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AN IMPROVED FASTENING DESIGN FOR FASTENER-LAMINATED TIMBER BRIDGE DECKS

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Abstract: This study was aimed at developing a more suitable type of fastener-laminated timber bridge decks that could obtain higher stiffness and longer life span without decreasing the load capacity. This could be reached in terms of developing an improved fastening design(s) by considering the parameters such as fastener type, fastener dimensions, and fastening design. In this study, the parameters taken into account included two fastener types (i.e. nails and screws), two diameters of nails (4.68mm and 7.24mm), one diameter of screws (5.80mm), and two fastening directions (i.e. perpendicular and 45-degree to the loading direction). The double-shear-fastener tests were designed and conducted via a universal electromechanical testing machine with reference to ASTM Standard. The stiffness, peak load, and energy dissipation of each fastening design were calculated and analyzed. It was found that use of screws could obtain lower stiffness, higher peak load and higher energy dissipation than that of nails. As a result, the 45-degree fastening arrangement of "zinc coat partial" screws was recommended due to its relatively large stiffness, peak load, and energy dissipation values of the connections made of them.

Keywords: Bridge deck; fastener-laminated timber; fastening design; double-shear-nail test; stiffness; peak load; energy dissipation

1 INTRODUCTION

Bridges with timber decks are commonly used in low-traffic volume areas in New Brunswick, Canada, because of many advantages over the conventional form-in-place concrete bridge. These advantages include shorter construction time period, higher prefabrication degree, lower cost, lower equipment requirement due to lower dead weight of structural components as compared to steel or concrete elements, and environment friendly utilization of readily available natural source (Ontario Highway Engineering Division, 1983). Timber bridge decks are in great demand in New Brunswick, Canada. According to the report published by New Brunswick's Department of Transportation Institute (NBDTI), there are 32 types of different bridge substructures supporting more than 700 bridges with timber decks in the province. The timber bridge decks currently used in New Brunswick are mainly made of nail-laminated timber (NLT), which refers to the timber deck with laminations nailed together perpendicular or parallel to the direction of the traffic flow. Based on DTI's experience, with its current nailing method, the NLT decks that are fabricated in New Brunswick have to be replaced every 10-15 years. Obviously, it is a costly practice for maintenance and replacement considering the number of bridges with timber decks as well as their current service life span.

The design of NLT decks in Canada largely follows the standard CAN/CSA-S6 “Canadian Highway Bridge Design Code and Ontario Highway Bridge Design Code” (Ontario Highway Engineering Division, 1983). The fasteners used follow the standard CSA B111 “Wire nails, Spikes and Staples” (CSA, 2003), and the sawn lumber species follows the standard CSA O141 “Softwood Lumber” (CSA, 2014). However, in CAN/CSA-S6, NLT is described as an empirical product, i.e., the relevant information is very limited, even in the standard level for the design of NLT. For example, the NLT design method adopted by NBDTI is described as follows: lumber in size 2x7 (38mm thick and 160mm wide); fastening each lamination to the preceding one at interval not exceeding 250mm; driving nails alternately near the top and bottom edge; at least one nail placed within 100mm to 125mm from the end of each lamination; and the nails being long enough to pass through two laminates and at least halfway through the third.

Screws provide higher strength and friction between lumbers because the screw threads pull the lumbers together more than nails. Bejtka and Blaß (Bejtka and Blaß, 2006) used screws as reinforcements in wooden beams, discovering that the load-carry capacity of self-tapping screws reinforced beam was at maximum 300% higher than the load-carrying capacity of non-reinforced beam, and the maximum ratio between the stiffness perpendicular to the grain of self-tapping screws reinforced beam and the corresponding stiffness of non-reinforced beam was about 5. Crocetti et al. (Crocetti et al., 2010) studied the load-displacement behavior of double-shear loaded single dowel joints reinforced with self-tapping screws under monotonic loading. The research indicated that scatter in test results was considerably reduced when reinforcing screws were used, and the reinforcing screws prevented the joint to fail due to premature splitting. Further, the reinforced specimens exhibited a very ductile load-displacement behavior. After the first drop in the load-displacement curve occurred, the joints still showed a significant reserve of load-carrying capacity.

Widmann (Widmann, 2001) studied use of screw laminated timber deck with screw arrangement at angles and found it could overcome the drawback of NLT decks as lacking load distributing efficiency. His concluded that screw laminated slab obtained a higher stiffness than nail laminated slab, but a lower stiffness than glue and stress laminated slab. Data from specimens without interface friction (by introducing a gap between laminations) showed the 45 degree fastening direction produced a peak shear load that was three times larger than the parallel fastening one (the direction perpendicular to the loading direction of slab). Advantages of this specially arranged screw laminated timber bridge deck included relatively high mechanical performance, and a semi-automated mean of installation for there was no need for predrilling.

.The objective of this study was to develop an improved fastening design for fabricating NLT decks that could provide better structural performance and longer service life. This paper was mainly emphasized on discussion on the proposed fastening designs in terms of stiffness, peak load, and energy dissipation.

2 MATERIALS AND METHODS

2.1 Materials and Specimens

The wood materials used in this study were 2" x 8" (38mm x 184mm) SPF lumber of No. 1 J grade, which were organized into three groups in terms of density, i.e. low-density group, middle-density group and high-density group. The average density and moisture content of the lumber are given in Table 1. Fasteners used included two types of nails (i.e. galvanized spiral nail in size 60d and 80d), and three types of screws (i.e. zinc coat partial threaded self-tapping screw, zinc coat fully threaded self-tapping screw, and stainless-steel partial threaded self-tapping screw). Additional specification and detailed information of the fasteners are provided in Table 2 and Figure 1.

Table 1: Average density (kg/m^3) and moisture content (%) of the lumber used

	Low	Middle	High
Density	427 (3)	452 (2)	472 (3)

MC	13.7 (10)	13.3 (6)	14.5 (10)

Note: the values in parentheses are CoV (%).

Table 2: Detailed information for fasteners used in tests (unit: mm)

Fastener Type	Brand	Name	Thread Diameter (d_{thread})	Shank Diameter (d_{shank})	Fastener Length (L)	Thread Length (L_{thread})
Galvanized Spiral Nail	Paulin	60d	-	4.68	152	-
		80d	-	7.24	203	-
Self-tapping Screw	SWG GmbH	Zinc coat partial	8	5.80	160	80
		Zinc coat fully	8	5.80	160	143
		Stainless-steel partial	8	5.80	160	80

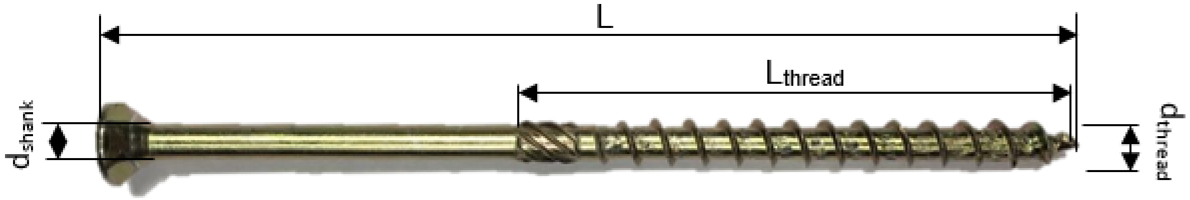

Figure 1: Zinc coat partial threaded self-tapping screw

Each specimen was fabricated with three lumber members and four fasteners of each type. The dimensions and fastening arrangement of an assembly as well as the detailed fastener configuration are given in Figure 2. Table 3 provides the details regarding the specimen, say fastener type and fastening direction. The replicates of each type were nine (9), among which 3 were made of low-density lumber, 3 of middle-density lumber, and 3 of high-density lumber.

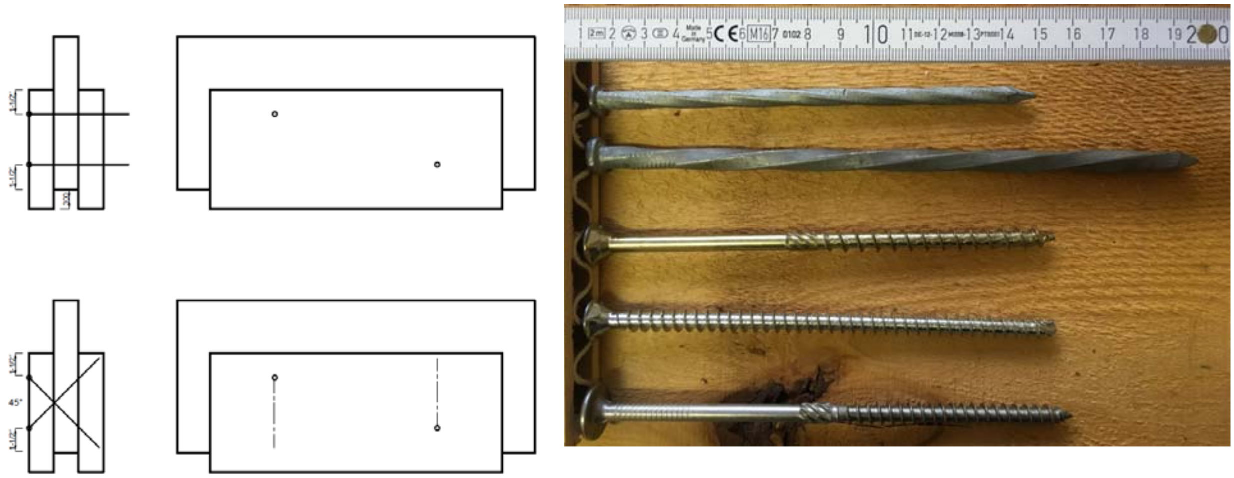

Figure 2: Assembly configurations of double-shear-nail specimen

Table 3: Double-shear-nail specimen test program

Test Group	Fastener	Fastening Direction
NP6	60d	Parallel
NI6	60d	45-degree
NP8	80d	Parallel
SZPP	Zinc Coat Partial	Parallel
SZIP	Zinc Coat Partial	45-degree
SZPF	Zinc Coat Fully	Parallel
SZIF	Zinc Coat Fully	45-degree
SSPP	Stainless-Steel Partial	Parallel
SSIP	Stainless-Steel Partial	45-degree

3 TESTING METHOD

The double-shear-nail tests were carried out on a universal electromechanical testing machine with reference to ASTM D1761 “Standard Test Methods for Mechanical Fasteners in Wood” (ASTM 2012). A specimen was loaded monotonically on the middle lumber member while the other two side members were seated on two bottom steel bars. Two LVDTs were mounted on the two side lumber members. See Figure 3 and 4. The loading rate was 2.54mm/min. A test was completed after the load passed the peak value and was reduced to 80% of the peak load or severe damage appeared. The load, crosshead movement, relative movement between the side and middle members (that recorded through two LVDTs) and elapsed time were recorded using a data logger at a frequency of 2.0 Hz.

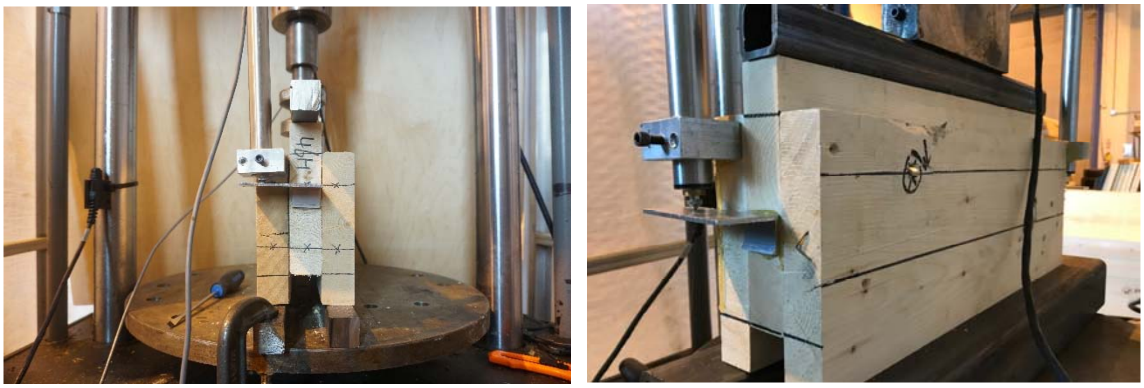

Figure 3: Double-shear-nail test setup

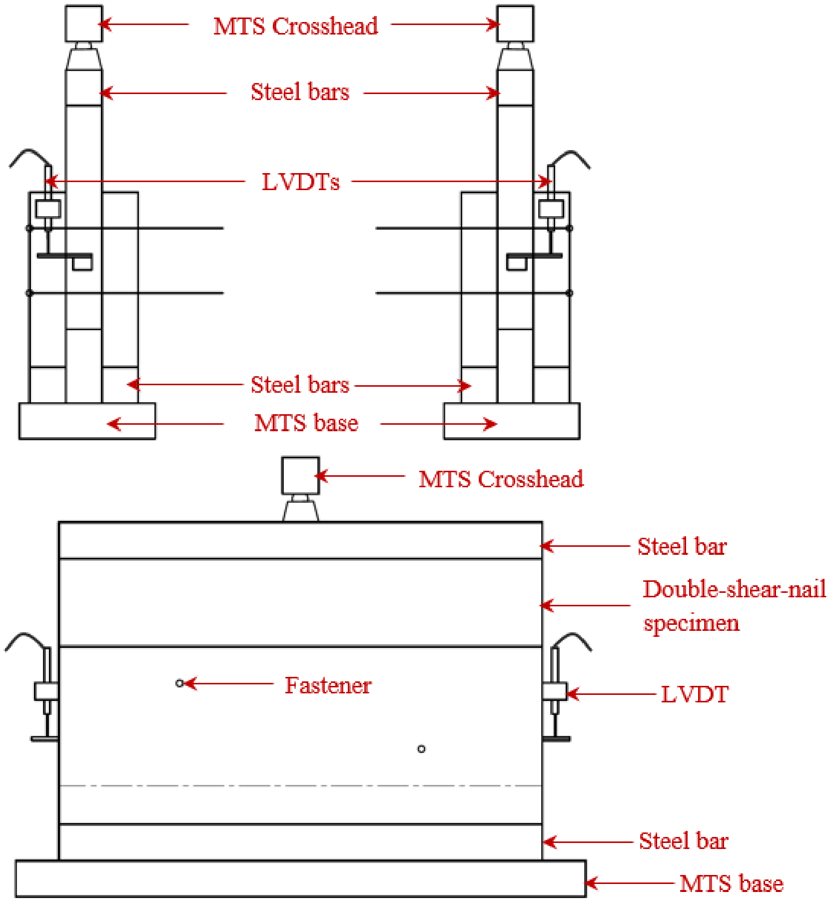

Figure 4: Apparatus for double-shear-nail test (Top: side views, and bottom: face view)

3.1 Calculation of mechanical **parameters**

Figure 5 illustrates the derivation of the mechanical parameters from the results, which include the initial stiffness per fastener (K), peak load and displacement (F_{peak}, Δ_{peak}), failure load and displacement ($F_{failure}$, $\Delta_{failure}$), yield load and displacement (F_{yield}, Δ_{yield}), energy dissipation at peak load (W_{peak}) and at failure point ($W_{failure}$). The energy dissipation was calculated by obtaining the area under the load-displacement curve above X-axis between zero and the targeted value.

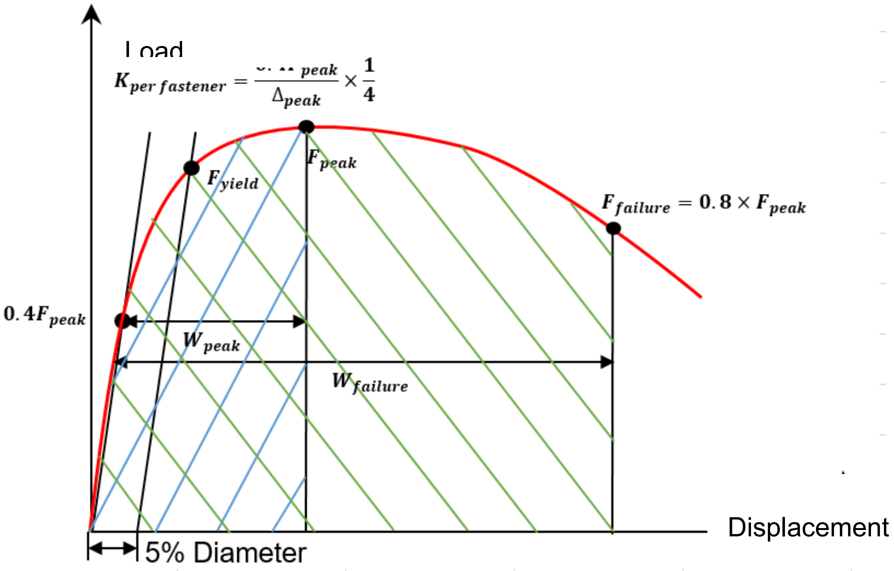

Figure 5: Definition of mechanical parameters used in this study

4 RESULTS AND DISCUSSION

4.1 Mechanical Responses

The average load-displacement curves of each type specimens are plotted in Figure 6, giving a total of 9 curves. Tables 4 summarizes the mechanical parameters.

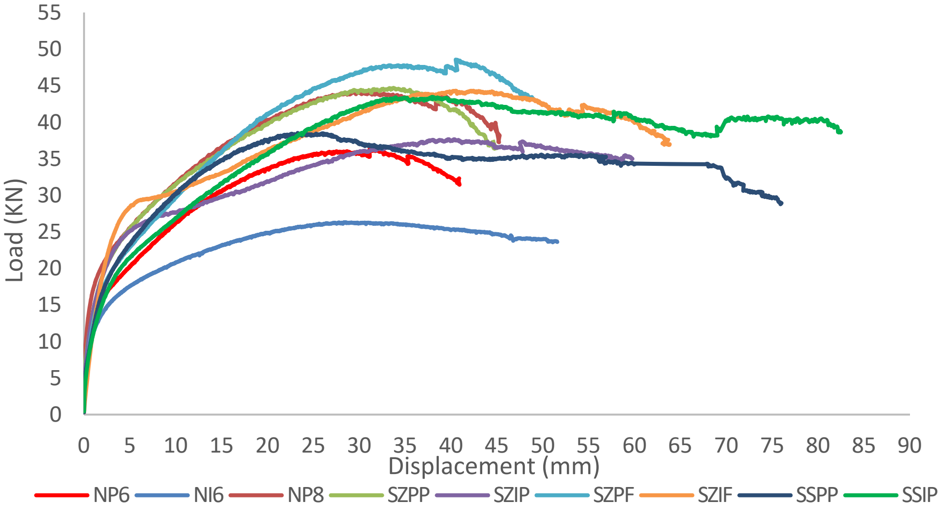

Figure 6: Load-displacement curves

Table 4: Stiffness, load properties and energy dissipation

Fastener Type	Test Group	Replicates	$K_{per\ fastener}$ (kN /mm)	F_{peak} (kN)	$F_{failure}$ (kN)	W_{peak} (kN·mm)	$W_{failure}$ (kN·mm)
Galvanized Spiral Nail	NP6	9	3.27(55)	36.77(11)	29.42(11)	794(15)	1219(14)
	NI6	9	3.60(41)	27.03(12)	21.50*(13)	720(13)	1229*(27)
	NP8	9	4.05(36)	45.14(9)	36.12(9)	1124(11)	1636(17)
Self-tapping Screw	SZPP	9	2.62(23)	45.54(10)	36.43(10)	1147(5)	1628(9)
	SZIP	9	3.29(30)	39.74(12)	31.59**(13)	1316(20)	1957**(24)
	SZPF	9	1.72(35)	49.09(8)	39.27(8)	1285(13)	1910(17)
	SZIF	8	2.68(29)	43.94(10)	35.29*(11)	1360(23)	2266*(28)
	SSPP	9	2.37(32)	43.72(11)	34.98(11)	1026(8)	2759(16)
	SSIP	8	1.61(28)	44.47(8)	29.34(28)	1354(31)	2420(32)

Note: the values in parentheses are CoV (%).

* $F_{failure}$ and $W_{failure}$ for test groups NI6 and SZIF were calculated based on 7 replicates.

** $F_{failure}$ and $W_{failure}$ for test groups SZIP were calculated based on 6 replicates.

4.2 Failure Modes

The failure of a specimen is defined as the load decreases to the 80% of the peak load recorded during the test or severe damage appeared on the specimen. The failure mechanisms could be categorized as three primary types: fastener withdraw, which occured in test group NP8 and SSPP (Figure 7(a) left and 7(b) right); wood splitting, with cracks propagation from the connection in the direction of parallel to the grain of lumber, which occurred mainly in test groups SZIP, SZIF, and SSIP (Figure 7(b) left); and fastener bending, for fasteners yielded in a “U” shape without plastic hinge (Figure 7(a) upper-right). The majority of specimens from test groups that were arranged with parallel fasteners appeared no or little damage to the wood.

(a) Nails (b) Screws

Figure 7: Failure modes of connections

4.3 Stiffness

The average stiffness of each joint (including fastener type, diameter and fastening arrangement) is plotted in Figure 8. Compared to NP6, the stiffness values of groups NI6 and NP8 were increased by 10% and 24%, which illustrates the 45-degree fastening arrangement of larger diameter fasteners could improve the stiffness. However, as shown in Figure 6, the load-displacement curves of groups NP6 and NP8 exhibited similar initial ascending portions, which might indicate that nail diameter had a proportionality effect on the initial stiffness of the nail. Compared to NP6, the stiffness of those groups made with screws, except for group SZIP, obtained lower stiffness values. Within the groups made by screws, Zinc Coat Partial (SZIP) appeared to exhibit better performance in terms of stiffness. Elsewise, with the same fastener, 45-degree fastening tended to have higher stiffness than that of parallel fastening except for SSIP. Compared to parallel fastening, the stiffness of 45-degree fastening increased by 10%, 21%, 23% for groups NI6, SZIP, and SZIF, and decreased by 22% for group SSIP.

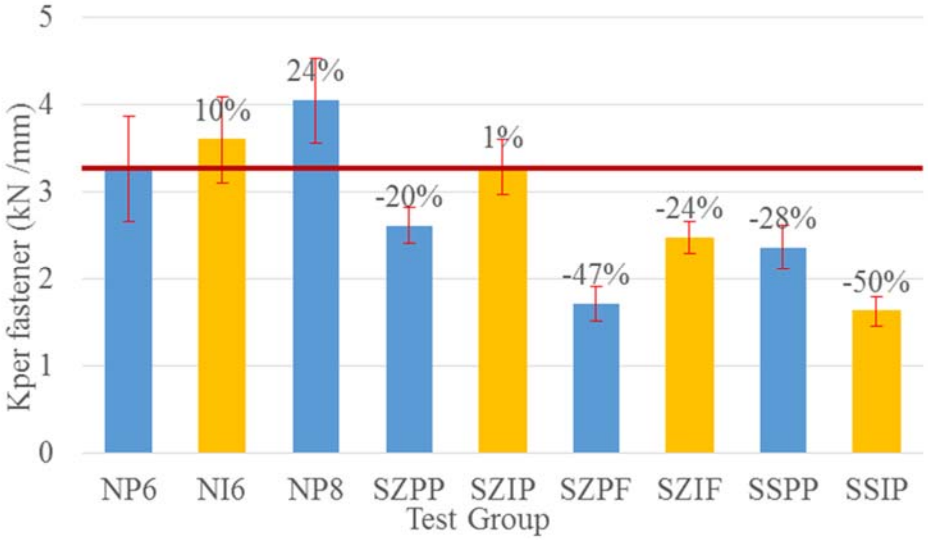

Figure 8: The means and standard errors of initial stiffness ($K_{\text{per fastener}}$) of 9 groups tested

(The values in parentheses stand for the standard error)

4.4 Peak Load

As shown in Figure 9, it can be found the peak load of group NI6 decreased by 26% compared to that of group NP6. Similarly, the peak load of groups SZIP and SZIF were 16% and 12% lower than that of groups SZPP and SZPF, respectively. This suggests the 45-degree fastening arrangement received lower peak load than that of parallel fastening except for group SSIP, with its peak load increased by 2% compared to group SSPP. The load-displacement curves in Figure 6 exhibited similar ascending portions for groups NP6 and NP8, which illustrates that nail diameter had a proportionality effect on the peak load. In summary, screws performed better in terms of peak load capacity, among which Zinc Coat Fully (SZPF) appeared with the highest peak load, for it was increased by 34% compared to group NP6.

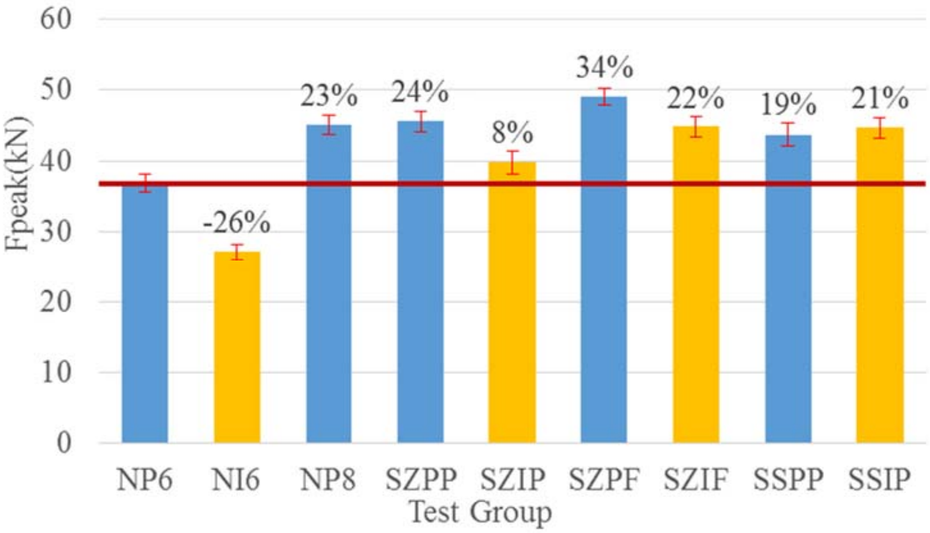

Figure 9: The means and standard errors of peak load (F_{peak}) of 9 groups tested

(The values in parentheses stand for the standard error)

4.5 Energy Dissipation

Figure 10 summarizes the energy dissipation capacities at the failure point for 9 test groups. It demonstrated that groups NP6 and NI6 had the same energy dissipation value as well as the similar standard error, which might indicate that parallel fastening and 45-degree fastening had the same effect on the laminated assembly with Galvanized Spiral Nail 60d. Compared groups NP8 and NP6, with larger nail diameter a proportionality relationship can be seen. In general, the specimens fastened by screws obtained higher energy dissipation capacities than that fastened by nails. Within the screw groups, the energy dissipation of groups SZIP and SZIF increased by 31% and 50%, respectively, compared to groups SZPP and SZPF while the energy dissipation of group SSIP decreased by 12% compared to group SSPP. Stainless-steel Partial (SSPP) tended to have the greatest performance with 126% increase in energy dissipation.

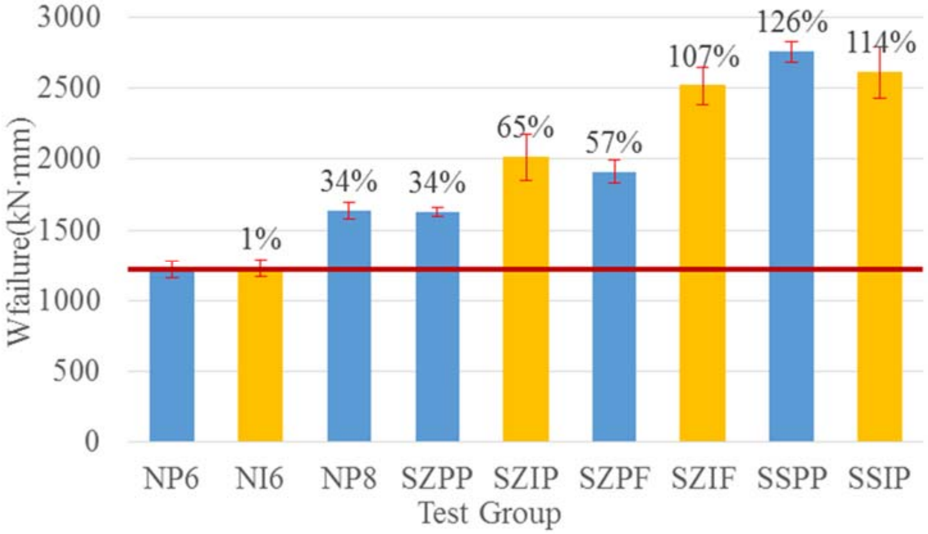

Figure 10: The means and standard errors of energy dissipation ($W_{failure}$) of 9 groups tested

(The values in parentheses stand for the standard error)

5 CONCLUSIONS

Based on the above results and discussion, the following conclusions could be drawn:

- The screwed lumber connections obtained lower stiffness, higher peak load and higher energy dissipation than nailed lumber ones did;
- Increase of the nail diameter provided a proportional increase in stiffness and peak load of the connections, but not in energy dissipation; and
- The 45-degree fastening arrangement of screw “zinc coat partial” is recommended due to its relatively large stiffness, peak load, and energy dissipation.

Further research has been planned to investigate the long-term performance of the full-scale laminated timber bridge decks under fatigue load with the fastener design proposed in this study.

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