WOOD I-JOIST MODEL SENSITIVITY TO ORIENTED STRANDBOARD WEB MECHANICAL PROPERTIES

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Abstract. Research on wood I-joist design has often used laboratory testing, but simulation using the finite element method (FEM) offers advantages, including the possibility to separately study different joist components. The objective of this project was to perform a sensitivity analysis using FEM to determine which oriented strandboard (OSB) properties have higher impact on I-joist shear strain and deflection. OSB mechanical properties were changed from 50 to 200% of the reference value to determine their impact on web shear strain and I-joist deflection. The model was primarily sensitive to in-plane web shear stiffness, which changed I-joist deflection up to 23%. The model was also sensitive to the web tensile modulus of elasticity parallel and perpendicular to joist length and, to a lesser extent, to web shear stiffness. These properties changed I-joist deflection up to 2 and 1%, respectively. These findings will be used to plan future work to experimentally determine sensitive OSB web properties required to develop a finite element model of the mechanical behavior of wood I-joists.

Keywords: Wood I-joists, web OSB, sensitivity analysis, numerical simulation.

INTRODUCTION

Wood I-joists are widely used in construction and sold in a competitive market. Therefore, there is a compelling need to optimize I-joist design and manufacturing processes. Most of

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research and development has focused on design and service performance (eg web openings, stiffeners, and creep) based on laboratory testing. The use of solid wood flanges has a strong impact on I-joist behavior. However, the optimization of web properties is challenging because it is difficult to isolate the web's contribution to I-joist performance for proper evaluation.

Fergus (1979) was the first to use the finite element method (FEM) to investigate wood I-joist behavior. This author studied many aspects of wood I-joist design, including web material properties and web openings. He considered I-joists made with laminated veneer lumber (LVL) flanges and oriented strandboard (OSB) webs, developed an FEM model of I-joist deflection, and performed a sensitivity analysis. In the sensitivity analysis, the I-joist properties considered were flange longitudinal modulus of elasticity (MOE) in tension, flange Poisson's ratio, web MOE in tension in the I-joist longitudinal direction, web transverse MOE in tension, in-plane web shear modulus, and web Poisson's ratio. Properties were changed individually to ± 2 standard deviations from the nominal value while all other properties remained at their original values. The sensitivity analysis was performed on FEM models developed for two wood I-joist configurations, shear and moment critical. The moment critical I-joist was 0.254 m deep by 7.32 m long and the shear critical I-joist was 0.559 m deep by 2.44 m long. Web thickness was 9.5 mm for the OSB web stock. Fergus (1979) found that results on the moment critical I-joist were sensitive only to flange material MOE in tension along the longitudinal axis of the wood flange. Results on the shear critical I-joist were sensitive to flange MOE in tension, shear modulus in the web plane, and web transverse MOE.

In a more recent study, Chui et al (2007) experimentally determined the influence of certain web material properties on I-joist behavior. They focused on the correlation between OSB web properties and I-joist performance in a shear test. Shear tests were performed on two different joist configurations with 0.241- and 0.356-m depths, respectively. Both used 38×63-mm lumber flanges. I-joists were 1.130 and 1.473 m long for 0.241- and 0.356-m deep I-joists, respectively. The authors found that I-joist shear capacity is mainly determined by OSB web shear strength. Coefficients of determination of 0.19 and 0.21 were found between joist shear capacity and web shear strength for 0.241- and 0.356-m deep I-joists, respectively. They also found that results were not sensitive to OSB web bending MOE. They noted that the use of stiff, high-quality wood flanges might have had an impact on their findings.

A sensitivity analysis of wood I-joist component properties was also performed by Chui et al (2007). The analysis was based on the two experimental setups described previously. Modeling was used to determine the influence of OSB web bending MOE and shear modulus on I-joist deflection. Properties were varied from 10 to 20 times with web bending MOE ranging from 1000 to 10,000 MPa and web shear stiffness from 100 to 2000 MPa. Numerical results showed that web bending MOE had almost no impact on deflection of the shallower joist and only a small impact on the deeper joist. The midspan bending deflection variation was less than 1 mm over the OSB bending MOE range for the 0.241-m deep I-joist (approximately 7-8 mm). The deflection variation was slightly higher than 1 mm over the OSB bending MOE range for the 0.356-m deep I-joist (approximately 14-15 mm). When less than 500 MPa, OSB web shear modulus had a significant impact on shear deflection. In the 100-500 MPa range, deflection varied 16-27 mm for the 0.356-m deep I-joist and 8-15 mm for the 0.241-m deep I-joist. When OSB web shear modulus was in the 500-2000 MPa range, deflection varied from 14 to 16 mm for the 0.356-m deep I-joist and 7-8 mm for the 0.241-m deep I-joist. Above 500 MPa, the influence of shear modulus was not significant. The model results were primarily sensitive to OSB web shear modulus.

It would be relevant to investigate properties other than web bending MOE and shear stiffness when considering OSB as an orthotropic material characterized by a set of engineering properties. Among others, Zhu (2003), Guan and Zhu (2004), and Zhu et al (2005, 2007) worked on I-joist modeling, but they did not perform a sensitivity analysis. Zhu (2003) experimentally determined most of the OSB mechanical properties except for shear stiffness in the board plane (G_{12}). Zhu (2003) and Morris et al (1996) determined G_{12} based on Eq 1 using three measured MOE values as follows:

$$G_{12} = \left(\frac{4}{E_{45^\circ}} - \frac{1 - \upsilon_{12}}{E_1} - \frac{1}{E_2} \right)^{-1} \quad (1)$$

where G_{12} is shear stiffness in the board plane, E_1 is MOE in tension along the strong axis in the board plane, E_2 is MOE in tension along the weak axis in the board plane, E_{45° is MOE at 45° between E_1 and E_2 in the board plane, and ν_{12} is Poisson's ratio in the board plane. The joints between the I-joist flanges and the web are usually considered rigid (Fergus 1979; Zhu 2003; Chui et al 2007), except when the joint itself is the element studied (Chui et al 2005). The last authors analyzed joints for bearing capacity to reduce knife-through failure.

Most studies on wood I-joist modeling have demonstrated a strong impact of the mechanical properties of wood flanges on deflection. However, questions remain about the impact of web OSB mechanical properties on deflection. Sensitivity analyses of the impact of web properties were not based on the same property set, and none considered a set of engineering properties that adequately described OSB as an orthotropic material. Fergus (1979) evaluated most, but not all, of these properties. Moreover, the moment critical I-joist considered was longer than the currently allowable span for the depth used, and the shear critical I-joist was too deep for the span used. Furthermore, local variations in web mechanical properties from OSB density variation in the plane and the rigidity of web-to-flange joints were not considered. Therefore, the objective of this research was to identify which of the web mechanical properties should be determined experimentally because of their impact on I-joist deflection and shear strain. To achieve this, a model sensitivity analysis was performed focusing on the impact of OSB web mechanical properties. The current study is the first step in a larger project aimed at developing a model to simulate the deflection of a loaded wood I-joist in the elastic domain while considering the impact of web local properties and their variation.

MATERIAL AND METHODS

I-Joist Web-to-Flange Joint

A series of tests was performed to determine if the web could slip in the flange joint when loaded (Fig 1). To prevent crushing, the OSB web was reinforced on both sides with 15.6-mm thick plywood glued and screwed onto the OSB. This compensated for the web slenderness and to generate stress in the joint. A mortising machine was used to remove the web material from the bottom of the joist, including the material glued in the flange grooves. The purpose was to allow the web OSB to slide in the flanges if slippage occurred when loaded. A compression load was applied to the reinforced part of the web using an 890-kN capacity Riehle universal testing machine at a crosshead speed of 5 mm/min. Tests were conducted until OSB web failure, and the failure mode was recorded.

Finite Element Model

Theoretical considerations. The FEM model was developed using Abaqus/CAE 6.4.1. This software has been used successfully in studies on layered wood composites (Blanchet et al 2005) and wood I-joists (Zhu 2003; Guan and Zhu 2004; Zhu et al 2005, 2007). The OSB web and the wood flanges were considered orthotropic (Zhu 2003). Figure 2 shows the reference coordinate system used for the I-joist and its components. For the OSB web, direction 1 stands for the strong axis in the board plane, direction 2 for the weak axis in the board plane, and direction 3 for the direction along board thickness. The OSB web and the wood flanges were considered elastic. The strain–stress relationship was described as follows (Eq 2).

$$\begin{bmatrix}\gamma_1\\ \gamma_2\\ \gamma_3\\ \gamma_{23}\\ \gamma_{13}\\ \gamma_{12}\end{bmatrix} = \begin{bmatrix}\frac{1}{E_1} & \frac{-\nu_{21}}{E_2} & \frac{-\nu_{31}}{E_3} & 0 & 0 & 0\\ \frac{-\nu_{12}}{E_1} & \frac{1}{E_2} & \frac{-\nu_{32}}{E_3} & 0 & 0 & 0\\ \frac{-\nu_{13}}{E_1} & \frac{-\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}}\end{bmatrix} \begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{bmatrix} \quad (2)$$

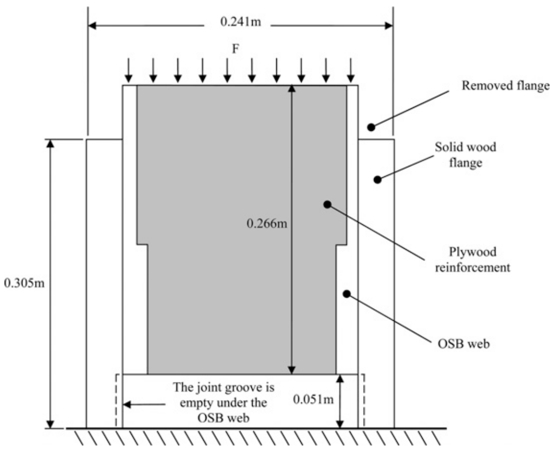

Figure 1. Web-to-flange joint test setup.

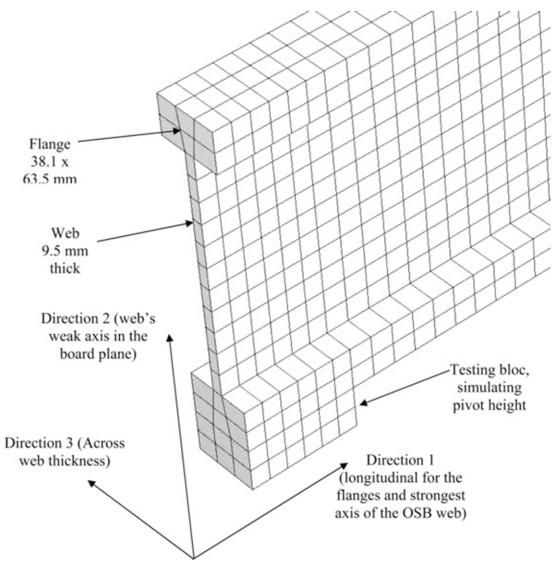

Figure 2. Reference coordinate system and finite element mesh.

The left-hand side of the equation is the strain tensor, the right-hand side first term is the compliance tensor, and the last term is the stress tensor. The material is described by its engineering properties (E_1, E_2, E_3, G_{12}, G_{13}, G_{23}, and υ_{12}, υ_{13}, υ_{23}) in the compliance tensor. The stiffness or compliance tensor for orthotropic material would normally be described by a 36- component matrix. Assuming material homogeneity at the macroscopic level (Maxwell's theorem) results in $S_{ij} = S_{ji}$, we are left with 21 components.

Convergence analysis. A convergence analysis was performed to determine the appropriate finite element mesh size. Abaqus/CAE automatically generates a mesh with a typical element size when seeding is not done manually. The proposed element size of 0.030 m was used as a reference value. The mesh size was then gradually reduced until the I-joist deflection converged. A brick element was used to suit the joist geometry. Two element types were studied: quadratic and linear bricks (20-node quadratic brick: C3D20R element type in Abaqus; 8-node linear brick: C3D8R element type). Typical element sizes considered were 0.030, 0.020, 0.015, and 0.0075 m. Abaqus/CAE was used for preprocessing, processing, and postprocessing. All elements were designed for orthotropic and elastic materials. The 0.020-m mesh is presented in Fig 2. Figures 3 and 4 show applied loads, symmetry, and physical constraints for 0.030-m mesh. A distributed load was applied to the top

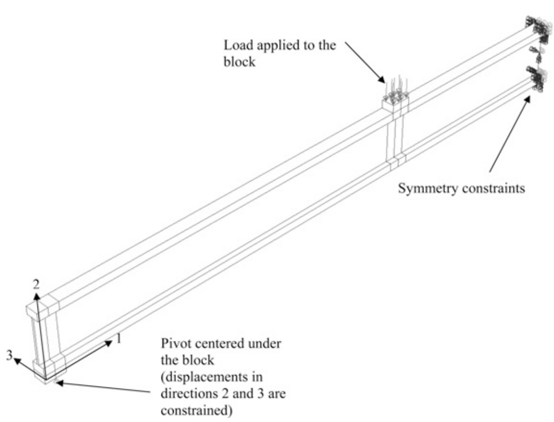

Figure 3. Simulated moment critical I-joist.

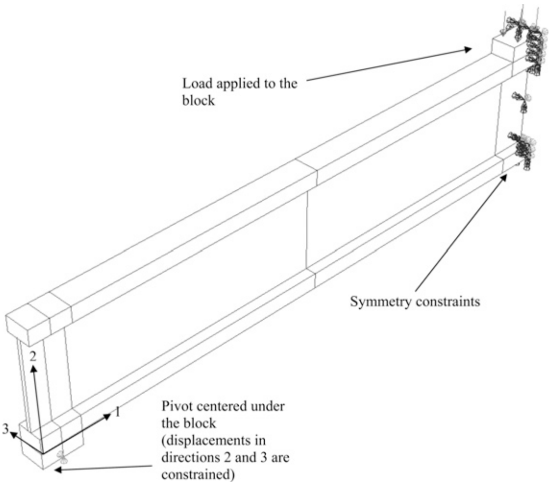

Figure 4. Simulated shear critical I-joist.

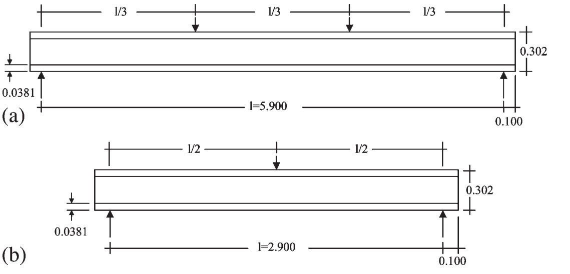

Figure 5. Test configuration and dimensions (m) for (a) the moment critical I-joist and (b) the shear critical I-joist.

surface of a block on the upper flange. To prevent deformation, the load block and reaction block were modeled as a homogenous isotropic elastic material with tensile MOE of 3×10^{11} MPa and Poisson's ratio of 0.3. Support depth matches the height over the pivot of the corresponding experimental setup. Block length is the same as for the experimental setup. The effect of element size and type was monitored for their impact on web and joist deflection behavior. Web behavior was determined by shear strain at a specific web node, and deflection was determined by the vertical displacement under the bottom flange.

Physical considerations. Wood I-joists are mainly subjected to shear stress or axial stress caused by the bending moment. Two models were developed to cover both cases. The first model, called "shear critical," has a high depth-to-length ratio; the second, called "moment critical," has a low depth-to-length ratio. The purpose was to cover potential variation in sensitivity induced by variation in depth-to-length ratio. This approach was also used by Fergus (1979), but the moment and shear critical I-joist depth-to-length ratio studied did not correspond to current practice. For instance, the moment critical I-joist was 7.32 m long but the current maximum allowable span should be about 4.6 m (Weyerhaeuser 2009). A 0.559-m deep joist with a 2.44-m span was also used, but these dimensions are not likely to be used in practice. In the present study, the shear critical I-joist had a 0.10-m central loading and the moment critical joist had 2-point loading. Figure 5 shows the two different cases. Only one I-joist depth was used with two different lengths representative of current practice. The 0.302-m deep I-joist is a commonly used depth. The flange section was 38.1×63.5 mm (2×3 lumber). Web nominal thickness was 9.5 mm. The length of the two I-joists considered was 3.0 and 6.0 m with corresponding spans of 2.9 and 5.9 m for the shear and moment critical I-joists, respectively (Fig 5). The 5.9-m span was selected, because it roughly represents the maximum allowed span for the selected I-joist section (Boise Cascade 2009).

Mechanical property variation. The imposed variations in engineering properties of the OSB web for the model sensitivity analysis were 50, 100, 150, and 200% of the nominal value. It is generally recognized that OSB properties are highly variable on a small scale and almost homogeneous on a larger scale. The 50-200% variation range was chosen based on available data and the literature (Fergus 1979; Karacabeyli et al 1996; Zhu 2003; Chui et al 2005; Chui et al 2007). Flange properties (Table 1) were taken from the literature and kept constant (Bodig and Jayne 1993; Jessome 1995; Ménard 1999). Tension MOE of flanges along the I-joist length (direction 1) is the most important property. Direction 1 for flanges also corresponds to the

Table 1. Elastic engineering properties of I-joist wood flanges (black spruce).

Property	E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	ν_{12}	ν_{13}	ν_{23}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
Value	[a]11528	[a,b]662	[a,b]662	[a]0.21	[a]0.23	[a]0.41	[a,b]666	[a,b]666	100

[a] Bodig and Jayne (1993).
[b] Averaged values in transverse direction from Bodig and Jayne (1993).

Table 2. Elastic engineering properties nominal values for the oriented strandboard web.

Property	E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	ν_{12}	ν_{13}	ν_{23}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
Value	[a]3650	[a]2600	[a]130	[b]0.18	[c]0.30	[c]0.30	[a]1370	[a]240	[a]240

[a] Rounded values from Zhu (2003).
[b] Grandmont et al (2006).
[c] Estimated value.

wood longitudinal direction. The principal radial (direction 2) and tangential (direction 3) directions of wood in flanges depend on the sawing pattern and are unknown in an actual I-joist. Because this sensitivity analysis focuses on the web, flange properties in directions 2 and 3 were simply averaged from the properties in the radial and tangential directions as per Ménard (1999).

OSB web engineering properties were also taken from the literature (Karacabeyli et al 1996; Zhu 2003; Chui et al 2005; Grandmont et al 2006; Chui et al 2007). Table 2 shows the nominal OSB web properties set before the variation imposed for the sensitivity analysis.

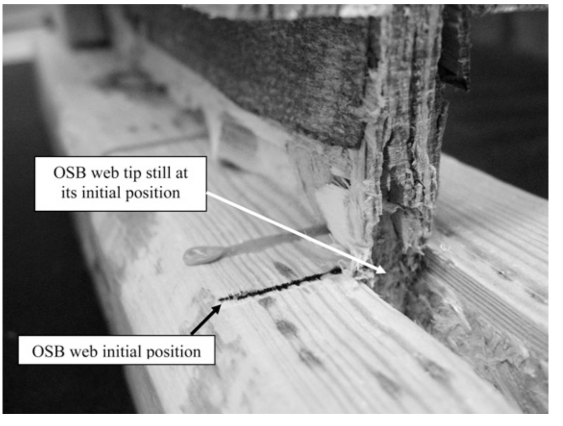

Figure 6. Oriented strandboard web-to-flange joint test specimen damaged in the web.

RESULTS AND DISCUSSION

Web-to-Flange Joint Testing

The web-to-flange joint did not slip during the 10 tests performed. In all cases, the OSB web tore in shear along the joint. Figure 6 shows no web movement in the joint groove. The same behavior was observed for all tests, demonstrating higher strength and stiffness in the web-to-flange than in the OSB web joint. The web-to-flange joint was therefore considered rigid in the model, in line with Fergus (1979), Zhu (2003), and Chui et al (2007).

Simulation Results

Convergence analysis. Table 3 shows the OSB web shear strain and I-joist deflection results for different mesh sizes (0.030-0.0075 m) for quadratic and linear element types. Results show that the element size proposed by Abaqus/CAE (0.030 m) is sufficiently small for use with quadratic brick elements and that reducing element size barely affects the results. Because the required computational time was not significantly longer, 0.020-m quadratic elements were used.

Table 3. Effect of element type and size on oriented strandboard (OSB) web shear strain and I-joist deflection.

Typical element size (m)	Element type	OSB web max. shear strain	Joist max. deflection (m)
0.030	Linear	−0.00722	−0.0352
0.030	Quadratic	−0.00719	−0.0337
0.020	Linear	−0.00719	−0.0337
0.020	Quadratic	−0.00718	−0.0339
0.015	Linear	−0.00718	−0.0339
0.015	Quadratic	−0.00718	−0.0338
0.0075	Linear	−0.00718	−0.0338
0.0075	Quadratic	−0.00718	−0.0339

Sensitivity analysis results for the shear critical I-joist. Figure 7 shows typical OSB web shear strain and I-joist deflection simulation results. The impact of web properties variation on shear critical I-joist deflection is shown in Table 4, and the impact on shear strain is shown in Table 5. According to these results, the model was primarily sensitive to G_{12} for the shear critical I-joist. A 23% increase in the maximum deflection was calculated when G_{12} was set to 50% of its nominal value. For the same G_{12} value, a 100% increase in shear strain was obtained. The results are less sensitive to other properties, although variations in E_1 and E_2 have a small impact. When E_1 or E_2 are set at 200% of their nominal value, the maximum deflection and shear strain change remain under 3%. These findings on the impact of E_1 and E_2 are in agreement with the results reported by Fergus (1979) and Chui et al (2007). It was also found that

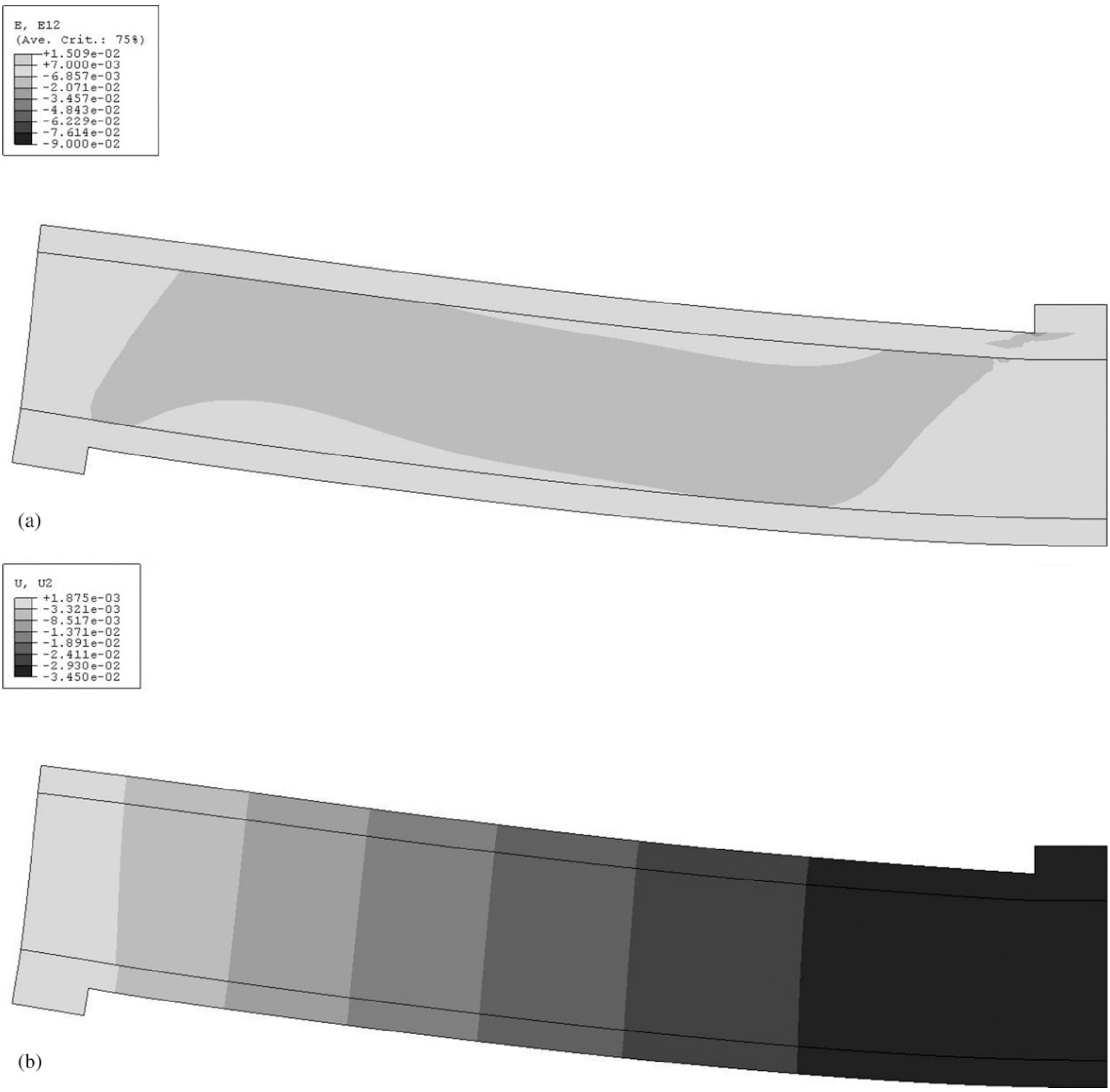

Figure 7. Three-meter-long I-joist typical simulation results for (a) shear strain and (b) deflection.

Table 4. Effect (%) of oriented strandboard web properties variation on the shear critical I-joist maximum deflection for 50-200% of the nominal value.

Properties	E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
0.5 × nominal value	1.2	0.8	0.0	0.1	0.0	0.0	22.9	0.0	0.0
Nominal value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5 × nominal value	−1.1	−0.3	−0.01	−0.1	0.0	0.0	−7.7	0.0	0.0
2.0 × nominal value	−2.2	−0.4	−0.01	−0.2	0.0	0.0	−11.6	−0.1	0.0

Table 5. Effect (%) of oriented strandboard web properties variation on the shear critical I-joist shear strain for 50-200% of the nominal value.

Properties	E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
0.5 × nominal value	−1.3	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
Nominal value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5 × nominal value	1.2	0.0	0.0	0.0	0.0	0.0	−33.3	0.0	0.0
2.0 × nominal value	2.4	0.0	0.0	0.0	0.0	0.0	−50.0	0.0	0.0

Table 6. Effect (%) of oriented strandboard web properties variation on the moment critical I-joist maximum deflection for 50-200% of the nominal value.

Properties	E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
0.5 × nominal value	1.6	0.2	0.0	0.0	0.0	0.0	5.9	0.0	0.0
Nominal value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5 × nominal value	−1.6	−0.1	0.0	0.0	0.0	0.0	−2.0	0.0	0.0
2.0 × nominal value	−3.0	−0.1	0.0	0.0	0.0	0.0	−3.0	0.0	0.0

Table 7. Effect (%) of oriented strandboard web properties variation on the moment critical I-joist shear strain for 50-200% of the nominal value.

Properties	E_1	E_2	E_3	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
0.5 × nominal value	−1.3	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
Nominal value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5 × nominal value	1.2	0.0	0.0	0.0	0.0	0.0	−33.3	0.0	0.0
2.0 × nominal value	2.4	0.0	0.0	0.0	0.0	0.0	−50.0	0.0	0.0

variations in E_3, ν_{13}, ν_{23}, G_{13}, and G_{23} have almost no impact on maximum deflection and shear strain of the shear critical I-joist. These results provide additional information on mechanical properties to that found by Fergus (1979) and Chui et al (2007).

Sensitivity analysis results for the moment critical I-joist. According to the results shown in Tables 6 and 7, the model's sensitivity to web properties is almost the same as for the shear critical I-joist. The model's results are most sensitive to shear modulus G_{12}, although they are less sensitive than for the moment critical I-joist. A 5.9% increase in maximum deflection was recorded when G_{12} was set at 50% of its nominal value. This is only about 25% of the change observed for the shear critical I-joist. In fact, for the same G_{12} value, a 100% increase in shear strain was recorded. Fergus (1979) did not find G_{12} to be sensitive for the moment critical I-joist. No gains or losses were recorded for midspan maximum deflection. Fergus (1979) use of high-tension MOE flanges (LVL) and a lower depth-to-length ratio could explain these differences. The calculated deflection is more sensitive to E_1 and less sensitive to E_2 compared with the shear critical I-joist. When E_1 or E_2 are set at 200% of their nominal value, maximum deflection decreases by 3 and 0.1%, respectively, and shear strain increases by 2.4 and 0%, respectively. Variation in E_3, ν_{12}, ν_{13}, ν_{23}, G_{13}, and G_{23} had almost no impact on maximum deflection or shear strain of the moment critical I-joist as was the case for the shear critical I-joist. The effect of shear modulus on maximum deflection was not linear, as observed by Chui et al (2007). At lower value than 1000 MPa, deflection becomes much more sensitive to variation in G_{12}. From these results, it appears that G_{12} and E_1 must be determined experimentally to properly model shear strain and I-joist deflection. This is in agreement with the results obtained by Chui et al (2007) on the effect of G_{12}, but not with those obtained by Fergus (1979). It appears that E_2, E_3, ν_{13}, ν_{23}, G_{13}, and G_{23} of the OSB web have no significant impact on I-joist maximum deflection or shear strain. These results also provide additional information on mechanical properties to that found in the studies by Fergus (1979) and Chui et al (2007).

The presented results and Eq 1 imply that Poisson's ratio in the board plane ν_{12} might also be considered important for the simulation of I-joist behavior. The sensitivity results show that Poisson's ratio has almost no effect on shear strain or I-joist deflection. However, the use of Eq 1 to determine G_{12} (Morris et al 1996; Zhu 2003) implies the use of ν_{12}. When determining shear modulus in this manner, the model can be considered sensitive to G_{12}, E_1, E_2, E_{45°, and ν_{12}. These properties must be experimentally determined for purposes of I-joist simulation.

CONCLUSIONS

A sensitivity analysis was performed to determine which OSB web mechanical properties must be precisely known for purposes of simulating wood I-joist deflection and shear strain. Results show that the finite element I-joist model is mainly sensitive to shear modulus in the OSB web plane (G_{12}). Sensitivity is greater for the shear critical than the moment critical I-joist. Longitudinal and perpendicular tensile MOE (E_1 and E_2) of the web have a slight impact on calculated I-joist deflection. Over the 50-200% variation range of G_{12}, deflection changed from 23 to –12% and from 6 to –3% for the shear and moment critical I-joists, respectively. Over the same variation range, E_1 changed deflection only, from 1.2 to –2.2% and from 1.6 to –3.0% for the shear and moment critical I-joists, respectively. Deflection change was even smaller for E_2, from 0.8 to –0.4% and from 0.2 to 0.1% for the shear and moment critical I-joists, respectively. Finally, if G_{12} is determined by solid mechanics equations, E_1, E_2, E_{45°, and ν_{12} are the properties that must be determined experimentally among a set of engineering properties.

ACKNOWLEDGMENTS

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