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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

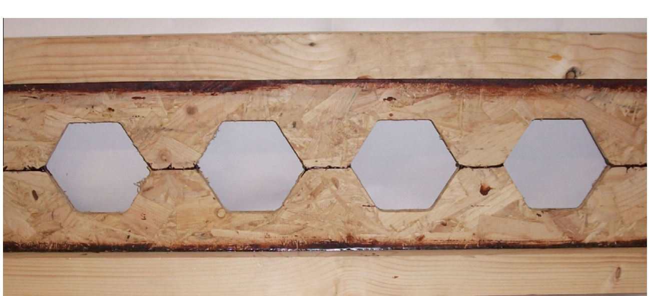

Fig. 1. Castellated joist.

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].

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