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Effects of the thickness of cross-laminated timber (CLT) panels made from Irish Sitka spruce on mechanical performance in bending and shear

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HIGHLIGHTS

- The thicker the CLT panel is, the lower its bending and rolling shear strength.
- Rolling shear strength values for Sitka spruce of 1.0–2.0 N/mm^2.
- 'Global' deformation results closely match theoretical stiffness.
- Cross-lamination provides no strengthening effect for in-plane bending behaviour.

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ABSTRACT

An investigation was carried out on CLT panels made from Sitka spruce in order to establish the effect of the thickness of CLT panels on the bending stiffness and strength and the rolling shear. Bending and shear tests on 3-layer and 5-layer panels were performed with loading in the out-of-plane and in-plane directions. 'Global' stiffness measurements were found to correlate well with theoretical values. Based on the results, there was a general tendency that both the bending strength and rolling shear decreased with panel thickness. Mean values for rolling shear ranged from 1.0 N/mm^2 to 2.0 N/mm^2.

1. Introduction

The construction industry has been undergoing continuous modification and improvement in order to successfully comply with the requirements of sustainable development, leading to a requirement for more durable, less labour- and service-intensive materials at a competitive price. One of the most promising materials meeting these requirements is cross-laminated timber (CLT). CLT is a prefabricated multi-layer engineered panel wood product, manufactured from at least three layers of parallel boards by gluing their surfaces together with an adhesive under pressure. The grain direction of consecutive layers is orientated orthogonally. The number of laminates in CLT is generally odd, therefore face layers are parallel to each other. This specific orientation results in excellent in-plane and out-of-plane strength, rigidity, and stability characteristics. The degree of anisotropy in properties and the influence of natural variations, such as knots, are reduced in comparison with construction timber [1–6]. Load-bearing CLT wall and floor panels are easily assembled on site to form multi-storey buildings, improving construction and project delivery time, reducing costs, and maximising efficiency on all levels [2,7–9].

Many timber species for CLT production have been investigated worldwide. Fortune and Quenneville [6] aimed to establish the use of CLT in New Zealand using locally grown Radiata pine bonded using resorcinol adhesive. CLT panels were generally, but not always, stronger than their constituent boards. CLT material fabricated using Southern pine was tested in bending, by Hindman and Bouldin [10], to establish the bending strength, bending stiffness, and shear strength. These properties exceeded the published values for the V3 grade [11]. Furthermore, prototype Sugi CLT floor panels were manufactured by Okabe et al. [12] and bending tests were carried out for different numbers of layers and thickness of CLT panels. The bending stiffness calculated using composite theory and the Monte Carlo method was in agreement with the

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experimental bending stiffness. It was found that the moment carrying capacity calculated by the deterministic design method underestimated the moment carrying capacity of the CLT panels. Park et al. [13] investigated 30 types of 3-ply parallel- and cross-laminated panels from five species (Sugi, Hinoki, Kiri, Katsura, and Buna). They found that the bending creep performance perpendicular to the grain was improved by cross-lamination. The effects of width and lay-up on the tensile strength of CLT were studied by Ido et al. [14]. The elastic modulus of CLT made of Sugi with different lay-ups was measured by dynamic and static methods, and tensile tests were conducted for different widths and lay-ups. The results showed that the variations in lay-ups affected the CLT. The estimated tensile strength of CLT, as calculated using the Young's modulus of the lamina of each layer, and the tensile strength of lamina were found to be in good agreement with the measured tensile strength of CLT. Recently, Wang et al. [15] evaluated on mechanical behaviour of timber composites. Four types of CLT panels, one generic CLT (used as control) and three types of Hybrid cross-laminated timber (HCLT), using lumber and/or laminated strand lumber (LSL), were fabricated. It was found that the HCLT had better bending performance (MOE 13%–19% higher, MOR 24%–36% higher).

Park et al. [13] found that the experimentally obtained Modulus of Elasticity (MOE) parallel to the grain of the face laminate of CLT was much lower than the calculated MOE due to the effect of the deflection caused by shear force on the MOE. In addition, there was an extremely high positive correlation between the Modulus of Rupture (MOR) and the measured MOE parallel to the grain of the face laminate of CLT. Their findings are in line with the study by Niederwestberg and Chui [16], who explored material and structural characteristics of laminates and their effects on the overall characteristics of CLT using modal testing and static testing. Comparing MOE values from the static tests with the values calculated by the shear analogy showed that the results from the static tests were about 50% lower than the calculated ones. This was explained by the high influence of shear deformation in bending tests with specimens with a span to thickness ratio of about 10. Blass and Fellmoser [17] proposed that only for span-to-depth ratios of at least 30 could the influence of shear be disregarded for loading perpendicular to the plane. In another study Vessby et al. [5] investigated the structural performance of 5-layer cross-laminated timber elements, made of 19 mm thick C24 boards glued together with PUR adhesive. The stiffness and strength of four cross-laminated timber elements (4955 mm long, 1250 mm wide and 96 mm thick) were studied during in-plane bending. The results showed the CLT elements possess a high degree of stiffness and strength, and a significant difference in behaviour was found between the two different ways in which the elements were connected to each other. Furthermore, investigations of the effect of different CLT specimen sizes on the tests results were performed. Steiger and Gülzow [18], and Steiger et al. [19] assessed bending strength and stiffness of the CLT by 4-point bending tests of strip-shaped specimens with a width of 100 mm, cut from the panels. For both parameters differences in strength and stiffness of up to 100% were found for strip-shaped specimens cut from the panels. This was attributed to local defects and non-homogeneities due to the quality of the raw material or due to the method of producing the panels as bending strength and stiffness of CLT panels can vary quite strongly within one single panel. Rolling shear failures, which frequently occurred when testing the 100 mm wide strip-shaped specimens, were not observed in destructive tests of gross CLT panels.

Cross layers in structural bonded timber elements loaded perpendicular to the plate show significant rolling shear deformations caused by the very low rolling shear stiffness of timber. Blass and Görlacher [20] established a characteristic value of 1.0 N/mm^2 for the rolling shear strength of European spruce, independent of the strength class. Their tests of different timber bonded elements confirmed the validity of the calculation model and verify the value for the rolling shear modulus of 50 N/mm^2 published by Neuhaus [21]. However, this value may differ slightly depending on certain wood properties such as density and annual ring orientation [17]. Zhou et al. [22] observed that cross layers with growth ring orientation in-between flat- and quarter-sawn could increase the rolling shear modulus in comparison to flat-sawn or quarter-sawn. In another study, Zhu et al. [36] indicated that the shear analogy method could be used to more accurately predict the deflection of a three-layer CLT specimen using the measured rolling shear modulus when the span-to-depth ratio was relatively small. Their CLT panels were made of Black spruce (Picea mariana) timber and fast-curing epoxy or one-component PUR. The average rolling shear strength of 3-layer down-scaled CLT was 2.74 MPa under 3-point bending tests at a span to depth ratio of 6. Furthermore, Zhu et al. [23] suggest that the bending test might be the most appropriate test method for the determination of the shear strength of CLT because it can produce a rolling shear failure mode that is encountered under bending. Moreover, an extensive study by Li [24] showed that the mean rolling shear strength value ranges from 1.41 MPa to 1.76 MPa, and confirmed previous claims that the rolling shear strength is affected by specimen size, loading type and loading protocol. In another study, Saavedra Flores et al. [25] investigated the rolling shear failure in CLT fabricated with Chilean radiata pine bonded with Emulsion Polymer Isocyanate (EPI) adhesive. However, a very limited number of specimens were tested and the study focused on developing cohesive zone models to simulate the cracking in the material. These numerical predictions were in line with experimental results.

Even though the technology of CLT production and the theory of the mechanical behaviour of CLT are well understood [2,26], there is still a lack of experimental data on the mechanical performance of CLT panels. Since a huge variety of wood species, even of low strength grades, confirmed potential for utilisation in CLT exists, further studies on using different timber species for CLT production should be carried out. One of the timber species with such potential is Irish-grown Sitka spruce, characterised as a fast growing, low density species due to the rapid growth conditions in Ireland and short rotation length. It is the most-widely grown species in Ireland, therefore its usage in construction, as a locally sourced material, would follow sustainable development trends [27]. Previous studies, which investigated the performance in bending, shear behaviour, and failure modes, confirmed its potential for production of engineered-wood products [28–36]. Furthermore, the mechanical behaviour of CLT panels made from Scottish Sitka spruce was investigated by Crawford et al. [37]. Two 3-layer and one 5-layer CLT panels were prefabricated using 40 × 95 mm Sitka spruce boards, graded to C16, and polyurethane (PUR) adhesive. Established bending strengths and stiffnesses in in-plane and out-of-plane were not dissimilar to the commercially available CLT panels, manufactured in Central Europe, indicating the potential for utilisation of Sitka spruce in CLT. The main objectives of this study were to determine the strength and stiffness properties of CLT panels made from Sitka spruce (Picea sitchensis) and to establish the effects of the thickness of the CLT panels on the mechanical performance in bending. Therefore, CLT samples of a variety of sizes and thickness were manufactured using the technical data determined in an earlier investigation [38]. This investigation led to the establishment of the optimal production technology parameters for manufacturing CLT from Irish Sitka spruce namely, the adhesive type, the spread rate, and the clamping pressure. For the purpose of this article, the established values were used during the manufacture of CLT panels for the structural performance assessment. Smaller 3-layer panels of two thicknesses were tested