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EXPERIMENTAL INVESTIGATION ON THE IN-PLANE PERFORMANCE OF NAIL-LAMINATED TIMBER FLOORS

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ABSTRACT: Nail-laminated timber (NLT) can be used as structural floors to transfer lateral force. However, the research on the in-plane performance of NLT floors is still insufficient. This paper presents the results of an experimental investigation on the in-plane performance of NLT floors. Three NLT floor configurations, a total of nine specimens, considering different sheathing nail spacings and orient strand board (OSB) sheathing fibre orientations, were subjected to fully reversed cyclic loading. Sheathing nail and lamina nail failure were observed as main failure mode during the cyclic loading. Sheathing orientation was noticed to have impact on the NLT floor deformation pattern. Equivalent energy elastic-plastic curves were obtained from each specimen group, from which the elastic shear stiffness, yielding load and displacement, ductility ratio, and shear strength were calculated. Secant stiffness and dissipated energy were also extracted from hysteresis loops. The comparison indicates that arranging OSB fibre perpendicular to lamina axis could significantly increase the elastic shear stiffness and ductility ratio of NLT floor, and a tightened sheathing nail spacing (i.e., 75 and 150 mm at the edge and centre, respectively) could provide higher elastic shear stiffness, shear strength, ductility, and improve energy dissipation capacity.

KEYWORDS: Timber structure, Nail-laminated timber, Timber floor, In-plane performance

1 INTRODUCTION

With its architectural aesthetics and structural reliability, timber structure has been increasingly accepted by both architects and structural engineers, and widely applied in recent years. Nail-laminated timber (NLT) is one of the mass timber products, which is constructed by nailing laminas side-by-side. NLT has been applied in timber decks and floors [1]. The existing research on NLT mostly focus on its bending performance. Derikvand et al. [2] investigated the modulus of elastic (MOE) of NLT constructed by fast grown eucalypt. The result shows that the overall MOE is higher than the MOE of most individual laminas, proving its ability to make good use of low-grade timber when properly arranged. Herberg [3] indicated that NLT could reach a similar MOE and flexural strength as solid timber, but with a relatively lower manufacturing cost. Other relevant research includes the nail connection in-between the laminas [4], push-out performance [5] and bending performance [6,7] of NLT-concrete composite floor. Moreover, a novel nail-cross-laminated timber (NCLT) was brought up to combine the advantages of both NLT and cross-laminated timber (CLT) [8,9].

Nevertheless, floor system not only transfers vertical loads using its bending performance, but also transfers lateral forces using its in-plane stiffness and bearing capacity. Tena-Colunga and Abrams [10] analysed the influence of timber floor on unreinforced masonry (URM) buildings. Results point out that the maximum horizontal acceleration of floors and walls increases as the in-plane stiffness of timber floor decreases. Similarly, Tamagnone et al. [11] analysed the influence of floor stiffness on the rocking behaviour of a CLT wall. Results show that the out-of-plane flexural stiffness of the floor is negligible to the CLT wall rocking behaviour, while the in-plane stiffness has a significant impact. Furtherly, Mendes [12] performed shaking table test on two URM buildings, one of which had the connection between timber floors and structure strengthened. Test results show that the damage index, which is defined as a function of natural frequency, of the strengthened URM building is 54% lower than the one of the original URM building. Moreover, the maximum horizontal displacement and maximum inter-storey displacement of the strengthened one is 20% and 31% lower than the original one, respectively. These test and/or analysis results indicate that the in-plane performance of floor system could play a critical role at seismic performance of the over-all structure.

Therefore, research on the in-plane performance of various timber floors have been widely investigated. Mirra et al. [13] studied the in-plane response of the traditional and retrofitted timber floor in Dutch, which is similar to those used in light-frame structure. Results show that the loading direction plays an important role on the in-plane response of a traditional flexible floor. An

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additional plywood sheathing panel can achieve a significant improvement in strength, stiffness, and energy dissipation. The deformation pattern was also observed to transform from mainly flexural to shear-related after retrofit. D'Arenzo et al. [14] developed a simplified equivalent frame model to predict the in-plane flexibility of CLT floor and validated using a planar finite element model. The model novelty included the effect of the floor-to-wall connection. Results show that connection to the supporting walls redistributes the bending moment but does not significantly affect the shear deformations between panels. Li et al. [15] studied the in-plane behaviour of timber-steel hybrid floor experimentally and numerically. Results indicate that shear deformation contributed up to 90% of the total in-plane deformation of the hybrid floor. The overall behaviour of the floor showed an obvious nonlinearity due to the screwed wood-steel connections. A numerical model was also developed to predict the behaviour of this hybrid floor. Newcombe et al. [16] conducted an in-plane experimental test of a timber-concrete composite floor. Results indicate that composite floor shows a high elastic stiffness compared to the connection between the floor and structure, and the composite floor can be modelled as single-degree-of-freedom in structural analysis.

To summarize the existing literatures, the in-plane performance of structural timber floors is critical to the seismic response of the overall structure. Research on the in-plane performance of various timber floors have been widely investigated. However, despite that there have been some applications of NLT floors, the research on its in-plane performance is still insufficient. This paper presents an experimental investigation on the in-plane performance of NLT floors. An in-plane shearing test of NLT floors is designed and carried out. Different sheathing nail spacings and orient strand board (OSB) sheathing fibre orientations were considered. Failure modes were observed. Equivalent energy elastic-plastic based in-plane performance characteristics, as well as energy dissipation capacity were extracted from the test.

2 TEST SET-UP

2.1 SPECIMEN DESIGN

A total of nine specimens at three different configurations, three specimen per configuration, were fabricated and tested. Comparing to control group, different sheathing nail spacings and OSB fibre orientations were considered in the remaining groups, respectively. The number of specimens was determined based on previous research considering the material deviation of timber, which also satisfied the requirement of American standard ASTM E2126-19. The three tested configurations are listed in Table 1, and detailed dimensions of specimens in the first group are shown in Figure 1. All tested specimens have an area of 2440 mm × 2440 mm and a thickness of 152 mm. Each specimen was constructed with a 140 mm thick NLT panel and a 12 mm thick OSB sheathing panel. The NLT panel was constructed by nailing roughly 61 pieces of 2440 mm long laminas side-by-side using nail gun. The nailing pattern of nail connections in-between the laminas followed the one described by Derikvand et al. [2], which is a staggered pattern with a nominal nail spacing of 135 mm per row, and a row spacing of 100 mm.

Table 1: *Overview of tested configurations*

Group	OSB nail spacing*	OSB fibre orientation**	Number of specimens
A-V	Spacing A	Vertical	3
B-V	Spacing B	Vertical	3
A-H	Spacing A	Horizontal	3

*: For OSB nail spacing, spacing A refers to an edge spacing of 150 mm and a centre spacing of 300 mm; spacing B refers to an edge spacing of 75 mm and a centre spacing of 150 mm.

**: For OSB fibre orientation, the horizontal is defined to be aligned with the direction of the lamina axial in NLT.

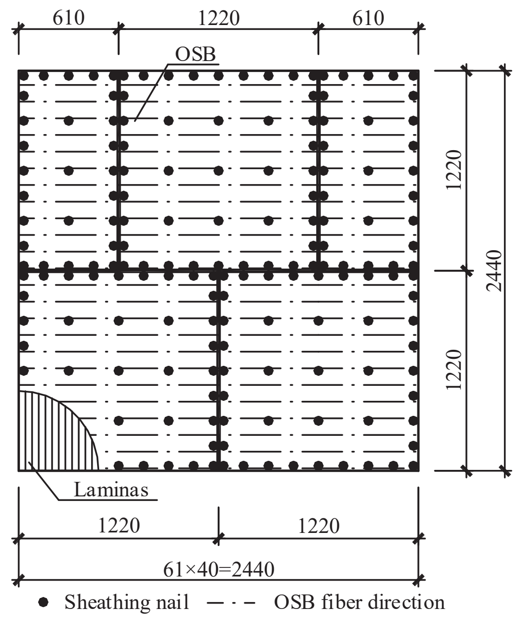

Figure 1: *Dimensions (in mm) of tested group A-V.*

2.2 MATERIAL

The materials used in the tests are listed as follows:

(1) Spruce-pine-fir (SPF) lamina, with a cross section of 40 mm × 140 mm (nominal 2″ × 6″), No. 2 and better grade according to Canadian National Lumber Grades Authority (NLGA) were used to construct NLT panels. Moisture content of each NLT specimen was measured using a moistures meter before testing, and the average value was 9.5%, with a coefficient of variation (CoV) of 10.6%. The density of SPF was evaluated after the test according to American code ASTM D143-22, and the average value was 462 kg/m^3, with a CoV of 5.4%.

(2) OSB with a thickness of 12 mm (APA rated 15/32) were used as sheathing material above the NLT.

(3) 3.3 mm × 83 mm smooth shank strip nails were used to construct NLT and to fasten OSB sheathing to the NLT panel. The tested yield strength according to American standard ASTM F1575-21 is 851 MPa with a CoV of 4.6%.

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2.3 TEST SETUP AND LOADING PROTOCAL

Figure 2 illustrated the test set-up. In a practical application, both ends of NLT floor is usually connected to the supporting steel or timber beam using self-tapping screws (STSs). In this test, to represent its real-life boundary condition, the NLT floor specimens was securely connected to the top-and-bottom steel beams using STSs. A load distribution beam was used to apply loading force to the trisection point of specimen. The load distribution beam was then connected to a hydraulic actuator with 300 kN capacity and a stroke length of ±250 mm.

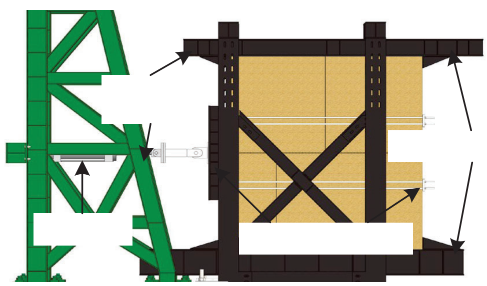


Figure 2: *Test set-up*

The cyclic loading protocol was established according to the CUREE method described in American standard ASTM E2126-19. The reference deformation Δ is determined as 70 mm by conducting a preliminary numerical analysis. The cyclic loading pattern is shown in Figure 3.

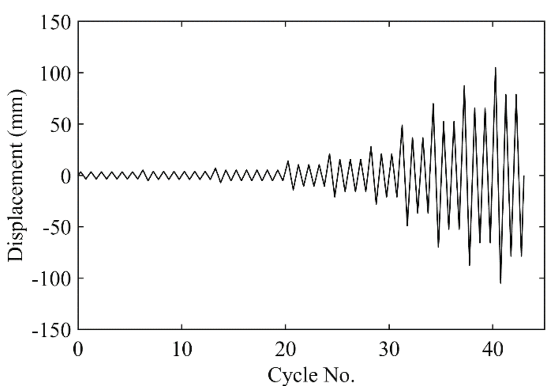


Figure 3: *Cyclic loading pattern.*

A total of 22 linear variable differential transformers (LVDTs) were attached to the specimen to acquire necessary displacement. As shown in Figure 4, LVDT 1-14 were evenly placed at the loading edges to acquire lateral deformation, LVDT 15-18 were placed at the trisection point of a loading edge to acquire shear deformation, and LVDT 19-22 were placed at the corners to acquire rotational deformation.

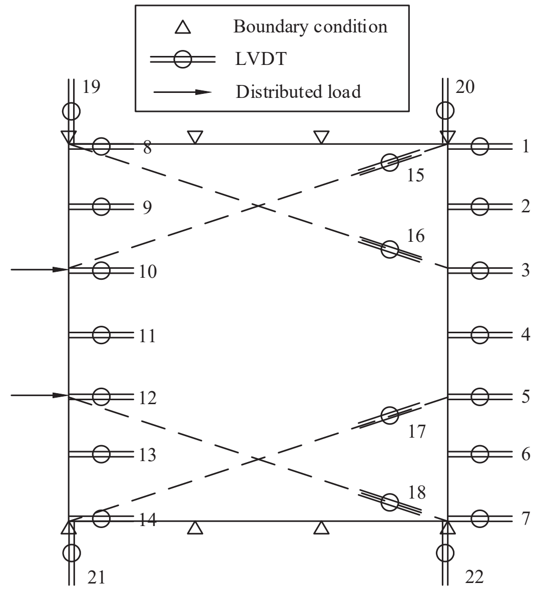
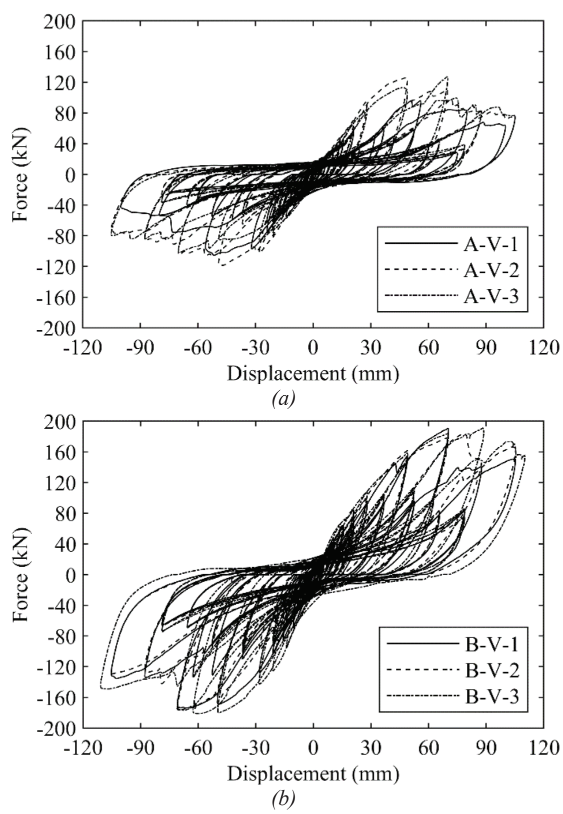


Figure 4: *Layout of LVDTs.*

3 RESULTS AND DISCUSSIONS

3.1 LOADING CURVES



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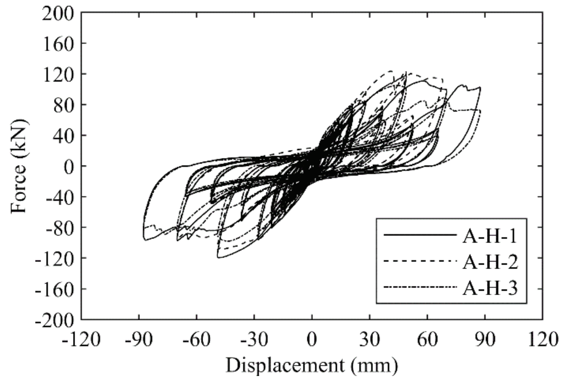


(c)

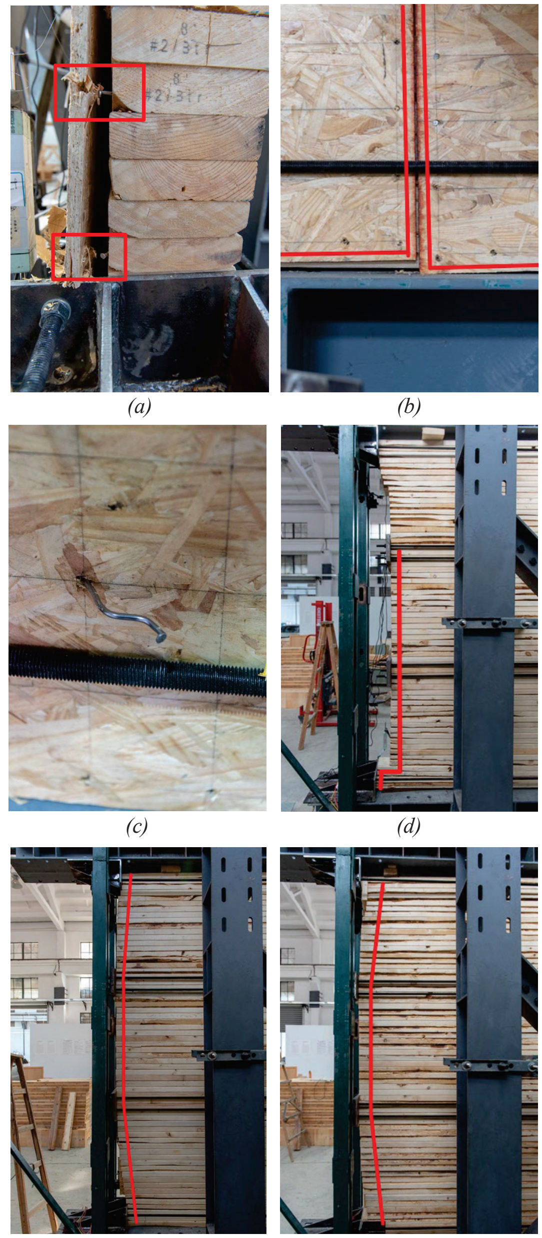
Figure 5: *Hysteresis loops of (a) group A-H, (b) group B-V, and (c) group A-V.*

Using the applied force from actuator as the force, and the average value of midspan displacement (LVDT 4/11) as the displacement, the force-displacement curves of tested specimens are shown in Figure 5. From the hysteresis loops, all specimens showed similar strength/stiffness degradation and pinching effect, due to the damage accumulation of nail connections, both in-between laminas and between lamina and OSB.

3.2 FAILURE MODES

The main failure modes observed were similar in all groups of specimens. During the loading process, sheathing nail embedment failure at the corners of sheathing panel (Figure 6(a)) was first noticed around cycle No. 20. Dislocation of adjacent sheathing panel (Figure 6(b)) was also observed at the peak of each cycle thereafter. As the loading displacement increases, beginning from roughly cycle No. 32, most sheathing nails were either embedded or withdrawn (Figure 6(c)). Finally, at around cycle No. 40, the failure of nail connection in-between laminas occurred (Figure 6(d)) and the floor lost its most capacity.

It's worth to mention that though all specimens showed the similar failure pattern, the difference of sheathing nail spacing did have impact on the deformation pattern of the floor. For the relatively larger nail spacing, which is an edge spacing of 150 mm and a centre spacing of 300 mm, the floor exhibited mostly shear deformation, as shown in Figure 6(e). While for the relatively smaller nail spacing, which is an edge spacing of 75 mm and a centre spacing of 150 mm, the floor exhibited a shear and flexural combined deformation, as shown in Figure 6(f). This difference is mainly due to that the tighten sheathing nail spacing enables the sheathing to coordinate the deformation of laminas. This thereafter led to the floor deformation pattern transform from shear controlled to shear and flexural combined.



(a) *(b)* *(c)* *(d)* *(e)* *(f)*

Figure 6: *Failure modes of (a) sheathing nail embedment, (b) sheathing dislocation, (c) sheathing nail withdraw, (d) lamina nail failure, (e) floor shear and flexural combined deformation of relatively larger sheathing nail spacing (group A-V), and (f) floor shear deformation of relatively smaller sheathing nail spacing (group B-V).*

3.3 PERFORMANCE CHARACTERISTICS

Based on the averaged envelope curve of each group obtained from the test, equivalent energy elastic-plastic (EEEP) curve was calculated according to American standard ASTM E2126-19. The following performance characteristics were extracted from EEEP curve:

(1) Elastic shear stiffness k_e=0.4P_{peak}/Δ_e, where P_{peak} is the maximum load in the envelope curve, and Δ_e is the displacement at 0.4P_{peak}.

(2) Yielding load P_{yield} and yielding displacement Δ_{yield}, in which the enclosure area under EEEP curve equals to the one under envelope curve.
(3) Ductility ratio $D=\Delta_u/\Delta_{yield}$, where Δ_u is the displacement at ultimate load.
(4) Shear strength $R_d=P_{yield}/2B$, where B is the width of the floor.

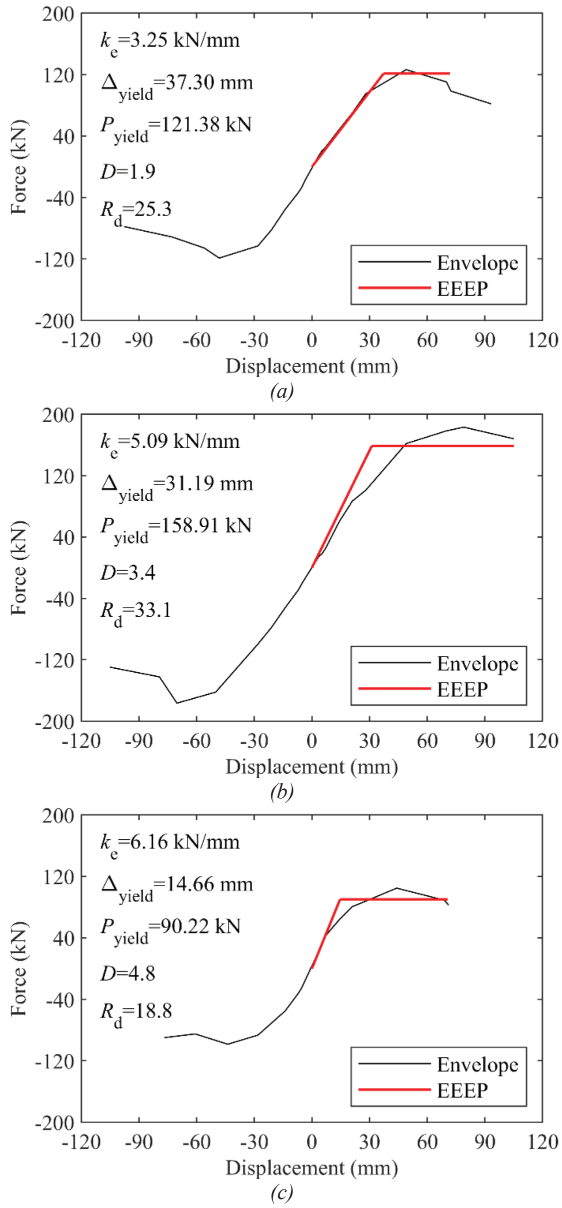


Figure 7: *EEEP analysis result of (a) group A-V, (b) group B-V, and (c) group A-H.*

Figure 7 shows the EEEP results of the three tested groups. In-between the tested groups, the EEEP analysis results indicate that reducing sheathing nail spacing by 50% could increase elastic shear stiffness, ductility ratio, and shear strength of the NLT floor by 56.6%, 78.9% and 30.8%, respectively. And by switching the OSB fibre orientation from aligning lamina axis to perpendicular, the elastic shear stiffness and ductility ratio increased by 89.5% and 152.6%, respectively, with no significant change on shear strength.

Similar to the discussion on the different floor deformation pattern, the EEEP analysis result also confirmed that the tighten sheathing nail spacing brought significant higher elastic shear stiffness, thereafter, led to a shear and flexural combined deformation patter.

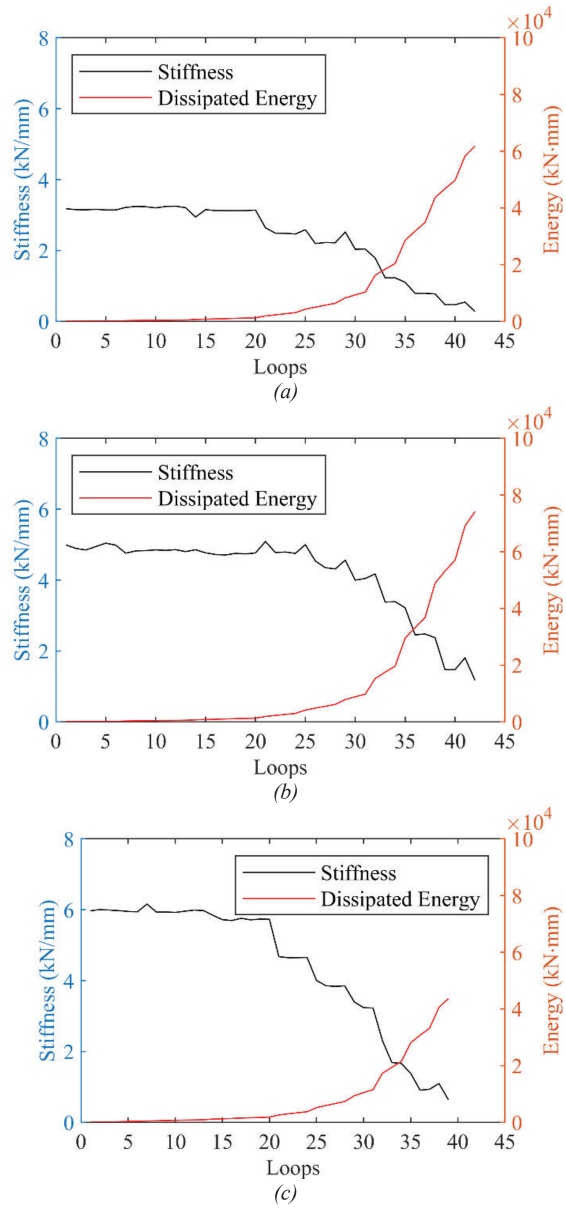


Figure 8: *Secant stiffness and cumulative dissipated energy per hysteresis loop of (a) group A-V, (b) group B-V, and (c) group A-H.*

Furthermore, the secant stiffness, calculated according to Chinese standard JGJ/T 101-2015, and cumulative dissipated energy was extracted from each hysteresis loop and shown in Figure 8. It can be noticed that the floors are basically linear elastic before cycle No. 20. Both reducing sheathing nail spacing and arranging OSB fibre

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perpendicular to lamina axis can increase initial elastic shear stiffness significantly. Moreover, the energy dissipation capacity is mainly controlled by sheathing nail spacing, or rather the quantity of nail connections, since the energy dissipation is mostly contributed by the embedment and/or the withdrawn of nail connections, both in-between laminas and between lamina and OSB sheathing.

4 CONCLUSIONS

This paper presents an experimental investigation on the in-plane performance of NLT floor. Failure modes were observed, and performance characteristics were obtained.

(1) For failure modes, sheathing nail spacing and OSB fibre orientation didn't change the failure pattern, which is from the failure of sheathing nail connections to the failure of lamina nail connections.

(2) The sheathing nail spacing did have impact on the floor deformation pattern. That is, tightening sheathing nail spacing transforms the deformation pattern of NLT floor from shear controlled to shear and flexural combined.

(3) Placing OSB fibre perpendicular to lamina axis could induce a stiffness and ductility increasement of 89.5% and 152.6%, respectively, compared to parallel to lamina axis. Elastic shear stiffness could also be further improved by reducing sheathing nail spacing.

(4) The energy dissipation capacity is mainly controlled by the sheathing nail spacing, or rather the quantity of nail connections.

In conclusion, in design of a NLT floor, in order to obtain an optimal performance, the results indicate that the sheathing nail spacing and sheathing material orientation should be carefully decided. Nevertheless, a more detailed and parametrical numerical analysis could be carried out to determine an optimal sheathing nail arrangement, and to provide a detailed design method.

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