Effect of Butt Joints on Flexural Properties of Nail Laminated Timber

by

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ABSTRACT

Nail laminated timber (NLT) is manufactured using dimension lumber laminations, stacked on edges, and fastened with nails, to create large flat structural components that are widely used for constructing timber bridge decks in North America. Butt joints usually exist due to the length limits of lumber, leading to concerns about the decrease of structural performance of NLT. This project was undergone to understand the impact of butt joints on flexural properties of NLT and investigate the methods for reinforcing the NLT containing butt joints. To reach this goal, four-point bending tests were performed on 7 types of 3-layer NLT specimens, 1 without butt joints as reference, 3 with butt joints and 3 with butt joints reinforced with nails. It was found that the effective stiffness (EI_{eff}) and load capacity (P_{peak}) of 3-layer NLT specimens with butt joints, in comparison to those without butt joints, could be reduced up to 64% and 71%, respectively. The reduction in EI_{eff} of NLT specimens with a certain 1-in-3 frequency pattern of butt joints was found to be 34%, which proved the applicability of the stiffness reduction factor in current CSA S6 standards. It was found that the nailing reinforcement was an effective approach to recover the EI_{eff} and P_{peak} of NLT specimens with a certain 1-in-3 frequency pattern of butt joints by 21% and 38%, respectively. This approach could be used to make NLT with butt joints, but more research is required.

Keywords: Effective stiffness, Load capacity, Nail laminated timber, Nailing reinforcement

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List of Symbols, Nomenclature or Abbreviations

American Society for Testing and Materials	ASTM
Canadian Highway Bridge Design Code	CHBDC
Canadian Standards Association	CSA
Canadian Wood Council	CWC
Coefficient of Variation	COV
Effective Stiffness	EI_{eff}
Linear Variable Differential Transformer	LVDT
Load Capacity (Peak Load)	P_{peak}
Material Testing System	MTS
Modulus of Elasticity	MOE
Moisture Content	MC
Nail-Laminated Timber	NLT
Ontario Highway Bridge Design Code	OHBDC
Spruce-Pine-Fir	SPF
Standard Deviation	S.D.
Stiffness of Lumber	EI
Wood Science and Technology Centre	WSTC

1. Introduction

1.1. Background

Timber and wood products have been used for constructing bridges and buildings for centuries. The origin of timber bridges can be traced back to sixteenth century Europe, when the modern-day bridge structures, which we are familiar with today, have yet to be developed. Figure 1 gives a sign of the way that people crossed the river by a log laid across the water, roads or valleys. A considerable span of log was required.

Figure 1 A log laid across river

Photographed by T.P. Curry in 1902, Retrieved from http://kdl.kyvl.org/catalog/xt71jw86jv7b_57_1

There are three general categories of timber bridges based on superstructure types: Beam Type, Arch Type and Suspension Type. According to Wanrong's information collecting result from 2017, there were 403 steel bridges containing timber decks in New Brunswick (Zhu, 2017). All of them can be classified as beam bridges. The most representative type of timber bridges in New Brunswick are covered bridges. Among them, the Hartland

Covered Bridge (see Figure 2) is famous for being the world's longest covered bridge. Crossing the Saint John River from Hartland to Somerville, it has been more of a Canadian artefact than primarily a traffic bridge. The covered roof is a typical mechanism to protect timber bridge from everyday humidity and climate extremes without extra treatment.

Figure 2 Hartland Covered Bridge

After the Industrial Revolution, the wood’s dominant place in bridge building materials was gradually replaced by steel and concrete. This helps explain that, in North America, the development of timber bridges was stagnated from the second half of the nineteenth century onwards. Steel and concrete have economic feasibility and high strength properties especially in long span bridges. Although these industrial materials are still the major building materials for large-scale bridges, the usage of timber in the superstructure of bridges can never be underestimated.

Since the 1970s, there has been a “renaissance" of wood as a building material for bridges (especially decks) in Europe (Crocetti, 2014). Numerous research programs and related topics have been implemented and published, cooperating with various universities, local government agencies, and industries in North America (Duwadi & Ritter, 1995). Topics implemented include System Development and Design, Lumber Design Properties, and Preservatives, etc. The findings contributed to the revise of the American Association of State Highway and Transportation Officials (AASHTO) standard and instructed the latter study on timber bridge decks.

Nowadays, the design of timber highway bridges has generally been completed. As such, EN 1995-1-2 Eurocode 5, Design of Timber Structures, Part 2: Bridges (CEN Europen Commitee for Standardization, 2004) and the AASHTO-LRFD Bridge Design (AASHTO, 2007) Specifications are the timber bridge building codes for Europe and the U.S. respectively. In Canada, the Canadian Highway Bridge Design Code (CHBDC) CAN/CSA S6-06 (Canadian Standards Association, 2010), whose predecessor is Ontario Highway Bridge Design Code (Ministry of Transportation of Ontario, 1991), and its companion code, Commentary on CAN/CSA-S6-06 (Canadian Standards Association, 2006), are used as authoritative standards. Other publications by Canadian Wood Council (CWC) also provide references and instructions for bridge engineers and architects. A comparative analysis of design codes for timber bridges in these three regions: Europe, the US, and Canada, was conducted (Wacker & Groenier, 2010).

In timber highway bridges construction, nailing is the most basic and simply used method to attach wood members together to form an entire deck. Those bridge decks are collectively called Nail Laminated Timber (NLT) Bridge Decks. NLT Bridge Decks consist of a series of graded dimension lumber laminations placed on edge and nailed together on their wide faces (J.Taylor & J.Keenan, 1992).

Presently, NLT technology is being acknowledged not only in application for timber bridge decks but also in other massive timber constructions. Some characteristic constructions to promote building with NLT technology was summarized (Natterer, 2002). In massive timber constructions, the possibility of using NLT in posts, beams, and joists along with the floors, walls and roofs are being developed. The structures consisting NLT floor elements are specially known as "mill construction" (Gong, 2019). The reasons for choosing NLT are as follows: it is well suited to onsite fabrication; it is capable because of the nails of absorbing energy damping vibrations caused by transient or sustained dynamic force (e.g., bridge wheel loads and reciprocating industrial equipment); and it has good fire performance. Disadvantages of NLT include that it is not particularly mechanically efficient if NLT elements are required to have high rigidity when loaded in-plane or as flexural elements, also there have been durability issues associated with bridge applications particularly. The disadvantages stem from the flexibility of nailed interconnections between laminations, and proneness to gaps to form at those interconnections (e.g., due to moisture movements in the laminations) (Gong, 2019).

1.2. Problem Statement

NLT bridge decks, a relatively traditional construction system, mainly depends on labourers' experiences. Its inherent drawbacks such as loose nails, butt joints, and delamination partially leads to a shorter life span. Moreever, research on NLT and NLT bridge decks were limited, causing a research gap to merge since the late 1990s. Till now, the CHBDC CAN/CSA S6-06 standard (abbreviated as CSA S6 in this report) does not provide complete design information for NLT bridge decks, in which several designs and construction guides also need extra complements:

1) A stiffness reduction factor, k, to modify the effect of butt joints on stiffness is given in the current CSA S6 standard, that seems to be conservative to some degree, resulting in a lower-than- ‘real’ stiffness value. It can be applied under any condition where the frequency of butt joints in a line or within a band of 1000 mm is at least 1-in-3. However, the placement of butt joints in a practical case can be different from that from arranged ‘theoretically’. The estimated reduction of stiffness may therefore be not acceptable.
2) Lack of agreed estimation on how butt joints negatively affect the strength capacity of NLT.
3) Lack of detailed reinforcing approaches for recovering the mechanical properties of NLT bridge decks with butt joints due to length restrictions, with limited supplies nowadays of long length lumber.
4) The assembly instructions for NLT bridge decks in CSA S6 standard are not adequately detailed (e.g. lack of specific nailing pattern). The information can be supplemented, referring other standards and building codes including CSA O86 standard (Canadian Standards Association, 2014), Wood Design Manual (Canadian Wood Council, 2017) as well as Nail-Laminated Timber Canadian Design &

Construction Guide (Binational Softwood Lumber Council and Forestry Innovation, 2017).

In fact, the NLT bridge deck system, with short fabrication durations and economic advantages, can perform better if they are efficiently designed. Research on the mechanical performance of NLT bridge decks with butt joints are needed to refine the CSA S6 standard.

1.3. Objectives and Scope of Research

The objectives of this research were as follows:

1) to determine how butt joints affect the flexural performance (effective stiffness EI_{eff} and load capacity P_{peak}) of NLT specimens with various patterns of butt joints;
2) to investigate the applicability of the stiffness reduction factor under various circumstances; and
3) to provide a feasible approach such as nailing reinforcement on butt joints, to neutralize the negative influences brought by the discontinuity of lumbers.

To reach the above objectives, a test program was developed at the Wood Science and Technology Centre (WSTC), University of New Brunswick, to systematically address the problems mentioned in Section 1.2. A total of 21 3-layer NLT specimens consisting of 7 types of configurations (one as reference, three having butt joints and three with additional nailing reinforcement) were fabricated and tested under four-point bending. The EI_{eff} and P_{peak} of these specimens were calculated and compared.

1.4. Organization of this thesis report

This thesis report consists of 5 major chapters:

Chapter 1 provides the background including historical track of timber bridges and application of NLT, along with a recognition of the origin of this thesis report project;

Chapter 2 reviews the literature related to NLT and NLT bridge decks;

Chapter 3 describes the entire procedure of four-point bending tests performed on 3-layer NLT specimens with different butt joint patterns and the approach used in data-processing;

Chapter 4 details the results of tests, compares the performance of NLT specimens with different butt joint patterns and discusses the potential explanation; and

Chapter 5 outlines a summary of the general conclusions and recommendations for future construction and research.

2. Literature Review

This chapter contains four sections. Section 2.1 provides a preliminary understanding of NLT bridge deck. Section 2.2 reviews various factors influencing EI_{eff} and P_{peak} of NLT members including number of laminations, nails arrangement, continuousness of the lamination, patterns of butt joints and, existence of outside butt joint reinforcement. Section 2.3 reviews the regulations on arrangement of butt joints in designing and constructing NLT bridge decks in current building code.

2.1. Nail-Laminated Timber Bridge Decks

Nailing is the most basic and simply used method to attach wood members in construction. Nails are manufactured in many lengths, diameters, styles, materials, finishes, and coatings, each designed for a specific purpose and application. Among those typical applications, wood deck assemblies are a historic one originating in early 19th century, when they were first used as floor elements. Those decks are collectively called Nail Laminated Timber (NLT) Decks. Then NLT decks were widely applied in bridge construction from the 1920's through the mid-1960's (Hong, 2017).

NLT Bridge Decks consist of a series of graded dimension lumber laminations placed on edge and nailed together on their wide faces. The thickness of lumber ranges from 38 to 89 mm, with depths between 89 and 286 mm and lengths up to 4.9 m. The lumber is normally No.2 grade (J.Taylor & J.Keenan, 1992). In-grade test results have shown that there is no strength difference between No.1 and No.2 grades of dimension lumber. The difference between them is in appearance, which is not usually of importance in bridge decks. So, the dimension lumber used in NLT bridge decks is usually supplied as a mixed grade called No.2 and Better. A good practice is to insert nails through two and a half laminations, normal to the surfaces of joined members, in a staggered row (Canadian Standards Association, 2014). It is designed to utilize the lateral load capacities of the nails. There is no extra treatment between adjacent laminations so the lateral transfer of bending moment and vertical shears between them are achieved through the nails.

There are three types of NLT bridge decks (See Figure 3): longitudinal NLT decks, transverse NLT decks and wood-concrete composite (WCC) decks, which can be considered as reinforced longitudinal NLT decks (J.Taylor & J.Keenan, 1992). In North America, most bridge decks from the 1920s through the mid-1960s were made of transverse NLT decks (laminations are oriented perpendicular to the direction of the traffic flow) with the exception of a few longitudinal NLT decks (the lumbers of decks are running parallel to the direction of traffic). NLT decks were suitable for low to medium volume bridges with short spans.

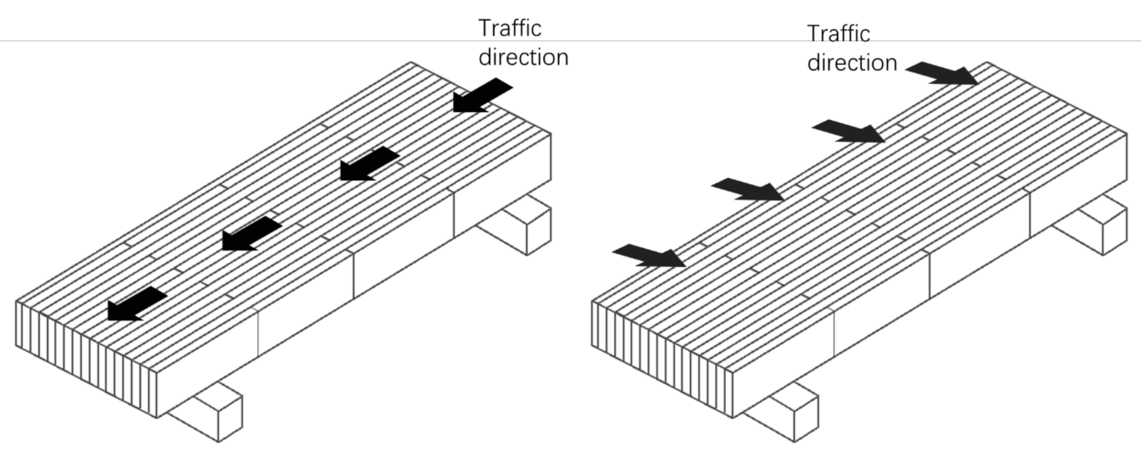


Figure 3 Longitudinal (left) and Transverse (right) NLT timber bridge deck

The simplest principle of NLT bridge decks is each transverse lamination nailed to the adjacent lamination, making the deck continuous across the bridge width (without intermediate supports). When testing specimens manufacturing, deck panels for transverse NLT bridges are designed as individual lumber beams of rectangular cross section. The bending, deflection, shear, and reactions distributed to each deck are assumed to be resisted by the entire deck cross section. In the mathematical analysis, NLT decks are modeled as orthotropic plates for decades (Bakht, 1988). The “orthotropic” means that the member has different stiffnesses in longitudinal and transverse directions. This allows the deck both to directly bear vehicular loads and to contribute to the bridge structure's overall load bearing behaviour. The deck may be integral with or supported on simple supports (Bakht, 1988).

Dimension lumber has limited lengths. As shown in Figure 4, use of short lumber pieces with end-to-end butt joints are a common and cost-effective practice for increasing the width of decks. The forces in a segment of a discontinuous lamination at a butt joint are transferred into the adjacent laminations through nails. The adjacent laminations carry the forces past the butt joint and shifts them back into the second segment of the discontinuous lamination.

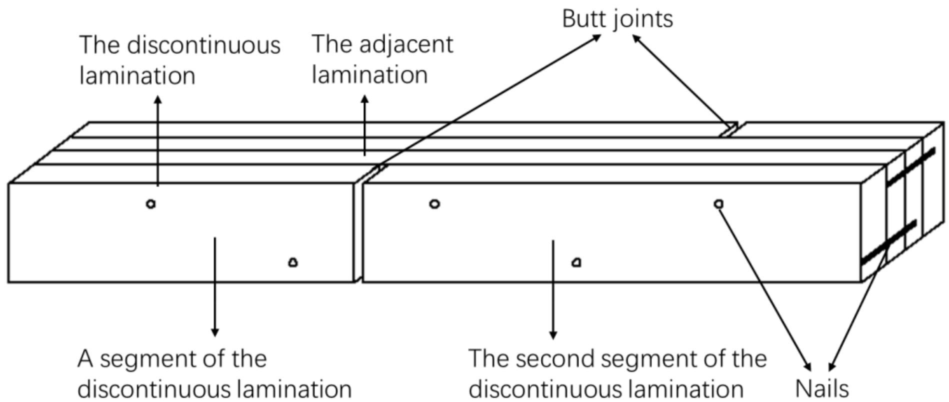


Figure 4 A portion of Nailed Laminated Timber deck with butt joints

2.2. Factors Influencing Flexural Properties of NLT Assemblies

There are various factors contributing to the flexural properties of NLT members. A complete model would account for variable factors, including lumber (species, grade, size), butt joints (number, location, spacing), fastener (type, density, pattern), and use (end conditions, position in structure, height).

2.2.1. Number of Lumber Layers

For NLT bending members, more layers of continuous lumber may allow somewhat greater bending stress than single members of the same size and quality. But they had similar mean stiffness. The reduced variability in strength and stiffness, brought about by load sharing effect of mixing of lumber, were highly acknowledged (D. Bohnhoff, 1988; Williams, Bohnhoff, & Moody, 1994; Wolfe & Moody, 1979). Similarly, for laminated timber decks without butt joints, the modulus E the modulus E equals to the average modulus of the lumber components (Taylor, Batchelor, & Van Dalen, 1983).

As for the research method for the laminated timber decks, researchers have always been using one complete pattern as representative of the deck to establish the bending stiffness of the wood assembly, and the response of a representative deck section can be modeled by orthotropic beam theory. However, both Sexsmith and Davalos found that a narrow deck section (that is, insufficient number of layers) may not be representative of the bending response of an actual bridge deck (Davalos, Kish, & Wolcott, 1993; Sexsmith, Boyle, Rovner, & Abbott, 1979). Davalos indicated 8-layer was not representative enough but 16-layer laminated timber showed a good result.

2.2.2. Arrangement of nails

Bohnhoff found that the most highly stressed nails are always located adjacent to a butt joint in an outer layer. This sometimes caused the failure of NLT. He also found that increasing nail density decreases maximum nail shear forces (D. Bohnhoff, 1989). The practice of properly adding more nails on butt joints (that is, without having an adverse effect on the ultimate strength of an assembly) was commonly applied in construction. Moreover, two nailing patterns were commonly used in construction: line pattern and staggered pattern (Binational Softwood Lumber Council and Forestry Innovation, 2017). Four-point bending tests were performed in dowel laminated timber (DLT) specimens with the two different nailing patterns in WSTC (Ogunrinde, 2019). It was suggested that the staggered fastening pattern outperformed the line pattern by increasing stiffness of DLT beams by approximately 5%.

2.2.3. Continuousness of the Lamination

It was proved that the solid-sawn bending members were significantly stronger than the discontinuous NLT bending members of similar size (Remund, Ghaseminia, Demarest, & Moore., 1982). The results bending tests on 4-layer NLT with or without butt joints showed that the reduction of strength and stiffness can be up to 60% and 75% respectively (Williams et al., 1994).

2.2.4. Patterns of Butt Joints

In fabrication of NLT, the random arrangement of butt joints should be avoided to prevent the existence of overconcentrated butt joints areas. Williams and others observed that the

NLT with shorter spacing of butt joints failed as the result of high shear force, but more NLT specimens with longer spacing of butt joints had failures related to wood bending. They also found that NLT with butt joints behaved stronger and stiffer when it had larger distance between butt joints in adjacent layers. They concluded that it could be attributed to the load transfer mechanism. NLT specimens with shorter spacing between butt joints in adjacent layers had to transfer load over a shorter distance (that is, with fewer nails), and consequently nail forces could be higher, so that maximum nail shear forces were reached before ultimate wood bending stresses were reached (Williams et al., 1994).

For NLT decks without butt joints, the modulus E is independent of the transverse pressure, and equal to the average modulus of the lumber laminations (Sexsmith et al., 1979). The bending stiffness of a laminated beam without joints is denoted by EI. For decks with butt joints, the adjustment factor, k, is used to calculate the reduced, or effective bending stiffness of laminated decks, written as

$$EI_{eff} = k(EI)$$

Equation 1

In which,

E = average modulus of elasticity; and

I = moment of inertia.

A table of butt-joint factors was proposed in the Design, Construction, Inspection and Maintenance Guide (Ritter, 1990). It was suggested that a 20% reduction for a 1-in-4 frequency, a 15% reduction for a 1-in-5 frequency and a 12% reduction for a 1-in-6 frequency. The 1-in-N frequency here means that butt-joint locations along a cross section of the deck is repeated every “N” lamination (see Figure 5).

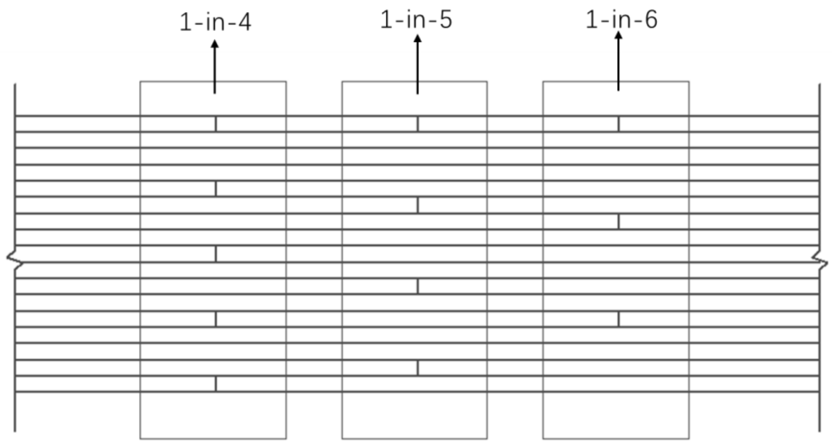


Figure 5 1-in-"N" frequency of butt joints

In the same year, a conservative expression for the reduction factor k was recommended in an unpublished paper (Jaeger & Bakht, 1990). The reduction in effective stiffness was $1 - k$.

$$k = \frac{N - 1}{N}$$

Equation 2

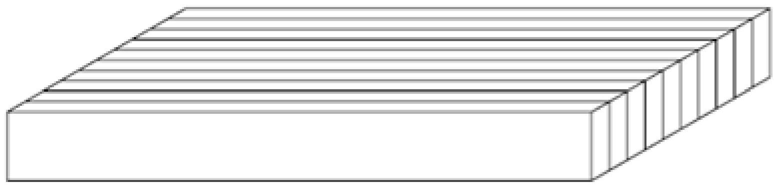
For example, applying three butt joint frequency shown in Figure 5 in equation 2, 25%, 20% and 17% reduction in stiffness for the 1-in-4, 1-in-5 and 1-in-6 frequency were calculated, respectively.

Davalos et al. did bending tests on 136 lumber laminations with nominal dimensions of 2 x 8’’ (3.81 x 19.05 cm) and found that the effect of butt joints (1 in 2, 1 in 4, 1 in 5) with regular patterns on bending stiffness of NLT decks well correlated to the butt joint reduction factor (Davalos et al., 1993).

Correspondingly, a more comprehensive study about the influence of butt joints along with its distribution on the bending stiffness was conducted (Haller & Pannke, 1998). The four-point bending test was performed with uniform load applied on the NLT decks. The test showed that regularly arranged butt joints reduced the bending stiffness by about 20%, with randomly or irregularly distributed joints behaving better. Additionally, it showed the poor distribution in transverse direction which could be improved by means of additional layers. By doing so, the entire element had more homogeneous structural properties.

In recent research in Europe, a Germany engineer put effort to deriving design equations for NLT deck system (Krämer, 2003, 2004). On the computer, he arranged four different butt joints patterns (see Table 1, from the top to bottom: Continuous, Alternative, Staggered, and Random), employed the simply supported beam theory, and simulated bending tests on those NLT deck elements more than 100 times each.

Table 1 n_{ef} basing on the four different patterns of butt joints proposed by Krämer (2003)

	$n_{ef} = 1$
	$n_{ef} = \frac{0.2}{\sqrt{\frac{l'}{l}}}$
	$n_{ef} = 0.29 \cdot (\frac{l}{h})^{0.15}$
	$n_{ef} = \frac{0.29 \cdot (\frac{l}{h})^{0.25}}{{a_1}^{1/9}}$

(Note: l = the span of NLT deck; l' = the location of the butt joints; a_1 = the nail spacing.)

He proposed the design equation for effective stiffness of the NLT deck:

$$EI_{eff} = E \cdot \frac{t \cdot h^3}{12} \cdot n_{ef}$$

Equation 3

In which, E = average modulus of elasticity; I = moment of inertia; t = thickness of laminations; h = height of laminations; and n_{ef} = effective numbers of laminations. Assuming the E as the mean value of the modulus of elasticity of lumbers, t and h are fixed, I is related to n_{ef}, the effective numbers of laminations. Krämer (2003) derived four equations for n_{ef} basing on the four different butt joints patterns as displayed in Table 1, for NLT deck under uniformly distributed load (load applied to span all laminations in the transverse direction). Although these design equations were claimed to demonstrate good agreement with test results, deeper researches are needed to validate them in the future.

In Europe, a general approach to the strength and stiffness reduction in laminated decks due to butt joints has been based on the reduction in the cross-sectional area at the position of the butt joints. Ekholm and Kliger (2014) held a different opinion that the reason for the variation in stiffness reduction of NLT could be attributed to the difference in actual cross-sectional reduction rather than the difference in the cross-sectional area reduction at the position of butt joints. Examples of elements 10 and 11 in their study are given in Figure 6, both having 1-in-4 butt joint configuration and 900 mm longitudinal butt joint spacing. The cross-sectional area at the position of the butt joints were decreased by 25% (1/4) in both conditions. However, at midspan, element 10 had 3 butt joints of 9 laminations and element 11 had 5 butt joints of 19 laminations. The actual cross-sectional reduction in this particular section were 33.3% (3/9) and 26.3% (5/19), respectively, instead of 25%. Thus, they concluded that the actual cross-sectional reduction impacted the stiffness more than the longitudinal spacing of the butt joints. They recommended to do further studies on stiffness reduction in full-scale decks and highlight actual cross-sectional reduction in future.

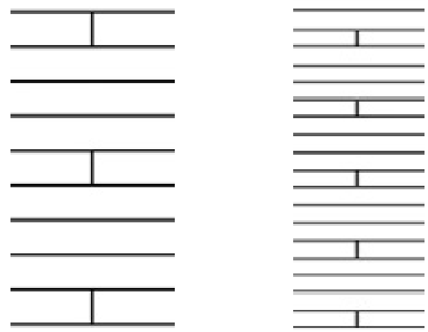


Figure 6 The particular section at midspan of Element 10 (left) and Element 11 (right) (Ekholm & Kliger, 2014)

By assuming a lamination with butt joints in perfect connection with its adjacent lamination, there was a flexural continuity at the locations of butt joints. Before, it was believed that the flexural rigidity would remain unaffected by butt joints. A paper showed that a presence of butt joints could reduce the load capacity even when the laminations were in perfect bond (Jaeger & Bakht, 1990). Ekholm and Kliger supposed that variable butt joint configurations had diverse strength (Ekholm & Kliger, 2014).

2.2.5. Existence of Outside Butt joints Reinforcement

Experiments investigating the outside reinforcement contribution to recovering effective stiffness and strength of NLT bending members with butt joints were conducted by Bohnhoff, Williams and others (1991 &1994). Metal plates were pressed into place where butt joints existed, after the specimens were fabricated, as shown in Figure 7. The metal plate used was high strength, 20-gauge (0.9-mm) toothed connectors with a width of 5.25 in. (133 mm) and a length of 8.75 in. (222 mm). The results of three-layer NLT showed that outside reinforcement could significantly increase mean bending strength (ultimate bending moment) by approximately 14%, the 5th percentile about 28%, and the initial stiffness around 25% (D. R. Bohnhoff et al., 1991). The results of four-layer NLT were increased by 26% for mean bending strength, by 40% for 5th percentile bending strength and by 17% for mean stiffness (Williams et al., 1994).

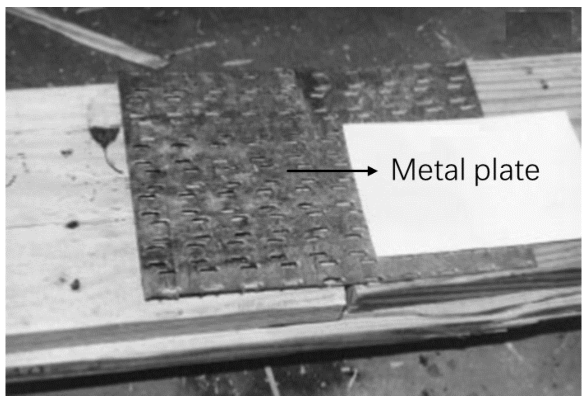


Figure 7 Metal plate used to reinforce butt joints (D. R. Bohnhoff et al., 1991; Williams et al., 1994)

2.3. Regulations on Butt Joints in the Building Codes

The review of building codes in current use shows that there are two main regulations on the arrangement of butt joints (i.e. placement of the laminations) to minimize their effect on the performance of decks. Figure 8 displays the regulations.

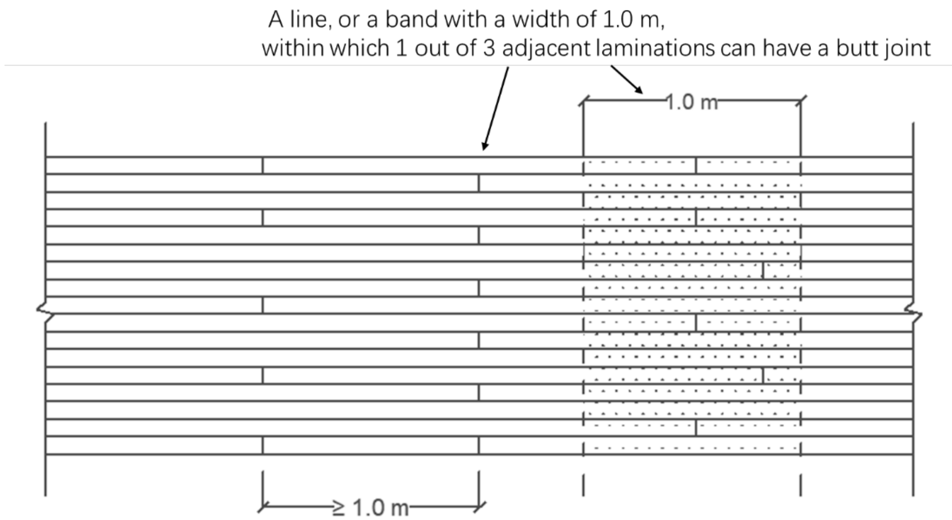


Figure 8 Regulations on butt joints

One is the distance between butt joints. First, the distance between butt joints in the same lamination (i.e. the length of a lamination) is limited. Furthermore, the spacing of butt joints in adjacent lamination is strictly controlled to minimize this "splicing" effect and to avoid a significant loss of strength and longitudinal stiffness in the deck. The “splicing” means the region where butt joints exist. Too short distance will result in “splicing” effect that butt joints are intensive in this region. According to OHBDC (Ministry of Transportation of Ontario, 1991), the length of a lamination should be at least 1.0 m. The minimum distance between butt joints of two adjacent lines parallel to the laminations is also 1.0 m (J.Taylor & J.Keenan, 1992; Jaeger & Bakht, 1990). The other one is that, the frequency of butt joints is properly limited along a line or a band with a width of 1.0 m perpendicular to the laminations. According to the older version of OHBDC, the frequency may not exceed 1-in-4, meaning that a butt joint shall not occur in more than one lamination out of any four adjacent laminations (J.Taylor & J.Keenan, 1992; Jaeger & Bakht, 1990). In the current CSA S6 standard, the limitation is eased to 1-in-3, meaning that a butt joint shall not occur in more than one lamination out of any three adjacent laminations (Canadian Standards Association, 2010). It is also recommended that butt joints be uniformly distributed along the deck (J.Taylor & J.Keenan, 1992).

2.4. Summary

NLT is an efficient technology in timber construction especially bridge decks. It is well accepted that use of higher quality lumber, proper nailing, increases in distance between adjacent butt joints, and addition of reinforcement to outside butt joints can significantly increase the performance of NLT bending members. For the stiffness reduction factor, it is related to the only variable 1-N, the frequency of butt joints in a cross section or a band with width of 1.0 m, which seems to be too conservative. Also, the practical application of the factor is controversial. More research is required to modify this equation.

3. Materials and Methods

3.1. Materials

Spruce-Pine-Fir (SPF) lumber pieces of No. 2 and Better Grade were used, which had dimensions of 38 mm in thickness, 140 mm in width, and 3,655 mm in length. The design values of No.2 SPF are given in Table 2.

Table 2 Material Properties of No.2 SPF (Canadian Standards Association, 2014)

Species	**Grade**	**Mechanical Properties (MPa)**					
		fb	*fv*	*fc*	*fcp*	*Ft*	*E*
SPF	No.1/ No.2	11.8	1.5	11.5	5.3	5.5	9,500

E = Modulus of elasticity; *fb, fv, fc, fcp, ft* = specified strengths in bending at extreme fibre, longitudinal shear, compression parallel to grain, compression perpendicular to grain, and tension parallel to grain

The type of nails used to construct the NLT was selected based on two criteria: 1) the length of the nails should be long enough to penetrate through the widths of two lumber pieces (Canadian Standards Association, 2006), and 2) installation should be efficient in terms of constructability. The type of 20d [102 mm (4 in) long with a diameter of 4 mm] hot galvanized spiral framing nails [See Figure 16(a)] was selected and used in the fabrication of 3-layer NLT specimens.

3.2. Testing Lumber Properties and Grouping

Density and Modulus of elasticity (MOE) of each lumber were tested prior to fabrication. The density of each lumber was determined by measuring the mass and volume of each piece. Moisture Content (MC) of each lumber for 3-lay NLT specimen was tested prior to testing. It was measured at three different locations (left, middle, and right) along the length direction with a moisture meter (Model: Wagner MMI 1100). Each lumber component was tested flatwise in bending under a center-point loading (see Figure 9), and the modulus of elasticity (MOE) was computed from the deflections at midspan, using Equation 4.

$$MOE = \frac{Pl^3}{4bd^3\Delta}$$

Equation 4

In which,

b = width of a specimen;

d = depth of a specimen;

P = Increment of applied load below proportional limit;

Δ = Increment of deflection of neutral axis at midspan corresponding load P;

l = span, the total distance between reactions on which a specimen is supported.

Figure 9 Experimental setup for measuring MOE of lumber

The three-point bending tests were conducted referring to ASTM D198 (ASTM International, 2015). A 50mm Linear Variable Differential Transformer (LVDT) was placed at the mid-span of a lumber specimen to measure the deflection. The LVDT was zeroed after applying a weight (i.e. pre-load) of 22 N (4.9 lbs). Then, the deflection was immediately recorded after the second weight of 136 N (30.5 lbs) was applied. To eliminate the influence of annual ring orientation and any warping effect on the MOE, each lumber was tested one more time by turning over the lumber specimen and repeating the practice. The MOE value was determined by averaging two measurements. If the difference between the MOE obtained from flatwise and edgewise bending tests were larger than 7%, those lumber pieces were not used for this study. The same procedure was taken by Davalos et al (1993).

In order to minimize the influence of material properties, such as density and MOE, on an NLT specimen, and to guarantee that densities and MOE values of lumbers in each group fell within a range of one standard deviation from the mean value, lumbers were sampled and grouped by excluding the data of extreme outliers. The procedure of grouping was achieved by dividing the lumber pieces into two samples: one for 3-layer specimen fabrication and the other for 5-layer specimen fabrication. Next, each sample of lumber was equally divided into 3 groups (H, M, and L), based on their MOE values. Lumbers in groups L, M, and H had low, medium, and high MOE, respectively. A flow chart is shown in Figure 10.

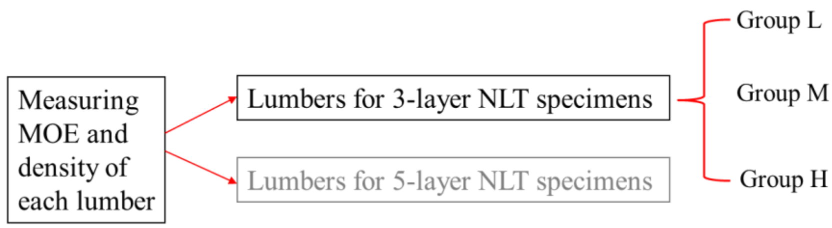


Figure 10 Grouping procedure

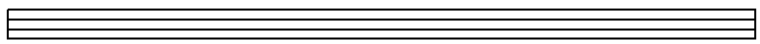
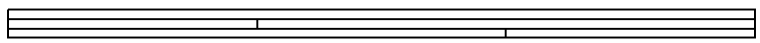
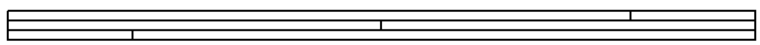
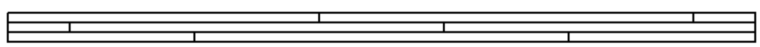
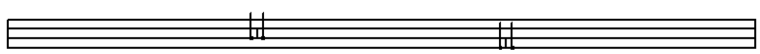
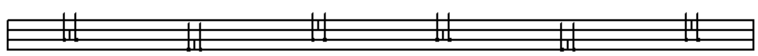
3.3. Fabrication of NLT specimens

3.3.1. Design of NLT Specimens

The specimens were designed with the consideration of three factors: 1) the design parameters shall represent the practicality of the construction of NLT bridge decks; 2) its geometry is such that the specimens can be tested using the available testing machines without requiring bracing, and 3) the nailing pattern, nail spacing, and end distance in the design should be in line with building codes and what evolved over many years of experience. The schematic diagrams of each type of NLT specimens are illustrated in Table 3. As a reference, Pattern 0 of butt joints did not have butt joints in laminations. Pattern 1 of butt joints had two butt joints spaced 1,000 mm in two laminations (one in each). Pattern 2 of butt joints had a total of 3 butt joints spaced 1,000 mm apart (one in each lamination). Pattern 3 of butt joints had a total of 6 butt joints spaced 500 mm apart (two in each lamination). These represented “conservative pattern”, “limit state”, and “aggressive pattern”, respectively. Referring to CSA S6, the frequency of butt joints along a cross section of the deck, or in a band with a width of 1,000 mm, shall not exceed 1-in-3. Pattern 2 of butt joints had the most pattern under limitations given in CSA S6, which was why the pattern was denoted as “limit state”. Type 0 NLT specimen had Pattern 0 of butt joints.

Types 1&4, 2&7, and 3&5 had the same butt joints patterns as 1, 2, and 3, respectively. The distinction between Types 1, 2, & 3 and Types 4, 7, & 5 was that nailing reinforcement was applied on the latters.

Table 3 3-layer Specimen Configurations

Pattern of butt joint	**Type of specimen**	**Demonstration**
0	0	
1	1	
2	2	
3	3	
1	4	
2	7	
3	5	

(Note: Type 6 was designed to apply steel plate reinforcement, which was not completed in this study due to time limit.)

The nailing patterns are illustrated in Figures 11 and 12. Edge distances to the top and bottom for nailing were 40 mm (Canadian Standards Association, 2010, 2014). The nails were driven alternately near the top and bottom edges (Staggered pattern). Common nails were used to fasten each lamination to the preceding one at intervals of 200 mm. One nail on each lamination was placed at 100 mm from the end of span.

It is well accepted that the discontinuity of NLT bending members reduces the strength and effective stiffness due to the weakness in the gap between lumber segments. An attempt to add external nails at the location of butt joints was applied in this study, to reduce the discontinuity by “holding separate parts together”. The details of reinforcing nails used in Types 4,7, and 5 NLT specimens are given in Figures 13 and 14.

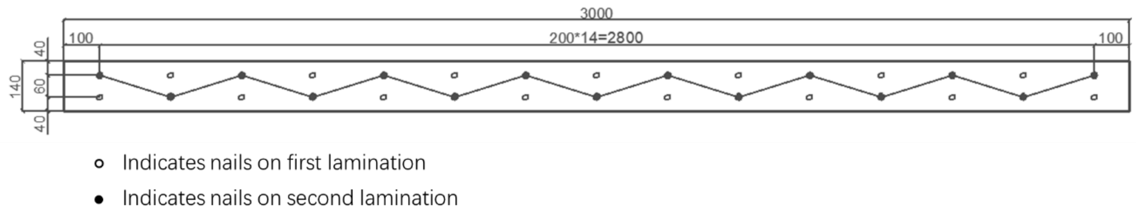


Figure 11 Nailing pattern of an NLT specimen (Front view)

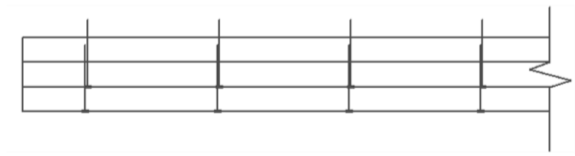


Figure 12 Nailing pattern of an NLT specimen (Top view)

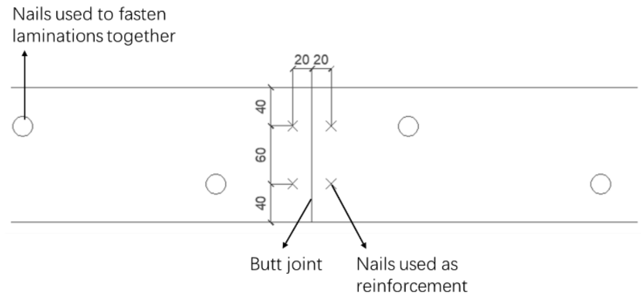


Figure 13 Schematic diagram of reinforcing nails

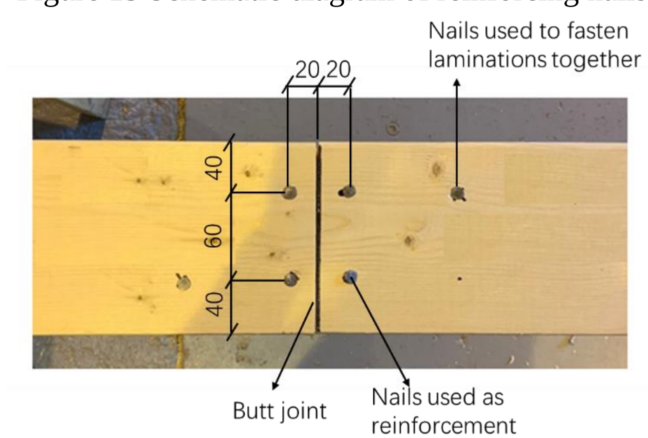


Figure 14 Illustration of reinforcing nails in Types 4,7, and, 5 NLT specimens

3.3.1. Fabrication of NLT Specimens

Fabrication of NLT specimens took place at the Wood Science and Technology Center (WSTC), situated at the University of New Brunswick, Fredericton, New Brunswick. An NLT specimen was fabricated according to the following procedure:

1) Three pieces of lumber were randomly selected from each group (L, M, and H) to fabricate an NLT specimen;
2) The cutting pattern of each lumber designed in Table 3 were marked before cutting;
3) Lumbers were cut to segments, if needed, by using a circular saw;
4) The moisture content of lumbers during fabrication were measured;
5) Arranged locations of nails were marked by drawing lines and dots on lumbers as shown in Figures 15 and 16; and
6) Nails were punched through two and a half laminations with a hammer or a R350PNF Palm Nailer.

Photos taken at various stages of fabrication are shown in Figure 17. In this study, there were 7 types NLT and 3 MOE groups, generating a total of 21 specimens. There was only 1 specimen tested at a given condition.

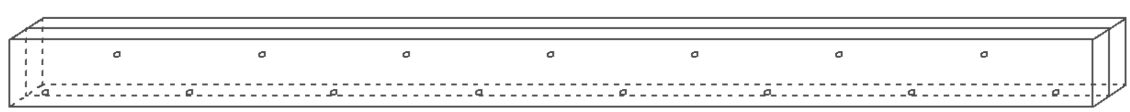


Figure 15 Nails located on the center lamination

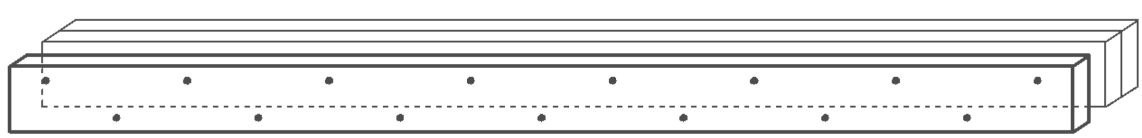


Figure 16 Nails located on the third lamination

(a)

(b)

(c)

(d)

(e) (f)

Figure 17 Fabrication of NLT specimens:

(a) 20d spiral nail getting through two and half laminations; (b) R350PNF Palm Nailer; (c) Lumbers stacked according to specimen configurations; (d) Sawed lumbers, with marks of reaction and nail locations; (e) Measuring MC of each lumber before fabrication; (f) An NLT specimen in assembly.

3.4. Four-point Bending Tests on NLT Specimens

3.4.1. Test Set-up and Instrumentation

The four-point bending tests were performed, in accordance with ASTM D198 (ASTM International, 2015), using a Universal Testing Machine (Model: MTS 810). A specimen was placed on two supports as illustrated in Figure 18. The center-to-center span was 3,000 mm. Consequently, the span-to-depth ratio is approximately 21.4 so that the effect of shear force is minimized. The total load on the specimen was applied equally at two points equidistant (one-third of the span, 1,000 mm) from two supports. Rather than placing a LVDT under the bottom of the NLT specimen, two LVDTs were attached to two hangers, on both sides of the specimen (See Figures 18 and 19). The deflection of the neutral axis of the specimen at the mid-span was measured. The load was applied at a rate of 4 mm/min so that the failure occurred within approximately 15 minutes. The load, crosshead movement, two LVDT readings, and elapsed time were recorded real-time, using a built-in data logger at a frequency of 5 Hz.

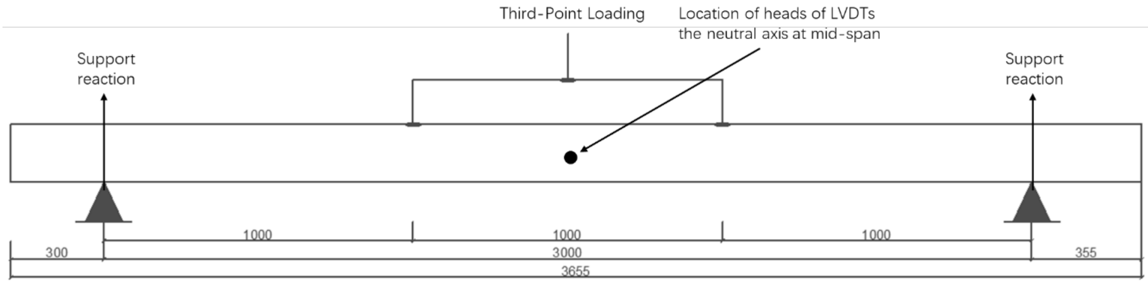


Figure 18 Test set-up schematic diagram

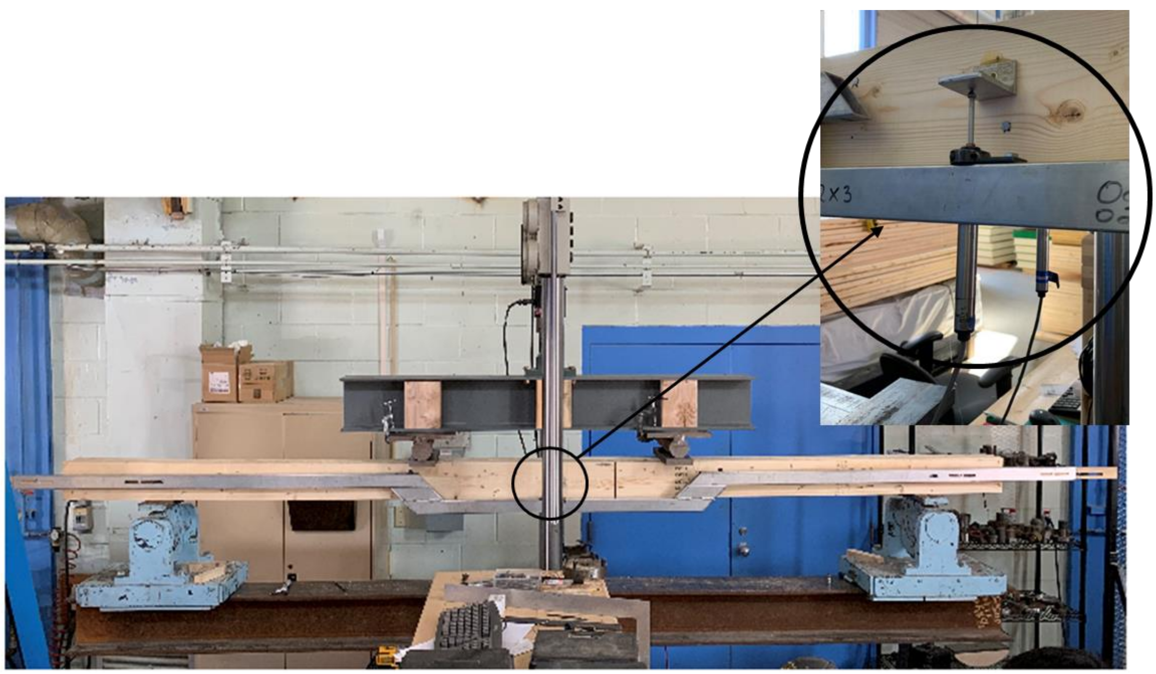


Figure 19 Test set-up at WSTC

3.4.1. Calculations

The density of each lumber was calculated from equation 5:

$$\rho = \frac{m}{V}$$

Equation 5

The MOE value of each lumber was calculated from equation 6:

$$MOE = \frac{P}{\Delta} \cdot \frac{l^3}{4bd^3}$$

Equation 6

In which,

P = Increment of applied load below proportional limit;

Δ = Increment of deflection of neutral axis at midspan corresponding to the load P;

l = span, the total distance between reactions on which the specimen is supported.

d = thickness of laminations;

b = height of laminations.

To apply the flexural property of lumbers in comparison to that of NLT specimens, MOE value of each lumber was converted to stiffness EI according to equation 7:

$$EI = MOE \cdot \frac{bd^3}{12}$$

Equation 7

In which,

d = thickness of laminations;

b = height of laminations.

The load-deflection curve of an NLT specimen tested is plotted in Figure 20 to understand the response of deformation to the load. The load capacity (P_{peak}) of the NLT specimen is defined as the maximum load applied. The effective bending stiffness (EI_{eff}) of the specimen is calculated by equation 8.

$$EI_{eff} = \frac{23}{1296} \cdot \frac{P}{\Delta} \cdot l^3$$

Equation 8

In which,

P = Increment of applied load below proportional limit;

Δ = Increment of deflection of neutral axis at midspan corresponding load P;

l = span, the total distance between reactions on which the specimen is supported.

$\frac{P}{\Delta}$ is defined as the load required to produce a per unit change in deformation, which is calculated via defining it as the slope of the line drawn between 10% and 40% of the peak load as shown in Figure 19. It is formulated by Equation 9.

$$\frac{P}{\Delta} = \frac{0.4P_{peak} - 0.1P_{peak}}{\Delta_{0.4\,P_{peak}} - \Delta_{0.1\,P_{peak}}}$$

Equation 9

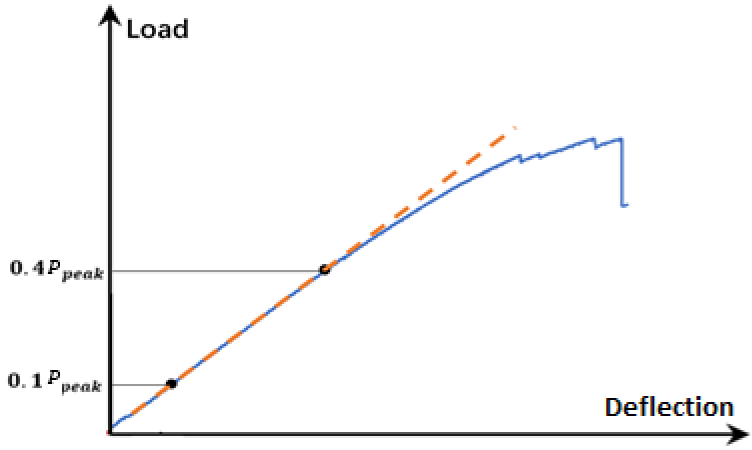


Figure 20 Typical load-deflection curve

The effect of butt joints is calculated from equation 10:

$$Reduction\ (\%) = \frac{Performance\ without\ butt\ joints^{*} - Performance\ with\ butt\ joints}{Performance\ without\ butt\ joints^{*}} \times 100$$

Equation 10

The effect of nailing reinforcement is calculated from equation 11:

$$Reinforcing\ effect\ (\%) = \frac{Performance\ with\ reinforcement - Performance\ without\ reinforcement}{Performance\ without\ reinforcement} \times 100$$

Equation 11

(Note: * Performance of Type 0 NLT specimen was taken as the reference in this study.)

4. Results and Discussion

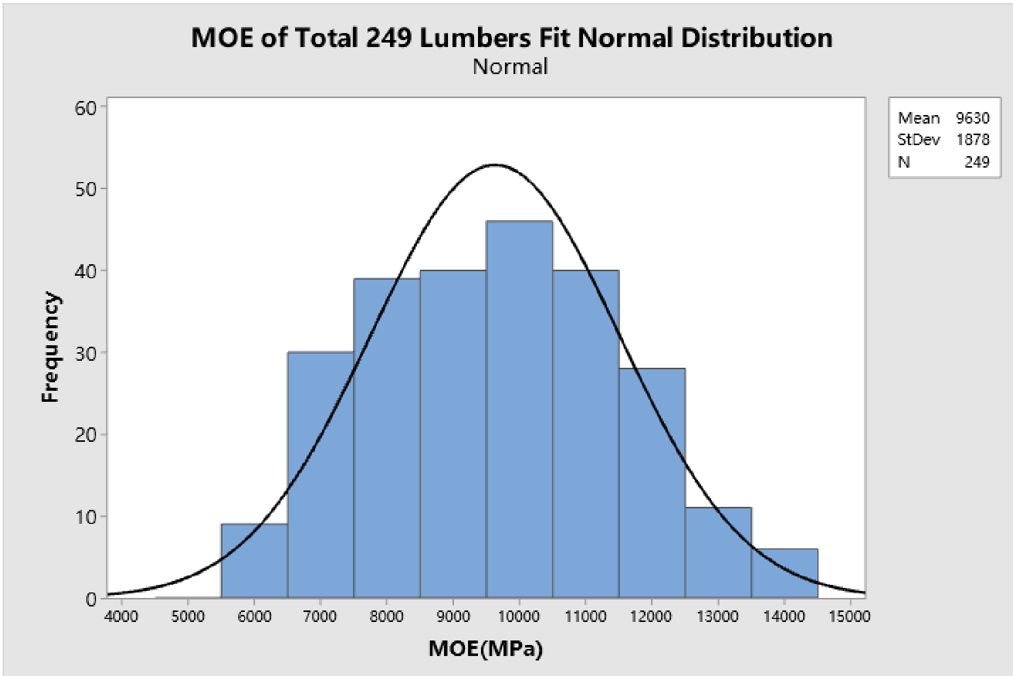
4.1. Density, MC and MOE of lumbers

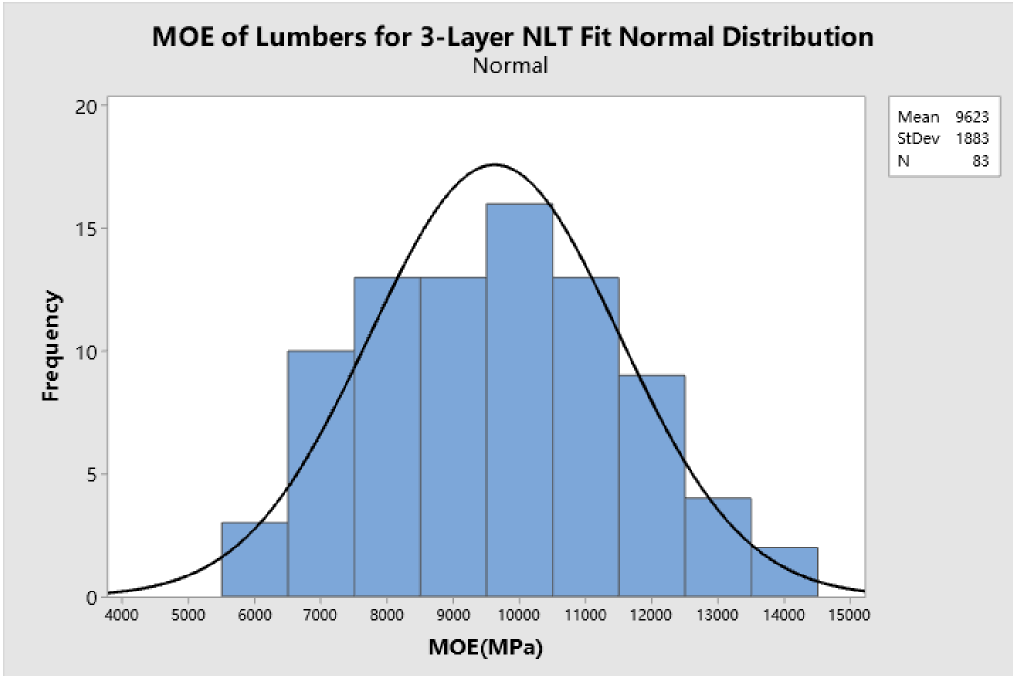
The average density of the lumber tested was 0.473 g/cm^3 with a coefficient of variation (COV) of 10%. The mean MOE of lumbers was 9,630 MPa with a standard deviation (S.D.) of 1,878 MPa. A total of 249 lumber pieces were, by excluding those pieces of extreme outliers (lumber No. 19 excluded due to extremely low MOE), divided into two samples: one, containing 83 lumber pieces, was named as "Lumber pieces for 3-layer specimens"; and the other one, containing 166 lumber pieces, was named as "Lumber pieces for 5-layer specimens". Only "Lumber pieces for 3-layer specimens" were used due to time constraints in this study, but the remaining lumber pieces will be completed tested in the future by other researchers. After that, lumbers in sample "Lumber pieces for 3-layer specimens" were equally divided into 3 groups (H, M, and L), based on their MOE values. Lumbers in group L have relatively low MOE, et cetera. Table 4 delivers the average values of the properties and their variations of all the lumbers used, those for 3-layer NLT, and those for 5-layer NLT.

Table 4 Basic properties of lumbers

Sample	**Count**	**Density** (g/cm^3)	**COV** (%)	**MC at test (%)**	**COV** (%)	**MOE** (MPa)	**S.D.** (MPa)	**COV** (%)
Total	249	0.473	10	N/A	N/A	9630	1878	20
3-layer	166	0.476	9	14.1	13	9623	1883	20
5-layer	83	0.471	11	N/A	N/A	9633	1882	20

Figure 21 illustrates the spread of MOE of all lumbers, lumbers for 3-layer NLT, and lumbers for 5-layer NLT, demonstrating that the MOE data well follows a normal distribution.





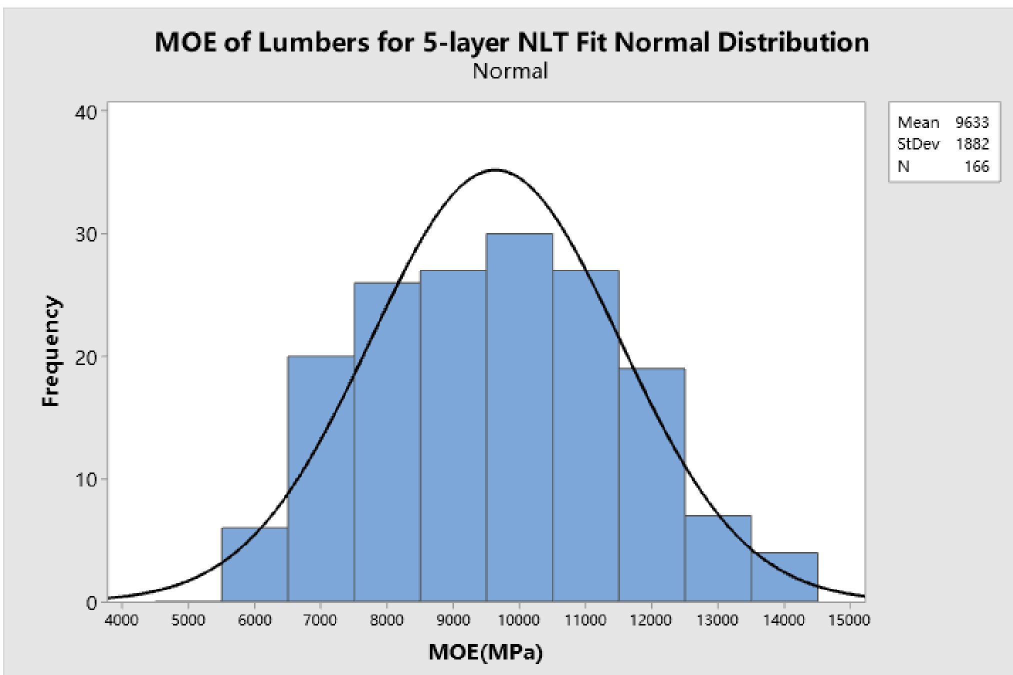


Figure 21 Distribution histograms of MOE for total lumbers (upper), lumbers for 3-layer NLT (middle), and lumbers for 5-layer NLT (bottom)

For lumbers used in the fabrication of 3- layer NLT specimens, the average density of the lumbers was 0.476 g/cm^3 with a COV of 9%, the average MC was 14.1% with a COV of 13%, and the average MOE was 9,623 MPa. After dividing them into three groups [i.e. low MOE grade (L), medium MOE grade (M), and high MOE grade (H)], the average MOE value for each group is given in Table 5 and the detailed properties of each specimen are shown in Table 6. Figures 22 shows that the MOE values of lumbers for 3-layer NLT specimens in each group (L, M, and H) fit normal distributions well.

Table 5 MOE values of three groups

Group	**Count**	**Mean**(MPa)	**Min**(MPa)	**Max**(MPa)	**S.D.**(MPa)	**COV** (%)
L	28	7,532	5,810	8,727	754	11
M	28	9,651	8,731	10,600	510	5
H	27	11,761	10,625	14,047	927	8

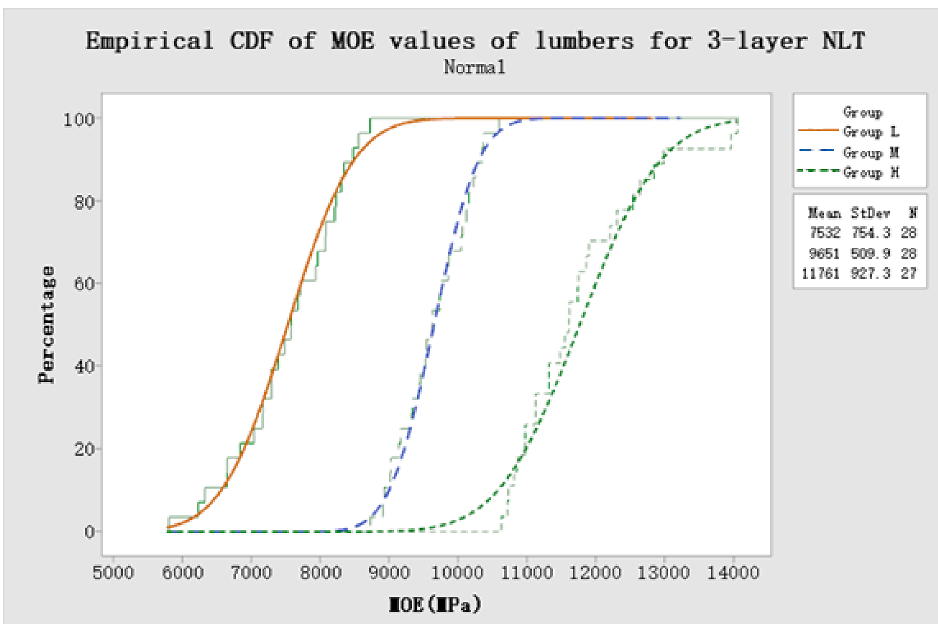


Figure 22 CDF diagram of MOE values of lumbers for 3-layer NLT specimens

Table 6 Basic properties of lumber making NLT specimens

Type	Specimen Code	MOE (MPa)	Density (g/cm^3)	MC (%)
0	3-0-L	7,373	0.479	13.6
	3-0-M	9,653	0.445	13.7
	3-0-H	11,282	0.480	14.1
1	3-1-L	7,427	0.442	12.8
	3-1-M	9,877	0.495	13.4
	3-1-H	11,336	0.510	14.8
2	3-2-L	7,148	0.459	13.6
	3-2-M	9,679	0.552	15.9
	3-2-H	11,317	0.483	12.9
3	3-3-L	7,294	0.454	15.4
	3-3-M	9,445	0.507	14.9
	3-3-H	11,328	0.451	14.5
4	3-4-L	7,645	0.427	14.0
	3-4-M	9,839	0.481	13.2
	3-4-H	11,359	0.490	14.8
7	3-7-L	7,736	0.460	12.9
	3-7-M	9,664	0.449	13.6
	3-7-H	12,717	0.531	16.7
5	3-5-L	7,365	0.420	13.8
	3-5-M	9,781	0.503	14.3
	3-5-H	11,430	0.490	14.4

4.2. Mechanical Responses

4.2.1. Load-deflection curves

The load-deflection curves of all groups are plotted in Figures 23, 24, and 25. Each curve represents the mechanical response of each specimen. The load increases with deflection in a linear pattern starting from the origin to about 60% of the peak load, then non-linearly until the peak load, and finally fails in a brittle way. No brittle failure appears in the curves for Type 3 NLT specimens because the load was removed once the deflection went beyond 100 mm. Type 3 NLT specimens were made with 6 butt joints spaced 500 mm apart, behaving more ductile, compared to Types 1 and 2. The load-deflection curves of Type 3 NLT specimens show a high ductility, the test of which was stopped when the deflection reached 100mm. Substantial and irreversible bending at butt joints was observed in Type 3 specimens. It was worth noting that by applying nailing reinforcement, the sharp drop reoccurred in curves of Type 5 NLT specimen.

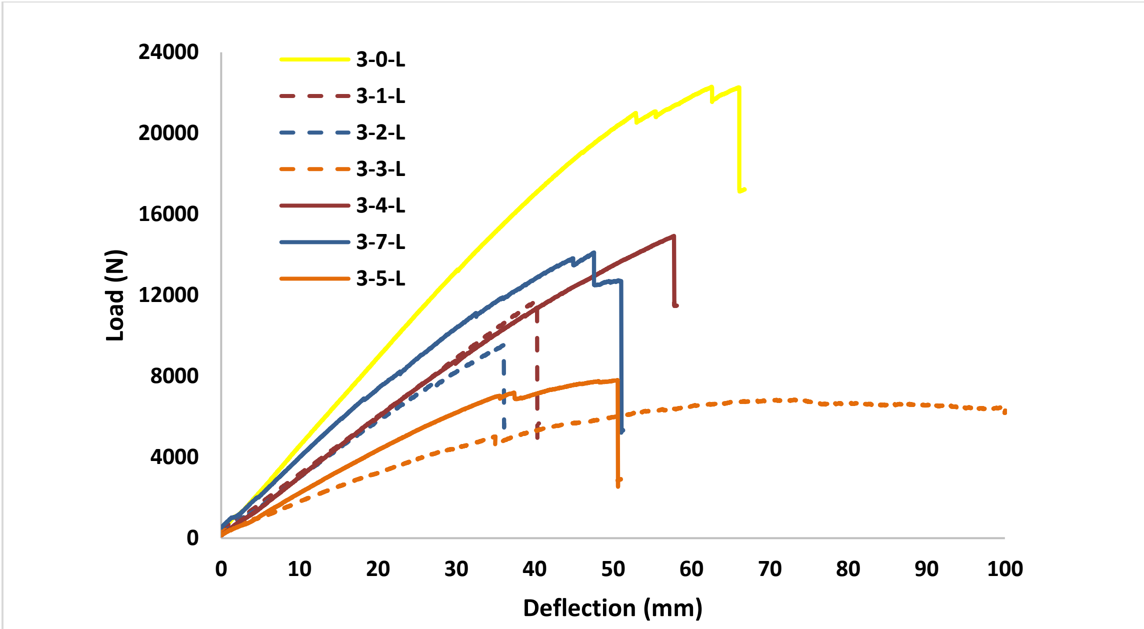


Figure 23 Load-deflection Curves of Group L specimens

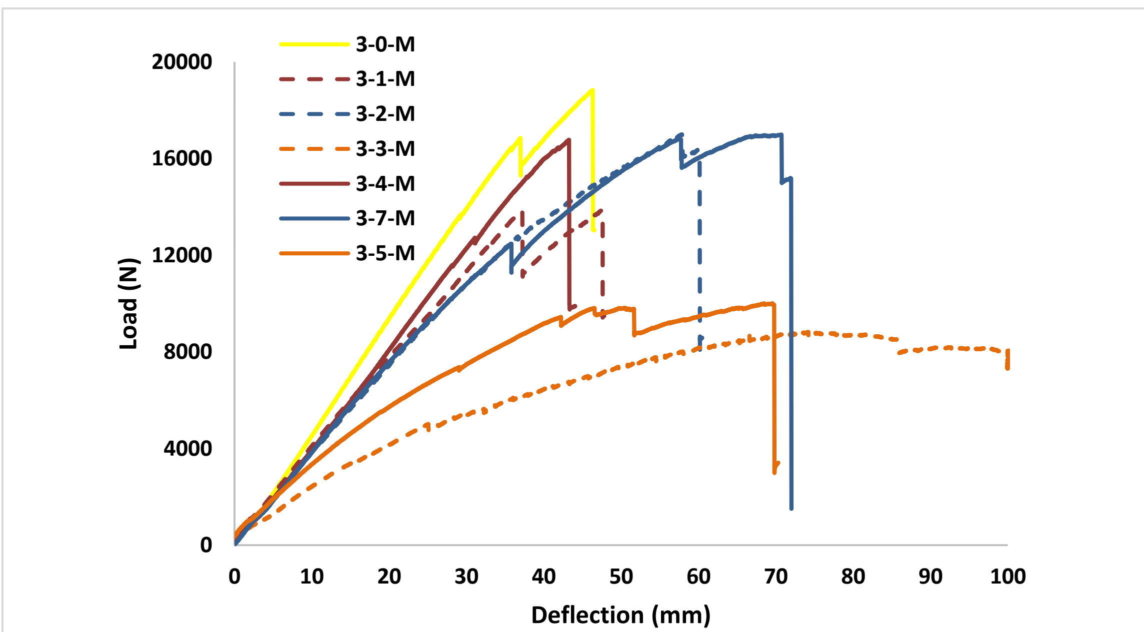


Figure 24 Load-deflection Curves of Group M specimens

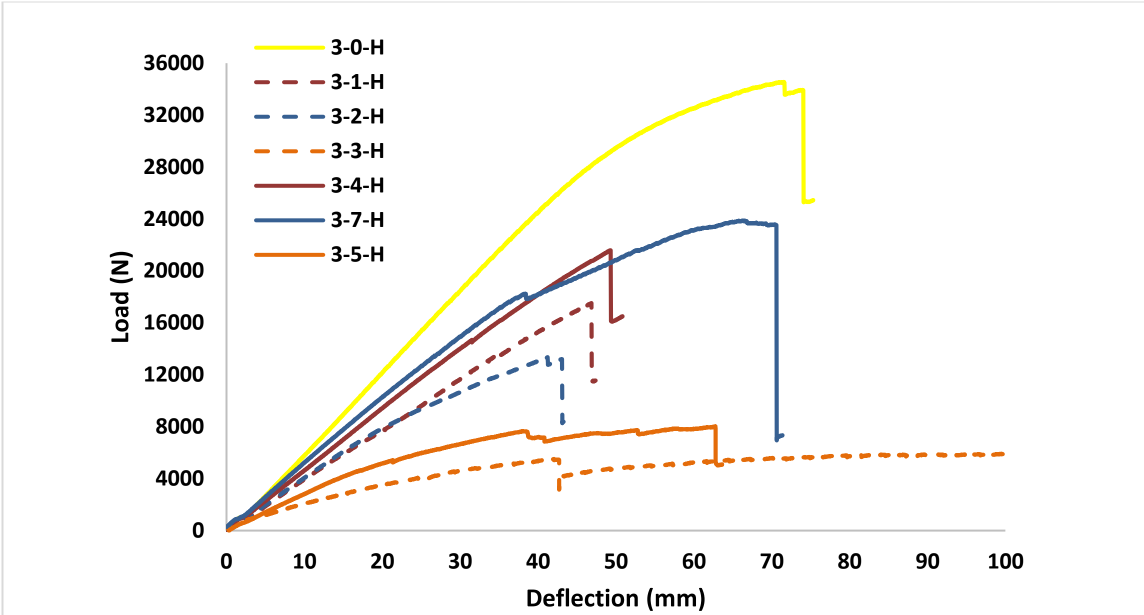


Figure 25 Load-deflection Curves of Group H specimens

4.2.1. Failure Mode

Each failure mode is discussed and accompanied by pictures in this section. Table 7 gives a summary of the failure mode of each specimen. Three failure modes were classified, i.e. tension failure, segment slip, and splitting failure. The dominant failure appearing in Type 0 NLT specimens was tension failure at the location of the knot(s). All Type 1 NLT specimens showed a tension failure combined with a slight segment slip. Tension failure was found in all Type 2 NLT specimens and segment slip as well as splitting failure was also observed on some butt joints. The segment slip was evident and substantial in Type 3 specimens and it was the only failure mode observed in this type. The failure modes in Type 4 NLT specimens varied. Although all Type 7 NLT specimens displayed the first two failure modes, splitting failure was rare. Failure was extensive in Type 5 NLT specimens demonstrating every type of failure.

Table 7 Occurrence of failure modes in each NLT specimen

Specimen type	Specimen code	Failure mode		
		Tension failure	Segment slip	Splitting failure
0	3-0-L	√		
	3-0-M	√		
	3-0-H	√		
1	3-1-L	√	√	
	3-1-M	√	√	
	3-1-H	√	√	
2	3-2-L	√	√	
	3-2-M	√	√	√
	3-2-H	√		√
3	3-3-L		√	
	3-3-M		√	
	3-3-H		√	
4	3-4-L		√	
	3-4-M	√		√
	3-4-H			√
7	3-7-L	√	√	
	3-7-M	√	√	
	3-7-H	√	√	√
5	3-5-L	√	√	√
	3-5-M	√	√	√
	3-5-H	√	√	√
Percentage of failure mode (%)		71	71	38

4.2.1.1. Tension Failure

Taking ASTM D143 as reference, tension failure is the dominant failure mode observed in this study. Figure 26 shows the typical simple tension failure modes observed.

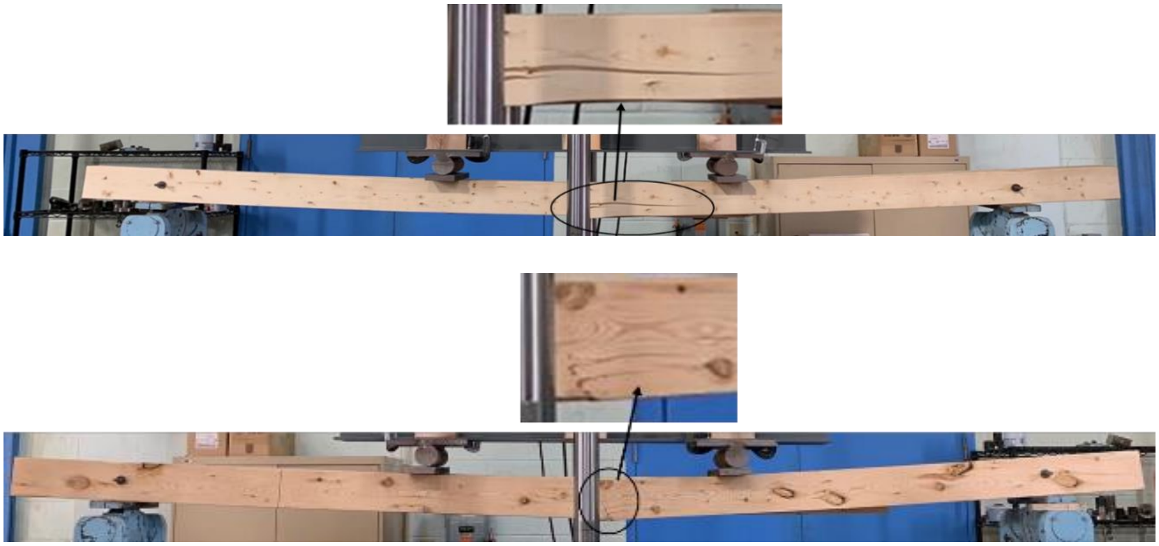


Figure 26 Simple tension failure at midspan of 3-1-M (top) and 3-2-M (bottom)

In addition to the tension failure at midspan, tension failures occurring close to the locations of the two loading points within the maximum bending moment area were also observed non-accidentally. Figures 27 and 28 show a cross-grain tension failure occurring within the maximum bending moment area, in the outer layer of 3-2-H and a simple tension failure occurring within the maximum bending moment area, in the outer layer of 3-7-H, respectively. This confirmed that the failure of NLT specimens with long butt joints spacing was more related to tensile stresses (Williams et al., 1994).

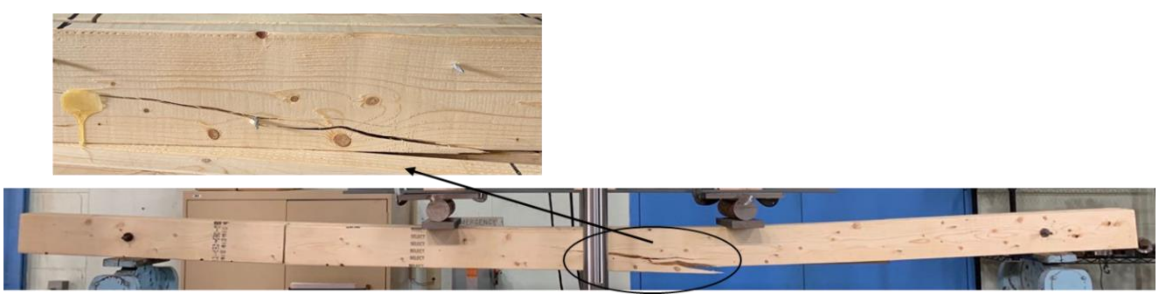


Figure 27 Cross-grain tension failure occurring in specimen 3-2-H within the maximum bending moment area

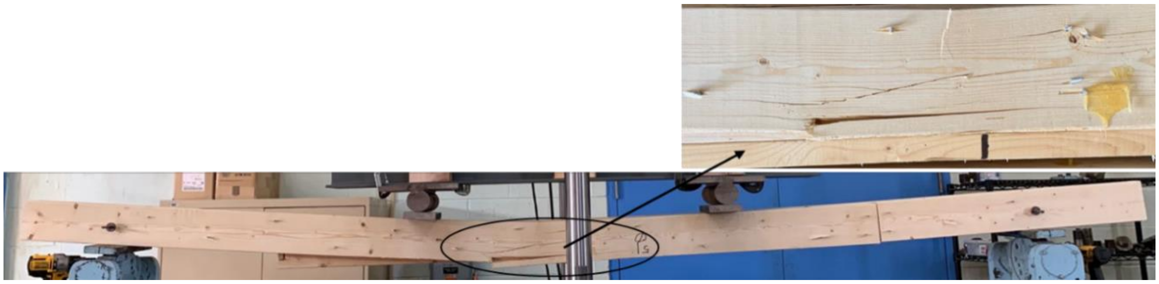


Figure 28 Simple tension failure occurring in specimen 3-7-H within the maximum bending moment area

4.2.1.2. Segment slip

The segment slip failure is defined as the slip of a segment in plane of the lamination. By observing other NLT specimens, the segment slip is a common failure mode in NLT specimens containing butt joints without reinforcing nails. Every specimen of Type 1 had this failure mode in each butt joint as indicated in Figure 29.

Figure 29 Slip between segments in Type 1 specimens

The segment slip was evident in Type 3 specimens. There were 6 butt joints in an NLT specimen of Type 3, and four of them demonstrate the segment slip, as shown in Figure 30. The other two butt joints, which were far away from the maximum bending moment area, did not show a notable failure. It could be caused by the high shear force. The NLT specimens with shorter spacing between the butt joints in adjacent layers had to transfer load over a shorter distance (i.e., through fewer nails), and consequently nail forces could be higher, so that maximum nail shear forces were reached before ultimate wood bending stresses were reached (Williams et al., 1994).

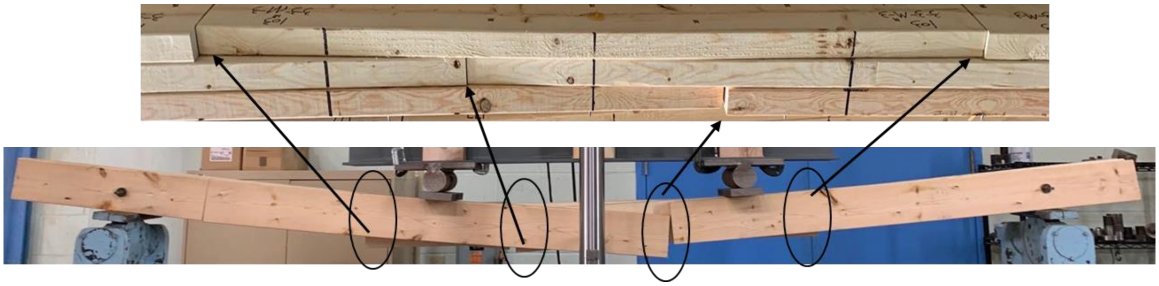


Figure 30 Typical failure mode of NLT specimens of Type 3

4.2.1.3. Splitting failure

In Type 2 of specimens, the dominant failure at the location of a butt joint was replaced by splitting failure combined with slip as shown in Figure 31. The reason why splitting failure occurred could be due to the short distance between the nail and the gap, in which a nail functioned as a wedge. In CSA Standard O86, Engineering Design in Wood, the minimum end distance parallel to grain is 12 mm (Canadian Standards Association, 2014). The end distance of nails applied to butt joints as reinforcement in this study was 20 mm. The splitting might be contributed by the unstable MC and lack of pre-drilled nail holes. It might suggest that more research is required to figure out the effect of end distance of nail(s) around a butt joint on an NLT and then further recommendation can be made to CSA S6.

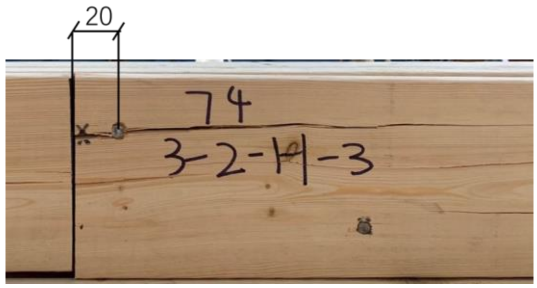


Figure 31 Splitting failure occurring at a butt joint in specimen 3-2-H

The nails going straight through laminations did not bear any force theoretically. However, by analyzing the failure of each specimen, the splitting failure that occurred from the butt joint, and through the nearby nail, was another typical failure mode in the outer lamination (i.e. the first lamination that nails got through). This outcome was consistent with commentary that the most highly stressed nails were always located adjacent to a butt joint in an outer lamination (D. Bohnhoff, 1989).

This phenomenon was particularly observed in nailing reinforcement types, and the reason could due to the stress concentration from the short end distance of the reinforcing nail and the butt joint. Figure 32 shows that there was a butt joint in the outer lamination (i.e. the first lamination that nails got through) in each Type 4 specimen. Additionally, the location of a butt joint happened to be under the loading point. The splitting failure began from the joint, extending through the location of the reinforcing nails, across the lumber grain, and then to either the less bending moment area (specimen 3-4-H) or to the larger bending moment area (specimen 3-4-M).

Figure 32 Splitting failure occurring in Type 4 specimens

In specimen 3-5-H as shown in Figure 33, there are two butt joints in the outer lamination (i.e. the first lamination that nails got through), near both ends of a span. Two instances of splitting starting from the butt joints, across the nails and growing along the direction to the mid-span were witnessed in the center segment.

Figure 33 Splitting failure in specimen 3-5-H

Splitting failure was observed at the butt joint even if it was 500 mm away from the maximum bending moment area. From Figure 34, it can be seen that the lower part of specimen 3-7-H outer lamination fell apart from upper lumber, leaving a line of nails exposed. As for specimen 3-7-M, the reinforcing nails in the same location got bent before splitting lumber apart.

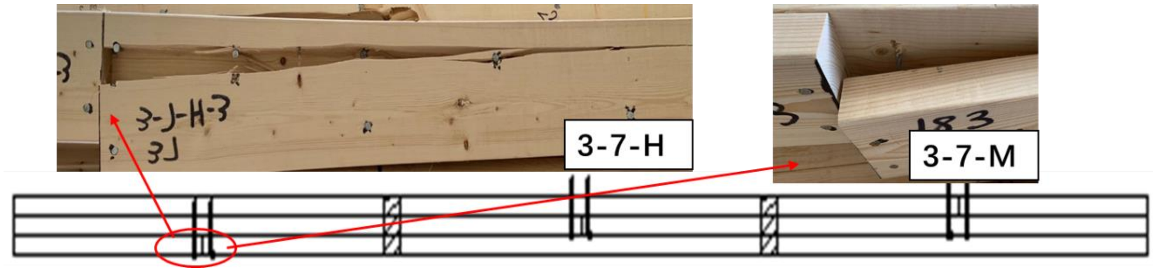


Figure 34 Long cracking along with nail line in specimen 3-7-H

Splitting failure in Type 5 specimens (see Figure 35) occurred where butt joint with reinforced nails existed in the maximum bending moment area in the outer lamination. The reinforcing nails provided a resistance to bending, resulting in the split of lumber through the location of the nails and across the lumber grain.

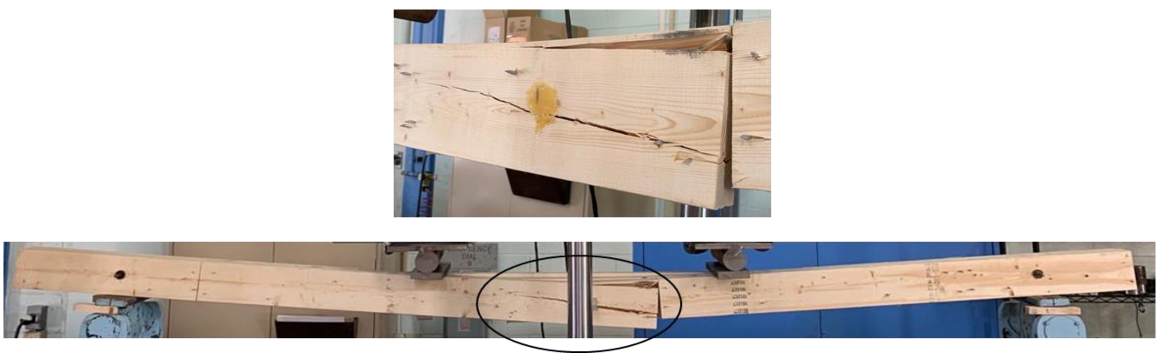


Figure 35 Specimens 3-5-L and 3-5-H showing the splitting failure mode around the midspan

4.2.1.4. Summary

By observing the failure modes of all the specimens, it was found that the tension failure and segment slip were the two dominant failure modes. In construction, defects of lumber such as knots should be avoided within a maximum bending moment area. For those NLT containing butt joints in large bending moment area, extra nails are suggested as complementary to help increase the load bearing ability and to help decrease the shear force on each nail. Meanwhile, attention should be paid on the distance between a nail and a butt joint to prevent splitting failure. Additionally, butt joints near mid-span in the outer lamination of NLT should be avoided if the length of segments is short (i.e. less than 1,000 mm, for example, 500 mm in this study). No restriction about minimum distance between a butt joint and a nail was placed in CSA S6. The minimum end distance 12 mm given in CSA O86 should seemingly be increased in application of NLT bending members. More specifications about nailing pattern including the minimum distance between a nail and a butt joint were suggested to CSA when revising the standard CSA S6. Based on the frequent occurrence of splitting in this study, a 30 mm distance may work better.

4.3. Effective Stiffness and Load Capacity

The effective stiffness (EI_{eff}) and load capacity (P_{peak}) of NLT specimens are shown in Table 8, in which the average stiffness EI (converted from the MOE values) of lumbers used to make an NLT specimen are also listed. It can be found that the EI_{eff} of the NLT specimen without butt joints was 247 $kN \cdot mm^2$, which was indeed close to the average stiffness of lumbers comprising the NLT specimen, 246 $kN \cdot mm^2$. This result coincides with the findings that the modulus E of the laminated timber decks without butt joints equaled the average modulus of the lumber components (Taylor et al., 1983). From the results of NLT specimens with butt joints, it can be seen that the existence of butt joints had a considerable negative impact on the EI_{eff} and P_{peak} of NLT specimens. EI_{eff} values of Types 1, 2, and 3 NLT specimens were 190, 164, and 89 $kN \cdot mm^2$ respectively.

P_{peak} values of these three NLT specimens were 14,379, 13,303, and 7,195 N. EI_{eff} values of Types 4, 7, and 5 NLT specimens were 189, 198 and 133 $kN \cdot mm^2$ individually. P_{peak} values of these three NLT specimens were 17,770, 18,325, and 8,606 N. The gap between the mechanical properties of solid NLT specimens and NLT specimens with butt joints are in agreement with the findings, i.e. the weakness of discontinuity, as investigated by Remund et al (1982).

Table 8 Test results of each specimen and its average value

		Lumber		NLT Specimens			
Type	**Specimen Code**	EI ($kN \cdot mm^2$)	**Average** EI ($kN \cdot mm^2$)	EI_{eff}($kN \cdot mm^2$)	**Average** EI_{eff} ($kN \cdot mm^2$)	P_{peak} (N)	**Average** P_{peak} (N)
	3-0-L	192		209		22,230	
0	3-0-M	252	246	229	247	18,838	25,209
	3-0-H	294		302		34,559	
	3-1-L	194		141		11,773	
1	3-1-M	257	249	184	190	13,851	14,379
	3-1-H	296		246		17,514	
	3-2-L	186		134		9,548	
2	3-2-M	252	244	163	164	17,007	13,303
	3-2-H	295		195		13,355	
	3-3-L	190		78		6,841	
3	3-3-M	246	244	100	89	8,828	7,195
	3-3-H	295		90		5,915	
	3-4-L	199		140		14,929	
4	3-4-M	256	250	203	189	16,782	17,770
	3-4-H	296		225		21,600	
	3-7-L	202		177		14,106	
7	3-7-M	252	262	175	198	16,989	18,325
	3-7-H	332		242		23,879	
	3-5-L	192		108		7,797	
5	3-5-M	255	248	134	133	10,000	8,606
	3-5-H	298		158		8,022	

4.3.1. Effect of butt joints on mechanical performance of NLT

NLT specimens without butt joints were Type 0 NLT specimens. NLT specimens with butt joint patterns 1, 2, and 3 were Types 1, 2, and 3 NLT specimens, respectively. It was found that the EI_{eff} of NLT specimens with butt joint pattern 1, 2, and 3 were 24%, 34%, and 64% lower than the NLT specimens without butt joints, respectively, which are indicated in Table 9 as well. Because of the half spacing and the triple amount of butt joints, EI_{eff} and P_{peak} of NLT specimens with butt joint pattern 3 were 89 $kN \cdot mm^2$ and 7,195 N, which were only about half of those of NLT specimens with butt joint pattern 1.The effect of butt joints on P_{peak} of NLT was more considerable than that on EI_{eff}. As indicated in Table 9, the reduction in P_{peak} of NLT specimen with butt joint patterns 1, 2, and 3 were 43%, 47%, and 71 %. This conveys that because of existence of butt joints, increase in number of butt joints and decrease in butt joint spacing, EI_{eff} and P_{peak} of NLT specimens were decreased.

Table 9 Effect of butt joints on mechanical performance of NLT

	EI_{eff}			P_{peak}		
Butt joint pattern	**Without butt joints (kN·mm²)**	**With butt joints (kN·mm²)**	**Reduction (%)**	**Without butt joints (N)**	**With butt joints (N)**	**Reduction (%)**
1		190	23		14,379	43
2	247	164	34	25,209	13,303	47
3		89	64		7,195	71

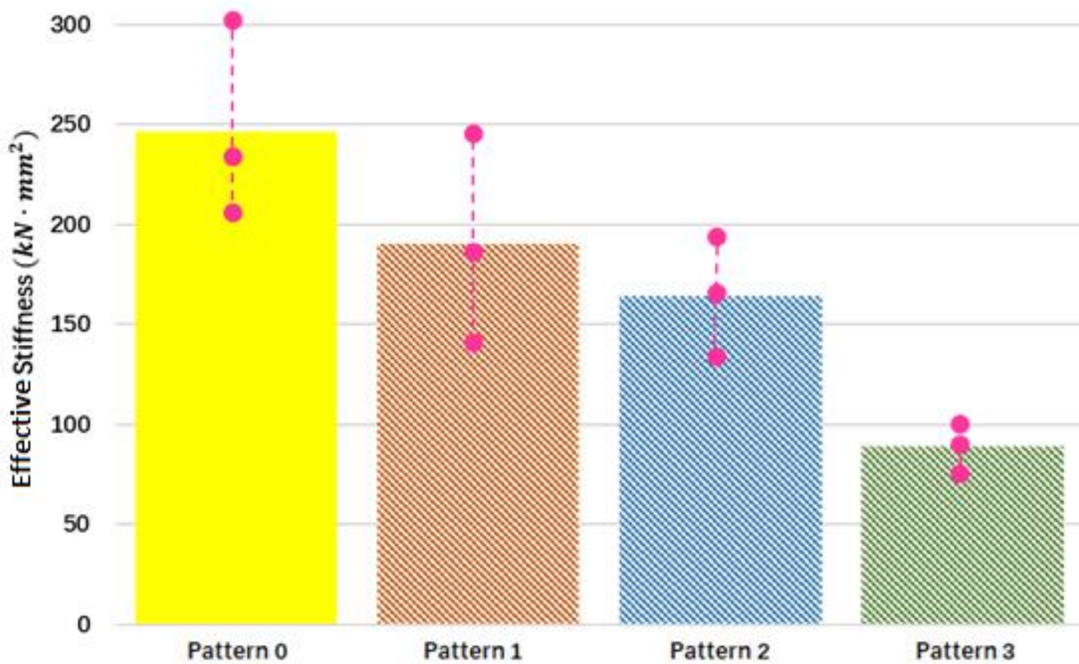


Figure 36 Effect of butt joints patterns on EI_{eff} of NLT with various butt joint patterns (Note: The dots represent the individual values)

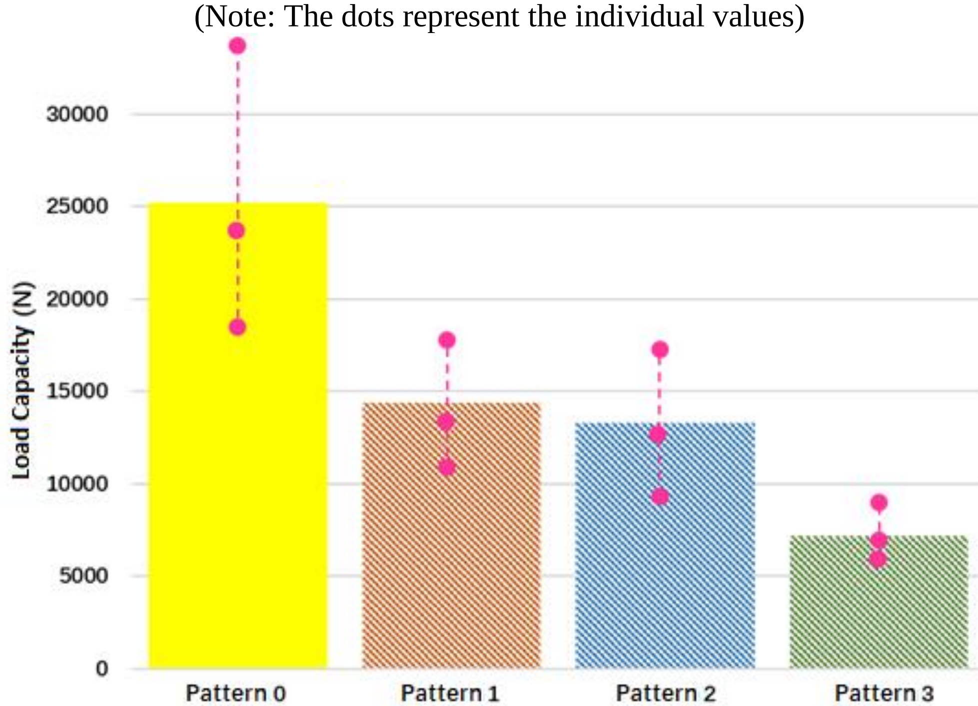


Figure 37 Effect of butt joints patterns on P_{peak} of NLT with various butt joint patterns (Note: The dots represent the individual values)

By observing the spread of data of each type (pink dots with vertical lines) in Figures 36 and 37, it is found that the existence of butt joints and a decline in butt joint spacing, that are inseparably interconnected with an increase in the amount of butt joints, reduced the variability in EI_{eff} and P_{peak} of NLT specimens. This might be attributed to a more frequent occurrence of failure due to the high nail shear force among the butt joints. In contrast to lumber, nails did not have variation, neither did the butt joints.

To summarize, an appropriately controlled pattern of butt joints helped reduce the variation of mechanical properties of NLT specimens, meanwhile causing less reduction.

4.3.2. Effect of nailing reinforcement on mechanical performance of NLT

Unreinforced NLT with butt joint patterns 1, 2, and 3 were Types 1, 2, and 3 NLT specimens, respectively. Nailing reinforced NLT with butt joint patterns 1, 2, and 3 were Types 4, 7, and 5 NLT specimens, respectively. Table 10 and Figures 38 and 39 conveys information about the effects of nailing reinforcement on the EI_{eff} and P_{peak} of NLT specimens with various butt joint patterns.

Table 10 Effect of nailing reinforcement on mechanical performance of NLT with butt joints

Butt joint pattern	EI_{eff}			P_{peak}		
	Unreinforced (kN·mm²)	**Reinforced (kN·mm²)**	**Recover (%)**	**Unreinforced (N)**	**Reinforced (N)**	**Recover (%)**
1	190	189	0	14,379	17,770	24
2	164	198	21	13,303	18,325	38
3	89	133	49	7,195	8,606	20

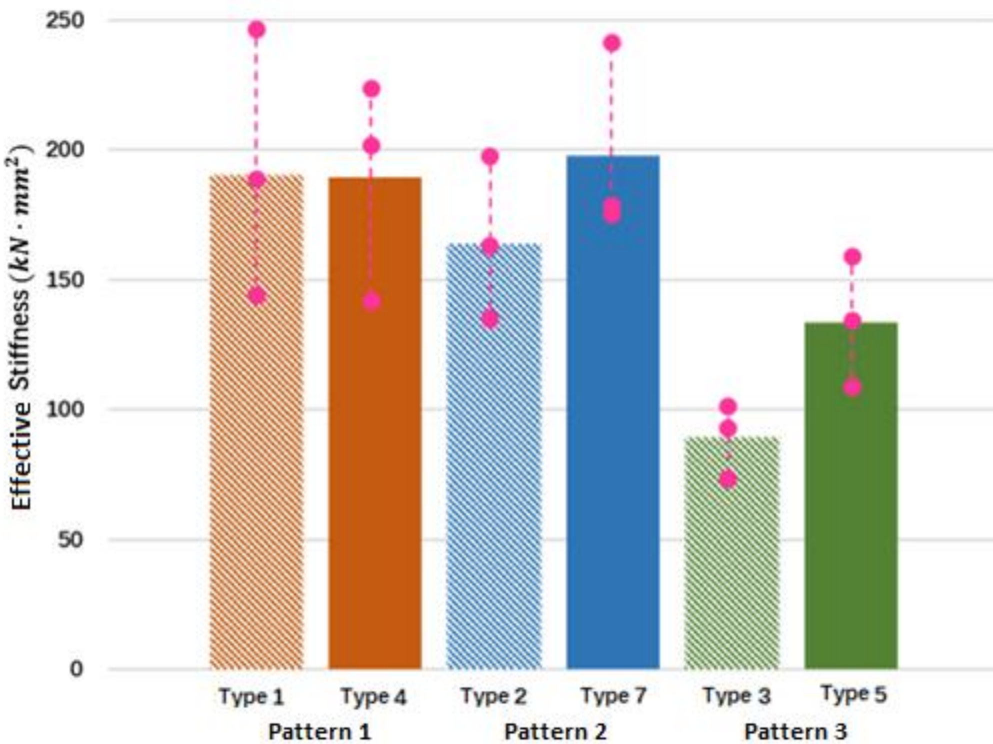


Figure 38 Effect of Nailing Reinforcement on EI_{eff} of NLT

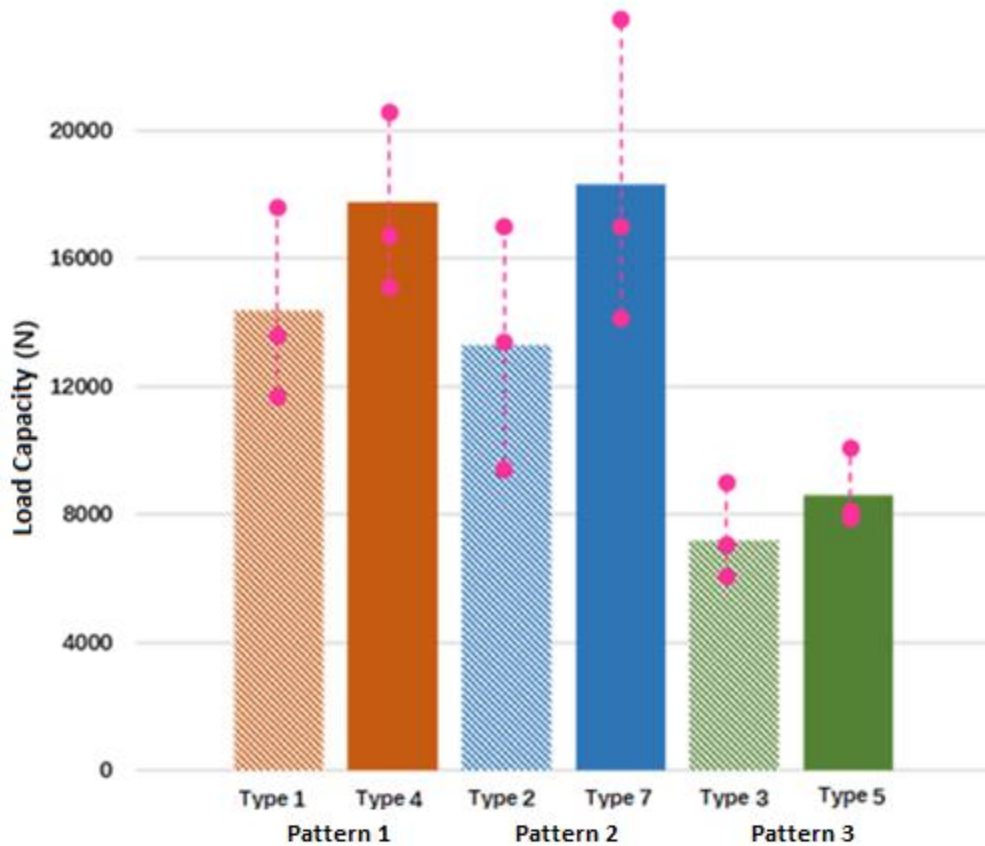


Figure 39 Effect of Nailing Reinforcement on P_{peak} of NLT

The EI_{eff} values of unreinforced and nailing reinforced NLT specimens with butt joint pattern 1 were 190 $\mathrm{kN} \cdot \mathrm{mm}^2$ and 189 $\mathrm{kN} \cdot \mathrm{mm}^2$, separately. No significant restoration of EI_{eff} resulting from nailing reinforcement was observed in NLT specimens having butt joints pattern 1. This suggests that applying nailing reinforcement to recover EI_{eff} of NLT specimens with a conservative butt joint pattern was not very helpful.

The recovering effect brought by nailing reinforcement on EI_{eff} of NLT specimens with butt joints patterns 1, 2, and 3 increased exponentially, which were 0%, 21%, and 49% individually. This implies that the existence of butt joints, an increase in the number of butt joints and a decrease in butt joint spacing, could increase the effect of nailing reinforcement on recovering EI_{eff}. In addition, nailing reinforced NLT specimens with butt joint patterns 1 and 3 could recover 24% and 20%, respectively, of P_{peak} of the specimens without reinforcing nails. These were less than the 38% recovery measured in NLT specimens with butt joint pattern 2. This implies that the effect of nailing reinforcement towards increasing P_{peak} of NLT specimens was most significant when they had a "limit state" butt joint pattern. What is more, compared to the results of metal plate high [strength, 20-gauge (0.9-mm) toothed connectors with a width of 5.25 in. (133 mm) and a length of 8.75 in. (222 mm)] reinforced 3-layer NLT, which were 25% and 14% (D. R. Bohnhoff et al., 1991), increase in EI_{eff} and P_{peak} of nailing reinforced NLT specimens with butt joint pattern 2 were 21% and 38%, indicating that applying nails as reinforcement might do more help to recover bending strength, than using metal plates as reinforcement.

The EI_{eff} of nailing reinforced NLT specimens with butt joint pattern 2 was 198 $\mathrm{kN \cdot mm^2}$, which was 8 $\mathrm{kN \cdot mm^2}$ larger than reinforced NLT specimens with butt joint pattern 1. Also, the P_{peak} of the nailing reinforced NLT specimens with butt joint pattern 2 slightly exceeded the P_{peak} of nailing reinforced NLT specimens with butt joint pattern 1 by 555 N, although the deviation among the values of P_{peak} was higher. Besides, through nailing reinforcement, EI_{eff} and P_{peak} of NLT specimens with butt joints patterns 3 was not recovered to a satisfactory degree, further verifying the weakness of butt joint pattern 3.

Furthermore, for NLT specimens having butt joint patterns 1 and 2, nailing reinforcement helped recover 24% and 38% on P_{peak} while it helped recover just 0% and 21% on EI_{eff}.

This might imply that the influence of nailing reinforcement was more significant on P_{peak} than on EI_{eff} for those NLT specimens with butt joint pattern in a "limit state" or a "conservative state".

In summary, the results might suggest that applying appropriate nailing reinforcement on NLT specimens with butt joints in a "limit state" could be the most economic and effective approach to construct NLT. The EI_{eff} and P_{peak} of nailing reinforced NLT specimens with such butt joint pattern were only 20% and 27% lower than the reference.

4.3.3. Discussion on the stiffness reduction equation in CSA S6

According to the bending stiffness reduction factor, $k = (N-1)/N$, proposed in the CSA S6 (Canadian Standards Association, 2010), the estimation of reduction on EI_{eff} of NLT deck can be calculated by:

$$Reduction\ in\ EI_{eff} = 1 - k$$

Equation 12

Taking the butt joint patterns 1, 2, and 3 as three completed patterns and repeating them in three NLT decks separately, the frequency of butt joints for Patterns 1 and 2 NLT decks were both found theoretically to be 1-in-3 in a band with a width of 1,000 mm. However, in butt joint pattern 3, the distance between butt joints in adjacent laminations was 500 mm which is 50% less than the minimum butt joint spacing regulated in the standard. Therefore, Equation 12 was only allowed to be used in estimating the reduction of EI_{eff} of NLT decks with butt joint patterns 1 and 2, and an estimation of 33% was calculated for both. Table

11 shows the estimated and measured reduction in EI_{eff} of NLT specimens with and without nailing reinforcement.

Table 11 Estimated and measured reduction in EI_{eff} of NLT specimens

Butt joint pattern	***Reduction on EI_{eff} (%)***		
	Estimated based on CSA S6	***Measured***	
		Without nailing reinforcement	***With nailing reinforcement***
1	33	23	23
2	33	34	20
3	N/A	64	46

The measured reduction in EI_{eff} of unreinforced NLT specimens with butt joint pattern 2 was 34 %, which was close to 33%, i.e. the estimated reduction based on the stiffness reduction factor k. However, for the unreinforced NLT specimens with butt joint pattern 1, it was measured that EI_{eff} was 23% lower than that of NLT specimens without butt joints. In addition, EI_{eff} values of nailing reinforced specimens with butt joint patterns 1 and 2 were 23% and 20% lower than the EI_{eff} of the reference, respectively. Measured reduction percentages on EI_{eff} of these three NLT specimens were 10% to 13% less than the estimated values. Although butt joint patterns 1 and 2 had the same “in theory” 1-in-3 frequency of butt joints in a band with a width of 1000 mm, their butt joint patterns were actually different and consequently produced different stiffness reduction results. The results in this study showed that the stiffness reduction factor k was only applied in unreinforced NLT specimens with butt joint pattern 2, where the butt joint pattern was under the "limit state".

To summarize, it could be reasonable to say that the definition of the stiffness reduction factor k in current CSA S6 standard was too conservative, providing an under-estimated stiffness. It could be suggested that additional conditions of using Equation 12 should be specified, such as more detailed specifications of the so-called 1-in-3 frequency of butt joints. The results of this study suggest that k could not be applicable in the majority of NLT specimens with butt joint patterns that were more conservative than those of "limit state", or under nailing reinforcement circumstances. This implies that modification could be done on k.

4.3.4. Effect of lumber groups on EI_{eff} and P_{peak} of NLT specimens

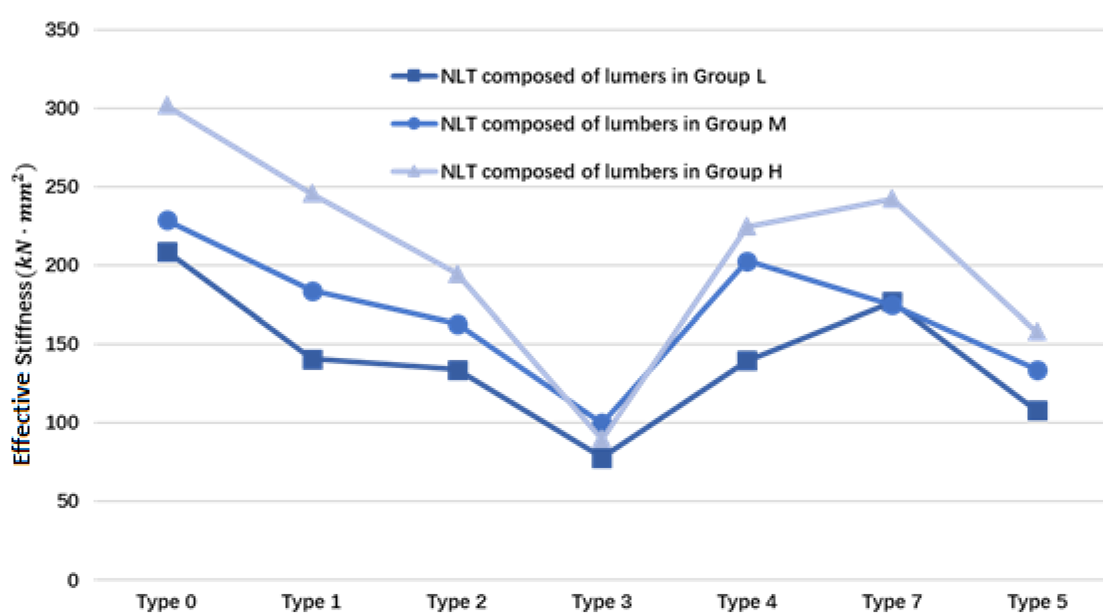


Figure 40 Effect of MOE of lumbers on EI_{eff} of NLT specimens

Figure 40 summarizes EI_{eff} of NLT specimens of various types regarding the MOE group of lumbers. Overall, EI_{eff} of NLT specimens follows the 'theory', i.e. the higher the MOE of lumbers is, the stiffer the NLT specimens are. However, EI_{eff} of specimen 3-3-H was an exception. The reason is not clear, which could be due to testing error.

EI_{eff} of specimen 3-7-M, overlapping on specimen 3-7-L, was found to be out of its predicted value in Figure 40. Efforts to figure out the reason was done by observing the failure mode. The segment slips in the location of butt joints combined with bent nails were observed in both center and outer laminations, as depicted by circles in Figure 41. No bent nail was observed in specimens 3-7-L and 3-7-H. This might be the reason for a surprisingly low EI_{eff} of specimen 3-7-M.

Figure 41 Segment slip accompanied with nail bended in specimen 3-7-M

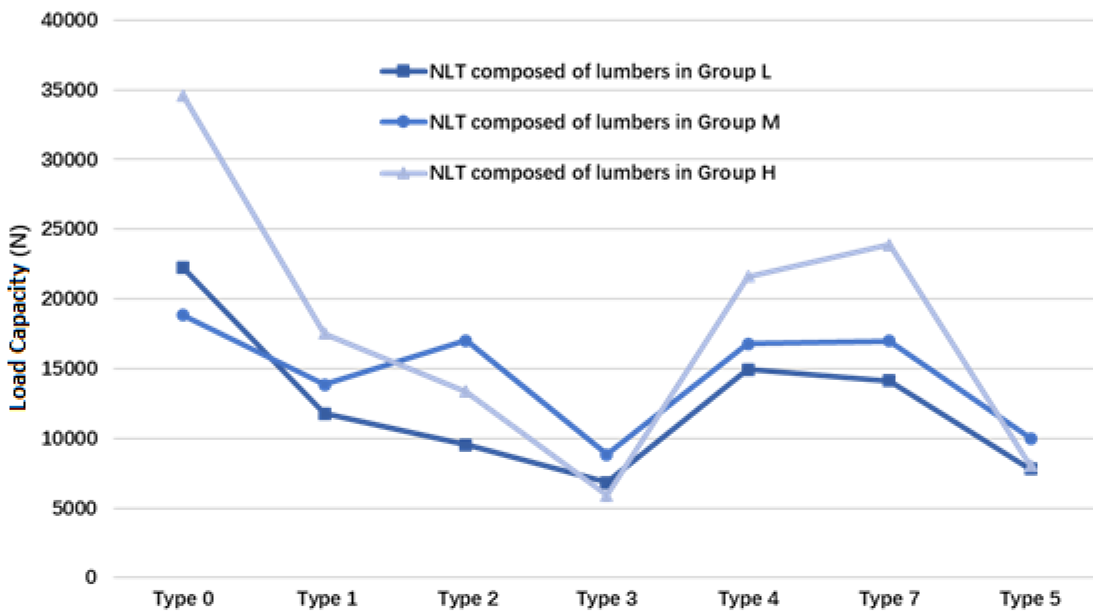


Figure 42 Effect of MOE of lumbers on P_{peak} of NLT specimens

The general increasing tendency of P_{peak} of each NLT specimen corresponding to the growing MOE was not as obvious as that of EI_{eff}, as shown in Figure 42, this could be attributed to the variation in properties of wood and a small sampling size (only one specimen in each MOE group given a configuration).

Some exceptions could be due to the defects of lumbers. The P_{peak} of specimen 3-0-M was lower than specimen 3-0-L, this could be excused by a knot in the bottom of an outer lamination, which was right under the location of one loading point, easily causing the failure of lumber with a lower stress (see Figure 43).

Figure 43 A knot existing at the location of failure in specimen 3-0-M

P_{peak} of specimen 3-2-H falls between specimens 3-2-L and 3-2-M, which is lower than the predicted value. In addition to a large tension failure within the maximum bending moment area, a crack almost throughout the length of lumber was witnessed in one outer lamination (lumber No. 74), as shown in Figure 44.

Figure 44 Extensive internal splitting in lumber (No. 74), specimen 3-2-H

However, some exceptions were hard to explain by observing the exterior failure of specimens. It can be noticed that specimen 3-3-H had a lower EI_{eff} and P_{peak} than specimens 3-3-L and 3-3-M, even though it was fabricated using the lumbers of high density and MOE. However, no obvious deviation compared to the other two specimens was visually observed from the appearance of the NLT specimen. Similarly, P_{peak} of specimen 3-5-H was unexpectedly low as well. By giving a close look at the failure modes of Type 5 NLT specimens, no distinct feature was found to explain why specimen 3-5-H had an unexpectedly low load capacity. Figure 45 shows the identical failure mode for 3-5-L and 3-5-H.

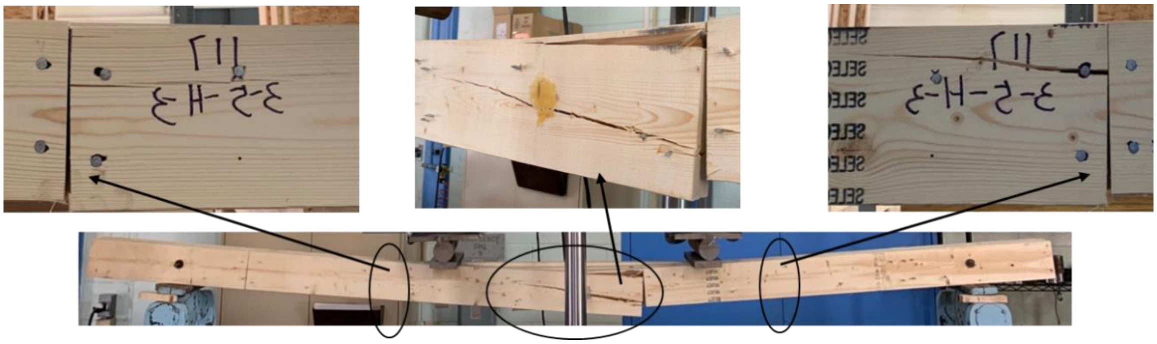


Figure 45 Identical failure mode for 3-5-L and 3-5-H

In summary, the mechanical properties of NLT specimens increased with increasing MOE of lumber used, which was particularly evident in EI_{eff}. The defects of lumbers had negative impacts on the mechanical properties of NLT specimens. The values out of expectation could be due to the limitations of guaranteeing straightly punching nails without any operational errors, the unexposed inherent flaws of lumbers in the center laminations, and the small sampling size with only one for each group. It is recommended to use lumber of high quality to fabricate NLT and minimize labour error during construction.

5. Conclusions and Future Work

The flexural properties including effective bending stiffness (EI_{eff}) and load capacity (P_{peak}) of 3-layer NLT specimens with three different butt joint patterns and either with or without nailing reinforcement, were tested and compared to those of unreinforced 3-layer NLT specimens without butt joints. Stiffness reduction factor k was examined based on the tested results. Additionally, the influence of lumber properties, i.e. MOE, of lumbers on the mechanical performance of the NLT specimens were discussed. Based on the results and discussion, the following conclusions could be drawn:

1) The average reduction in EI_{eff} of unreinforced NLT specimens with a "limit state" butt joint pattern was 34%, compared to those without butt joints, i.e. the reference specimens. It was the only circumstance in this study where tested reduction was in good agreement with the result estimated according to the stiffness reduction factor $k = (N-1)/N$ in CSA S6 standard. It could be suggested that additional conditions when using k to estimate stiffness reduction should be specified, such as a more detailed statement of the so-called 1-in-3 frequency of butt joints. Besides, k seems too conservative and could not be applicable in the majority of NLT specimens with butt joint patterns that were "conservative" rather than "limit state", or under nailing reinforcement circumstances. This implies that modification could be done on k;
2) Because of the existence of butt joints, an increase in butt joint number, and a decrease in butt joint spacing, both EI_{eff} and P_{peak} of NLT specimens were

reduced to some degree. The reduction in EI_{eff} and P_{peak} of 3-layer unreinforced NLT specimens with an aggressive butt joint pattern could be as much as 64% and 71%, respectively. However, it was highly acknowledged that the variability in EI_{eff} and P_{peak} of NLT specimens, caused by the variations in properties of lumber, was reduced by taking into account the uniform arrangement of butt joints.

3) Nailing reinforcement could be an effective and convenient approach to increase the EI_{eff} and P_{peak} of NLT specimens with butt joints. Placing four extra nails at butt joints helped recover EI_{eff} and P_{peak} of NLT specimens with butt joint pattern in a "limit state" by 21% and 38%, respectively. The EI_{eff} and P_{peak} of nailing reinforced NLT specimens with such a butt joint pattern were only 20% and 27% lower than the reference; and
4) It was suggested that using a lumber of higher quality, minimizing labour error during construction, arranging butt joints in the pattern of a "limit state" and, applying appropriate nailing reinforcement, could be the most economic and effective way to construct NLT. It could help maintain the overall mechanical performance and reduce variability.

Based on the findings from this thesis project, the following recommendations are made for potential future work:

1) Similar bending tests are encouraged to be performed on NLT specimens with more laminations to verify the applicability of the bending stiffness reduction factor provided in the current standard;

2) The nailing reinforcement should be re-examined by placing more nails (e.g. 6 in total) or adopting steel plates in a butt joint to see the degree of reinforcement in recovering the properties of NLT specimens. The end distance of nails used in reinforcement and placement should be specified by modelling and testing; and
3) Dynamic tests should be conducted on NLT specimens of butt joints when used for timber bridge decks.

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