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INVESTIGATION ON THE MECHANICAL PROPERTIES OF OPEN-HOLE SPRUCE AND DOUGLAS FIR

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ABSTRACT

Spruce and Douglas fir are the main materials of today's modern wooden structure buildings. In wooden structure buildings, holes often have to be created on the building components in order to reserve channels for pipelines. At present, there are no detailed studies regarding the mechanical properties of these two kinds of lumber under open-hole condition. In this paper, universal mechanical testing machine was utilized to perform three-point bending tests on small samples of spruce and Douglas fir with open-hole (opening diameters being Ø13, Ø16, Ø20 respectively) and without open-hole. The bending strength and modulus of elasticity of open-hole and no open-hole samples were compared, the effects of hole sizes on samples' mechanical properties were analyzed and discussed, and the samples' failure patterns and failure mechanisms were also studied. The experiments were loaded at a constant speed 5 mm·min^{-1} until the sample was broken, with the loading time controlled within 2 - 3 minutes. The results showed that: open-hole had significant impact on the bending strength of both kinds of lumber. In terms of failure modes, most of the Douglas fir samples were deformed only at the compression point before failing, while the Spruce samples not only formed grooves at the compression point but also cracked at the bottom. This indicated that compared with Douglas fir, the impact of open-hole on Spruce lumber was greater, thus open-hole should be avoided on Spruce components during construction. The experimental results provided a basis for future studies on the failure modes of these two materials and also the strength design of relevant components.

KEYWORDS: Spruce, Douglas fir, open-hole, bending strength, modulus of elasticity.

INTRODUCTION

Because of its natural, environment-friendly, energy-saving features and many other advantages, wooden structure buildings have always been favored by people (Song et al. 2014, 2012). In wooden structure buildings, in order to reserve channels for water and electricity pipelines as well as other facilities, holes often have to be created on beams, floor components or studs. Open-hole would weaken the lumber's effective cross-section and change the transmission paths of stress inside the lumber, resulting in reduced supporting capacity and stiffness compared to those lumber without open-hole (Chen et al. 2015, Ardalany et al. 2013). For these reasons, the stress distribution around the hole and the supporting capacity of open-hole materials require further and more detailed studies.

In recent years, studies on the mechanical properties of open-hole materials could be divided into two aspects: one is the effects of opening diameter on the mechanical properties of materials; the other is the effects of opening location on the mechanical properties of materials. Studies on opening diameter have shown that the stress distribution and deflection changes inside open-hole bamboo I-beams no longer fit perfectly with traditional bending theories. When the hole diameter was greater than 1/4 of beam height, open-hole had significant impact on the supporting capacity of bamboo I-beams (Chen et al. 2015). For LVL joists made of Douglas fir, open-hole had seriously affected their mechanical properties; moreover, with the increase of hole diameter, their supporting capacities were increasingly weakened (Xu and Que 2016). It has also been concluded by tensile tests that damage to natural fiber/fiberglass hybrid composites due to openings is unavoidable (Salleh et al. 2013).

Some researchers have also conducted studies on the impacts of opening location on material's mechanical properties. During the experiments concerning the impacts of opening location on the mechanical properties of joists, Ardalany et al. (2013) created holes above, at and below the geometric center of the surface where the holes were located, and found that supporting capacities of joists only had minor differences under the three situations. In addition to studies on opening size and location, some researchers have also applied mechanical methods to accurately predict the strength of holes with different depths and sizes, and provided a conservative estimate of the general failure load (Pirzada et al. 2008). Furthermore, from studies on different shapes of holes on two series of wooden I - beams with different depths, the conclusion was reached that the failure load was much higher than the specified design load (Morrissey et al. 2009).

Currently, studies on the mechanical properties of open-hole materials are mainly concentrated on polymer materials and composites as well as traditional building materials, while the research and analysis on lumber under open-hole condition are not sufficient. This paper utilized WDW-300E microcomputer control electronic universal mechanical testing machine, used spruce and Douglas fir as objects of study, and investigated the limit load and modulus of elasticity of open-hole LVLs with different opening diameters, while also analyzed their failure patterns and failure mechanisms and compared with lumber without open-hole in order to reach corresponding conclusions.

MATERIALS AND METHODS

Sample preparation

The materials used in this experiment were Douglas fir dimension lumber made in Canada and spruce dimension lumber made in Europe (38 x 89 x 3000 mm). Measured average densities were: Douglas fir 0.51 g·cm^{-3}, spruce 0.41 g·cm^{-3}; average moisture contents were: Douglas fir 12.8%, spruce 12.2%. Meanwhile, according to the experimental scheme, these two kinds of materials were sawed and converted to small samples of 17 x 40 x 300 mm standard. The samples were divided into four groups: one group without open-hole, and three groups with open-hole, opening diameters being 13 mm, 16 mm and 20 mm respectively. The open-hole locations were at the geometric center of the side of the lumber (40 x 300 mm), as shown in Fig. 1:

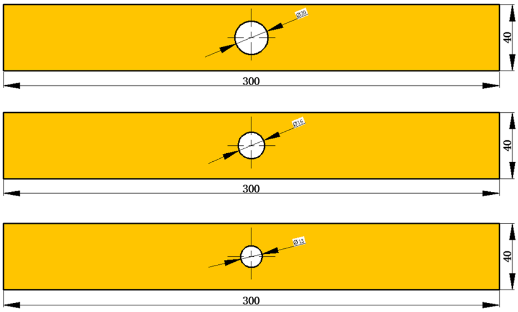


Fig. 1: Test samples (17 x 40 x 300 mm) with open-hole and the diameters are 13mm, 16 mm, 20 mm.

Tab. 1: The parameters of the samples.

Sample serial number	Average density(g·cm^{-3})	Open-hole Type	Hole size (mm)	Sample size (mm)	Species
YS1-6	0.40	-	-	17 x 40 x 300	spruce
YS7-14	0.40	Round	13	17 x 40 x 300	spruce
YS15-22	0.40	Round	16	17 x 40 x 300	spruce
YS22-30	0.40	Round	20	17 x 40 x 300	spruce
HQS1-8	0.50	Round	-	17 x 40 x 300	Douglas fir
HQS 9-16	0.51	Round	13		Douglas fir
HQS17-22	0.50	Round	16		Douglas fir
HQS23-28	0.51	Round	20		Douglas fir

Experimental equipments and loading scheme

The experiments used WDW-300E microcomputer control electronic universal mechanical testing machine, and used force sensor with 0.25 kN accuracy to measure the applied loads. Experiment loading procedures referred to GB/T 50329-2012 and GB/T 1936.1-2009 (Fig. 2).

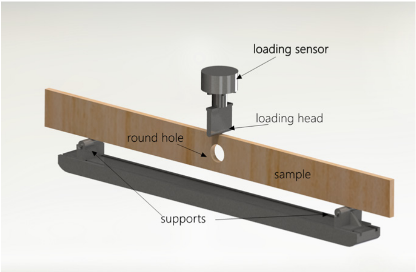


Fig. 2: Three-point bending testing setup.

During the experiments, the main parameters measured were midspan deflection and sample limit load. The whole loading process was under displacement control; three-point bending tests were performed at a constant loading speed 5 mm·min^{-1} until the sample was broken, with persistent time being 2-3 minutes.

RESULTS

The experimental data collected from different batches were calculated to obtain the mean bending strength and bending modulus of spruce and Douglas fir samples with and without open-hole, as shown in Fig. 3 and Fig. 4.

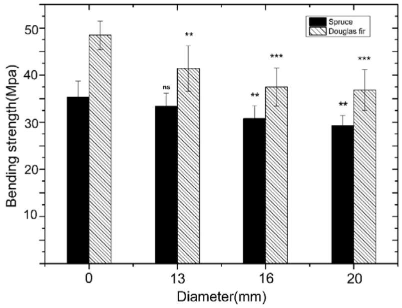


Fig. 3: Bending strength and ANOVA significant levels corresponding to different opening diameters.

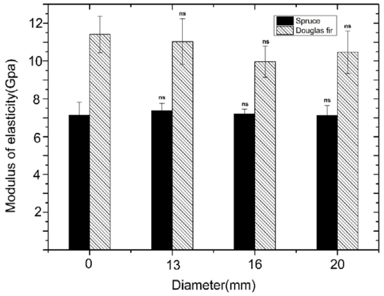


Fig. 4: Modulus of elasticity and ANOVA significant levels corresponding to different opening diameters.

Tab. 2: Results of bending strength, modulus of elasticity values and ANOVA significant levels corresponding to different tree species and opening diameters.

Tree species diameter		Bending strength (GPa)			Modulus of elasticity (MPa)		
		Average	Standard deviation	ANOVA sig. level	Average	Standard deviation	ANOVA sig. level
Spruce	0	35.30	3.43	-	7.14	0.69	-
	13	33.42	2.70	ns	7.36	0.40	ns
	16	30.08	2.69	**	7.21	0.25	ns
	20	29.27	2.19	**	7.12	0.52	ns
Douglas fir	0	48.06	3.03	-	11.41	0.96	-
	13	41.40	4.83	**	11.03	1.21	ns
	16	37.50	4.04	***	9.96	0.83	ns
	20	36.83	4.34	***	10.46	1.12	ns

** $P<0.01$, *** $P<0.001$.

It could be seen from Fig. 4 that the mean values of modulus of elasticity of samples with different opening diameters were quite similar for whether spruce or Douglas fir. The variance analysis also showed that at 0.05 level there was no significant difference between the mean values of modulus of elasticity of open-hole spruce and Douglas fir small samples compared with samples without open-hole of the same tree species. On the other hand, it could be seen from Fig. 3 and Tab. 2 that during three-point bending tests, the bending strength values of spruce and Douglas fir samples with and without open-hole were significantly different. The mean values of bending strength of the 13 mm, 16 mm and 20 mm open-hole spruce samples were 33.42 Mpa, 30.08 Mpa and 29.27 Mpa respectively, which were lower than the mean value of bending strength of the spruce samples without open-hole (35.30 Mpa) by 5.32%, 14.16% and 17.08% respectively. At the same time, the variance analysis showed that at 0.05 level, there were significant differences (P <0.001) in the mean values of bending strength of spruce small samples of the same size with different opening diameters. Similarly, the mean value of bending strength of the Douglas fir samples were 13.86%, 21.97% and 23.37% lower than the samples without open-hole respectively. The variance analysis showed that at 0.05 level, there were significant differences (P <0.001) in the mean values of bending strength of Douglas fir small samples of the same size with different opening diameters. It could be seen that the effects of open-hole on Douglas fir were much greater than that on spruce, and when opening diameter was larger than 1/3 of height (the 16 mm and 20 mm diameters), the impacts of hole sizes on the bending strength of spruce and Douglas fir were significantly larger.

DISCUSSION

Deformation characteristics and failure mechanisms of Douglas fir small samples

Fig. 7a shows the four load-displacement curves of the Douglas fir samples with and without open-hole in the three-point bending process. It could be seen from the graph that at the beginning of loading, no open-hole and open-hole samples had good bending resistance (displacement within 0-3 mm). At this time, there was no obvious damage on the surface of the samples, and the slopes of the four curves were approximately the same in the linear range. This implied that for the same kind of material, whether there was open-hole and the size of hole had little effects on the modulus of elasticity of samples. When the loading continued, all of the four curves entered the yield stage. Compared with linear stage, the displacement caused by the same increase in load of no open-hole samples was significantly larger. When the sample reached the limit load it could bear, supporting capacity was rapidly lost. The model and load mechanism are shown in Fig. 5.

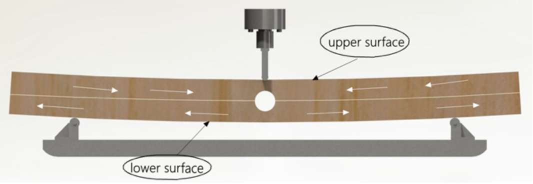


Fig. 5: Two dimensional model and the bending force mechanism.

After the open-hole samples entered from linear stage into yield stage, the increase in supporting capacity of the samples was obviously slowed down, and the larger the opening diameter was, the smoother the curve was. In this stage, the vicinity of the loading point on the surface of the sample began to show transversal cracks, mainly caused by partial micro-bending on the sample surface. As the loading increased, eventually a compression damage area appeared near the loading point which ran through the whole width of the sample. The damage area expanded in both vertical and horizontal directions with increase in loading, and gradually formed a groove-like area, as shown in Fig. 6 at the compression point.

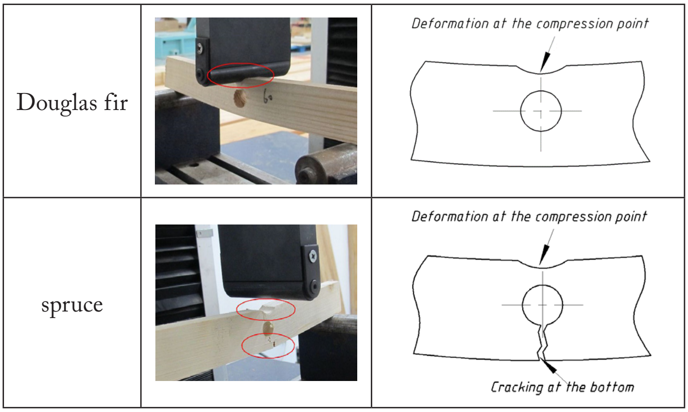
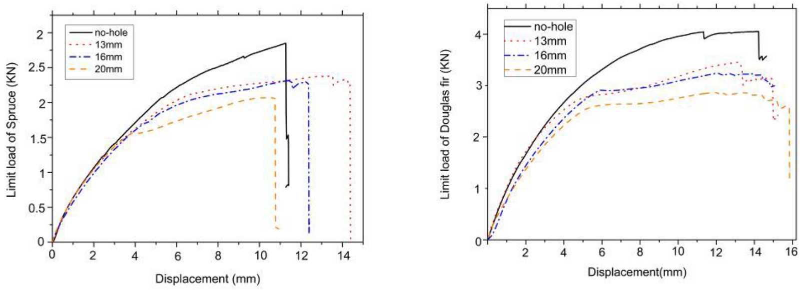


Fig.6: Bending test and failure of the samples.

During the compression process, the sample was not only under compression force but also tensile force at the bottom. When part of the sample bottom was pulled apart, the sample would reach the limit load, and then the load would drop rapidly; afterwards, the part that had not yet been damaged would continue the loading, and then this part was pulled apart again. This declining load-unload fluctuation process would continue for several rounds until the sample was completely pulled apart (Gao et al. 2015, Yang and Du 2012, Clouston et al. 2005, Ghasemi and Moradi 2017).

Deformation characteristics and failure mechanisms of spruce small samples

Fig. 7b shows the four typical load-displacement curves of the spruce samples with and without open-hole. It could be seen from the graph that the load-displacement curves of spruce had both similarities and differences with those of Douglas fir. In the initial stage of loading (displacement within 0-4 mm), open-hole and no open-hole samples all had good bending resistance. The curves showed relatively obvious linear features, and the four curves almost coincided in the linear stage.



a **b**

Fig. 7: Typical displacement-limit load curves corresponding to different tree species and opening diameter.

This indicated that like Douglas fir, artificial open-holes on spruce would not affect the modulus of elasticity of the material itself like natural wormholes and knots would do. As load continued to increase, the elastic stage came to an end. Before reaching the maximum load, the curves showed a certain degree of non-linearity, and in this non-linear range, open-hole and no open-hole samples exhibited distinct characteristics: for the same load increase, the displacement change of open-hole samples was much larger than no open-hole samples; also, it could be seen clearly from the graph that the larger the opening diameter was, the smaller the ultimate failure load of the sample would be. This was because the open-hole was not only under compressive stress but also tensile stress (Yeoh et al. 2011, Yudhanto et al. 2012, Morais 2000). At this time, the deformation of material could continue to increase, while the stress was no longer increasing. As the load increased, the additional force was borne by materials on the cross-section that were not yet yielded, so that the stress at other points on the cross-section would increase in succession to the yield limit. This made the stress on the cross-section tend to be stable, reduced the stress unevenness, but also limited the ultimate load value the sample could bear (Falk et al. 2003, Soutis 1994, Yoshihara 2016, Clouston et al. 2005). Therefore, open-hole would have significant impacts on the samples' supporting capacities. Comparing the load-displacement curves of spruce and Douglas fir samples, it could be seen from the two graphs that the limit loads of spruce samples were much smaller than that of Douglas fir, and unlike the Douglas fir samples, when the load exceeded the failure limit of spruce samples, they didn't show the noticeable repeated load-unload process like the Douglas fir samples, but fractured and failed almost immediately. After the samples were broken, as shown in the figure, it could be seen that like Douglas fir, the spruce samples had a significant stress concentration at the compression point, forming a deep groove. However, unlike the Douglas fir samples, open-hole spruce samples were subjected to greater impact of the bottom's tensile force, and ultimately cracked at the bottom, broken into two halves.

CONCLUSIONS

1. It could be seen from the experiments that open-hole had significant impacts on the bending strength of both kinds of materials. Both of them exhibited linear elasticity features before failure, but showed different failure modes due to the difference in material. The load-displacement curves of Douglas fir samples had obvious ladder phenomenon, which indicated that the sample still had a certain loading capacity after the failure of the material at the compression point. Spruce samples, on the other hand, showed a clear brittle fracture mode. When the loading reached the limit, the sample was cracked at the bottom. There was no follow-up supporting capacity, and the load curve dropped instantaneously. The fracture of the sample ran through the whole thickness direction, and was relatively parallel and level.
2. Compared with open-hole spruce samples, open-hole Douglas fir samples had greater bending deformation capabilities and bending strengths. In terms of failure modes, most of the Douglas fir samples were deformed only at the compression point before failing, while the spruce samples not only formed grooves at the compression point, but also cracked at the bottom. This indicated that compared with Douglas fir, the impact of open-hole on spruce was greater, thus open-hole should be avoided on spruce components during construction process. The experimental results provided a basis for future studies on the failure modes of these two materials and also the strength design of relevant components.

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