings sized at 46% of the web height and a 92% opening located near the mid-span (both circular and square) as "acceptable". These openings rarely triggered cracks in the hole itself. Instead, failures primarily occurred through tensile fractures in the flanges or web buckling, which were deemed less critical for structural integrity. In contrast, the I-joists with the same opening configurations but with one of the 46% openings closer to the support (2D-4D) shifted to 92% opening were classified as "unacceptable." It was found that cracks frequently originated within the openings, particularly those closest to the support with 2D. Through the experimental investigations, it was found that square openings exacerbated strength loss, reducing load-carrying capacity by up to 12% compared to circular openings under UDLs. However, the effect of openings on joist stiffness remains ambiguous when evaluated using load-displacement curves at both the ultimate and serviceability limit states. The findings emphasise the importance of limiting the size of openings in critical areas and prioritising circular-shaped openings to reduce premature failure, whilst also appealing for further research to identify the effect of openings on stiffness.

Zhu et al. [12] conducted detailed finite element (FE) analyses to evaluate the impact of web openings on the strength of I-joists. Their studies employed nonlinear three-dimensional FE models that incorporated elasto-plastic orthotropic material properties to simulate the anisotropic behaviour of wood I-joists. Through both experimental work and FE modelling, a critical safe distance of 500 mm between adjacent openings was identified. When openings were spaced closer than 500 mm, the load-carrying capacity decreased linearly, and failure patterns shifted significantly—often transitioning from localised cracking to cracks connecting two openings.

Unlike most of the research work on circular or square-shaped web openings, Harte and Bayer [13] explored the applicability of castellated timber I-joists to accommodate service ducts. However, the method faced challenges due to structural impracticality and the complexity of fabricating castellated web geometries, ultimately preventing its wide adoption. Subsequent research shifted focus to retrofitting and reinforcing existing web openings. Morrissey et al. [5] demonstrated that steel angles attached around circular openings could enhance ultimate load capacity by up to 33%, though this approach proved less effective for square openings. Polocoser et al. [14] expanded on retrofitting strategies, proposing techniques including bonding solid wood plates, OSB collars, or LVL plates to the top and bottom of circular openings, as well as the sides of I-joists. These methods proved to be effective, provided that the panel thicknesses were carefully calibrated, and the connectors were designed to avoid premature shear failure. Further research by Shahnewaz et al. [15] highlights the efficacy of multi-layer OSB collars, which are 2-5 times longer than the length of the opening and can increase the load-carrying capacity by up to 20%. Overall, these studies highlight the importance of reinforcement in mitigating strength loss, particularly for critical opening configurations.

Existing research on the structural performance of I-joists with web openings has predominantly focused on circular and square configurations, with particular emphasis on their effects on load-carrying capacity. However, rectangular openings—common in practical construction due to their alignment with service ducts—remain understudied, with limited experimental or analytical data available in the public domain. Industry guidelines explicitly recommend positioning square or rectangular openings at a minimum distance of twice the joist depth (2D) from supports to avoid high-shear zones. Despite these recommendations, builders on construction site frequently disregard this criterion, placing openings near supports where shear stresses peak, thereby increasing the risk of premature failures. Notably, this critical discrepancy between design guidelines and real-world application has yet to be thoroughly addressed in academic literature.

This study aims to bridge this gap by providing a comprehensive analysis of rectangular openings' influence on the structural behaviour of I-joists. Specifically, it investigates (1) the effect on load-carrying capacity and stiffness as a function of opening size and location along the span, (2) crack initiation and propagation mechanisms, and (3) failure modes associated with such openings. By correlating geometric parameters (e.g., opening dimensions and proximity to supports) with mechanical performance, this work seeks to establish design recommendations that align construction practices with structural safety, particularly for scenarios where openings cannot feasibly comply with existing guidelines.

2 – MATERIAL AND METHOD

2.1 Test specimen

The wood I-joists involved in this study were manufactured by James Jones & Sons Ltd. in Forres, Scotland. 245 mm deep I-joists with a 2.45 m span were randomly sampled from four production batches corresponding to distinct manufacturing dates from the same production line. The selection of 245 mm depth reflects its common application in UK residential construction, ensuring practical relevance to typical building practices. The flanges, measuring 47 mm in width and 45 mm in depth, were fabricated from European Spruce (Picea abies) graded to strength class C24. This classification guarantees a characteristic bending strength of 24 N/mm² and a modulus of elasticity of 11,000 N/mm². The web sections comprised a 9.2 mm thick Oriented Strand Board (OSB), classified as grade 3. These OSB panels, supplied by West Fraser (Scotland), were manufactured using a blend of Spruce (Picea spp.) and Pine (Pinus spp.) strands. The outer layers of the OSB were oriented longitudinally along the web's strong axis to optimise tensile and compressive resistance, while the core layers were aligned perpendicularly to enhance dimensional stability. The flange-web assembly was bonded through adhesive, with a 13 mm deep groove in the flanges to accommodate the web, resulting in a clear web height of 155 mm. During production, moisture content was monitored and maintained within a range of 15–18%, consistent with typical service conditions for structural timber.

In accordance with WIMJA [4] and ASTM D5055 [7] guidelines, rectangular opening sizes in this study were proportioned relative to the clear web height (155 mm), with three ratios selected: 41% (64 mm), 66% (102 mm), and 82% (127 mm) of the web height. These ratios, designated as R64, R102, and R127, were evaluated across varying widths to systematically analyse their structural impact. The R64 group incorporated widths of 100 mm, 130 mm, and 200 mm, while the R102 and R127 groups included widths of 130 mm, 200 mm, and 260 mm. This multi-dimensional approach ensured a comprehensive assessment of both height-to-web ratios and width effects on load capacity.

Three critical locations along the I-joist span were examined to isolate the effects of shear and bending

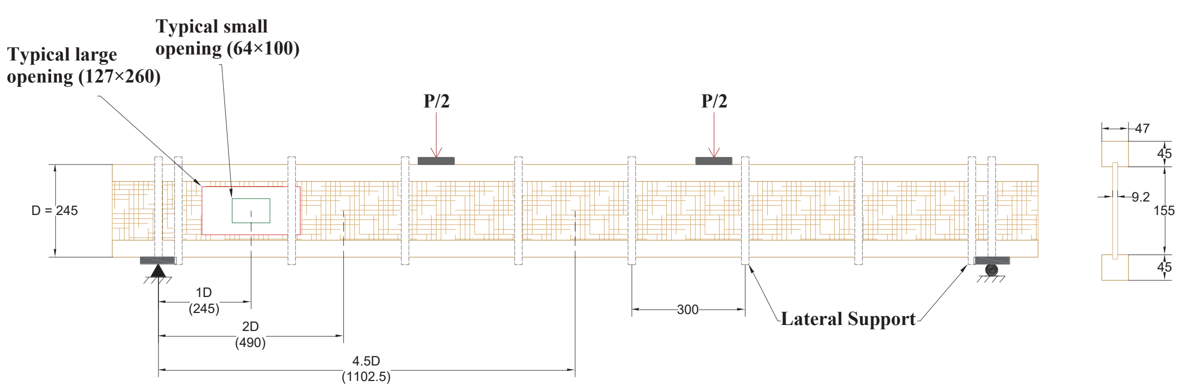

Figure 1. Test set-up

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Table1: Test results

Group	Opening height to web depth ratio (%)	Opening Location (from support)	Opening Size	No. of Specimen	Load-carring capacity			Stiffness	
			height×width (mm)		Average failure load (kN)	COV (%)	Reduction (%)	N/mm	COV (%)
Baseline	0		0	8	29.8	12		1577	12
R64	41	1D	64×100	5	20.8	14	30	1466	10
			64×130	5	21.1	9	29	1684	8
			64×200	5	15.4	6	48	1579	7
		2D	64×130	3	20.4	9	31	1569	13
			64×200	3	15.4	15	48	1611	8
R102	66	1D	102×130	5	15.8	3	47	1671	10
			102×200	5	14.2	6	52	1539	5
			102×260	5	13.3	14	55	1416	12
		2D	102×130	5	16.7	5	44	1693	7
			102×200	5	14.4	11	52	1704	2
			102×260	5	13.2	9	56	1448	9
		4.5D	102×260	3	31.5	5	-6	1793	13
R127	82	1D	127×130	5	14.6	10	51	1452	7
			127×200	5	13.6	17	54	1399	9
			127×260	5	12.7	14	57	1318	12
		2D	127×130	5	15.2	3	49	1524	5
			127×200	5	13.7	14	54	1480	10
			127×260	5	12.8	1	57	1215	10
		4.5D	127×130	5	29.2	10	2	1724	12
			127×260	10	27.7	23	7	1585	14

stresses. The high shear zone, positioned at 1×D (245 mm) from the end supports (Fig. 1), was selected due to its susceptibility to peak shear stresses under loading. Testing openings in this zone aims to quantify strength reductions and characterise failure mechanisms under dominant shear conditions. The combined shear-bending zone, located at 2×D (490 mm) from supports, was studied to evaluate interactions between shear and bending stresses and assess how load-carrying capacity was affected. The pure bending zone, positioned at 4.5×D (1,103 mm) from supports, was chosen to isolate flexural behaviour by eliminating shear influences, enabling an examination of bending stress effects.

Openings were cut using a handheld router. Custom templates constructed from timber and OSB ensured precise dimensional control, with corners rounded to a 3 mm radius to mitigate stress concentrations.

2.2 Test setup

Testing was conducted at the James Jone & Sons Timber System Division, including a total of 109 specimens, comprising 10 baseline joists (without openings) and 99 joists with rectangular openings, as detailed in Table 1. All specimens were tested under four-point bending over a simply supported span of nine times the joist depth (9D), deviating slightly from the EOTA [16] recommendation of 10D to accommodate practical constraints in opening placement. The joists were laterally restrained at supports and at 300 mm intervals along the span to prevent lateral buckling. Steel plates

(70×100×20 mm) were positioned at loading points and supports to mitigate flange crushing.

A 100 kN capacity servo-electric ram was used to apply displacement-controlled loading at a rate of 4.2 mm/min. Mid-span deflection was monitored through a strain gauge-based displacement transducer. The ultimate load-carrying capacity was defined as the peak load preceding crack initiation, a sudden load drop, or uncontrolled deflection. The stiffness was derived via linear regression analysis of the load-deflection curve between 10% and 40% of the ultimate load. Moisture content was at 12–15% throughout testing. The experimental setup is illustrated in Fig. 1.

3 – RESULTS AND DISCUSSION

3.1 Opening size

The test results are summarised in Table 1. Two specimens within the baseline group were not considered due to the material defects which resulted in early failure. Fig. 2 illustrates the strength ratio (capacity of I-joist with opening over the I-joist without opening) as a function of opening width for varying heights at the high shear zone (1D location).

Openings near the support exhibited substantial strength reductions, particularly for heights exceeding 66% of the web depth (R102 and R127 groups). The largest openings (R127×260 mm) reduced capacity by 57% with a coefficient of variation (COV) of 14%, with minimal sensitivity to width—a 6% decrease when width doubled from 130 mm to 260 mm. Similarly, R102 openings showed an 8% reduction with doubled width, confirming that larger heights dominate strength degradation, overshadowing width effects. In contrast, smaller openings R64 group demonstrated greater width sensitivity. Increasing the width from 100 mm to 200 mm caused an 18% capacity loss, culminating in a 48% total reduction for the 64×200 mm opening configuration. A comparison of capacity reductions between 64×100 mm and 64 ×130 mm openings revealed a marginal 1% difference, suggesting that small increases in opening width have negligible effects on I-joist performance when the openings are sufficiently small.

Regarding the effect of opening size on stiffness, most joists in the R64 and R102 groups exhibited no significant reduction in stiffness. However, when the opening height was increased to 127 mm at the 1D and 2D locations, all tested configurations resulted in stiffness reductions ranging from 3% to 23%. This indicates that stiffness is sensitive to opening height.

3.2 Opening location

Fig. 3 compares the load-carrying capacity of openings at different locations. Openings at 2D exhibited nearly identical strength reductions to those at 1D, differing by only 3–5%. For instance, I-joist with 64×130 mm openings failed at an average load of 21.1 kN (1D) and 20.4 kN (2D), a 3% variance, while 127×260 mm openings showed a difference within 1% (12.7 kN vs. 12.8 kN). This difference is likely due to the material characteristic of flange material and OSB rather than the effects of location.

Openings in the pure bending zone (4.5D) had negligible impact, with capacities deviating within 7% from baseline values. For example, 102×260 mm specimens achieved 6% higher capacity than baseline joists (COV = 5%), while 127×260 mm specimens showed a 7% reduction (COV = 23%). Notably, two 127×260 mm

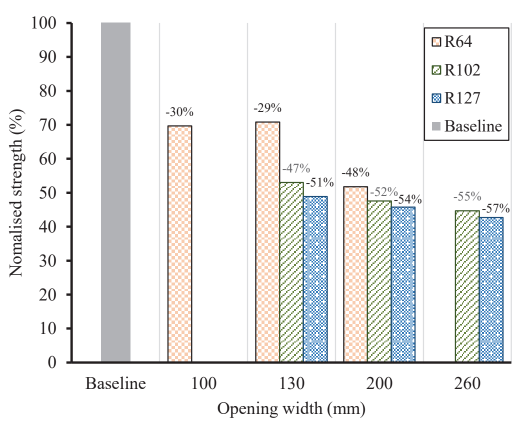

Figure 2. Influence of opening size on the load-carrying capacity of tested joists

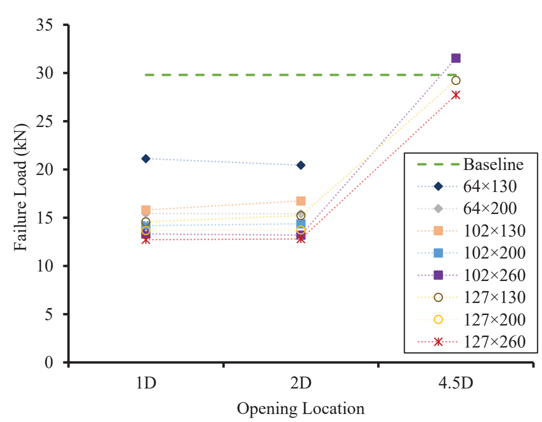

Figure 3. Impact of openings on I-joist strength along its length

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specimens failed prematurely at 18.5–19.3 kN due to the material defects in the bottom flange, similar average capacity was achieved as baseline joists excluding these two.

These findings indicate that shear, not bending, predominantly governs strength reduction. This aligns with Afzal et al. [10], who emphasised shear-dominated zones for opening placement criteria. However, real-world applications under uniformly distributed loads (UDLs) may exhibit reduced sensitivity to openings farther from supports, as variable shear stresses decrease with distance. The experimental four-point bending setup, which enforces constant shear between supports and loading points, likely amplified similarities between 1D and 2D results. Such agreement highlights the criticality of shear in design protocols while bending effects remain secondary.

3.3 Effect of opening on load-deflection response

Fig. 4 illustrates the load-deflection responses of R64 openings at 1D and 2D locations. Both locations exhibited predominantly elastic behaviour with abrupt load drops at failure, characterised by smooth curves lacking visible initial cracking load (ICL) indicators. A sharp post-peak decline suggested rapid crack propagation from opening corners toward the web-flange joint, with minimal post-failure resistance observed in select 64×200 mm specimens. ICL was defined as the first visible load reduction in the curve.

For R102 specimens (Figs. 5–7), ICL occurred at 80–90% of ultimate load, signalling a transition from elastic to elasto-plastic behaviour. While 102×130 mm specimens largely maintained elasticity until failure, 102×200 and

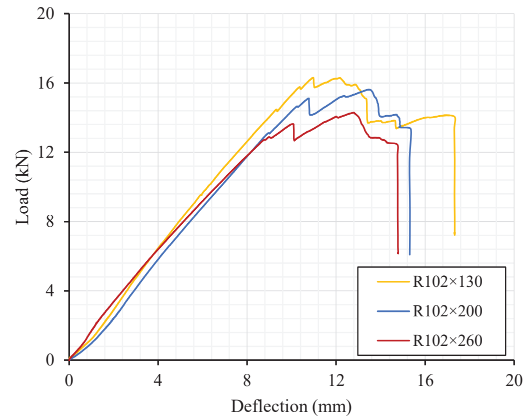

Figure 5. Typical load-deflection curves for R102 at location 1D

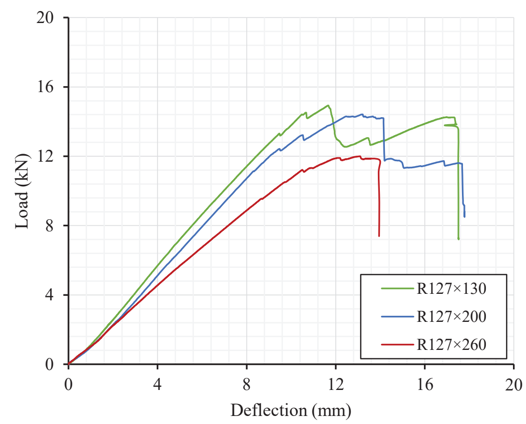

Figure 6. Typical load-deflection curves for R127 at location 1D

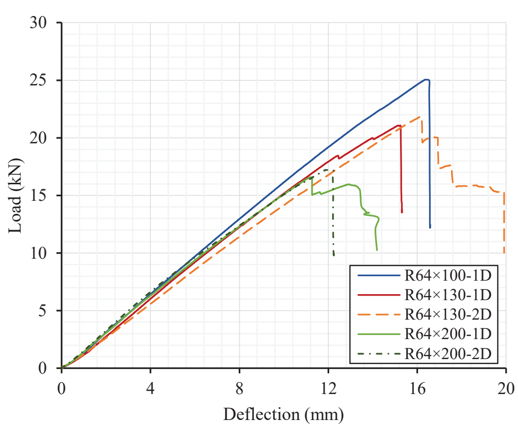

Figure 4. Typical load-deflection curves for R64 group at locations 1D and 2D

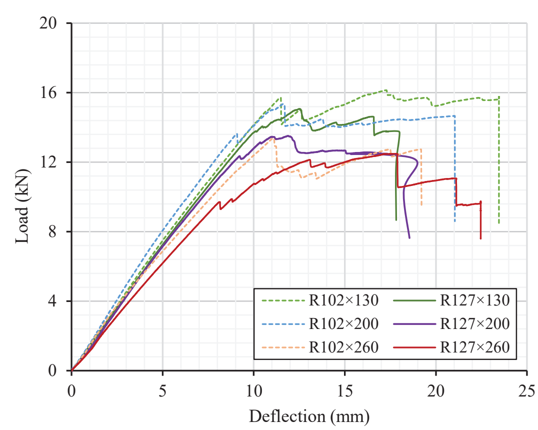

Figure 7. Typical load-deflection curves for R102 and R127 at location 2D

102×260 mm configurations demonstrated progressive cracking post-ICL, culminating in fracture. Responses at 2D matched those at 1D, showing shear-dominated failure mechanisms.

R127 specimens exhibited ICL at 75–90% of peak load, with pronounced plasticity post-ICL. Larger openings (127×200 and 127×260 mm) displayed incremental load increases or sawtooth-patterned spikes (Fig. 6) before failure, reflecting intermittent crack growth. At 2D, plasticity intensified, marked by sequential cracks and large displacements (Fig. 7). Notably, 127×260 mm specimens exhibited variability: one subset showed incremental load rise without spikes, while another demonstrated post-failure resistance.

These findings highlight the role of opening size in governing failure progression. Smaller openings (R64) failed catastrophically, while larger configurations (R102, R127) transitioned through progressive damage, emphasising the need for ICL-based design thresholds to avoid sudden collapses in shear-critical zones.

3.4 Failure mechanism

All specimens with openings located at 1D and 2D failed through opening corners, characterised by two tensile cracks in tension zones (Fig. 8). For the R64 group, these cracks propagated through the web, terminating at the flange-web joint without inducing joint fracture, ultimately leading to web failure, as shown in Fig. 9. This can be attributed to the stress concentration in the web which caused the fracture. However, in the R102 and R127 groups, tensile cracks propagated gradually toward the web-flange joint, triggering debonding and resulting in abrupt failure (Fig. 10). This effect was most pronounced in 127×260 mm openings positioned at the 2D location. The span between the 2D position and the support generated shear stress and bending moments within the web, ultimately causing full fracture. Notably, the tensile cracks were primarily tiggered from slightly below the corner offset due to the 3mm radius corner design, as shown in Fig. 11(a).

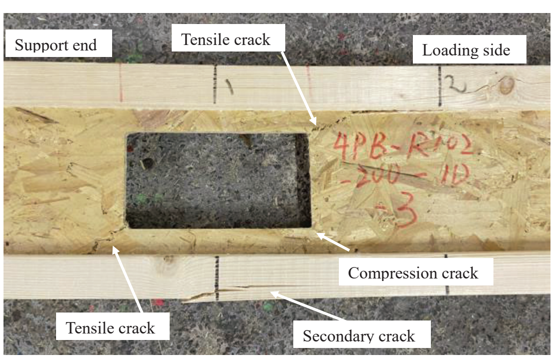

Figure 8. A typical opening failure of I-joist

Additionally, specimens with 127×260 mm openings at 1D exhibited a visible web slippage, as illustrated in Fig. 11(b). This behaviour arose because of failure in the

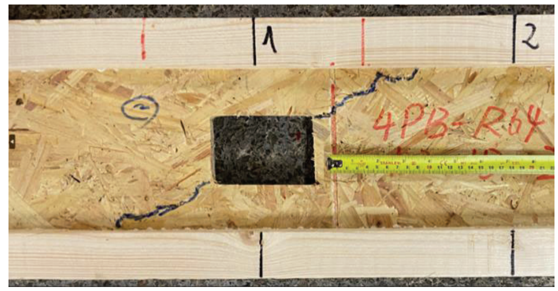

Figure 9. Typical failure mode in R64 specimen with web joint close to opening

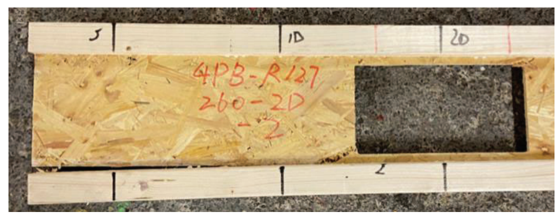

Figure 10. A typical failure in 127×260 specimen

Figure 11. Typical failure patterns in I-joist

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interface between the web and flange due to the horizontal shear forces.

Compressive failures, though non-critical, induced lateral deformation and buckling in outer web strands (Fig. 11(c)). Resin joint fractures in the core layer produced wedge-shaped splits, while outer strands exhibited longitudinal or transverse tearing, forming sharp edges (Figs. 11(d–e)). It was also found that web joints near the openings were not associated with the initiation of crack formation and exhibited negligible influence on structural performance of I-joists.

4 – CONCLUSION

This study systematically evaluated the influence of rectangular web openings on the structural performance of timber I-joists, focusing on the effect of opening size and opening location on the load-carrying capacity and failure mechanisms. Key findings and implications are summarised as follows:

1. Openings in shear-dominated regions near supports significantly reduce load capacity, while those in bending zones have minimal impact, emphasising the critical role of location in design.
2. The greater the height of the opening, the greater the effect of the width, suggesting the need for height-to-web ratio limits in shear-critical zones.
3. Failures are consistently initiated at opening corners, propagating as tensile or shear cracks.
4. The effect of opening on the stiffness is more pronounced in opening with a larger height (i.e., 82% of web depth).
5. The research could be extended to investigate more opening configurations (e.g., multiple openings) as well as under real-world loading conditions.

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