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Strain-softening response and failure prediction in notched oriented strand board (OSB)

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Abstract

The strain-softening response and failure of oriented strand boards (OSB) are investigated both experimentally and numerically. Standard tests are used to characterize the elastic (MOE) as well as damage properties (damage height, damage initiation strain and fracture energy) of OSB in two principal (parallel and perpendicular) directions. Experimental data are then used in conjunction with a recently developed physically-based damage model to simulate the nonlinear response of notched OSB samples under tension using the finite element (FE) method. Acceptable agreement between the FE simulations and experimental data are found. The results suggest that a strain-softening approach is capable of accurately modelling the damage progression in notched OSB samples.

Keywords

Oriented strand board, wood, composite, strain-softening, finite element method, fracture

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Introduction

The motivation for this work comes from the needs of the engineered wood products industry where wood strands are widely being used in products such as oriented strand board (OSB) and oriented strand lumber (OSL). Due to their high stiffness and strength properties at reasonable costs, compared to conventional construction materials such as plywood, strand-based wood composites are manufactured using a wide range of wood species around the world (Akrami et al., 2014). For instance, in North America, Europe, and Australia, OSB is widely being used as wall and roof sheathing, and web of I-joists in wood framed buildings (Guan and Zhu, 2009; Akrami et al., 2014). In Europe, OSB is very popular for other structural applications in modular buildings such as structural insulated panels (SIP), as well as trailer liners and vehicle flooring (Akrami et al., 2014; Chen and Hao, 2015; Meng et al., 2018). Similar to wood, bamboo culms may be cut and used as strands for fabricating similar products such as bamboo oriented strand boards in South-East Asia and Latin America (Sumardi et al., 2008; Malanit et al., 2011; Febrianto et al., 2012; Chen et al., 2015; Chaowana and Barbu, 2017).

The use of strand-based wood and bamboo OSBs in structural products demands certain requirements of their structural performance under various loading conditions. There are many parameters and variables that affect the mechanical properties and ultimately the structural response of strand-based composites, such as strand size and orientation distribution, type and species, resin type and content, void content, moisture content, etc. (Malekmohammadi, 2014; Malekmohammadi et al., 2015). The elastic properties, including the modulus of elasticity (MOE), of strand-based composites have been investigated extensively in the literature (Painter et al., 2006; Yadama et al., 2006; Benabou and Duchanois, 2007; Chen et al., 2010; Stürzenbecher et al., 2010; Sebera and Muszyński, 2011; Zhang and Lu, 2014). Gereke et al. (Gereke et al., 2012) proposed a two-step numerical multi-scale framework for predicting the flexural modulus of a PSL beam. Malekmohammadi et al. (2015) extended the multi-scale model of Gereke et al. (2012) by developing a more comprehensive multi-scale analytical framework for predicting elastic response of strand-based composites under bending loads. Several parameters were considered including wood species and their combination; strand dimensions, orientation, compaction and density profile; void content; fines content; as well as resin type, content, and distribution. The methodology has recently been applied to bamboo OSBs (Dixon et al., 2017) to predict their flexural MOE by accounting for the different microstructures of wood and bamboo.

Although the elastic response of various wood and bamboo based OSBs have been well investigated in the literature, there is a paucity of information on the nonlinear stress-strain behaviour of such materials (especially around notches). It is well known that OSBs can withstand loads even after reaching their maximum strength values (Chen and Hao, 2015; Chen and He, 2017), especially under bending and compression. Analysing the nonlinear structural response of elements that contains OSB (e.g. I-joists and hybrid floor systems with OSB panels) requires having an improved understanding of stress-strain behaviour of strand-based composites up to failure. Nevertheless, only few researchers have studied the stress-strain response of OSB under axial tension and compression recently (Chen and He, 2017). Empirical relations were established between stresses and strains using experimental data and it was found that the loading directions had a significant effect on failure response of OSB. A refined empirical model was suggested by Chen and He (2017) to simulate the behaviour of OSB panels. The above works did not consider the effect of sharp cracks, holes or notches on the structural response of OSB. Openings such as holes in OSB are often encountered in OSB webbed I-joists (Guan and Zhu, 2009; Morrissey et al., 2009; Chen et al., 2015). These openings could affect the structural performance of beams significantly depending on their size, location, and the member geometry.

From a materials viewpoint, structural wood products, such as OSB (Chen and He, 2017), Glulam (Blank et al., 2017) and LVL (Franke and Quenneville, 2014) exhibit quasi-brittle behaviour similar to advanced fibre-reinforced composites (e.g. CFRP of GFRP) and concrete. This is due to inherent inhomogeneities in wood and its composites (Blank et al., 2017). It is well known that during damage propagation in notched samples of quasi-brittle materials such as concrete and advanced fibre reinforced composites in general, a failure process zone (FPZ) is formed in front of the notch within which material properties including stiffness are degrading. Unlike brittle type failure, there is a characteristic length (i.e. damage height also known as damage width) associated with FPZ that is independent of testing geometry and loading conditions (Bazant and Planas, 1998; Bažant and Le, 2017). It should be noted that the size of the FPZ, related to the scale of the material heterogeneity, leads to a deterministic-type size effect which is different from a statistical (Weibull-type) size effect (see e.g. (Bazant and Planas., 1998)). Therefore, determining the characteristic length of FPZ is crucial for analysing the damage response of such materials. Considering multitude of failure mechanisms and their associated interactions in quasi-brittle materials, many established models are available for analysis of damage growth and failure. These range from simple models with few parameters to characterize (e.g. maximum stress/strain theories) to complex multi-damage mode models.

From a computational viewpoint, three main categories of numerical approaches exists for damage simulation in these materials: Continuum Damage Models (CDM), discrete damage models and embedded crack models (Forghani et al., 2015). Among these approaches, CDM and smeared crack methods have enjoyed wide popularity due to their ease of implementation in commercial finite element codes. In this approach, the damage behaviour of material across the FPZ is represented in a smeared manner using strain-softening curves (i.e. degradation of apparent stiffness with progressive loading). Although such an approach does not include micro-details of damage progression including interaction of discrete damage modes (e.g. splitting and delamination), it provides an effective response of the damaged material on the macro-scale.

Strain-softening models have been applied successfully to a variety of applications including prediction of global damage response in concrete structures (Bazant and Oh, 1983; Bažant et al., 1984; Bažant and Pijaudier-Cabot, 1988) and progressive damage growth in advanced composites under both static and dynamic loads (Williams and Vaziri, 2001; Zobeiry et al., 2015, 2017). Usually, shape of the strain-softening curve is either assumed (e.g. simple linear or bilinear (Bazant et al., 1991; Elices et al., 2002), exponential (Jirásek and Patzák, 2002) or higher order polynomials (Williams et al., 2003; McGregor et al., 2008) or determined experimentally (Zobeiry et al., 2015, 2017). Based on this initial assumption, several damage parameters have to be measured to characterize the strain-softening response. This may include damage initiation strain(s), damage saturation strain(s), damage height, fracture energy and associated fracture energy density for a representative volume element (RVE). Damage initiation strains are usually obtained by conducting ASTM standard tests such as tensile or bending tests. Fracture energies are obtained using established test methods such as Compact Tension (CT), Over-height Compact tension (OCT) and Compact Compression (CC) (Kongshavn and Poursartip, 1999; Zobeiry et al., 2015, 2017). In these tests, positive geometries of notched specimens are used to ensure a controlled and self-similar damage growth. This allows for accurate measurement of damage parameters.

OSBs are increasingly being used in several structural members (e.g. OSB webbed I-joists) and the effects of notches and holes need to be taken into account in the design of such members as well as design standards (Guan and Zhu, 2009; Morrissey et al., 2009; Chen et al., 2015). A methodology that considers size effects in such composites is therefore needed for analysing their failure response. Characterization and simulation of the nonlinear response of strand-based composites up to failure would enable us to better evaluate the structural response of OSB with openings for design purposes. Furthermore, it will help materials engineers to optimize the microstructure of these green materials and improve their performances under extreme loading conditions such as earthquakes and impacts.

According to (Chen and He, 2017), OSB could carry significant amount of load within the nonlinear region of its stress-strain curve. However, the fracture energy and damage properties of OSB have never been quantified rigorously in the literature. In the following section, we present a methodology to examine the damage response of notched OSB up to failure. Furthermore, we illustrate how a multi-scale modelling approach could be combined with a sub-laminate based damage model to simulate the damage response of notched OSB in Results and Discussion section. In Summary and Conclusions section, we compare the OSB fracture energies (parallel and perpendicular to grain directions) with those reported for other structural wood products (Glulam and LVL) in the literature.

Methodology

The methodology presented in this paper uses a combination of experiments (bending and OCT tests) and numerical simulations to describe the nonlinear response of OSB under tensile loading.

Experiments involve tests to determine the behaviour of un-notched samples under bending as well as notched ones under uniaxial tension.

Experiments

The flexural stiffness and strength of OSB panels in their two main directions are measured using a three-point bending test setup following the ASTM standard. In total, 20 tests parallel to grain and 25 tests perpendicular to grain directions were carried out. The OSB samples were made from Aspen strands and provided by FPInnovations. The specimen nominal dimensions for the three-point bending tests as well as the main findings from the three point bending tests conducted (Standard deviations are in brackets) are given in Table 1. The modulus of rupture (MOR) and MOE values were calculated using ASTM test standard formulae in ASTM D1037 (ASTM, 2013).

As shown in Table 1, for anisotropic samples, the MOR and MOE for loadings parallel to grain are higher compared to loadings perpendicular to grain. Even though loading parallel to grain provides a higher MOR and MOE, such loading causes the standard deviation to rise significantly, probably due to higher values of Young's modulus of wood in its longitudinal direction and its significant effect on the panel MOE in its parallel direction (see (Malekmohammadi et al., 2013)). Such higher standard deviations for parallel to grain MOE are consistent with experimental data reported in (Chen et al., 2010; Malekmohammadi et al., 2015).

The mechanical behaviour of OSB depends on the vertical density profile (e.g. see (Chen et al., 2010)). Therefore, a series of density profile measurements were conducted on a commercially available QMS QDP-01X Density Profiler at FPInnovation. The measured density profiles are shown in Figure 1. Profiler had a resolution of 0.05 mm and step sizes ranging from 0.025 mm to 0.5 mm. The step size used for these measurements was 0.08 mm.

Considering the vertical density profiles and the input data provided in (Malekmohammadi et al., 2015), Malekmohammadi's multi-scale model was employed to estimate the elastic properties of the panels. Multi-scale model predictions are given in Table 2. Note that parallel face layers are considered as 1/3rd of the total panel thickness. Some important input parameters used in the multi-scale model are listed in Table 3. As measuring the shear properties is quite challenging, we use the predicted values from the multi-scale model for both MOE and shear modulus, G, in damage simulations. Additionally, the effective elastic modulus, E, of the face layer combined with strength value (or MOR) has been used to estimate the damage initiation strain required for the simulations.

The damage properties of notched OSB panels were characterized using OCT tests. Schematic of the OCT test geometry is shown in Figure 2. Tests were performed with a 20 kips (89 kN) screw-driven Instron uniaxial testing machine. During each test, pin-opening-displacement (POD) was measured using an Instron 2620-825 extensometer (±5 mm travel). The specimens were loaded under a displacement-controlled mode at a rate of 0.25 mm/min. All tests were conducted at ambient temperature and humidity.

After each test, the specimen was sectioned using a slow-speed diamond saw. Cross-sections were then analyzed to identify the extent of damage zone in front of the initial notch.

Modelling

Having determined the elastic properties and fracture energies of OSB in both directions, its nonlinear response is simulated using a sublaminate-based damage model. To predict the nonlinear damage response of notched OSB panels, a simplified version of the established damage model CODAM and its second variant CODAM2 which were originally developed for laminated composite materials (Forghani et al., 2013; Zobeiry et al., 2017) is used.

The damage law is based on a simple linear softening curve as shown in Figure 3(a). The damage model is characterized by damage initiation strain, ε_i and fracture energy density, g_f. Fracture energy density is calculated based on the experimentally measured fracture energy, G_f and characteristic damage height, h_c as follows:

$$g_f = \frac{G_f}{h_c} \tag{1}$$

Damage saturation strain is then defined as:

$$\varepsilon_s = \frac{2g_f}{E\varepsilon_i} \tag{2}$$

where E is the Young's modulus in the direction of loading. It should be noted that for orthotropic materials such as OSB panels, separate damage laws have to be defined for each direction of the material. In this study, CODAM2 which is implemented as a built-in material model, MAT_219, in the explicit finite element code LS-DYNA (LSTC, 2015) was used. A structured mesh with an element size of 0.25 mm in front of the initial notch was used as shown in Figure 4. Bazant's crack band theory was applied to modify the strain-softening curve based on this element size.

It should be noted that the problem of localization and mesh sensitivity attributed to all continuum damage models are usually dealt with methods such as crack band theory (Bazant and Oh, 1983) or nonlocal averaging techniques (Forghani et al., 2013; Zobeiry et al., 2017). While crack band theory is used to remedy mesh size sensitivity, nonlocal averaging is used to remedy both mesh size and orientation dependencies. In this study, due to the local nature of damage propagation in OCT loading geometry, the local form of MAT_219 in LS-DYNA (LSTC, 2015) with crack band theory was used. In this approach, the strain-softening curve is modified based on the size of the element, h_e, to ensure that the total amount of energy dissipated due to damage propagation is preserved regardless of the element size. As shown in Figure 3(b), in crack band theory, the damage saturation strain is modified using a scale factor, *n*, given by:

$$n\varepsilon_s = \frac{2G_f}{h_e E \varepsilon_i} \tag{3}$$

Using this method, however, a small element (i.e. small h_e) may undergo large strains during damage propagation leading to its fracture energy capacity being fully consumed. Since in LS-DYNA (LSTC, 2015) strains are treated as true strains, the above value has to be further modified (scaled) as shown in Figure 3(c) in order to account for the effect of large deformations (Zobeiry, 2010):

$$(\varepsilon_s)_{scaled} = ln(1 + n\varepsilon_s) \tag{4}$$

Results and Discussion

In the following, the failure responses of OSB specimens are presented and compared to model predictions. Differences between the model and experimental data are discussed.

As described in the Introduction section, unlike uniaxial tension or bending tests, the OCT loading geometry produces stable damage initiation and self-similar crack growth. The load-displacement response of the three notched specimens obtained from OCT tests are presented in Figure 5. Two of those (E1 and E2) were tested in their strong (parallel to face grain) directions while the third one (E3) was tested in its weak (perpendicular to face grain) direction. To better understand the damage mechanism and identify the damage characteristics, OCT specimens were sectioned after testing. Several cross-sections and the identified damage zone in specimen E2 are shown in Figure 6.

The damage zones for each specimen were identified using the line analysis techniques as described in (Kongshavn and Poursartip, 1999). The extent of the damage zone is depicted for three different specimens in Figure 7. It should be noted that the extent of the highlighted damage zones are approximately similar in shape.

From these zones, a characteristic damage height was determined to be roughly in the range of h_c = 19 to 22 mm. The fully damaged length or crack length (Δa) was also found to vary from 21 to 28 mm. Once the damage zone was identified, the fracture energy, G_f, was calculated using the following equation:

$$G_f = \frac{W}{b\Delta a} \tag{5}$$

in which W is the dissipated work of fracture corresponding to the area below the load-POD curve (Figure 5) and bounded by the linear elastic unloading path to the origin, b is the thickness of the specimen and Δa is the damage length as shown in Figure 7. The reader is referred to (Zobeiry, 2010)for more details on calculating the fracture energy, G_f.

Using Equation 5, a fracture energy of about 2.9 to 5.8 kJ/m^2 was obtained for OSB in its parallel direction. In the perpendicular direction, a fracture energy of about 8.9 kJ/m^2 was obtained. It should be noted that to the best of the authors' knowledge the fracture energy of OSB has never been reported in the literature. Experimental results from OCT tests are summarized in Table 4.

Having determined the elastic properties and fracture energies of OSB panels, simulations were performed on notched samples using the built-in material model MAT_219 in LS-DYNA. Bazant's crack band theory described in the Methodology section was applied to modify the strain-softening curve based on this element size. A damage initiation strain of 2.6% was assumed based on the bending tests. This value was estimated from MOR tests knowing the face layer's effective modulus. The effective modulus of the OSB face layer was determined from the multi-scale model based on the vertical density profile of the panel. The damage saturation strains were then estimated using Equations 2. Three sets of simulations were performed based on loading direction and the elastic moduli of samples presented in Table 1. The input values for parameters used in FE simulations are summarized in Table 5. Simulation results for load-POD curves are superposed on the corresponding experimental results in Figure 5 to facilitate the comparison between the predictions and test results.

Results show that the sub-laminate modelling approach, originally developed for fibre-reinforced composites, is capable of predicting the nonlinear damage response of notched OSB samples in both parallel and perpendicular directions. The post-peak behaviour of wood composites is not well known and has rarely been reported in the literature. The results suggest that extracting the strain-softening behaviour of wood composites is necessary in order to predict the failure response of notched samples with relatively good accuracy.

The variability observed in Figure 5 could be related to the natural variability of wood arising from the distribution of growth characteristics such as knots and defects (Blank et al 2017) as well as variability of process conditions which lead to presence of micro voids and variable resin distribution between wood strands. Blank et al. (2017) reported a relatively higher (~10 kJ/m^2) fracture energy for glued laminated timber (GLT). Considering the much lower cost and relatively high fracture energy of OSB (~3-9 kJ/m^2 obtained in this study) compared to wood (~0.1-0.8 kJ/m^2, e.g. see (Stanzl-Tschegg et al., 1994; Dourado et al., 2015)) and other structural wood products such as LVL (~0.6-1.8 kJ/m^2 according to (Franke and Quenneville, 2014)) makes OSB an attractive structural material and one that demands more rigorous study. For instance, the vertical density profile and the effect of strand orientations on the fracture energy could be explored more systematically using the strain-softening approach described in this paper.

Summary and Conclusions

In this study, the damage response and failure behaviour of notched oriented strand board (OSB) samples were studied using a combined experimental and numerical approach. Established experiments for advanced composites including overheight compact tension (OCT) tests were conducted to characterize OSB damage properties such as fracture energy and damage height. The positive notched geometry in OCT tests allows for self-similar damage growth and observation of post-peak response in OSB panels. This means that after an initial period for formation of process zone and growth of damage height, damage progresses in a self-similar manner with a constant characteristic damage height. During the initial period of FPZ formation, the critical fracture energy is small due to the small damage height. During the self-similar damage growth, however, when damage height is at its maximum value (about 20 mm in this study), the fracture energy is large. This is referred to as the R-Curve of the material. It should be noted that the energy value measured in this study is the fracture energy for self-similar damage growth. To measure the full R-Curve of the material, interruptive tests have to be conducted where the damage zone is measured at more intervals.

Aside from damage properties, elastic properties were also determined using a multi-scale analytical approach that utilizes the measured density profile as input. Using the combined elastic and damage properties, strain-softening responses of OSB in both parallel and perpendicular directions were constructed. Numerical simulations of notched samples were then performed using an established damage model for composite materials, CODAM2, which is implemented in the commercial FE code, LS-DYNA, as MAT219. The successful prediction was used as a validation of the approach.

Through this study, the fracture energy of OSB panels in Mode I failure was measured from OCT tests for the first time in both parallel and perpendicular directions. The wide range of fracture energy was associated to differences between parallel and perpendicular directions, variability of wood strands, and processing-induced defects including micro voids and variation of resin distribution. It should be noted that the estimated fracture energy of OSB (3-9 kJ/m^2) is higher than wood (~0.1-0.8 kJ/m^2) and LVL (0.6-1.8 kJ/m^2), and is comparable to that of Glulam (~10 kJ/m^2). This can be attributed to the large failure process zone and damage height of about 20 mm observed in OSB panels. Cross sectioning of the specimens showed a multitude of delamination and matrix cracking across the damage zone which combined with multiple strand failures, increases the fracture energy of OSB well beyond that of wood and LVL.

The successful approach presented here instils confidence in employing a similar approach to characterize and predict the damage behaviour and size effect in other wood-based products. It also suggests that a strain-softening approach is well suited to describe the nonlinear inelastic behaviour of wood composites.

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Tables

Table 1: Summary of three point bending tests. The overall panel density is 0.64 g/cm^3.

Sample orientation	Dimensions (mm)			MOE (GPa)		MOR (MPa)	
	Thickness	Width	Length	Mean	STD	Mean	STD
Parallel (PAR)	11	76	319	5.0	0.85	33.1	7.1
Perpendicular (PER)	11	76	319	2.9	0.72	22.2	6.1

Table 2: Predicted elastic properties from the multi-scale model for OSB. The predicted mean values are used in damage simulations.

Sample orientation	MOE (GPa)		Shear Modulus (GPa)	
	Mean	**STD**	**Mean**	**STD**
Parallel (PAR)	5.17	0.17	0.41	0.012
Perpendicular (PER)	2.98	0.10	0.38	0.010

Table 3: Summary of input parameters used in the multi-scale framework (Malekmohammadi et al., 2015).

No	Variable	Symbol	Value
1	Moisture Content	MC	7%
2	Fines Content by weight	W_{f_fines}	10%
3	Resin Content by weight	W_{f_resin}	3.0%
4	Max void content in the core	Void	5%
5	Resin Density (kg/m3)	ρ_{resin}	1400
6	Wax density (kg/m3)	ρ_{wax}	780
7	Strand length (mm)	L	100
8	Strand thickness (mm)	t	0.69
9	Strand width (mm)	W	14.25
10	Resin properties (MPa)	E_r	7000
11	Resin properties (MPa)	v_r	0.3

Table 4: Summary of OCT experimental results.

Experiment #	Loading Direction	Damage Length Δa (mm)	Damage Height h_c (mm)	Fracture Energy G_f (kJ/m^2)
E1	PAR	25.6	21.8	2.90
E2	PAR	21.8	21.8	5.73
E3	PER	27.8	19.6	8.95

Table 5: Input parameters used in MAT_219 for FE simulations.

Simulation #	Damage Initiation Strain	Fracture Energy (kJ/m^2)	Damage Saturation Strain	Loading Direction	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)
S1	2.6%	2.90	14%	PAR	2.98	5.17	0.41
S2	2.6%	5.84	28%	PAR	2.98	5.17	0.41
S3	2.6%	8.95	65%	PER	5.17	2.98	0.41