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Finite element modelling of castellated timber I-joists

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HIGHLIGHTS

- Numerical modelling of a novel castellated timber I-joist is validated against experimental data.
- Castellated joists shown to have bending stiffness 15–16% lower than equivalent solid–web joists.
- A parameter study to determine the optimum castellation geometry is described.

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ABSTRACT

This paper focuses on the structural analysis of innovative composite timber I-joists with castellated webs. The castellation process is carried out by cutting the web in a zig–zag pattern at mid-depth and then rejoining at an offset distance to create hexagonal holes. The flanges of the joists were made from Norway Spruce whilst the webs were made from oriented strandboard (OSB). The joists were analysed using the finite element method (FEM) with the component materials modelled as linear elastic orthotropic materials in both tension and compression. Good correlation was found between the experimental results and the FE simulations. The stiffness ratios obtained from test and FEA data (EI_{test}/EI_{FEA}) were between 1.03 and 1.36 for the 241 mm joists and between 0.89 and 1.10 for the 305 mm joists. At peak load the FEA model predicted displacements of between 0.80 and 1.02 times that of the test for the 241 mm joists and between 0.98 and 1.16 times that of the test for the 305 mm joists. The validated FE models are compared to equivalent solid webbed joists to assess the effect the castellated webs have on their structural performance. A geometric parameter study was carried out to determine the optimum web opening geometry in terms of structural performance.

1. Introduction

The structurally engineered timber I-joist was successfully introduced into the construction market in the 1970s as an alternative to larger-dimension solid sawn timber. Compared to solid sawn timber, I-joists are more efficient for structural use with a better environmental impact. The reduced amount of timber used in I-joists compared to solid structural timber make them lighter and easier to position on site. I-joists have the added benefits of reduced material resource impacts through the use of smaller diameter timber and lower embodied energy than solid timber joints.

In addition, the advantage of a lower variability of performance and a better dimensional stability have led to extensive use in Europe and North America in both residential and commercial buildings e.g. for floor joist and roof applications such as suspended intermediate floors, suspended ground floors, purlins and rafters. The flanges are made from solid timber or laminated veneer lumber (LVL) and the web is made from oriented strandboard (OSB), plywood or particleboard [1,2].

Openings can be incorporated in the web to allow services to pass through. By accommodating services within the depth of the floors, the overall structural depth can be reduced or greater headroom provided. However, the presence of openings makes the stress distributions in the web more complicated and, depending on the configuration of the openings, can reduce the load carrying capability of the joist [3–5]. Manufacturers produce design guidance literature specifying permitted web hole requirements [6]. These guidance documents are generally restricted to circular or rectangular openings and limits are provided on the dimensions of the openings as well as restricting the positioning of openings to low shear areas.

This paper addresses the concept of a timber I-joist using hexagonal openings which result from the castellation manufacturing process, an example of which is seen in Fig. 1. Castellation is already well established for steel but has yet to be applied using timber. Castellated timber joists have a series of hexagonal shaped openings along the entire span, which provide flexibility in the

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Nomenclature

x	direction parallel to joist span
y	direction parallel to joist depth
z	direction parallel to joist thickness
E_x	modulus of elasticity in x direction
E_y	modulus of elasticity in y direction
E_z	modulus of elasticity in z direction
f_x	strength in x direction
f_y	strength in y direction
f_{45}	strength at 45° direction
G_{xy}	shear modulus in x–y direction
G_{yz}	shear modulus in y–z direction
G_{xz}	shear modulus in x–z direction
v_{xy}	Poisson's ratio in x–y direction
v_{yz}	Poisson's ratio in y–z direction
v_{xz}	Poisson's ratio in x–z direction
$L1$	horizontal joint length
$L2$	hole depth
$L3$	joint overlap
$L4$	web depth
$L5$	I-joist depth
$L6$	flange depth
$L7$	flange penetration depth
$L8$	flange width
$L9$	web width
R	cutter radius
θ	cutting angle
EI_{test}/EI_{FEA}	stiffness ratios obtained from test and FEA data
$\Delta_{0.4}$	displacement at 0.4 times the test peak load
Δ_{max}	displacement at test peak load

routing of services at construction stage, and also the rerouting of services during building retrofit. The authors have carried out a program of tests on castellated joists of two different depths to evaluate their structural behaviour [7]. Further work is required to gain a better understanding of their behaviour and to optimise the design. Castellated joists are highly indeterminate structures, which are not susceptible to simple methods of analysis. For this reason, the finite element method is used to model the behaviour of the I-joists. This paper describes a three-dimensional finite element model, which has been developed to model the structural performance of castellated timber joists. The model is validated using experimental data and is then used in a parameter study, which seeks to determine the influence on the structural response of a number of geometric characteristics of the castellated openings. From this study, the optimum design parameters are selected.

2. Literature review

To date a large body of research exists on the structural behaviour of steel I-beams with different types of openings [3,8–13]. Experimental studies have identified a number of different failure modes associated with these joists including: excessive stresses in the tee-sections above and below the holes, failure of the web-post between two adjacent holes, web-buckling of the web post, and, formation of four plastic hinges in the tee-sections above and below the openings resulting in a 'Vierendeel' type mechanism. It is generally accepted that the shapes of the web openings are critical in the structural behaviour of perforated sections, such as transformation of global actions to local forces, yield patterns at failure, and also failure mechanisms [3]. The presence of large web openings may have a severe penalty on the load carrying capacities of beams, depending on the shapes, the sizes, and the location of the openings [10].

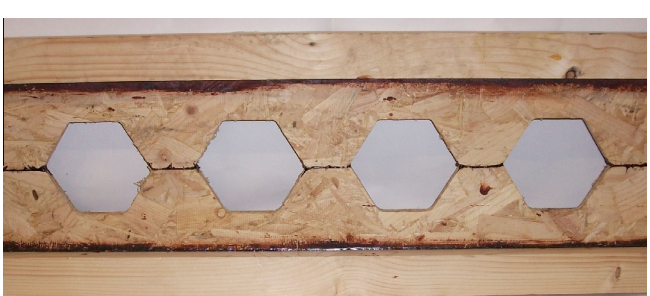

Fig. 1. Castellated joist.

Numerical modelling of the structural behaviour of steel I-joists with openings has been successfully undertaken by a number of researchers [3,11–13]. Kohnehpooshi and Showkati [11] used 4-noded shell elements in the finite element modelling of castellated steel I-joists, using a hardening bilinear material law for the steel. The purpose of the study was to obtain accurate estimates of the effective flexural, tensile, shear and torsional stiffnesses of the joists for design purposes. Redwood and Demirdjian [12] also used shell finite elements to model the web buckling response of castellated steel I-joists. An elastic analysis was deemed to be adequate as the predicted buckling loads were lower than the loads which caused inelastic action due to shear at mid-depth in the web. The maximum loads from tests on four joists all exceeded the finite element predictions. Predicted buckling loads were between 88% and 96% of the measured values. Chung et al. [13] investigated the Vierendeel mechanism in steel I-joists with large circular openings. In order to model the formation of plastic hinges, a bilinear stress–strain curve together with a von Mises yield criterion was implemented for the steel. A finite element mesh incorporating over 750 8-noded shell elements was developed to model the joists. Using a geometrically non-linear analysis, the model predictions closely matched the moment capacities and deformations found experimentally. Liu and Chung [3] extended this work to examine the performance of joists with eight different opening shapes and found that all behaved in a similar manner.

A number of authors have reported on the numerical modelling of timber joists with circular or rectangular web openings [4,14–16]. For the most part, these consider single openings or pairs of openings. Zhu et al. [4] developed a three-dimensional nonlinear finite element model for OSB-webbed timber I-joists with a single circular and square web opening. In addition, joists with pairs of openings with different spacing were examined and critical distances where interactions became serious were identified. They used 8-noded solid elements, which have linear orthotropic elastic properties in tension and orthotropic elastic–plastic properties in compression. Tension failure of the OSB was defined using an improved Tsai-Hill failure criterion. Model predictions compared well with results of experimental testing, which showed that square openings had a bigger impact than circular openings due to the stress concentration at the corner of the square. Four-point bending tests revealed that opening location in the region of constant shear did not affect the load carrying capability significantly. To investigate the effect of opening size the openings were positioned 1000 mm away from the mid-span and their size varied from 0.25 to 0.75 of the web depth. It was found that both initial cracking and ultimate loads decrease linearly with opening size. FE analysis of one of the beams tested revealed that the same beam without any openings could carry up to 37.3 kN if buckling was prevented. This would be reduced by 17 kN by the presence of a square opening. If it were a same sized circular opening in the same position as the square opening, the load carrying capability would be 24.0 kN. This indicates that a square opening causes more loss than does a same sized circular one. For both shapes, failure was initiated as a tension crack at the corners of the openings. The authors used the FE model to develop empirical expressions for the load carrying capacity of joists with a single circular or square hole and also to determine the critical distance between pairs of openings. When the openings were less than the critical distance apart, the failure mode changed to web shear failure between the openings.

Morrissey et al. [14] undertook a series of tests on 38 commercial timber I-joists of two different depths to determine the effects of circular and square openings and also to examine retrofitting to reinforce the holes. Joists were tested over a simply supported span using a simulated uniform load. The joists failed by tension flange failure through a finger joint or knot in 14 of the joists, including all 6 reference joists without openings. Web shear failure was found in 21 of the joists and compression flange failure in the 3 remaining joists. Finite element modelling was also undertaken to gain a fuller understanding of the stress distributions and the failure mechanisms involved. Three-dimensional finite element models were developed to model each experimental set-up. The elements used were 10-noded tetrahedral solid elements. The flange material was modelled as a linear elastic orthotropic material and the OSB web material was treated as a planar isotropic material. The numerically predicted service load deflections were between 97% and 114% of the experimental values for the 241 mm high joists and between 85% and 111% of the measured deflections for the 302 mm high joists. The model predicted a decrease in stiffness when web openings were located closer to high shear areas. Significant increases in the web principal stress around the openings were observed as the opening was moved closer to the support.

Jahromi et al. [15] investigated the behaviour of single and multiple plywood-webbed I-joists with different diameter circular web openings located in the region of maximum shear force. No reduction in stiffness was found for any of the joists tested. As the opening size increased the load carrying capacity decreased. For the 290 mm high I-joists, the strength reduction was 0%, 6% and 19% for opening diameters of 76 mm, 102 mm and 156 mm, respectively. Finite element modelling was performed to identify the location of peak stresses and failure locations. Pirzada et al. [16] developed an analytical model based on curved beam theory to predict the peak tensile stresses in the vicinity of circular openings. The model predictions were shown to be in good agreement with a finite element model and provide conservative estimates of the failure load for I-joists with a circular opening but the authors noted that further material testing would be required to provide accurate estimates of some of the model parameters.

As far as the authors of the current work are aware, they are the first to publish experimental results for castellated timber I-joists in Harte and Baylor [7]. The experimental program involved tests on 241 mm and 305 mm high castellated joists in four-point bending. The load–deflection response, failure loads and failure modes were recorded. The load–deflection response was found to be nearly linear to failure. Failure occurred abruptly in one of two failure modes for all joists tested, namely, web shear failure between the openings and tension cracking emanating for a corner of the opening and propagating at 30–45° to the longitudinal axis of the joist towards the flange. The geometry of the castellation was constant for each joist type. The influence of changes to the geometry of the openings is best studied using a numerical approach in the first instance and that is the focus of the present paper.

3. Experimental programme

The I-joists tested by Harte and Baylor [7], which are the focus of the current work, comprised flanges made from grade C24 Norway Spruce and castellated webs made from oriented strand board, grade OSB/3. The I-joist depths chosen for the study were 241 mm and 305 mm. These are standard commercial sizes used by many manufacturers. The flange sizes were 50 mm × 50 mm and 60 mm × 50 mm for the 241 mm and 305 mm depths, respectively, as shown in Fig. 2. *X*, *Y* and *Z* describe the length, depth and through-thickness, respectively, as shown in the Figs. 2 and 3. The castellated webs were 11 mm thick with hexagonal shaped 110 mm high openings. The openings were created by forming a zig–zag cut in an OBS blank using a CNC router. The top and bottom halves of the web, thus formed, were separated and then joined at mid-depth by a finger joint. The flange-web joint is formed by routing a 19 mm deep groove in the flanges into which the web is inserted and adhesively bonded.

For the joists, a solid end section of minimum length 275 mm is provided so that joists can be trimmed on site to suit. Additionally there is a critical zone near the supports where the shear stresses are highest. This is the region where the I-joist is most susceptible to failure and the existence of the solid end section reduces this risk.

Manufacture of the joists was carried out at the Wood Technology Centre at the University of Limerick. Prior to manufacture of the joists, all of the flanges were tested non-destructively using a Cook Bolinders machine grader so that the actual modulus of elasticity is known and this data is used in the numerical modelling. Joists were tested in four-point bending over a simply supported span of 18 times the joist depth in accordance with the EOTA TR002 standard [17]. This required a span of 4.338 m for the 241 mm I-joist and 5.490 m for the 305 mm.

4. Finite element model

A three-dimensional finite element model of each joist was created using ANSYS Ver. 11 [18]. The mesh was created using the Solid92 element. This is a 10 node tetrahedral structural solid element, having 3 degrees of freedom at each node, namely, translations in the nodal *x*, *y*, and *z* directions.

Due to symmetry, it was only necessary to model half the span and half the width of the I-joist. The geometric quarter model is shown in Fig. 3. The mesh nodes on the vertical plane, which divide the model at mid-span, were fixed in the longitudinal (*x*-axis) direction. The mesh nodes on the vertical plane, which divide the model along the centre-line of the width, were fixed in the

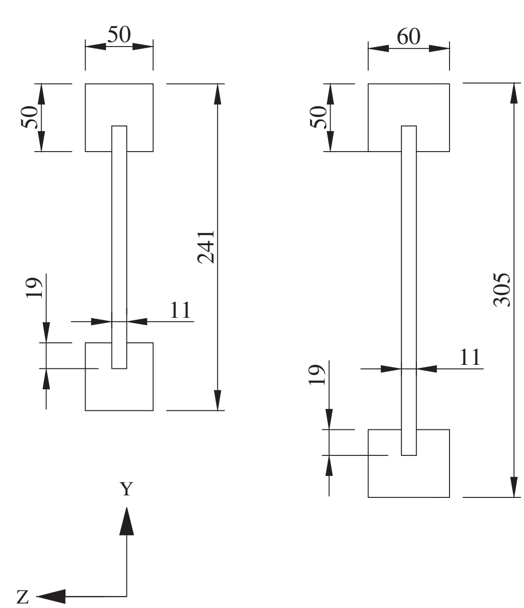

Fig. 2. Section through joists. Dimensions in mm.

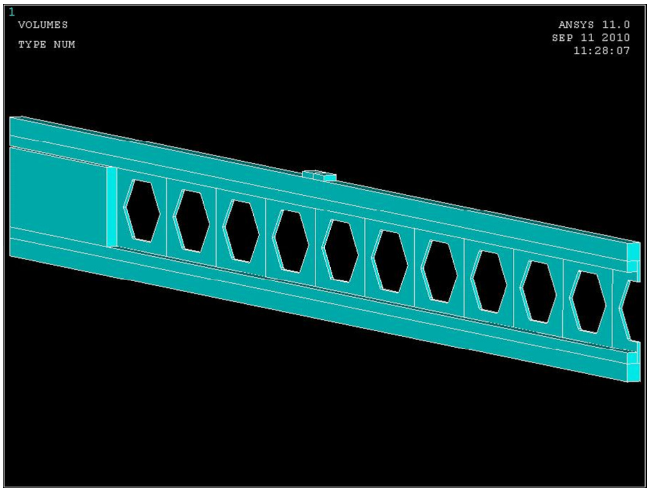

Fig. 3. Geometric quarter FE model used for 4 point bend test.

through-thickness (z-axis) direction. The vertical component of displacement was set to zero at the support location to simulate a roller condition. In the model, the web and flange were assumed to be fully bonded as no failures were observed in this joint during testing [7]. In the laboratory tests, the loading was applied through steel plates and these were included in the model. In the FE model, the point load was converted to an equivalent pressure load (= point load/bearing plate area) which was applied to the top surface of the bearing plate.

The four-point bend test was modelled for the purposes of validating the FE model against laboratory tests (Section 5). Subsequently the same model was used to carry out a parameter study in order to determine an optimum castellated hole design (Section 7). Additionally, similar models, albeit with solid webs, were used for each size of joist to investigate the structural performance of the castellated joists compared to their equivalent solid webbed counterparts (Section 6). Fig. 4 shows an example plot of the FE model with initial and final deflected shapes.

A mesh sensitivity analysis revealed that a mesh element size of 20 mm was required to adequately model the load–deflection response for both sizes of joist. However a mesh size of 10 mm was required to adequately model the stresses in the web and flange. At this size, further mesh refinements did not alter the shear stress or 1st principal stress in the web or the longitudinal stress in the bottom flange. A mesh element size of 10 mm requires a total number of elements of approximately 60,000 for a typical

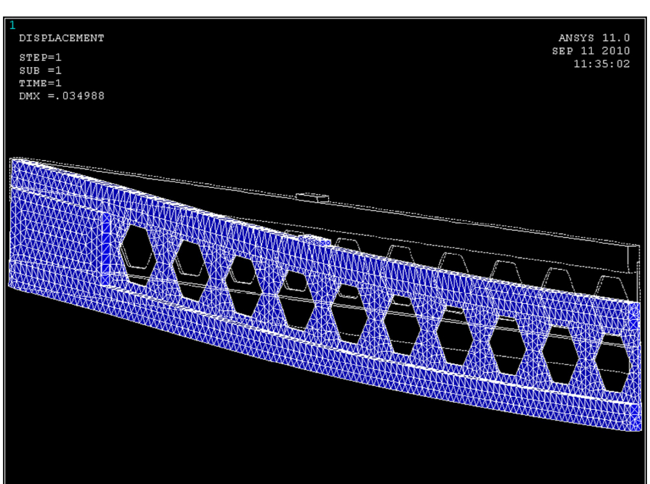

Fig. 4. Initial and final deflected shape.

241 mm I-joist (26,700 in the web, 33,000 in the flanges and 250 for the steel plate).

4.1. Material modelling

The OSB web and the grade C24 Norway Spruce flanges were modelled as orthotropic linear elastic materials, while the steel loading plates were modelled using isotropic linear elastic properties. Timber and timber products behave in a linear fashion in tension but in compression display non-linear behaviour. During testing of the castellated joists, brittle tensile failure occurred at the corners of the openings before and significant nonlinear compression behaviour developed. This was also reported by Zhu et al. [4] for other shapes of opening. This behaviour is in contrast with that of steel castellated joints which behave plastically in both tension and compression. For the timber joists, it is therefore unnecessary to use a nonlinear material description.

In order to accurately simulate the bending behaviour of the joists, accurate material data is required. Due to the anisotropy associated with timber products, this requires the specification of nine mechanical coefficients for the web and flange materials. Determination of these properties experimentally would be a major undertaking due to the variability associated with timber materials. O'Toole [19] carried out a finite element material sensitivity analysis on I-joists with Sitka Spruce flanges and OSB solid webs, whereby the load–deflection response was assessed for both short and long span I-joists. The study revealed that the significant material parameters which affect the response were the longitudinal modulus of elasticity (E_x) for both the flange and web materials and also the panel shear modulus (G_{xy}) for the web. The remaining 15 parameters had insignificant influence on the response. For this reason, the longitudinal modulus of elasticity of each flange was measured and the values were found to vary between 7554 and 11,764 N mm^{-2}. The other flange stiffness properties were taken from Bodig and Jayne [20]. The flange strength properties used were the characteristic values for C24 timber given in EN338 [21].

For the web material, the values for the tension modulus of elasticity and strength were taken from McTigue and Harte [22], and panel shear modulus and strength from O'Toole [19] as these values are based on tests carried out on OSB sourced from the same manufacturer as that used in the current study. The remaining OSB properties were taken from O'Toole [19]. A full list of the material properties of the web and flange material used in the finite element model is given in Table 1. For the steel plates, Young's modulus was taken as 205 N mm^{-2} and Poisson's ratio as 0.3.

4.2. Geometric modelling

The full I-joist geometry is defined using the following parameters: Horizontal Joint Length ($L1$), Hole Depth ($L2$), Joint Overlap

Table 1
Material Properties used for FEA.

Material property	Norway spruce C24	OSB/3
E_x (N mm^{-2})	7554–11,764	4089
E_y (N mm^{-2})	771	3531
E_z (N mm^{-2})	407	10
G_{xy} (N mm^{-2})	676	1409
G_{yz} (N mm^{-2})	57	141
G_{xz} (N mm^{-2})	636	163
v_{xy}	0.37	0.183
v_{yz}	0.47	0.312
v_{xz}	0.42	0.364
f_x (N mm^{-2})	14.4	10.9
f_y (N mm^{-2})		9.3
f_{45} (N mm^{-2})$^{\circ}$		8.5–10.0
τ_{xy} (N mm^{-2})		9.1

($L3$), I-Joist Depth ($L5$), Flange Depth ($L6$), Flange Penetration Depth ($L7$), Cutter Radius (R), Cutting Angle (θ), Flange Width ($L8$) and Web Width ($L9$). The Web Depth ($L4$) is a dependent geometric parameter. These are illustrated in Figs. 5 and 6. As already stated, the solid end length has a specified minimum length of 275 mm. The solid end length may be longer as the number of castellations that fits into the span will change depending on the geometry of the hole.

The path created by the router (Fig. 6a) creates a fillet radius on the top and bottom corners of the hexagonal hole corresponding to the radius of the cutter (e.g. location (a) in Fig. 7). The corners at mid-depth are sharp due to the overlapping of the finger joint (e.g. location (b) in Fig. 7). The resulting hole is located at mid-depth.

Once a geometric design has been chosen, it is necessary to translate the geometry of the hole into a cutting pattern for manufacture. This has not been addressed in previous publications dealing with castellated beams. The first four positions for the centre of the cutter are shown in Fig. 7a and are denoted ($X1$, $Y1$), ($X2$, $Y2$), ($X3$, $Y3$) and ($X4$, $Y4$). The cutter follows a linear path between these positions. This pattern can then be repeated for the full length of the OSB blank. Taking the bottom left hand corner of the blank OSB web as the origin of the local (X, Y) Cartesian plane (Fig. 7a), the first four positions of the cutter in terms of the geometric parameters are determined using Eqs. (1)–(9).

$$X1 = L1/2 + R * \cos\theta \tag{1}$$

$$Y1 = Y2 + (L2 + L3)/2 \tag{2}$$

$$X2 = X1 + (L2 + L3)/(2 * \tan\theta) \tag{3}$$

$$L4 = L5 - (L6 - L7) * 2 \tag{4}$$

$$Y2 = (L4 - L2)/2 + R \tag{5}$$

$$X3 = X2 + 2 * R * \cos\theta + L1 \tag{6}$$

$$Y3 = Y2 \tag{7}$$

$$X4 = X3 + (X2 - X1) \tag{8}$$

$$Y4 = Y1 \tag{9}$$

These positions can then be used to create the geometry in a CAD file which can then be used to define the path for the CNC cutter. Note that these equations would change slightly for a steel castellated I-beam as the joint between the top and bottom sections would be created using a weld as opposed to an overlapping finger joint as is the case here. Also these equations ensure that the web depth (and in turn the total I-joist depth) remains constant for the purposes of this study.

To create the geometric model for the FEA, a section of each castellated hole is created based on the chosen geometric design variables. This geometric section is then repeated along the length of the web in between the solid end length segments at each end. The hole segment length (Fig. 7) is calculated using the following equation:

$$\text{Hole segment length} = X1 + X4 \tag{10}$$

If an odd number of hexagonal holes result for the full length of the I-joist, then mid-span will be in the middle of the hole (Fig. 3). For an even number of holes, mid-span will be halfway between two holes (Fig. 4).

5. Numerical results

5.1. Numerical versus experimental displacement response

The test and corresponding FE data are shown in Tables 2 and 3 for the 241 mm and 305 mm I-joists, respectively. In Tables 2 and 3, $\Delta_{0.4}$ refers to the displacement at 0.4 times the peak load (i.e. the maximum load reached during the test) whereas Δ_{max} refers to the displacement at peak load. The maximum load applied to each model corresponds to the test failure load. The Ansys post processing function DMAX was used to calculate the maximum displacement. This function returns the maximum displacement either for the whole model or a user-defined portion of the model. For each model the maximum displacement returned by DMAX occurred on the bottom face of the lower flange at mid-span. The data in the FEA columns is the instantaneous displacement at the corresponding load using the FE model described in Section 4. The physical test data in Tables 2 and 3 were taken from Harte and Baylor [7].

As shown in Table 2, the FEA model predicted displacements of between 0.70 and 0.90 times that of the test at $\Delta_{0.4}$. At peak load the FEA model predicted displacements of between 0.80 and 1.02 times that of the test. The stiffness ratios (EI_{test}/EI_{FEA}) which correspond to the slope of the load–displacement curve between 0.1 and 0.4 of the peak load were between 1.03 and 1.36.

As shown in Table 3, the FEA model predicted displacements of between 0.87 and 1.07 times that of the test at $\Delta_{0.4}$. At peak load the FEA model predicted displacements of between 0.98 and 1.16 times that of the test values. The stiffness ratios (EI_{test}/EI_{FEA}) were between 0.89 and 1.10.

Figs. 8 and 9 show the load–displacement test results and FE model predictions for representative 241 mm and 305 mm deep

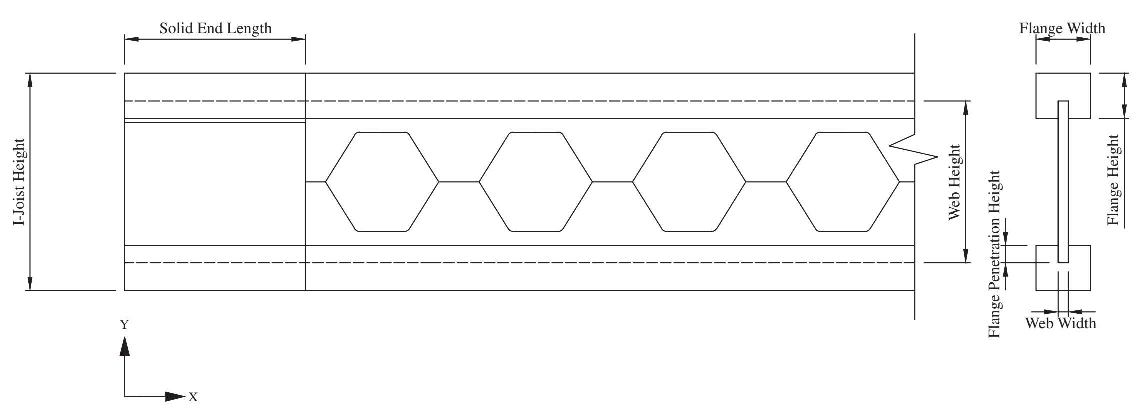

Fig. 5. Longitudinal section and cross section of castellated I-joist with geometric parameters.

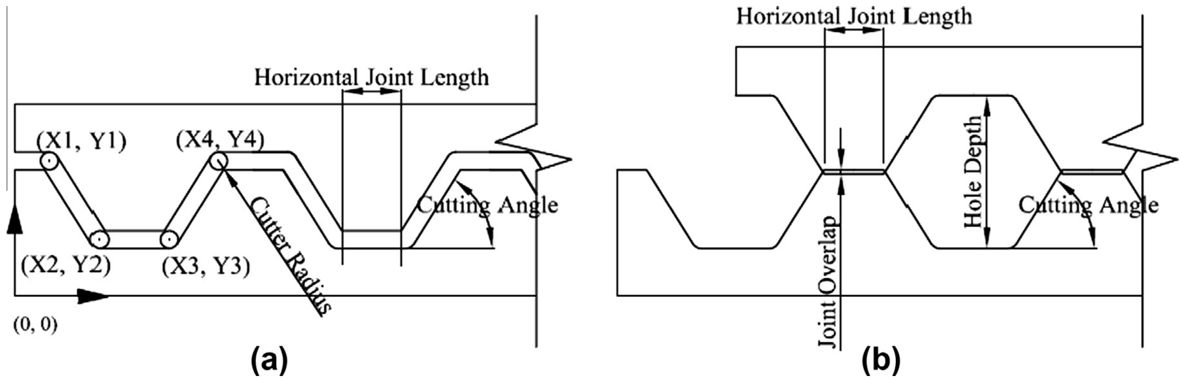

Fig. 6. Web geometric parameters (a) OSB blank with cutting profile and (b) resulting castellated web.

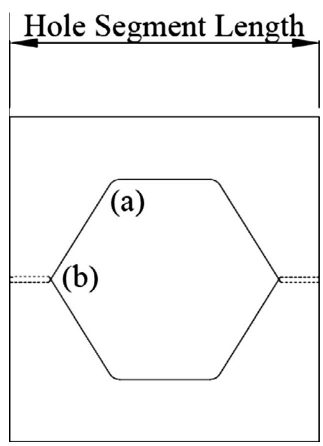

Fig. 7. Hole segment length used in FEA.

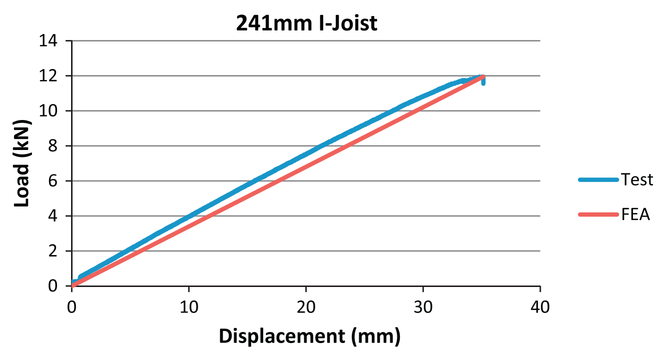

Fig. 8. Test versus FE Load–deflection results for I-joist 241_3.

Table 2
Bending test results for 241 mm OSB joists.

Joist ID	Peak load (kN)	$\Delta_{0.4}$ (mm)		$\Delta_{0.4}$ Test/$\Delta_{0.4}$ FEA	Δ_{max} (mm)		Δ_{max} Test/Δ_{max} FEA	EI_{test}/EI_{FEA}
		Test	FEA		Test	FEA		
241_1	12.3	11.3	16.2	0.70	32.1	39.9	0.80	1.24
241_2	13.9	14.3	18.6	0.77	41.2	46.1	0.89	1.23
241_3	12.0	12.2	16.0	0.76	35.1	40.1	0.88	1.20
241_4	9.4	11.2	12.4	0.90	30.3	30.5	0.99	1.08
241_5	11.5	11.7	15.2	0.77	33.1	37.6	0.88	1.18
241_6	11.9	13.4	15.8	0.85	39.7	38.9	1.02	1.03
241_7	12.8	12.4	17.3	0.72	36.2	42.7	0.85	1.36
241_8	11.7	12.0	15.9	0.75	34.3	39.4	0.87	1.25
241_9	12.7	14.4	16.9	0.85	40.1	41.2	0.97	1.15
Mean	12.0	12.5	16.0	0.79	35.8	39.6	0.91	1.19

Table 3
Bending test results for 305 mm OSB joists.

Joist ID	Peak load (kN)	$\Delta_{0.4}$ (mm)		$\Delta_{0.4}$ Test/$\Delta_{0.4}$ FEA	Δ_{max} (mm)		Δ_{max} Test/Δ_{max} FEA	EI_{test}/EI_{FEA}
		Test	FEA		Test	FEA		
305_1	14.3	17.5	20.2	0.87	50.4	51.2	0.98	1.10
305_2	14.3	22.1	20.7	1.07	60.8	52.5	1.16	0.89
305_3	11.2	16.9	17	0.99	48.0	43.0	1.12	0.95
305_4	13.9	20.0	20.3	0.99	54.7	50.4	1.08	0.95
305_5	13.1	16.9	18.4	0.92	46.3	46.5	1.00	1.03
305_6	13.5	20.1	20.1	1.00	55.9	51.0	1.10	0.92
305_7	13.8	17.6	19.8	0.89	53.2	50.0	1.06	1.01
305_8	15.7	22.3	21.7	1.03	60.6	55.1	1.10	0.96
Mean	13.7	19.2	19.8	0.97	53.7	50.0	1.07	0.98

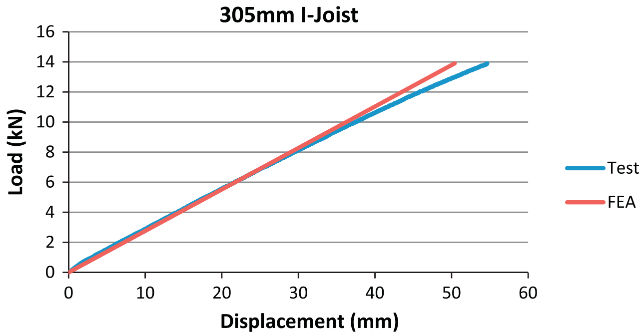

Fig. 9. Test versus FE Load–deflection results for I-joist 305_4.

joists, respectively. Joists 241_3 and 305_4 were chosen as their peak loads were the closest to the mean values for each size of joist. As can be observed from these figures, there is good correlation between the test data and the FE results up until the peak load. The load displacement response for each of the 17 joists tested displayed predominantly linear behaviour. According to EC5 [23] the allowable deflection for serviceability is L/250 for floor joists with plasterboard and L/150 without plasterboard (Table 4). FEA was carried out on joists 241_3 and 305_4 with a design load of 3.06 kN m^{-2} according to EC1 [24] for 400 mm and 600 mm spacing. As shown in Table 4, both joists are within the serviceability limit for deflection with plasterboard at 400 mm spacing between joists. At 600 mm spacing both sizes of joist exceeded the serviceability limit with plasterboard but are within the serviceability limit without plasterboard.

5.2. FE Comparison of solid web versus castellated web

Subsequent to the validation of the FE model with the test data, further analysis was performed on the two I-joist sizes. Table 5 compares the behaviour of joists 241_3 and 305_4 at peak load, with and without castellated openings. For the solid webbed joists the results in Table 5 were calculated using the transformed section method [25].

As shown in Table 5, the displacement of the castellated joists is 16.1% and 15.2% higher than the equivalent solid webbed joist for the 241 mm and 305 mm depth, respectively. According to Darwin [26] and Chung et al. [13], in the analysis of beams with holes in the web, each web opening leads to additional mid-span deflections due to shear and bending effects. Often the additional deflections due to one opening are small, typically less than 2% of that of the unperforated composite beam, but may be significant when summed over a series of large openings.

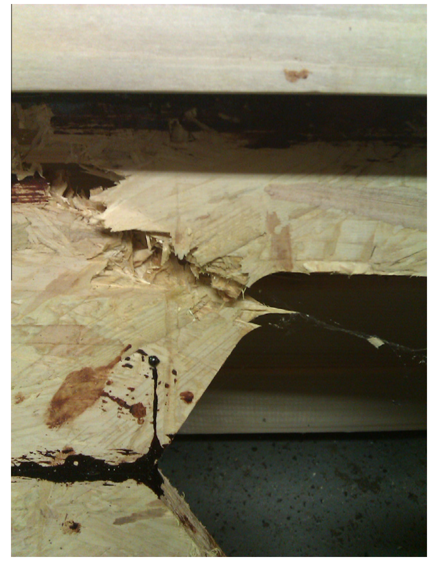

Fig. 10. Tension failure at corner of opening.

As observed by the authors in Harte and Baylor [7], the predominant failure modes for both sizes of joist were tension failure in the web at the corner of the openings and shear failure in the web at mid-depth between the openings. An example of tension failure at the corner of an opening is shown in Fig. 10. When both failure modes occurred, it was not possible to determine where the cracking initiated due to the rapid nature of failure. The stress distributions at these two locations were further examined using the FE model. Figs. 11 and 12 show the 1st principal stress and shear stress distributions, respectively, in the web of the 241_3 joist. Peak values of these stresses are given in Table 5. Table 5 also includes analytical calculations for the solid webbed joists for the shear stresses at mid-depth in the web and for the maximum tensile stresses in the bottom flange.

The FE model revealed that high 1st principal stresses occur at the first 5 holes close to the support (Fig. 11). For the 241 mm joist the 1st principal stresses at the corners of the first 5 holes range between 36.5 N mm^{-2} and 41.1 N mm^{-2}, all of which occur at the bottom left corner of each hole. It should be noted that these values far exceed the OSB characteristic strength value (f_{45}) (Table 1). For the 305 mm joist the 1st principal stresses are only slightly lower with the maximum being 37.8 N mm^{-2} in this case. The FE model revealed that the maximum shear stresses at the web posts between the holes were 13.7 N mm^{-2} and 11 N mm^{-2} for each size of joist respectively. It can be noted that these values have just sur-

Table 4
FEA comparison of design load deflection to EC5 allowable serviceability deflection.

Joist ID	Span L (mm)	Δ_{design} 400 mm Spacing	Δ_{design} 600 mm Spacing	Δ_{allow} With plasterboard L/250 (mm)	Δ_{allow} Without plasterboard L/150 (mm)
241_3	4338	13.5	20.1	17.4	28.9
305_4	5490	18.4	27.4	22	36.6

Table 5
FEA comparison of castellated and equivalent solid webbed joists at peak load.

I-Joist depth (mm)	Web type	Δ_{max} (mm)	$\sigma_{1,max}$ Web (FEA) (N mm^{-2})	τ_{max} Web mid depth (FEA) (N mm^{-2})	τ_{max} Web (analytical) (N mm^{-2})	$\sigma_{x,max}$ Flange (FEA) (N mm^{-2})	$\sigma_{x,max}$ Flange (analytical) (N mm^{-2})
241	Castellated	40.3	41.1	13.7	–	26.4	–
241	Solid	34.7	–	2.8	3.3	22.5	22.2
305	Castellated	50.7	37.8	11	–	22.2	–
305	Solid	44	–	2.5	2.7	20.2	20.2

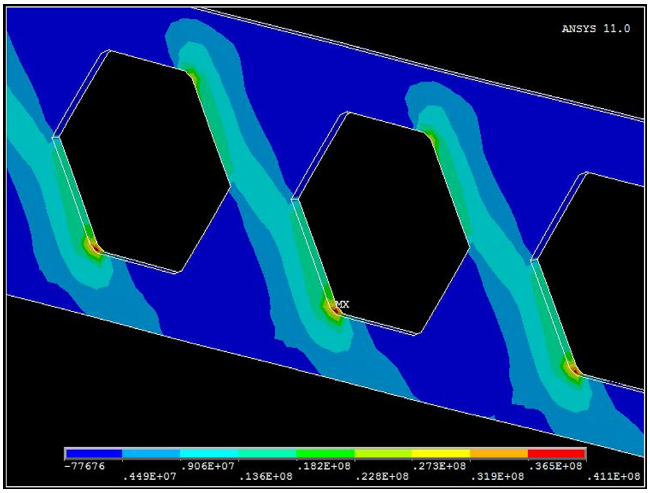

Fig. 11. First principal stress distribution in web (Nm^{-2}).

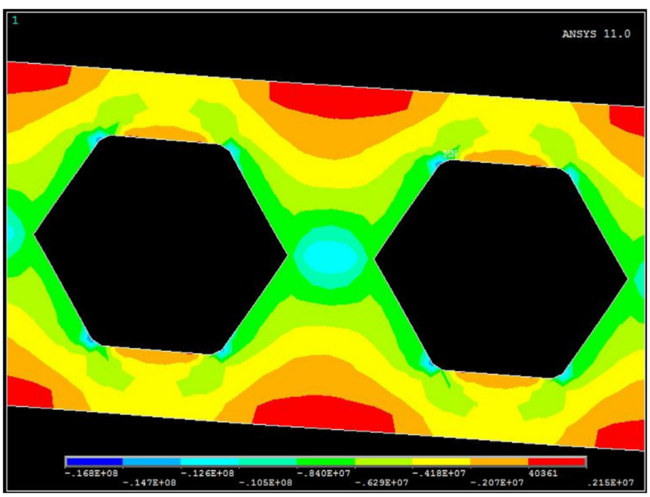

Fig. 12. Web shear stress distribution (Nm^{-2}) at peak load between 3rd and 4th hole of 241 mm I-joist.

passed the OSB characteristic shear strength (τ_{xy}) of 9.1 N mm^{-2} (Table 1).

In comparing the maximum 1st principal stresses and the maximum shear stresses (Table 5) to their characteristic strength values (Table 1) at the respective failure locations, the results suggest that cracking initiates at the corners of the hole and this then facilitates cracking at mid-depth. This is due to the fact that the 1st principal stresses exceeded the characteristic value by a far greater amount than the shear stresses. As noted in the literature review, previous studies on I-joists with noncastellated holes in the web observed failure by cracking from the corners of the holes as shown by Zhu et al. [4].

In comparing the maximum shear stress at mid-depth for the castellated web to its solid web counterpart it is 4.9 times larger for the 241 mm joist and 4.4 times larger for the 305 mm joist.

At peak load the tensile stresses of 26.4 N mm^{-2} and 22.2 N mm^{-2} in the bottom flange of the 241 mm and 305 mm joists, respectively, exceeded the characteristic strength of 14.4 N mm^{-2} given by BS EN 338: 2003 [21] for grade C24 structural timber.

6. FEA parameter study

An FEA investigation was carried out to determine if the structural performance of the joists could be improved by varying the geometric parameters of the castellated hole. The aim was to maximise the stiffness and minimise the shear and 1st principal stresses in the web. For the 241 mm I-joist, the following geometric parameters were fixed: Joint Overlap ($L3$) = 3 mm, Flange Depth ($L6$) = 50 mm, Flange Penetration Depth ($L7$) = 19 mm, Flange Width ($L8$) = 50 mm, Web Width ($L9$) = 11 mm. In the case of the 305 mm I-joist the only difference to the fixed variables is the flange width which changes to 60 mm.

The Horizontal Joint Length ($L1$), Hole Depth ($L2$), Cutter Radius (R) and Cutting Angle (θ) were then varied. Two sizes of cutter radius were available: 3.18 mm and 6.35 mm. The cutting angle was varied between 30° and 70°. Hole depths of 110 and 100 were considered and the horizontal joint length was varied between 20 and 60.

Following FEA investigation of the full range of possible designs, the displacement varied between 38.8 mm and 41.5 mm, the maximum 1st principal stress at the hole corners varied between 27.5 N mm^{-2} and 42.5 N mm^{-2} and the maximum shear stress in the web varied between −12.8 N mm^{-2} and −22.0 N mm^{-2} at mid-depth. The optimum design, in terms of stiffness and strength, was determined to consist of the following parametric values: Horizontal Joint Length ($L1$) 50 mm, Hole Depth ($L2$) 110 mm, Cutter Radius (R) 6.35 mm and Cutting Angle (θ) 45°. For this design the maximum shear stress and 1st principal stress in the web are −13.9 N mm^{-2} and 29.8 N mm^{-2}, respectively, the displacement is 39.4 mm and the maximum tensile stress in the bottom flange is 26.2 N mm^{-2}.

Depending on the combination of the parameters, the maximum shear stress may occur at the top or bottom corners of the hole or in between holes at mid-depth. The maximum 1st principal stress may occur at the bottom corners of the holes or at the corners of the holes at mid-depth (point (b) in Fig. 7). A larger cutter radius and a smaller web angle had the greatest effect on the shear and 1st principal stress. For the optimum design the maximum shear stress occurs in between holes at mid-depth whereas the maximum 1st principal stress occurs at the bottom corner of a hole. Previous studies in timber comparing square versus circular holes observed the stress concentrations at the corner of the square holes reduced peak load compared to circular holes [4,5].

For a cutting angle of 45° and a cutter radius of 6.35 mm, a minimum horizontal joint length of 20 mm is required to accommodate a 110 mm diameter duct. This opening size can easily accommodate a 101.6 mm (4 in.) pipe which is a common size for routing plumbing services. However, this creates a small web post and results in higher stresses in this location. It was noted that increasing the horizontal joint length to 50 mm reduces the stress on the web post and also reduces the maximum 1st principal stress at the corner of the hole.

The reduction of the hole size from 110 mm to 100 mm results in only minor reductions in shear and 1st principal stresses in the web and does not warrant the smaller hole depth and in turn the loss of additional flexibility for routing of services.

In the case of the 305 mm joists the optimum castellation geometry for the 241 mm joists was used for the initial design. The variations to the web parameters did not offer any significant improvement to its structural performance.

7. Conclusions

Two composite timber I-joists with Norway Spruce flanges and castellated OSB webs have been modelled using finite element analysis. The component materials were modelled as linear orthotropic elastic materials in both tension and compression.

- Good correlation was obtained between the FE models and physical test data for nine 241 mm deep joists and eight 305 mm deep joists.

– The stiffness ratios obtained from test and FEA data (EI_{test}/EI_{FEA}) were between 1.03 and 1.36 for the 241 mm joists and between 0.89 and 1.10 for the 305 mm joists.
– At peak load the FEA model predicted displacements of between 0.80 and 1.02 times that of the test for the 241 mm joists and between 0.98 and 1.16 times that of the test for the 305 mm joists.

- The effect that the castellated webs have on the structural behaviour of the joists was analysed by comparing the joists to FE models with equivalent solid webbed joists. There was an increase in displacement of 16.1% and 15.2% for the 241 mm and 305 mm I-joists, respectively, for the castellated webbed I-joist over the solid webbed counterpart at the peak load.
- A design load of 3.06 kN m^{-2} (EC1) was applied to the FE model on each joist size using 400 mm and 600 mm spacing. Both sizes of joist are within the EC5 serviceability limit for deflection with plasterboard at 400 mm spacing between joists. At 600 mm spacing both sizes of joist exceeded the serviceability limit with plasterboard but are within the serviceability limit without plasterboard.
- FEA suggests that joist failure initiates with tensile cracking at the corners of the hole which in turn facilitates shear cracking at the web posts between the holes at mid-depth.
- A FEA parameter study was carried out on each size of joist to determine the optimum design of the castellation geometry to maximise stiffness and to minimise shear and 1st principal stresses in the web. The same optimum design resulted for both sizes of joist.

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