

Creep Behaviour of Thin Cross-Laminated Timber under Short-term Loading

By

Meizhen Chen

Bachelor of Science in Engineering (Wood Science and Engineering), Nanjing Forestry University, P. R. China, 2020

A Report Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Forestry Engineering

in the Graduate Academic Unit of Forestry and Environmental Management

Supervisory Committee: Meng Gong, PhD, FOREM, Supervisor
Brad Wang, Ph.D., FOREM-Adjunct Professor, Co-supervisor

Examining Board: Ling Li, PhD, FOREM-HRA, University of Maine

This report is accepted by the
Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

August 2021

©Meizhen Chen, 2021

Abstract

Cross-laminated timber (CLT) has been developed and used in building applications, such as walls, roofs, and floors, which are subjected to long-term loading in the perpendicular-to-grain direction. Thus, the creep performance of CLT is critical in the design and construction of a building using CLT panels. The creep behaviour of a material, component, connection, or system is defined as the deformation increases with time under constant load. This thesis report examined the creep of CLT using the thin specimens. Two loading levels (60% and 30% of proportional limit (PL), or 93kg and 25kg), two relative humidities (30% and 65%), and two panel directions (major and minor). A total of four groups of thin CLT specimens were fabricated, and each group had six specimens (three for major and three for minor), producing a total of 24 specimens. The third-point static bending tests were performed to determine the load levels for creep tests. A constant load was applied on each specimen, and the flexural deflection was recorded in the course of loading. It was found that 1) In third-point bending test, the PLs of thin CLT specimens in the major and minor directions were 3,000N and 800N, respectively. The average MOE_{app} and MOR_{app} of the specimens in the major direction were 8,510 MPa and 46.64 MPa, respectively, and the average MOE_{app} and MOR_{app} in the minor direction were 809 MPa and 9.48 MPa, respectively; 2) With increasing load level up from 30% to 60% PL, the minor strength direction specimens deflected 81.04% than that of 30% PL. And for major strength direction specimen, the deflection increased 32.07%; 3) With decreasing the RH, the deflection of CLT specimens showed a slower increment. At the load level of 60% PL,

the deflection of creep specimens in the minor direction showed a difference of about 2 mm after 7 days. However, at the load level of 30% PL, RH showed little impact on creep. 4) CLT in the major direction exhibited a superior load-bearing capacity than those in the minor direction. At the load level of 30% PL, the maximum deflection in the minor direction was about 1.8 times larger than that in the major one, and at the load level of 60% PL, the deflection in the minor direction was approximately 2.5 times larger than that in the major one. 5) The Burger model could well describe the 7-day creep of thin CLT specimens with a high r-square value around 0.9135 tested in this study. It could be recommended to investigate the long-term creep behaviour of full-size CLT members by taking cyclic humidity and edge-bonding into account for at least one to three months.

Keywords: Creep, cross-laminated timber, modelling, panel direction, relative creep, relative humidity, load level

Acknowledgements

Firstly, my deepest gratitude goes and foremost to Dr. Meng Gong, my supervisor, for his constant encouragement, guidance, and patience. He talked me through all the stages about how to write this report and gave me precious advice and suggestions all the time. He also helped me a lot in my daily life during the COVID-19 quarantine time. Mr. Brad Wang, my co-supervise, steered me in the right direction of this report and gave me much useful academic advice. Also, Dr. Ling Li, my advisory committee member, reviewed my report and provided me with her comments and suggestions. Without the constructive and consistent instructions from Drs. Gong, Wang and Li, this report could not have reached its present form. I appreciate all the help and work they have done for me, which helped me advance quickly in both my studies and daily life. Those things mean a lot to me during these two years.

Secondly, I would like to express my acknowledgements to Mr. Dean McCarthy and Mr. Greg McCarthy, the technicians in the Wood Science and Technology Centre, the University of New Brunswick, who helped a lot to make the specimens for my experiments and encouraged me to do my best in this project.

Thirdly, I would like to extend my gratitude to the New Brunswick Innovation Foundation's Innovation Research Chair Program and the 3+1+1 program between the University of New Brunswick and Nanjing Forestry University (China). I really appreciate their support in this project.

Lastly, my thanks go to my beloved family, Hongle Zhang, Yuzheng Cheng, boyfriend Yuyang

Zhou, and Mr. Zizhen Gao, Yujing Luo, Luji Xiong for their support, considerations, and high confidence in me all through years. I also owe my sincere gratitude to my friends and roommates who worked with me and gave me their help and time listening to me and helping me work out the problems together during this challenging period both in courses and in life.

Thank you all.

Table of Contents

Abstract:	i
Acknowledgements	iii
Table of Contents	v
List of Figures	viii
List of Tables	xii
List of Terminology and Symbols	xiii
1 Introduction	1
1.1 Background	1
1.1.1 Mechanical properties of CLT	6
1.1.2 Materials and manufacturing process of CLT in industrial	11
1.2 Creep behaviour	14
1.2.1 Creep in wood	14
1.2.2 Creep in CLT	19
1.3 Classical modes of creep	20
1.3.1 Maxwell model	20
1.3.2 Kelvin Model	23
1.3.3 Generalized Kelvin Model	26
1.3.4 Burger Model	29
1.4 Technical review on the creep of CLT and other wood-based products	34

1.5	Objectives and Scope of Research	51
2	Materials and Specimens.....	52
2.1	Specimen design.....	54
2.2	Specimen preparation	60
2.2.1	Laminations.....	60
2.2.2	Edge-bonding	65
2.2.3	Lay-up (face-bonding), vacuum-pressing and curing	68
2.2.4	Cutting	71
3	Methods.....	74
3.1	Third-point bending.....	74
3.1.1	Calculations	76
3.2	Short-term creep tests	79
3.2.1	Calculations	84
3.3	Modeling of creep behaviour.....	85
4	Results and Discussion.....	86
4.1	Mass	86
4.2	Flexural test results	88
4.3	Short-term creep test results	98
4.3.1	Creep Curves.....	98
4.3.2	Relative Creep	105

4.4	Creep model	110
5	Conclusions.....	114
	References	116
	Appendix: A General results of specimens and tests	121
	Curriculum Vitae	

List of Figures

Figure 1.1 CLT roof and floor.....	2
Figure 1.2 A typical five-layer CLT panel configuration with strength directions	5
Figure 1.3 In- and out-of-plane loading patterns	9
Figure 1.4 Rolling shear effect for a linear load.	9
Figure 1.5 The failure of CLT because of rolling shear.	10
Figure 1.6 The manufacturing process of CLT.	13
Figure 1.7 The bent roof beam because of long-term loading.....	15
Figure 1.8 Force- and Deformation-time curve.	16
Figure 1.9 Typical creep curve in different stage.....	18
Figure 1.10 Maxwell Model.	22
Figure 1.11 Kelvin Model.....	25
Figure 1.12 Generalized Kelvin Model.	28
Figure 1.13 The representation of creep behaviour of Burger’s model.	30
Figure 1.14 Burger Model.....	33
Figure 1.15 Deflection of MDF under creep loading along the plane of board.....	36
Figure 1.16 Deflection of MDF under creep loading along the edge of board.....	37
Figure 1.17 One creep Deflection-Time curve of SIP	41
Figure 1.18 The anisotropy of initial and creep compliance of 6 wood species with four types of laminated wood specimens.	43

Figure 1.19 Parallel-laminated and cross-laminated wood specimens.	45
Figure 1.20 Creep deflection of CLT specimens.	48
Figure 1.21 Creep compliance of the specimens tested under various load levels.	49
Figure 2.1 The procedure of making specimens.	53
Figure 2.2 The flexural test method of four-point bending.....	56
Figure 2.3 The diagram of a whole CLT panel.	59
Figure 2.4 Cutting length using a circular saw (upper) and ripping width using a table saw (bottom).	61
Figure 2.5 Ripping lumber using the heavy-duty bandsaw (upper) and planing wood strips to a given thickness using a planer (bottom).	62
Figure 2.6 The wood strips piled in the conditioning chamber.....	64
Figure 2.7 Original Gorilla Glue.....	66
Figure 2.8 The clamping setup.....	69
Figure 2.9 Vacuum Bagging to press the panel.....	70
Figure 2.10 Cutting patterns of Panels 1 and 2.....	72
Figure 2.11 Cutting patterns of Panels 3 and 4 in major and minor strength direction, respectively.....	72
Figure 2.12 Cutting patterns.	73
Figure 3.1 Flexural test setup.....	75
Figure 3.2 Typical Load-Deflection Curve of W1B BA2.....	77

Figure 3.3 Creep test setup with an LVDT in the middle span of each specimen.	80
Figure 3.4 Loading the specimens.	81
Figure 3.5 Supporting steel rod at the end of the loading span.....	82
Figure 4.1 Normal distribution of Lamination mass.....	87
Figure 4.2 Load-Deflection Curves of Group W1 (major strength direction).	89
Figure 4.3 Load-Deflection Curves of Group W2 (minor strength direction).....	90
Figure 4.4 Failure modes of Group W1.	92
Figure 4.5 Rolling shear failure of Specimen at lamination 126.	93
Figure 4.6 Failure mode of W1 specimens.	95
Figure 4.7 Brush failure (upper) and fracture at a knot (lower).....	96
Figure 4.8 Average creep deformation curves of 30% load level Group1 (65%RH) and Group 2 (30%RH).	98
Figure 4.9 Average creep deformation curves of 60% load level Group3 (65%RH) and Group 4 (30%RH).	99
Figure 4.10 Average creep deformation curves of 65% RH Group1 (30% PL) and Group 3 (60% PL).....	100
Figure 4.11 Average creep deformation curves of 30% RH Group 2 (30% PL) and Group 4 (60% PL).....	101
Figure 4.12 Relative creep curves of Group1 (65%RH) AND Group 2 (30%RH) tested at 30% load level.	105

Figure 4.13 Relative creep curves of Group3 (65%RH) AND Group 4 (30%RH) tested at 60% load level.	106
Figure 4.14 Average initial deflections of 4 groups.	108
Figure 4.15 Maximum deflections of 4 groups.....	109
Figure 4.16 Burger model curve vs. General Kelvin curve of C2O.	113

List of Tables

Table 1.1 The specimens used for different types of tests on SIP.	39
Table 1.2 Short-term bending result after creep, foam flush end.....	40
Table 1.3 Creep ratios of measured values to the calculated values of initial compliance and creep compliance.....	46
Table 2.1 The distribution of lamination in each layer and summary.	57
Table 2.2 The size of a specimen in each step.	58
Table 2.3 Panel allocation.	67
Table 3.1 The specimen group of creep tests under the load of 7 days.....	83
Table 3.2 Generalized Kelvin model and Burger model.....	85
Table 3.3 Constants in curve fitting equations.....	85
Table 4.1 Allocation of laminae 12 one-layer surface panels and 4 middle layer panel...	86
Table 4.2 3-layer CLT panel allocation and mass	86
Table 4.3 Curve fitting equations of 4 groups specimens in major direction.	112
Table A.0.1 One-layer panel.	121
Table A.0.2 MC of each test specimens.	121

List of Terminology and Symbols

The major terminologies relating to CLT and the mechanical properties are given below.

(ANSI/APA, 2019):

CLT Panel: a single piece of CLT.

Edge Joint: a joint of the narrow faces of adjacent laminations within a CLT layer with or without gluing.

Face Joint: a joint of the wide faces of the adjacent layer within a CLT panel with or without gluing.

Lamination: a piece of sawn lumber, which has been prepared and qualified for laminating.

Layer: an arrangement of laminations laid out parallel to each other in one plane

Longitudinal layer: a layer with the laminations oriented parallel to the major strength direction.

Transverse layer: a layer with the laminations oriented perpendicular to the major strength direction.

Lay-up: an arrangement of layers in a CLT panel determined by the grade, number, orientations, and thickness of layers

Major Strength Direction: the direction parallel to strength direction of the laminations in the outer layers of the CLT panel.

Minor Strength Direction: the direction of the inner layers grain perpendicular to the major strength direction of the CLT panel.

MOE_{app}: the apparent modulus of elasticity, psi (MPa).

MOR_{app} : the apparent modulus of rupture, psi (MPa)

K: the bending stiffness in beams is also known as flexural rigidity

PL: the proportional limit

τ_{max} : the maximum shear stress, psi (MPa).

MC: the moisture content

1 Introduction

1.1 Background

The timber structure is a green, safe, low-carbon, renewable, and environmentally friendly sustainable structure that has been vigorously advocated in recent decades. It has a warm and close-to-natural appearance, which is one of its aesthetic advantages. In recent decades, many mass timber products have been developed.

Cross-laminated timber (CLT) was originated in Europe in the 1990s. As a new type of engineered wood product (EWP), CLT has globally been used to construct residential and non-residential buildings along with concrete and steel and more and more widely used in mid-rise (6-8 stories) and high-rise (more than eight stories) buildings (FPInnovations, 2019), see Figure 1.1. The first CLT buildings appeared in Switzerland (1993), Germany (1995), and Austria (1998), and later, the first multi-storey CLT project was completed in Styria, Austria (Bowyer, 2016). In 1998, the Austrian National Building Code recognized for the first time that multi-storey buildings could be constructed with CLT materials.



Figure 1.1 CLT roof and floor (Source: <https://www.structurlam.com/construction/products/d/cross-laminated-timber-clt/>)

Now, CLT has become a global research hotspot, especially in Europe and North America. As the mainstream research material of modern timber structure, the basic characteristics of its configuration, pros and cons of CLT are also discussed in the following section.

Normally, CLT panels consist of an odd number of laminates, which start at least three layers and press together on their wide faces and sometimes on narrow faces. This odd layer lay-up is arranged to establish a symmetric configure with one-layer lumber in the middle to avoid brittle fracture in the bonding section and improve the mechanical properties of CLT products. The layers of board alternate the orientation in neighbour layers, typically at 90 degrees (shown in Figure 1.2), providing a two-way action capability: one, the major strength axis, is parallel to the longitudinal direction of lumber, and another one is the minor strength direction, which is perpendicular to the longitudinal direction (Gong, 2019). Wood is often primarily used in the longitudinal direction, which has the highest strength and stiffness. In some particular configurations, doubled major axis direction of outer layers is available to increase load-carrying capacity (FPInnovations,2019). However, no matter what kind of the crossed configuration of the laminates inside the CLT product, the laminations within one layer, which along the same direction, should be made of sawn lumber with the same grade lumber, and the same species to keep the consistency.

During the construction, all these full-size structural members like the floor slabs, wall panels

and roof slabs, as well as some linear timber members, are directly transported to the site for quick installation, which can increase the speed and efficiency of construction. Moreover, the excellent sound and thermal insulation, good environmental performance (comparing with the concrete system), fire resistance and beautiful appearance also make this product increasingly popular in construction and wood industries throughout the world.

While the code and production system of CLT products are established in Europe and North America, there are still many requests for research to advance CLT products with innovative manufacturing technologies and building techniques.

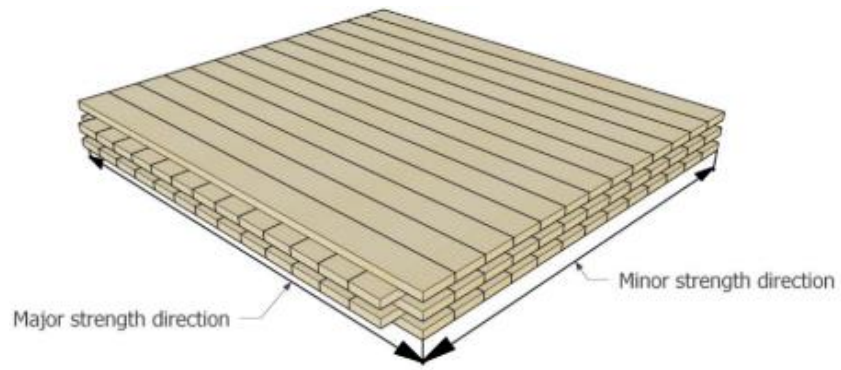


Figure 1.2 A typical five-layer CLT panel configuration with strength directions

1.1.1 Mechanical properties of CLT

Because of the nature of its cross laminae which consists of layers of dimension/MSR lumber (typically three, five, or seven) oriented at right angles to one another and then bonded using adhesives (Gong, 2019). It is quite versatile in load-bearing and more suitable for a high-rise building as structural and loading-carrying members like floor slabs, walls, roofs, girders, and columns to bear the in-plane and out-of-plane loads (shown in Figure 1.3).

GLT (GLT or glulam) is a structural product composed of multiple pieces of finger-jointed dimension lumber, or other types of EWP, adhesively face-to-face bonded to create a desired form. (Gong, 2019) Compared to solid lumber or GLT, CLT has excellent dimensional stability. The conventional structure of adjacent CLT layers results in similar shrinking and swelling performance in the major and minor directions of a CLT panel. Studies have shown that the linear shrinking-swelling coefficient of CLT is 0.02%, and its dimensional stability is 12 times that of solid wood and GLT in the cross-grain direction (Fu, 2012). Also, given the nature of CLT with the orthogonal arrangement of layers that are bonded with structural adhesive, CLT is more prone to time-dependent deformations under load (creep) than other engineered wood products such as GLT.

Besides, this deformed structure can also have similar strength properties in the major and minor directions of CLT product, higher strength in the plane and out of the plane, and the

ability to prevent the connector from splitting because of the orthogonal arrangement of the layup. CLT sheet structure has the characteristics of high rigidity, good plasticity and energy consumption. There is almost a gap between the CLT building components, which forms a space for shrinking and swelling. Due to the anisotropy of the mechanical properties of the wood and the structural characteristics, the rolling shearing stiffness and strength of CLT are the key to determining the mechanical properties of floor and roof panels. Moreover, CLT is prone to time-dependent deformations (creep) under load than other engineering wood products such as GLT. Therefore, creep behaviour is also a critical characteristic that should be taken into consideration.

Additionally, the rolling shear impacts other mechanical properties of CLT to a large degree. Rolling shear stress is defined as the shear stress leading to shear strains in a plane perpendicular to the grain (Fellmoser and Blass, 2004). Due to the basic lay-up configuration of regularly used CLT, the rolling shear properties of a cross-layer (i.e., radial and tangential plane in wood) are very low (Zhou, 2014). It has been proved that even the duration of load effect on the rolling shear strength in the core layers of CLT (shown in Figure 1.4) and the non-edge glued CLT, in which gaps exist between laminations, is more challenging for the study of load duration (Yuan, 2016). The gaps between lumber could provide some tolerances for wood movement due to the change in moisture in service. However, the European practice appears to widely apply edge-gluing with an aim to offer good stiffness and strength of a CLT panel

(Gong, 2019). Figure 1.5 is a typical failure, which is caused by rolling shear.

Overall, CLT obtains the advantages of better dimensional stability, good heat insulation and fire resistance, more considerable compressive rigidity and strength, etc., and a higher degree of assembly. However, CLT members are prone to rolling shear stress in the flexural test. To solve this problem in the industry, the hybrid CLT product with some better shear resistant lumber products can be considered due to its low production cost and high shear strength and rigidity. To minimize the effects caused by rolling shear, edge bonding was applied in this study.

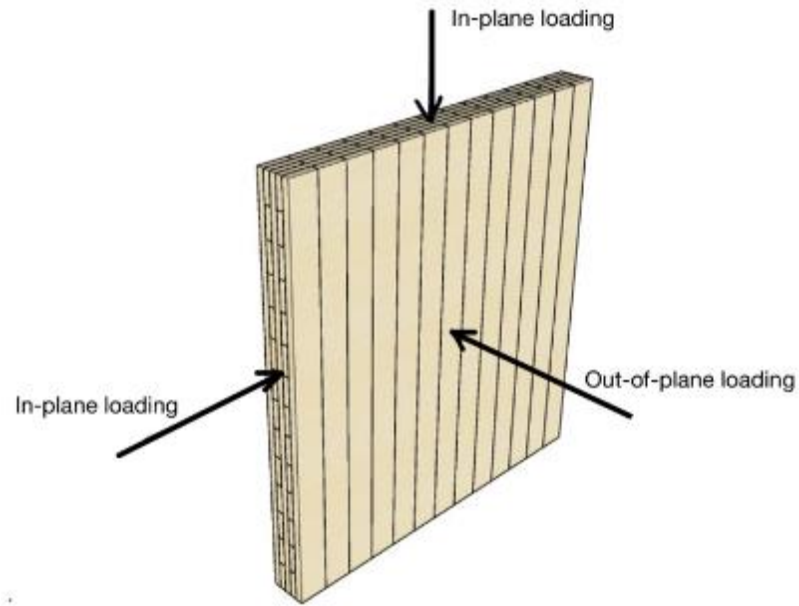


Figure 1.3 In- and out-of-plane loading patterns

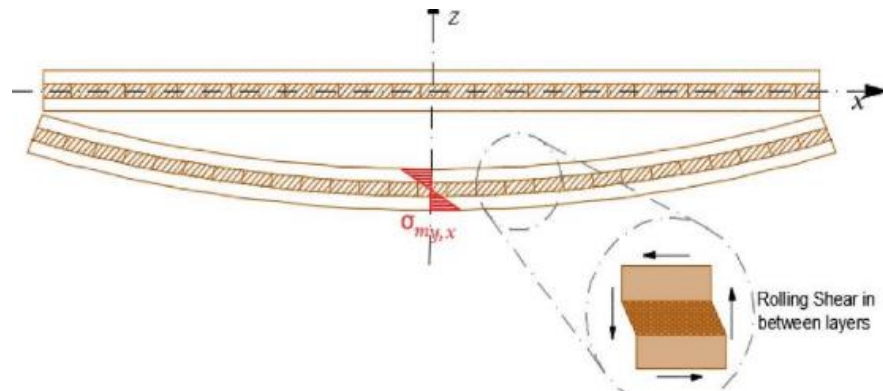


Figure 1.4 Rolling shear effect for a linear load (Pereira, 2019).



Figure 1.5 The failure of CLT because of rolling shear (Yuan 2016).

1.1.2 Materials and manufacturing process of CLT in industrial

The wood species are commonly softwoods, such as spruces and pines, in North America with the minimum specific gravity of 0.35 (ANSI/APA, 2019), which are evaluated through PS20 (ALSC, 2020) in America, CSA O141 (CLSAB, 2005) and CAS O86 (CLSAB, 2019) in Canada. The lumber is kiln-dried and graded. The moisture content is 15%. The grading of sawn lumber uses visual classification and mechanical classification. Generally, low-grade sawn lumbers are used for the inner layer with low-quality requirements, and high-grade sawn lumbers are used for the outer layer. The commonly used lumber products in the manufacturing of CLT are dimension lumber of a grade of No. 1/No. 2 or MSR lumber of a grade of 1200f-1.2E or better in its major strength direction, and dimension lumber of a minimum grade of No.3 in its minor strength direction (Gong, 2019).

The basic process of producing the CLT panel including nine steps shown in the flow chart below and some critical points will be highlighted in this sector referring to the CLT Handbook (FPInnovations, 2019). In step 5, normally the elongated lumber is used to face-to-face and/or edge-by-edge laminating to form two-dimension components, which is a crucial role in maintaining the integrity of the timber structure and in providing strength, stiffness, stability. The use of edge-gluing or not slightly differs in the manufacturing of CLT between North America and Europe. In North America, edge-gluing of lumber isn't a standard follow because of the supplemental producing costs. The gaps between lumber on edge face could provide

some tolerances for shrink and swell movement due to the change in moisture in service. However, which method the European practice is to widely apply edge-gluing with an aim to improve the integrity and offer good stiffness and strength of a CLT panel. Thus, to achieve the harmonization between production cost and improved performance of the panel, edge-gluing of selected layers as needed could be adopted. (Gong, 2019)

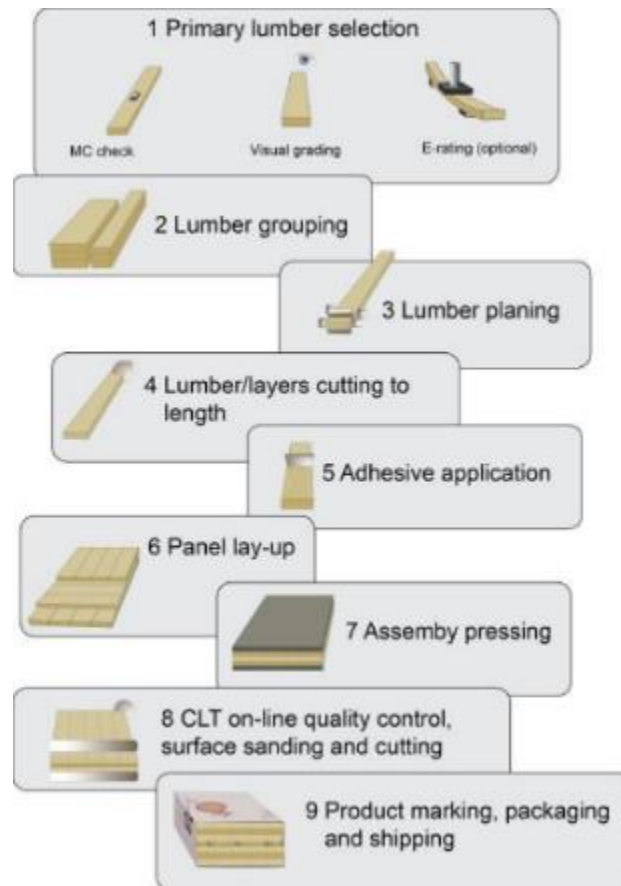


Figure 1.6 The manufacturing process of CLT. (FPInnovations, 2019)

1.2 Creep behaviour

1.2.1 Creep in wood

The phenomenon that the strain of wood increases with time under constant stress is called creep (Ferry 1980). Figure 1.7 shows the basic deformation-time curve of a structure under constant load and then with the load removed from t_2 . From the diagram, the total deflection measured at a specific time minus the initial deflection is the creep deflection at that point, and the initial deformation is the deflection right after the application of load. Relative creep is the ratio of creep deformation to initial deformation.

This phenomenon occurs due to long-term exposure to levels of stress that are below the yield strength of the material. Generally, wood will undergo creep under stresses such as bending, stretching, compression, and shearing. Factors such as wood species, grain direction and variation of different wood properties, applied load (stress) level, exposure time, and environmental variables such as temperature and relative humidity, may have an impact on the rate of creep deformation to an uncertain degree. Therefore, depending on the magnitude of the applied load and its duration, deformation may become so large that a component cannot perform its function. Figure 1.8 shows the effects of creep behaviour in roof beams after a long period under dead load.



*Figure 1.7 The bent roof beam because of long-term loading.
(Source: <https://www.iom3.org/wood-technology-society/creep>)*

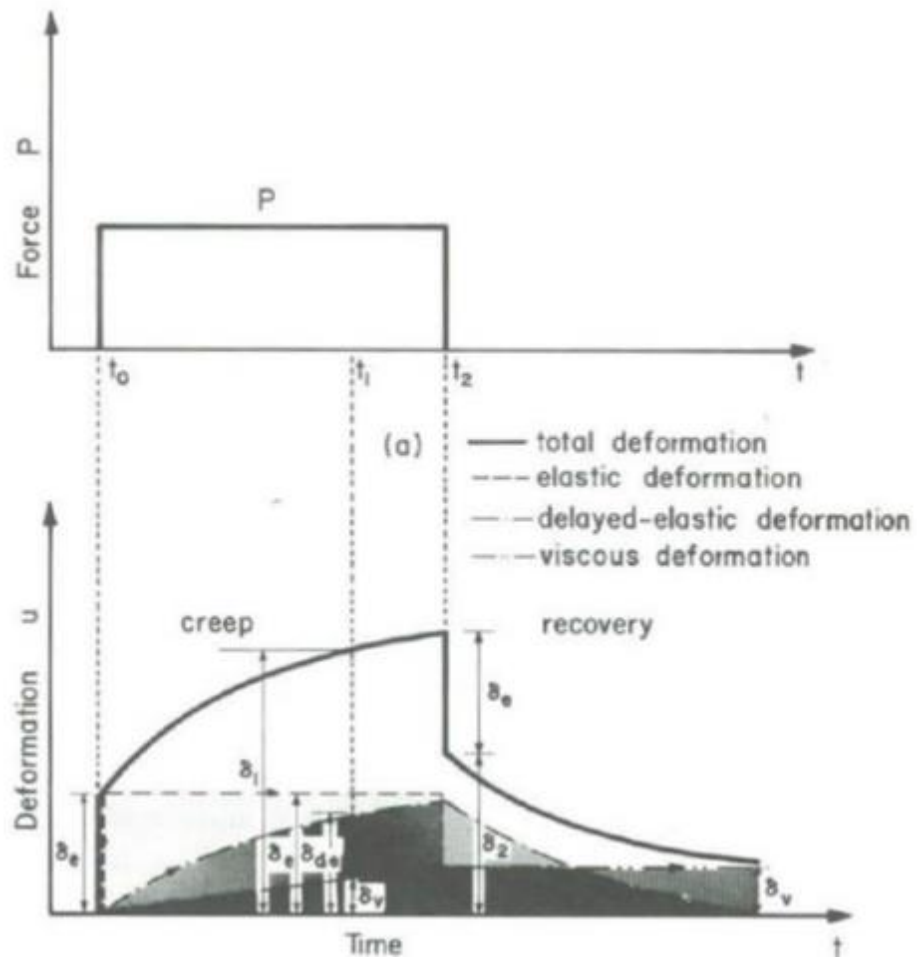


Figure 1.8 Force- and Deformation-time curve.

Creep includes three distinct types of behaviour (Figure 1.9), which are difficult to separate because they can all operate simultaneously. As a kind of visco-elasticity material, at least within the linear range of viscoelastic response in Figure 1.9, all the above tests are interrelated in mathematical expressions combining Hooke's law and dashpot. Also, as the figure shows, the strain suddenly increases dramatically after decades, and then the specimen will fail. These are a time-dependent (viscoelastic) creep; mechano-sorptive, which is the deformation of loaded wood under dynamic temperature and moisture (Ma, 2008); and the pseudo-creep and recovery that has been ascribed to differential swelling and shrinkage (Hunt, 1999). Other behaviours related to creep include relaxation, stress decrease under the constant deformation, and recovery, the recovery from strain once a load is removed (Bodig and Jayne, 1982).

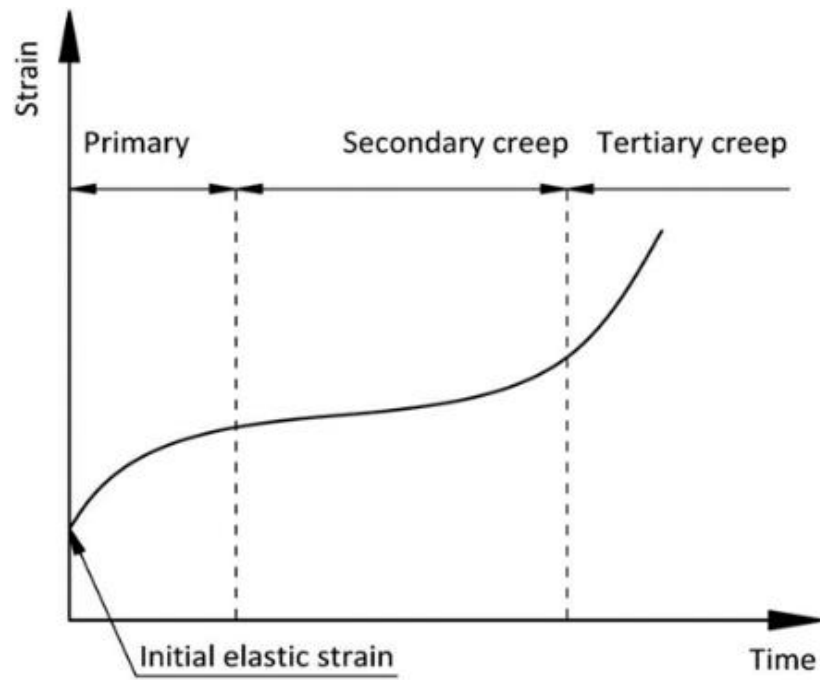


Figure 1.9 Typical creep curve in different stage.

1.2.2 Creep in CLT

As for CLT, which is made of laminated lumber, the additional factors will affect its creep behaviour. Unlike one-dimensional wood products like GLT and laminated veneer lumber (LVL), CLT, plywood, and oriented strand board (OSB) are deemed as two-way action capability products. Since regular lumber is anisotropic material and only obtain the highest strength in longitudinal direction. The variance between directions when the load applied reflects different physical properties. However, by gluing the laminae at a 90-degree, the variance between directions would be offset to some degree. The direction of structural specimens and the rolling shear stress between laminations also affect the creep behaviour to a large degree, and these factors need to be taken into consideration within this report.

Researchers have collected extensive creep data for numerous wood species. However, not all of these are directly applicable to modelling the long-term creep behaviour of wood structures because of adverse experimental objectives (Holzer, 2007). Also, if the relative humidity is too high, the CLT members will spontaneously absorb moisture from the environment, leading to large creep deformation to a structure.

Therefore, the factors must be kept consistent during the test, except for load-level, relative humidity, which are taken into consideration of comparing the results to analyze which factor affects the mechanical performance most and best predicts its lifespan.

1.3 Classical modes of creep

In summary, many factors impact the creep behaviour of wood, including temperature, moisture, relative humidity, grain direction, loading conditions, size, wood variability, and anatomical characteristics, resulting in an extremely complex creep behaviour. It is not easy to build a universal model to simulate such a time-dependent deformation of wood. However, some classical models have the ability to interpret this complex behaviour and get an approximately predicted result to help understand and observe the mechanical properties of the composite. These models have been, based on some assumptions, simplified to a large degree and basically include a spring and a Newtonian dashpot. The combination of these two elements can represent the time-dependent creep behaviour of composites. The most commonly used models are Maxwell Model, Kelvin Model, Generalized Kelvin Model, and Burger Model.

1.3.1 Maxwell model

The Maxwell model (Figure 1.10) is consisted of a spring and a dashpot in series which only can account for the elastic and viscous behaviour (Bodig and Jayne, 1982). The force P_1 acting on a spring equals P_2 which is also applied on dashpot. Therefore, E_1 represents the Module of Elasticity of spring, an η_1 is the viscosity coefficient of dashpot. The total displacement $u = u_1 + u_2$.

$$u_1 = \frac{P_1}{E_1} = \frac{P}{E_1} \quad (1)$$

$$u_2 = \frac{P_2}{\eta_1} = \frac{P}{\eta_1} \quad (2)$$

$$u(t) = \frac{P}{E_1} + \frac{P}{\eta_1} = \frac{P}{E_1} \left(1 + \frac{E_1}{\eta_1} t\right) \quad (3)$$

The Maxwell model, which is subjected to a constant strain, is a linear model and the equation can be expressed as below.

$$u = \frac{P}{\eta} t + \frac{P}{E} \quad (4)$$

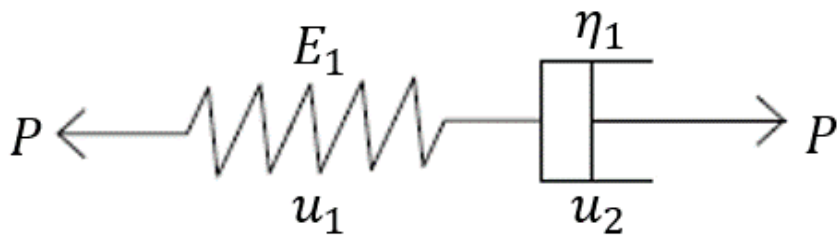


Figure 1.10 Maxwell Model.

1.3.2 Kelvin Model

The Kelvin model is most often used to represent the delayed elastic component of material behaviour (Bodig and Jayne, 1982). It joins the spring and dashpot parallel to each other which imposes the same displacement of the spring and dashpot, $u = u_1 = u_2$. And the total constant load is the sum of two elements, $P = P_e + P_v$.

The constitutive equation can be derived from Maxwell model:

$$u_1 = \frac{P_1}{E_1} \quad (5)$$

$$u_2 = \frac{P_2}{\eta_1} \quad (6)$$

$$P_e = uE_1 \quad (7)$$

$$P_v = u\eta_1 \quad (8)$$

$$P = uE_1 + u\eta_1 = uE_1 + \frac{du}{dt}\eta_1 \quad (9)$$

Then dividing η_1 and integrating the equation on both sides:

$$\frac{P}{\eta_1} = \frac{E_1}{\eta_1}u + \frac{du}{dt} \quad (10)$$

$$u = \frac{P}{E} + Ae^{-\frac{t}{\tau_1}} \quad (11)$$

When $t=0$, $P=0$ will yield:

$$A = -\frac{u}{E} \quad (12)$$

τ is the relaxation-time constant which is η/E , representing the spring and dashpot's properties.

The creep equation will be:

$$u = \frac{P}{E} (1 - e^{-\frac{t}{\tau_1}}) \quad (13)$$

$$A = \frac{u}{E} \quad (14)$$

$$B = \frac{1}{\tau} \quad (15)$$

This linear differential equation has the solution: $u = A(1 - e^{-Bt})$

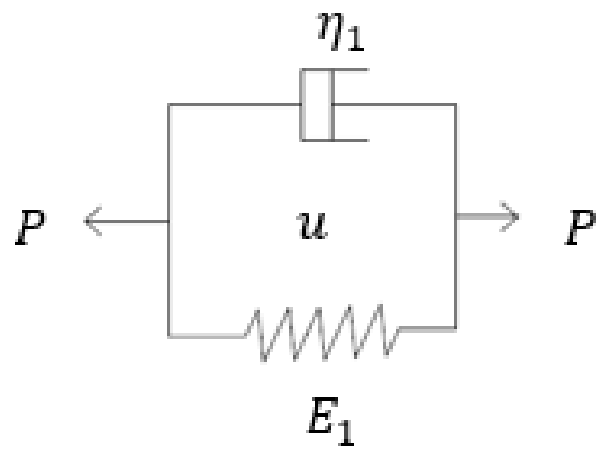


Figure 1.11 Kelvin Model.

1.3.3 Generalized Kelvin Model

The properties of viscoelastic materials can be expressed in the former conceptual model consisting of series or parallel elastic and viscous elements. The generalized Kelvin rheological model (Figure 1.12) consists of springs representing instantaneous stiffness with one or numbers of Kelvin body series. In this part, the equation is developed based on one Kelvin with one spring. The total force P is the constant load and therefore P equals in two parts, $u = u_1 + u_2$

$$u = u_1 + u_2 \quad (15)$$

$$u_1 = u_v = u_e \quad (16)$$

For the parallel part (right part):

$$u_e = \frac{P_e}{E_1}, u_v = \frac{P_v}{\eta_1} = \frac{1}{\eta_1} P_v t \quad (17)$$

Therefore:

$$P_v = \frac{du_v}{dt} \eta_1 \quad (18)$$

Similar to the Kelvin model:

$$u_1 = \frac{P_1}{E_1} (1 - e^{-\frac{t}{\tau_1}}) \quad (19)$$

$$u = u_1 + u_2 = u_1 = \frac{P_1}{E_1} \left(1 - e^{-\frac{t}{\tau_1}}\right) + \frac{P_2}{E_2} \quad (20)$$

Assuming that $A = \frac{P_1}{E_1}$, $B = \frac{1}{\tau}$, $D = \frac{P_1}{E_1} + \frac{P_2}{E_2}$ in the equation above, then the equation is simplified to $u = -Ae^{-Bt} + D$

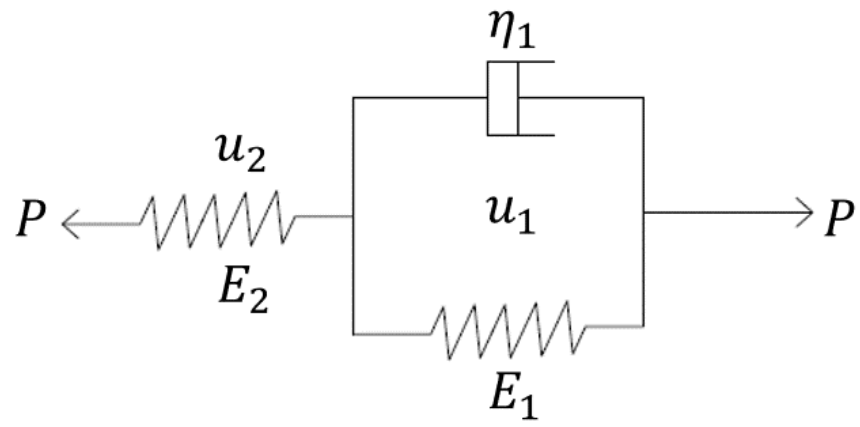


Figure 1.12 Generalized Kelvin Model.

1.3.4 Burger Model

The Burger model combines two sets of models, using one purely viscous damper and one purely elastic spring with a Kelvin in between as shown in Figure 1.13, including the deformation stage and recovery stage. The original length of this set is l . K_e is the top spring, r_{de} is the dashpot in the middle Kelvin model, r_v is the dashpot. The bottom r_v is another dashpot.

Before t_1 , there is no force applied on the dashpot. Then, suddenly apply a force on the dashpot to pull it. The upper spring will immediately generate an elastic deformation with the increase of its length to $l + u_e$. When pulling this set-up till t_2 , all the spring and dashpot reach the total deformation where the total deformation of Burger model is u . After reaching the maximum deflection, remove the force and the spring contracts and produces a deflection of u_e . At time t_4 , which may recover for the long term, the Kelvin model's deformation is almost approaching zero. Finally, an unrecoverable deformation u_v remains in the lower viscous dashpot.

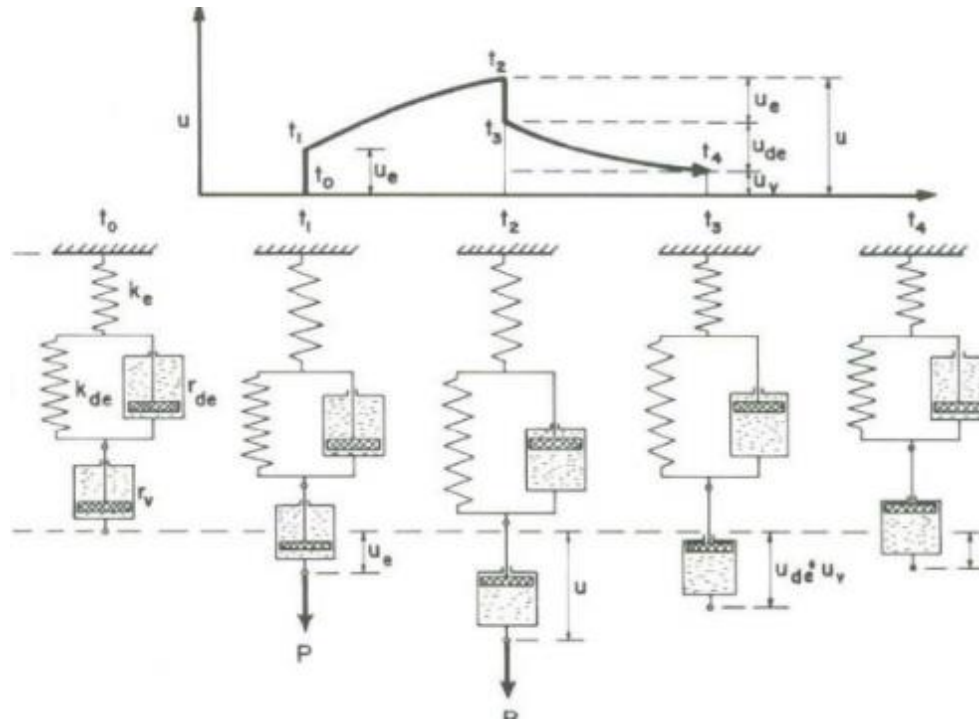


Figure 1.13 The representation of creep behaviour of Burger's model. (Bodig and Jayne, 1982)

The advantage of this model is that it turns creep behaviour into an easy-understood simplified model. Also, the parameters of the model are expressed on a unit basis, relating time dependent stress-strain behaviour to the moduli of elasticity and rigidity and to the coefficients of the viscosity of composites (Bodig and Jayne, 1982). However, according to the former description of the whole process from t_1 to t_4 , this Burger's model can not perform and predict the third stage of creep where the specimen will fail. Therefore, this model is more suitable for creep testing before failure.

First, defining the constitutive equation of Burger model, which are:

$$P = P_1 = P_2 = P_3 \quad (21)$$

$$u = u_1 + u_2 + u_3 \quad (22)$$

Based on the Maxwell model and the Kelvin model, the u_1 , u_2 and u_3 can be substituted with:

$$u = u_1 + u_2 + u_3 = \frac{P}{E_1} + \frac{P}{\eta_3}t + u_2 = \frac{P}{E_1} \left(1 + \frac{E_1}{\eta_3}t \right) + u_2 \quad (23)$$

$$u_2 = \frac{P}{E_2} \left(1 - e^{-\frac{E_2}{\eta_2}t} \right) \quad (24)$$

And to simplify the constant, $\tau_1 = E_1/\eta_3$, $\tau_2 = E_2/\eta_2$

$$u = u_1 + u_2 + u_3 = \frac{P}{E_1} + \frac{P}{\eta_3}t + \frac{P}{E_2} - \frac{P}{E_2}e^{-\frac{t}{\tau_2}} \quad (25)$$

Assuming that $A = \frac{P}{E_2}$, $B = \frac{1}{\tau_2}$, $C = \frac{P}{\eta_3}$ $D = \frac{P}{E_1} + \frac{P}{E_2}$ in the equation above, then the equation

is simplified to $u = -Ae^{-Bt} + Ct + D$

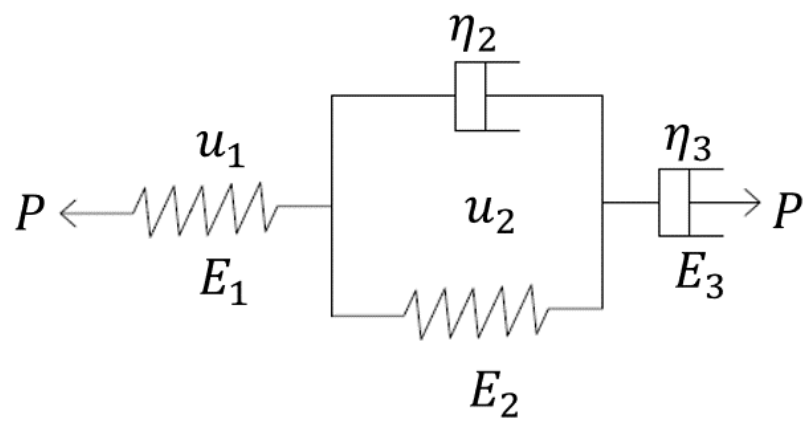


Figure 1.14 Burger Model.

1.4 Technical review on the creep of CLT and other wood-based products

Numerous studies have shown that the time-dependent stress-strain behaviour of materials is critical in timber buildings. The deflection of beams and other wood members subjected to the long-term loading oftentimes governs their performance.

Previously, many studies on the creep of wood and wood products have been reported (Yu *et al.*, 2017; McDonald *et al.*, 2018; Byeon *et al.*, 2017; Park *et al.*, 2006; Huang *et al.*, 2016). Zaijun and Mizi (2017) conducted the short- and long-term performance of wood-based panel types, namely plywood (PW), particleboard (PB), medium-density fibreboard (MDF) and oriented strand board (OSB) subjected to five different modes of mechanical tests, including flatwise-bending, edgewise-bending, panel shear, planar shear and concentrated load stresses and evaluate the different responses. A load was applied with a rate based on the principle that the samples should fail at 5 min of duration for the short-term loading, and 5 months for the long-term loading. The results showed that the stress modes have a significant effect on the magnitude of the deflections during creep loading. The creep deflection of flatwise bending is 6 times higher than that of edgewise bending under 6 months of loading. The example of MDF is shown in the figures below. Secondly, the theoretically calculated deflection was much higher than the measured under short-term tests but lower than the measured values under creep tested.

Also, both viscous and viscoelastic deformation under creep loading have made a significant contribution to the total deflection. The effect of stress modes on relative creep varied among the materials tested.

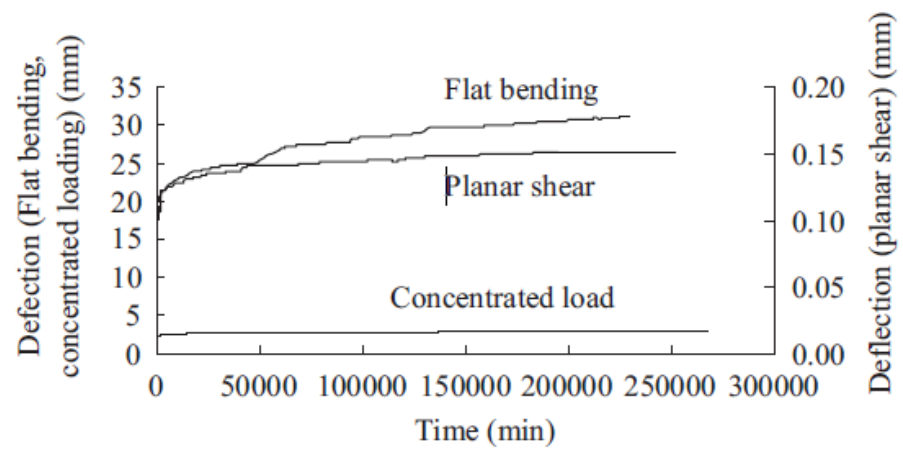


Figure 1.15 Deflection of MDF under creep loading along the plane of board.

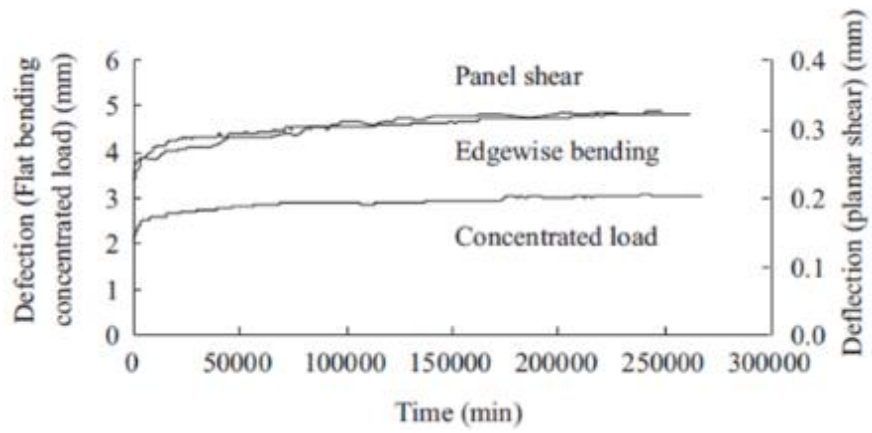


Figure 1.16 Deflection of MDF under creep loading along the edge of board.

The evaluation of SIP (structural insulated panel) was conducted by McDonald Dwight (2018). Specimens were third-point loaded to 1.58kN which is approximately one-third of the short-term failure load for both specimen depths. The specimens were subjected to three long-term test loads (33%, 22%, and 11% of the average maximum short-term failure load) under the environment of 21.1°C and 60% relative humidity for the time period of 90 days. After the creep recovery period for 30 days, the creep-tested specimens were statically tested in the same orientation to determine the residual strength and flexibility of the specimens after the 90-day creep loading. The load-deflection curve was shown in Figure 1,17 with half-tone curve line, and the dash line is the theoretical estimated curve. Dwight (2018) found that SIP exhibited the duration of load performance that was characteristic of structural lumber in its dry-use condition. Table 1.1 shows the specimen distribution in the different tests. Table 1.2 shows the short-term bending result after creep, foam flush end, which is no dimension lumber blocks required at the ends of the specimens.

Test number	End condition	Load level	Number of samples	Duration
1	Foam flush	Average max. load of short term bending tests	3	1 min
1a	Foam flush	(Test no.1 load) x 1/3	3	90 days
1b	Foam flush	(Test no.1a load) x 2/3	3	90 days
1c	Foam flush	(Test no.1a load) x 1/3	3	90 days

Table 1.1 The specimens used for different types of tests on SIP.

Sample ID	EI (*10 ³ kN/mm ²)	Max. M (10 ³ N/mm)	Slope (N/mm)	Deflection _{max} (mm)	P _{max} (kN)
3A	1058.35	7.36	150.35	36.50	5.19
15A	1059.72	7.72	150.50	39.57	5.45
20A	1048.00	8.07	148.80	40.87	5.69
4A	1052.14	7.62	149.47	37.41	5.38
9A	1061.79	13.03	150.75	67.67	9.19
19A	1008.01	7.86	143.12	40.87	5.55
2A	1026.63	7.34	145.77	36.68	5.18
8A	1047.31	13.91	148.71	74.57	9.81
18A	1005.95	8.14	142.89	42.11	5.75
Average	1040.88	9.01	147.82	46.25	6.35
Cov	0.02	0.28	0.02	0.31	0.28

Table 1.2 Short-term bending result after creep, foam flush end.

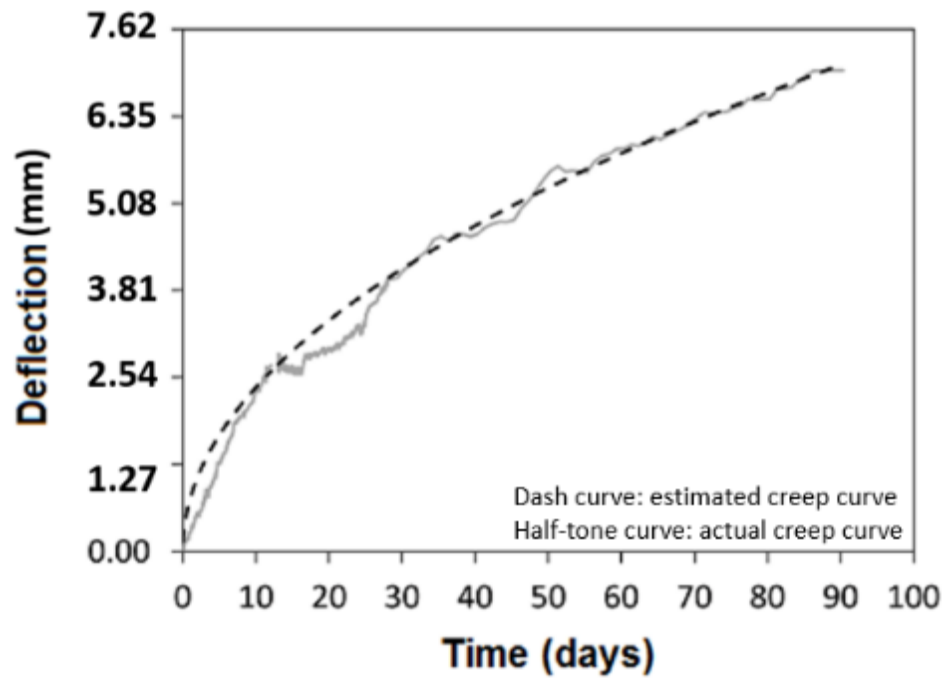


Figure 1.17 One creep Deflection-Time curve of SIP

The creep compliance is the total load strain per unit of stress. Byeon *et al.* (2017) conducted creep tests on various CLT products made of six Korean wood species (Japanese cedar, Japanese cypress, Japanese larch, chestnut, tulip, and oriental oak) with an aim to determine the bending creep properties of the CLT and the direction of CLT through the creep test and its load-deflection curves. By cross-laminating, initial and creep compliance of parallel-laminated woods which all laminae along the same direction (in Figure composed of perpendicular-direction laminae in all layers considerably decreased. The extent of the decrease was greater in creep deformation than in initial deformation (Figure 1.18). The initial and creep compliance of cross-laminated wood is the highest among low-density Japanese cedarwood and the lowest among high-density oriental oak.

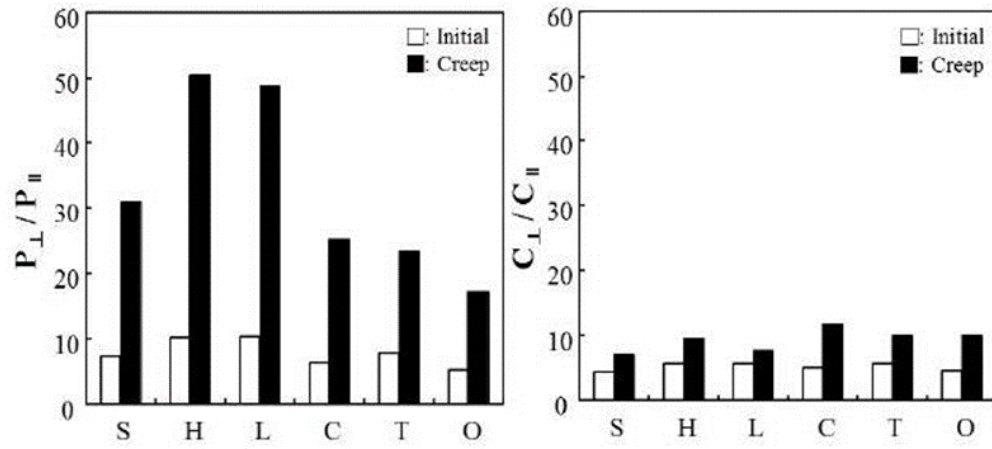


Figure 1.18 The anisotropy of initial and creep compliance of 6 wood species with four types of laminated wood specimens.

In the fourth study of bending creep performances of three-ply cross-laminated woods made with five species (Park *et al.*, 2006), the specimens subjected to the third-point bending for 168h (7 days) in a constant atmosphere maintained at 20°C and 65% relative humidity (RH) under the stress corresponding to 20% of the breaking stress obtained from static bending test. Specimen types are shown in Figure 1.19. The creep deformation perpendicular to the grain was decreased by cross laminating.

They found that the creep deformation of specimens which were perpendicular to the grain of parallel-laminated specimens and face laminae of cross-laminated specimens, and which were parallel to the grain of face laminae of cross-laminated specimens tended to decrease with increasing density. Also, they found that the extent of the decrease was greater in creep deformation than in initial deformation. Moreover, the degrees of anisotropy for both deformations of laminated wood specimens were markedly decreased by cross laminating. A higher density species obtains a low creep deformation. The data are shown in Table 1.3.

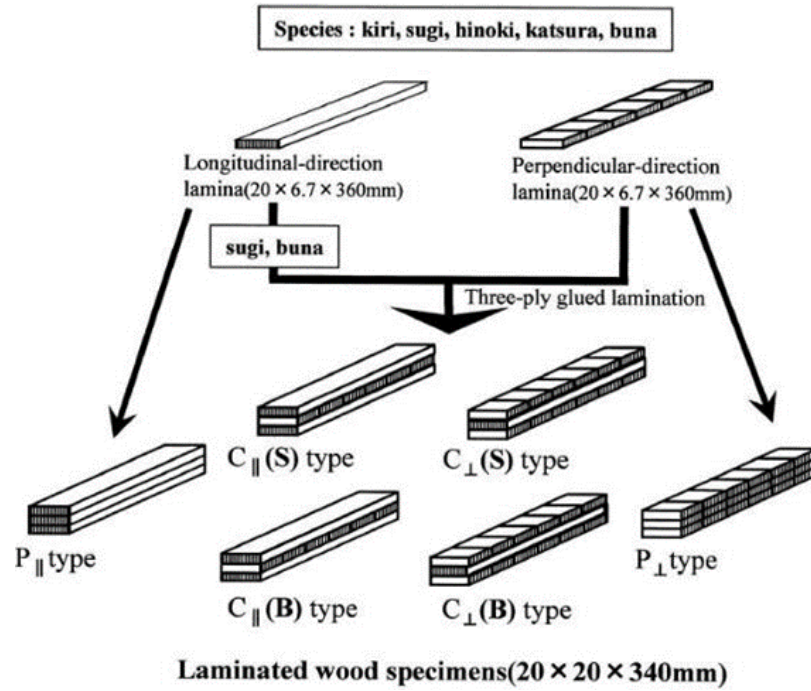


Figure 1.19 Parallel-laminated and cross-laminated wood specimens. S and B of cross-laminated woods mean that sugi and buna, respectively, were used as longitudinal direction laminae.

Type	D _a (0.008) (10 ⁻¹¹ Pa ⁻¹)	D _{ca} (168) (10 ⁻¹¹ Pa ⁻¹)	D' _a (0.008) (10 ⁻¹¹ Pa ⁻¹)	D' _{ca} (168) (10 ⁻¹¹ Pa ⁻¹)	Ratio of D _a (0.008) to D' _a (0.008)	Ratio of D _{ca} (168) to D _{ca} (168)
C _p (SKI)	16.56	2.90	12.61	1.01	1.31	2.87
C _p (SSU)	17.08	3.73	12.60	1.01	1.36	3.69
C _p (SHI)	15.04	2.78	12.59	1.01	1.19	2.74
C _p (SKA)	13.21	1.59	12.57	1.02	1.05	1.56
C _p (SBU)	13.39	1.67	12.55	1.02	1.07	1.63
C _p (BKI)	17.49	3.76	12.91	1.83	1.35	2.05
C _p (BSU)	19.37	5.63	12.90	1.83	1.50	3.07
C _p (BHI)	16.60	4.24	12.89	1.84	1.29	2.31
C _p (BKA)	13.51	2.83	12.86	1.84	1.05	1.30
C _p (BBU)	14.60	3.50	12.85	1.84	1.14	1.90

Table 1.3 Creep ratios of measured values to the calculated values of initial compliance and creep compliance. C means cross laminated.

The research on how the ambient environment affects CLT creep behaviour is limited. However, it is clear that not only the degree of load but also the moisture content (*MC*) changes are the essential conditions for the mechano-sorptive (*MS*) creep of wood, specimens were loaded in three-point bending under different humidity cycles (Huang, 2016). Because wood is a hygroscopic material, it will absorb the moisture from the environment spontaneously which is the mechano-sorptive. The applied load varied from 15% to 35% of the short-term breaking load for each set. It was found that the wood specimens exhibited a partial recovery of 0.1mm during all the adsorption phases and deflection increase during all the desorption phases when a low load level was applied. According to prior research, this phenomenon was very different from the creep behaviour after the first adsorption, which is recognized as reversible creep deformation with moisture changes due to pseudo-creep (Matar, 2003). The results also indicated that an amplified load effect existed within the creep under cyclic moisture changes, which usually resulted in a fast-increasing rate of viscoelastic creep to veil pseudo-recovery in the first humidifying stage.

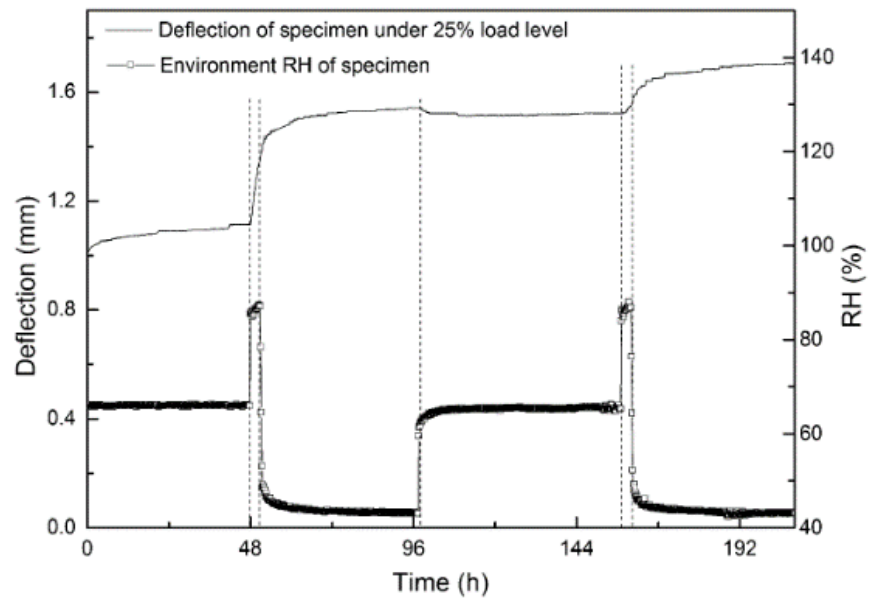


Figure 1.20 Creep deflection of CLT specimens under 25% load level and the first adsorption: 65–89 % RH; the first desorption: 89–42 % RH; the second adsorption: 42–65 %; the third adsorption: 65–89 % RH; the second desorption: 89–42 % RH.

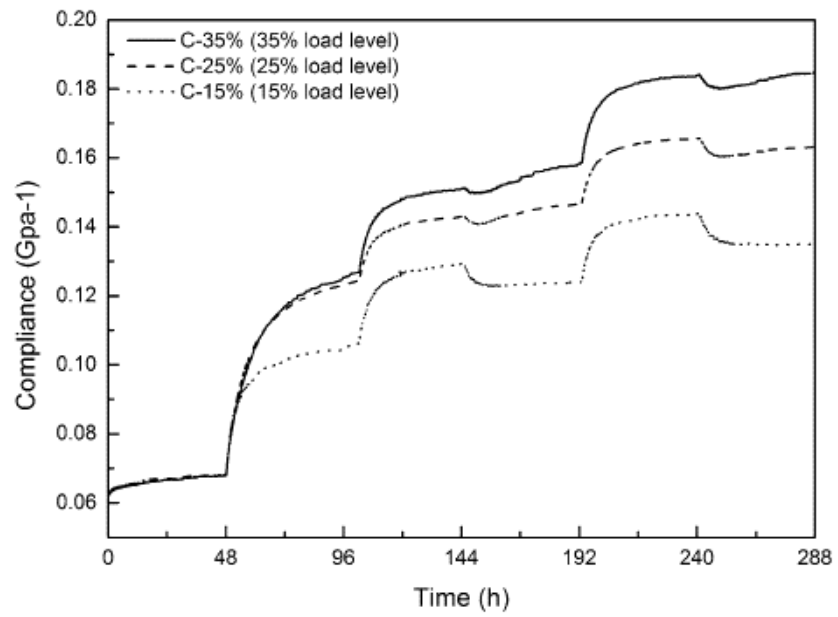


Figure 1.21 Creep compliance of the specimens tested under various load levels.

In summary, creep of CLT member owns a splendid perspective in terms of the various elements including direction of fibre orientation, ambient factors, and loading patterns. Comprehensive research will be operated via comparative work to investigate the contribution of variants to mechanical performance.

1.5 Objectives and Scope of Research

This thesis report was aimed at examining the creep behaviour of thin CLT by taking load level, humidity level and panel direction into account. To achieve this, the scope of the research includes:

- 1) Measuring the apparent modulus of elastic (MOE_{app}), apparent modulus of rupture (MOR_{app}), and proportional limit (PL) of thin CLT under the static bending.
- 2) Conducting the short-term creep tests considering the factors such as load level, relative humidity and panel direction; and
- 3) Identifying the most suitable model simulating the creep of thin CLT specimens.

2 Materials and Specimens

Figure 2.1 illustrates the steps of preparing specimens. There were two parallel projects under the testing program: development of OSB-lumber CLT panels, and examination of the creep behaviour of generic CLT. The study proposed in this thesis report is the second one; however, the mechanical properties of generic CLT under the static loading were shared between these two projects.

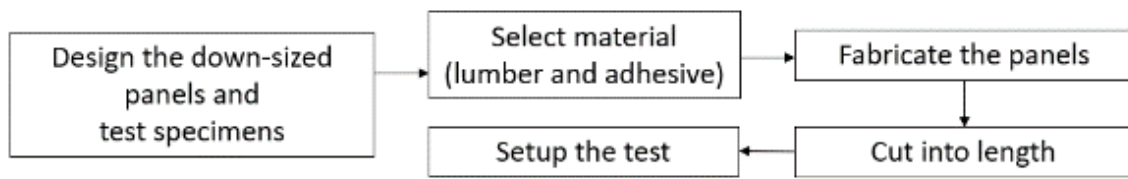


Figure 2.1 The procedure of making specimens.

2.1 Specimen design

In this study, four (4) thin three-layer CLT specimens were made. In essence, two panels were used in the first stage static test, one was used to load in the major strength direction, and the other panel was used to load in the minor strength direction.

The second test, i.e., the creep test, required two similar panels that were loaded in the two strength directions. This part is illustrated in the third section of this report. The laminations of panels were cut from the 2×6 No 2 grade SPF (Spruce-Pine-Fir) lumber with the moisture content of $12 \pm 2\%$. The difference in moisture content between adjacent layers of sawn timber was less than 5%. The dimensions of each lamination were thinner and smaller than standard size to accommodate with the thickness (12.7mm / 1/2") of OSB in the parallel study. Therefore, the thickness of the CLT designed was 38mm (1 1/2"). After the sanding of lumber and OSB panels, the thickness of each layer was reduced from 12.7mm to 11.0 mm.

Therefore, according to the adjusted one-layer thickness and the ASTM standard "Standard Test Methods of Static Tests of Lumber in Structural Sizes" (ASTM, 2015a), the total specimen length includes the span (measured from center to center of the reaction supports) and the length of the overhangs (measured from the center of the reaction supports to the ends of the specimen). The suggested flexural specimen size in standard "Evaluation of Duration of Load and Creep Effects of Wood and Wood-Based Products" (ASTM, 2015b) is to control the span-

to-depth ratios over 14 for none-structural use. Sufficient length shall be provided so that the specimen can accommodate the bearing plates and rollers and would not slip off the reactions during the test. Figure 2.2 shows the flexural test method of four-point bending.

Overall, with the span-to-depth ratio of 16, the total length of the span was 528mm (21”) plus the length of two overhangs of 5.08mm (2”) equals 584.2mm (23”) and the width of each specimen is 63.5mm (2 1/2”). The thickness is 33mm (1.3”). Figure 2.3 shows the lamination distribution of each layer.

Table 2.1 and Figure 2.2 show the lamination distribution of each layer. The following tables and figures illustrate the final size's summaries in each step and the designed panel and specimen diagram. Then, after cutting, the specimens were ready for the flexural test based on the setup in Figure 2.2. The deflection of the midspan was measured with a LVDT hanging at the natural axis.

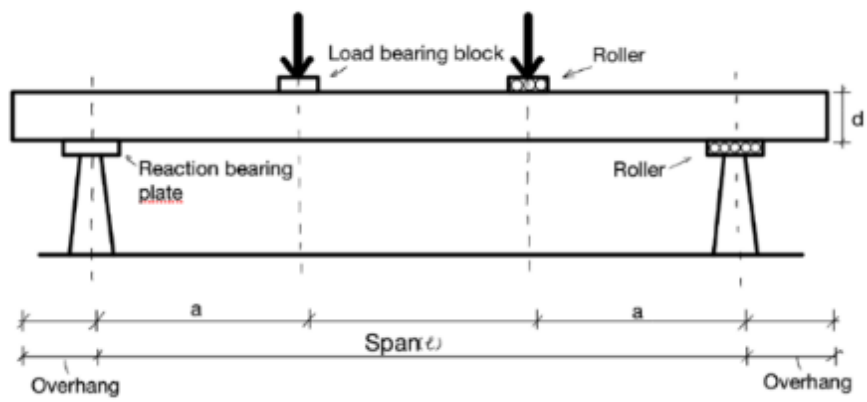


Figure 2.2 The flexural test method of four-point bending.

Number of wood strips in each layer in a thin CLT specimen				
	Panel-1	Panel-2	Panel-3	Panel-4
Top layer	14	14	14	14
Core layer	14	14	14	14
Bottom layer	14	14	14	14
Sum of each panel	42	42	42	42

Table 2.1 The distribution of lamination in each layer and summary.

	Thickness x Width x Length mm (inch)
Size of one lamination	11 × 50.8 × 711.2 (0.43 × 2 × 28)
Size of one layer	11 × 711.2 × 711.2 (0.43 × 28 × 28)
Size of one panel	33 × 711.2 × 711.2 (1.3 × 28 × 28)
Size of one specimen	33 × 63.5 × 584.2 (1.3 × 2.5 × 23)

Table 2.2 The size of a specimen in each step.

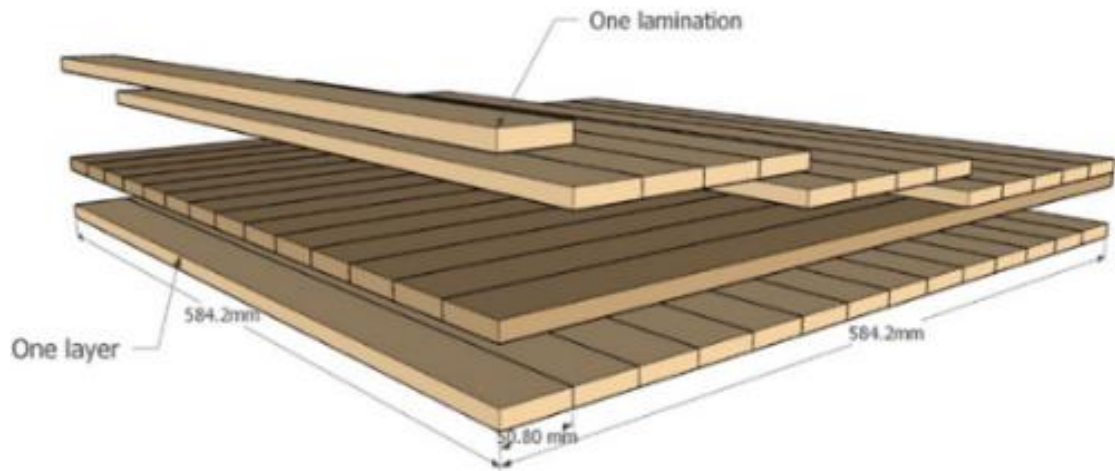


Figure 2.3 The diagram of a whole CLT panel.

2.2 Specimen preparation

No. 2 grade 2×6 lumber was selected from the woodpile in the lab with fewer knots and defects, making the material “green” to avoid their effects on mechanical properties. Then the selected pieces of lumber were ready to be cut.

2.2.1 Laminations

First, the 2×6 lumber was cut in length about 711.2mm (28") by using the circular saw. The shortened lumbers were moved to the table sawn (shown in Figure 2.4) to cut to width. Then, the pieces of lumber were halved in thickness equally. The final step was to use the shaving machine (shown in Figure 2.5) to shave the strips into the designed thickness of 12.7mm (1/2").

Overall, 239 pieces of lumbers were labelled with numbers, and then 30 pieces were picked from them randomly, which were weighed by balance, and the actual thickness and width were recorded to calculate the density of each as a record. Furthermore, all the strips were measured by mass.



Figure 2.4 Cutting length using a circular saw (upper) and ripping width using a table saw (bottom).



Figure 2.5 Ripping lumber using the heavy-duty bandsaw (upper) and planing wood strips to a given thickness using a planer (bottom).

It is important to group the lumber according to its stress level because the surface layer, which is the main strength direction, requires a higher strength lumber than the core layer. Therefore, in this step, all the strips were sorted into two groups by mass. The first group included the first 56 pieces, the first 56 pieces which were ranked among the low-density group, were used in the core layer, and the second group, including the rest higher density strips, were assigned to the surface layers. Then, the low-density group and high-density strips into 4 (core layer) and 12 panels (surface layer) were randomly grouped, using Excel. Overall, 12 of these panels were used to make the generic CLT, and another two were employed to fabricate hybrid CLT with OSB as cores. The details for grouping are given in Appendix 6.1.

After all preparation work was completed, the wood strips were piled layer by layer and put into the conditioning chamber at a temperature of 20°C and RH of 65%, where each layer was spaced apart by three strips at 90 degrees, to leave enough space to adjust the moisture content evenly through every piece. Figure 2.7 shows the pile of wood strips in the conditioning chamber.



Figure 2.6 The wood strips piled in the conditioning chamber.

2.2.2 Edge-bonding

CLT products without edge-glued laminations may have lower load-carrying capacities than those with edge-glued ones. However, no specific research has shown that there is a certain correlation between the rolling shear modulus of edge-glued / non-edge-glued laminations and its effect on the load-carrying capacity of the CLT element. Therefore, to improve the integrity of the panel and minimize the stress concentration, edge-bonding was applied in each layer of each panel.

In this step, all the narrow faces of every lamination were sanded and kept clean before applying the Original Gorilla Glue from Gorilla in Figure 2.8. This Gorilla Glue is a moisture activated polyurethane adhesive. According to the instructions and suggested spray rate, clean all sanded surfaces which will contact the glue and spray one side of the wood with water, another side should manually spray the glue. And 10g of adhesive should be applied on the narrow face of lumber. Then use the three sets of steel bar and clamping set up to clamp the whole panel for at least 2 hours and curing in the conditioning chamber where the moisture content is 12% for 24 hours. Figure 2.9 shows the clamping set-up of one layer. After taking the panel out from the clamp, the mass, thickness, and length of all 12-edge bonded one-layer panels were recorded. Also, assigned panels to groups according to Table 2.3.



Figure 2.7 Original Gorilla Glue.

3-layer Panel	1-layer Panel Number		
W1	12	13	4
W2	6	14	9
W3	2	15	3
W4	8	16	7

Table 2.3 Panel allocation.

2.2.3 Lay-up (face-bonding), vacuum-pressing and curing

Before face-bonding, each edge-bonded panel should be pre-sanded to the same thickness of 12 mm and the extra foam adhesive removed. The actual thickness after sanding is around 11mm. Following the former step, using the steel bars to maintain the panels' position, the 3-layer CLT panels were vacuum bagged in groups of 3 for 2 hours and then cured for 24 hours in the conditioning chamber.



Figure 2.8 The clamping setup.

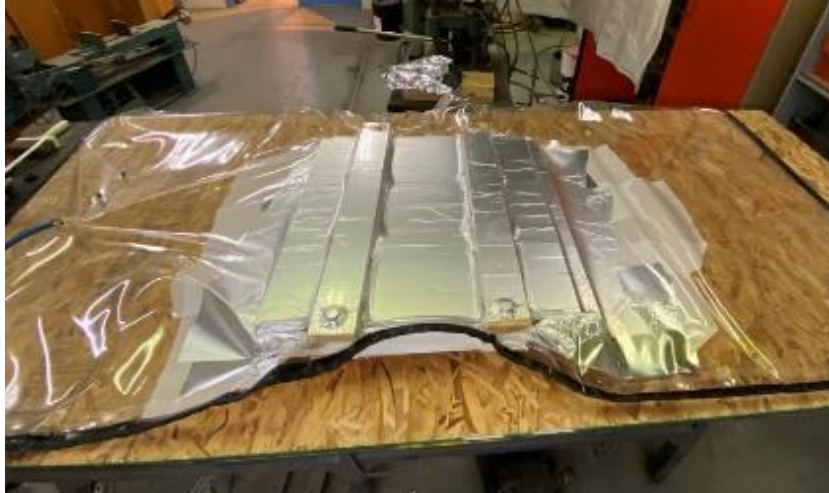


Figure 2.9 Vacuum Bagging to press the panel.

2.2.4 **Cutting**

The panels were cut on the table saw according to the cutting pattern below. Thirty-two specimens were selected for the flexural and creep tests. Twelve pieces of specimens were from Panel 1 and 2 for testing the breaking stress in major and minor directions. The shorter specimens are used for testing short span bending in another parallel study. All specimens' data were shared. And the 20 pieces specimens from Panel 3 and 4 were used in the creep test.

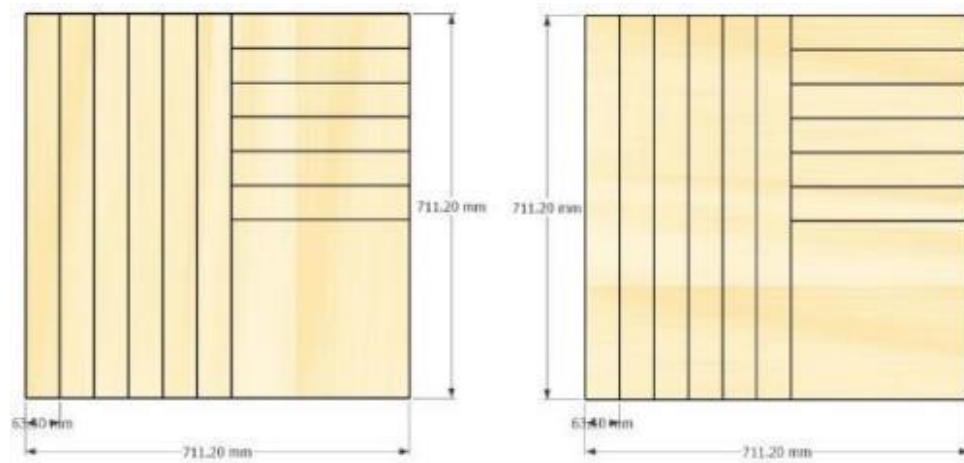


Figure 2.10 Cutting patterns of Panels 1 and 2 (Left: the panel in major strength direction, and Right: the panel in the minor strength direction.)

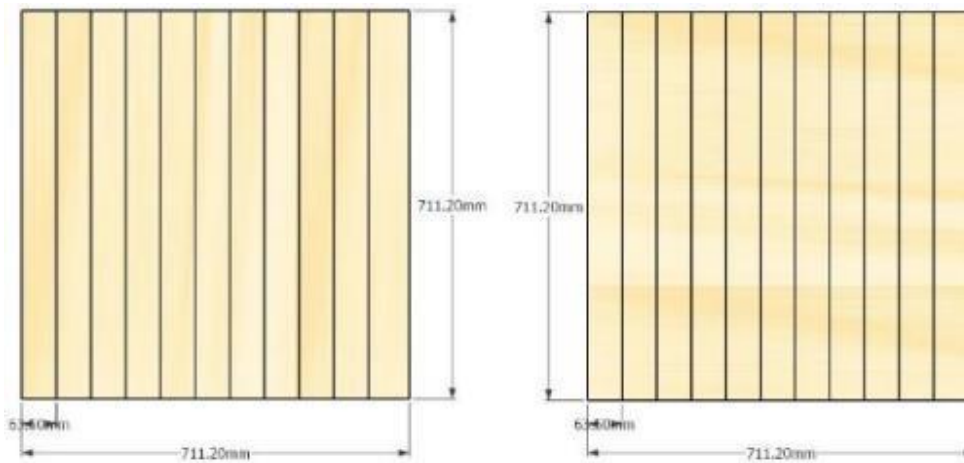


Figure 2.11 Cutting patterns of Panels 3 and 4 in major and minor strength direction, respectively.



Figure 2.12 Cutting patterns.

3 Methods

3.1 Third-point bending

The flexural tests were conducted based on the standard ASTM D198-15 (ASTM,2105). Flexure specimens were loaded with two loading points with an equal distance from each reaction end, which is called third-point loading, and subjected to a bending moment by supporting it near its ends, at locations called reactions, and applying transverse loads symmetrically, imposed between these reactions. The specimen is deflected at a prescribed rate and coordinated observations of loads and deflections were made until rupture occurs (Byeon, 2013). Before the testing, the short-term and long-term test materials were conditioned for at least 30 days in the anticipated test environment. Conditioning generally ensures compliance with the 62 % moisture content change criterion (ASTM, 2015). According to the ASTM D198-15 (ASTM, 2015), the span-to-depth ratio of long-span testing is 17 and that of short-span testing is 5, and the loading should progress at a constant deformation rate such that the average time to maximum load for the test series shall be at least 4 min. The deflection of the midspan was measured with a LVDT.

The analysis of the distribution of load shows that the load span (in Figure 2.1) is the part that has no shearing stress, which is more accurate to analyze the cause of the failure and is not affected by the shear stress where is free from shear and stress concentrations.

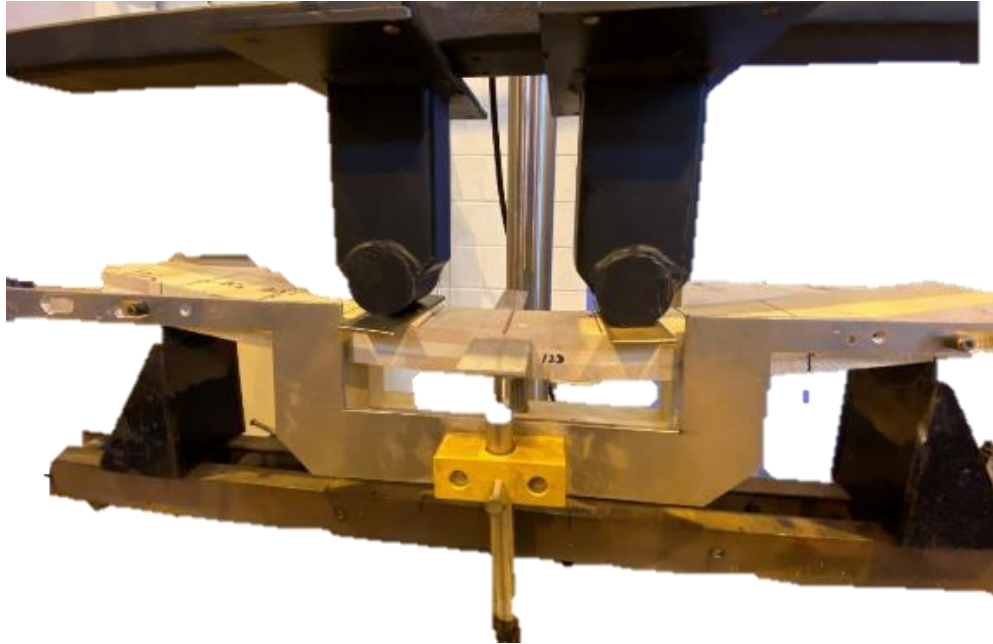


Figure 3.1 Flexural test setup.

3.1.1 Calculations

3.1.1.1 Proportional limit (PL)

The proportional limit (PL) is the point on a stress-strain curve where the linear, elastic deformation region transitions into a non-linear, plastic deformation region. (Shown in Figure 3.2). In other words, the proportional limit determines the greatest stress that is directly proportional to strain which can be estimated from the load-deflection curve.

3.1.1.2 Apparent modulus of elasticity (MOE_{app})

The MOE_{app} is determined through the use of the linear part (shown in Figure 3.2) of the load-deflection (or stress-strain) curve. The maximum slope should be fitted to the load-deformation data by an acceptable statistical or graphical method. Historically, it has been determined graphically, using a straight-line slope through the linear portion of the load-deflection curve (ASTM, 2015). Equation 1 is used for calculating MOE_{app} .

$$MOE_{app} = \left(\frac{\Delta P}{\Delta d}\right) \frac{23l^3}{108bh^3} \quad (26)$$

Where:

$\frac{\Delta P}{\Delta d}$ = slope of the straight-line portion of the load-deflection curve (N/mm),

l = length of span (mm).

b = width of specimen measured in dry condition (mm), and

h = depth of specimen measured in dry condition (mm).

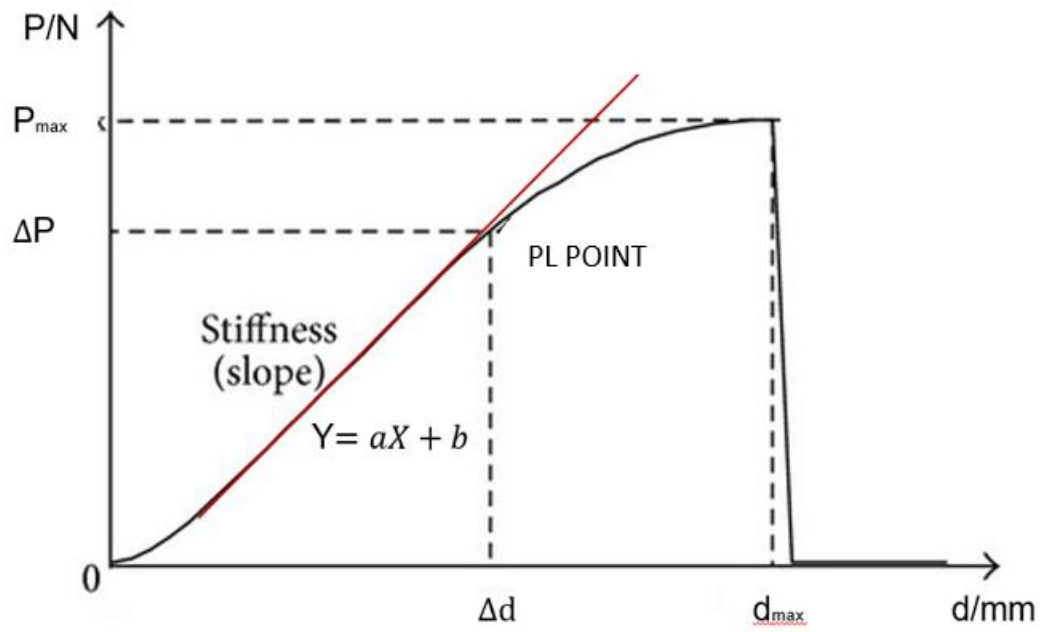


Figure 3.2 Typical Load-Deflection Curve.

3.1.1.3 Apparent modulus of rupture, MOR_{app}

$$MOR_{app} = \frac{P_{max}l}{bh^2} \quad (27)$$

Where:

P_{max} = load at failure (N/mm).

3.1.1.4 Moisture content (MC)

After the bending test, a 50.8 x 63.5mm block was cut from the specimens and measure the mass was measured to calculate the moisture content of the specimen.

$$MC_o = \frac{m_a - m_o}{m_o} \times 100\% \quad (28)$$

Where,

m_a = air dry mass (g), and

m_o = oven-dried mass (g).

3.2 Short-term creep tests

In this thin CLT creep test, the strength direction, load level, and RH were the variables. The whole loading period was selected as 7 days due to the limited time of graduate studies, with the loading level of 30% and 60% of PL. Since the RH is a variable in this test. The creep tests were conducted in the small conditioning chamber at UNB Wood Science and Technology Centre and the deflection of each specimen was measured by an LVDT at a logging frequency of 1 Hz.

The creep setup shown in Figure 3.3 was composed of a brace frame spacing at 21” six test specimens at a time with an LVDT in the middle span of each specimen. On the top plate of the steel columns, two steel rods were welded as the loading support point of the creep test. Two steel bars spacing at 177.8 (7”) were welded to a 9.5 kg steel panel as a platform for holding the rest of the panels. As aforementioned, 3 replicates were taken for each individual test (each stress mode, each panel direction type, and each humidity condition)



Figure 3.3 Creep test setup with an LVDT in the middle span of each specimen.



Figure 3.4 Loading the specimens.



Figure 3.5 Supporting steel rod at the end of the loading span.

Group	Major Direction			Minor Direction		
	Load Level	RH (%)	Specimen Number	Load Level	RH (%)	Specimen Number
1	30% PL	65	3	30% PL	65	3
2		30	3		30	3
3	60% PL	65	3	60% PL	65	3
4		30	3		30	3

Table 3.1 The specimen group of creep tests under the load of 7 days.

3.2.1 Calculations

3.2.1.1 Relative creep

In order to compare experimental data from different sources and conditions it is convenient to define relative creep C_r as follows (Bodig and Jayne, 1982):

$$C_r = \frac{\delta_1 - \delta_0}{\delta_0} \quad (29)$$

Where:

δ_0 = initial deflection, mm; and

δ_1 = deflection at time t_1 , mm.

3.3 Modeling of creep behaviour

As reviewed in section 1.3, the generalized Kelvin model and Burger model can be closer to the real creep behaviour. Creep curved tests could be fitted based on these two models.

Model	Equation
Generalized Kelvin Model	$u = -Ae^{-Bt} + D$
Burger Model	$u = -Ae^{-Bt} + Ct + D$

Table 3.2 Generalized Kelvin model and Burger model

Where:

Parameters	Generalized Kelvin Model	Burger Model
A	P_1/E_1	P/E_2
B	$1/\tau$	$1/\tau_2$
C	NOT APPLICABLE	P/η_3
D	$P_1/E_1 + P_2/E_2$	$P/E_1 + P/E_2$

Table 3.3 Constants in curve fitting equations

E = the Module of Elasticity of spring

η = the viscosity coefficient of dashpot

P = is the force applied

τ = is the relaxation-time constant which is η/E

4 Results and Discussion

4.1 Mass

During the fabrication process, the mass of all laminations, 3-layer panels was recorded in

Tables 4.1 and 4.2.

For surface layer														
Panel	Number of laminae													
1	125	156	1	58	193	148	140	7	9	196	231	165	133	97
2	139	216	19	200	166	232	166	23	73	115	233	187	81	10
3	42	185	47	141	121	99	220	30	153	175	188	28	169	76
4	80	106	9	164	211	190	29	186	177	129	16	228	159	24
5	180	184	66	119	3	44	168	104	70	195	43	86	55	67
6	122	145	15	194	84	44	92	150	61	161	103	14	8	52
7	91	114	62	223	297	151	60	163	158	93	100	204	138	63
8	127	25	39	218	110	236	11	207	71	237	41	13	22	74
9	101	5	94	120	214	227	235	46	50	199	111	38	238	2
10	154	143	57	117	230	171	212	131	33	107	65	68	147	40
11	124	192	53	144	172	88	149	162	130	18	118	98	87	76
12	12	191	89	221	64	32	35	83	69	36	102	112	59	45
For middle layer														
13	189	113	72	239	6	179	174	170	181	215	146	109	222	34
14	229	128	64	108	37	208	160	167	173	59	234	21	210	217
15	208	17	85	49	27	225	95	136	90	115	198	205	79	134
16	137	202	48	135	51	77	206	183	123	78	201	26	56	219

Table 4.1 Allocation of laminae 12 one-layer surface panels and 4 middle layer panel.

3-layer Panel	1-layer Panel Number			Mass (kg)
W1	12	13	4	33.18
W2	6	14	9	33.09
W3	2	15	3	33.15
W4	8	16	7	32.68

Table 4.2 3-layer CLT panel allocation and mass

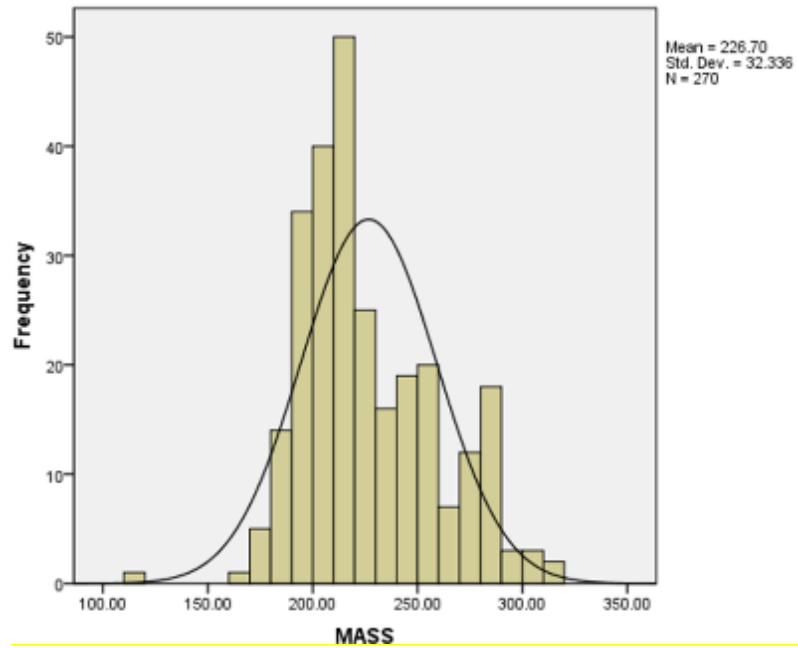


Figure 4.1 Normal distribution of Lamination mass.

4. Flexural test results

The third-point bending test of generic CLT had gone through successfully. The load-deflection curves and failure modes are provided in Figure 4.3 to 4.6. From Figure 4.2, the PL of each specimen could be determined, which was about 3000 N. The average PL of specimen W2 was around 800 N. Then based on this load level, the further creep test load level can be defined. After this stage, the curve of W1 specimens increased with curve shape and went to the peak load around 6.09 kN, and that of W2 was 1.25 kN then failed. An exception was the specimen W1 BA1 (in Figure 4.2), which failed at a lower stress level, which might be caused by delamination or poor lamination at the edge of the panel. Therefore, this set of data was culled from the analysis.

After the flexural test, the load level of the creep test can be determined according to PL. However, due to the limitation of space and the weight of 185 kg is hard to make it feasible, so the adjustment was made according to the test condition. For specimens in group 3 and 4, the width of specimens was halved and used the 93 kg and 25 kg as its load level of 60%PL.

Overall, the total weight should be placed on the major direction specimens were 93 kg and 185 kg, and the 25 kg and 50 kg for minor direction specimens.

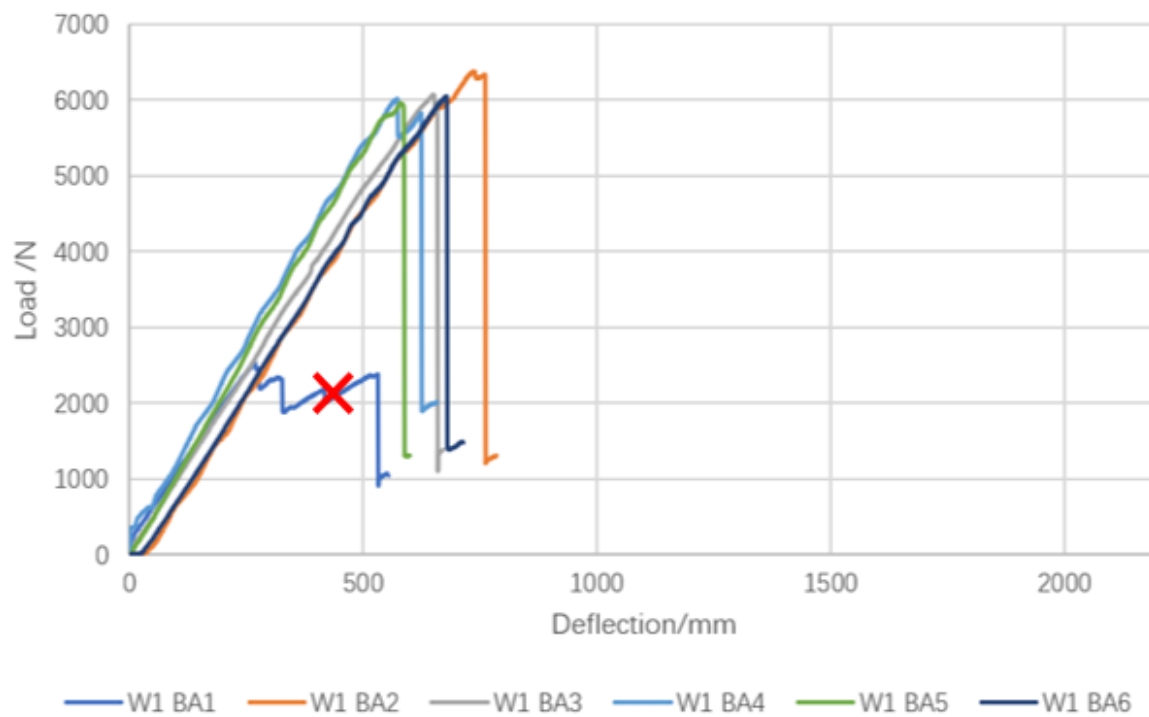


Figure 4.2 Load-Deflection Curves of Group W1 (major strength direction).

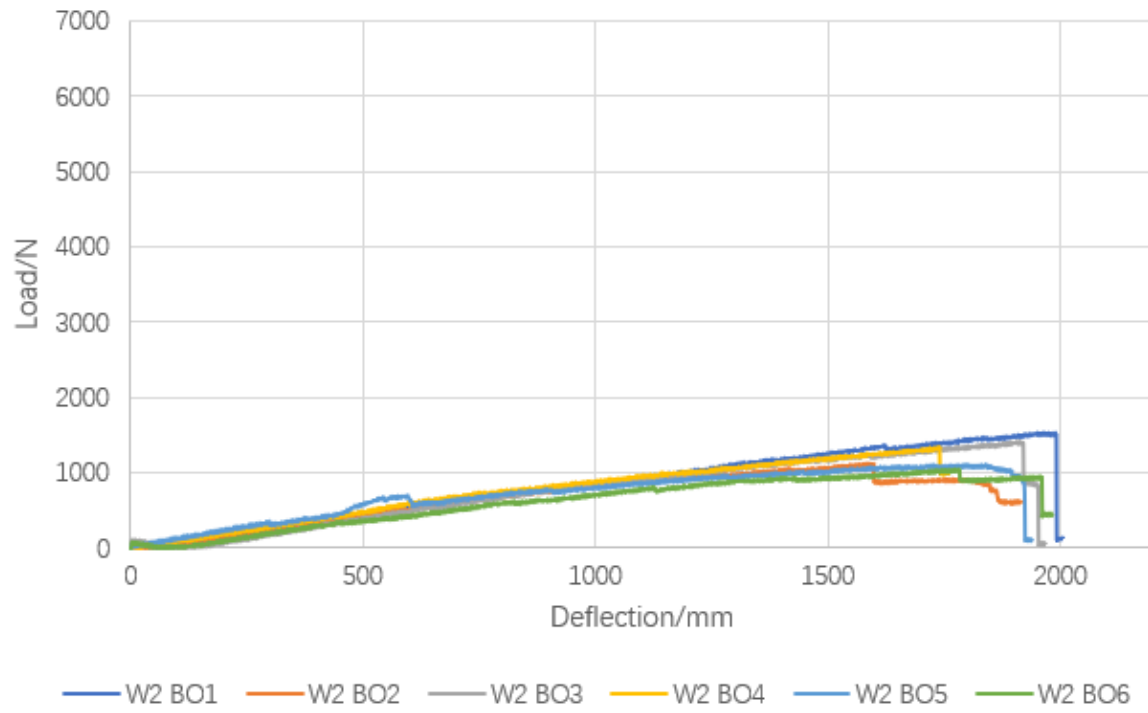


Figure 4.3 Load-Deflection Curves of Group W2 (minor strength direction).

The failure of specimens in group W1 (shown in Figure 4.4, 4.5 below) almost showed an identical way. Due to the rolling shear in CLT middle layer, lamination 126 failed at an angle of about 45 degrees, and perpendicular to that lamination's annual ring then delaminated to the end and failed.



Figure 4.4 Failure modes of Group W1.

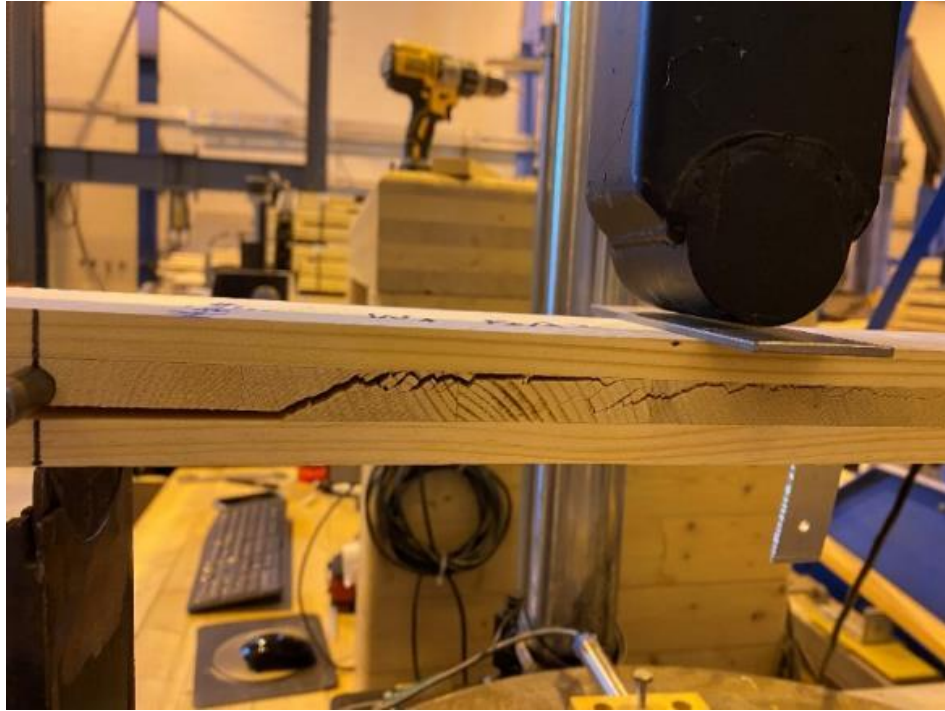


Figure 4.5 Rolling shear failure of Specimen at lamination 126.

In group W2, two types of failure modes were observed. The first one is the brash failure happening in specimens BO1, BO3, and BO5. The bottom laminations were broken in its latewood shown in Figure 4.7 (upper). The second failure type is the fracture along the glue line near the middle span then the stress caused the simple tension in the middle layer or delamination between the bottom and middle layers.

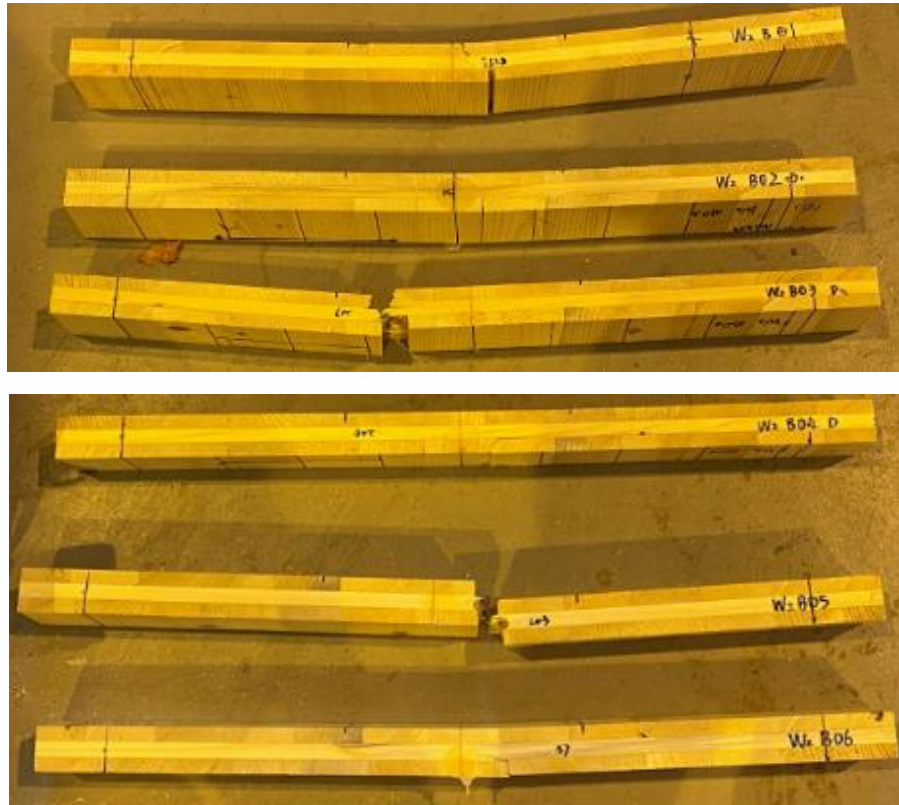


Figure 4.6 Failure mode of W1 specimens.

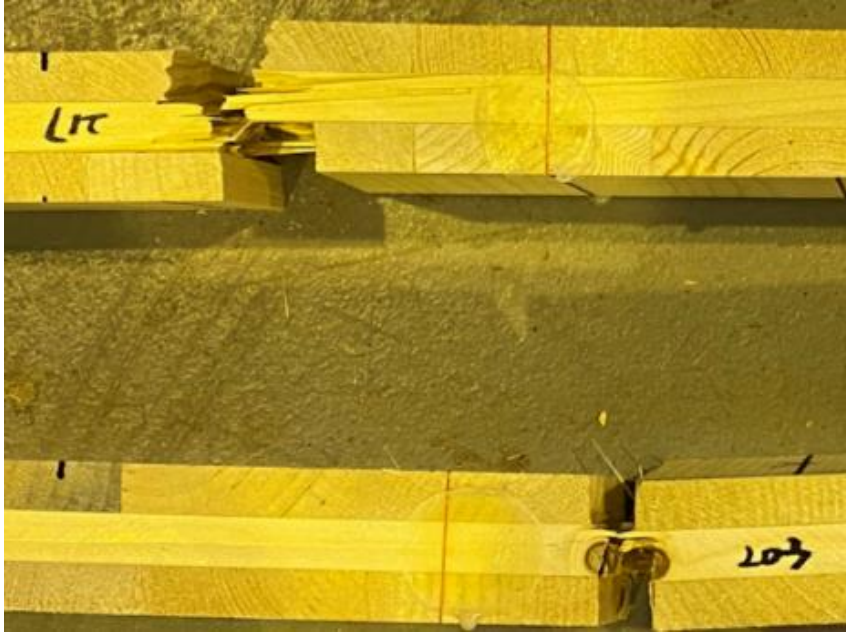


Figure 4.7 Brush failure (upper) and fracture at a knot (lower).

Before the start of all tests, during the edge-bonding section, an interesting observation was observed. The panels assigned to the middle layers with lower mass and density were easily warped and twisted after taking them out from the clamps. In addition, before the layup, all one-layer samples were temporary fixed under a huge panel in an attempt to avoid the poor connection and delamination in vacuuming and cutting. The importance of the grouping process as well as considering the orientation of lumber of CLT in real industrial manufacturing was magnified in this thin test. Overall, the average MOE_{app} of specimens along longitudinal axials was 8,510 MPa, MOR_{app} equals to 46.64, and MOE_{app} of minor direction specimens is 809 MPa, $MOR_{app}= 9.48$.

4.3 Short-term creep test results

4.3.1 Creep Curves

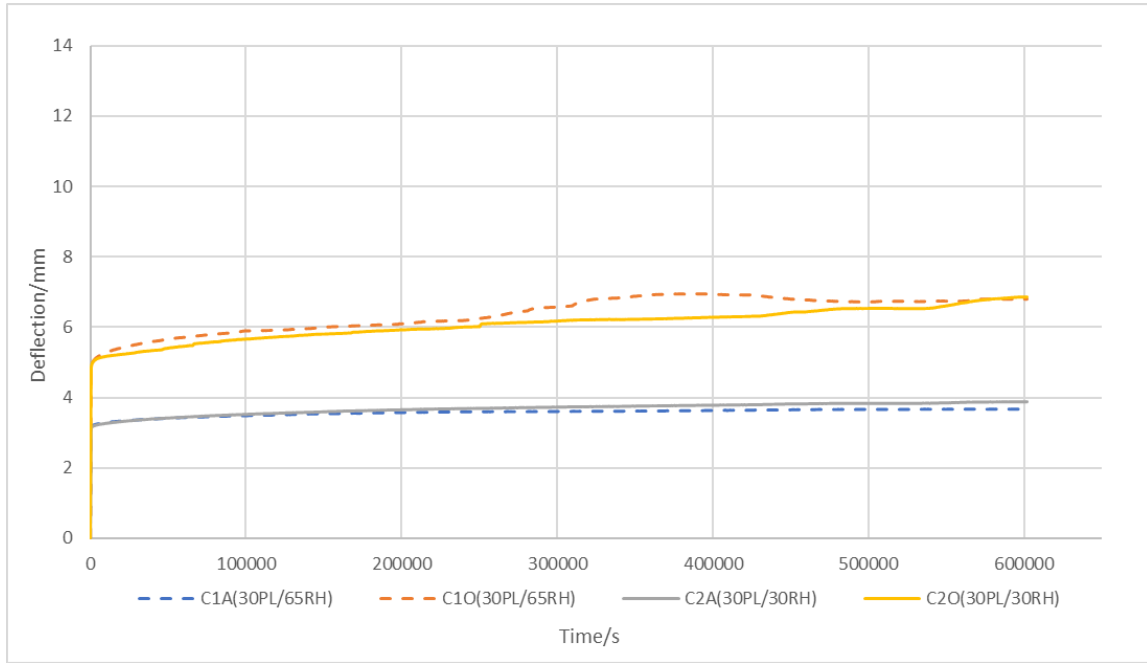


Figure 4.8 Average creep deformation curves of 30% load level Group1 (65%RH) and Group 2 (30%RH).

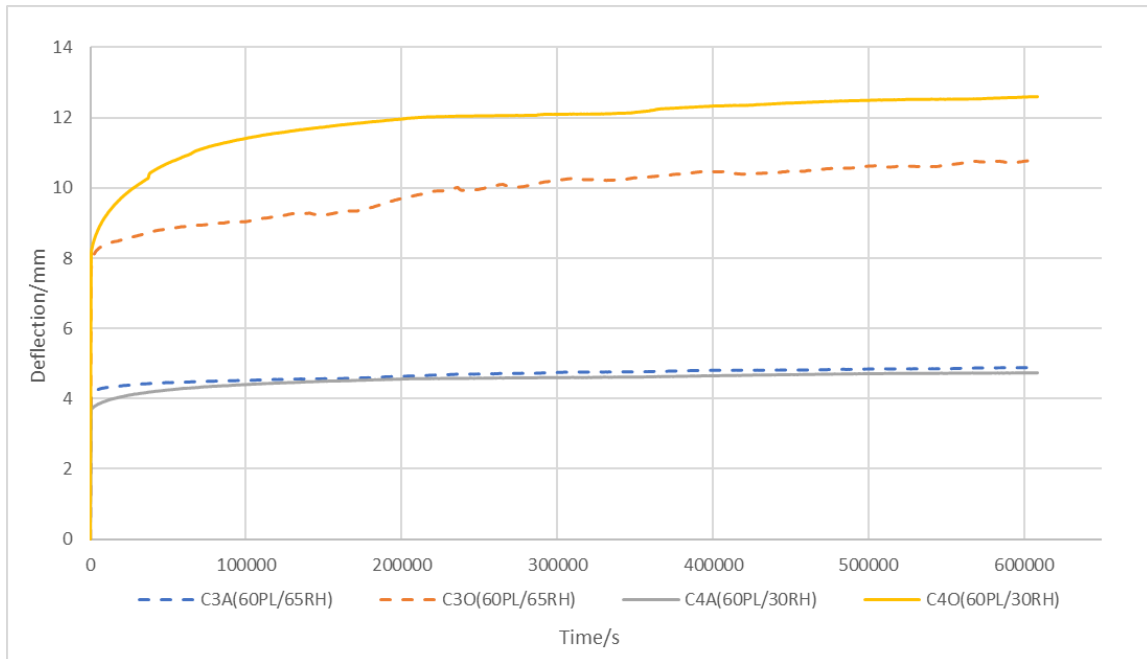


Figure 4.9 Average creep deformation curves of 60% load level Group3 (65%RH) and Group 4 (30%RH).

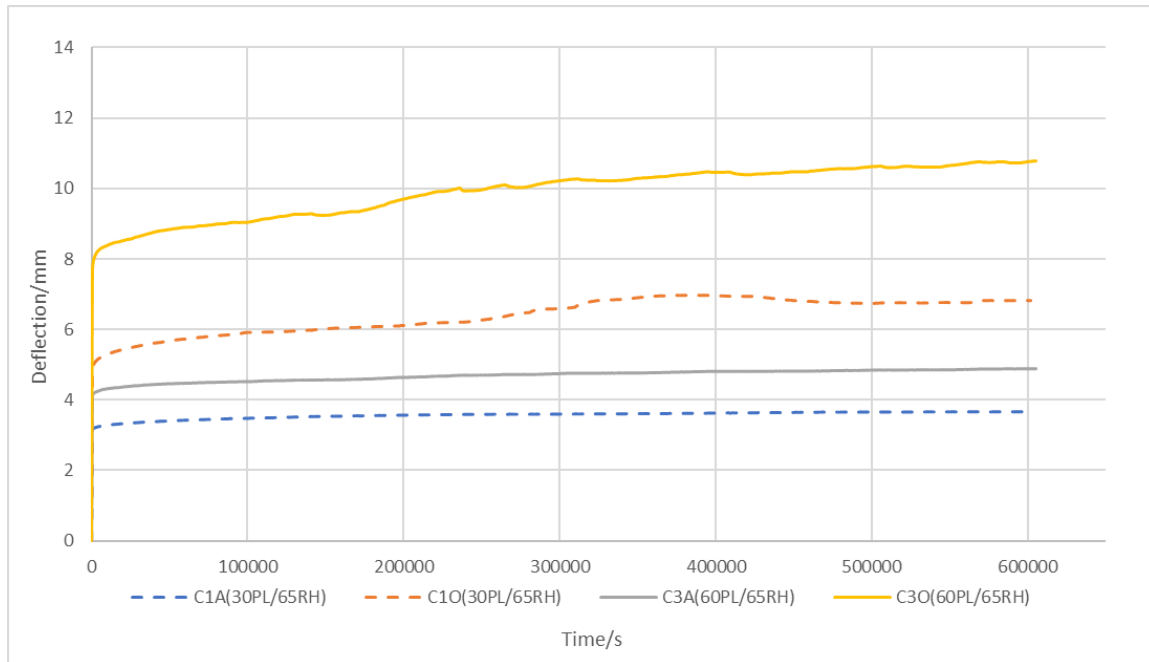


Figure 4.10 Average creep deformation curves of 65% RH Group1 (30% PL) and Group 3 (60% PL).

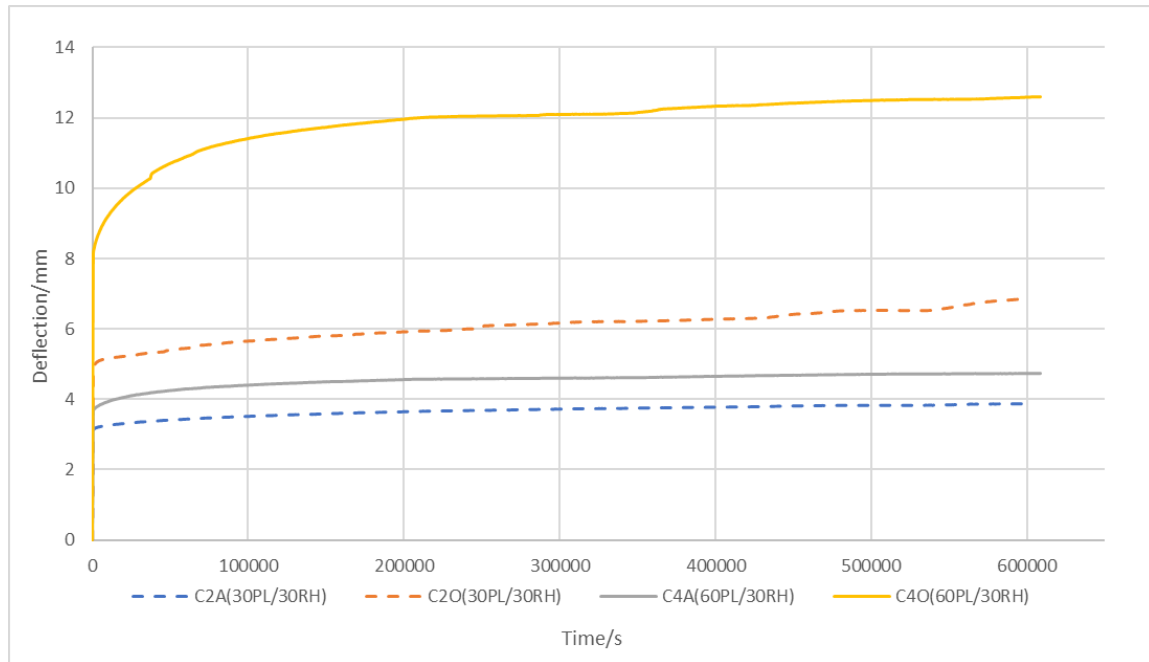


Figure 4.11 Average creep deformation curves of 30% RH Group 2 (30% PL) and Group 4 (60% PL).

Each curve in Figures 4.8 to 4.11 represents the average of a group and illustrates the creep deformations of all specimens at two panel directions, two load levels, and two RHs. A typical creep curve can be divided into three stages: first, when the load applied, there was an accelerated growing stage after an immediate deflection which initial creep; then the second stage turned to steady and last for the rest of the test. All major specimens followed the principle of creep. However, fluctuations existed in the curve of minor samples after 48 hours (2 days). Due to the time limit, the third stage, which is an abrupt acceleration of deflection then failed did not show in this test.

The sample in the minor direction tended to show a lower load capacity in this creep test than the samples in the major direction. And the load level shows a large effect on its load-bearing capacity. For the specimens in groups 1 and 2 under the load of 30%PL, the deflection increased to an approximately average value of 2.7 mm (major) and 4.4mm (minor) of group 1. Group 2 samples reached 3.07mm in major direction and 3.99 mm in minor. Group 3, under the load level of 60%, major specimens reached around 3.56 mm and 7.22 for minors. And the last group, group 4 (RH 30%, Load level 60%) deflection went to around 3.13 for major samples and 7.25 for minor specimens. Then after 7 to 8 hours of primary creep, secondary creep followed. In addition, the creep rate during the first 7 hours is the largest. In the following days, the total deflection of minor samples under the load level of 60% PL almost doubled than that of 30% PL. According to the shape of curves, the major direction of samples exhibited

smaller variance, which means the performance of specimens in the major direction were more steady, and an increase of more than one-half of the initial deflection.

Relative humidity effects: The Figure 4.8 and 4.9 compared the effects of different moisture conditions under the same load level. With the increase of RH, the samples' mechano-sorptive ability spontaneously absorbed moisture from the environment than which led to the increase of MC. This weakens the mechanical properties of wood. But the effect of load level still has a major impact among the groups. Also, the ambient condition owns a significant effect on these CLT samples. the transverse layer in minor direction facilitated the appearance of the curve. Thus, wood is an anisotropic material, the radium direction has the lowest strength among all. As the temperature or the moisture rises, the absorption of energy will cause the extension and/or slippage of the molecular chains of the cell wall, leading to the rupture of intramolecular chemical bonds, thereby increases the mobility and ductility of the chains, increasing the creep rate and creep compliance (Placet, 2007).

Load level effects: Comparing the results between groups (in Figure 4.10 and 4.11), with the rise of load, there was an increase of 72% in the deflection of minor specimens. This doubled in major samples under the RH of 65%. But the effect of RH shows slight differences in the second graph (load level of 30PL) which indicated that this 30%PL is not enough for the test due to the test condition limit. Therefore, considering the peak load as load level reference of

flexural test could be recommended in the future.

Panel direction effects: The impact of direction of CLT specimens was evident from Figure 3.19. Samples in major direction exhibited a superior ability of resisting deflection against constant load than samples in minor direction. It is additionally clear that samples in major direction entered the secondary creep stage slightly later than those in minor direction. This distinction is probably going because the tensile strength and compressive strength of the wood along the grain direction are the largest, and the transverse grain direction is the smallest. The adjacent veneers with crossed textures make the intensity in each direction very balanced in panel system specimens. Overall, CLT in the major direction exhibits a superior load-bearing capacity than those in minor direction, and direction of CLT layers domain the influence on the creep deformation.

From the result of the CLT creep test, the decreasing creep rate, and the creep curves of all CLT samples follow Burger's model. As a result, the specimens remained, along the major axis, stable after a few hours. CLT specimens gradually deformed under the sustained load. Table A 0.3 and Table A 0.4 in the appendix show the physical testing results for these samples. These results demonstrated that it was possible to prolong the lifetime of CLT under adjusted bending load. However, due to the limit of monitoring of the time, the curves of minor CLT specimens experienced some fluctuation within a small range. Refer to the results from static bending, the

bottom layer of CLT where took the procedure of edge-bonding was the weakest part of the specimen. The failure mode of third-point bending test specimens demonstrated that the cracks may happen in the weakest bond line first, and then cause the tension force onto the bottom of middle layer, next that concentration caused a fracture to the middle structure even the whole CLT specimen. As a result, a fluctuation curve appeared at a low load level and the range of it was 0.387 within 2.8 days (250000s). If the test time could be extended to a longer term, the curves could show a smoother as well as steadier tendency.

4.3.2 Relative Creep

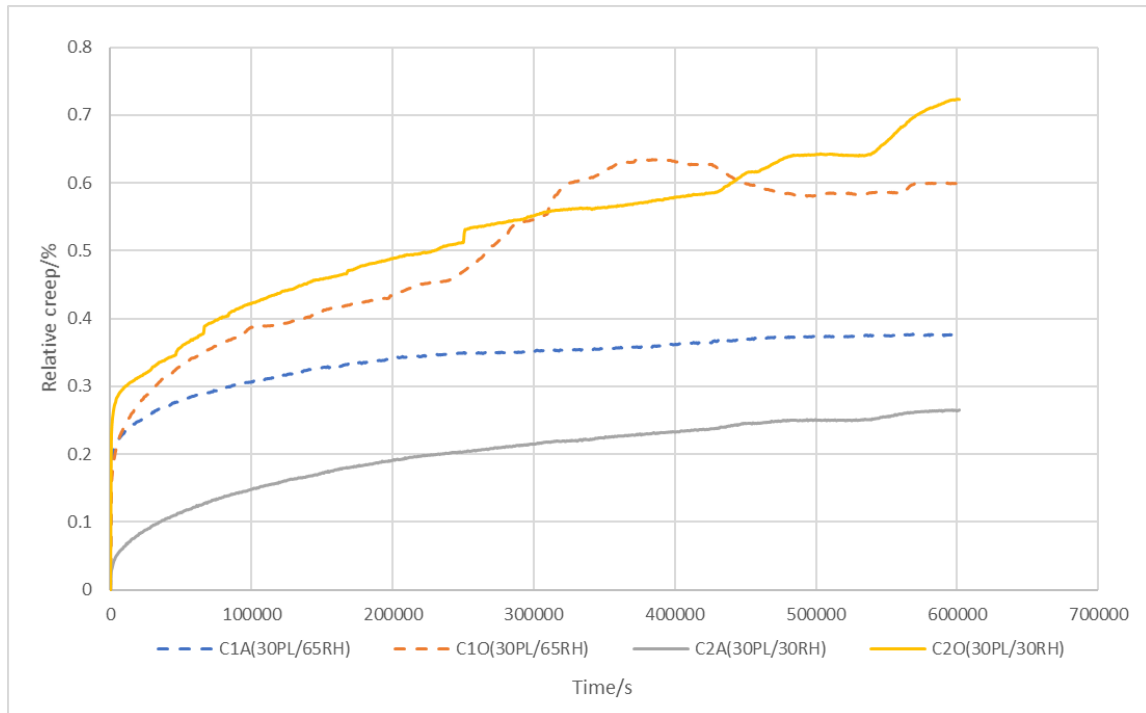


Figure 4.12 Relative creep curves of Group1 (65%RH) AND Group 2 (30%RH) tested at 30% load level.

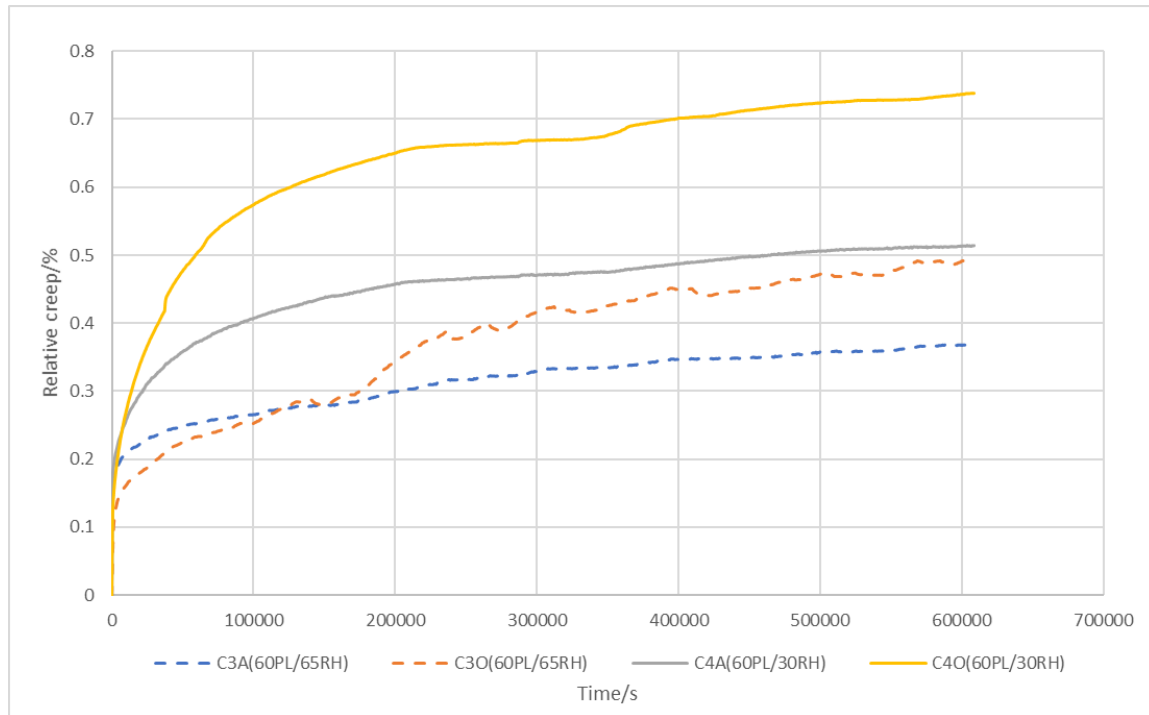


Figure 4.13 Relative creep curves of Group3 (65%RH) AND Group 4 (30%RH) tested at 60% load level.

The relative creep was conducted through divided by the deflection right after applying the whole steel panels on. Some relative creep curves overlapped a lot but with the same general shape and similar slope in the steady stage. The initial deflection of each specimen was shown in Figure 4.14. All the curves showed an increasing creep rate, so the test did not reach to the steady stage of the second stage. From the curves in Figure 4.12 to 4.13 above show the relative creep rate (%) plotted against time for CLT samples when 30% and 60% of maximum bending strength obtained at the identical condition were applied for 7 days. Primary creep was complete within the first 3 hours (10800s). The initial strain was observed to increase dramatically after the application of the load, which is a phenomenon of primary creep response. All the creep rates started around 0.12 and increased very fast for the first few hours, then, after 7 days, all the creep rates reached a range from 0.25 to 0.72 because of the variability of the wood. As Figure 4.12 shows, under the same loading level, with the increase of the RH, the creep rate shows a higher creep rate. And the curve of Group C2 along the minor axis fluctuated a lot, but no cracks or delamination was found in the specimens tested. Therefore, the only possibility could be some technical problems occurring in the conditioning chamber at the very first groups during testing. However, the overall trend between groups shows that the creep rates are similar with the narrowest range of variability. This further justifies the aim of developing and manufacturing engineered wood products, i.e., to reduce the variability of natural wood materials.

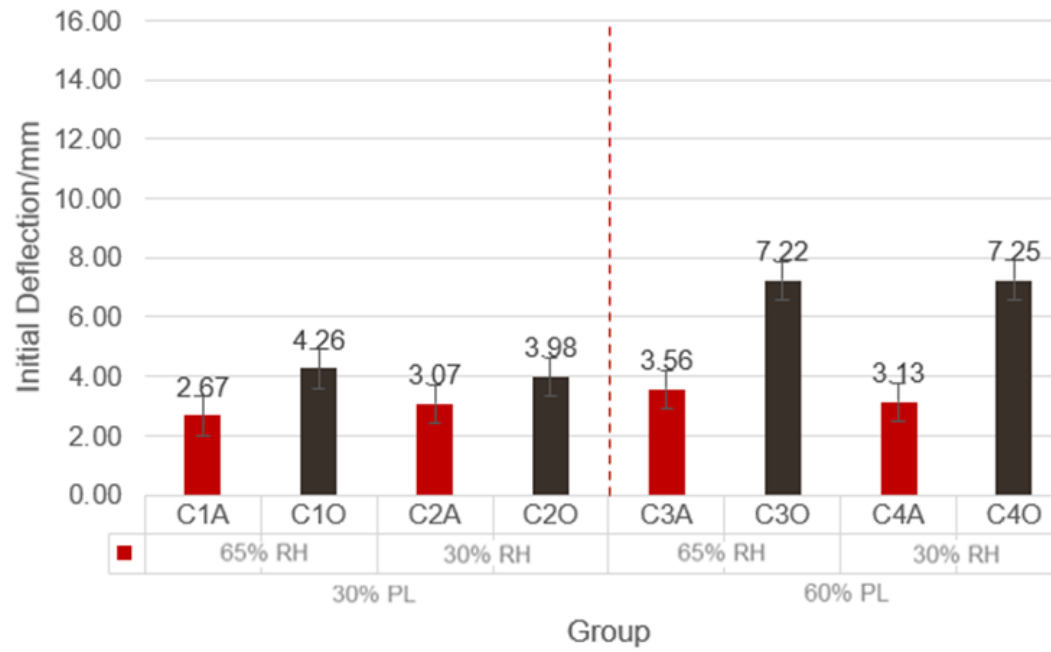


Figure 4.14 Average initial deflections of 4 groups.

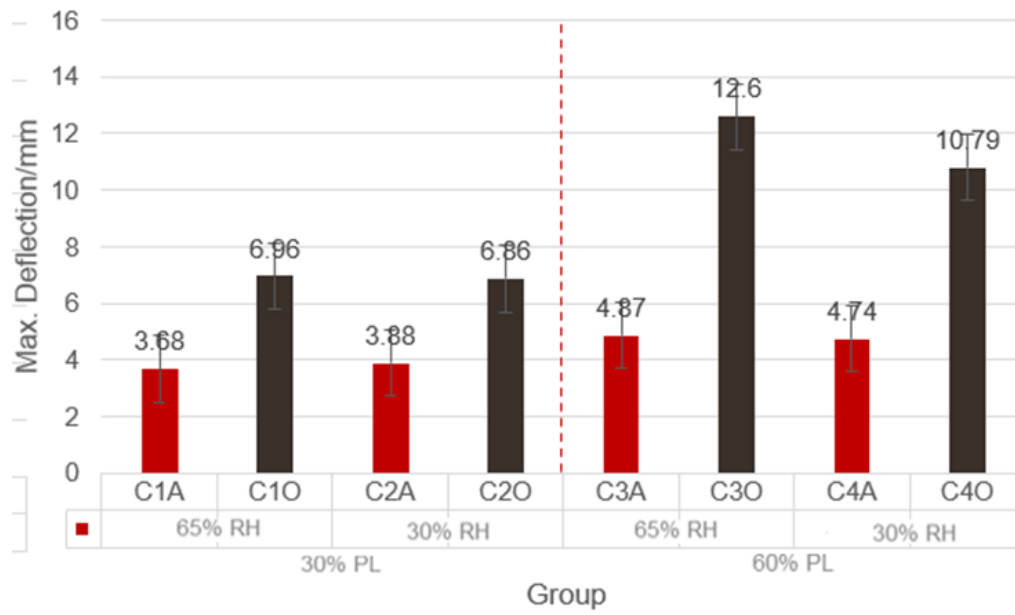


Figure 4.15 Maximum deflections of 4 groups.

4.4 Creep model

In section 1.3 the parameters of the General Kelvin model formula and the Burger model were defined. In this section, the raw data were analyzed via MATLAB's curve fitting tool to figure out the parameters in each model. The results of each group are given in Table 4.5 and Figure 4.16 shows the results comparing the fitted Burger model and General Kelvin model of Group C20. The General Kelvin model could well predict the deflection before 3.5 days (3×10^5 s), but it was off a lot before and after this time. However, the Burger model can almost fit the deflection at a given time tested from beginning to the end and makes a great long-term prediction for creep.

Combining the equations with test data, the r-square of the Burger model is larger and more stable than the General Kelvin model after the regression analysis. A three-element General Kelvin model consisting of a spring in series with a Kelvin chain can simulate the elastic and hysteresis parts of the wood creep process and cannot simulate permanent deformation that cannot be recovered. This model can describe the first stage of creep, and it is not effective and recommended to use this creep model to predict long-term creep (Dinwoodie *et al.*, 1990). The four-element Burger body in series of two models contains all the creep characteristics of wood and can simulate the first and second stages of these thin CLT specimens under 7-day creep tests. The fitting results in this study further supported this conclusion. By assigning 10 year to the time in Equation $u = -Ae^{-Bt} + Ct + D$, the deflections of the specimens in the major

and minor strength directions will reach around 260 mm and 730 mm, respectively. These values are not reasonable, since the creep curve of these specimens tested in this project did not level off showing the full second stage. Therefore, to provide better simulation of the creep behaviour of this type of thin CLT, the loading period needs to be longer, such as one year or more, until the creep rate reaches to zero.

Also, in order to better simulate the creep of CLT for extended tests in the future, a complex model consisting of multiple components can be considered and developed, but this multi-component model also has some limitations. For example, when solving parameters, the precision of different parameter combinations is close, which cannot get the solution of unique parameters (Yu *et al.*, 2007). Therefore, the parameter simulation results in Appendix A 0.5-0.8 of each specimen were not similar or within a range.

Group	Direction	Model	Equation	R-Square
C1	Major	GK	$u = -7.272e^{-0.0.7088t} + 3.581$	0.5754
		B	$u = -3.604e^{-0.04965t} + 0.0000005t + 3.431$	0.9136
	Minor	GK	$u = -8.162e^{-0.2435t} + 6.401$	0.1478
		B	$u = -6.381e^{-0.1233t} + 0.00000252t + 5.643$	0.8398
C2	Major	GK	$u = -5.917e^{-0.4733t} + 3.689$	0.3501
		B	$u = -5.725e^{-0.5132t} + 0.000000861t + 3.43$	0.9291
	Minor	GK	$u = -10.93e^{-0.5893t} + 6.093$	0.1702
		B	$u = -6.206e^{-0.145t} + 0.00000239t + 5.372$	0.9672
C3	Major	GK	$u = -11.91e^{-0.9341t} + 4.683$	0.4778
		B	$u = -11e^{-0.9106t} + 0.000000843t + 4.427$	0.9556
	Minor	GK	$u = -15.51e^{-0.4455t} + 9.935$	0.1677
		B	$u = -13.9e^{-0.3998t} + 0.000003818t + 8.779$	0.9319
C4	Major	GK	$u = -9.621e^{-0.7482t} + 4.555$	0.3673
		B	$u = -6.65e^{-0.4427t} + 0.000000924t + 4.273$	0.8489
	Minor	GK	$u = -14.97e^{-0.2289t} + 11.91$	0.191
		B	$u = -13.59e^{-0.229t} + 0.00000361t + 10.81$	0.7409

Table 4.3 Curve fitting equations of 4 groups specimens in major direction.

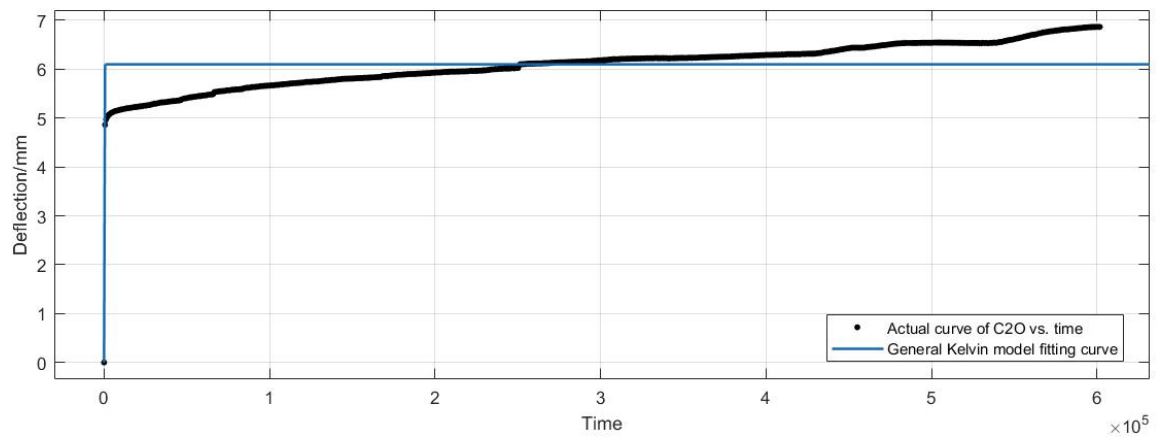
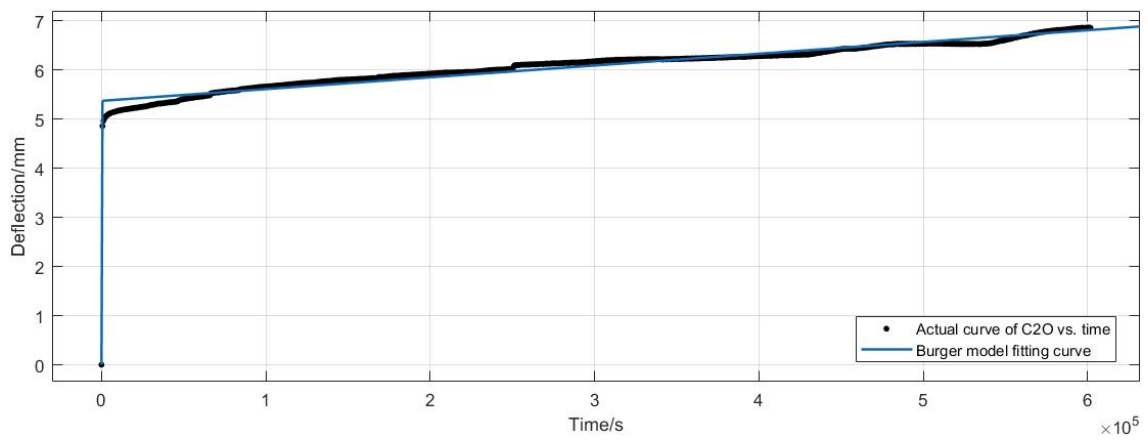


Figure 4.16 Burger model curve vs. General Kelvin curve of C2O.

5 Conclusions

Based on what was obtained and discussed above, the following conclusions could be drawn:

1) In third-point bending test, the PLs of thin CLT specimens in the major and minor directions were 3,000N and 800N, respectively. The average MOE_{app} and MOR_{app} of the specimens in the major direction were 8,510 MPa and 46.64 MPa, respectively, and the average MOE_{app} and MOR_{app} in the minor direction were 809 MPa and 9.48 MPa, respectively.

2) With increasing load level up from 30% to 60% PL, the minor strength direction specimens deflected 81.04% than that of 30% PL. And for major strength direction specimens, the deflection increased 32.07%. But due to the limit of the experiment condition, referring to the maximum load of flexural test will be more obvious for the major strength direction specimens. The relative creep in two directions showed a variance due to the variability of wood itself.

3) With decreasing the RH, the deflection of CLT specimens showed a slower increment. At the load level of 60% PL, the deflection of creep specimens in the minor direction showed a difference of about 2 mm after 7 days. However, at the load level of 30% PL, RH showed little impact on creep. The increment of moisture content will aggravate the mechano-sorptive ability of wood and lead to a larger displacement.

4) CLT in the major direction exhibited a superior load-bearing capacity than those in the minor direction. At the load level of 30% PL, the maximum deflection in the minor direction was about 1.8 times larger than that in the major one, and at the load level of 60% PL, the deflection in the minor direction was approximately 2.5 times larger than that in the major one.

5) The Burger model could well describe the 7-day creep of thin CLT specimens tested in this study. The time-deflection curves fit the Burger model equation with a high r-square value around 0.9135 and the equations can be used as a reference for future long-term research.

For future research, it could be recommended to investigate the long-term creep behaviour of CLT members by taking cyclic humidity and edge-bonding into account, and being loaded for one year at least to reach the creep rate of zero.

References

ASTM International. (2015a). *Standard test methods of static tests of lumber in structural sizes*. Designation: D198-15, ASTM International, West Conshohocken, PA, USA.

ASTM International. (2015b). *Standard Specification for Evaluation of Duration of Load and Creep Effects of Wood and Wood-Based Products*. Designation: D6815-15, ASTM International, West Conshohocken, PA, USA.

ASTM International. (2018). *Standard Specification for Adhesives for Bonded Structural Wood Products for Use Under Exterior Exposure Conditions*. Designation: D2559-12a, ASTM International, West Conshohocken, PA, USA.

APA -The Engineered Wood Association. (2019). *Standard for Performance-Rated Cross Laminated Timber*, ANSI/APA PRG 320. Tacoma, WA, USA.

Bodig, J., & Jayne, B. A. (1982). *Mechanics of wood and wood composites* (Vol. 712). New York: Van Nostrand Reinhold.

Bowyer, J., Bratkovich, S. T. E. V. E., Howe, J. E. F. F., Fernholz, K. A. T. H. R. Y. N., Frank, M. A. T. T., Hanessian, S. A. M. I. R. A. Groot, H. A. R. R. Y & Pepke, E. D. (2016). *Modern tall wood buildings: Opportunities for innovation*. Dovetail Partners Inc.: Minneapolis, MN, USA.

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products*, 74(3), 331-351.

- Byeon, J. W., Kim, T. H., Yang, J. K., Byeon, H. S., & Park, H. M. (2017). Bending Creep Property of Cross-Laminated Woods Made with Six Domestic Species. *Journal of the Korean Wood Science and Technology*, 45(6), 689-702.
- Byeon, J. W., Kim, T. H., Yang, J. K., Byeon, H. S., & Park, H. M. (2018). Static Bending Performances of Cross-Laminated Wood Panels Made with Tropical and Temperate Woods. *Journal of the Korean Wood Science and Technology*, 46(6), 726-734.
- CSA. (2017). Evaluation of Adhesive for Structural Wood Products (Limited Moisture Exposure), Designation: O112.10-08, Canadian Standards Association (CSA), Mississauga, ON, Canada.
- CSA. (2019). Engineering Design in Wood, Designation: O86-19, Canadian Standards Association (CSA), Mississauga, ON, Canada.
- Dinwoodie, J. M., Higgins, J. A., Paxton, B. H., & Robson, D. J. (1990). Creep research on particleboard. *Holz als Roh-und Werkstoff*, 48(1), 5-10.
- Fu, M. (2012). Experimental research on the mechanical performance of CLT bridge deck, Doctoral Dissertation, Changan University, Xi'an, Shanxi, China.
- Fellmoser, P., & Blaß, H. J. (2004). Influence of rolling shear modulus on strength and stiffness of structural bonded timber elements. In the Proceedings of *CIB-W18 meeting* (Vol. 37), August, Edinburgh, United Kingdom.
- Ferry, J. D. (1980). *Viscoelastic properties of polymers*. John Wiley & Sons Ltd, Canada
- Fredriksson, M., Bomark, P., Broman, O., & Grönlund, A. (2015). A trapeze edging method

- for cross laminated timber panel production. In *International Wood Machining Seminar*: 323-332 (DOI: 14/06/2015-19/06/2015), Universite Laval, Quebec City, QC, Canada.
- FPIInnovations (2019). *CLT Handbook - Canadian Edition* (2nd ed.). Karacabeyi, Erol & Gagnon, Sylvain (Eds.), Pointe-Claire, QC, Canada.
- Gong, M. (2019). Lumber-Based Mass Timber Products in Construction. In *Timber Buildings and Sustainability*. IntechOpen.
- Holzer, S. M., Loferski, J. R., & Dillard, D. A. (2007). A review of creep in wood: Concepts relevant to develop long-term behavior predictions for wood structures. *Wood and Fiber Science*, 21(4), 376-392.
- Huang, Y. (2016). Creep behavior of wood under cyclic moisture changes: interaction between load effect and moisture effect. *Journal of wood science*, 62(5), 392-399.
- Hunt, D. G. (1999). A unified approach to creep of wood. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 455(1991), 4077-4095.
- Li, Y. (2015). *Duration-of-load and size effects on the rolling shear strength of cross laminated timber*, Doctoral Dissertation, University of British Columbia, Vancouver, BC, Canada.
- Li, Y., & Lam, F. (2016). Low cycle fatigue tests and damage accumulation models on the rolling shear strength of cross-laminated timber. *Journal of wood science*, 62(3), 251-262.
- Ma, Y. R., Luo, Y. S., & Li, X. J. (2008). Advances and expectations of study on wood rheology.

- Journal of Central South University of Technology*, 15(1), 545-549.
- Matar, A. (2003). *The mechano sorptive creep of softwood in bending*, Doctoral Dissertation, South Bank University, London, UK.
- McDonald, D. E., Begel, M., Senalik, C. A., & Williamson, T. (2018). Evaluation of creep performance of structural insulated panels (SIPs): phase 2. *Res. Paper FPL-RP-697*. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA.
- Nairn, J. A. (2017). Cross-laminated timber properties including effects of non-glued edges and additional cracks. *European Journal of Wood and Wood Products*, 75(6), 973-983.
- Park, H. M., Fushitani, M., Sato, K., Kubo, T., & Byeon, H. S. (2006). Bending creep performances of three-ply cross-laminated woods made with five species. *Journal of Wood Science*, 52(3), 220-229.
- Pereira, M. C. D. M., & Calil Junior, C. (2019). Strength and Stiffness of Cross Laminated Timber (CLT) panels produced with Pinus and Eucalyptus: experimental and analytical comparisons. *Matéria (Rio de Janeiro)*, 24(4).
- Pirvu, C., & Karacabeyli, E. (2014). Time-dependent behaviour of CLT. In *World Conference on Timber Engineering*, Vancouver, BC, Canada.
- Yu, Z., & Fan, M. (2017). Short-and long-term performance of wood based panel products subjected to various stress modes. *Construction and Building Materials*, 156, 652-660.
- Yu H., Zhao R., Liu X., Fei B., (2007). A Review of Models of Creep in Wood. *Scientia Silvae*

Sinicae, 43(7): 101-105.

Zhou, Q., Gong, M., Chui, Y. H., & Mohammad, M. (2014). Measurement of rolling shear modulus and strength of cross laminated timber fabricated with black spruce. *Construction and Building Materials*, 64, 379-386.

Appendix A: Test results

Panel		Thickness (8 points)								Mean	Length1	Length2	Weight
		mm									mm	mm	g
1	11.01	11.19	10.98	10.93	11.05	11.21	11.04	10.92	11.04	7130	7130	2472	
2	11.11	11.21	10.99	11.17	11.18	11.27	10.95	11.11	11.12	7130	7110	2680	
3	11.18	11.18	11.22	11.11	11.02	10.93	11.14	10.95	11.09	7100	7130	2545	
4	11.26	11.09	11.15	11.87	11.15	11.21	11.04	11.01	11.22	7120	7140	2493	
5	11.01	11.34	11.14	11.02	11.25	11.32	11.20	10.91	11.15	7130	7170	2450	
6	11.26	11.08	10.76	10.78	10.96	11.12	11.15	10.97	11.01	7200	7140	2390	
7	11.11	11.03	10.93	10.80	10.70	10.94	10.85	10.60	10.87	7145	7125	2541	
8	11.10	11.05	10.63	10.57	11.05	10.88	10.61	10.48	10.8	7100	7125	2766	
9	11.18	11.07	11.09	10.93	10.96	11.26	11.10	10.63	11.03	7140	7140	2428	
10	11.05	11.10	10.88	10.82	10.80	11.32	11.06	10.89	10.99	7150	7130	2593	
11	11.01	11.5	11.15	10.8	10.85	10.99	10.82	10.85	11.00	7100	7140	2548	
12	11.13	11.25	11.05	11.01	10.92	11.17	10.99	10.86	11.05	7140	7140	2408	
13	10.91	11.01	10.82	10.9	10.8	11.01	10.91	10.88	10.91	7150	7120	2073	
14	11.07	11.36	11.15	10.86	10.99	11.07	10.97	10.94	11.05	7150	7120	2068	
15	10.89	11.02	10.93	10.86	10.80	11.17	11.07	10.79	10.94	7110	7130	2224	
16	11.12	11.19	10.96	10.86	11.21	11.11	10.90	10.74	11.01	7140	7190	2120	

Table A.0.1 One-layer panel.

Moisture Content (%)															
W1		W2		Group C1 (65%RH)			Group C2 (30%RH)			Group C3 (65%RH)			Group C4 (30%RH)		
(BA)		(BO)		Before		After	Before		After	Before		After	Before		After
1	24.84	1	9.46	A1	10.70	11.90	A1	11.20	9.20	A1	11.50	11.60	A1	11.30	8.90
2	10.53	2	10.10	A2	12.60	10.70	A2	11.20	8.80	A2	10.70	11.20	A2	12.10	8.40
3	10.46	3	10.00	A3	12.80	11.50	A3	11.60	8.50	A3	10.50	11.50	A3	12.70	8.70
4	9.86	4	10.13	O1	9.80	12.00	O1	13.30	9.50	O1	11.30	10.90	O1	10.30	9.10
5	9.88	5	10.08	O2	13.90	13.40	O2	12.10	8.90	O2	12.60	11.80	O2	11.50	9.40
6	10.39	6	10.09	O3	14.10	12.10	O3	12.40	10.20	O3	11.10	11.90	O3	10.70	10.50

Table A.0.2 MC of each test specimens.

W1					
Number	MOE_{app} (MPa)	MOR_{app} (MPa)	PL (%)	P max (N)	Displacement (mm)
W1 BA1	7561	19.32	0.54	2522.73	9.20
W1 BA2	8172	48.84	0.58	6375.59	13.01
W1 BA3	8104	46.42	0.58	6064.58	11.14
W1 BA4	9190	46.34	0.65	6021.24	10.89
W1 BA5	9110	45.52	0.65	5957.47	9.89
W1 BA6	7976	46.10	0.57	6048.61	11.87
Mean	8510	46.64	0.61	6093.50	11.36
St_{Dev}	589	1.28	0.04	162.91	1.16
Median	8172	46.34	0.58	6048.61	11.14

Table A 0.3 Test results of W1 specimens

W2					
Number	MOE_{app} (MPa)	MOR_{app} (MPa)	PL (%)	P max (N)	Displacement (mm)
W2 BO1	804	11.65	0.06	1524.14	33.35
W2 BO2	734	8.49	0.05	1117.12	31.87
W2 BO3	796	10.62	0.06	1400.97	32.80
W2 BO4	812	10.03	0.06	1324.85	29.35
W2 BO5	895	8.29	0.06	1095.97	32.34
W2 BO6	811	7.81	0.06	1033.24	33.04
Mean	809	9.48	0.06	1249.38	32.13
St_{Dev}	52	1.51	0.00	195.92	1.46
Median	807	9.26	0.06	1220.99	32.57

Table A 0.4 Test results of W2 specimens.

Coefficients (with 95% confidence bounds):

Specimen	Model	Equation	R-Square
C1A1	GK	$u = -5.89e^{-0.004941t} + 4.956$	0.2837
	B	$u = -5.867e^{-0.005667t} + 6.225t + 4.769$	0.8649
C1A2	GK	$u = -2.561e^{-0.002137t} + 2.403$	0.3102
	B	$u = -2.652e^{-0.002714t} + 3.676t + 2.292$	0.8048
C1A3	GK	$u = -3.944e^{-0.003584t} + 3.386$	0.2813
	B	$u = -3.978e^{-0.004233t} + 4.915t + 3.237$	0.8508
C1O1	GK	$u = -2.074e^{-0.004539t} + 7.076$	0.8883
	B	$u = -3.833e^{-0.001022t} + 2.779t + 5.536$	0.8108
C1O2	GK	$u = -1.47e^{-0.00465t} + 6.394$	0.8841
	B	$u = -5.335e^{-0.002108t} + 1.978t + 5.31$	0.8402
C1O3	GK	$u = -2.014e^{-0.004296t} + 7.645$	0.8850
	B	$u = -3.068e^{-0.002241t} + 2.718t + 6.111$	0.8274

Table A 0.5 Curve fitting equations of group C1.

Specimen	Model	Equation	R-Square
C2A1	GK	$u = -6.231e^{-0.008225t} + 5.024$	0.08947
	B	$u = -6.19e^{-0.00996t} + 1.063t + 4.703$	0.8743
C2A2	GK	$u = -0.5204e^{-0.005371t} + 2.688$	0.9088
	B	$u = -2.912e^{-0.003746t} + 7.083t + 2.322$	0.892
C2A3	GK	$u = -4.282e^{-0.006845t} + 3.51$	0.09442
	B	$u = -4.314e^{-0.008686t} + 8.048t + 3.267$	0.9292
C2O1	GK	$u = -5.518e^{-0.001811t} + 5.526$	0.09241
	B	$u = -5.934e^{-0.003189t} + 2.047t + 4.907$	0.9275
C2O2	GK	$u = -2.131e^{-0.002779t} + 6.934$	0.9444
	B	$u = -6.414e^{-0.002873t} + 2.714t + 5.085$	0.9504
C2O3	GK	$u = -1.731e^{-0.004656t} + 7.431$	0.8977
	B	$u = -7.829e^{-0.002782t} + 2.391t + 6.136$	0.9061

Table A 0.6 Curve fitting equations of group C2.

Specimen	Model	Equation	R-Square
C3A1	GK	$u = -5.428e^{-0.007175t} + 4.927$	0.1486
	B	$u = -5.603e^{-0.009011t} + 7.569t + 4.698$	0.9202
C3A2	GK	$u = -4.122e^{-0.002518t} + 3.537$	0.193
	B	$u = -4.24e^{-0.003384t} + 8.329t + 3.284$	0.925
C3A3	GK	$u = -6.871e^{-0.004162t} + 5.586$	0.2423
	B	$u = -6.943e^{-0.004998t} + 9.299t + 5.304$	0.9266
C3O1	GK	$u = -3.749e^{-0.003876t} + 12.05$	0.9211
	B	$u = -11.81e^{-0.001779t} + 5.031t + 9.097$	0.9118
C3O2	GK	$u = -9.377e^{-0.009722t} + 9.621$	0.1692
	B	$u = -11.24e^{-0.002028t} + 3.342t + 8.602$	0.9354
C3O3	GK	$u = -10.08e^{-0.00134t} + 9.581$	0.1711
	B	$u = -11.27e^{-0.00232t} + 2.996t + 8.67$	0.9145

Table A 0.7 Curve fitting equations of group C3.

Specimen	Model	Equation	R-Square
C4A1	GK	$u = -0.8913e^{-0.009605t} + 5.474$	0.9162
	B	$u = -5.181e^{-0.006132t} + 1.036t + 5.009$	0.7674
C4A2	GK	$u = -0.7668e^{-0.001146t} + 3.67$	0.8507
	B	$u = -3.424e^{-0.001764t} + 8.112t + 3.316$	0.7725
C4A3	GK	$u = -5.223e^{-0.003119t} + 4.779$	0.1812
	B	$u = -5.697e^{-0.004525t} + 9.05t + 4.503$	0.8176
C4O1	GK	$u = -3.819e^{-0.001385t} + 13.26$	0.9351
	B	$u = -3.684e^{-0.002757t} + 1.905t + 12.45$	0.9811
C4O2	GK	$u = -3.516e^{-0.009645t} + 12.35$	0.9672
	B	$u = -3.085e^{-0.001552t} + 1.513t + 11.62$	0.9791
C4O3	GK	$u = -3.147e^{-0.001465t} + 11.51$	0.9149
	B	$u = -3.066e^{-0.002892t} + 1.533t + 10.87$	0.9626

Table A 0.8 Curve fitting equations of group C4.

Curriculum Vitae

Candidate's full name: Meizhen Chen

Universities attended:

Nanjing Forestry University, Bachelor of Science in Engineering (Wood Science and Engineering), P.R. China, 2020

University of New Brunswick, Master of Forest Engineering, 2021

Publication:

Chen MZ and Gong M. 2020. Use of engineered wood products in restoration of Notre-Dame Cathedral. International Wood Industry 50(4): 10-15 (in Chinese).