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Study the effects of Thermal Modification on the energy absorption of
Western Hemlock wood

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Abstract

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Wood is increasingly being considered for structural applications because of its sustainability, availability, cost effectiveness, and favorable mechanical performance relative to its weight. Thermal modification is commonly used to improve the durability, dimensional stability, and moisture resistance of wood; however, its effect on the response of wood under impact loading is not yet fully understood. This is particularly important for applications involving dynamic loading, such as timber-based military shelter systems.

This study investigates the low-velocity impact behavior of unmodified and thermally modified Western Hemlock, with particular emphasis on the influence of modification temperature and natural wood topology on energy absorption and failure behavior. Specimens were tested under three-point bending using an Instron 9250HV drop-weight impact system. The resulting force–displacement response was used to evaluate energy absorption, while high-speed imaging and Digital Image Correlation (DIC) were used to examine the development of strain and damage during impact. Post-impact fracture surfaces were further characterized using Scanning Electron Microscopy (SEM), and thermal analyses using Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) were performed to investigate changes associated with thermal modification.

Three dominant failure mechanisms were identified: tensile fiber failure, inclined inter-granular failure associated with local deviations in fiber orientation, and grain shear slip

involving interfacial delamination along the wood structure. The occurrence of these mechanisms was observed to be influenced by the local fiber and growth-ring orientations relative to the impact direction, demonstrating that the natural topology of wood plays an important role in governing its impact response. The failure mechanisms also exhibited distinctly different energy absorption capacities, with inclined inter-granular failure generally dissipating the least energy, followed by tensile fiber failure, while grain shear slip resulted in the greatest energy dissipation. Within a given failure mechanism, specimens modified near 180 °C exhibited the highest energy absorption, followed by a reduction in energy absorption at higher modification temperatures. Thermal analysis further indicated evidence of limited degradation of the fundamental molecular components of wood over the investigated modification range, while temperature-dependent changes in molecular interactions provided additional insight into the observed mechanical response.

Overall, the results demonstrate that the low-velocity impact behavior of thermally modified Western Hemlock cannot be described by modification temperature alone. Both thermal modification and the underlying wood topology must be considered when evaluating failure and energy absorption. These findings provide the mechanical behavior understanding of the impact response of thermally modified Western Hemlock and highlight the importance of controlling material topology and modification conditions when designing wood-based structures for applications subjected to dynamic loading.

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GLOSSARY

ACLT: Abbreviation for Advanced Cross-Laminated Timber.

CRTC: Abbreviation for Composite Recycling Technology Center.

DIC: Abbreviation for Digital Image Correlation.

DSC: Abbreviation for Differential Scanning Calorimetry.

EARLYWOOD: The less-dense portion of a growth ring, generally characterized by larger cells and thinner cell walls.

ENERGY ABSORPTION: Mechanical energy dissipated by the specimen through deformation and damage during impact loading.

GRAIN SHEAR SLIP: Shear-dominated failure mechanism involving interfacial delamination and relative sliding along the local wood structure or growth-ring interfaces.

GROWTH RING: A layer of wood produced during one growth cycle, consisting primarily of earlywood and latewood regions.

GROWTH-RING BOUNDARY: The interface between successive growth rings, associated with a distinct change in cellular structure and mechanical properties.

INCLINED INTER-GRANULAR FAILURE: Failure mechanism involving fiber-wall rupture and/or intercellular separation associated with transverse stresses generated by local deviations in fiber orientation.

L: Abbreviation for the longitudinal direction of wood, aligned parallel to the primary fiber direction.

LATEWOOD: The denser portion of a growth ring, generally characterized by smaller cells and thicker cell walls.

LOW-VELOCITY IMPACT: Impact loading occurring at relatively low impact velocities, during which structural deformation and damage develop over the duration of contact.

MIDDLE LAMELLA: The intercellular bonding layer between adjacent wood cells and an important interface for intercellular separation and crack propagation.

ML: Abbreviation for Middle Lamella.

PRINCIPAL STRAIN: Normal strain acting along a direction in which the associated shear strain is zero. The first principal strain represents the maximum principal strain.

R: Abbreviation for the radial direction of wood, oriented perpendicular to the growth rings and extending radially outward from the center of the tree.

RAY CELLS: Cells oriented primarily in the radial direction that provide transverse transport and can locally influence crack propagation.

SEM: Abbreviation for Scanning Electron Microscopy.

T: Abbreviation for the tangential direction of wood, oriented tangent to the growth rings.

TENSILE FIBER FAILURE: Failure mechanism involving tensile rupture and splitting of the longitudinal wood fibers.

TGA: Abbreviation for Thermogravimetric Analysis.

THERMAL MODIFICATION: Controlled heating of wood to alter its physical, chemical, and mechanical properties.

TM: Abbreviation for Thermally Modified wood.

TRACHEIDS: Also, termed as fibers are elongated tubular cells that constitute the majority of softwood and provide structural support and fluid transport.

UM: Abbreviation for Unmodified wood.

WESTERN HEMLOCK: A softwood species used in this study.

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DEDICATION

To my parents, Sushama Yelve and Rajan Yelve,
for always believing in me, standing by me, and giving me the courage to pursue my
dreams.

Chapter 1

INTRODUCTION

1.1 Wood as a Material in Commercial Structural Applications

Wood is widely available across the United States, with different species naturally distributed across various regions, many of which have commercial value. Its long-standing use in construction reflects its ability to perform reliably as a structural material [5]. Historical timber structures provide strong evidence of its durability and structural performance over extended periods of service. One such example is the Cornish–Windsor Covered Bridge (See Fig.1.1a), the longest wooden covered bridge in the United States. Originally constructed in 1866 and spanning approximately 460 ft (140 m), the bridge remains in service today. Its continued performance under vehicular loading and varying environmental conditions demonstrates that properly designed timber structures can provide sufficient strength, stiffness, and durability for long-term structural applications. Building on this long history, wood continues to play an increasingly important role in modern construction, where it is extensively used in residential and commercial buildings for structural elements such as beams, columns, floor systems, and framing members.

Advances in engineered wood products have further expanded the use of timber in large-scale engineering applications. A notable example is Ascent MKE (See Fig. 1.1b) in Milwaukee, Wisconsin, completed in 2022 and recognized as the world’s tallest timber-concrete hybrid building, standing approximately 284 ft (86.6 m) tall and demonstrating the feasibility of timber in high-rise construction. Timber has also been successfully incorporated into long-span structures, such as SkyBridge Michigan (See Fig. 1.2a), completed in 2022 and recognized as the world’s longest timber-towered suspension bridge, spanning approximately 1,200 ft (366 m). Beyond buildings and bridges, engineered timber has also entered renewable-energy infrastructure, as demonstrated by Modvion’s wooden wind turbine tower in Sweden (See Fig. 1.2b), recognized as the world’s tallest wooden wind turbine tower,

a



b



Figure 1.1: Examples of timber in structural applications: (a) Cornish–Windsor Covered Bridge and (b) Ascent MKE timber high-rise building

with a hub height of approximately 345 ft (105 m). These examples demonstrate that wood can be successfully used in structures requiring high strength, low structural weight, and long-term durability while maintaining reliable performance under service loading. The increasing adoption of timber is reflected in the projected 9.2 percent annual growth of the global timber construction market over the coming decade as shown in Figure. 1.3. This growth is driven by wood's widespread availability, ease of processing, cost-effectiveness, and growing demand for sustainable construction materials. Furthermore, certification programs such as the Forest Stewardship Council (FSC), Sustainable Forestry Initiative (SFI), and American Tree Farm System (ATFS) promote responsible forest management, ensuring that timber is sourced sustainably while maintaining ecological balance, making wood both a practical and environmentally responsible structural material.

Wood is generally classified into hardwoods and softwoods based on botanical characteristics rather than properties such as strength or density. Hardwoods are flowering species and tend to have a more complex and porous internal structure. In contrast, softwoods are

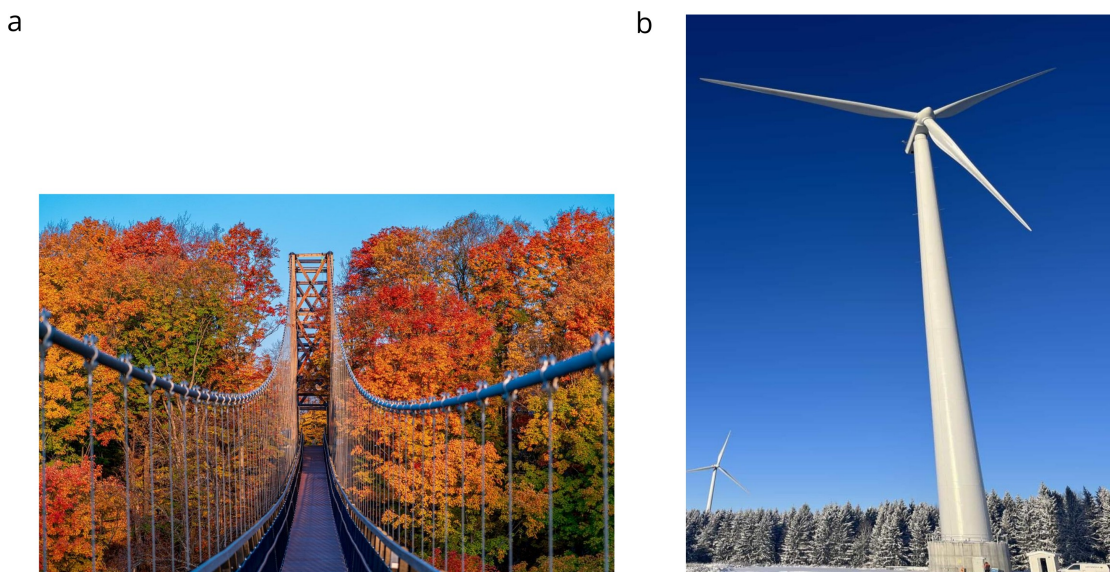


Figure 1.2: Emerging applications of timber in large-scale engineering structures: (a) Sky-Bridge Michigan timber-towered suspension bridge and (b) Modvion wooden wind turbine tower

typically associated with cone-bearing trees that have needle-like leaves, and they exhibit a simpler and more uniform cellular structure, primarily composed of tracheids which will be discussed in further details later in the chapter. In this study, Western hemlock softwood (See Fig. 1.4) is considered, which belongs to the softwood category.

Western hemlock (*Tsuga heterophylla*): Western hemlock is a tall evergreen native to the North Pacific West, found west of the Cascades and along the British Columbia coast from California to Alaska, and is recognized as Washington State's tree. Its wide availability in Washington makes it an important part of the regional timber supply. The wood appears light in color, often showing dark streaks and knots that are not directly related to its strength. From a material standpoint, it offers moderate strength, stiffness, hardness, and shock resistance while remaining relatively lightweight, though it shows moderately high shrinkage similar to Douglas-fir and has limited resistance to decay. It is used in construction as well as in products like boxes, furniture, and ladders, and its availability, ease of

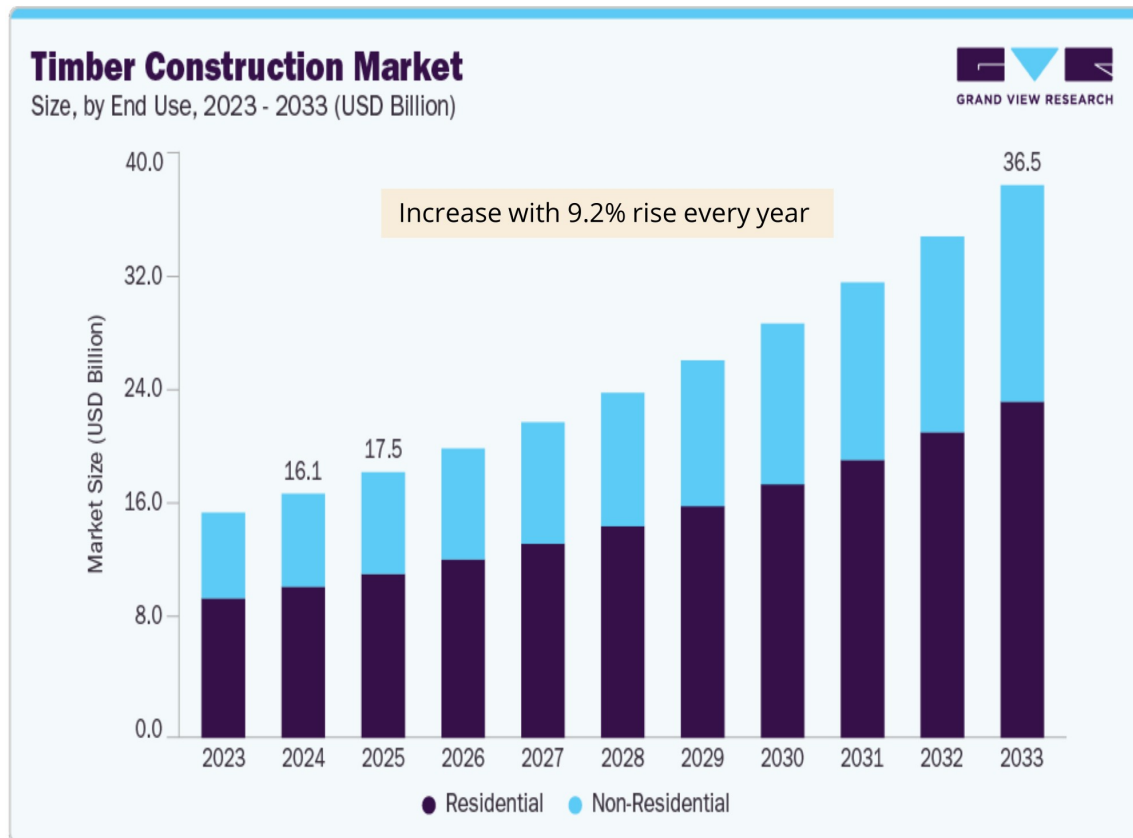


Figure 1.3: Global timber construction market growth and projected trends

processing, and mechanical behavior have made it a relevant material for studying structural response, damage, and energy absorption under loading.

Wood shows natural variation in structure depending on direction, so its growth and basic anatomy can be useful to keep in mind when looking at mechanical behavior. When a tree is cut, concentric growth rings are visible, formed through seasonal cycles. These rings consist of earlywood and latewood (See Fig. 1.5), reflecting changes in growth conditions. Earlywood forms during favorable conditions and tends to have larger, thinner-walled cells (See Fig. 1.6), making it lighter and more porous. Latewood forms later, with smaller, thicker-walled cells (See Fig. 1.6), which may result in higher density and stiffness. The transition between earlywood and latewood is defined by the growth ring boundary. Since the microstructure changes across this boundary, it introduces local variations in material



Figure 1.4: Western Hemlock Softwood

properties, creating a layered architecture that can influence stress distribution, crack initiation, and damage propagation under mechanical loading.

At the cellular level (See Fig. 1.7), softwoods such as Western Hemlock are primarily composed of tracheids, which act as both load-bearing fibers and fluid transport elements. These appear as elongated tubular structures, and in cross-section, the cell walls often form a honeycomb-like pattern. In addition to tracheids, ray cells extend horizontally across the longitudinal tracheids, facilitating the transport and storage of nutrients within the wood. These cells also serve as local variations and thus can influence damage propagation during mechanical loading. This arrangement is commonly observed in SEM analysis and can help



Figure 1.5: Macroscopic structure of wood showing growth rings, growth-ring boundaries, earlywood, and latewood.

relate microstructural features to deformation and damage mechanisms.

Wood is also directional (See Fig. 1.8), with three principal material orientations: longitudinal (along the grain), radial (from pith to bark), and tangential (along the growth rings). Since the cellulose fibers and tracheids are aligned predominantly in the longitudinal direction, wood exhibits its greatest strength and stiffness when loaded parallel to the grain. In contrast, the radial and tangential directions are loaded across the fibers, making them comparatively weaker [2] and more prone to crack initiation and propagation. These directional differences play an important role in the deformation and failure behavior of wood under mechanical loading. The strengths of wood in these directions are given in the Tables 1.1 and 1.2

At the molecular level, wood can be viewed as a natural composite (See Fig. 1.9). Cellulose forms the primary load-bearing framework and contributes to the strength and stiffness of wood through aligned microfibrils. Hemicellulose surrounds and connects the cellulose microfibrils, helping to bond the cell wall components together. Lignin acts as the

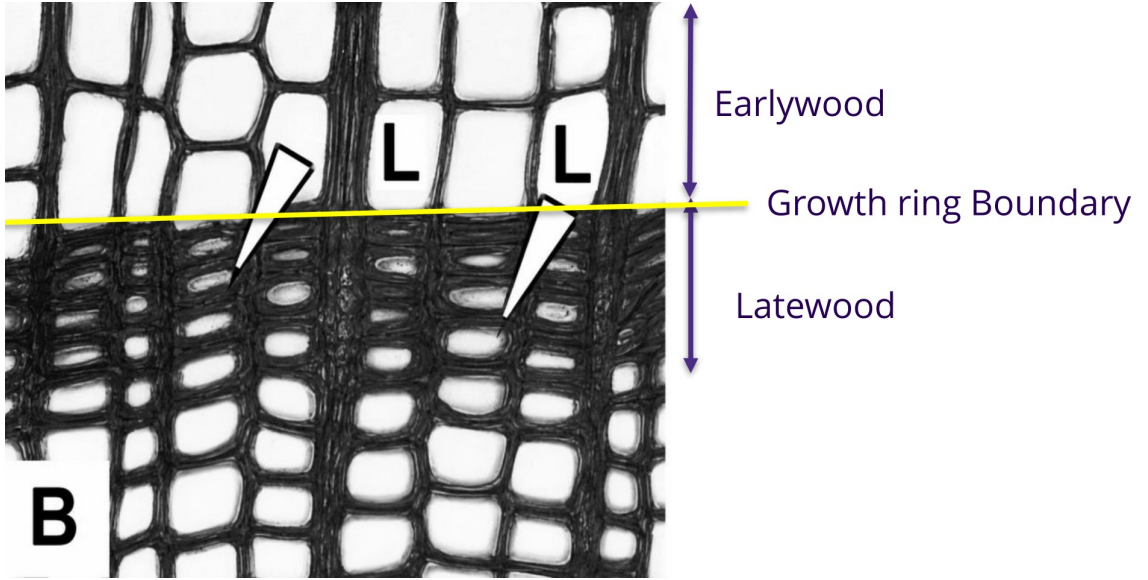


Figure 1.6: Cellular structure across a growth-ring boundary showing the transition between earlywood and latewood [1]

E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L
0.031	0.058	0.038	0.032	0.003

Table 1.1: Elastic moduli ratios of Western hemlock (12% moisture content) [5].

Flexural (L)	Tensile (L)	Tensile (L)	Compressive (transverse)	Compressive (transverse)	Shear (transverse)
78000	89600	49000	3800	8600	2300

Table 1.2: Strengths of Western hemlock (12% moisture content) in kPa [5].

matrix by filling the spaces between cellulose and hemicellulose, contributing to rigidity and resistance to deformation. Furthermore, the cell wall (See Fig. 1.10) is separated by the middle lamella, bonding neighboring cells together and contributing to load transfer between them. The middle lamella is often considered as the weakest interface between adjacent cells,

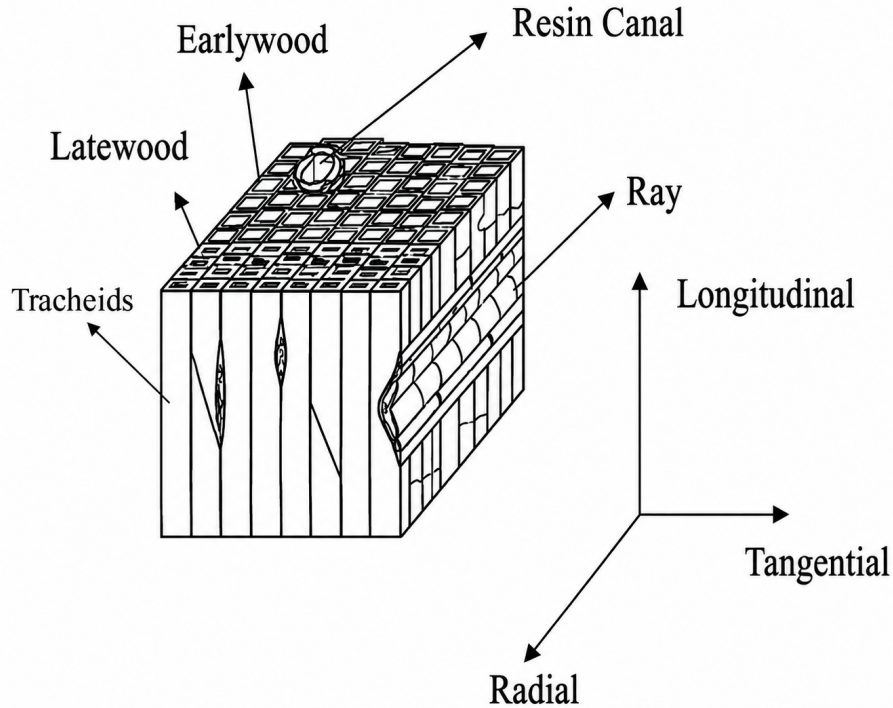


Figure 1.7: Cellular structure of softwood showing tracheids, ray cells, earlywood, latewood, and the principal material directions [2]

it can serve as a preferred path for damage propagation under mechanical loading. Together, this structure affects how wood responds under loading, particularly in terms of stiffness, damage progression, and energy dissipation.

1.2 Effects of Thermal Modification at the Molecular Level

Wood is moisture sensitive, thus it readily absorbs moisture from its surroundings. Prolonged exposure to moisture promotes fungal decay, causing external wood rot and deterioration of the cellular structure (See Fig. 1.11). This degradation can lead to shrinkage, swelling, and reduced mechanical performance. To improve durability and dimensional stability, thermal modification is a widely used technique in the industry to reduce the moisture sensitivity of wood.

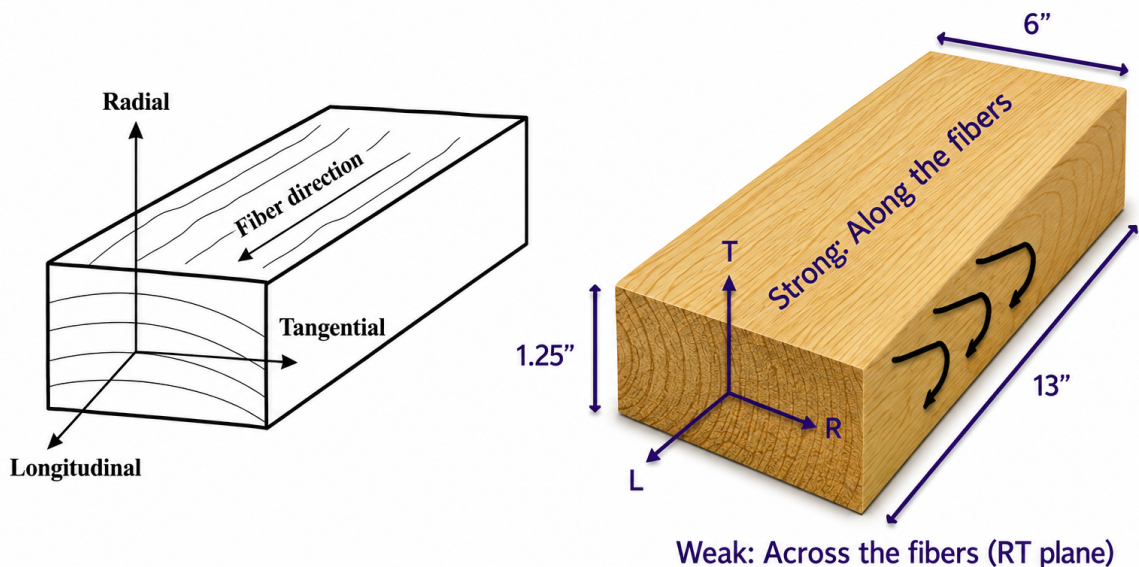


Figure 1.8: Orthotropic material directions of wood and their relationship to fiber orientation and mechanical strength [1]

Thermal modification refers to heating wood at elevated temperatures under low-oxygen and controlled moisture conditions, which can lead to a reduction in hydroxyl ($-OH$) groups. Studies such as Kim et al. suggest that heat treatment may cause cleavage of ether bonds and condensation reactions within lignin, resulting in increased molecular rigidity and reduced polarity. These changes can reduce moisture sensitivity and may improve dimensional stability.

At the same time, hemicelluloses may undergo depolymerization and partial degradation, which can reduce the number of accessible $-OH$ groups and potentially weaken bonding interactions with cellulose with increasing temperature. Cellulose is generally more stable under moderate heat treatment and may continue to maintain the primary load-bearing framework of the cell wall.

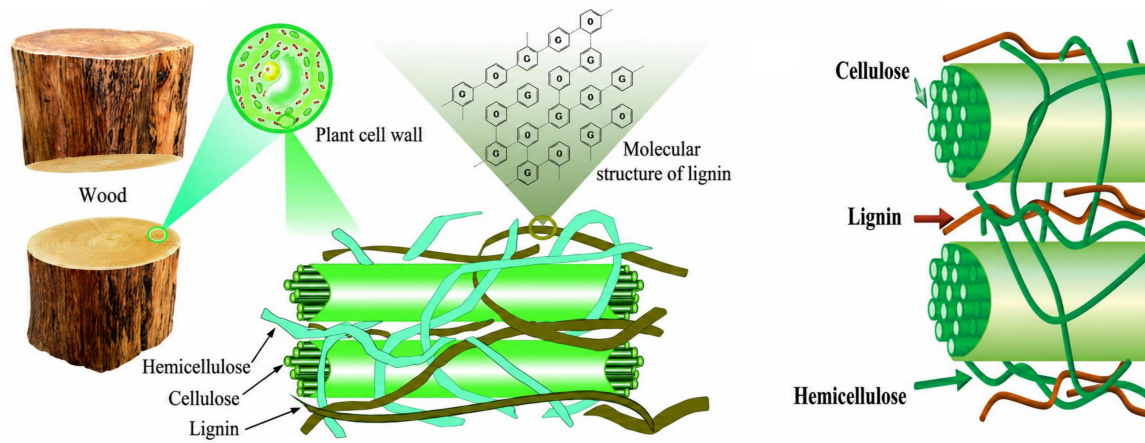


Figure 1.9: Molecular structure of wood showing the organization of cellulose, hemicellulose, and lignin within the cell wall [3]

Together, these molecular-level changes can influence stiffness, toughness, moisture response, and energy absorption behavior, helping explain trends observed in thermally modified wood during mechanical and impact testing.

1.3 Literature Review

This review focuses on several studies that have investigated the influence of thermal modification on the physical, chemical, and mechanical properties of wood. These studies provide insight into how thermal treatment alters the wood microstructure and affects its mechanical performance. This section summarizes the key findings from the literature that are relevant to the present work.

Curling *et al.* [6] investigated the relationship between mechanical properties, weight loss, and chemical composition during brown-rot decay in southern pine sapwood exposed to *Gloeophyllum trabeum* and *Postia placenta*. They found that measurable weight loss began only after approximately 40 percent reduction in bending strength (MOR), while the initial loss in strength was primarily associated with degradation of hemicellulose components. Their findings provided important insight into the relationship between microstructural degradation and mechanical performance loss in wood materials, which is relevant to

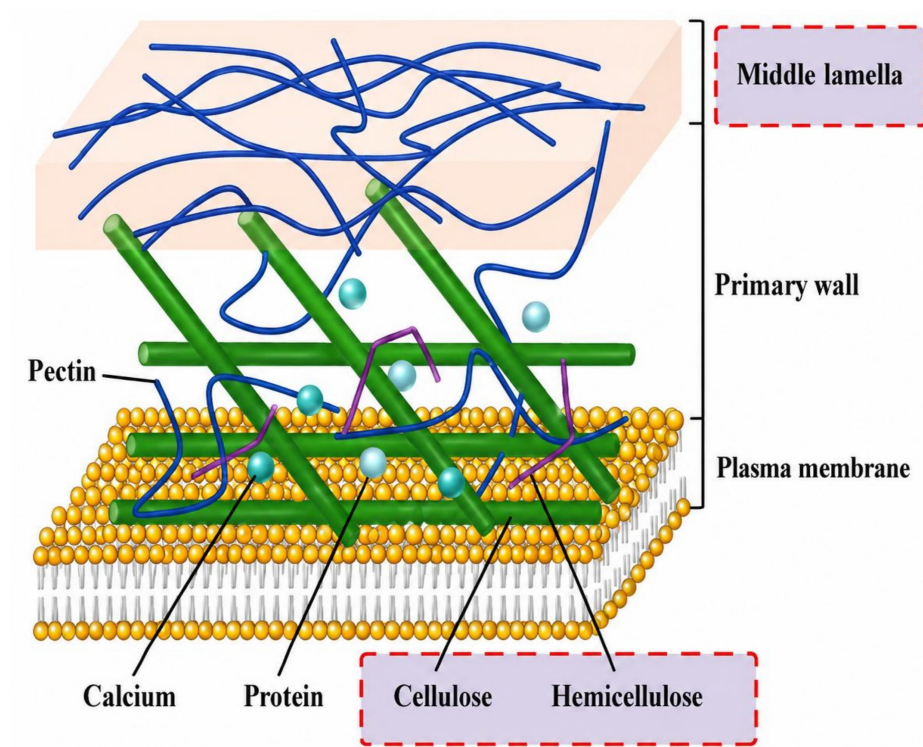


Figure 1.10: Schematic representation of the plant cell wall and middle lamella, showing the distribution of major structural components [3]



Figure 1.11: Moisture-induced degradation of wood at the macroscopic and cellular scales [4]

understanding damage progression and energy dissipation behavior in the present study.

Mantanis *et al* [7] investigated the swelling behavior of different wood species in water by evaluating the effects of temperature and extractive removal on swelling characteristics. They found that increasing water temperature significantly increased both the swelling rate and the maximum equilibrium swelling of wood, while the removal of extractives further enhanced swelling and reduced the energy activated required for the swelling process. Their findings provided useful insight into the influence of temperature and wood chemical composition on moisture-related behavior, which is relevant for understanding the structural response and dimensional changes of wood materials under varying environmental conditions.

Sandberg *et al* [8] reviewed thermo-hydro (TH) and thermo-hydro-mechanical (THM) wood processing techniques, including heat treatment, densification, bending, and wood welding, with the aim of improving the performance and sustainability of wood products. They reported that TH and THM processing can enhance dimensional stability, durability, hardness, and shape stability of wood, although high-temperature treatments may also reduce strength and increase brittleness due to hemicellulose degradation. Their review provided important insight into the physical and chemical changes occurring during thermal processing of wood, which is relevant to the present study in understanding how thermal modification influences the mechanical and impact behavior of wood materials.

Boonstra *et al.* [9] investigated the influence of thermal modification on the mechanical behavior of softwood species and reported that heat treatment significantly altered their strength properties. Tensile and impact strengths decreased considerably after treatment, while compressive strength parallel to the grain and modulus of elasticity (MOE) increased. The authors attributed these changes to chemical modifications within the wood structure, including degradation of hemicelluloses, crystallization or degradation of amorphous cellulose, and lignin polycondensation reactions. Although heat-treated wood exhibited increased brittleness and sensitivity to natural defects such as knots and grain irregularities, the study concluded that thermally modified timber still possesses strong potential for structural and construction applications due to its improved stiffness and dimensional stability. The authors also emphasized the need for further research on long-term behavior, cyclic loading, and impact resistance under service conditions.

Nhacila *et al.* [10] investigated the influence of thermal modification on the physical and mechanical properties of the lesser-used Mozambican hardwood species *Brachystegia spiciformis* and *Julbernardia globiflora*. They reported that thermal treatment caused noticeable reductions in equilibrium moisture content and density, while also producing darker wood coloration and improved dimensional stability. The mechanical properties, including bending strength, stiffness, compression strength, and hardness, generally decreased with increasing treatment intensity, indicating increased brittleness after thermal modification. Despite these reductions, the authors suggested that thermally modified wood from both species still shows strong potential for applications such as flooring and interior products due to its improved hydrophobicity, enhanced appearance, and reduced moisture sensitivity.

Nakagawa *et al.* [11] investigated the effects of thermal modification on the flexural properties, fracture energy, and hardness of western hemlock in both longitudinal and transverse material directions. They reported that thermal modification had little influence on the longitudinal modulus of elasticity (MOE) and modulus of rupture (MOR), while significantly reducing the transverse strength, fracture energy, and Janka hardness of the material. The study also showed that thermally modified western hemlock exhibited increased brittleness and lower energy dissipation capability, particularly in the radial-longitudinal and tangential-longitudinal fracture systems. Their findings provide important insight into the influence of thermal modification on the damage tolerance and impact-related behavior of western hemlock, forming a key foundation for the present study.

Korkut *et al.* [12] investigated the influence of heat treatment on the technological and mechanical properties of Scots pine (*Pinus sylvestris* L.) subjected to treatment temperatures of 120, 150, and 180 °C for durations of 2, 6, and 10 h. They reported that thermal modification generally reduced compression strength, bending strength, modulus of elasticity, hardness, impact bending strength, and tensile strength perpendicular to the grain, with greater reductions observed at higher temperatures and longer treatment durations. However, milder treatment conditions produced only slight changes in the mechanical properties. The authors also highlighted that appropriate heat treatment techniques can improve the usability and dimensional stability of wood while enabling the utilization of low-commercial-value wood species in broader structural and industrial applications. Their findings provide

useful insight into the relationship between treatment severity and mechanical degradation, which is important for understanding the structural performance of thermally modified wood materials.

Gaff *et al.* [13] investigated the effect of thermal modification at temperatures of 160, 180, and 210 °C on the chemical composition and impact bending strength (IBS) of European oak and Norway spruce wood. They reported that thermal treatment at 160 °C initially increased the impact bending strength of both wood species by nearly 30 percent; however, further increases in treatment temperature caused significant reductions in IBS. The greatest decrease was observed at 210 °C, where IBS reduced by approximately 32 percent in oak and 40 percent in spruce compared to unmodified wood. The study also showed a strong correlation between the reduction in IBS and chemical changes within the wood structure, particularly changes associated with cellulose and hemicellulose content. Their findings highlighted the strong influence of thermal modification severity on the toughness and dynamic mechanical behavior of wood, emphasizing that treatment temperatures should be carefully selected depending on the intended structural application of thermally modified wood.

Salviato *et al.* [14] investigated the quasi-brittle fracture behavior and energy absorption characteristics of textile composites through experimental and numerical size effect analyses. The study demonstrated that textile composites exhibit a pronounced quasi-brittle response, where structural behavior transitions from relatively ductile to increasingly brittle with increasing specimen size. The authors emphasized that accurate measurement of fracture energy is critical for predicting energy absorption and crashworthiness performance. Their results showed that reductions in fracture energy significantly decreased the crushing load and energy dissipation capacity of composite structures, highlighting the strong dependence of crash performance on fracture behavior. The study further concluded that conventional strength-based approaches and classical LEFM are insufficient to capture the quasi-brittle nature and finite fracture process zone of textile composites, making fracture-energy-based modeling essential for reliable energy absorption predictions and structural scaling analyses. Similar observations have been made for other quasibrittle materials such as UD composites [15, 16, 17, 18, 19, 20], 3D woven composites [21], discontinuous fiber composites [22, 23,

24, 25], polymers [26], nanocomposites [27, 28, 29], polymer nanofoams [30] and many other quasibrittle materials which, like wood, exhibit large fracture process zones [31]. Recently, Chen *et al.* proposed a novel topology-informed size effect regression approach which was shown to successfully be able to extract fracture energy and effective Fracture Process Zone (FPZ) size for Western Hemlock [32].

Jae-young kim's *et al.* [33] study demonstrated that heat treatment caused significant structural and thermal modifications in milled wood lignin (MWL). As treatment temperature increased, lignin exhibited gradual weight loss due to the release of volatile phenolic compounds from terminal phenolic groups. The analyses revealed simultaneous depolymerization through cleavage of β -O-4 ether linkages and condensation reactions between lignin fragments, indicating extensive structural rearrangement at elevated temperatures. Thermal analysis further showed improved thermal stability and increased condensation of the lignin structure with increasing treatment temperature. Additionally, DSC results suggested enhanced endothermic behavior at higher temperatures, indicating ongoing physical and chemical transformations within the lignin during heat treatment.

Grottesi *et al.* [1] investigated the thermo-hygro-mechanical behavior of wood, with particular emphasis on the combined effects of moisture variations and mechanical loading. The study showed that cyclic changes in moisture can induce stresses and strains within wood, while the simultaneous action of moisture and mechanical loads can produce mechanosorptive effects and increase time-dependent creep. The authors also emphasized that the wood-moisture interaction and resulting mechanical response become increasingly complex in multi-layer wooden structures. Based on their review, combining experimental characterization with numerical and mathematical modeling was identified as an effective approach for predicting long-term deformation and potential damage under varying temperature, humidity, and mechanical loading conditions.

1.4 Thesis Motivation

Wood has gained increasing attention as a sustainable structural material due to its favorable mechanical properties and widespread availability. Previous studies have shown that thermal modification can improve the dimensional stability, durability, and moisture resistance

of wood by altering its chemical composition and microstructure. As a result, thermally modified wood has become a promising material for structural applications.

Although several studies have investigated the mechanical behavior of thermally modified wood, only a limited number have examined its response under impact loading. Most existing impact studies have relied on standardized Charpy tests, which provide impact strength measurements but offer limited insight into the evolution of damage and failure mechanisms during loading. In addition, previous research has primarily focused on wood species other than Western Hemlock, despite the differences in anatomy and mechanical behavior among species.

Wood also exhibits several natural local variations, including growth rings, ray cells, and interfaces such as the middle lamella, which can influence stress distribution, crack initiation, and damage propagation. However, the role of these microstructural features in the impact response and failure behavior of thermally modified Western Hemlock has not been systematically investigated. This combination of research gaps motivated the Composite Recycling Technology Center (CRTC), in collaboration with the University of Washington and the U.S. Army, to explore the use of thermally modified Western Hemlock for military shelter construction applications, where impact resistance and structural energy absorption are critical.

This combination of research gaps, together with the growing interest in wood-based structural systems, motivated the Advanced Cross-Laminated Timber (ACLT) project, involving the Composite Recycling Technology Center (CRTC), the University of Washington, and the U.S. Army. The broader project investigates the feasibility of using thermally modified Western Hemlock for military shelter construction. As part of this effort, timber-based shelter systems are being evaluated under demanding structural loading conditions, including full-scale seismic testing, as shown in Figure 1.12. Military environments are highly dynamic compared with conventional construction environments, exposing shelter systems to various loading conditions, including blast waves and low-velocity impacts from debris, vehicle collisions, and crashes as shown in the Fig.1.13. Therefore, understanding the impact resistance, energy absorption, and associated failure mechanisms of thermally modified Western Hemlock is important for evaluating its potential use in such structural applica-

tions. It is worth mentioning that this study resulted in a journal publication which can be found in [34].



Figure 1.12: Full-scale seismic testing of a timber-based military shelter conducted as part of the U.S. Army ACLT Project

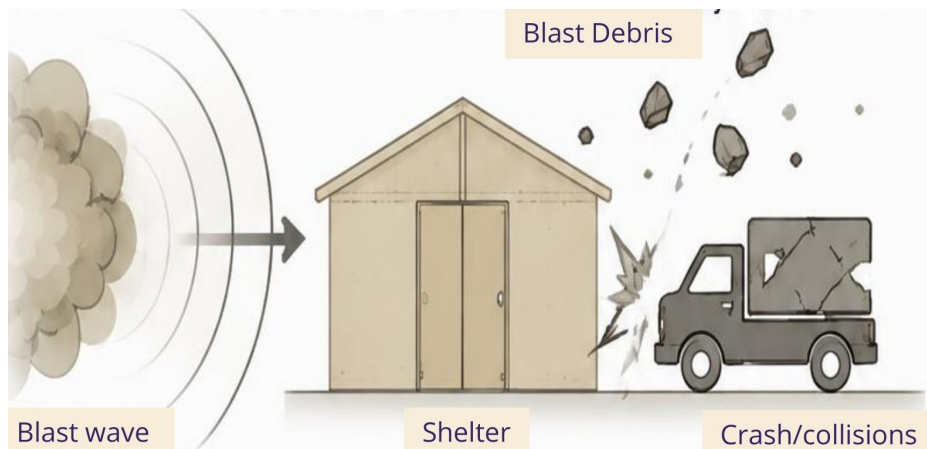


Figure 1.13: Representative dynamic loading conditions experienced by military shelter systems, including blast waves, debris impact, and vehicle collisions

Chapter 2

EXPERIMENTAL SETUP

2.1 Material Selection, Harvesting, and Pre-Processing

2.1.1 Selection of Western Hemlock

Western hemlock (*Tsuga heterophylla*) was selected for this study due to its extensive availability along the Pacific Coast of North America and its status as one of the most abundant softwood species in the Pacific Northwest. The species is commonly used in building materials and structural components, as well as in the manufacture of boxes, pallets, crates, flooring, furniture, and ladders, making it representative of construction-grade softwoods used in buildings and related infrastructure. Its moderate density, strength, stiffness, and shock resistance make it a suitable candidate for structural performance investigations.

Thus, the timber was harvested in the Makah Reservation in Neah Bay, Washington for this study. After harvesting, the logs were transported to the Makah Sawmill, a tribally operated facility in Neah Bay that processes locally sourced timber into rough and dimensional lumber for structural and commercial applications. Figure 2.1 shows the rough lumber boards with nominal dimensions of 13 in $\times$ 6 in $\times$ 5/4 in (330.2 mm $\times$ 152.4 mm $\times$ 31.75 mm) that were milled from the wood logs. Wood exhibits orthotropic behavior, with mechanical properties varying along the longitudinal (L), radial (R), and tangential (T) directions (See Fig. 2.1). In this study, the boards were milled such that their length was aligned as closely as possible with the longitudinal (L) direction. This alignment was chosen as the longitudinal direction generally exhibits higher stiffness and strength compared to the radial and tangential directions, as that is the fiber direction.

Following milling, the lumber was kiln dried to a target moisture content of approximately 12 percent [1] using a Nyle dry kiln (See Fig. 2.2), which operates under controlled low-temperature conditions with regulated heat, humidity, and airflow. During drying, the boards were stacked to allow uniform air circulation, and the drying conditions were grad-

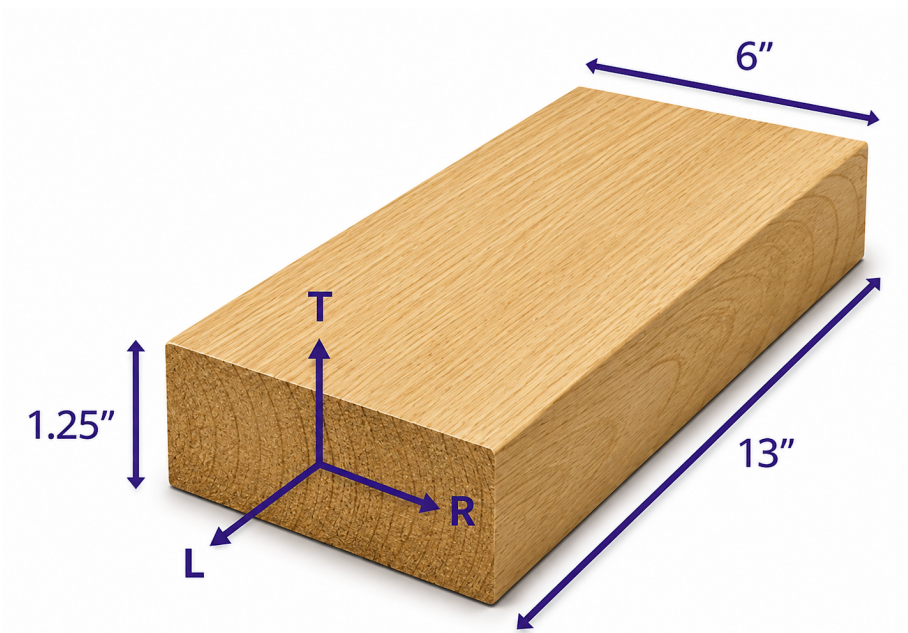


Figure 2.1: Geometry and dimensions of Western Hemlock boards prepared for kiln drying

ually adjusted to promote even moisture removal while minimizing defects such as warping or cracking. This process resulted in wood with relatively uniform moisture content, representative of typical service conditions, and helped reduce moisture-related variability in subsequent mechanical behavior. A target moisture content of approximately 12% was selected as it is commonly associated with equilibrium moisture conditions for wood used in indoor or sheltered environments in temperate climates in the Washington State [1]. At this level, dimensional changes due to moisture variation are minimized, and the mechanical properties of wood are generally more stable and representative of in-service structural performance. Drying to significantly lower moisture contents may introduce additional drying stresses or increased brittleness, while higher moisture contents can lead to greater variability in stiffness and strength due to moisture-dependent softening effects. These boards were used to obtain the unmodified samples.

The dried boards were then transported to the Composite Recycling Technology Center



Figure 2.2: Kiln drying of Western Hemlock boards at Makah Sawmill

(CRTC) in Port Angeles, Washington, where thermal modification, and specimen preparation were carried out on the remaining boards. At CRTC, some of the boards were retained under ambient laboratory conditions and designated as the unmodified (UM) group, while the remaining boards were assigned to thermal modification treatments at different peak temperatures.

2.2 Thermal Modification Procedure

Thermal modification was applied to alter the chemical structure of wood through controlled exposure to elevated temperatures. The treatment was carried out using a Maspell thermo-vacuum kiln (See Fig. 2.3) operating under the pressure of approximately 350 mbar. The use of vacuum conditions was intended to suppress oxidative degradation and to promote more uniform heat transfer throughout the wood volume.

The remaining boards were subjected to thermal modification following the Compos-



Figure 2.3: Maspell Thermo-Vacuum system at CRTC used for thermal modification of Western Hemlock boards

ite Recycling Technology Center (CRTC)'s internal thermal modification procedure, which consisted of a five-stage heating schedule with controlled heating and dwell phases. Peak treatment temperatures of 180 °C, 190 °C, 200 °C, and 214 °C were selected based on previous literature and the thermally modified wood boards available at CRTC for this study. Following evaluation of the unmodified specimens, 180 °C and above treatment temperatures were selected as the thermal modification temperatures based on findings from the literature review. At approximately this temperature, thermally induced chemical changes in wood become sufficiently pronounced to improve resistance to fungal decay, while the mechanical properties can remain relatively well preserved or, in some cases, exhibit improved performance. Therefore, 180 °C was considered a suitable starting point for evaluating whether thermal modification could enhance impact performance without substantial deterioration of the wood structure.

During the thermal cycle, specimens were heated at a uniform ramp rate of 7 °C/hr through the PH, P1, P2, and P3 stages to limit thermal gradients and reduce the risk

of internal cracking. Dwell times were set to 180 minutes for the Preheating (PH) stage, 90 minutes each for intermediate stages P1 and P2, and 180 minutes for target thermal modification stage P3, followed by a controlled cooling stage of 360 minutes. Tables 2.1 and 2.2 list this entire process. This staged heating approach allowed gradual thermal exposure and was intended to promote more uniform heat penetration across the specimen cross-section.

The selected temperature range was chosen to progressively modify the chemical and mechanical behavior of the wood, particularly to almost eliminate moisture sensitivity of wood. For each treatment group, specimens were heated through intermediate temperature plateaus before reaching the designated peak temperature at the P3 stage, followed by controlled cooling to approximately 90 °C. Upon completion of the cycle, the boards were allowed to cool gradually within the kiln to minimize residual thermal stresses and reduce the likelihood of warping or cracking.

	PH	P1	P2	P3	Cool
Dwell Time (min)	180	90	90	180	360
Pressure (mbar)	350	350	350	350	350
Ramp Rate (°C/hr)	7	7	7	7	N/A

Table 2.1: Dwell time, pressure, and ramp rate settings of the 5-stage thermal modification.

Peak Temperature (°C)	PH	P1	P2	P3	Cool
180	155	162	173	180	90
190	155	173	182	190	90
200	155	183	191	200	90
214	155	198	206	214	90

Table 2.2: Temperature settings of the 5-stage thermal modification at different modification temperatures.

2.3 Batch Categorization

The wood boards were machined into specimens with nominal dimensions of $7 \times 1 \times 1$ in. (See Fig. 2.4 for specimen dimensions), selected to match the drop tower test setup. The specimens were then divided into three experimental batches to progressively refine the investigation of impact behavior, with each batch incorporating an increasing level of microstructural control. During specimen preparation, boards were visually inspected, and efforts were made to avoid specimens containing excessive knots, checks, or other macroscopic defects to minimize variability unrelated to the experimental variables of interest. The specimen selection criteria and objectives for each batch are discussed in the following sections.

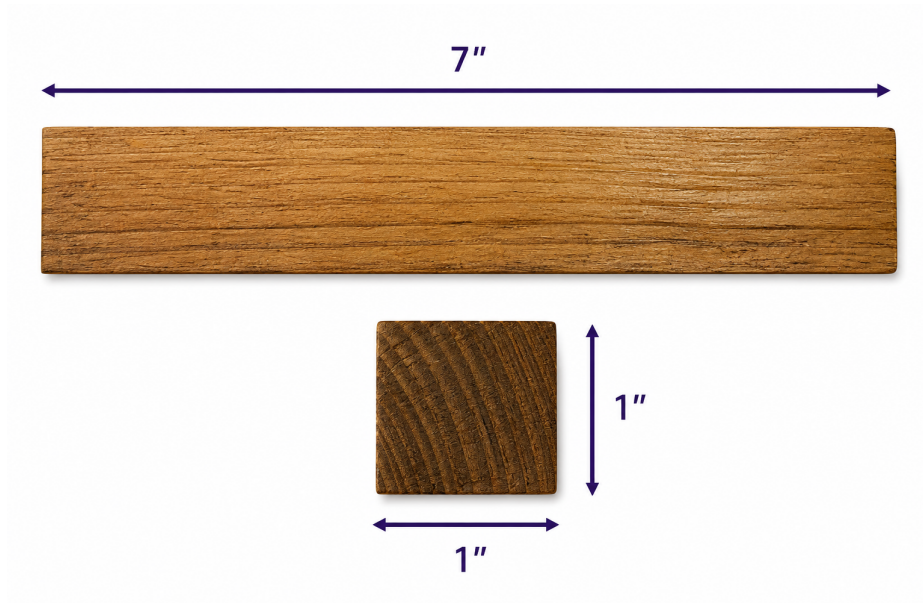


Figure 2.4: Final Western Hemlock specimen dimensions prepared for low-velocity impact testing

2.3.1 Batch 1 and 2 Specimens: Temperature Optimization Study

The first batch was prepared to establish baseline low-velocity impact behavior and to identify dominant failure mechanisms without imposing constraints on cross-sectional grain geometry. The wood topology that is both longitudinal and transverse grain orientation was not explicitly controlled, resulting in a natural distribution of growth-ring spacing and orientation across the specimen population. The wood topology for these specimens will be understood in more detail while exploring the failure mechanisms observed. This approach allowed the observation of multiple failure mechanisms arising from inherent material heterogeneity. All specimens in this batch were tested at an input energy of 50 J. The results provided initial insight into energy absorption behavior and indicated the presence of multiple distinct failure modes, which motivated further refinement in subsequent batches.

Data from Batches 1 and 2 together helped with the identification of temperature-dependent trends in impact performance while also highlighting the significant influence of grain orientation and growth-ring interfaces on failure behavior.

2.3.2 Batch 3 Specimens: Mechanism 3 validation study

The third batch was designed as a validation study to evaluate the impact response of specimens with controlled topology identified from the previous batches. Based on the observations from Batches 1 and 2, specimens exhibiting denser fiber spacing running parallel along the longitudinal direction and inclined perpendicular to the impact direction and denser growth-ring spacing and growth-ring orientations inclined approximately 30° – 45° relative to the impact direction along the transverse direction (R-T plane) demonstrated higher energy absorption (See Fig. 2.4 for topology alignment of batch 3 samples). Therefore, batch 3 specimens were intentionally selected with these characteristics to validate the observed trends and to further investigate failure mechanisms associated with interfacial shear and delamination along growth-ring boundaries. The impact energy was increased to 100 J, as many specimens from the previous batches absorbed the entire 50 J input energy without complete failure.

This approach enabled the study of impact behavior under more controlled grain con-

figurations and provided insight into how specific grain orientations may influence energy absorption under varying loading conditions.

2.4 Drop Tower Equipment Setup

Low-velocity impact tests were conducted using the experimental setup as shown in the figure 2.5 an Instron 9250 HV drop tower with a three-point bending fixture. Mechanical response was recorded using the Dynatup data acquisition system, while Digital Image Correlation (DIC) was employed to monitor full-field deformation and failure progression during impact. The individual components of the experimental setup and their operating parameters are discussed in detail in the subsequent slides.

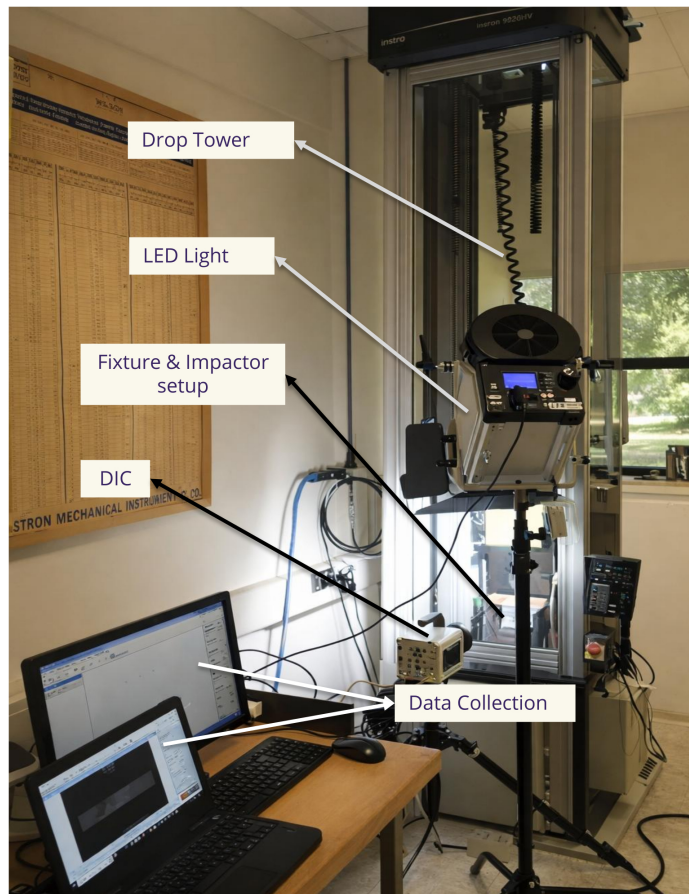


Figure 2.5: Overall Experimental Setup

2.4.1 *Drop Tower*

Low-velocity impact experiments were conducted using an instrumented Instron Dynatup 9250HV drop-weight impact tower (See Fig. 2.6), available in the UW mechanical engineering department's Mechanical Testing Lab (MEB). In this system, a known mass is released from a prescribed height to impact the specimen, while the response is recorded through an instrumented load cell. The drop tower captures impact force, impact velocity, and contact time during each event. From these measurements, specimen deflection and absorbed energy are calculated. System control, data acquisition, and analysis were performed using Instron Impulse software. The Instron Dynatup 9250HV is a gravity- and spring-assisted falling-weight impact system with electronically controlled drop height and impact mass. The system can simulate drop heights of up to 20.4 m and supports an energy range of approximately 4.6 J to 826 J, with a maximum impact velocity of 20 m/s. The impactor was equipped with a 15 kN load cell, and a total impact mass of approximately 23 kg was used for all tests. Data were recorded at high acquisition rates, with up to 8192 data points captured per impact event.

Pendulum-based impact testers were not employed in this study. While such systems are commonly used to determine impact bending strength (e.g., ISO 13061-10). They do not readily support synchronized high-speed imaging required for detailed analysis of failure mechanisms under low-velocity impact. For these reasons, a drop-tower-based approach was selected.

Force displacement and rate of energy absorption curves were obtained directly from the drop tower measurements, which is computed by integrating the force displacement response. This approach enabled consistent comparison of energy absorption behavior across different specimens and experimental batches.

2.4.2 *Three-Point Bending Fixture and Impactor Setup*

A custom three-point bending fixture made up of stainless steel (See Fig. 2.7) was designed in SolidWorks and fabricated to accommodate the specimen geometry and experimental objectives. The fixture consisted of two cylindrical support rollers with a diameter of 0.5

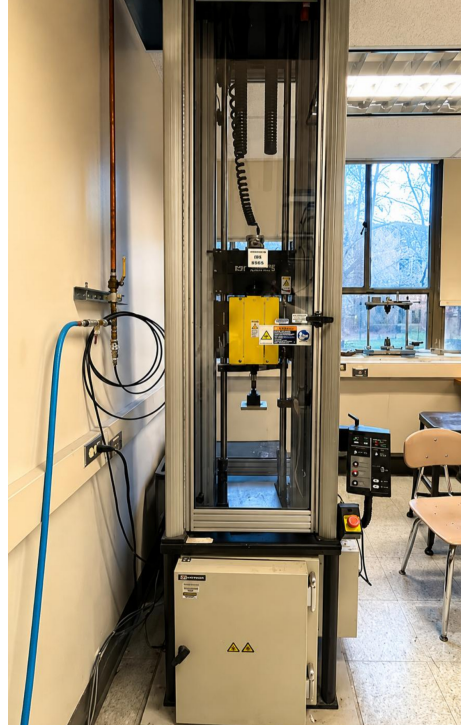


Figure 2.6: Instron 9250 HV Drop Tower

in and a fixed support span of 6.5 in. A semi-cylindrical impactor was used to apply the impact load at the center of the specimen, with an impactor width of 1.25 in (31.75 mm). The fixture was rigidly bolted to the drop tower base to minimize compliance and to maintain consistent boundary conditions across tests. The fixture geometry is explicitly reported due to the absence of a standardized drop-weight impact configuration for wood materials in the ASTM standards. Also, for batch 1 aluminum impactor was used; however, for batches 2 and 3 it was changed to stainless steel because of load coupling issues. This will be further discussed in detail in the conclusion section.

2.4.3 Data Acquisition and Signal Considerations

Force, velocity, displacement and energy data were obtained in real time as shown in Figure 2.8. Force and absorbed energy were obtained directly from the dynamic load cell integrated into the impactor, while displacement was derived from the drop tower crosshead motion.

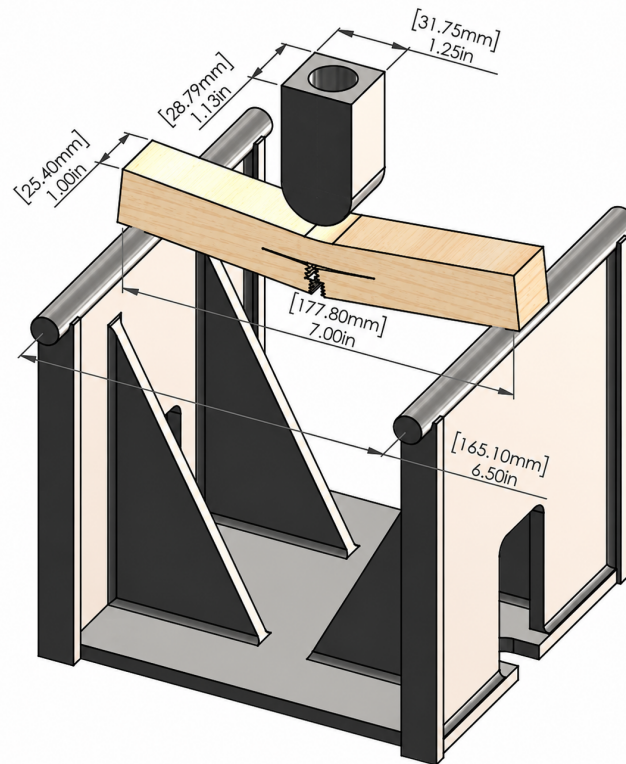


Figure 2.7: SolidWorks model of stainless steel 3-point bending test fixture

These measurements were used to evaluate the response of each specimen. During initial testing, an aluminum impactor was used for Batch 1. To address load-cell coupling effects observed in the preliminary data, the impactor material was changed to stainless steel for Batches 2 and 3. This modification had minimal influence on the force–displacement response but improved signal stability and overall data reliability.

Summary of Drop Tower Methodology: The drop tower experimental setup provided a controlled and repeatable framework for investigating the low-velocity impact behavior of thermally modified Western Hemlock. By systematically varying impact energy and specimen characteristics across batches while maintaining consistent boundary conditions, the experimental design enabled comparison of energy absorption and failure mechanisms as functions of thermal modification and grain orientation.

Index	Time	Ch 1 Raw Data	Ch 1 Load	Ch 1 Energy	Ch 1 Velocity	Ch 1 Deflection
#	ms	A/D Counts	kN	J	m/s	mm
0	-2.75635	512	-0.00448	0	2.098975	0
1	-2.75391	513	0	0	2.098975	0
2	-2.75146	514	0.004475	0	2.098998	0
			Goes on			
8191	17.24121	514	0.004475	10.654809	2.061413	34.529938

Figure 2.8: Representative impact data recorded from the drop tower using the Impulse/-Dynatup drop-tower software

2.5 Image Acquisition Equipment Setup for Failure Evaluation

High-speed Digital Image Correlation (DIC) was employed in this study to obtain full-field surface displacement and strain measurements during impact. The technique relies on tracking the evolution of a random speckle pattern applied to the specimen surface by correlating subsets of pixels between reference and deformed images. This approach enables the calculation of displacement fields, from which strain distributions can be derived.

Digital Image Correlation (DIC) is an effective full-field optical measurement technique for investigating deformation and failure processes that are difficult to characterize using conventional discrete measurements. It enables the visualization of localized strain development, crack initiation, and failure propagation throughout the loading process. In this study, DIC is used to correlate the evolution of local strain fields with the observed failure modes under impact loading.

2.5.1 Phantom T2410 High Speed DIC camera

The image acquisition parameters were optimized to obtain high-quality images suitable for Digital Image Correlation (DIC) (See Fig. 2.9). Image acquisition was performed using a Phantom T2410 monochrome high-speed camera equipped with a Nikon AF-S NIKKOR 50 mm f/1.8G lens (See Fig. 2.10). The 50 mm focal length provided an appropriate field of

view and spatial resolution for capturing the entire specimen while maintaining sufficient image detail for DIC analysis. The camera was operated at a resolution of 1280×800 pixels and an acquisition rate of approximately 38,043 fps (See Table. 2.11 that show these camera parameters in the PCC software) Since the impact event occurred within only a few milliseconds, a high frame rate was necessary to capture sufficient intermediate images for accurately monitoring the evolution of deformation and failure throughout the loading event.



Figure 2.9: Phantom T2410 DIC Camera

Table 2.3 shows the shutter speed and aperture values used for this testing. An exposure time (shutter speed) of $1 \mu\text{s}$ was selected to minimize motion blur caused by the rapid motion of the impactor and specimen during impact. Such a short exposure time ensured that each frame represented an instantaneous image of the specimen, preserving the sharpness of the speckle pattern required for accurate image correlation. Because a shorter exposure significantly reduces the amount of light reaching the camera sensor, the aperture was adjusted between f/4-f/5.6 to allow sufficient light while maintaining adequate image sharpness and



Figure 2.10: AF-S NIKKOR Lens

Resolution	1280 x 800
Acq Resolution	1280 x 800
Post Trigger	42758
Bits per pixel	P10 (Packed 10 log)
Acquisition bpc	12
Sample Rate(fps)	38043 fps
	Real: 38043.4783 fps
	Period: 26.29 μ s

Figure 2.11: Camera Specifications

depth of field across the specimen surface.

Table 2.3: Shutter Speed and Aperture values

Camera Parameter	Setting
Shutter Speed (μ s)	1.000
Aperture	f/4-f/5.6

Image focus was carefully adjusted over the entire specimen length to ensure that the speckle pattern remained sharp throughout the region of interest. The grayscale histogram (See Fig. 2.12) displayed in Phantom Camera Control (PCC) software was used to optimize the lighting conditions by achieving balanced dark and light intensity distributions (adjusting histogram peaks to equal heights), thereby maximizing image contrast. These optimized imaging parameters provided high-quality images that improved the reliability of the DIC measurements and the subsequent evaluation of deformation and failure mechanisms.

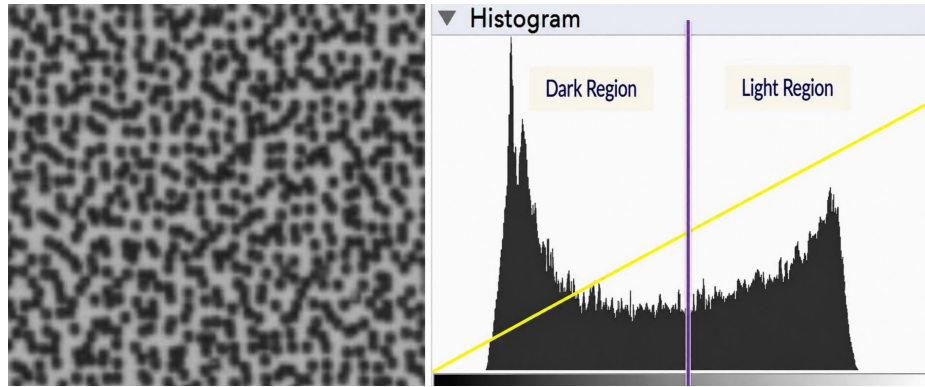


Figure 2.12: Representative DIC speckle pattern and intensity histogram used to assess image contrast and focus quality

2.5.2 Illumination System

High-speed DIC measurements require stable and sufficiently intense illumination to support microsecond-scale exposure times. In this study, illumination was provided using an Intellytech Light Cannon F-485 high-power LED source (See Fig. 2.13), selected for its high luminous output and continuous, flicker-free operation. The light source was positioned at an oblique downward angle relative to the specimen surface to reduce specular reflections while enhancing contrast between the speckle pattern and the background material. The standoff distance and pitch angle were adjusted prior to testing to achieve uniform illumination across the region of interest. This configuration helped with exposure times on the order of $1\ \mu\text{s}$, preserving sufficient image brightness and contrast for reliable correlation during

impact loading.



Figure 2.13: Intellytech Light Cannon F-485 high-power LED

2.5.3 Speckle Pattern Design and Application

Figure 2.14 shows the speckle pattern applied to the specimen surface for Digital Image Correlation (DIC) analysis. A random, high-contrast speckle pattern was applied to the tensile surface of each specimen to facilitate DIC analysis. The speckle pattern was transferred using printed temporary tattoo paper, which provided strong adhesion and minimal pattern degradation during high-strain-rate deformation. The speckle pattern was designed based on DIC best-practice guidelines, with the following key characteristics:

- Average speckle diameter: 5 pixels (0.86 mm)
- Speckle density: approximately 40% dark regions and 60% light regions
- Spatial distribution: Random distribution

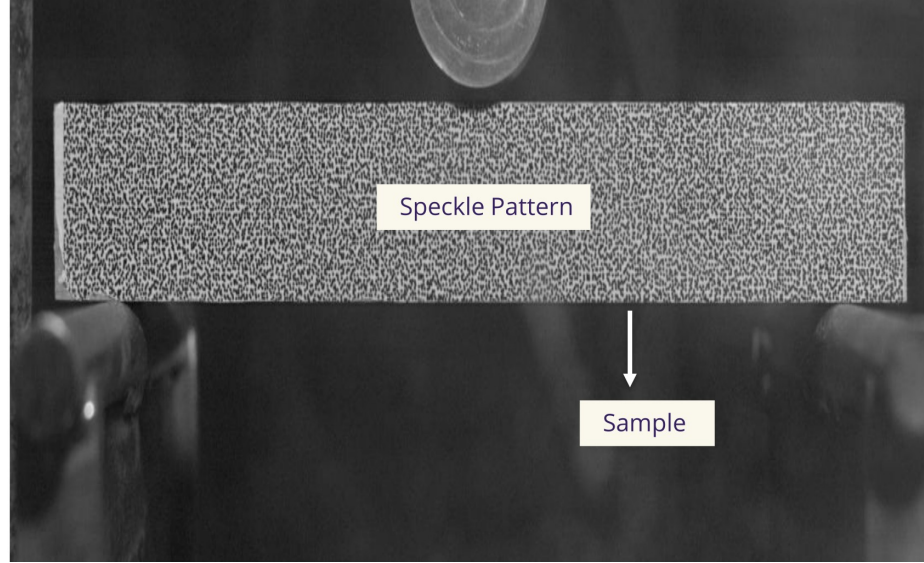


Figure 2.14: DIC speckle pattern applied to the specimen surface for high-speed image acquisition and deformation analysis

The average speckle diameter of approximately 5 pixels corresponded to a physical diameter of about 0.86 mm based on the calibrated imaging setup. The image scale was determined using the known specimen length of 7 in. (220 mm) and the camera image width of 1280 pixels, which were used to convert pixel dimensions into physical dimensions. The image scale was determined from the known specimen length captured within the camera field of view as:

$$\text{Image Scale} = \frac{220 \text{ mm}}{1280 \text{ pixels}} = 0.172 \text{ mm/pixel} \quad (2.1)$$

The physical speckle diameter was then calculated as:

$$\text{Speckle Diameter} = 5\text{pixel} \times 0.172\text{mm/pixel} = 0.86 \text{ mm}. \quad (2.2)$$

A random spatial distribution of the speckles was selected to eliminate directional bias and to provide unique grayscale features across the entire region of interest, enabling reliable correlation throughout the specimen surface. During DIC analysis, the software tracks the movement of these unique speckle patterns between successive images captured during the

impact event. The displacement of each tracked point is then used to compute the full-field displacement and strain distributions, allowing deformation and failure evolution to be characterized with high spatial resolution.

After application, the pattern was allowed to dry briefly to ensure adhesion without introducing moisture-related effects into the wood substrate.

2.5.4 Data Acquisition Procedure

Image acquisition was performed using an Ethernet connection to transfer data between the camera and the computer while recording the video using the Cine-based workflow of the Phantom Camera Control (PCC) software. In Preview mode, a live image stream was displayed on the control computer to allow adjustment of optical alignment, illumination, focus, and acquisition parameters prior to recording. When the camera was placed into record mode. Each recorded Cine was assigned a descriptive name, which was stored permanently within the Cine header for traceability during post-processing.

2.6 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) (See Fig. 2.15) was performed to examine the microstructural characteristics of the fracture surfaces and to better understand the damage caused at the cellular level within the wood structure after impact testing. The analysis was conducted using a Phenom ProX SEM at the Washington Clean Energy Testbeds. Since wood is inherently non-conductive, the fractured specimens were first prepared using a sputter coater to deposit a thin layer of gold on the surface, which improves electrical conductivity, reduces surface charging under the electron beam, and enables clearer SEM imaging. The coated specimens were then placed inside the SEM chamber under vacuum and imaged at different magnifications. The resulting micrographs were used to examine features such as cell-wall damage, fiber rupture and pull-out, cracking, crushing, and separation between the wood microstructural features, providing microscale insight into the fracture mechanisms observed during impact testing.

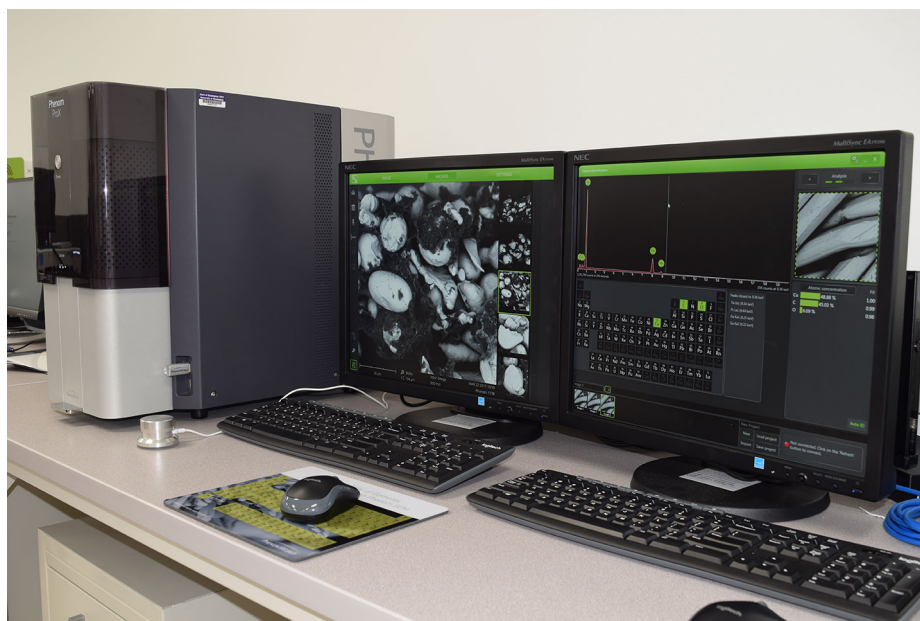


Figure 2.15: Phenom ProX Scanning Electron Microscope

2.7 Thermogravimetric Analysis (TGA)

Thermogravimetric analysis (TGA) (See Fig. 2.16) was performed at the Washington Clean Energy Testbeds using a Mettler Toledo TGA 3+ to investigate the thermal stability and degradation behavior of the wood constituents and to determine whether thermal modification resulted in changes to components such as hemicellulose, cellulose, and lignin. A small quantity of each wood sample was first placed in an aluminum crucible, which provides a lightweight, thermally conductive, and temperature-stable container that allows efficient and relatively uniform heat transfer to the specimen without significantly interfering with the measurement. The sample was then subjected to a controlled heating program while the instrument continuously recorded its mass as a function of temperature. The resulting mass-loss curves were used to identify different stages of weight loss, including initial moisture removal and subsequent thermal decomposition of the major wood constituents.

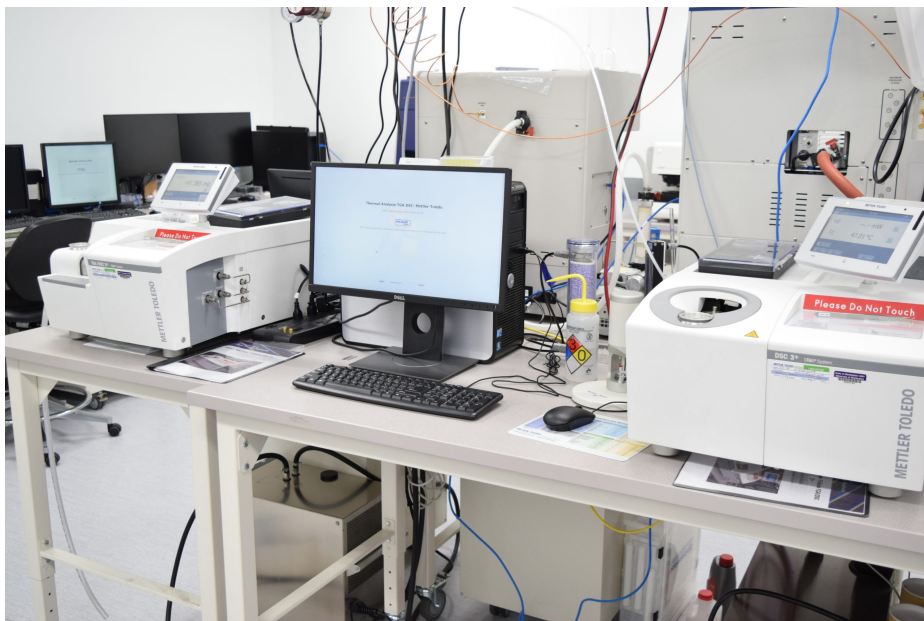


Figure 2.16: TGA and DSC

2.8 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) (See Fig. 2.16) was performed at the Washington Clean Energy Testbeds to investigate the thermal behavior of the wood and determine how heat was absorbed or released during heating. A small quantity of each wood specimen was placed in an aluminum crucible, which provides good thermal conductivity and allows efficient heat transfer between the instrument and the sample. The specimens were then subjected to a controlled heating while the DSC continuously measured the heat-flow response as a function of temperature. The resulting DSC curves were used to identify endothermic and exothermic thermal events associated with changes in the wood constituents and to compare the thermal response of the unmodified and thermally modified specimens, providing insight into changes produced by the thermal modification process.

Overall, the experimental setup combined mechanical impact testing, DIC, SEM, TGA, and DSC to characterize the mechanical response, failure mechanisms, microstructural damage, and thermal behavior of unmodified and thermally modified wood.

Chapter 3

RESULTS AND ANALYSIS

3.1 Low-Velocity Impact Response and Failure Analysis

The low-velocity impact response of Western Hemlock was found to be influenced by the interaction between the specimen geometry, natural wood topology, and thermal modification condition. Although all specimens were tested under nominally similar impact and three-point bending conditions, variations in the orientation of the longitudinal fibers, growth rings, and local cellular structure relative to the impact direction resulted in different damage initiation and propagation paths. Thermal modification further altered the mechanical response of the wood and influenced the energy dissipated during these failure processes.

Based on the experimental observations, three dominant failure mechanisms were identified:

1. Tensile fiber failure (M1),
2. Inclined inter-granular failure (M2), and
3. Grain shear slip (M3).

The occurrence of these mechanisms was closely related to the local wood topology and its orientation relative to the stresses induced during impact. In specimens where the longitudinal fibers were approximately aligned with the specimen axis, flexure-induced tensile stresses promoted tensile fiber rupture and splitting. Local deviations in fiber and growth-ring orientation introduced transverse stress components and promoted inclined inter-granular failure, while favorable growth-ring orientations relative to the applied loading facilitated interfacial shear and grain shear slip. Therefore, specimens subjected to the same nominal impact conditions could undergo substantially different failure processes depending on their underlying morphology.

The three mechanisms also exhibited distinctly different energy-absorption characteristics, demonstrating that the effect of thermal modification could not be evaluated independently of the governing failure mechanisms. Consequently, the following sections examine each mechanism individually using high-speed imaging and Digital Image Correlation (DIC) to identify failure initiation and strain development, post-impact observations to characterize the macroscopic fracture morphology, and Scanning Electron Microscopy (SEM) to investigate the corresponding damage at the cellular level. This approach establishes the relationship between wood topology, local stress and strain development, fracture morphology, and the resulting impact response.

3.1.1 Mechanism 1: Tensile Fiber Failure

Failure Mechanism 1 is classified as tensile fiber failure. Figure 3.1 shows the progressive development of this failure mechanism as captured by the high-speed imaging used for DIC analysis in GOM Correlate.

To understand the observed failure mechanism, it is important to first establish the wood topology, principal strain direction, and induced tensile stress direction. The global coordinate system is defined by the specimen geometry and loading direction, while the local coordinate system is defined by the fiber and growth-ring orientations within the wood structure. For this failure mechanism, the fibers are predominantly aligned with the longitudinal (L) direction, such that the local fiber direction approximately coincides with the global X-direction, as illustrated in Figure 3.2. The black lines schematically represent the longitudinal fiber orientation, while the red arrows indicate the flexure-induced tensile stresses σ_x developed at the bottom surface of the specimen. Figure 3.3 shows the first principal strain field computed in GOM Correlate software at the instant of failure initiation, with the circled region identifying the failure initiation site. Within this region, it can be seen that during this instant, the first principal strain direction approximately coincides with the longitudinal fiber (L), indicating a tension-driven failure. Thus, the induced tensile stresses act predominantly along the L-direction, resulting in tensile rupture and splitting of the longitudinal fibers.

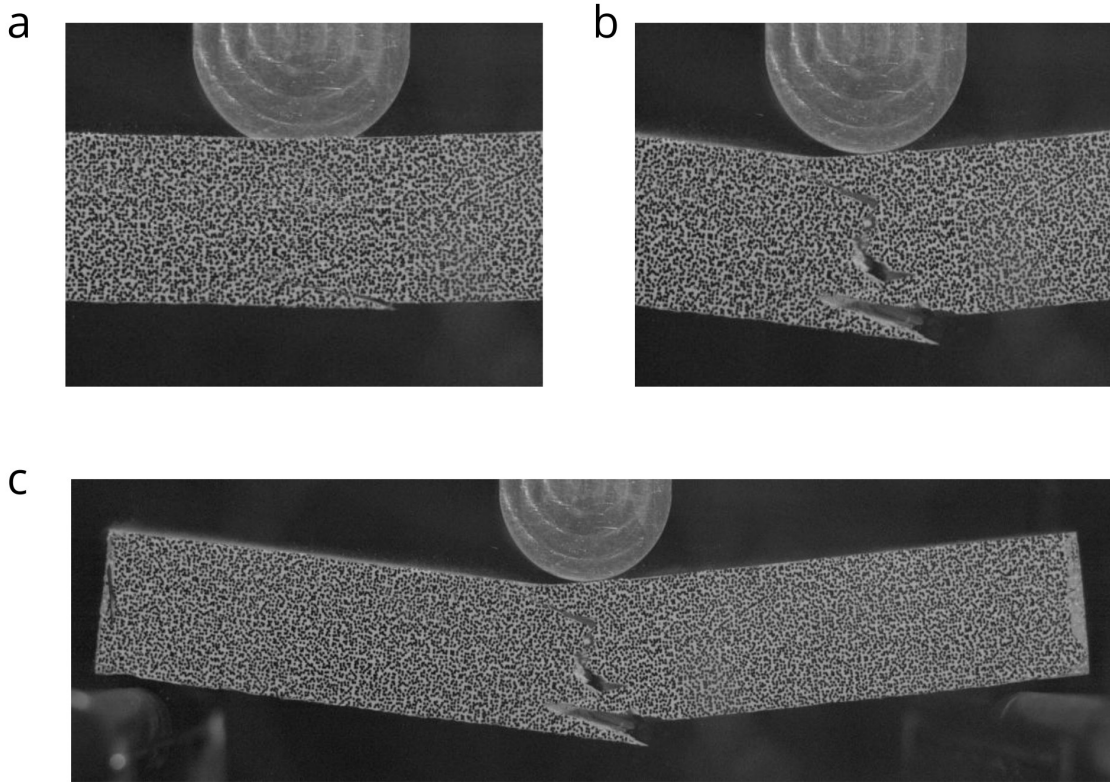


Figure 3.1: Progressive failure dominated by the tensile fiber failure mechanism, as captured by high-speed imaging for DIC analysis. The crack initiates at the bottom tensile surface and progressively propagates through the longitudinal fiber layers, resulting in a rough fracture path.

The progressive development of tensile fiber failure is illustrated in Figure 3.4, using a representative specimen that failed through this mechanism to explain the failure schematically. For simplicity, the specimen response is represented using a three-point bending configuration, as shown in Figure 3.4a, where flexural loading produces compression above the neutral axis and tension below it, with the maximum tensile stresses occurring at the bottom surface. Figure 3.4b illustrates the longitudinal fiber arrangement, represented by the black lines extending continuously along the specimen forming layers. As the flexure-induced

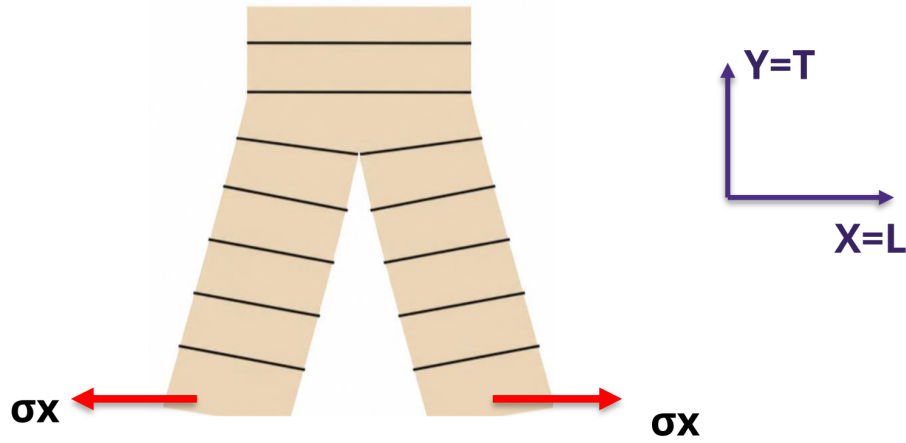


Figure 3.2: Schematic of longitudinal fiber alignment ($X = L$) and the induced tensile stress direction at the failure initiation site, acting parallel to the fibers

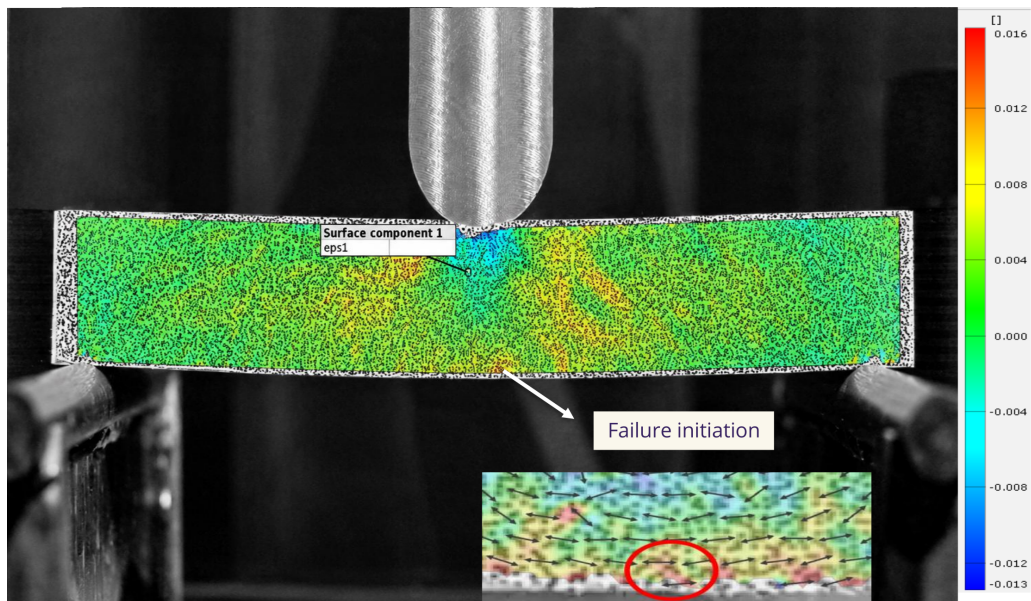


Figure 3.3: First principal strain field obtained using GOM Correlate at the instant of tensile fiber failure initiation

tensile stress (σ_x) increases, failure initiates at the bottom tensile surface and causes rupture of the longitudinal fibers. The subsequent progression of the crack is illustrated schematically in Figure 3.4c using layers L1–L4. Rather than propagating continuously through the specimen, the advancing crack interacts with the growth-ring boundaries, which act as local interfaces that arrest or deflect the crack and promote its re-initiation within the adjacent layer as loading continues. This repeated process of crack arrest, deflection and layer by layer propagation produces a stepped fracture path. Consequently, the failed specimen exhibits the macroscopically rough and layered fracture surface shown in Figure 3.4d, which is characteristic of the tensile fiber failure mechanism.

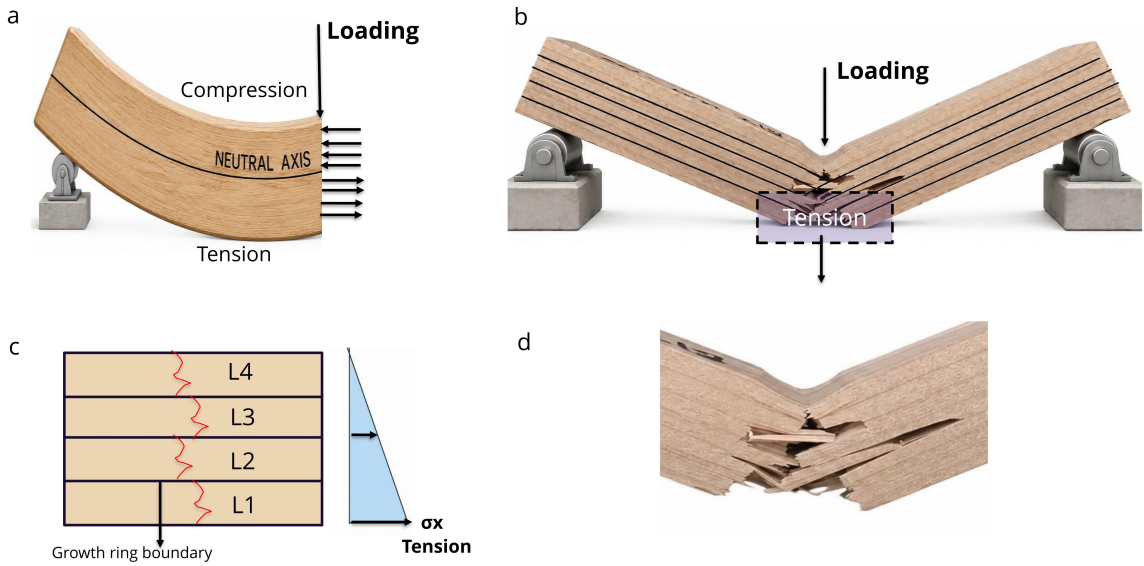


Figure 3.4: Progressive development of tensile fiber failure under flexural loading: (a) schematic of the flexural stress distribution showing the compression and tension regions; (b) longitudinal fiber orientation and tensile failure under three-point bending; (c) schematic of progressive crack propagation, arrest, and re-initiation across growth-ring boundaries; (d) representative rough fracture surface following tensile fiber failure

The fracture surface was further examined using Scanning Electron Microscopy (SEM), as shown in Figure 3.5 to view the damage at the cellular level. Figure 3.5a identifies the

A–A cross-section of the failed specimen from which the sample was extracted for SEM examination, while Figure 3.5b shows the corresponding micrograph of the fracture surface. Consistent with the proposed tensile fiber failure mechanism, the micrograph reveals fractured tracheids forming a stepped fracture morphology across the earlywood and latewood regions. The growth-ring interface and torn ray cells further act as local interfaces for crack deflection, supporting the observed crack deflection and layer by layer propagation responsible for the macroscopically rough fracture surface.

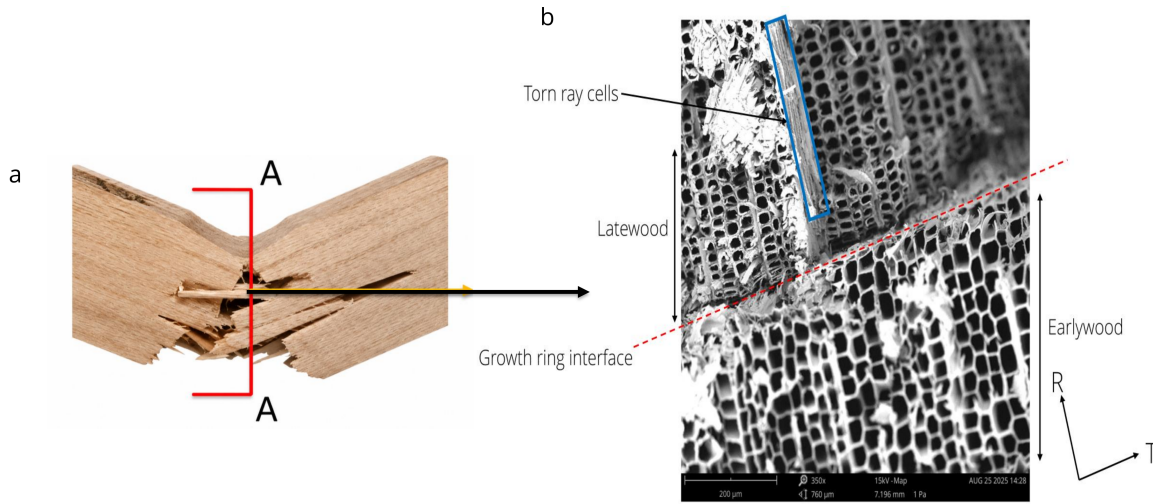


Figure 3.5: SEM examination of the fracture surface associated with tensile fiber failure: (a) location of the A–A cross-section extracted from the failed specimen for SEM analysis; and (b) corresponding SEM micrograph showing fractured tracheids, the growth-ring interface, and torn ray cells

Overall, the experimental observations indicate that this failure mechanism is governed by the alignment between the flexure-induced tensile stresses direction and the continuous fiber direction running throughout the length of the specimen at the failure initiation instant. Tensile stresses at the bottom surface first cause rupture of the longitudinal fibers and initiate cracking. Further propagation is influenced by local variations in the wood microstructure, including differences in tracheid structure, earlywood and latewood regions,

growth-ring boundaries, and ray cells, resulting in crack deviation and an irregular fracture path. Growth-ring boundaries can interrupt the advancing crack, requiring a new crack to initiate in the neighboring layer as deformation continues. The combined effect of these processes can be assumed to contribute to the progressive fiber splitting and rough, layered fracture morphology characteristic of tensile fiber failure.

3.1.2 Mechanism 2: Inclined Inter-granular Failure

Failure Mechanism 2 is classified as inclined inter-granular failure. Figure 3.6 shows the progressive development of this failure mechanism as captured by the high-speed imaging used for DIC analysis. The sequence shows the initiation and subsequent propagation of an inclined crack through the specimen during impact loading, eventually resulting in complete failure of the specimen.

To understand this failure mechanism, both the global and local coordinate systems must be considered. The global X–Y coordinate system is defined by the specimen geometry and loading direction, whereas the local L–R–T coordinate system represents the wood topology and follows the local fiber and growth-ring orientations. Unlike Failure Mechanism 1, the fibers do not remain continuously parallel to the global X-direction but exhibit local deviations along the specimen, as shown by the black lines in Figure 3.7a. As a result, the local longitudinal (L) direction is inclined relative to the global X-direction, and the two coordinate systems no longer coincide. Figure 3.7b shows the growth-ring orientation of a representative specimen relative to the applied impact direction. In this configuration, the impact direction is more closely aligned with the local tangential (T) direction, promoting transverse tensile stresses along the weaker T-direction and making inclined inter-granular failure more favorable.

Figure 3.8 shows the first principal strain field computed using GOM Correlate at the instant of failure initiation. The enlarged view of the failure initiation region shows that the first principal strain direction is highly inclined relative to the specimen length and the global X-direction. This inclination is associated with the local deviation of the longitudinal fiber orientation and indicates the presence of tensile stress components acting transverse to

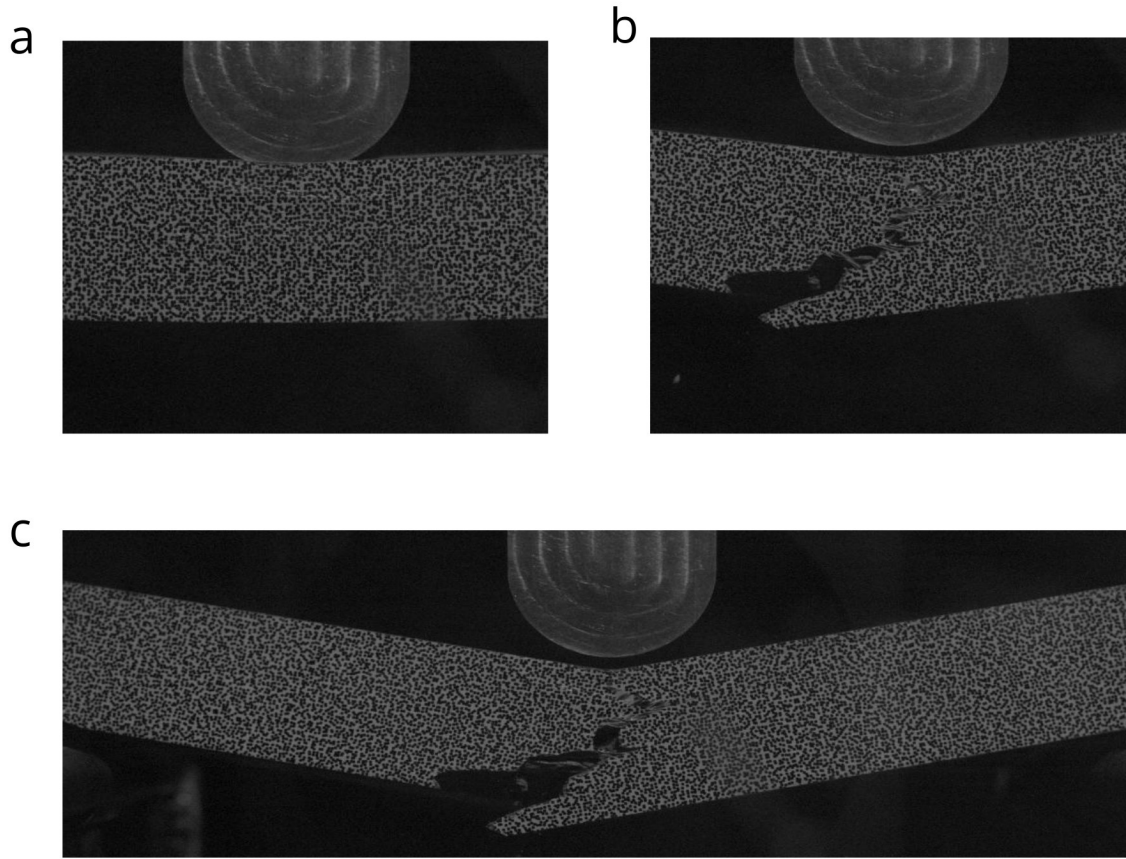


Figure 3.6: Progressive failure dominated by the inclined inter-granular failure mechanism, as captured by high-speed imaging for DIC analysis. The crack initiates at the bottom tensile surface and progressively propagates through the longitudinal fiber layers, resulting in a rough fracture path.

the local L-direction. An important observation is that the failure does not initiate directly beneath the impactor, where the bending moment is maximum, but instead occurs at an eccentric location. This indicates that crack initiation is weakest-link-driven, with failure beginning at a locally weaker region associated with the variation in fiber orientation rather than being governed solely by the location of maximum bending moment.

The development of inclined inter-granular failure is illustrated schematically in Figure

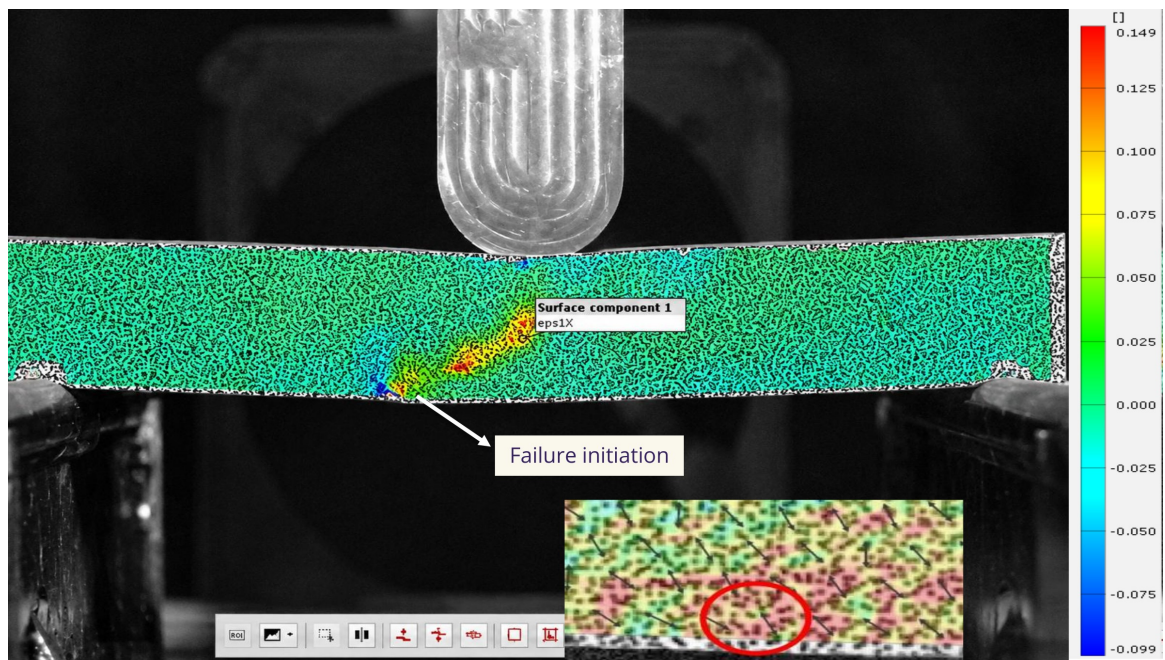


Figure 3.7: Wood topology and local fiber orientation associated with inclined inter-granular failure: (a) deviation of the local L–T coordinate system from the global X–Y coordinate system due to local fiber orientation; and (b) growth-ring orientation (T-direction) relative to the applied impact direction

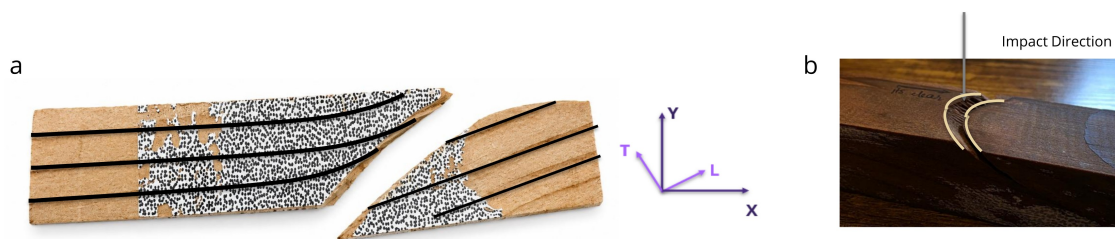


Figure 3.8: First principal strain field and failure initiation location for inclined inter-granular failure obtained using GOM Correlate

3.9, using a representative specimen that failed through this mechanism. For simplicity, a three-point bending scenario is considered, as shown in Figure 3.9a, with the lower portion

of the specimen forming the tensile zone. Focusing on this region, Figure 3.9b shows that the flexure-induced tensile stress (σ_x) acts along the global X-direction; however, due to the local deviation of the fibers, this direction does not coincide with the local longitudinal (L) direction of the wood. Considering the inclined layer L1 near the failure region, the global tensile stress can therefore be resolved into the local material coordinates, producing longitudinal normal stress (σ_L), transverse normal stress (σ_T), and shear stress components (τ_{LT} and τ_{TL}), as illustrated in Figure 3.9c. In particular, the presence of the transverse tensile stress component (σ_T) promotes rupture across the local fiber direction. Since wood is considerably weaker under transverse tension, particularly in the T-direction, the failure in this region is governed by σ_T , causing the crack to initiate and propagate along the local T-direction. The resulting crack follows the inclined local wood structure, producing the relatively smooth and inclined fracture surface shown in Figure 3.9d.

The fracture surface associated with inclined inter-granular failure was further examined using Scanning Electron Microscopy (SEM), as shown in Figure 3.10. Figure 3.10a identifies the A–A cross-section of the failed specimen from which the sample was extracted for SEM examination, while Figure 3.10b shows the corresponding fracture surface at the cellular level. The red dashed line indicates the growth-ring interface separating the earlywood and latewood regions. A clear difference in fracture morphology can be observed across this interface: the earlywood region exhibits a relatively rough surface with extensively torn tracheid walls, whereas the latewood region appears comparatively smooth. In earlywood, the thinner cell walls are more easily ruptured by the transverse tensile stresses. In contrast, the thicker latewood cell walls are more resistant to rupture, causing the crack to preferentially propagate along the weaker intercellular bonding layers, particularly the middle lamella (ML). This results in middle-lamella splitting in the latewood and explains the distinct fracture morphologies observed on either side of the growth-ring interface.

Overall, inclined inter-granular failure is governed by local deviations in fiber orientation, which generate transverse tensile stresses along the weaker T-direction. These stresses promote tearing of the thinner cell walls in earlywood, while in latewood the crack preferentially follows the weaker intercellular bonding layers between the thicker-walled cells. The combination of these microscale failure processes results in the characteristic inclined and

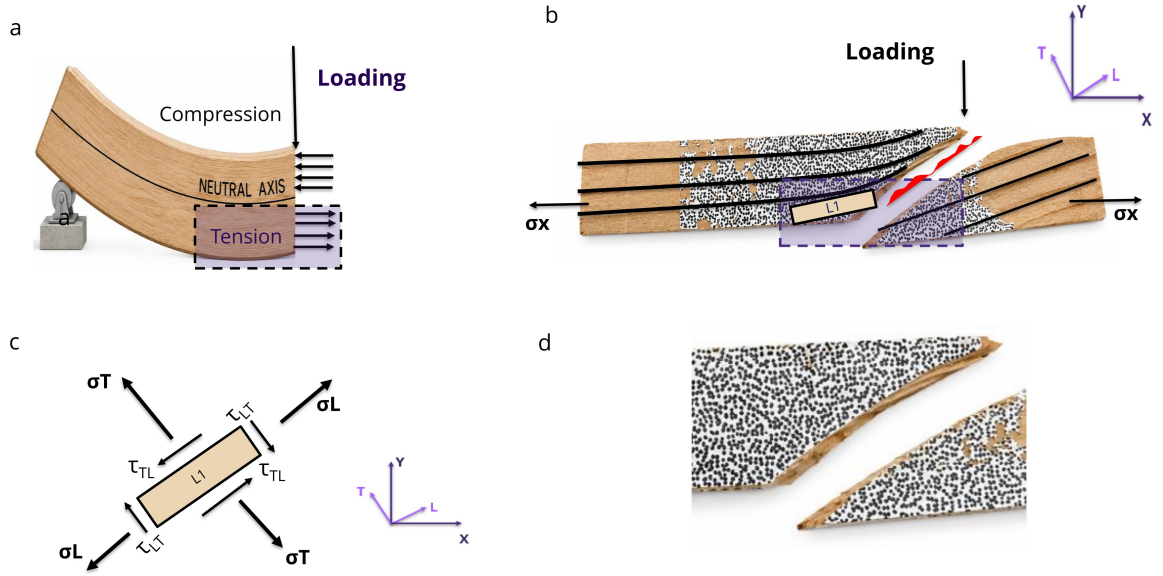


Figure 3.9: Schematic representation of the inclined inter-granular failure mechanism: (a) flexural stress distribution showing the tensile zone; (b) local deviation of the longitudinal fiber orientation relative to the global tensile stress direction; (c) resolution of the global tensile stress into longitudinal, transverse, and shear stress components in the local L-T coordinate system; and (d) resulting inclined fracture surface.

relatively smooth fracture surface observed for this mechanism.

3.1.3 Mechanism 3: Grain Shear Slip

Failure Mechanism 3 is classified as grain shear slip. Figure 3.11 shows the progressive development of this failure mechanism as captured by the high-speed camera during impact loading. The image sequence shows the initiation and subsequent propagation of interfacial delamination along the specimen length, accompanied by relative sliding between the separated wood layers.

For Failure Mechanism 3, the wood topology is characterized by longitudinal fibers running continuously and approximately parallel to the length of the specimen, as illustrated in Figure 3.12. Thus, the global X-direction approximately coincides with the local longitudinal

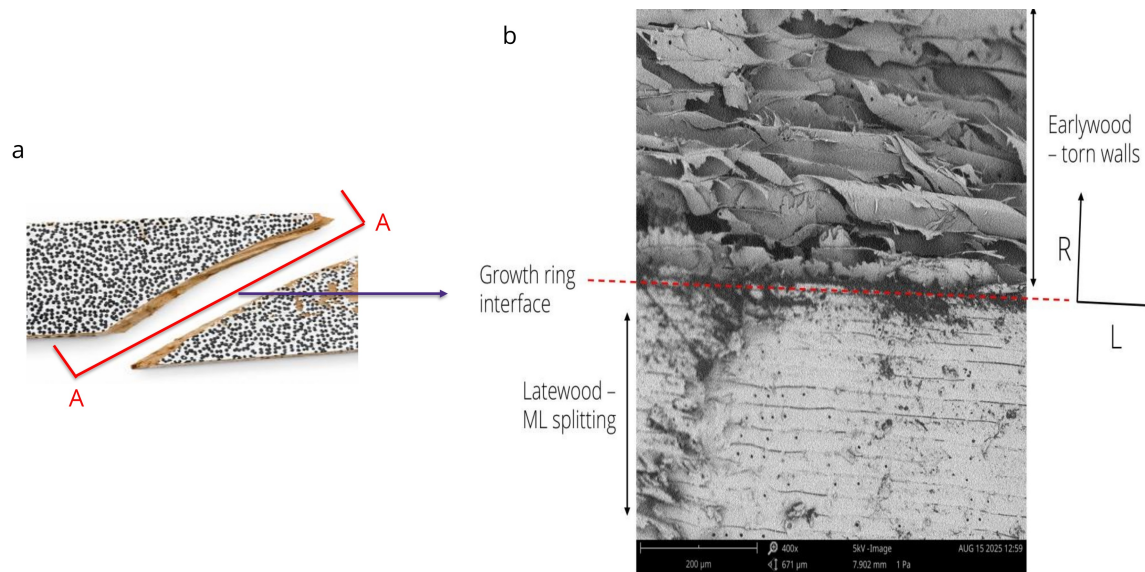


Figure 3.10: SEM examination of the fracture surface associated with inclined inter-granular failure: (a) location of the A–A cross-section extracted from the failed specimen for SEM analysis; and (b) corresponding SEM micrograph showing torn earlywood cell walls and middle-lamella (ML) splitting in the latewood across the growth-ring interface

(L) direction, and the impact direction is approximately perpendicular to the longitudinal fibers. However, the complete global and local coordinate systems do not coincide because the radial (R) and tangential (T) directions are governed by the orientation of the growth rings. In the specimens exhibiting this mechanism, the cross section was oriented such that the growth rings were inclined approximately 30° – 45° relative to the impact direction. Consequently, although $X \approx L$, the local R–T material directions remain inclined relative to the global specimen coordinates. This particular combination of continuous longitudinal fibers and inclined growth-ring interfaces provides the characteristic wood topology associated with the grain shear slip mechanism.

The development of the grain shear slip mechanism is illustrated in Figure 3.13 using a representative specimen that failed through this mechanism. As shown in Figure 3.13a, impact loading produces a localized crushing zone beneath the impactor, where the inclined growth-ring layers undergo compression and relative sliding. The corresponding

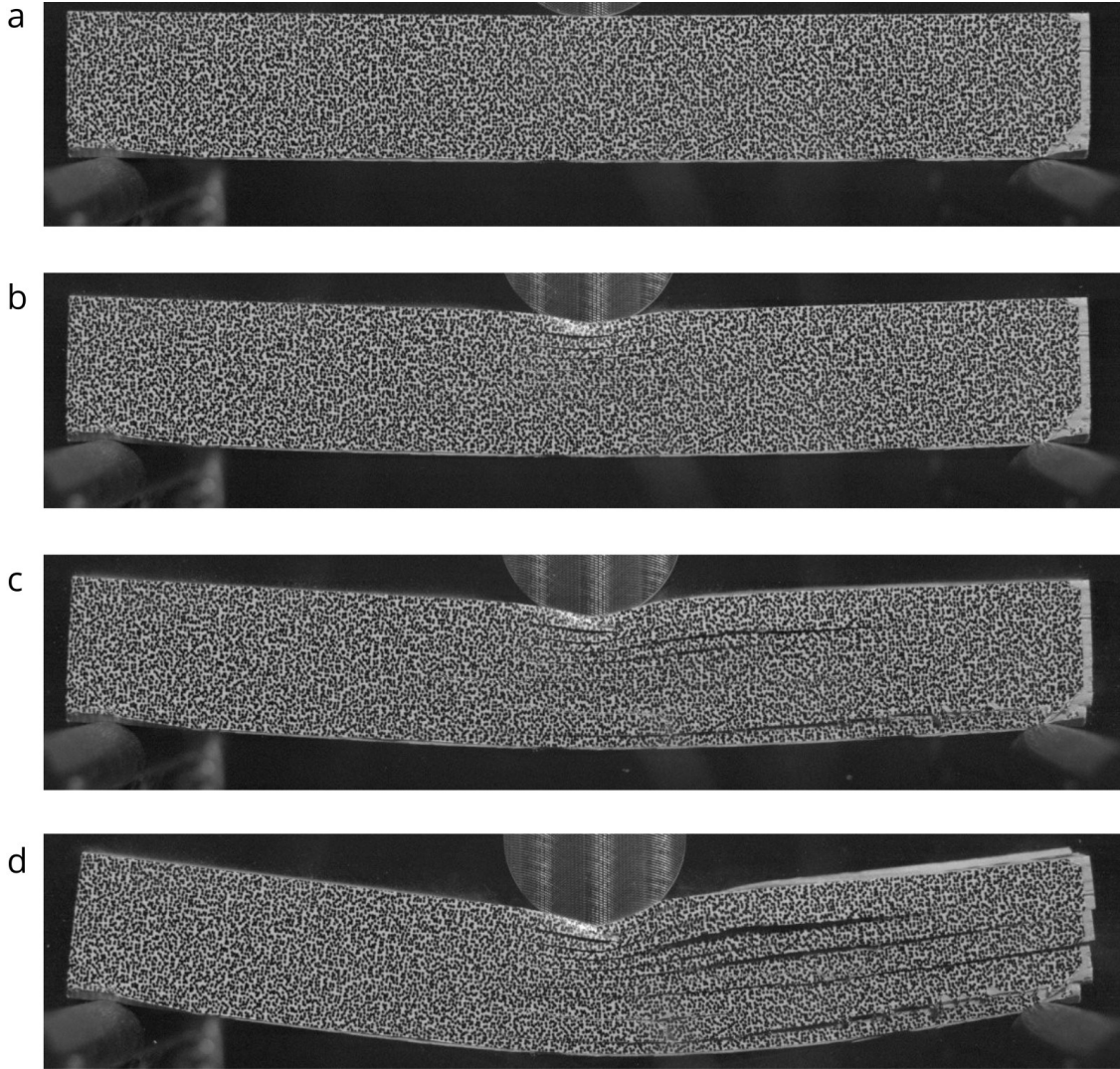


Figure 3.11: Progressive damage evolution in a specimen exhibiting M3 (grain shear slip) failure, showing the transition from initial deformation to shear-induced interfacial delamination and subsequent layer separation along the growth-ring boundaries

cross-sectional response is illustrated in Figure 3.13b, where the applied compressive stress (σ_y), acting on the inclined wood topology, generates shear stresses along the local material planes. Figure 3.13c illustrates the resolved shear components, acting along the RL- and TL-planes. These shear stresses become concentrated at local cell-wall turning points and

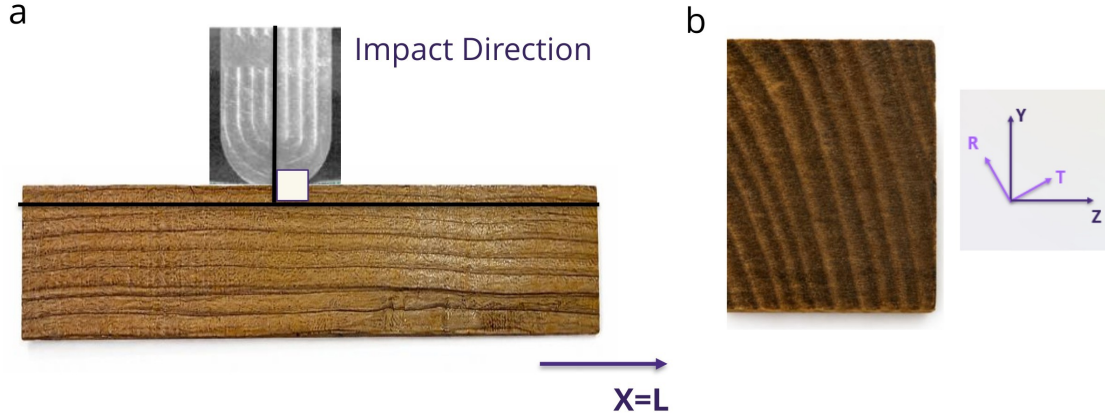


Figure 3.12: Wood topology and growth-ring orientation associated with grain shear slip: (a) longitudinal fiber orientation relative to the impact direction, with $X \approx L$; and (b) cross-sectional growth-ring orientation and corresponding local R - T coordinate system

promote tearing and separation between adjacent layers. Once interfacial delamination initiates within the crushing zone, the relative downward motion of the layers causes inter-layer slip, with one layer sliding relative to the neighboring layer, as schematically represented by L1 and L2 in Figure 3.13b. The growth-ring boundaries provide preferential paths for this separation, with delamination along the TL-plane being particularly favored because the growth-ring boundary represents a structural discontinuity. The approximately 30° – 45° orientation of these interfaces relative to the impact direction further promotes the resolved shear stress, with an orientation near 45° being most favorable for triggering this mechanism. The resulting inter-layer sliding and Mode-II-dominated propagation produce the characteristic grain shear slip and crushed fracture morphology shown in Figure 3.13d.

The fracture surface associated with the grain shear slip mechanism was further examined using Scanning Electron Microscopy (SEM), as shown in Figure 3.14. Figure 3.14a identifies the A–A cross-section from which the sample was extracted, while Figure 3.14b shows the corresponding SEM micrograph. The micrograph reveals crushed and torn cell walls produced by the downward sliding motion between adjacent wood layers. These ob-

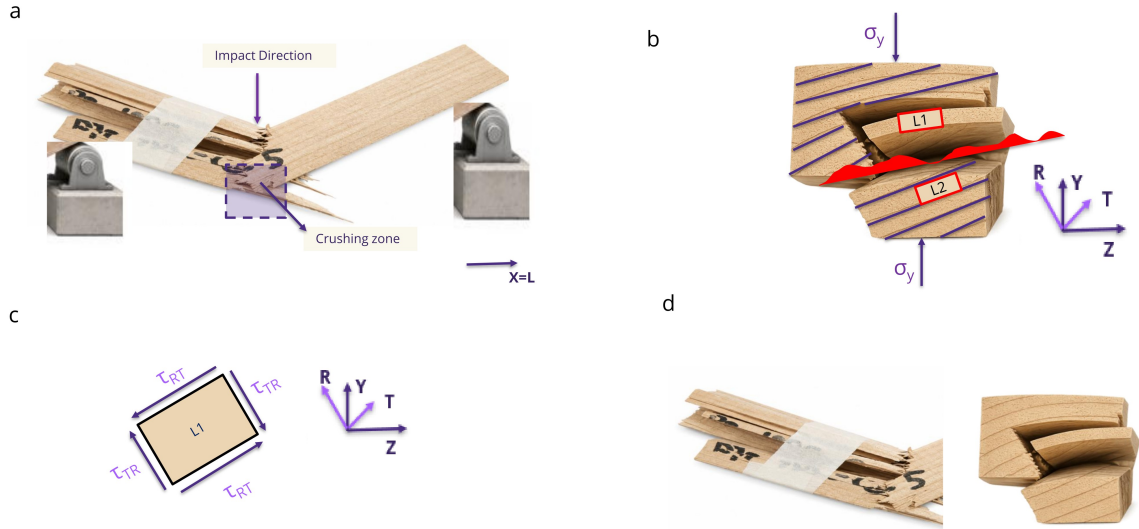


Figure 3.13: Schematic representation of the grain shear slip mechanism: (a) representative specimen showing the localized crushing zone beneath the impactor; (b) cross-sectional view illustrating relative sliding between adjacent growth-ring layers; (c) resolved shear stress components acting along the local material planes; and (d) resulting grain shear slip and fracture morphology

servations support the proposed mechanism, where concentrated shear stresses cause local cell-wall tearing, followed by inter-layer sliding and Mode-II-dominated delamination along the wood structure.

Overall, the experimental observations indicate that the grain shear slip mechanism is governed by the orientation of the growth-ring interfaces relative to the impact direction. When these interfaces are inclined near 30° to 45° , the applied loading generates significant shear stresses along the local material planes, promoting interfacial delamination within the crushing zone. The resulting relative motion between adjacent layers leads to progressive inter-layer sliding, local cell-wall tearing, and Mode-II-dominated crack propagation. Together, these processes produce the characteristic crushing and extensive grain shear slip observed in this failure mechanism.

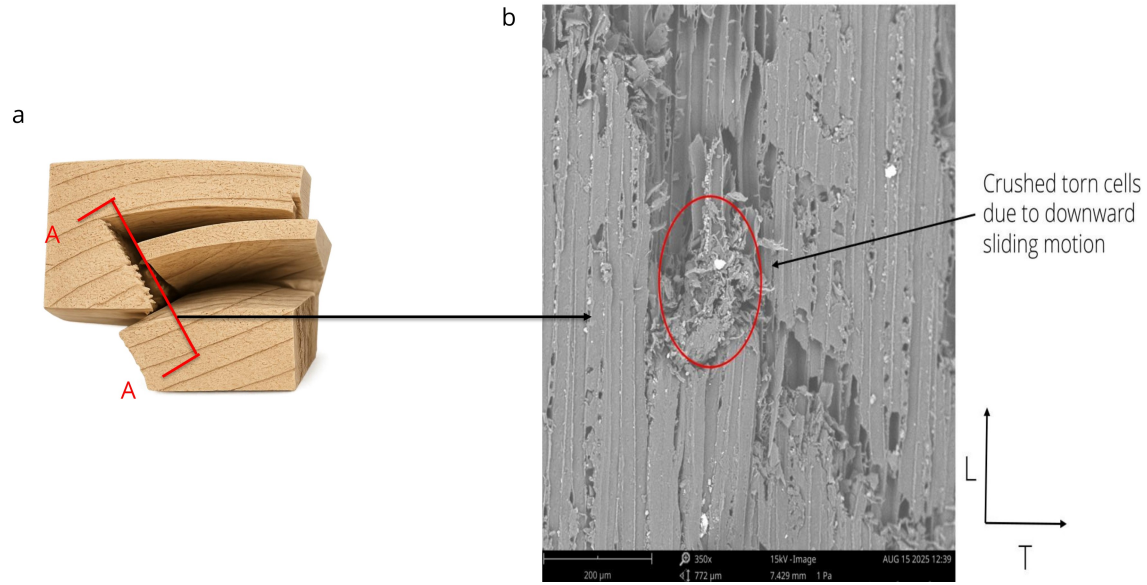


Figure 3.14: SEM examination of the fracture surface associated with grain shear slip: (a) location of the A–A cross-section extracted from the failed specimen for SEM analysis; and (b) corresponding SEM micrograph showing crushed and torn cell walls resulting from the downward sliding motion between adjacent wood layers

3.2 Effects of Thermal Modification and Wood Topology

Following the impact experiments, the data obtained from the drop-tower tests were compiled and systematically categorized according to thermal modification temperature, specimen wood topology, and the observed dominant failure mechanism. The experimental data were then processed and analyzed in MATLAB to organize the results and visualize the energy-absorption distributions across the different test conditions. This structured analysis enabled the effects of thermal modification and wood topology on the low-velocity impact response to be evaluated independently and compared across the tested specimens.

3.2.1 Batches 1 and 2: Temperature Optimization Study

The energy absorption results obtained from the first two experimental batches are presented as violin plots in Figure 3.15, where the specimens are categorized according to their domi-

nant failure mechanism and thermal modification temperature. The shape and width of each violin represent the distribution and spread of the energy absorption data, while the individual data points represent the measured energy absorption of each tested specimen. Since the three identified failure mechanisms exhibit considerably different energy-absorption capacities, direct comparison between specimens undergoing different failure mechanisms would not provide a meaningful assessment of the effect of thermal modification. Therefore, the temperature-dependent response was evaluated by comparing specimens within the same dominant failure mechanism.

Results: Batch 1 & 2

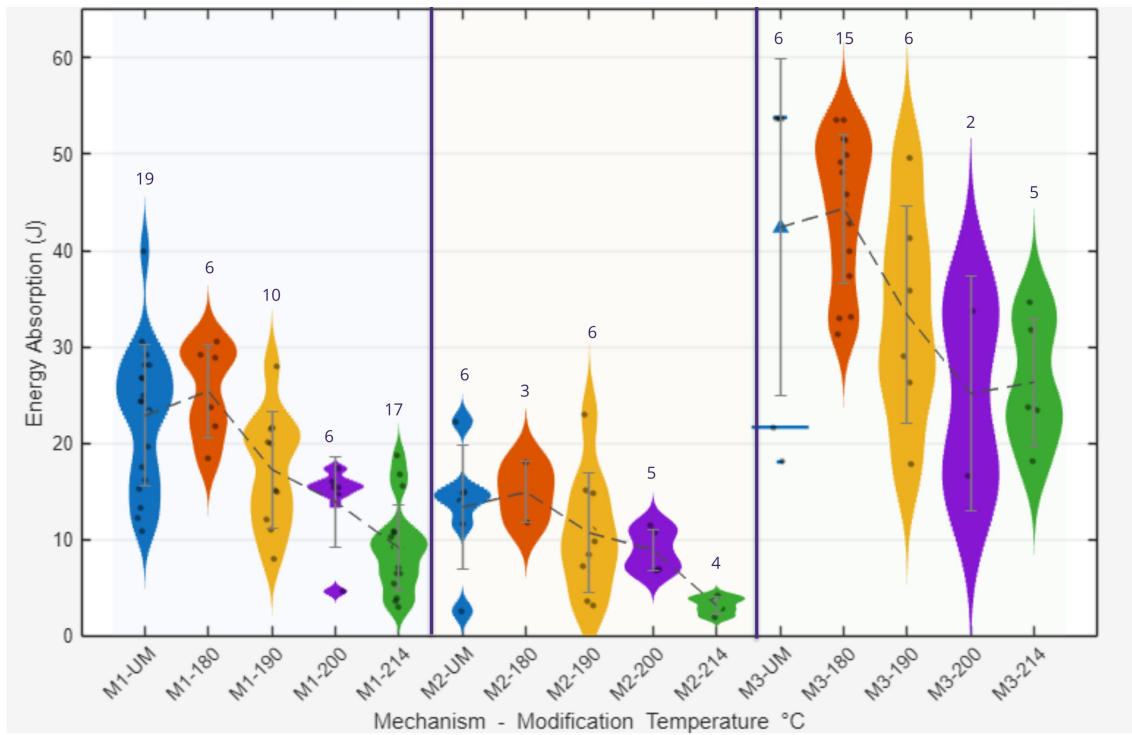


Figure 3.15: Energy absorption of Batch 1 and Batch 2 specimens categorized by dominant failure mechanism and thermal modification temperature

As shown in Figure 3.15, a consistent temperature-dependent trend can be observed within the individual failure mechanisms. The energy absorption initially increases with

thermal modification and reaches its maximum at a treatment temperature near 180°C, where the thermally modified specimens can exhibit greater energy absorption than the corresponding unmodified specimens. With further increases in modification temperature, the energy absorption decreases, indicating a progressive reduction in the ability of the material to dissipate energy at the higher treatment temperatures. This trend demonstrates that moderate thermal modification can improve the low-velocity impact response of Western Hemlock, whereas excessive modification produces a less favorable impact response.

The distribution of the dominant failure mechanisms for each modification condition is summarized in Table 3.1. In addition to the increase in energy absorption observed near 180°C, the 180°C condition also exhibited the highest proportion of Mechanism 3 failures, with 15 specimens (62.5%) undergoing grain shear slip. In comparison, only 6 specimens (19.4%) in the unmodified condition exhibited Mechanism 3. This observation further indicates that thermal modification influences not only the energy absorption within a given failure mechanism, but also the likelihood of activating a particular failure mechanism.

Overall, the results indicate that a thermal modification temperature of approximately 180°C can provide favorable balance between stiffness, ductility, and energy absorption under low-velocity impact. However, the results also emphasize that thermal modification temperature cannot be considered independently of the governing failure mechanism and wood topology, since it can be construed that both influence the measured energy-absorption capacity.

Table 3.1: Population of Batch 1 and Batch 2 specimens exhibiting each dominant failure mechanism.

	Mechanism 1	Mechanism 2	Mechanism 3
UM	19 (61.3%)	6 (19.4%)	6 (19.3%)
180°C	6 (25.0%)	3 (12.5%)	15 (62.5%)
190°C	10 (45.5%)	6 (27.3%)	6 (27.2%)
200°C	6 (46.2%)	5 (38.5%)	2 (15.3%)
214°C	17 (65.4%)	4 (15.4%)	5 (19.2%)

3.2.2 Batch 3: Mechanism 3 Validation Study

The results from Batches 1 and 2 provided the basis for designing the third experimental batch. Several specimens exhibiting Mechanism 3 absorbed the complete available impact energy of 50 J, indicating that the applied energy was insufficient to fully characterize the energy-absorption capacity associated with this mechanism. In addition, the previous observations showed that activation of Mechanism 3 was seen to be dependent on the wood topology. Therefore, Batch 3 specimens were intentionally selected with continuous longitudinal fibers aligned approximately with the specimen length ($X \approx L$), dense growth rings, and growth-ring orientations of approximately 30°-45° relative to the impact direction. These geometrical conditions were selected to more reliably promote the grain shear slip mechanism. To ensure sufficient energy for complete failure, the input impact energy was increased from 50 J to 100 J.

The Batch 3 study included unmodified (UM), 190°C, and 200°C specimens, as these were the treatment conditions available for the additional testing campaign. The corresponding energy absorption results are presented in Figure 3.16 and categorized according to both modification temperature and dominant failure mechanism. Similar to the previous results, the violin plots represent the distribution and spread of the measured energy absorption values, while the individual points correspond to the energy absorbed by each tested specimen. The number of specimens associated with each modification condition and failure mechanism is additionally summarized in Table 3.2.

The Batch 3 results provide further support for the proposed triggering conditions for Mechanism 3. By intentionally controlling the cross-sectional topology and orienting the growth rings approximately 30°-45° relative to the impact direction, a substantially larger proportion of the specimens exhibited grain shear slip compared with Batches 1 and 2. This shows that the occurrence of Mechanism 3 is dependent on the growth-ring geometry and its orientation relative to the applied impact loading.

An additional observation was that Mechanism 3 occurred considerably less frequently in the unmodified specimens than in the thermally modified specimens. This indicates that thermal modification affects not only the energy-absorption capacity of specimens failing

Results: Batch 3

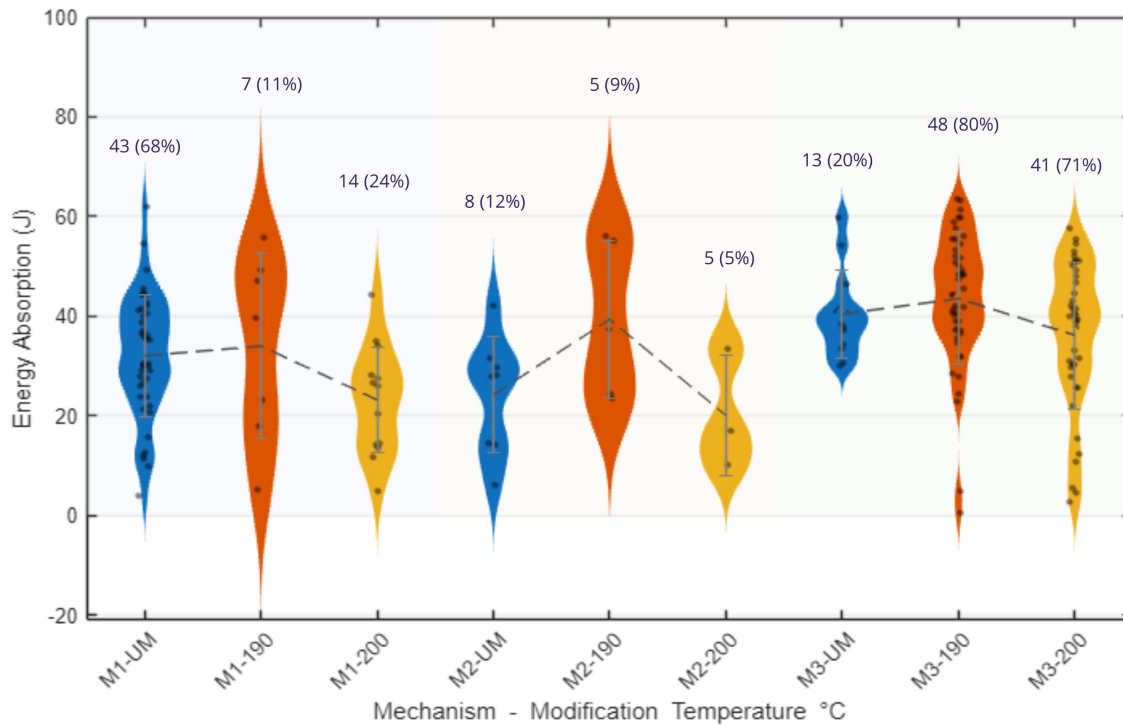


Figure 3.16: Energy absorption results for Batch 3 specimens categorized by dominant failure mechanism and thermal modification temperature

through the same mechanism, but also the likelihood of activating a particular failure mechanism. Therefore, the low-velocity impact response of Western Hemlock is governed by the combined influence of thermal modification and wood topology, with both factors affecting the resulting failure behavior and energy dissipation.

3.3 Thermal Characterization of the Specimens

Following the evaluation of the impact response, thermal characterization was performed to try to investigate the underlying material-level changes associated with thermal modification.

	Mechanism 1	Mechanism 2	Mechanism 3
UM	43 (67.2%)	8 (12.5%)	13 (20.3%)
190 °C	7 (11.7%)	5 (8.3%)	48 (80.0%)
200 °C	14 (24.1%)	3 (5.2%)	41 (70.7%)

Table 3.2: The population of the 3rd batch specimens failed with specific dominant mechanisms.

The TGA and DSC analyses were done with the intention of examining whether the different modification temperatures produced changes in the thermal and molecular behavior of the wood that could provide additional insight into the observed differences in energy absorption and failure response.

3.3.1 Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) Analysis Results

Figure 3.17 presents the thermal characterization results obtained from Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) for the unmodified and thermally modified Western Hemlock specimens. In the TGA results shown in Figure 3.17a, the sample temperature was progressively increased, while the corresponding change in mass was monitored. All specimens exhibit a generally similar mass-loss trend over the investigated temperature range, with only a small overall reduction in mass, indicating limited degradation of the wood components within this range. The DSC results shown in Figure 3.17b present the specific heat-flow response as a function of sample temperature. The curves again follow a broadly similar trend across the different modification conditions, with positive heat-flow behavior suggesting the occurrence of exothermic processes. Although differences between the treatment conditions are observed, the TGA and DSC curves alone do not provide sufficient evidence to identify the exact molecular changes responsible for these variations. Therefore, these results are primarily used to support the interpretation of the thermal-modification effects discussed in the following section.

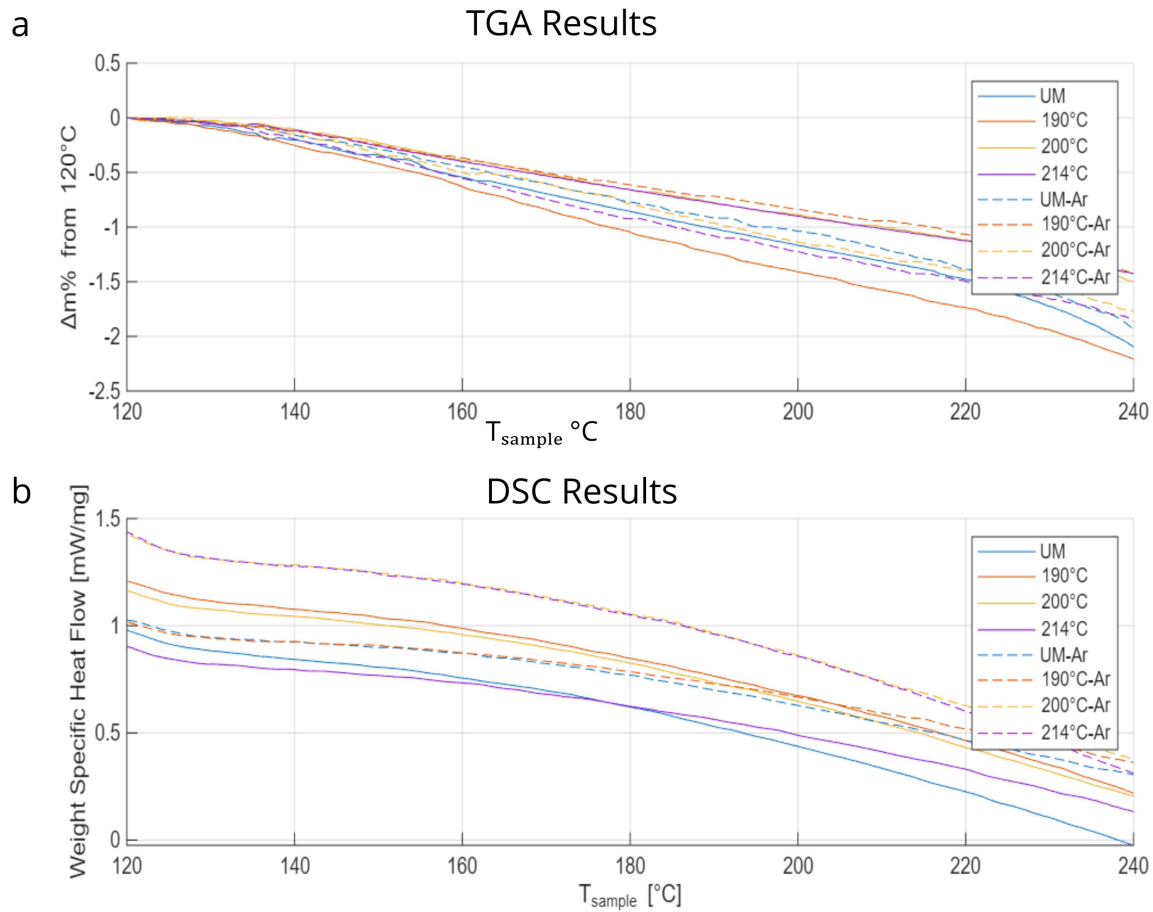


Figure 3.17: Thermal characterization of unmodified and thermally modified Western Hemlock specimens: (a) TGA results showing mass change with increasing sample temperature, and (b) DSC results showing the corresponding specific heat-flow response

Overall, the TGA and DSC results show limited mass loss and broadly similar thermal-response trends across the specimens, indicating that no major degradation occurred within the investigated temperature range.

Chapter 4

CONCLUSIONS AND FUTURE SCOPE**4.1 Overall Conclusions***4.1.1 Combined Effects of Thermal Modification and Wood Topology on Impact Performance*

The low-velocity impact response of Western Hemlock shows that it was governed by the combined effects of thermal modification temperature and the underlying wood topology. Three distinct failure mechanisms were identified: tensile fiber failure (M1), inclined intergranular failure (M2), and grain shear slip (M3), each exhibiting a different energy-absorption capacity. Among these mechanisms, grain shear slip generally resulted in the greatest energy dissipation. The occurrence of each mechanism was found to be influenced by the orientation of the fibers and growth-ring structure relative to the applied impact loading. Unmodified specimens were more likely to exhibit tensile fiber failure, whereas thermal modification increased the likelihood of the delamination-dominated grain shear slip mechanism. These observations indicate that thermal modification influences both the energy absorption within a given failure mechanism and the preferential activation of different failure mechanisms.

Approximate comparisons obtained from the energy-absorption distributions (from figures 3.15 and 3.16) further illustrate these effects as shown in the Tables 4.1 and 4.2. For Batches 1 and 2, thermal modification near 180°C increased the energy absorption by approximately 5-13% when specimens exhibiting the same failure mechanism were compared. However, when the comparison also accounted for a transition from tensile fiber failure (M1) in the unmodified condition to grain shear slip (M3) after thermal modification, the increase was substantially greater, reaching approximately 83% based on the plotted mean values (~ 23 J to ~ 42 J). Also, for batches 1 and 2, many samples did not fail completely under 50 J so, the energy absorption values can be construed as the lower bound values. It can be greater than 83%. A similar behavior was observed in Batch 3, where within-mechanism

increases were approximately 7-25%, while a transition from M1 to M3 corresponded to an approximate 38% increase (~ 32 J to ~ 44 J). These approximate comparisons emphasize that the improvement in impact performance cannot be attributed to thermal modification temperature alone; a substantial contribution can arise from the change in the dominant failure mechanism and its interaction with the wood topology.

Table 4.1: Approximate comparison of energy absorption for Batch 1 and Batch 2 specimens.

Mechanism Comparison	Energy Absorption (J)	Approx. Increase (%)
M1-UM $\rightarrow$ M1-180	$\sim 23 \rightarrow 25$	~ 9
M2-UM $\rightarrow$ M2-180	$\sim 13 \rightarrow 15$	~ 13
M3-UM $\rightarrow$ M3-180	$\sim 42 \rightarrow 44$	~ 5
M1-UM $\rightarrow$ M3-180	$\sim 23 \rightarrow 42$	≥ 83

Table 4.2: Approximate comparison of energy absorption for Batch 3 specimens.

Mechanism Comparison	Energy Absorption (J)	Approx. Increase (%)
M1-UM $\rightarrow$ M1-190	$\sim 32 \rightarrow 34$	~ 7
M2-UM $\rightarrow$ M2-190	$\sim 25 \rightarrow 40$	~ 25
M3-UM $\rightarrow$ M3-190	$\sim 41 \rightarrow 44$	~ 8
M1-UM $\rightarrow$ M3-190	$\sim 32 \rightarrow 44$	~ 38

Overall, moderate thermal modification, particularly near 180°C , provided the most favorable impact response, while higher treatment temperatures resulted in reduced energy-absorption capability within comparable failure mechanisms. More importantly, the results demonstrate that thermal modification temperature and wood topology act together in governing both the activated failure mechanism and the resulting energy dissipation, highlighting the potential for controlling both processing conditions and material topology when designing wood structures for improved impact performance.

It should also be noted that the specimens were obtained from different Western Hemlock boards; therefore, inherent board-to-board variability in wood topology and material characteristics may have contributed to the observed variation in impact response.

Also, as discussed in the experimental setup section, the impactor material was changed from aluminum to stainless steel after Batch 1, and the stainless-steel impactor was subsequently used for Batches 2 and 3. During the initial tests, the aluminum impactor experienced localized deformation under repeated 50 J impacts, which could alter the contact geometry and introduce additional variability into the measured response. Stainless steel was therefore selected to provide greater resistance to permanent deformation and maintain a more consistent impactor geometry throughout testing. Although stainless steel has a higher Young's modulus than aluminum (approximately 190–200 GPa compared with approximately 70 GPa), both materials are substantially stiffer than Western Hemlock. Consequently, the effect of the change in impactor elastic stiffness on the global force–displacement and energy-absorption response is expected to be secondary compared with the deformation and failure occurring within the wood specimen. Nevertheless, the change in impactor material should be considered when directly comparing Batch 1 with Batches 2 and 3.

4.1.2 TGA and DSC Analysis Conclusions

The TGA and DSC results provide additional insight into the possible material-level changes occurring during thermal modification; however, firm conclusions regarding the underlying molecular mechanisms cannot be obtained from these analyses alone. TGA showed broadly similar mass-loss trends across the different modification conditions, with only limited mass loss over the investigated temperature range. This suggests that extensive degradation of the primary wood components is unlikely; however, the specific chemical or molecular changes responsible for the observed mechanical behavior cannot be identified directly from the TGA results.

The positive heat-flow response observed in the DSC measurements under an argon environment may indicate an exothermic process, potentially associated with bond formation or reorganization. Based on the interpretation proposed in the low-velocity impact study,

it can be speculated that limited bond reorganization and changes in molecular interactions may increase the stiffness of the microfibril–matrix interfaces at moderate modification temperatures, potentially contributing to the enhanced energy absorption observed near 180°C. At higher modification temperatures, further molecular-level degradation, increased bond breakage or reorganization, and restricted molecular mobility may occur, which could promote local stress concentrations and a more brittle response. These mechanisms, however, remain hypotheses based on the combined thermal and mechanical observations and cannot be conclusively established from TGA and DSC alone.

Overall, the thermal characterization suggests that the observed changes in impact performance may be associated more with temperature-dependent molecular interactions and bond reorganization than with extensive degradation of the wood components; however, further chemical and microstructural characterization would be required to confirm these mechanisms.

4.2 Future Scope

Future work should focus on further understanding the interaction between thermal modification, wood topology, and the resulting impact failure mechanisms. Additional testing with a larger and more uniformly distributed specimen population across all modification temperatures would improve the statistical characterization of the observed energy-absorption trends. In particular, specimens with intentionally controlled growth-ring orientations and densities could be investigated to better quantify the conditions that promote the high-energy-absorbing grain shear slip mechanism. Further chemical and microstructural characterization is also required to validate the molecular-level mechanisms suggested by the TGA and DSC results, including the possible effects of bond reorganization and degradation at higher modification temperatures. Finally, the experimental observations obtained in this study could be incorporated into numerical models to predict damage initiation, crack propagation, and energy absorption, ultimately supporting the design and optimization of thermally modified wood structures for impact-resistant applications.

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