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Research Article

Mechanical Properties of Glued-Laminated Timber with Different Assembly Patterns

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A glued-laminated timber section with mixed-grade laminae could make an efficient use of material strength and reduce the cost. A 4-point bending test was conducted on a total of 18 specimens to investigate the mechanical properties of glued-laminated timber. Uniform-grade, asymmetrical mixed-grade, and symmetrical mixed-grade patterns were used to assemble the beam sections. The bending stiffness and reliability of the beams were assessed according to the experimental results. The influence of the assembly pattern on the bending behavior of glued-laminated timber was investigated by finite element models. The results show that the assembly pattern of the section has little influence on the failure mode of glued-laminated timber. Relative lower strength in compressive area of the section is beneficial for delaying the occurrence of the first crack on the glued-laminated timber beam. An equation for apparent bending stiffness of glued-laminated timber was proposed, whose results match well with the experimental results. The beam section assembled by the asymmetrical mixed-grade pattern retains the higher level of safety compared to those assembled by uniform-grade and symmetrical mixed-grade patterns. The grade of the second bottom lamina in tensile has little influence on the performance of glued-laminated timber, while lower grade laminae in compressive area of the section would cause a bending stiffness reduction at smaller deflection.

1. Introduction

Structural glued-laminated timber is widely used in wooden constructions. This material product is known as a material glued up from selected pieces of wood by joining the lumber end to end, edge to edge, and face to face [1]. Compared with sawn timber, glued-laminated timber may be designed with longer span and with a variable cross section, according to specific applications [2–7]. Also, naturally occurring strength-reducing defects are randomized throughout the volume of structural component. The appearance of glued-laminated timber fundamentally solved the problem that wood could not meet the engineering requirements on size dispersion and defects. It should be mentioned that structural components made of glued-laminated timber are overdesigned for strength due to its brittle failure mode. An important feature of glued-laminated timber is that the bonding of lamina can result in sections of higher strength than the strength of the single lamina from which they are constructed [8].

Many studies have been performed on the performance of glued-laminated timber. Toratti et al. [9] conducted a reliability analysis of a glulam beam which showed that the influence of strength variation is not remarkable. Tomasi et al. [10] investigated the flexural behavior in mixed and reinforced glued-laminated timber beams. The results showed that steel reinforcement seemed once more capable of providing a simple and reliable solution. Hiramatsu et al. [11] conducted a study on the strength properties of glued-laminated timber. The results implied that the use of glued edge-joints had no influence on the failure of specimens. Anshari et al. [12] proposed a new approach to strengthen glulam beams which was tested under bending. Teles et al. [13] performed a nondestructive test to assess the deflection of glulam beams made from hardwood. Rohanova and Lagana [14] made a description on quality parameters and the according requirements of structural timber. Fink et al. [15] proposed and illustrated a probabilistic method for simulating the capacity of glued-laminated timber. Carrasco et al. [16] conducted several tests to investigate the influence of the scarf joint in the performance of the glued-laminated timber beam. Blank et al. [17] proposed an analytical model which demonstrated that the performance of glued-laminated timber beams is significantly enhanced if the quasi-brittleness is considered. Kandler et al. [18] carried out a test on glued-laminated timber beams with knot morphology whose results showed that the mechanical models for timber elements must be developed to realistically predict the mechanical properties.

In traditional design and fabrication of glued-laminated timber, uniform-grade laminae are used across the section. The influence of the assembly pattern on the structural components is not considered which is a waste of materials. A glued-laminated timber section with mixed-grade laminae could make an efficient use of material strength and reduce the cost. Even though several basic assembly patterns have been covered by some design guidelines and standards [19–22], more studies need to be conducted on the influence of assembly patterns on the performance of glued-laminated timber. In this study, 4-point bending tests on beams are performed to assess the mechanical properties of glued-laminated timber. Three types of assembly patterns are used, which include uniform-grade assembly, asymmetrical mixed-grade assembly, and symmetrical mixed-grade assembly. Based on the experimental results, the bending stiffness and reliability of the beams are evaluated by various methods. A parametric analysis by ABAQUS is also conducted.

2. Experimental Program

2.1. Material Properties. The glued-laminated timber specimens tested in this study were made by using six grades of laminae made of Douglas fir, from Grade Me 8 to Me 14. The specimens of laminated timber were made and tested for ultimate strength and elastic modulus as shown in Figure 1. The material properties of lamina timber are listed in Table 1. The epoxy paste for the bonding had an elastic modulus of 1.28×10^4 MPa with a tensile strength of 23–26 MPa and shear strength of 13–16 MPa which are provided by the suppliers.

2.2. Design and Fabrication of Specimens. Grade 21 and Grade 24 glued-laminated timber were designed according to Chinese Standard GB/T 26899-2011 [19] while the laminae were glued together in 6 layers as shown in Figure 2. Three types of assembly patterns were used, which included uniform-grade assembly (TC_T), asymmetrical mixed-grade assembly (TC_{YF}), and symmetrical mixed-grade assembly (TC_{YD}). Three specimens were designed for each profile in which case that total 18 specimens were fabricated. The width and depth of all specimens were 90 mm and 200 mm, respectively. The span of all specimens was 3750 mm. The span to depth ratio was 18.75 which favored the flexural performance rather than the shear performance. The specimens were clamped with 0.5 MPa pressure for 24 hours as shown in Figure 3 and postcured at ambient temperature for 7 days.

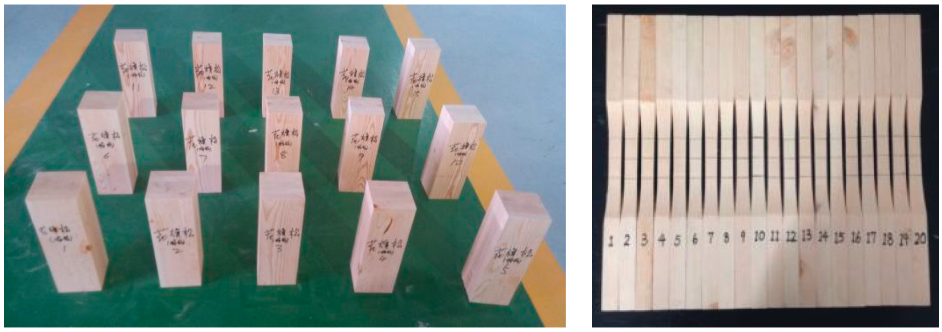
2.3. Test Setup and Procedure. A 4-point static flexural test was carried out on the specimens as shown in Figure 4. Vertical loads were exerted at 1,400 mm and 2200 mm of the span through a 100 kN testing machine at a rate of 2 mm/min in accordance with GB/T 50329-2002 [23]. The displacement-control method was used, and the total loading duration was set between 6 min and 14 min. Six strain gauges were placed on each lamina at the midspan section of the beam. The settlement at support and the deflection of the specimen were recorded by using linear variable differential transformers (LVDTs).

3. Experimental Results

3.1. Failure Behavior of Specimens. The ultimate load and failure mode of 18 specimens are listed in Table 2. It can be seen that the strength of the asymmetrical mixed-grade assembly section and symmetrical mixed-grade assembly section was both higher than that of the uniform-grade assembly section. Figure 5 shows the failure phenomena of the typical specimens. Except for specimen TC_T-21, tensile failure of bottom lamina was observed in all specimens. Most of the cracks were initiated from the knots on the bottom lamina. No compressive failure and debonding were observed. It should be mentioned that the delamination shown in Figure 5 actually occurred after the tensile failure of specimens. Some delamination is even in the lamina itself, not in adhesive layer. That is the reason that the shear stress between laminae is not considered in the study. It may imply that the assembly pattern would not affect the failure mode of glued-laminated timber.

3.2. Load-Deflection Response of Beams. Figure 6 shows the load-deflection response of the specimens. Only one typical curve of each assembly pattern is presented. The analysis of the load-displacement curves indicates that even the cracks were initiated and propagated along with the vertical load increasing, the behavior of the specimens remained almost linear and no significant reduction of stiffness occurred until the specimens failed. It can be seen that the stiffness of the mixed-grade assembly sections was both higher than that of the uniform-grade assembly section. It could be concluded that the behavior of bottom lamina exhibited the most influence on the strength and stiffness of glued-laminated timber, rather than the middle lamina.

The cracking load of asymmetrical mixed-grade assembly section is larger than those of uniform-grade and symmetrical mixed-grade assembly section in both Grade 21 and Grade 24 glued-laminated timber sections. This fact may indicate that relative lower strength in compressive area of the section is beneficial for delaying the occurrence of first

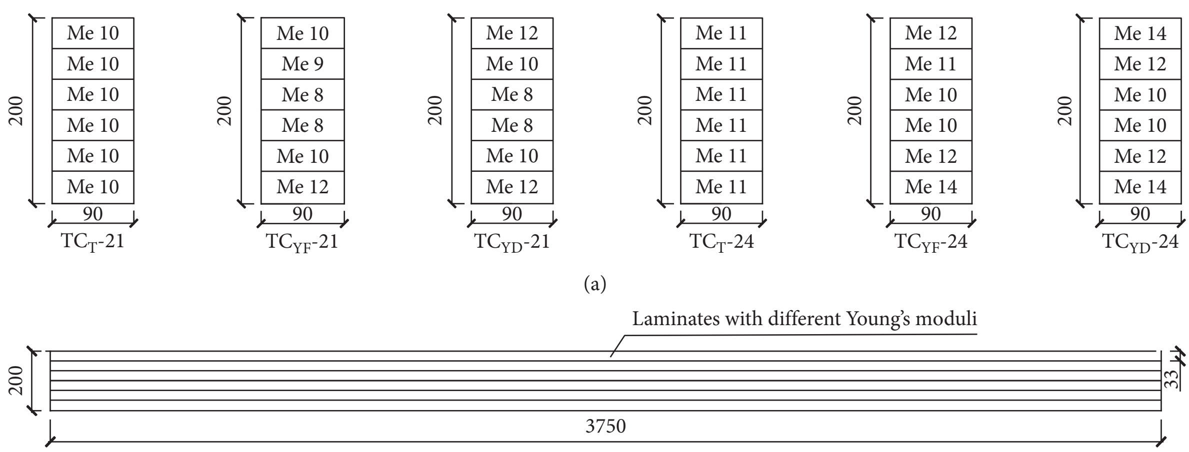


(a) (b)

Figure 1: Material tests. Specimens for (a) compressive test and (b) tensile test.

Table 1: Material properties of lamina timber.

Grade	Ultimate tensile stress (MPa)	Elastic modulus in tension (MPa)	Ultimate compressive stress (MPa)	Elastic modulus in compression (MPa)
Me8	18.1	8636	33.6	8787
Me9	21.8	9381	37.7	9692
Me10	22.6	10336	40.9	10828
Me11	24.6	11538	43.3	11629
Me12	26.3	12318	46.6	12630
Me14	32.8	14063	57.2	14282



(a)

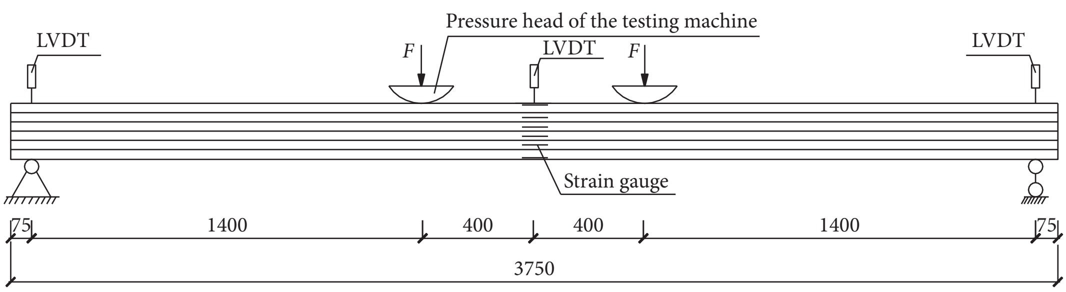
(b)

Figure 2: Specimen description. (a) Profiles of specimens. (b) Dimensions of the specimen.

(a) (b)

Figure 3: Preparation of specimens.

(a)



(b)

FIGURE 4: Experimental setup. (a) Loading setup. (b) Arrangement of LVDTs and strain gauges.

TABLE 2: Ultimate load and failure mode of specimens.

No.	Ultimate load (kN)		Failure mode
	Test results	Average value	
TC_T-21(1)	30.02		
TC_T-21(2)	28.91	29.06	Tensile failure of bottom lamina
TC_T-21(3)	28.24		
TC_{YF}-21(1)	40.53		
TC_{YF}-21(2)	39.03	39.23	Tensile failure of bottom lamina
TC_{YF}-21(3)	38.13		
TC_{YD}-21(1)	45.03		
TC_{YD}-21(2)	43.37	43.59	Tensile failure of bottom lamina
TC_{YD}-21(3)	42.37		
TC_T-24(1)	38.27		
TC_T-24(2)	37.16	37.34	Tensile failure of bottom lamina
TC_T-24(3)	36.59		
TC_{YF}-24(1)	50.77		
TC_{YF}-24(2)	50.10	49.84	Tensile failure of bottom lamina
TC_{YF}-24(3)	48.65		
TC_{YD}-24(1)	56.63		
TC_{YD}-24(2)	55.67	55.38	Tensile failure of bottom lamina
TC_{YD}-24(3)	53.83		

crack on glued-laminated timber beam, comparing with those on uniform-grade and symmetrical mixed-grade assembly section. Figure 6 also shows that mixed-grade assembly sections present larger ultimate deflection than uniform-grade assembly section. Comparing Grade 21 and Grade 24 glued-laminated timber sections with the same assembly pattern, it could be seen that the deformation capacity of glued-laminated timber would decrease with the increase of lamina grade.

3.3. Strain Distribution in the Section at Midspan. The laminae of section are numbered by 1 to 6 from the top of the section. Figure 7 shows the midspan section strain distribution

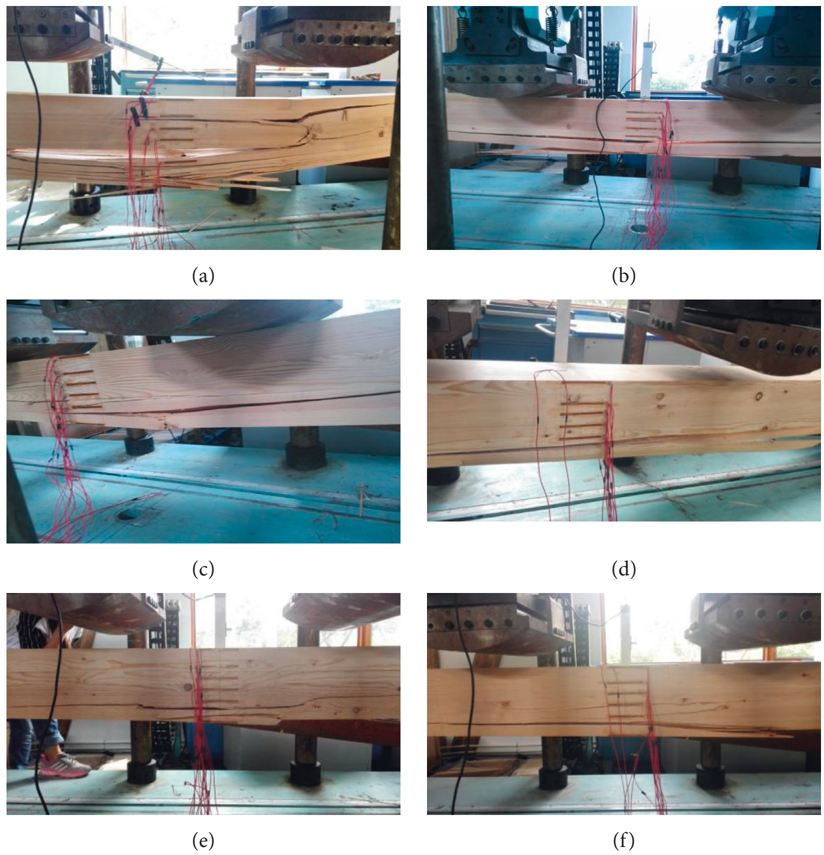


FIGURE 5: Failure phenomena of typical specimens. (a) TC_T-21(2). (b) TC_{YF}-21(2). (c) TC_{YD}-21(2). (d) TC_T-24(2). (e) TC_{YF}-24(2). (f) TC_{YD}-24(2).

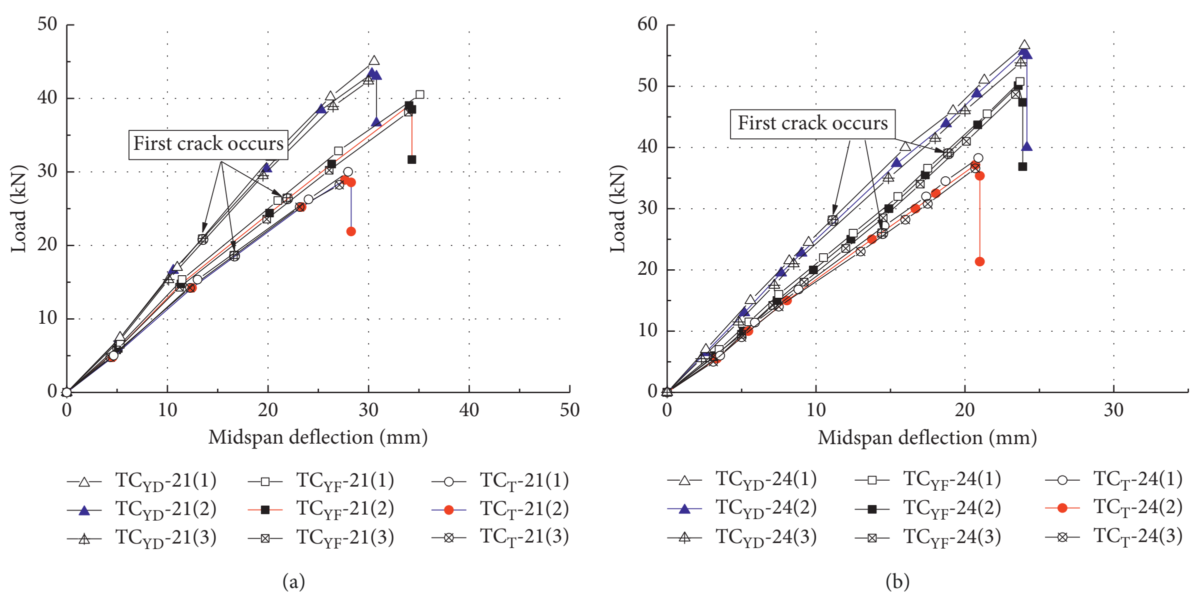


FIGURE 6: Load-midspan deflection curves of the specimens. (a) TC-21. (b) TC-24.

of the typical specimens at different load levels. For totally six sections in Grade 21 and Grade 24, the sections in both tension and compression are in elastic at the early phase of loading which confirms that no slip at the interface between laminae in the section. After cracking, nonlinearity was observed in tensile and compressive strains indicating the further development of cracks in the specimens. The values listed in Table 3 show that the asymmetrical assembly pattern permits higher

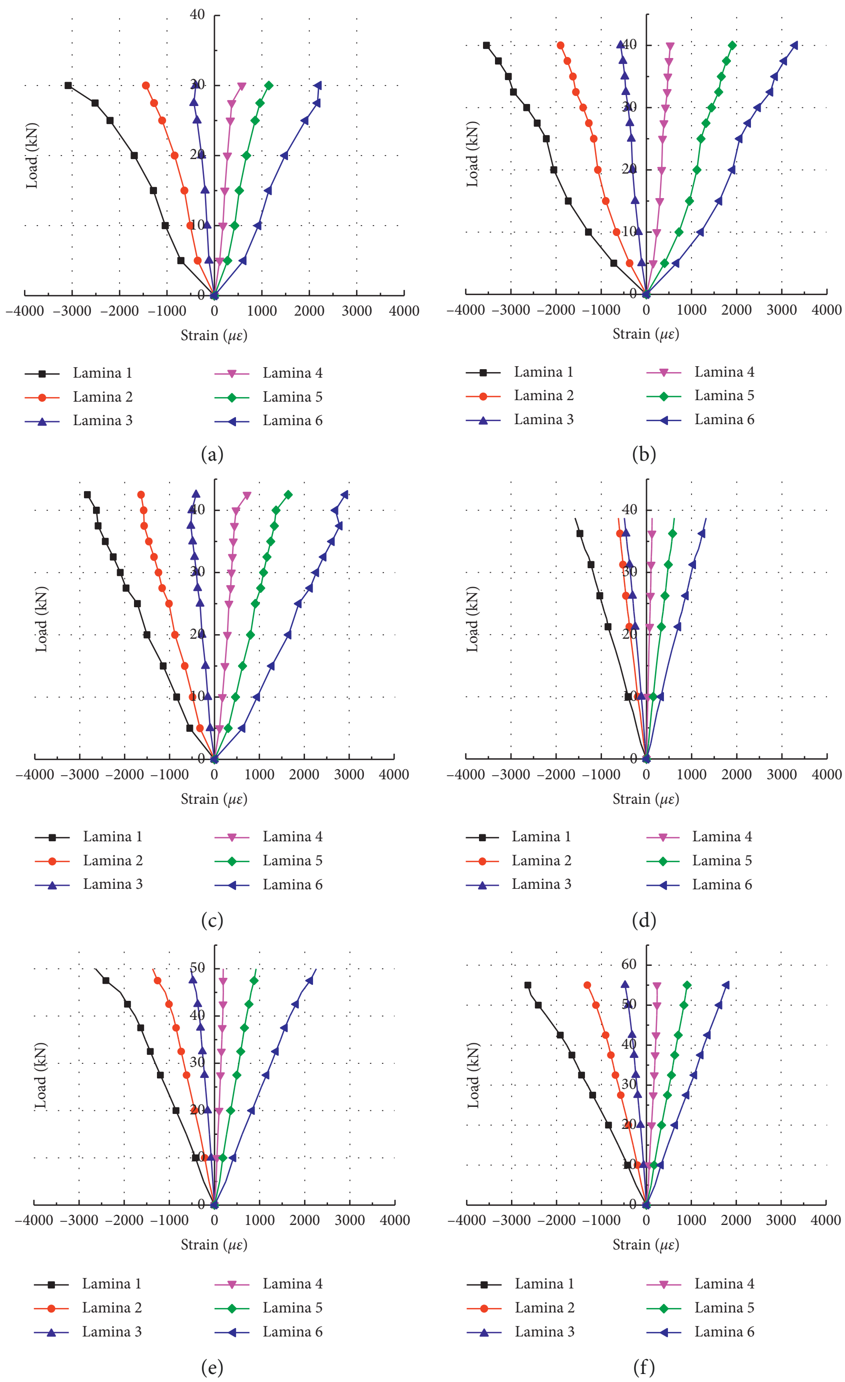


Figure 7: Strain distribution in the typical specimens. (a) TC_{T}-21(2). (b) TC_{YF}-21(2). (c) TC_{YD}-21(2). (d) TC_{T}-24(2). (e) TC_{YF}-24(2). (f) TC_{YD}-24(2).

stress in glued-laminated timber at failure than the symmetrical assembly pattern.

4. Discussion of Results

4.1. Bending Stiffness. The experimental apparent bending stiffness $(EI)_{e.app}$ of the glued-laminated timber beam for the whole span [23] could be derived from the load-deflection curves by using the following equation:

$$(EI)_{e.app} = \frac{l_s\left(3L^2 - 4l_s^2\right)}{48}\left(\frac{\Delta F}{\Delta\omega}\right), \qquad (1)$$

where $\Delta F/\Delta\omega$ is the the slope of the load-deflection curve, l_s is the distance between loading point to support, and L is the the span of the beam.

The theoretical bending stiffness $(EI)_{em}$ of the glued-laminated timber beam could be derived from elastic model

Table 3: Stresses and strains of bottom laminae at failure.

No.	Load at failure (kN)	Maximum tensile strain in bottom lamina ($\mu\varepsilon$)	Maximum tensile stress in bottom lamina (MPa)
TC_T-21(1)	30.02	2200	22.7
TC_T-21(2)	28.91	2100	21.7
TC_T-21(3)	28.24	2050	21.2
TC_{YF}-21(1)	40.53	3050	37.6
TC_{YF}-21(2)	39.03	3000	36.9
TC_{YF}-21(3)	38.13	2900	35.7
TC_{YD}-21(1)	45.03	2750	33.8
TC_{YD}-21(2)	43.37	2600	32.0
TC_{YD}-21(3)	42.37	2550	31.4
TC_T-24(1)	38.27	1500	18.0
TC_T-24(2)	37.16	1400	16.8
TC_T-24(3)	36.59	1350	16.2
TC_{YF}-24(1)	50.77	2250	27.7
TC_{YF}-24(2)	50.10	2200	27.1
TC_{YF}-24(3)	48.65	2050	25.2
TC_{YD}-24(1)	56.63	1900	26.6
TC_{YD}-24(2)	55.67	1800	25.3
TC_{YD}-24(3)	53.83	1650	23.1

Table 4: Comparison between theoretical and experimental results (10^{11} MPa·mm^4).

No.	$(EI)_{\mathrm{e.app}}$	$(EI)_{\mathrm{em}}$	$(EI)_{\mathrm{em}}/(EI)_{\mathrm{e.app}}$	$(EI)_{\mathrm{ec}}$	$(EI)_{\mathrm{ec}}/(EI)_{\mathrm{e.app}}$
TC_T-21(1)	5.05	6.16	1.23	5.77	1.14
TC_T-21(2)	4.97	6.16	1.24	5.77	1.16
TC_T-21(3)	4.93	6.16	1.25	5.77	1.17
TC_{YF}-21(1)	5.45	6.44	1.18	6.01	1.10
TC_{YF}-21(2)	5.23	6.44	1.23	6.01	1.15
TC_{YF}-21(3)	4.98	6.44	1.29	6.01	1.21
TC_{YD}-21(1)	6.02	6.89	1.14	6.40	1.06
TC_{YD}-21(2)	5.88	6.89	1.17	6.40	1.09
TC_{YD}-21(3)	5.76	6.89	1.20	6.40	1.11
TC_T-24(1)	5.76	6.74	1.17	6.27	1.09
TC_T-24(2)	5.43	6.74	1.24	6.27	1.15
TC_T-24(3)	5.38	6.74	1.25	6.27	1.17
TC_{YF}-24(1)	6.80	7.50	1.10	6.98	1.02
TC_{YF}-24(2)	6.56	7.50	1.14	6.98	1.06
TC_{YF}-24(3)	6.36	7.50	1.18	6.98	1.10
TC_{YD}-24(1)	7.38	7.92	1.07	7.29	0.99
TC_{YD}-24(2)	7.01	7.92	1.13	7.29	1.04
TC_{YD}-24(3)	6.88	7.92	1.15	7.29	1.06

using equation (2). Interlayer slips and the contribution of epoxy adhesives are not considered in the calculation:

$$(EI)_{\mathrm{em}} = \sum_{i=1}^{6} E_i\left(I_i + A_i a_i^2\right), \tag{2}$$

where E_i is the elastic modulus of layer i, I_i is the inertia of layer i, A_i is the area of layer i, and a_i is the distance between the centroid of layer i and neutral axis.

An equation from reference [21] which could consider shear deformation and span-to-depth ratio of glued-laminated timber beam is also used to calculate theoretical bending stiffness $(EI)_{\mathrm{ec}}$ of the glued-laminated timber beam:

$$\frac{1}{(EI)_{\mathrm{ec}}} = \frac{1}{\sum_1^6 E_i I_i} + \frac{0.1kH^2}{\left(3L^2 - 4l_s^2\right)G_{\mathrm{w}}\sum_1^6 I_i}, \tag{3}$$

where G_{w} is the shear modulus of laminae which is 730 MPa [24], H is the beam depth, and k is the shear deformation factor determined by

$$k = 1 + 6\frac{H}{h_{\mathrm{w}}}\left(1 - \frac{H}{h_{\mathrm{w}}}\right)\left(1 - 2\frac{H}{h_{\mathrm{w}}}\right)\left(\frac{b}{b_{\mathrm{w}}} - 1\right), \tag{4}$$

where h_{w} is the web height, b_{w} is the web width, and b is the beam width.

As listed in Table 4, the bending stiffness for the Grade 21 beam section based on the simple elastic model is higher than the experimental results while that for the Grade 24 beam section is lower than the experimental results. While considering the shear deformation and span-to-depth ratio, the theoretical values become lower for both Grade 21 and Grade 24 beam sections.

Since equation (3) is too complicated to use, a correction factor K_v for the theoretical bending stiffness was proposed in references [7, 25]:

$$(EI)_{\text{theo}} = \frac{(EI)_{\text{em}}}{K_v}, \tag{5}$$

$$K_v = m + n\left(\frac{L}{H}\right) + p\left(\frac{H}{L}\right), \tag{6}$$

where m, n, and p are constants determined by tests.

Based on the experimental results in this study, a correction factor K_{v1} is proposed as follows:

$$K_{v1} = 0.25 + 0.02\left(\frac{L}{H}\right) + 10\left(\frac{H}{L}\right). \tag{7}$$

Figure 8 shows the comparison between experimental results and theoretical bending stiffness. It could be seen that the theoretical bending stiffness with the proposed correction factor in this study fits best with the experimental results. The correction factor K_v calculated by the methods in references [7, 25] is too low to match the experimental results in this study. It may be explained by the fact that composite sections were used for the specimens in the tests in references [7, 25]. More studies should be conducted in the future to enhance the calculation accuracy of theoretical bending stiffness of glued-laminated timber beams.

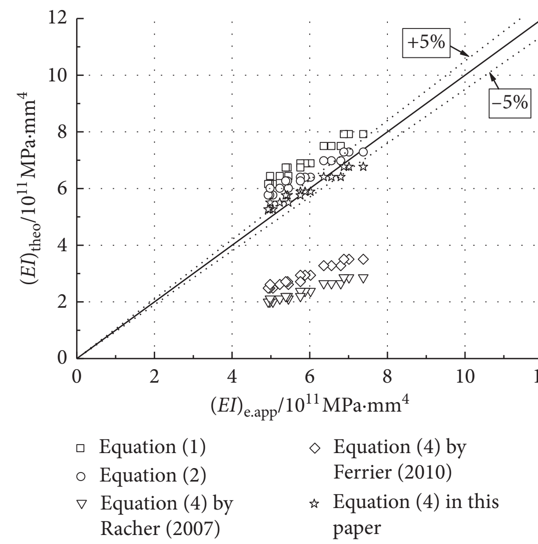


Figure 8: Comparison between experimental results and theoretical bending stiffness.

4.2. Reliability. In order to assess the efficiency of mixed-grade glued-laminated timber, serviceability criteria in Eurocode 5 [21] are used to conduct the analysis. The bending moment referring to the limitation deflection of $L/300$ is defined as M_{300}. The factor α is defined as the ratio between the bending moment M_{300} of mixed-grade and uniform-grade assembly sections. The factor β is defined as the ratio between the ultimate bending moment M_u and the bending moment M_{300}. Referring to these factors as a standard, the behavior of beams with different assembly patterns under service loads could be evaluated.

As Table 5 listed, the efficiency of glued-laminated timber is significantly improved by using the mixed-grade assembly pattern: moment M_{300} is enhanced by 14–40% relative to the uniform-grade assembly pattern. It also could be seen from Table 5 that the factor β of asymmetrical assembly pattern which presents the safety level is larger than that of other two assembly patterns. The fact means that the beam section assembled by the asymmetrical mixed-grade pattern retains the higher level of safety than those assembled by the uniform-grade and symmetrical mixed-grade assembly patterns when the beams exhibit the same bearing capacity.

Table 5: Serviceability criteria.

No.	M_u (kNm)	M_{300} (kNm)	$\alpha = M_{300\text{-mixed}}/M_{300\text{-uniform}}$	$\beta = M_u/M_{300}$
TC_T-21(1)	48.03	21.82	—	2.20
TC_T-21(2)	46.26	21.36	—	2.17
TC_T-21(3)	45.18	20.76	—	2.18
TC_{YF}-21(1)	64.85	26.65	1.22	2.43
TC_{YF}-21(2)	62.45	24.78	1.16	2.52
TC_{YF}-21(3)	61.00	23.66	1.14	2.58
TC_{YD}-21(1)	72.05	32.36	1.48	2.23
TC_{YD}-21(2)	69.39	29.67	1.39	2.34
TC_{YD}-21(3)	67.79	28.26	1.36	2.40
TC_T-24(1)	61.23	35.89	—	1.71
TC_T-24(2)	59.46	34.56	—	1.72
TC_T-24(3)	58.54	33.36	—	1.75
TC_{YF}-24(1)	81.23	40.86	1.14	1.99
TC_{YF}-24(2)	80.16	39.55	1.14	2.02
TC_{YF}-24(3)	77.84	37.96	1.14	2.05
TC_{YD}-24(1)	90.61	48.92	1.36	1.85
TC_{YD}-24(2)	89.07	47.58	1.38	1.87
TC_{YD}-24(3)	86.13	45.97	1.38	1.87

5. Numerical Analysis

5.1. Finite Element Model. Finite element models are developed using ABAQUS to investigate the influence of the assembly pattern on the bending behavior of glued-laminated timber. C3D8R solid elements are used to model the laminae which are connected together by "Tie"

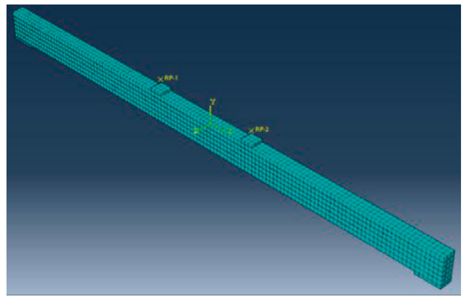


Figure 9: Finite element model.

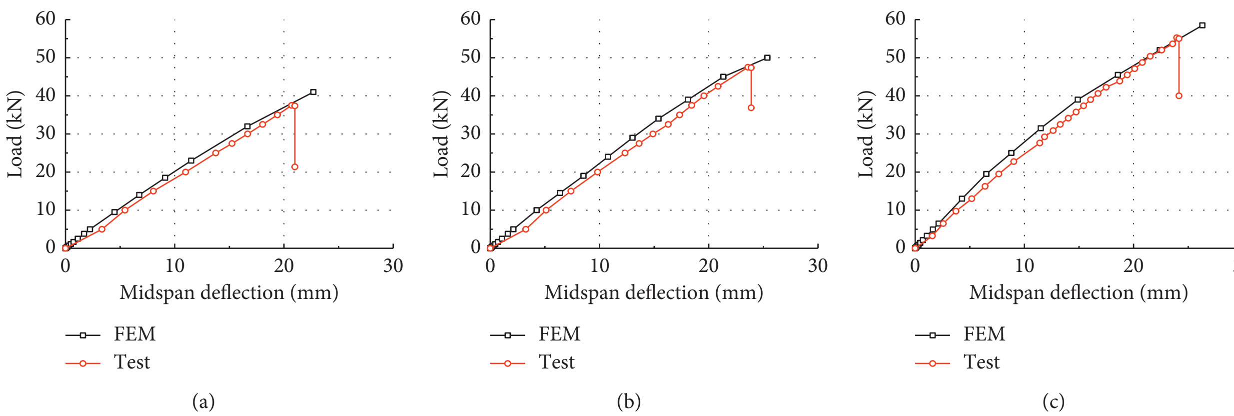


Figure 10: FE model validation of typical specimens. (a) TC_{T}-24(2). (b) TC_{YF}-24(2). (c) TC_{YD}-24(2).

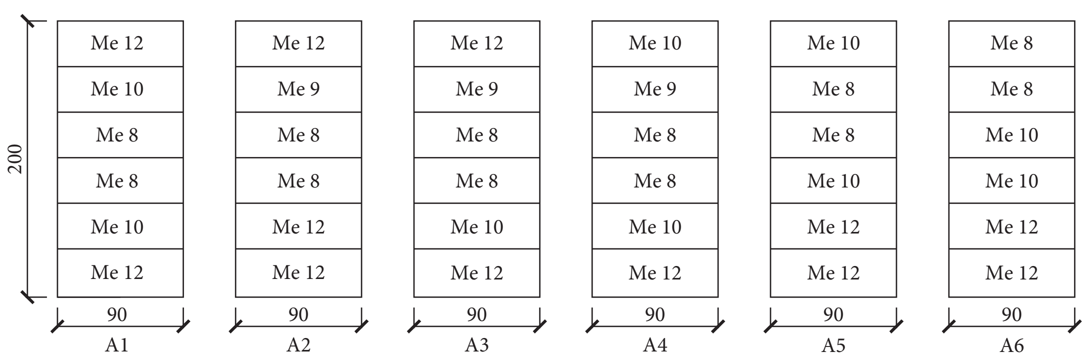


Figure 11: Beam sections for parametric analysis.

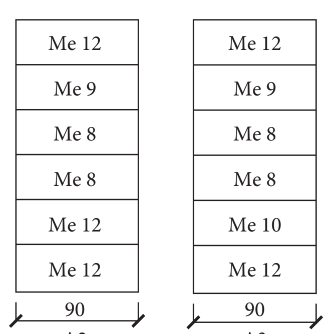
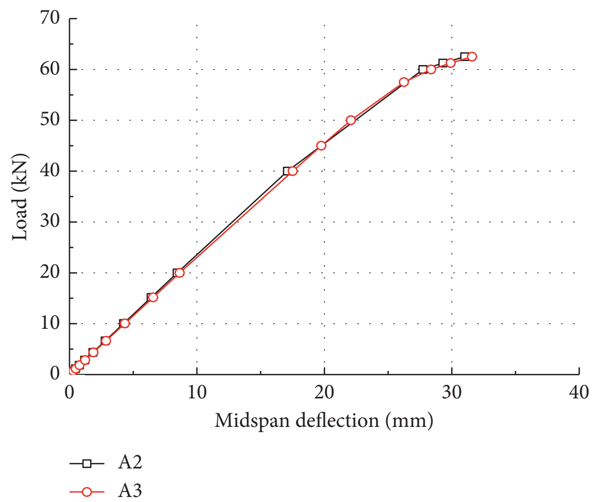
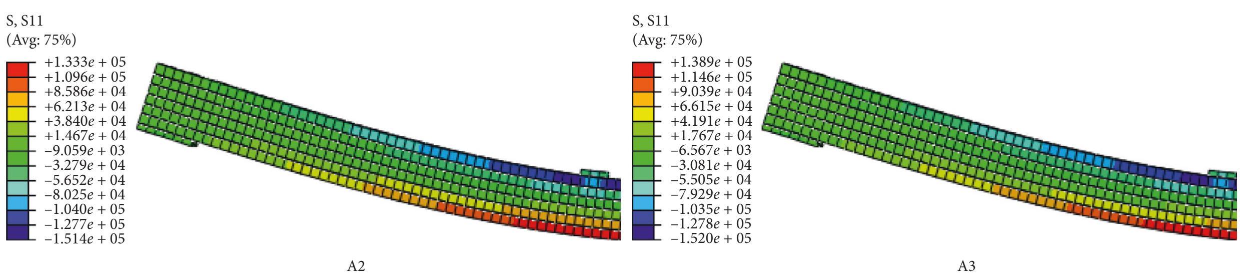


Figure 12: Sections with different second bottom laminae in tensile.



(a)



(b)

Figure 13: Influence of second bottom lamina in tensile. (a) Load-deflection curves. (b) Stress nephogram.

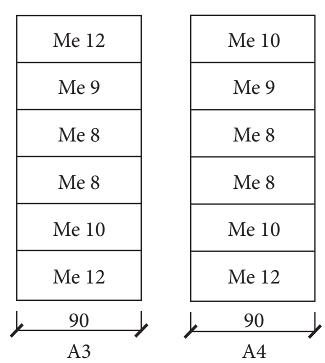


Figure 14: Sections with different top laminae in compression.

command as shown in Figure 9 since no slip was observed in the test. Vertical loads are applied at the same position as the 4-point bending test. The dimensions and material properties of the model are identical to those of the specimens.

5.2. Model Validation. The finite element (FE) models of typical specimens are validated against the test results as shown in Figure 10. The numerical results fit well with the test results in the bending stiffness and strength of the specimens. Due to the existence of defects and knots in the specimens, the slope of the curves representing numerical results is a little higher than those representing test results. In general, the FE models are accurate enough to perform parametric analysis.

5.3. Parametric Analysis. Six sections of glued-laminated timber are assembled for parametric analysis as shown in Figure 11. Section A1 is based on specimen TC_{YD}-21. The standard mechanical properties provided from reference [19] are introduced into the models for parametric analysis hereinafter. Achieving of maximum tensile stress at bottom lamina is defined as the failure of the models, according to the failure modes exhibited in the tests.

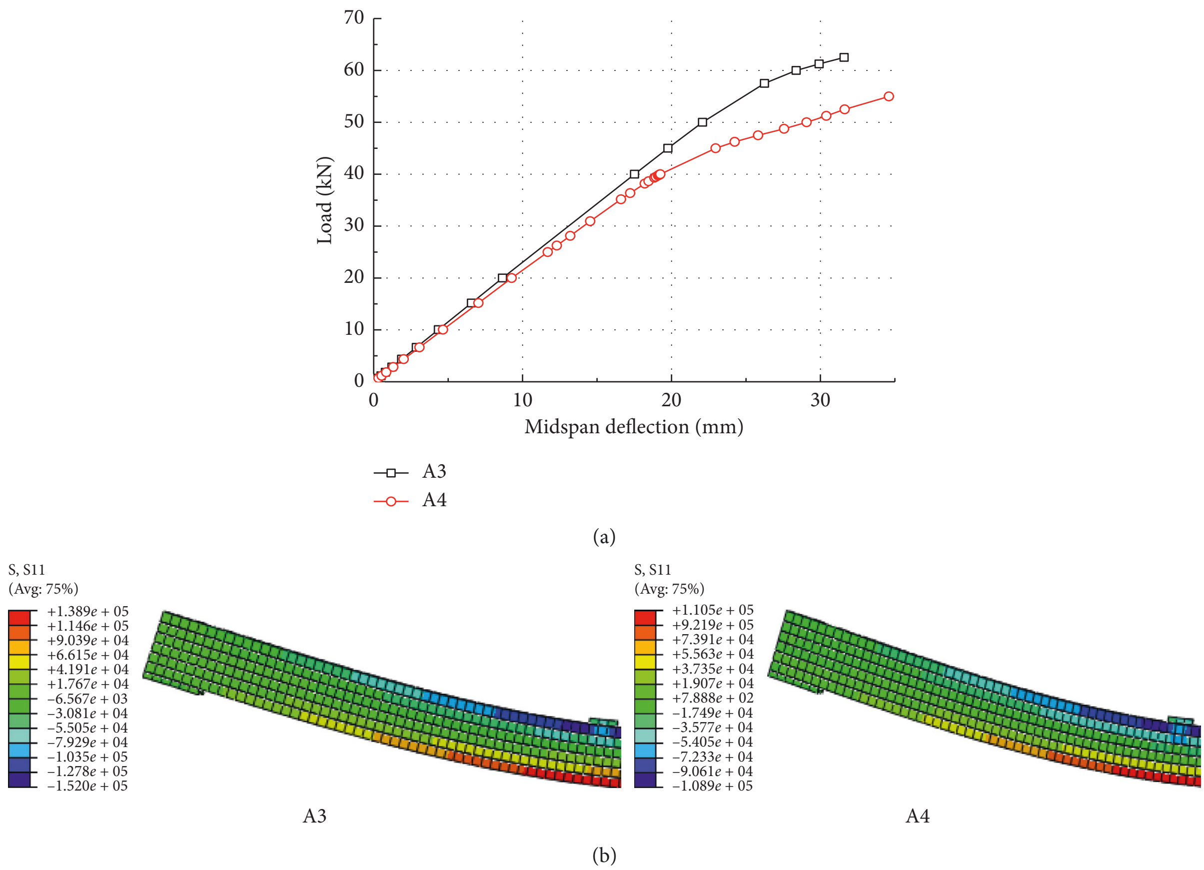


Figure 15: Influence of top lamina in compression. (a) Load-deflection curves. (b) Stress nephogram.

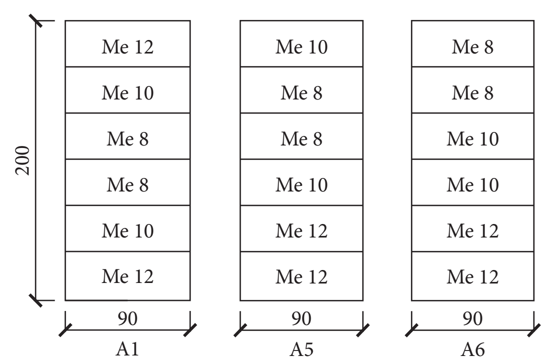
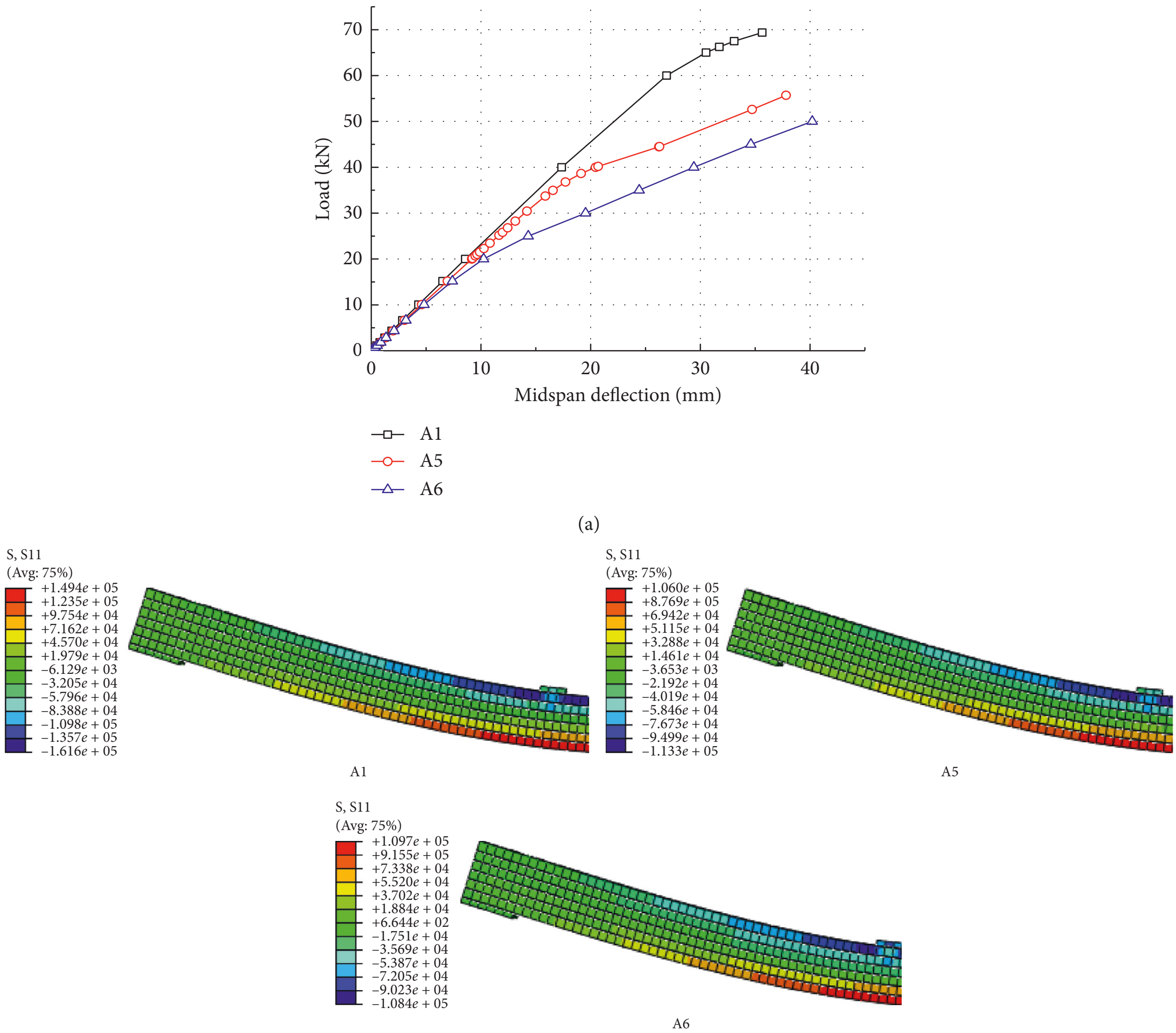


Figure 16: Assembly sequence.

5.3.1. Second Bottom Lamina in Tensile. Due to the failure modes of bottom lamina in tensile observed at all 18 specimens, it is convinced that the behavior of bottom lamina in tensile definitely plays a critical role in the mechanical properties of glued-laminated timber. Based on this well-known fact, the influence of second bottom lamina in tensile is studied as shown in Figure 12. Figure 13(a) shows the load-deflection curves of models A2 and A3. It can be seen that the grade of second bottom lamina in tensile has little influence on the performance of glulam beam, including bending stiffness, bending strength, and ultimate deflection. Figure 13(b) shows the stress nephogram of models where little difference is observed.

5.3.2. Top Lamina in Compression. Even no compressive failure was observed in the tests, top lamina in compression is supposed to affect the mechanical properties of glued-laminated timer. To this end, two sections with different top lamina in compression are assembled as shown in Figure 14. Figure 15(a) shows the load-deflection curves with different-grade top laminae. It can be seen that the bending stiffness and strength of the models increase with the increase in the strength grade of top lamina, while the ultimate deflection of the models shows a reverse trend. Figure 15(b) shows the stress nephogram of models. The maximum compressive stress and tensile stress in model A3 are both higher than those in model A4.



(b)

Figure 17: Influence of assembly sequence. (a) Load-deflection curves. (b) Stress nephogram.

5.3.3. Assembly Sequence. With the same grade and quantity of laminae, three sections are assembled by different sequences as shown in Figure 16. The grade of laminae in the compressive area of section is decreased. Figure 17(a) shows the influence of assembly sequence on bending performance of models. It can be seen that the bending stiffness and strength of the models decrease with the decrease in the lamina grade in compressive area of section while the ultimate deflection of the models shows a reverse trend. Meanwhile it is worth noticing that a bending stiffness reduction is observed at increasingly smaller deflection with lower grade laminae in the compressive area of the section.

6. Conclusions

Totally 18 specimens were tested by the 4-point bending test to investigate the mechanical properties of glued-laminated timber. Uniform-grade assembly, asymmetrical mixed-grade assembly, and symmetrical mixed-grade assembly were used to fabricate the beam sections. Based on the experimental results, the bending stiffness and reliability of the beams are evaluated by various methods. In addition, a numerical analysis is conducted for further investigation. The following conclusions are made as follows:

(1) The assembly pattern of section has little effect on the failure mode of glued-laminated timber. Relative lower strength in compressive area of the section is beneficial for delaying the occurrence of first crack on the glued-laminated timber beam.

(2) The grade of second bottom lamina in tensile has little influence on the performance of glued-laminated timber while lower grade laminae in compressive area of the section would cause a bending stiffness reduction at smaller deflection.

(3) The beam section assembled by the asymmetrical mixed-grade pattern retains the higher level of safety

than those assembled by uniform-grade and symmetrical mixed-grade patterns.

(4) An equation for apparent bending stiffness of glued-laminated timber was proposed which shows good agreement with the experimental results.

Data Availability

The experimental and numerical data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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