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AN EXPERIMENTAL INVESTIGATION INTO THE STRUCTURAL PERFORMANCE OF TIMBER I-JOISTS WITH CIRCULAR WEB OPENINGS

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ABSTRACT: Wood I-joists are widely used in residential construction. Openings are often made in the webs of I-joists to accommodate building services. This study investigates the structural behaviour of timber I-joists with circular openings of varying sizes at different locations along the length of joist. A four-point bending test was conducted to evaluate the load-carrying capacity, stiffness, and failure modes of I-joists with and without openings. The concepts of high shear, combined shear bending, and pure bending zones were introduced. The results revealed that openings located in the high shear and combined shear bending zones had a similar impact on the capacity of I-joists, with larger openings leading to higher reductions, and up to 36% reduction was observed when opening size was 82% to the web height. Most joists with openings in shear zones exhibited shear failure through openings. In contrast, openings in the pure bending zone did not affect the load-carrying capacity of joists and the failure modes were similar to I-joist without openings. These findings emphasise that the opening location must be carefully considered in I-joist design. Reinforcement might be needed to ensure safety when the openings are placed near supports.

KEYWORDS: Wood I-joist, Web opening, Stiffness, Load-carrying capacity, Failure mechanism

1 – INTRODUCTION

1.1 Wood I-joist and web opening

The development of timber I-joists in the late 1960s marked a significant advancement in engineered wood products, addressing the limitations of traditional sawn timber in structural applications. Inspired by the geometry of steel I-joists, timber I-joists were optimised to use less material while maintaining structural performance. By combining two flanges and a web to maximise strength-to-weight ratios while minimising material usage, the design offers flexible span capacity and enhanced dimensional stability compared to solid timber, making it exceptionally well-suited to the demands of construction [1].

Early designs of timber I-joists featured high strength-to-weight ratios with flanges made of solid wood or laminated veneer lumber (LVL) and webs made of plywood. In the 1980s, timber I-joists gained popularity, especially in residential and light commercial buildings, due to their longer span and greater stability compared to traditional solid timber [1]. Materials also advanced significantly during this period, as oriented strand board (OSB) began to replace plywood webs due to its better cost-effectiveness and shear strength. Standardisation efforts ensured consistent product quality and performance, further promoting adoption by builders.

In the 1990s, with advances in manufacturing technology and the integration of engineered wood systems, timber I-joists became an integral part of modern construction. By combining I-joists with other engineered wood products, manufacturers created efficient and reliable framing systems that can be used in the construction of floor and

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roof. Improvements in web and flange materials, including the refinement of OSB and the development of durability in flange material, enhanced the structural performance of I-joists. By the 2000s, I-joists had become a standard structural member in residential and light commercial construction, prized for their flexibility, structural strength, and efficient use of resources [2].

In wood frame construction, limited headroom constraints often require the introduction of openings in the I-joists for the installation of piping, wiring, and other utilities [1, 3]. On construction sites, builders frequently cut openings in the web of I-joists to facilitate the installation of these systems. However, inappropriate modifications of these I-joists can severely compromise the structural performance of the I-joists and may lead to premature failures that affect the safety of the entire system. The influence of such openings primarily depends on their size, shape, and location along the length of the joists. The following section provides more details on published studies that were conducted to examine these factors.

1.2 Opening size

Limited research has been conducted to evaluate the effect of openings on the structural performance of I-joists, with a main emphasis on opening size, which is commonly determined in conjunction with web height (h_w). Afzal et al. [4] experimentally investigated the influence of circular opening and square opening ranging from 25%-100% and 20%-100% of h_w, respectively. The test comprised testing 302 mm and 406 mm deep I-joists through three-point bending. I-joists with circular openings that were 100% of the web depth experienced a significant reduction in strength, losing approximately 72% of the capacity. Whereas, circular openings with a size equal to 25% of the joist depth had minimal or no impact on the strength and stiffness of the I-joists. Results indicated that the relationship between the increase in opening size and reduction in capacity appeared to be almost linear, suggesting that a mathematical model could be developed to quantify this correlation.

A similar result was reported by Zhu et al. [5], who investigated the structural performance of wood I-joists with two adjacent openings (circular or square) and their interaction through experimental-based four-point bending tests and Finite Element (FE) modelling. They suggested that the minimum distance should be twice the opening diameter to avoid interaction occurring. They also introduced the concept of initial cracking load, which was defined as the load at which the OSB web first develops cracks, typically originating from the tension corners of the openings. The initial cracking load was determined through audible cracking noises, strain gauge reading, and visual inspection. The FE predicted results showed that both initial cracking and ultimate loads decreased linearly with an increase in opening size.

Morrissey et al. [6] investigated the effect of opening size on I-joist with multiple openings and also reported that larger web openings in I-joists result in greater reductions in ultimate load capacity and stiffness. The study involved testing specimens with depths of 241 mm and 302 mm under uniformly distributed loading. Of the 241 mm deep I-joists, opening configurations were classified as either "acceptable" or "unacceptable" according to the manufacturer's guidelines which specified the minimum distance from opening centre to the support with regard to the opening size and dimension of joists [7]. The 302 mm deep joists were tested with a single 152 mm opening at varying distances from the support, where 152 mm openings reduced ultimate loads by up to 44% and increased service load deflections by up to 17% compared to joists with 76 mm openings.

1.3 Opening location

In practice, joist manufacturers advise placing openings in regions subjected to lower shear stress, such as midspan of joist, to minimise the impact on the structural performance of the joist. However, in some cases, openings are required to be located close to the support due to the feasibility of electrical and drainage systems. The location of a web opening within the length of the I-joist is critical and needs to be considered. In the research conducted by Zhu et al. [5], the effect of opening location on the load-carrying capacity was found to be small as the specimens experienced different bending but constant shear under four-point bending loading conditions. It was recommended that further research was required to assess the impact of opening location on the capacity under different loading conditions.

Morrissey et al. [6] discovered that large web openings located closer to the high shear regions near the supports resulted in greater reductions in load capacity, up to 53% lower than solid joists under uniformly distributed load. Moreover, the presence of web openings reduced the overall stiffness of the joists, with deflections increasing up to 37% at service loads when openings were in high shear zones.

Shahnewaz et al. [8] investigated the influence of openings in shear-dominant (3.6 m long) and bending-dominant (6.1 m long) joists. In total one hundred specimens were tested under four-point bending to evaluate the effects of single circular openings with varying sizes and locations. A 58% reduction was

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observed in a 94% sized opening (with respect to the web depth) when it was located at 2D from support. The reduction in capacity was more pronounced in shorter-span I-joists compared to longer-span I-joists. It was also pointed out that openings spaced closer than to support have compounded negative effects. However, the openings located in the pure bending zone were not assessed in the research.

1.4 Existing analytical model

Although timber I-joists are commonly used for roof and floor systems in timber frame buildings, there is limited guidance available for determining the load-carrying capacity and deflection of joists with web openings. Some I-joist manufacturers published guidelines including tables and charts providing information on the allowable web hole sizes and locations for their products, the information published is generally based on the results of empirical testing procedures specified by ASTM D5055 [9] and guidelines published by the Wood I-Joist Manufacturers Association (WIJMA) [10] with limited applicability.

Some attempts have been made to develop mathematic models that can predict the load-carrying capacity of joists with web openings. To allow design engineers to estimate the load-carrying capacity of I-joists with web openings for any loading condition and span, Pirzada et al. [3] developed a mechanic-based method to predict the strength of wood I-joists with a circular opening. By incorporating the Winkler-Bach curved beam theory to calculate stresses around the opening and finite area method to predict the failure load from calculated stresses, the simplified equation was developed and shown as follows:

$$P_{failure} = 2\sqrt{x_0 E^* G_C / 2\pi}\left[\sigma_t\left(2\sqrt{(pk)\pi x_0} - (pk)\pi\right)\right]^{-1} P_{applied} \quad (1)$$

Where $P_{applied}$ is applied load, x_0 is length parameter, E^* is equivalent modulus of elasticity for an orthotropic web material, G_C is critical fracture energy of web, σ_t is peak stress at the boundary of the hole, p is web hole ratio, k is empirical constant

The method was validated against test results from experiments conducted by Afzal et al. [4]. However, the method tends to underestimate the failure load within 75-92% of test results, and the effect of opening location was not taken into consideration in the proposed model.

Zhu et al. [5] derived an empirical equation to predict the failure load of I-joists with web openings through regression analysis based on the results from experimental work and FE modelling. The equation was developed on taking account of opening size and web depth but it did not consider the opening location and I-joist dimension:

$$P_{ult} = 36.4 - 25.9(d/h_w) \quad (2)$$

Where P_{ult} is applied load, d is opening diameter, h_w is web height

Shahnewaz et al. [8] developed a regression analysis-based equation to predict the load-carrying capacity of I-joists with a circular opening. The two major variables that affect the load-carrying capacity, suggested by Afzal et al. [4] were included in the models:

$$P = 64.8 - 1.5(L/D) - 54.3(d/h_w) + 1.9(L/D)(d/h_w) \quad (3)$$

Where P is load-carrying capacity; L is span length; D is joist depth; d is opening diameter; h_w is height of web

There is a good correlation between the experimental and numerical simulation results derived from those equations. Future work was recommended to validate these equations on I-joists with different lengths and depths.

A review of existing literature shows that although researchers have attempted to evaluate the effects of openings on the structural performance of I-joists. However, to the authors' knowledge, there remains a gap in understanding the behaviour of I-joists with circular openings—specifically regarding the influence of opening size and location along the joist span. Existing mathematical models are not adequately validated, highlighting the need to assess their applicability. This research addresses these gaps and investigates the impact of openings on the stiffness of I-joists, which has not been fully explored. In addition to this, failure mechanisms and associated load-deflection responses are presented.

2 – MATERIAL AND METHOD

2.1 Test specimen

A total of thirty-six, 245 mm deep I-joists with a span of 2.45 m were used. I-joist flanges had a nominal cross-section of 47×45 mm, made from C24 Picea abies with an allowable bending strength of 24 N/mm^2. The moisture content was within 15%-18% when it was fabricated. OSB webs of grade 3 were made from spruce and pine strands with the out layer aligned longitudinally to the span. The thickness of web was 9.2 mm with a tolerance of ± 0.8 mm. Webs were manufactured with 2.44 m spacing between web-to-web joints. All specimens were fabricated at the James Jones & Sons.

Timber Systems Division, Scotland. The specimens were from same production line and chosen from random packs comprising 4 production dates. Circular holes were made using a hole saw. The circular openings had three different diameters: 64 mm, 102 mm, and 127 mm, corresponding to approximately 41%, 66%, and 82% of the web depth, respectively.

Openings were located at three locations that were subjected to different shear and bending stress ratios. Opening locations of high shear zone (1D from support), combined shear bending zone (2D from support), and pure bending zone at mid-span (4.5D from support) were chosen. The three opening locations are illustrated in Fig. 1.

2.2 Test setup

All the I-joists were tested under four-point bending in accordance with EOTA standard [11] and ASTM D5055 [9]. The joists were simply supported as shown in Fig. 1, lateral restraints were provided on both sides of the flanges along the length of I-joists at a spacing of 300 mm to avoid possible lateral buckling. Loading points were placed at 3D and 6D from support. At each loading point, 95×70×18mm steel plates were placed on the top flange to prevent local crushing of the flange. The load was applied through a servo-electric ram with a maximum load capacity of 100 kN. Testing was displacement controlled with a constant loading rate of 4.2 mm/min to ensure failure occurred within 600 ± 300s to comply with EOTA standard [11]. All the specimens were tested until they failed. Load-carrying capacity (load at failure) was measured from the load cell. The deflection was measured at mid-span using strain gauge based displacement transducers with a range of 25 mm.

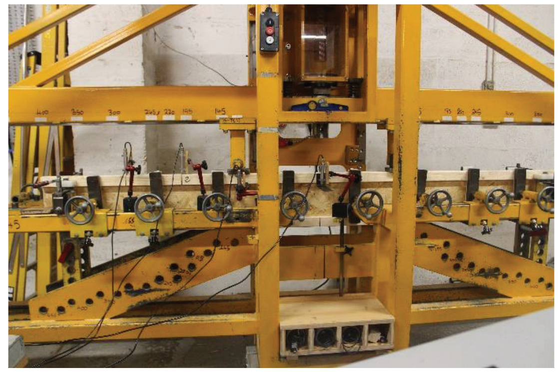

Figure 2. The test rig

3 – RESULTS AND DISCUSSION

Table 1 summarises the average load-carrying capacities, stiffness values, and corresponding coefficients of variation (COVs) for each test group. The load-carrying capacity was determined at the point where crack propagation caused ultimate failure, leading to an abrupt load loss. Stiffness was calculated using regression analysis of the load-deflection data between 10% and 40% of the failure load, in compliance with BS EN 408 standards [12].

3.1 Load-carrying capacity of i-joists

Two specimens were excluded from the baseline group (i.e., I-joists without openings) due to material defects. The average load-carrying capacity of the baseline group was 29.8 kN, with a COV of 12%, a maximum of 34.4 kN, and a minimum of 22.8 kN. The observed average failure load slightly exceeded the predicted capacity based on characteristic material properties (27.3 kN).

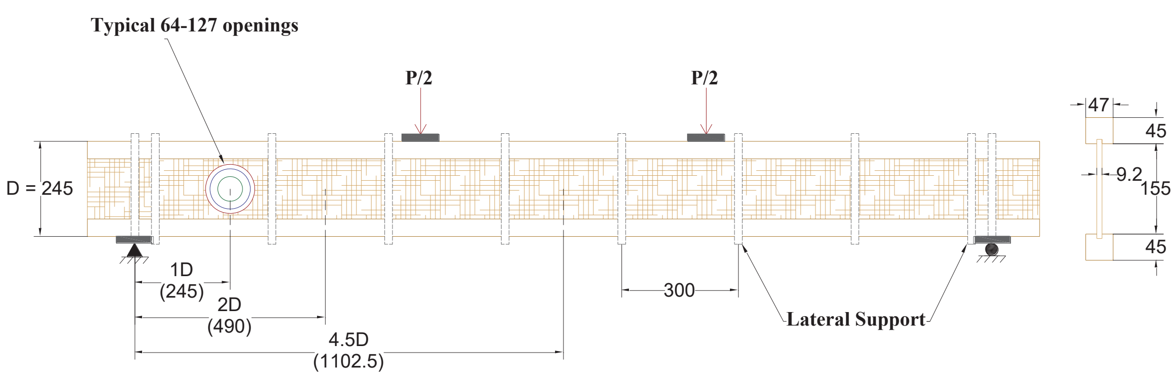

Figure 1. Test set up

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Table 1: Test results

Group	Opening Size	Opening height to web depth ratio (%)	Opening Location (from support)	No. of Specimen	Load-carrying capacity			Stiffness	
	Diameter (mm)				Average failure load (kN)	COV (%)	Reduction (%)	N/mm	COV (%)
Baseline	0	0		8	29.8	12		1577	12
C64	64	41	1D	3	27.7	14	7	1711	14
C102	102	66	1D	3	22.3	2	25	1613	2
			2D	6	22.2	7	25	1557	7
C127	127	82	1D	3	20.1	1	32	1529	1
			2D	6	19.1	7	36	1542	7
			4.5D	5	32.8	9	-10	1718	7

With the introduction of openings, a 64 mm diameter opening had a minimal impact on capacity, reducing the load-carrying capacity by only 7% within the high shear zone (1D). Among the three tested specimens, two achieved a higher load-carrying capacity than the average value of baseline joists. Therefore, 64 mm openings were not considered for the 2D or 4.5D configurations, as their effects were not considerable. A similar result was found by Shanewaz et al [8] when they tested similar opening size which led to a 10% decrease in capacity.

However, in this work, it was observed that larger openings resulted in significantly higher reductions in capacity. Specifically, C102 openings at 1D decreased capacity by 25%, while C127 openings at the same location led to a reduction of 32%. These findings agree well with previous research, which indicated that the relationship between an increase in opening size and a reduction in capacity is nearly linear [5].

The most significant reduction in load-carrying capacity (36%) occurred with 127 mm diameter openings positioned 2D from the support, slightly exceeding the reduction observed for the same-sized opening placed within the high shear zone by 4%. The difference might be attributed to the interaction between shear and bending moment. For 102 mm openings, both 1D and 2D placements resulted in identical 25% reductions in capacity. Which indicated that larger openings might be more sensitive to the additional bending moment.

It can be concluded from the results that C102 openings resulted in a similar reduction in capacity regardless of their location as well as C127 openings, suggesting a negligible difference between openings in the high shear zone and those in the combined shear bending zone. The similar impact on the capacity across both opening locations indicates that the influence of bending may not be considerable.

To further investigate the effect of opening on the bending strength, the impact of openings at 4.5D, located in the pure bending zone, was assessed. All the openings within the pure bending zone did not influence the load-carrying capacity even when the opening diameter was 82% of the web depth. This is demonstrated by comparing the baseline group with C127 group, where the baseline achieved a failure load of 29.8 kN, while C127 slightly exceeded it at 32.8 kN. This small increase can be attributed to variations in individual specimen strength, as the COV for the baseline joists was 12%, whereas C127 had a lower COV of 7%.

3.2 Load-deflection response

As shown in Fig. 3, the load-deflection behaviour of the baseline group primarily exhibited two types: four out of eight joists demonstrated elastic behaviour and failed, while the other four exhibited elasto-plastic curves, resulting in nonlinear behaviour.

For specimens with openings, as similar load-deformation responses were observed among individual specimens, only representative curves are presented in Fig. 4.

In terms of joists with openings at 1D and 2D, the specimens demonstrated an initial linear elastic phase dominated by elastic deformation of the flanges and web, followed by a gradual transition to an elastoplastic phase as yielding propagated through critical regions. Notably, the curves remained smooth throughout testing, devoid of abrupt discontinuities (e.g., load drops or successive spikes), indicating a stable progression of deformation mechanisms without brittle fracture or sudden instability

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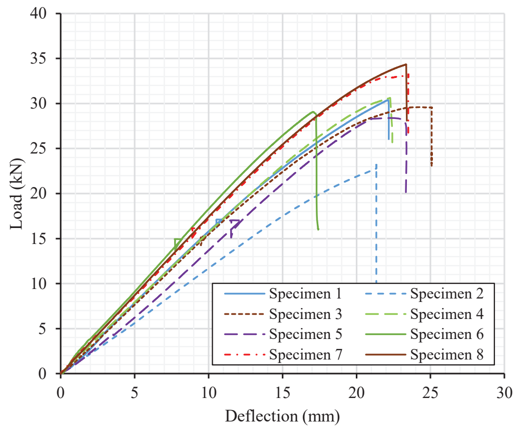

Figure 3. Load-deflection curve of baseline group

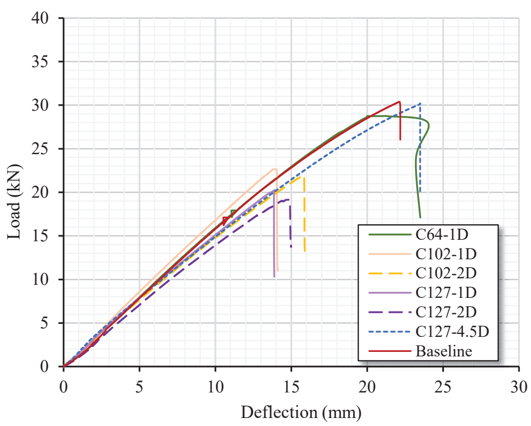

Figure 4. Typical load-deflection curves

As for mid-span stiffness, there was no obvious impact due to the presence of web openings compared to the baseline joists. Similar findings were reported by Fergus [13], who investigated the impact of circular openings on moment-governed I-joists (7.3 m long) and shear-governed I-joists (2.4 m long), finding no significant reduction in stiffness even when up to 70% of the total web height was removed.

The results showed that the stiffness of series C64-1D, C102-1D, and C127-4.5D was greater than that of the baseline joist. This suggests that the presence of openings in the bending zone does not adversely affect the structural performance of I-joists.

3.3 Existing analytical model

A comparison between test results and predictions on the capacity of I-joists from (1), (2), and (3) was conducted to evaluate the applicability of existing analytical models. The predictions from the three models are compared with test results of openings at 1D, illustrated in Fig. 5 and summarised in Table 2. Table 2 also provides the percentage errors of the models relative to the test data. While Pirzada's model and Zhu's model show agreement, the latest model from Shahnewaz et al. [8] differs significantly from other predictions. Zhu's model shows good predictions of capacity for small openings, with a 7% error, whereas it has errors of 13% and 24% for the C102 and C127 openings, respectively. Pirzada's model consistently underpredicts capacity, with errors ranging from 12% to 14% for different opening sizes.

Shahnewaz's model demonstrates suitability for large web openings with a web depth ratio of 82% but overestimates capacity for smaller openings. It can be concluded that the mechanics-based model is more applicable compared to empirical equations. However, existing models do not provide accurate predictions compared to test results from this research. A more sophisticated model with more applicability is needed.

Table 2: Predicted and experimental failure loads

Group	Failure Load						
	F_{ex}	$F_{Pirzada}$ [a]		F_{zhu} [b]		$F_{Shahnewaz}$ [c]	
		kN	(%)	kN	(%)	kN	(%)
C64-1D	27.7	24	-14	25.7	-7	35.9	30
C102-1D	22.3	19	-13	19.4	-13	26.8	20
C127-1D	20.1	18	-12	15.2	-25	20.8	3

a. Pirzada et al. [3]
b. Zhu et al. [5]
c. Shahnewaz et al. [8]

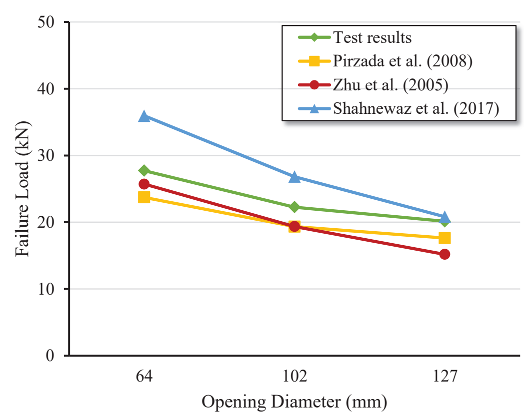

Figure 5. A comparison between test results and predictions

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3.4 Failure mechanisms

3.4.1 Failure mode of baseline joists

The baseline I-joists exhibited two main failure modes: (1) combined tension shear failure, and (2) compression failure in the top flange and web buckling, as shown in Fig. 6. Out of the 10 tested specimens, two were excluded due to the unsatisfactory quality of the OSB, which caused premature failure and achieved low load-carrying capacity of 15.2 kN and 18.7 kN, much lower than the design value. Four specimens exhibited compression failure in the top flange, characterized by localized crushing resulting from wood embedment effects (e.g., stress concentrations at support interfaces). The remaining four specimens failed due to tension failure at the bottom flange which propagated up through the web and top flange.

3.4.2 Failure mode of I-joists with web openings

Apart from one joist with a 64 mm diameter opening, which did not fail through the opening but through web buckling as half of the baseline joists, all I-joists with openings located in the high shear zone and the shear-bending combined zone failed through the openings. The typical failure pattern of I-joist with opening is shown in Fig. 7. Cracking sounds were heard at 50–80% of the ultimate failure load. Despite these noises, no visible cracks appeared on the specimen surfaces or signs in the load-deflection curves during this phase, suggesting energy and damage accumulation prior to macroscopic failure. This can be attributed to the layers of strands and glue in the OSB providing resistance. The failure of specimens occurred abruptly, with two simultaneous cracks initiating in the tension zone near the openings (Fig. 7). These cracks propagated diagonally toward the flanges, leading to failure in flanges or ripping the web-flange joint, leading to a loss of composite action between the web and flanges. Fig. 8 compares failure modes across I-joists with different-sized openings at 1D.

It can be observed that all circular openings initiated similar cracks regardless of size, with smaller openings leading to a larger accumulation of energy and a higher degree of post-failure damage. This occurs as smaller openings resist loading for longer durations and achieve higher capacities compared to I-joists with larger openings.

For openings located at 4.5D, all joists failed in a similar manner to the baseline joists, as shown in Fig. 9. Since openings at mid-span do not change the failure pattern or lead to a reduction in the capacity of I-joists, it can be concluded that openings at 4.5D do not adversely affect the structural performance of I-joists. This suggests that circular openings can be safely placed at mid-span of I-joists regardless of their size.

4 – CONCLUSION

1. Openings located in high shear zone and combined shear bending zone can lead to up to 36% reduction in load-carrying capacity of I-joist. This suggests that existence of openings must be considered in design, specifically if they are nearer the support conditions.
2. Circular openings of sizes less than 50% of the web depth have a low impact, whereas openings with sizes above 50% have a substantial impact on the load-carrying capacity of I-joists.
3. Openings in pure bending zone have no influence regardless of the opening size.
4. Openings in the shear zone tend to lead to a more brittle failure related to tension stresses in the OSB web.
5. Existing analytical models lead to overestimation or underestimation of the strength of I-joists with

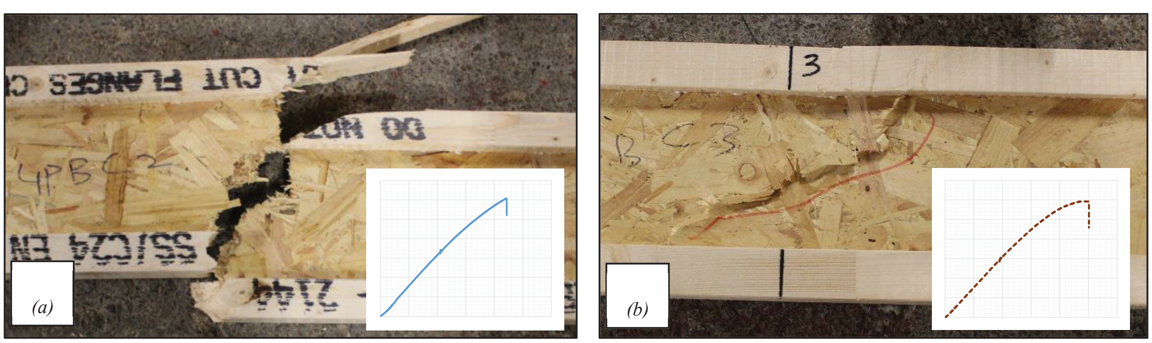

Figure 6. Failure mode of baseline joists
(a) failure and load-deflection curve of specimen 1(b) failure and load-deflection curve of specimen 3

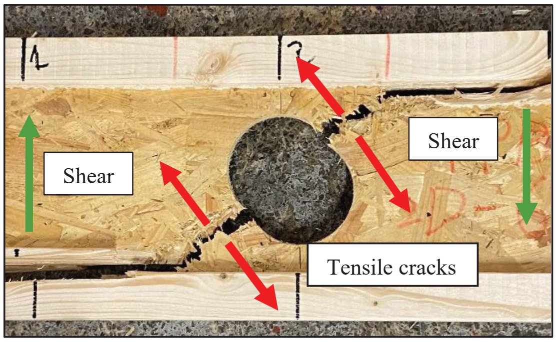

Figure 7. Typical failure mode

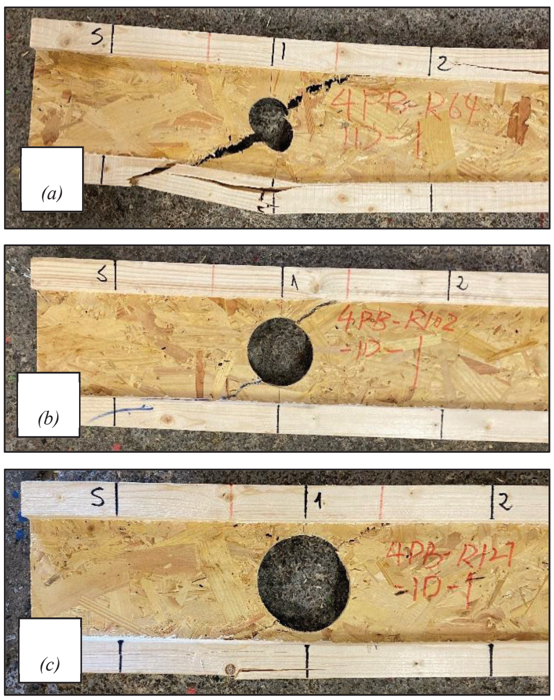

Figure 8. I-joists with opening located at 1D
(a) C64 opening; (b) C102 opening; (c) C127 opening

openings. More sophisticated models are needed to predict the effect of web openings on the strength of I-joists, taking into account different moment and shear ratios.

6. Mid-span deflection for the tested I-joists was unaffected with web openings ranging from 41%-82%.

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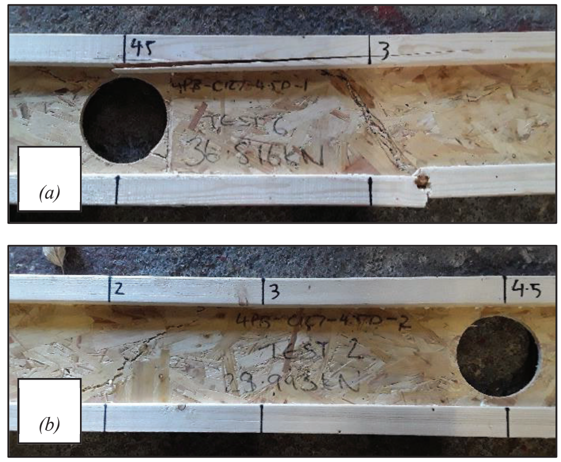

Figure 9. Failure mode of C127-4.5D specimens
(a) bottom tension failure
(b) compression and web buckling failure

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