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Application of Finite Element Analysis in Properties Test of Finger-jointed Lumber

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Abstract

Finger joints have been used to produce engineered wood products for their excellent mechanical performance. The properties of finger-jointed lumber are affected by many different factors. End-pressure is one of the important parameters in the finger-jointed lumber production and it should be identified before the finger joints are jointed.

The mechanical properties are the most concerned properties for structural used finger-jointed lumber. The mainly mechanical properties include the modulus of elasticity and the bending strength. Experimental tests are commonly used in the testing of these properties at present. With the development of nondestructive test technology, many researchers applied such methods in the testing of mechanical properties for wood based products.

Finite element analysis (FEA) has been used as a numerical method for the modeling of properties of different materials. In this paper, ANSYS, a software for FEA, was used to modeling the end-pressure, modulus of elasticity and bending strength of finger-jointed lumber made from *Pinus Sylvistriv* var. under three different fitness lever.

FEA applied in the end pressure tests showed a narrower range compared with the modeling results. Besides, the upper limit obtained from modeling process is close to the optimum end pressure which obtained from experimental test. It indicates that the FEA can be used in the prediction of the end pressure for finger-jointed lumber.

The modeling results for modulus of elasticity (MOE) test were about 20% higher than experimental results. The error may result from the neglection of the natural flaws existing in the lumbers and the manufacturing deficiencies when conducting the modeling process. Moreover, the modeling results showed the same trend as experimental test results under three different fitness levels.

The modeling results for bending strength (MOR) test of finger-jointed lumber also showed some discrepancies compared with the experimental test results. The plastic deformation developed from the loading of end pressure in finger-jointed lumber manufacturing process caused the decrease of the fitness and lengthened the finger joints which is helpful for guarantee the strength of the finger-jointed lumber. But in the modeling process, the effect of the factor was neglected. Also, the damage of the finger joints under end pressure when fitness is 0mm which was not taken into account in the modeling process resulted in the different trend between experimental and modeling results of MOR for finger-jointed lumber under three fitness levers.

The conclusion could be made that FEA is a feasible way in analyzing the properties of finger-jointed lumber if the errors could be eliminated properly. Some modifications should be made on the models in order to realize the modeling of the properties of finger-jointed lumber more accurately.

Keywords: finite element analysis; finger jointed lumber; end-pressure; modulus of elasticity in static bending; bending strength

1. Introduction

Finger joint is a type of end joint developed from scarf joint; it has been used for many years (Roland, 1981). Such joints can not only joint the short pieces of lumber to long ones, but also effectively enhance the utilization of low-grade materials. They are commonly used to produce engineered wood products for their excellent mechanical performance (Cecilia, 2003). Finger-jointed lumber production has now become the most extensively applied method for splicing lumbers together endwise.

The properties of finger-jointed lumber are affected by many different factors such as the wood species, adhesive, length of finger joints, processing parameters, et al. End-pressure refers to the pressure applied on the end of the lumbers to be jointed lengthwise, which bring the mating surfaces so close together that the glue forms a thin and continuous film between them (Cecilia, 2003).Several authors research on end pressure indicated that the pressure must be applied to force fingers together to form an interlocking connection (Raknes,1982), however, the excessive pressure which cause the cell damage or spitting of the finger root could induce the decrease of the strength of finger joints (Marra 1984, Kutscha and Caster,1987). So the end pressure should be identified before the finger joints be jointed. Finger-jointed lumber is classified as two different groups according to it’s use, structural and nonstructural use finger-jointed lumber. Nonstructural use finger-jointed lumber is more emphasis on the appearance quality while the structural use finger-jointed lumber focus on the mechanical properties. The mainly mechanical properties to be tested for structural use finger-jointed lumber include the modulus of elasticity in static bending and the bending strength. The mainly method for testing these properties at present is experimental method. With the rapid development of the nondestructive test technology, more and more researchers applied these methods such as the acoustic emission method (Kiyoko Y, et al, 2007), stress wave method (Liang, et al, 2008), ultrasonic method (Lin, et al, 2007), vibration method (Zhang, et al, 2005), the near infrared spectrum technology (Zhao, et al, 2009) in the testing of mechanical properties tests for wood based products.

As an efficient method of numerical analysis, finite element analysis（FEA）is now extensively used in the modeling analysis of materials’ properties. Several researchers have successfully applied this method in the properties analysis for wood based materials (Tabiei A. et al, 2000, Moses D.M. 2004, Serrano E. 2004, Davalos J.F. 1995)

In order to save materials which should be used in experimental tests, the present study investigated the end-pressure range, the modulus of elasticity in static bending and the bending strength for *Pinus sylvistriv* var. finger-jointed lumber under three different fitness ratio (0mm, 0.1mm, 0.3mm) using ANSYS, a software for FEA. With the FEA modeling results compared with the experimental test results, it’s possible to find the relationship between these two kinds of results and use the FEA to predict the properties of finger-jointed lumber.

2. Materials and Methods

2.1 Materials

The dimensions of the lumbers used in the experiment are 600×88×24mm^3 (Length×Width×Thickness). The moisture content (M.C.) of the lumbers ranges from 8% to 11% while the density ranges from 0.4 to 0.7g/cm^3. The resin used in the production of finger-jointed lumber was a mixture of water-borne carbamate emulsion (the main agent) and macromolecular isocyanate (the firming agent) with a mixture ratio of 100:15 (Dynea, Shanghai). The solid content of the resin is 53%, and the pH is 7.3. The amount of resin sprayed on the finger joints is 250-300g/m^2.

2.2 Methods

2.2.1 Finger joints manufacturing

Finger joints with three different fitness ratio were cut in the cutting machine (FS-520R, Japan) according to the parameters showed in Table 1.

Tab.1 Parameters of finger-jointed lumber

Fitness/mm	Length of Fingers/mm	Tip Thickness/mm	Pitch/mm	Slope
0	25	1.2	8.2	1/8.6
0.1	23.7	1.3	8.2	1/8.6
0.3	21	1.5	8.2	1/8.6

2.2.2 End-pressure testing

A series of 15 finger-jointed lumbers were produced in the end-pressure test experiment. Each fitness lever was represented by 5 finger jointed lumbers. The two finger joints of the same fitness were jointed together by hand after sprayed with resin. They were subsequently loaded lengthwise on the cross section of the lumber in a mechanical experimental machine (INSTRON 5582, America) until they were compressed to crush. At the same time, keep a record of the curve of Load-Displacement when the finger joints were loaded.

2.2.3 Finger-jointed lumber manufacturing

54 finger-jointed lumbers were manufactured in the finger jointing machine (FJ-500OA-2, Japan). Each fitness lever was represented by 18 finger-jointed lumbers. The end pressure applied on the finger joints was determined by the end pressure test experiment. Keep the pressure for 5~10s and then the finger-jointed lumbers were kept in room temperature for at least 48h to let the glue cure completely. All finger-jointed lumbers were tested for modulus of elasticity in static bending (MOE; n=18) and bending strength (n=18). Analysis of variance (ANOVA) was performed to compare the means of each test ($P < 0.05$).

2.2.4 FEA for finger-jointed lumber

The lumber was assumed to be an orthotropic, linear elastic and nonlinear elastoplastic material having the following engineering constants and yield stress as show in Table 2 and Table 3. The data input for the glue and gaskets (Zheng et al, Li et al) were listed in Table 4.

Tab.2 The elastic constants of different directions for *Pinus sylvestris* var.

Elastic Constants											
E_L/MPa	μ_{LR}	μ_{LT}	E_T/MPa	μ_{TR}	μ_{TL}	E_R/MPa	μ_{RT}	μ_{RL}	G_{RT}/MPa	G_{LT}/MPa	G_{LR}/MPa
9171	0.472	0.558	460.4	0.337	0.033	831.6	0.765	0.053	44.48	521.7	666.7

Tab.3 The yield stress of different directions for *Pinus sylvestris* var.

	Longitude	Radial	Tangential
Tensile(MPa)	32.290	4.00	4.00
Compression(MPa)	11.031	4.74	4.36
Shear(MPa)	4.130	4.41	4.13

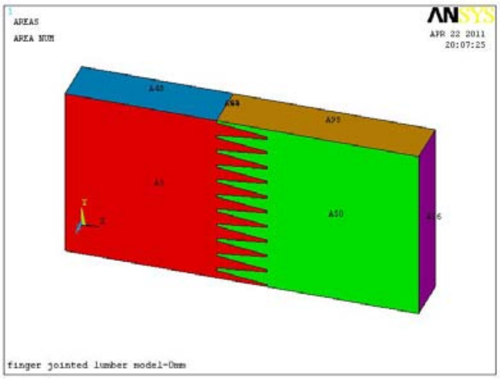
Tab.4 Parameters of adhesive and gaskets

Materials	Constants for Materials	
	E/MPa	μ
Adhesive	3000	0.37
Gaskets	1000	0.2

Take the software of ANSYS to set up the 3-D models for end-pressure test, modulus of elasticity and bending strength tests. Choose Solid45 as the finite element type and mesh the model with free meshing method.

1) FEA of end-pressure test

Figure 1 and figure 2 shows the model created by ANSYS and its mesh results for the end-pressure test of finger-jointed lumber. The three dimensional displacement constraints were added to one end of the model and the pressure was applied on the other end following the load step which was shown in figure 3. Then the calculation was carried out in the software and the relation between the displacement and load step (the same as load) was output in the post-process part of the software.



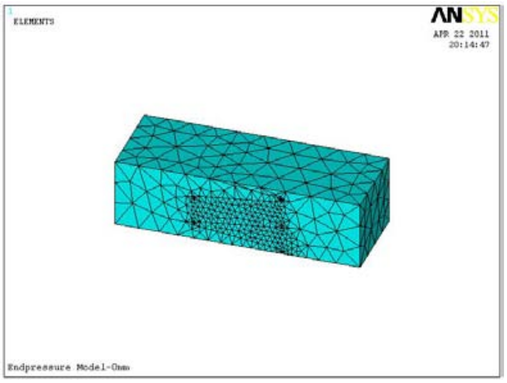


Fig.1 End-pressure FE model(fitness 0mm)

Fig.2 Mesh result of end-pressure FE model(fitness 0mm)

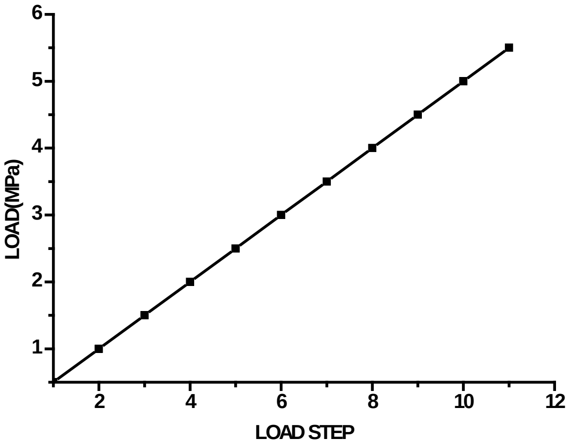


Fig.3 Loading rate of end-pressure test

According to the principles for finger-jointed lumber manufacturing, the end pressure applied on the finger joints should not be too large to result in the fracture of the lumber which may decrease the strength of the finger-jointed lumber. Thus the stress of the elements under pressure should not be larger than the yield stress of the lumber, and the end pressure which caused the damage of the elements is the upper limit whereas the lower limit pressure should be high enough to cause the plastic deformation ensuring the good adhesion of the finger joints.

2) FEA of MOE

Figure 4 and figure 5 shows the model created by ANSYS and its mesh results for the MOE test of finger-jointed lumber. After adding the appropriate displacement constraints to the model and applying the pressure on the loading gaskets follow the load step which was show in figure 6, the calculation was carried out in the software.

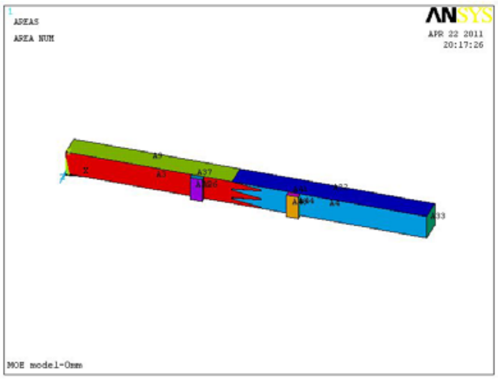


Fig.4 MOE FE model(fitness 0mm)

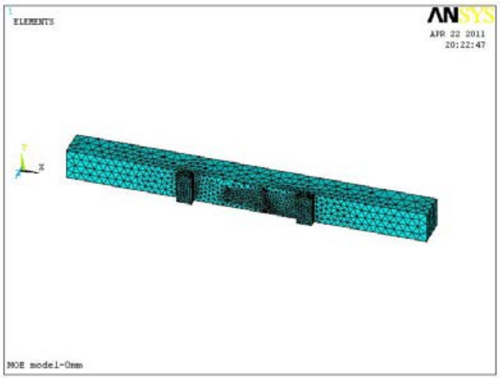


Fig.5 Mesh result of MOE FE model(fitness 0mm)

When the calculation was done, check the modeling results and find out the node which exhibited the largest deformation along the loading direction. Then output the displacement-load curve for the node and keep a record of the displacement when the load increases from the lower limit to upper limit. The MOE of the finger-jointed lumber can be calculated according to the equation (1) below.

$$E = \frac{23Pl^3}{108bh^3 f} \qquad (1)$$

Where E is the MOE of finger jointed lumber (MPa); P is the load difference between the upper limit and lower limit (N); l is the span length (mm); b is the width of the specimen (mm); h is the height of the specimen (mm); f is the deformation of specimen when the load increase from the lower limit to upper limit (mm).

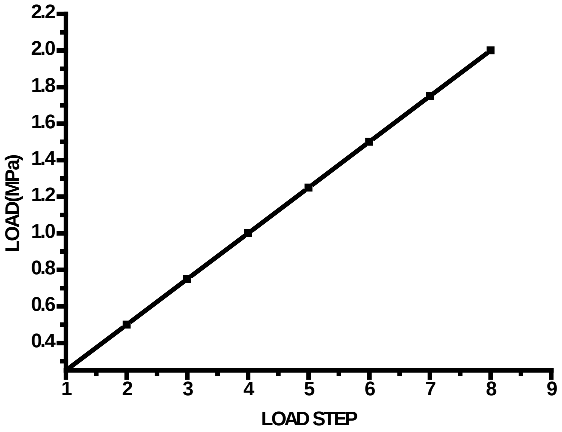


Fig.6 Load rate of MOE test

3) FEA of bending strength

Figure 7 and figure 8 shows the model created by ANSYS and its mesh results for the bending strength (MOR) test of finger-jointed lumber. Add the appropriate constraints to the model and applying the pressure on the loading gasket follow the load step which was show in figure 9. Then the calculation was carried out in the software and the relation between the displacement and load step (the same as load) was output in the post-process part of the software.

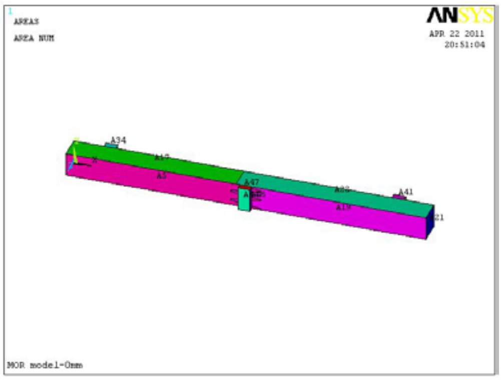


Fig.7 MOR FE model(fitness 0mm)

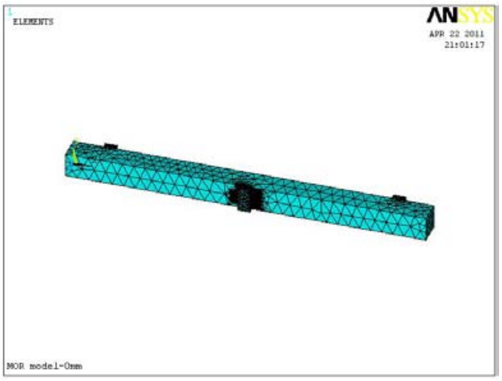


Fig.8 Mesh result of MOR FE model(fitness 0mm)

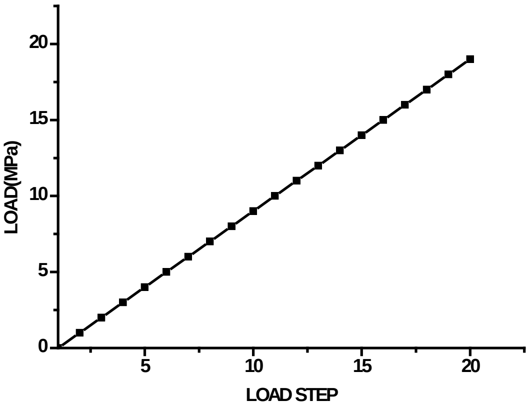


Fig.9 Load rate of MOR test

After the calculation was done, check the modeling result and find the node which exhibited the stress exceed the yield stress of the lumber. Then output the displacement-load curve for the node and keep a record of the pressure when the deformation reached the highest value. The bending strength of the finger-jointed lumber can be calculated according to the equation (2) below.

$$\sigma = \frac{3P_{\max} l}{2bh^2} \qquad (2)$$

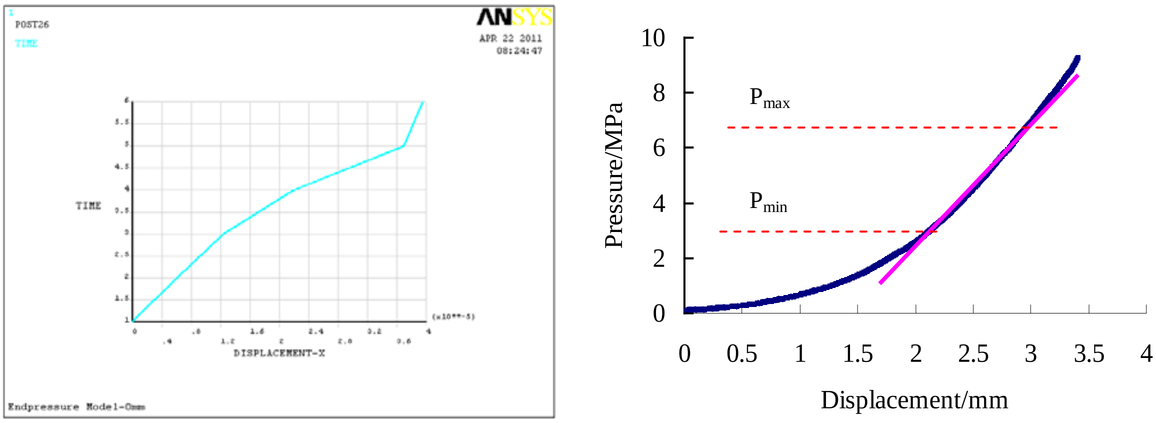
Where σ is the bending strength of finger jointed lumber (MPa); P_{max} is the ultimate bending load (N); l is the span length (mm); b is the width of the specimen(mm); h is the height of the specimen(mm).

3. Results and discussion

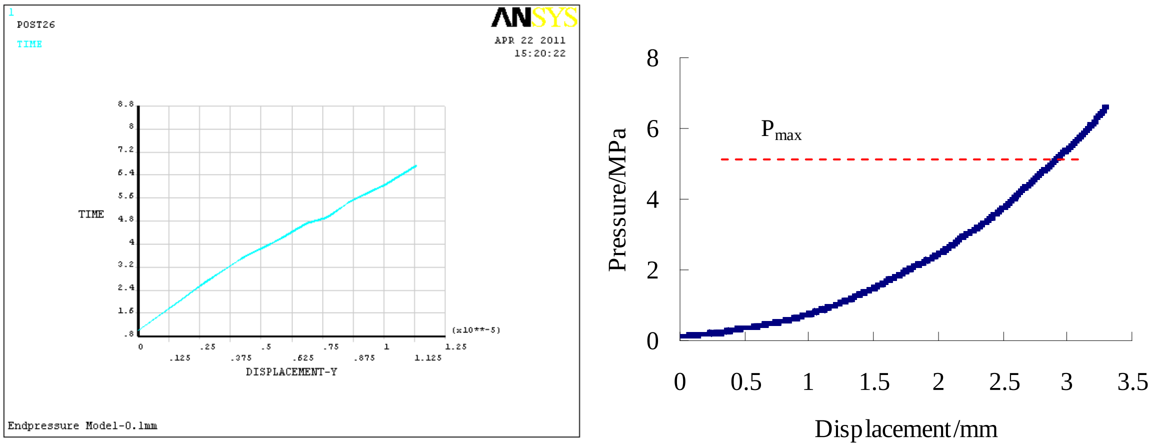
3.1 end-pressure test

When the load was applied on the end of finger joints, the stress were mainly concentrate on the top of the finger joints according to the modeling results. With the increasing of pressure, elastic deformation was first developed, when the stress exceeded the elastic limited stress, the plastic deformation was then developed. After the stress exceeded the yield stress of the lumber, it indicates that the collapse happened in the finger joints which would affect the ultimate strength of the finger-jointed lumber.

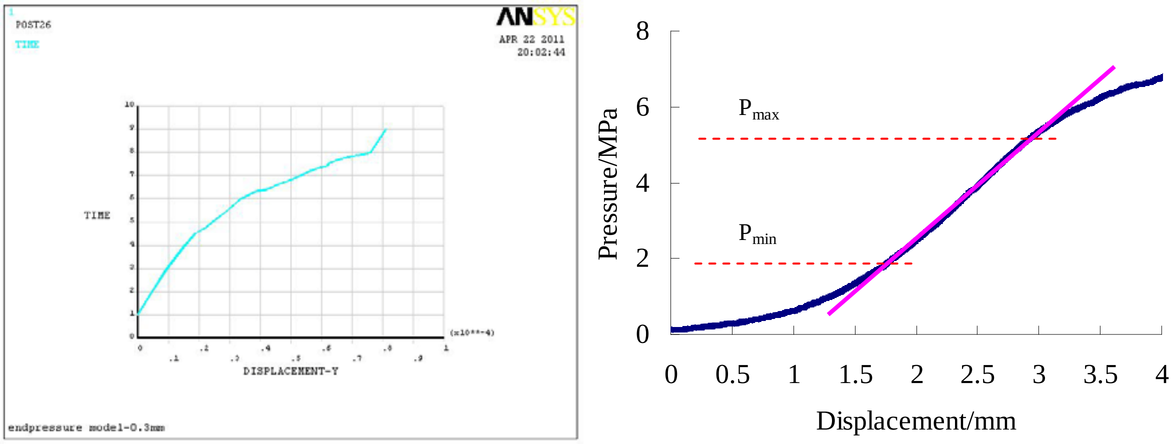
The appropriate end-pressure for finger-jointed lumber manufacturing is between the value causes the plastic deformation and failure of the finger joints. Figure 10 shows the modeling results and experimental results of end pressure test for finger joints at three different fitness levers (0mm; 0.1mm; 0.3mm). From the modeling results, it can be concluded that the end pressure range are 1.5MPa~3.0MPa, 2.0MPa~3.5MPa and 2.5MPa~4.5MPa for fitness 0mm, 0.1mm and 0.3mm respectively.



a) Fitness-0mm



b) Fitness-0.1mm



c) Fitness-0.3mm

Fig.10 Modeling and experimental results for end-pressure test

The modeling results showed some discrepancies compared with the experimental results. First, the node developed elastic deformation when the end pressure was low in the modeling process while the displacement increases fast with the increase of pressure in the experimental process because two finger joints can not fit seamlessly which cause a process that two finger joints fit together (the gap between them eliminated gradually under low end pressure). The difference showed in the initial part of the pressure-displacement curves of modeling and experimental results. Secondly, as the table 5 shows, both the lower limit (P_{min}) and upper limit (P_{max}) of end pressure in modeling tests were lower than the experimental test results, extremely for the upper limit. It was mainly caused by the different ways of judging the failure of finger joints under pressure. In the experimental tests, the upper limit of end pressure was set as the macroscopic crack developed in the finger joints, whereas the failure was accounted as the stress on one node of exceeded the yield stress in the modeling process; when one node of the model reached the failure, the others are still in good state. Thus, it is reasonable that the end pressure was smaller in FEA than experimental test results.

Tab.5 Comparison of end-pressure between experimental and modeling results

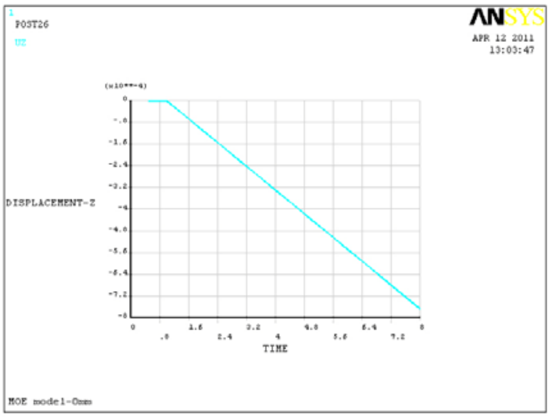
Fitness/mm	Experimental results/MPa		Modeling results/MPa	
	P_{min}	P_{max}	P_{min}	P_{max}
0	2.6	5.8	1.5	3.0
0.1		5.9	2.0	3.5
0.3	2.6	5.3	2.5	4.5
Average	2.6	5.7	2.0	3.7

As the appropriate end pressure range was determined through experimental and modeling tests, three levels of the end pressure (2.6MPa; 3.5MPa; 4.4MPa) were selected in a experiment conducted to find the optimum end pressure for *Pinus Sylvistriv* var.

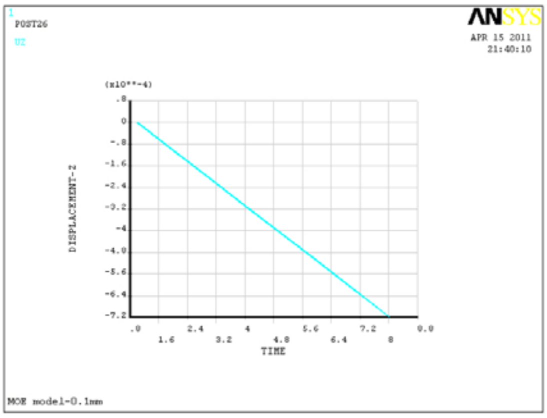
finger-jointed lumber. The experiment test results showed that finger-jointed lumber manufactured when end pressure was 3.5MPa exhibited the highest mechanical strength compared with other two levels of end pressure (He, 2011). It is close to the upper limit of the modeling test results. So it can be concluded that the optimum end pressure for finger-jointed lumber manufacturing could be found through FEA process.

3.2 MOE test

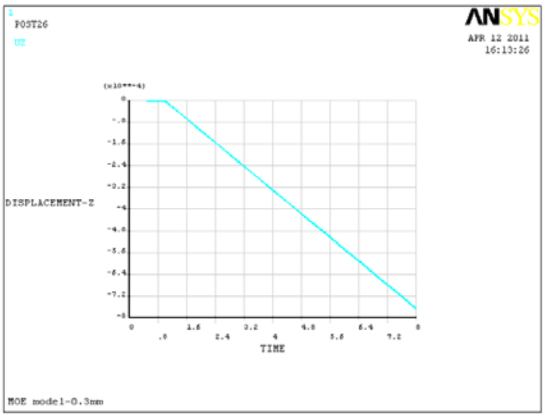
Under low pressure, the stresses spread on the finger-jointed lumber were quite uniform. In the direction along the load, elements exhibited the largest deformation. Figure 11 shows the relationship between the displacement and time (the same as load) of the node which developed the largest deformation. According to the national standard for testing the MOE of wood, the deformation taken in the calculation of MOE should be the increment when the load increases from 300N to 700N. It can be drawn from the figure 11 that when fitness is 0mm, the corresponding deformation is 0.45mm, whereas the deformation when fitness is 0.1mm and 0.3mm are 0.4mm and 0.44mm respectively. Thus the MOE for finger-jointed lumber of three different fitness are 16.36GPa, 18.40GPa and 16.73GPa respectively.



a)Fitness-0mm



b)Fitness-0.1mm



c)Fitness-0.3mm
Fig.11 The modeling results for MOE test

As the table 6 shows, the modeling test results for MOE were more than 20% higher than the experimental test results under three different fitness levers. The error may comprise of two parts. First, knots, rot, oblique grain and other flaws would weaken the strength of the timber which results in the strength decrease of finger-jointed lumber (Xu, 2000). However, in the modeling process, the timber was regarded as a cylinder symmetry and orthotropic material without taken the defects of timber into account. The parameters input in the modeling process were measured using flawless specimens. So it is possiblely cause the difference between these two testing methods. Besides, the other cause of the error could be the manufacturing deficiencies such as the broken of the finger joints, the impurity of the glue mixed with sawdust, ect., these will greatly affect the strength of the finger-jointed lumber (Liu, 1995); but they were neglected in the modeling process.

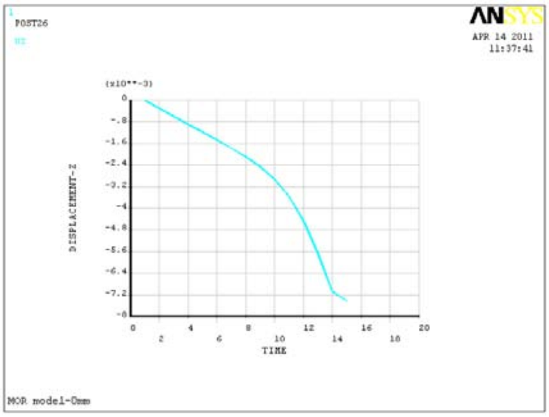
Tab.6 Comparison of MOE properties between experimental and modeling results

Fitness/mm	Experimental result/GPa	Modeling result/GPa	Error/%
0	13.42	16.36	21.9
0.1	14.40	18.40	27.8
0.3	13.19	16.73	26.8

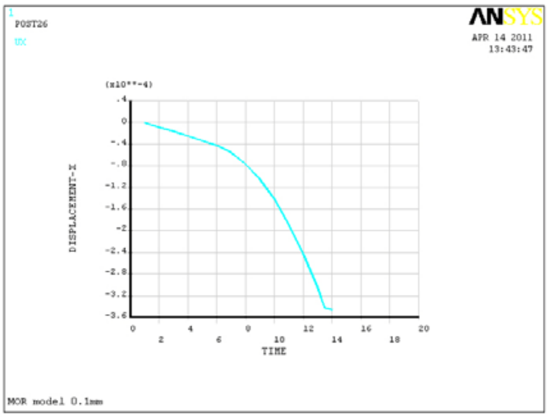
As both the experimental and modeling results shown, the MOE of finger-jointed lumber when fitness was 0.1mm exhibited the highest value whereas the MOE for fitness 0mm and 0.3mm didn't show significant difference. The filling of adhesive in the tip top will definitely increase the strength of finger-jointed lumber, thus it is natural that the MOE for fitness 0.1mm is higher than the lumber of fitness 0mm. However, with the increase of fitness, the length of finger joints decrease which result in the decrease of bond area. As the results for scarf joint shows, the increase of bond area would make the joints to withstand higher load (Roland, 1981), namely increase the strength of the joints, including the MOE. So it is reasonable that the MOE for lumbers of fitness 0.3mm were lower than fitness 0.1mm. The combined effects of filling of adhesive and the length of finger joints resulted in the insignificant difference for lumbers of fitness 0mm and 0.3mm.

3.3 Bending strength test

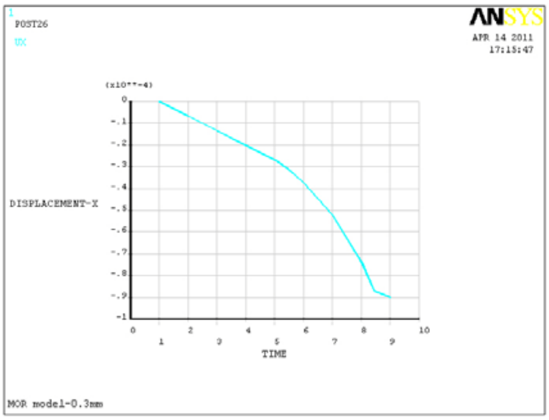
With the increase of pressure, the deformation of the finger-jointed lumber along the direction of the load increases until the stress in the finger joints reaches the yield stress. The load (corresponding to load step) when the node reaches failure is the ultimate load of bending for finger joints. Figure 12 shows the relationship between displacement and time (load step) for node which reached the yield stress. The ultimate load of bending under three different fitness levers for finger-jointed lumbers were 2600N, 2400N and 1500N respectively from the figure. Thus the corresponding bending strength were 78.0MPa, 72MPa and 45.0MPa.



a) Fitness-0mm



b) Fitness-0.1mm



c) Fitness-0.3mm

Fig.12 Modeling results for MOR test

Compared with the experimental results, the modeling results showed some discrepancies in table 7, especially for lumbers manufactured when fitness is 0.3mm (35.3%). The lumbers of fitness 0.1mm exhibited the highest value for MOR while the corresponding value for fitness 0mm and 0.3mm almost at the same lever in the experimental results. However, the MOR for fitness 0mm shows the highest value in modeling result, fitness 0.1mm followed, and the lowest is the lumbers of fitness 0.3mm.

Tab. 7 Comparison of MOR properties between experimental and modeling results

Fitness/mm	Experimental result/MPa	Modeling result/MPa	Error/%
0	68.4	78.0	14.0
0.1	75.9	72.0	-5.1
0.3	69.6	45.0	-35.3

Same as the explanation for results of MOE, the filling of adhesive in tip top will increase the strength which makes the MOR for lumbers of fitness 0.1mm higher than that for fitness 0mm; but when the fitness is too large (0.3mm), the length of finger joints decrease too much, it will affect the strength of finger joints to a large extend. Also, the filling of adhesive in large tip top gap will decrease the strength as bond area for adhesive and the lumber will develop the concentration of stress because adhesive has different prosperities compared with wood, thus the MOR for lumber of fitness 0.3mm is lower than that when fitness is 0.1mm.

The modeling process is different from the actual condition in experimental process to a certain extent. The finger joints would have some plastic deformation when load with end pressure in finger-jointed lumber manufacturing process. This phenomenon will cause the decrease of the fitness and lengthen the finger joints which is helpful for guarantee the strength of the finger-jointed lumber. But in the modeling process, the effect of the factor was neglected, so it can be seen that the modeling results for fitness 0.1mm and 0.3mm are lower than the experimental results. For lumbers of fitness 0mm, the compression under end pressure would cause some damage to the finger joints as there were no tip top gaps between two finger joints, and then it would decrease the strength of the finger-jointed lumber. This was not taken into account in the modeling process, so the modeling results were higher than experimental results in such condition.

4 Conclusions

FEA applied in the end pressure tests showed a narrower range compared with the modeling results. This was mainly caused by the different ways of judge the failure of finger joints under pressure. In the experimental tests, the upper limit of end pressure was set as the macroscopic cracking developed in the finger joints; whereas the failure was accounted as the stress on one node of exceed the yield stress in the modeling process. Moreover, the upper limit from modeling results is close to the optimum end pressure for finger-jointed lumber manufacturing which obtained from experimental test. It indicates that the FEA can be used in the prediction of the end pressure for finger-jointed lumber.

The modeling results for MOE test of finger-jointed lumber were about 20% higher than experimental results. The error may result from the neglection of the natural flaws existing in the lumbers and the manufacturing deficiencies when conducting the modeling process. Besides, the modeling results showed the same variation tendency for MOE of finger-jointed lumber under three different fitness levels. Thus the conclusion could be made that FEA is a feasible way in analyzing the MOE of finger-jointed lumber if the errors could be eliminated properly.

The modeling results for MOR test of finger-jointed lumber also showed some discrepancies compared with the experimental test results. The modeling process was different from the actual condition in experimental process to a certain extent. The plastic deformation developed from the load of end pressure in finger-jointed lumber manufacturing process caused the decrease of the fitness and lengthen the finger joints which is helpful for guarantee the strength of the finger-jointed lumber. But in the modeling process, the effect of the factor was neglected. Also, the damage of the finger joints under end pressure when fitness is 0mm which was not taken into account in the modeling process resulted in the different trend between experimental and modeling results of MOR for finger-jointed lumber under three fitness levers.

In order to realize the modeling of the properties of finger-jointed lumber, some modification should be made on the models. Further studies are in progress to investigate the ways for diminishing of the errors in the modeling processes.

References

Cecilia B. et al, Effect of curing time and end pressure on the tensile strength of finger-jointed black spruce lumber, forest product journal 2003;53(11):85-89.

Davalos J. F., Kim Y Ch, et al. A layerwise beam element for analysis of frames with laminated sections and flexible joints[J]. Finite Elements in Analysis and Design, 1995, 19: 181-194.

He S. Study of finite element modeling analysis for Pinus *sylvestris* L. var. finger-jointed lumber[D]. Jiangsu: Nanjing Forestry University. 2011.

Kiyoko Y, Takeshi O, Yasuhide M, et al. Evaluation of Sugi finger–jointed laminae with a knot and starved joints by acoustic emission[J]. J. Fac. Agr., Kyushu Univ., 2007,52 (1):111–116.

Kutscha P., R.W. Caster, Factors affecting the bonding quality of hem-fir finger-joints. Forest Prod. J. 1987,37(4):43-48.

Liang S.Q. et al, Developments and applications of nondestructive tests for wood in North America[J]. China wood industry, 2008,22(3):5-8.

Lin L.Y. et al, Comparative study of MOE on three methods of nondestructive test forecasting four kinds of lumber[J]. Wood processing machinery, 2007,18(3):24-29.

Li X.M. Research on Mechanical Property Simulation of Timber with Finite Element Method and Optimization of Timber[D]. Inner Mongolian: Inner Mongolian Agricultural university. 2009.

Liu Z.F. The influence of flaws in finger joints on the strength of finger-jointed lumber[J]. Forestry Abroad,1995,25(1): 99-101.

Marra G. The role of adhesion and adhesives in the wood products industry. In: adhesives for wood. Research applications, and needs. R. H. Gillespie, ed. USDA forest serv., Forest Prod. Lab., Madison, WI. 1984, pp.2-9.

Moses D.M., Prion H.G.L.. Stress and failure analysis of wood composites: a new model [J].Composites: Part B, 2004, 35: 251–261.

Roland W. Finger-jointed wood products. Research paper FPL 382, 1981.

Raknes, E. The influence of production condition on the strength of finger-joints. In:Proc. Procdution, Marketing and Use of Finger-jointed Sawnwood. C.F.I.. Prins, ed. Timber

Committee of the United Nations Economic Commission for Europe. Martinus Nijhof/Dr. W. Junk Publishers. The Hague, The Netherlands. 1982, pp.154-168.

Serrano E. A numerical study of the shear-strength-predicting capabilities of test specimens for wood–adhesive bonds[J]. International Journal of Adhesion & Adhesives, 2004, 24: 23–35.

Tabiei A, Wu J. Three-dimensional nonlinear orthotropic finite element material model for wood [J].Composite Structures, 2000, 50:143-149.

Xu Y.J. The properties of timber[J].Wood in China,2000(5): 21-22.

Zhang H.J. et al, Measuring elastic modulus of wood using vibration method[J]. Journal of Beijing Forestry University, 2005(11):91-94.

Zhao R.J. et al, Estimation of Modulus of Elasticity of Eucalyptus Pellita Wood by Near Infrared Spectroscopy[J]. Spectroscopy and Spectral Analysis, 2009(9):2392-2395.

Zheng X.L. et al, Numerical analysis for effect of adhesive thickness on the stress distribution in butt joint[J]. Adhesion In China, 2004,25(5):30-32.