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Structural evaluation of castellated timber *I*-joists

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ABSTRACT

A novel timber *I*-joist with a castellated web is presented. While castellated webs are common in steel joists, this concept is new to timber joists. The openings provided by the castellation process provide for the easy passage of services during construction or subsequent remodelling of a building. The manufacturing process is described together with details of tests on twelve 241 mm and eleven 305 mm deep joists. The load–deflection response, failure loads and modes of failure are given. The mean failure moment and shear force for the 241 mm deep joists were found to be 8.2 kN m and 6.0 kN, respectively. The corresponding values for the 305 mm deep joists were 12.5 kN m and 6.9 kN. The predominant failure modes were tension failure in the web at the corner of the openings and shear failure in the web at mid-depth between the openings. The effect of the web openings on the joist stiffness is not significant but the shear capacity is reduced. The reduction in shear capacity compares favourably with the shear capacity of commercial joists of equivalent sizes with circular or rectangular openings.

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1. Introduction

Timber *I*-joists are now widely used as primary structural elements in floor and roof applications in residential construction [1,2]. They have a number of advantages over solid lumber joists: by concentrating most of the material away from the neutral axis, the flexural stiffness and load carrying capacity are enhanced; in common with all engineered wood products, they have improved dimensional stability; and they are lighter and easier to handle. In order to minimise construction depth, services are often integrated into floors by passing them through openings in the web.

As web openings result in a reduction in shear capacity, manufacturers of *I*-joists specify limits on the size and location of openings to ensure that the structural integrity of their product is not compromised. There is always the danger that these rules will be contravened during initial construction or subsequent remodelling of a building.

A new castellated timber joist design is proposed that incorporates pre-formed holes in the web, as seen in Figs. 1 and 2. These novel joists will facilitate the installation of services as they can easily pass through the web openings. Other advantages associated with the castellation of the web include enhancement of the flexural capacity due to increased section depth and minimisation of the material waste that occurs when drilling holes. The shear capacity of the joists, on the other hand, is reduced due to the presence of the web openings.

The widespread use of castellated steel beams has led to several studies of their structural performance. A number of different failure modes have been identified for these beams including: shear failure of the tee-sections above and below the holes, shear failure of the web weld at mid-depth, in-plane web buckling and distortional buckling [3,4]. Redwood and Demirdjian [3] carried out tests on four steel castellated joists, all of which displayed buckling of the web-post between the holes. They found that the failure loads were not sensitive to the moment-shear ratio. Zirakian and Showkati [4] investigated the distortional buckling of steel castellated beams. They tested six beams and in all cases the beams underwent lateral buckling accompanied by web distortion. Liu and Chung [5] used a numerical model to investigate the influence of opening shape, opening depth and beam size on the structural performance of castellated steel beams. They found that the load–displacement responses and failure modes were similar for the different sizes and shape openings. The modes of failure reported were shear failure, flexural failure and yielding of the tee-section above and below the holes, and these depended on the loading, the support conditions and the location of the openings.

As the use of castellated webs in timber *I*-joists is a new concept, there have been no studies published on their structural behaviour. The impact of circular and square web openings on the structural performance of timber joists has been examined in a number of studies [6–9]. These researchers have focused mainly on joists with one or two openings. Afzal et al. [6] carried out three-point shear tests on a large number of commercial *I*-joists of two different depths, each having either one or two circular or square web holes located in the centre of the shear span. The percentage reduction in failure load for a particular hole-size to web-depth ratio was found to be independent of joist depth. Square holes were found to have a

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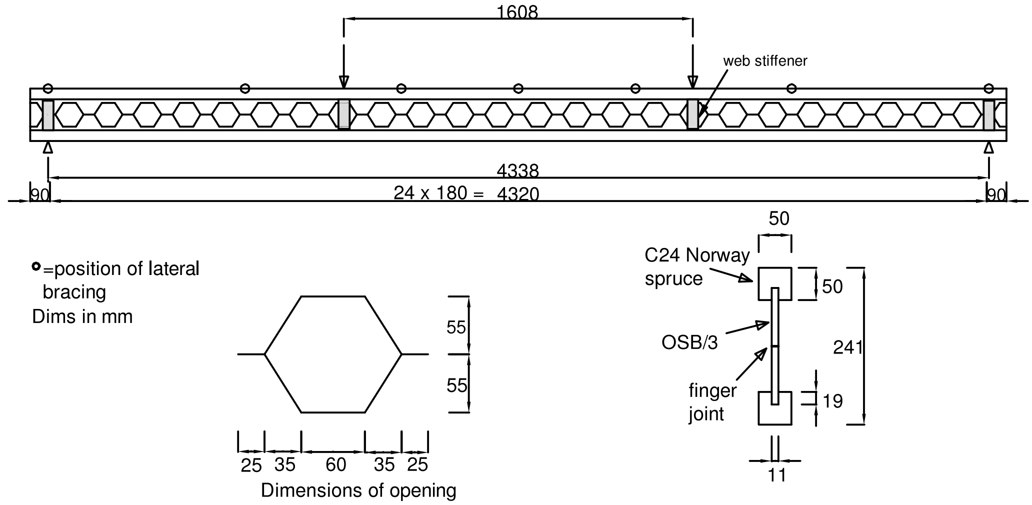

Fig. 1. Details of 241 mm deep castellated joist — bending test arrangement.

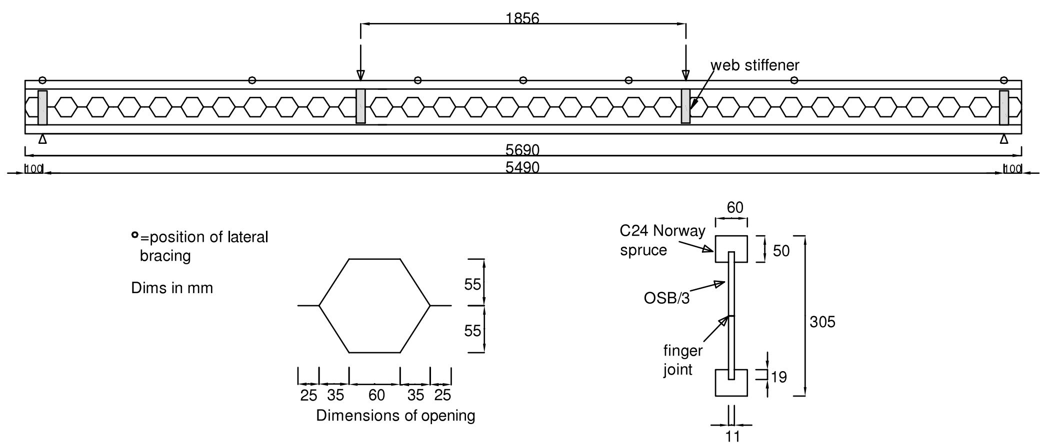

Fig. 2. Details of 305 mm deep castellated joist — bending test arrangement.

bigger negative impact on strength than an equivalent circular hole due to the stress concentration effect in the corners. Web buckling did not occur in any of the tests. Morrissey et al. [7] carried out tests on commercial *I*-joists with circular and square openings of different sizes. They found that the presence of openings resulted in a change of failure mode from failure of the tension flange in a series of control joists without openings to shear failure through web openings for both circular and square openings. Flexural testing of joists with holes located in zones considered acceptable by the manufacturer and also in unacceptable zones showed that, while the load capacities were reduced, they were still well above the prescribed design loads. This would seem to indicate that the current restrictions on web openings are conservative. They also reported that as the hole size increased, the failure mode changed from tension failure of the bottom flange to failure in the web with failure planes through the openings at 30°–45° to the horizontal. Zhu et al. [8] carried out tests on *I*-joists with circular and square openings. They found that failure initiated in the tension zones of a hole with the opening of cracks, which then developed at about 45° to the axis of the beam. Collapse occurred when the crack reached the flange. Square openings resulted in a greater reduction in load-carrying capacity than circular openings, while the location of the opening had no effect. They investigated the interaction between a pair of openings and found that when the distance was reduced below a critical value, shear failure of the web between the openings occurred. Wang and Cheng [9] examined the shear response of timber *I*-joists with rectangular openings by testing beams of three different depths with a single opening. Openings of different dimensions were studied. Three different failure modes were observed: the web/flange connection failure, tension failure at corners of openings and web buckling. They also examined the influence of the corner radius on the performance and found that it was negligible.

This paper presents the results of an experimental programme, which involved the testing of castellated timber joists of two different depths in both bending and shear. The stiffnesses, load capacities and failure modes are presented in each case. An assessment of the performance of these joists is made by comparing them with published design values for commercially available *I*-joists.

2. Manufacture and testing of joists

Castellated joists were manufactured in two depths using grade C24 Norway spruce flanges and OSB/3 castellated webs. Full details of each joist are given in Figs. 1 and 2. The manufacturing process involved a number of steps. In the first step, the castellated webs were formed by cutting a saw-tooth pattern in the OSB using a CNC router. The first four positions of the router are shown in Fig. 3(a). The router follows a linear path between these positions and this pattern is continued along the full length of the web. Each separate web section is then glued to the top and bottom flanges with a PRF adhesive. A 19 mm deep groove was routed in the flanges to accommodate the web. The two sections of the

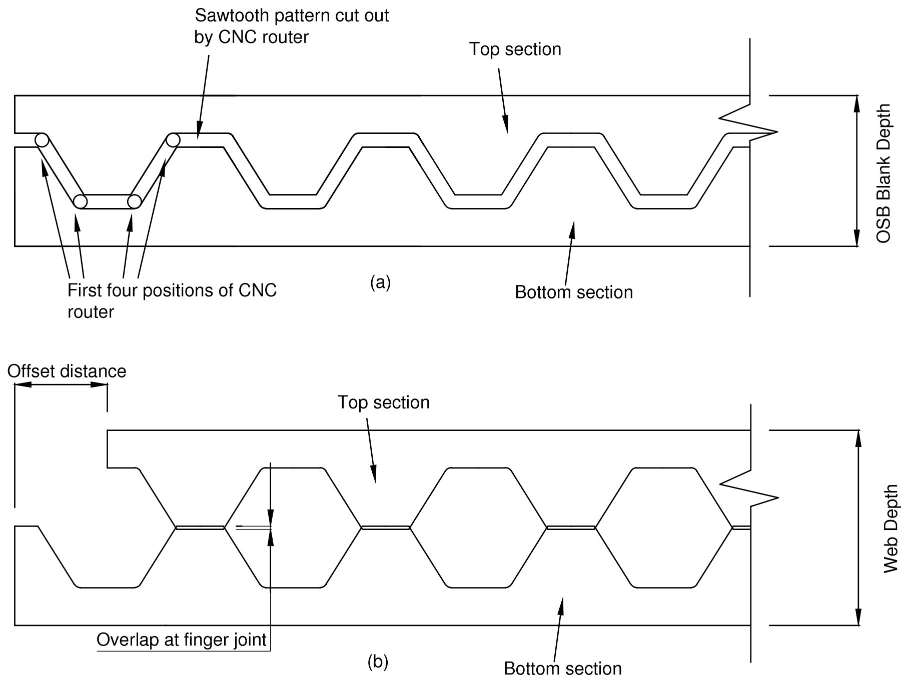

Fig. 3. Manufacture of castellated web: (a) Original OSB blank panel with sawtooth pattern; (b) Castellated OSB web.

Fig. 4. Solid end section.

I-joist are then offset and connected together using finger joints. This results in a web pattern with hexagonal holes as shown in Fig. 3(b). Two different cutter diameters were used in the cutting of the castellation pattern, namely 6.35 and 12.7 mm. Depending on the cutter used, the fillet radii for the top and bottom corners of the openings were varied. For all joists, OSB/3 panels, having a nominal thickness of 11 mm, were used. The flange sizes for the 241 and 305 mm deep joists were 50 × 50 mm and 60 × 50 mm, respectively. For each flange, the modulus of elasticity in bending was determined using a Cook Bolinders machine grader. In order to provide for some flexibility in the joist length, a solid end section is provided at the ends of the web near each support (Fig. 4). A minimum length of 275 mm was chosen to ensure an adequate length is available to enable site adjustments. Web stiffeners are provided at the positions of the point loads in order to cater for the effects of bearing. Where the loading point is over an opening, the opening is infilled with OSB prior to the attachment of the stiffener. Manufacture of the joists was carried out at the Wood Technology Centre at the University of Limerick.

The experimental programme involved testing of 23 joists in total. Of these, Test Series 1 comprised bending tests on 9 joists with an overall depth of 241 mm while, in Test Series 2 bending tests were performed on 8 joists, with a depth of 305 mm. For the final series, 3 joists of each depth were tested in shear. All testing was carried out in the Timber Testing Laboratory at the National University of Ireland, Galway. Bending and shear tests were carried out for each joist in accordance with EOTA standard TR002 (2000): test methods for light composite wood-based beams and columns [10]. All joists were tested in four-point bending over a simply-supported span of 18 times the joist depth for the bending tests and 10 times the joist depth for the shear tests. The testing arrangement and dimensions for each test are given in Figs. 1 and 2 and Table 1. All tests were displacement controlled in order to track the response close to failure. Prior to testing, all joists were conditioned at a relative humidity of 65% and temperature of 20 °C. Fig. 5 shows a castellated joist undergoing a bending test. Lateral restraints were provided to ensure that premature failure due to lateral buckling would not occur. It is anticipated that the *I*-joists being considered in the current work are to be used in residential floor construction where the nail contact between the floor and the *I*-joist will resist buckling of the top flange. Additionally, blocking is commonly used to resist buckling in practice. The joist stiffness was determined by loading each joist up to 40% of the load capacity and measuring the mid-span deflection using an LVDT. For the strength tests, the joists were loaded at a rate that ensured that failure occurred within 600 ± 300 s, as required by the EOTA standard [10].

Table 1
Test geometry.

Joist depth (mm)	Test	L (mm)	L/d	a (mm)	a/L
241	Bending	4338	18	1365	0.31
305	Bending	5490	18	1817	0.33
241	Shear	2410	10	438	0.18
305	Shear	3050	10	610	0.20

3. Test results

3.1. Series 1: bending tests on 241 mm deep joists

The bending test results for the 241 mm deep joists are summarised in Table 2. The load/deflection response was determined from the slope of the load–displacement curve between 0.1 and

Table 2
Bending test results for 241 mm deep joists.

Joist ID	Stiffness (kN/mm)	Peak load (kN)	Failure mode	Failure moment (kN m)	Failure shear (kN)
241_1	0.4113	12.30	*T*	8.39	6.15
241_2	0.3810	13.85	*T* + *S*	9.45	6.90
241_3	0.3685	11.95	*T* + *S*	8.16	5.98
241_4	0.3354	9.40	*S*	6.42	4.70
241_5	0.3560	11.45	*S*	7.81	5.73
241_6	0.3117	11.85	*T* + *S*	8.09	5.93
241_7	0.4040	12.80	*T* + *S*	8.74	6.40
241_8	0.3702	11.70	*T*	7.99	5.85
241_9	0.3471	12.65	*T*	8.63	6.33
Mean	0.3650	11.99		8.19	6.00
Std dev	0.0318	1.21		0.83	0.60
5 percentile		10.00		6.83	5.00

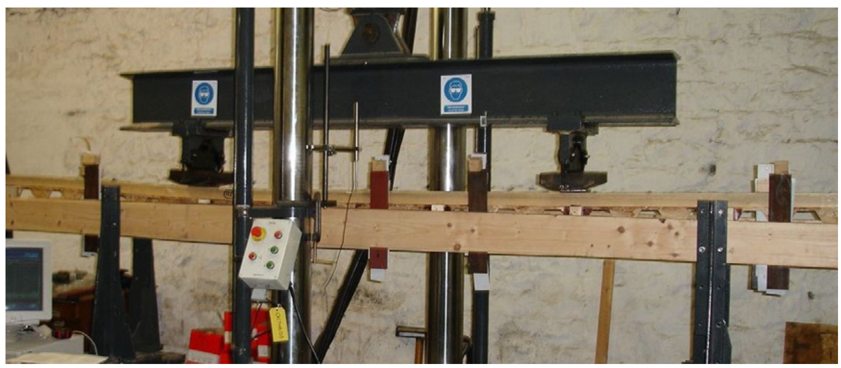

Fig. 5. Castellated joint under test.

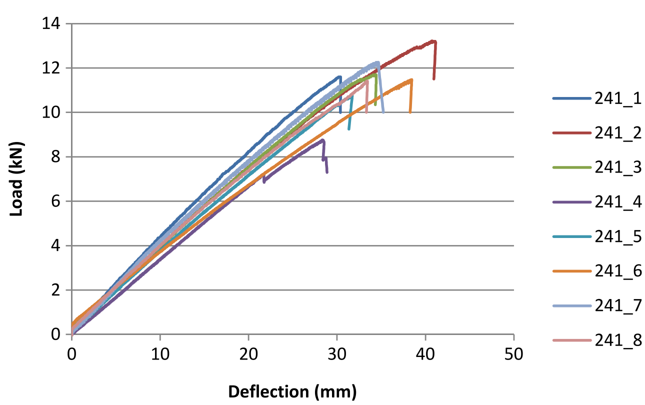

Fig. 6. Load–displacement curves for 241 mm deep joists in bending.

0.4 of the peak load. The peak load and mode of failure were also recorded for each test. The load–displacement response for all joists was fairly linear to failure as can be seen in Fig. 6.

The mean stiffness (load/deflection) value from the nine tests was found to be 0.365 kN/mm. This value is comparable with the theoretical load/deflection values for the equivalent joist with no opening. This is found by getting the inverse of deflection/load value calculated using Eq. (1)

$$\frac{\delta}{W} = \frac{a}{48EI}\left(3L^2 - 4a^2\right) + \frac{a}{A_W G_W} \tag{1}$$

where δ is the midspan deflection, W is the total applied load, a is the distance between the support and load point in the four-point bending test, L is the span, EI is the flexural rigidity of the entire section, A_W is the area of the web, and G_W is the shear modulus of the web material. The second term in Eq. (1) is Roark's approximation for the shear deflection [11]. The mean of the measured modulus of elasticity values of all the Series 1 flanges was 11 677 MPa. Using this value, the theoretical load/deflection value is 0.309 kN/mm. As the measured stiffness was 1.2 times the theoretical stiffness of the joists with no opening, it can therefore be concluded that the stiffness of the joists is not adversely affected by the presence of the openings.

The mean load at failure was 11.99 kN, which corresponds to a bending moment at failure of 8.19 kN m and a shear force at failure of 6.00 kN. Assuming that the joist strengths are normally distributed, the 5% ile value of the failure load is found to be 10.00 kN and the corresponding bending moment and shear force are 6.83 kN m and 5.00 kN, respectively. The peak load for joist 241_4 was only 9.4 kN, which was significantly lower than the other joists and is 18% lower than the next lowest value of 11.45 kN. There were two contributing factors to this premature failure. First, the mean web thickness for this joist was only 10 mm or 9% lower than the nominal value of 11 mm and second, the quality of the finger joint was poor. If the substandard joist was disregarded, then the 5% ile load at failure would increase to 11.13 kN with the corresponding bending moment and shear force values of 7.59 kN m and 5.56 kN.

One manufacturer of commercial *I*-joists with solid webs gives permissible values for moment and shear for their joists [12]. For 241 mm deep joists with a similar flange size to the castellated joists, the short-term maximum moment in non-load-sharing situations under Service Class 2 conditions is 7.41 kN m and the maximum short-term shear is 8.05 kN. The moment capacity of the castellated joists, excluding the defective joist, is 7.59 kN, which is very close to the commercial joist capacity; however, the shear capacity is lower due to the web perforations. The manufacturer [12] gives formulae to calculate the reduction in shear capacity of their joists due to circular or rectangular openings. The shear capacity of joists with a circular hole in the web, V_{circ}, is given as

$$V_{circ} = 0.75\, V_{full\text{-}section}\left(1 - \frac{D}{H}\right) \tag{2}$$

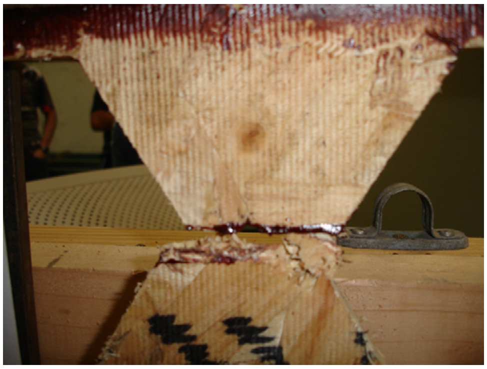

Fig. 7. Shear failure at finger joint.

where $V_{full\text{-}section}$ is the shear capacity of the joist without holes, D is the hole diameter and H is the joist depth.

For a rectangular hole in the web, the shear capacity is

$$V_{rect} = 0.5\, V_{full\text{-}section} \left(1 - \frac{D}{H}\right) \left(\frac{D}{W}\right)^{0.5} \tag{3}$$

where D is the hole depth and W is the hole width.

A circular hole of 100 mm diameter and a rectangular hole, 95 mm wide × 110 mm deep, would provide a smaller opening than in the castellated joist. For the circular opening, the shear strength is reduced to 0.44 times the shear capacity of the full section, or 3.56 kN, while for the rectangular opening the capacity is reduced to 0.29 times the full capacity, or 2.33 kN. The castellated joist performance compares very favourably with this and does not have the added restriction on the position of the openings. Excluding the defective joist, the 5 percentile value of the failure shear force for the castellated joists is greater than the design capacity of the commercial joist with a single circular or rectangular opening by factors of 1.56 and 2.39, respectively.

Two modes of failure occurred, namely, tension failure in the web at the top or bottom corners of the openings (T) or a shear failure in the web at mid-depth either beside or in the finger joint (S). For the case of the tension failure, a crack developed from the corner of the opening to the flange. The crack angle varied between 30° and 45° to the horizontal. In all cases, failure occurred suddenly. Where two failure modes occurred, it was not possible to tell which mode of failure occurred first. Examples of both modes of failure can be seen in Figs. 7 and 8. Tension failure at the corners of openings has been commonly reported in the literature [6–8]. Shear failure of web weld between openings has been reported in steel castellated joists [3,4] while Zhu [8] reported web shear failures in timber I-joists with closely spaced openings. There was no evidence of web buckling during the tests as has been found with both steel and timber joists. This is due to the low web depth to width ratio.

The fillet radius does not appear to influence the structural performance of the joists. Joists 241-1 and 241-2 had fillet radii of 3.18 mm while the remaining seven joists had fillet radii of 6.35 mm. This agrees with the findings of Wang and Cheng [9] for the case of rectangular openings.

3.2. Series 2: bending tests on 305 mm deep joists

The bending test results for the 305 mm deep joists are summarised in Table 3. The load–deflection curves for this series are shown in Fig. 9, where the response is seen to be fairly linear to failure. The mean stiffness (load/deflection) response for the 8 joists was 0.275 kN/mm. For these joists, the mean flange modulus of elasticity was 10 679 MPa. Using this value in Eq. (1),

Fig. 8. Tension failure at corner of opening.

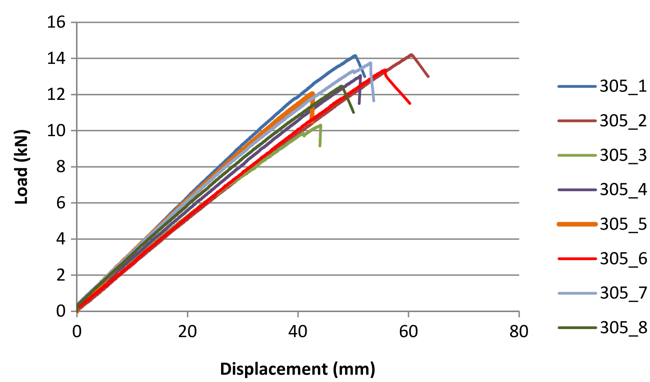

Fig. 9. Load–displacement curves for 305 mm deep joists in bending.

the theoretical load/deflection value is 0.295 kN/mm. In contrast to the findings for the shallower beam, the experimental stiffness of the 305 mm deep joists is 7% lower than the theoretical value. In this case, without further testing, it cannot be definitively stated whether or not the openings influence the deformation response.

The mean load at failure was 13.71 kN corresponding to a bending moment of 12.46 kN m and a shear force of 6.86 kN. The 5 percentile value of the failure load is found to be 11.64 kN and the corresponding bending moment and shear force are 10.57 kN m and 5.82 kN, respectively. For a 302 mm deep commercial I-joist without web openings, the short-term maximum shear force in non-load-sharing situations under Service Class 2 conditions is 9.80 kN [11]. Introducing a 100 mm diameter circular opening or a 95 mm wide × 110 mm deep rectangular opening into the web reduces this to 4.93 and 3.35 kN, respectively. The castellated joist performance compares well with the commercial joist with openings. The 5 percentile value of the failure shear force for the castellated joists is greater than the design capacity of the commercial joist with a single circular or rectangular opening by factors of 1.18 and 1.74, respectively.

The modes of failure of 7 of the 8 joists were similar to those for the 241 mm deep joists. For these joists, the failure was either in tension at the corners of the web openings, in shear at or near the finger joint in the web or both. For joist 305_6, the failure mode was a tension failure in the lower flange at mid-span (F).

Table 3
Bending test results for 305 mm deep joists.

Joist ID	Stiffness (kN/mm)	Peak load (kN)	Failure mode	Failure moment (kN m)	Failure shear (kN)
305_1	0.3237	14.25	*T*	12.95	7.13
305_2	0.2421	14.30	*T*	12.99	7.15
305_3	0.2473	11.20	$T + S$	10.18	5.60
305_4	0.2654	13.90	$T + S$	12.63	6.95
305_5	0.3012	13.10	*S*	11.90	6.55
305_6	0.2492	13.50	*Tf*	12.26	6.85
305_7	0.2847	13.80	*S*	12.54	6.90
305_8	0.2875	15.65	*S*	14.22	7.83
Mean	0.2751	13.71		12.46	6.86
Std dev	0.0272	1.26		1.15	0.63
5 percentile		11.64		10.57	5.82

Table 4
Shear test results.

Joist ID	First failure load (kN)	Peak load (kN)	Failure mode	Failure shear (kN)
241_1S	17.25	18.20	$S + T$	8.63
241_2S	16.50	20.30	$S + T$	8.25
241_3S	16.40	19.10	*S*	8.20
305_1S	13.45	13.45	*S*	6.73
305_2S	15.65	15.65	*S*	7.83
305_3S	16.05	16.05	*S*	8.03

On examination of this joist, a large knot was present in the flange at the failure location, which precipitated failure. This mode of failure could be avoided by more careful selection of the flange material.

3.3. Series 3: shear tests on 241 and 305 mm deep joists

The results of the shear tests performed on two types of joists are summarised in Table 4. The mechanical behaviour during these tests was different to the bending tests, as can be seen in the load-mid-span displacement curves in Figs. 10 and 11 for the 241 and 305 mm deep joists, respectively. For these tests, the response was linear up to a certain load level at which a cracking sound was heard together with a fall-off in the load. This load level is referred to as the first failure load in Table 4. After this the test continued and large increases in displacement were accompanied by small increases in load for the 241 mm deep joists until collapse occurred at the peak load. For the 305 mm deep joists, increasing displacement after the first failure load was not accompanied by increases in load but displayed an almost perfectly plastic response. All joists experienced web failure. The shear capacity of each joist was taken as the shear force at the first failure load. The mean values for the failure shear forces were 8.36 and 7.53 kN for the 241 and 305 mm deep joists, respectively. As these were greater than the shear force at failure in the bending tests, it was decided to discontinue this series. The design shear force capacity should be determined on the basis of the Series 1 and 2 tests.

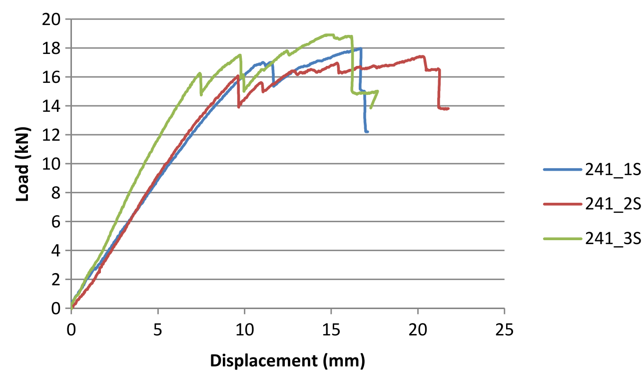

Fig. 10. Load–displacement curves for 241 mm deep joists in shear.

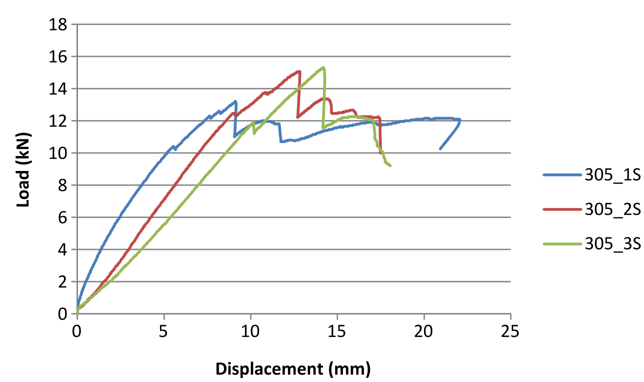

Fig. 11. Load–displacement curves for 305 mm deep joists in shear.

4. Conclusions

The short-term behaviour of castellated timber-based *I*-joists has been investigated experimentally. From the results of the testing programme, which comprised a total of 23 joists of two different depths tested in bending or shear, the following conclusions can be drawn.

- The bending response is fairly linear elastic to failure.
- For the 241 mm deep joists, the stiffness is not affected by the presence of web openings.
- The reduction in shear capacity due to the presence of the openings compares well with the shear capacity of commercial joists with circular or rectangular openings of equivalent size. For the 241 mm deep castellated joists, the mean shear capacity is greater than the design capacity of a commercial joist with a single circular or rectangular opening by factors of 1.56 and 2.39, respectively. The corresponding factors for the 305 mm deep joists are 1.18 and 1.74.
- Failure occurs in the web, unless the tension flange contains a significant defect in the zone of maximum moment.

- Two web failure modes are found, namely, tension failure at the top and bottom corners of the openings and shear failure in the finger joint at the mid-depth.
- The fillet radius at the top and bottom corners of the opening does not appear to have an influence on the load carrying capacity.
- Further testing is required to establish the long-term performance of these joists.

Castellated timber joists are an attractive alternative to existing commercial *I*-joists that facilitate the installation of service ducts within the joist depth at any time during the service life of a structure. Potential for openings being cut from the web of an inappropriate size or in an inappropriate location is significantly reduced.

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