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Mass Timber Cultures: Developing Welded-Wood Nail Laminated Timber (wNLT) as an Accessible and Local Building Material in North America

All-wood, mechanically fastened mass timber technologies provide a pathway for meeting the state and regional US Forest Service goals of keeping forestland healthy and resilient in the context of climate change, increasing demand for products that utilize domestic wood, and supporting well-being in small communities near forestlands.[1] A critical factor in achieving these goals is the ability to maintain easy access to user-friendly design guidelines, fabrication techniques, and updated code language that encourages affordable, locally sourced alternatives to high-performing ANSI-certified Cross-Laminated Timber (CLT) and other precisely engineered glue-laminated products. Demonstration buildings serve as an intuitive means of exploring questions related to new material technologies and sharing discoveries with a broader audience. This article documents new lessons learned while constructing a pilot welded-wood Nail Laminated Timber (wNLT) building in Guilford, Connecticut.

Keywords: Welded-Wood, Nail-Laminated Timber (NLT), Dowel-Laminated Timber (DLT)

Introduction

What effort is required to fabricate all-wood, mechanically fastened Mass Timber building products in North America, and which structures might they be viable for? Do underutilized tree species and non-merchantable wood thinnings from forests to reduce the risk of catastrophic wildfires present an opportunity for innovative building products and durable carbon storage? How might welded-wood Nail Laminated Timber (wNLT) support local production chains and forestry-related jobs with improved indoor working conditions? These questions guided the research presented in this article.

All-wood mechanically fastened mass timber products, such as Nail Laminated Timber (NLT) and Dowel Laminated Timber (DLT), in North America typically incorporate stress-graded dimensional lumber, with structural design values determined by the American Softwood Lumber Standard PS 20. The International Building Code (IBC) provisions for commonly used conventional light wood frame and heavy timber construction systems provide additional guidance on mechanically fastening wood members.[2] Glue-laminated and engineered wood mass timber products, such as Cross Laminated Timber (CLT), on the other hand, follow a unique and more recently created set of design and fabrication guidelines to ensure proper surface adhesion, panel compression, and strength achieved during the glue curing process. These high-performing glued products require specialized facilities and fabrication knowledge, which many conventional wood systems carpenters and builders struggle to access. Glued panels can require a more significant up-front investment in equipment for manufacturing panel products that meet the Standard for Performance-Rated Cross-Laminated Timber ANSI/APA PRG 320.[3] Recent changes to the IBC include additional guidelines for the fire performance of adhesives in CLT, which can be problematic due to delamination and exposure of uncharred wood in the later stages of a fire.[2]

While advances are being made to develop new nontoxic adhesives and reduce the toxicity of urea-formaldehyde, there are still concerns about emissions and Indoor Air Quality, especially when adhesive-fastened products are curing, exposed to heat, or compromised by moisture.[5]

Market development for innovative types of all-wood mechanically fastened mass timber products and the code language to support their use in North America lags Europe, Japan, and Canada. A strong case can be made for these products in locally produced, low-rise building retrofits and new affordable housing in North America. High-quality fastener products, including compressed and heat-treated hardwood dowels and nails, can enhance the structural performance and environmental impact of mechanically fastened DLT and NLT panel products. Avoiding glue and metal fasteners in mass timber panels maximizes the potential for end-of-life disassembly, machine routing, and utilization as feedstock for Bioenergy with Carbon Capture and Storage (BECCS) or carbon offsets in Biomass Carbon Removal and Storage (BiCRS).

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◁ Opening Figure. Drawing and photo collage of hybrid wNLT and light wood framing on Demonstration Building, Guilford, Connecticut, 2024. (Credit: Authors for all figures unless otherwise noted.)

△ Figure 1. wNLT Demonstration Building, Guilford, Connecticut, 2024.

To further explore the advantages of all-wood mechanically fastened timber products, the authors constructed a pilot welded-wood Nail Laminated Timber (wNLT) building in Guilford, Connecticut. Using an innovative Making as Knowing approach and Design Thinking for research resulted in a unique set of discoveries about the potential of wNLT as an accessible and locally sourced building construction material in North America (Figure 1).

Methodology

The project employed the research methods of Making as Knowing and Design Thinking (DT). The book *From Lived Experience to the Written Word* by Columbia University Professor of the History of Science Pamela Smith describes knowledge in the world of things as a history of trial and error that is more embodied than language based. Research methodologies used at Smith's Making and Knowing Project lab highlight intersections of craft-making and scientific knowing, where imitating and reconstructing-making techniques serve to access and record valuable information. The idea that complex trials can be carried out in the mind, guided by the work of trained hands, is particularly noteworthy as a benefit of the Making as Knowing research approach. Hands and objects made by hand serve as

△ Figure 2. Hybrid wNLT and light wood framing on Demonstration Building, Guilford, Connecticut, 2024.

repositories of information more often than written descriptions of objects and techniques.[6]

Making as Knowing methods are often used in building construction; for example, the International Building Code (IBC) outlines written and interpreted prescriptions for construction. The authors devised a unique translation of existing light wood frame and heavy timber construction codes within the permit and construction drawings for the wNLT building described in this article. Another form of Making-as-Knowing arose in the project when local builders began to intuitively frame out window and door headers, wall sills, double-top plates, and roof rafters as part of the wNLT wall panel system. The conventional framing details were not needed from an engineering standpoint. Likewise, the architect had not specified conventional light-frame wood techniques in the construction drawings. The intention was to create a tilt-up building constructed with panelized wNLT and avoid the horizontal framing members employed in light-frame construction. The project team had yet to anticipate how important it would be to employ hybrid construction to increase builder confidence. Adding the light wood framing elements inspired discussions among builders who had been unfamiliar with wNLT technology up to that point, and they now answered new questions about the wNLT quickly and with assurance. This process eased frustration and insecurity regarding learning curves and knowledge transfer between team members (Figure 2).

Making as Knowing works effectively within a broader Design Thinking (DT) framework because both prioritize continuously refined solutions through rapid iteration cycles. Prototypes are often intentionally left "unfinished" to explore new solutions. Common-sense judgment (the kind exercised through the lived experience of the body and its senses) or consensus among a group provides the validation necessary to proceed to the next solution. These methods contrast with the Scientific Method (Question, Research, Hypothesis, Experiment, Analysis, and Conclusion), which remains valid even when results do not lead to a solution.[7] The Hasso-Plattner Institute of Design defines DT phases as *Understanding, Observing, Defining Point of View, Ideating, Prototyping, and Testing*. However, the DT process does not always progress in that order.[8]

Understanding involves creating a specific context or describing the background conditions for a solution to a problem. *Observing* includes gathering interviews, case studies, and conducting a literature survey. *Defining a Point of View* prioritizes the common sense or lived experiences of end users and project team stakeholders. *Ideating*, *Prototyping*, and *Testing* often involve an iterative and nonlinear cycle of synthesizing lessons learned (Figure 3).

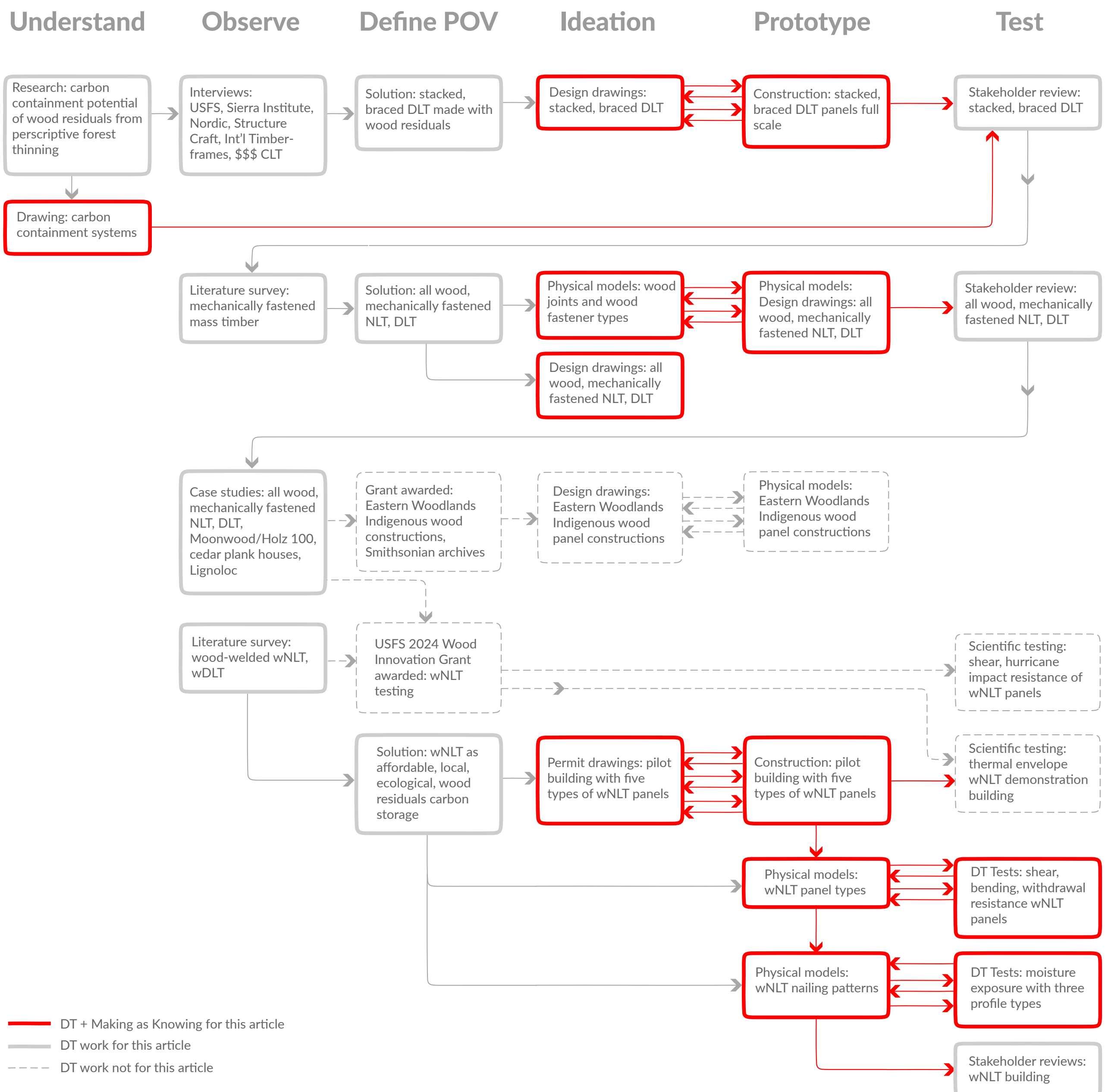
DT reflects a broad, generalist structure for research, where social factors and engagement with community stakeholders are essential. DT supported the project team's desire for audience-defined outcomes and assessments. The intent was to gain as much knowledge as possible by constructing a demonstration building with a team of experienced builders. Where precise metric data is unavailable, the resulting demonstration building serves as important validation.[9]

Discussion

Understanding: US Forest Carbon Cycling and Residual Wood as a Context for Alternative Mass Timber Technologies

The project team defined a context for alternative mass timber technologies through the lens of forest systems, climate change, and carbon offset markets. US forests are estimated to store 58.7 billion metric tons of carbon (647 billion tons) and sequester 211 million metric tons (228 million tons) of carbon annually.[10] Without intervention, severe wildfires in the US may reduce the carbon sequestration potential of forests by >50%.[11] Forest managers utilize mechanical thinning beneath the forest canopy to remove small-diameter "ladder fuel" and insect-damaged trees. These treatments support forest stands with a mix of tree ages, increase forest resilience during insect outbreaks, and decrease the likelihood that forests will burn at high intensity.[12] Tree thinning provides a carbon benefit by reducing carbon emissions from wildfires, allowing young trees to grow and absorb more carbon, and promoting tree survivorship in the event of a fire.[13] To provide perspective on the enormity of the treatment needed on US federal land alone, approximately 60 million acres (24 million hectares) are at risk of unnaturally severe fires.[14] To manage this land would require a significant increase in the pace and scale of annual treatments.[15]

Allowing dead wood and wood residuals from mechanical forest thinning to remain in the forest to decay is often considered an ecologically beneficial and inexpensive practice.[16] Proactive, controlled burning of wood residuals gathered into "slash piles" is standard since it is considered the least expensive method to prevent accumulated woody biomass from fueling severe forest fires in high fire risk areas. While slash pile burning is not ideal because it releases carbon into the atmosphere, it has also raised concerns from the scientific community due to lasting changes in soil pH, decreased soil fungal colonization, and poor tree seedling performance in persistent



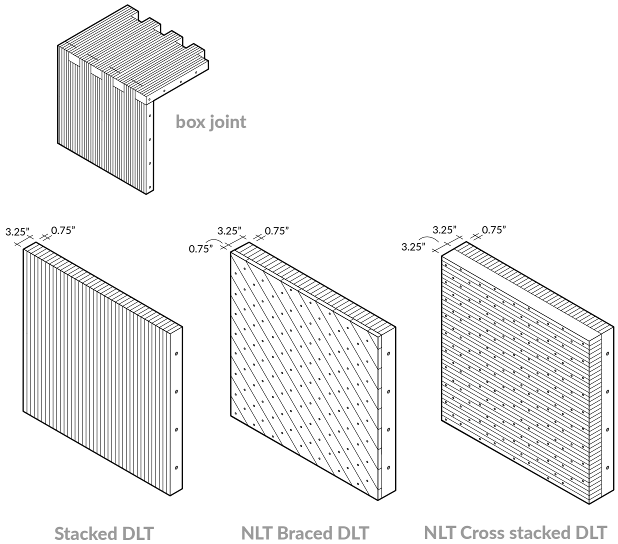
△ Figure 3. Flow chart illustrating Design Thinking and Making as Knowing process.

burn scars.[17] Public perception and air quality problems caused by excess wood smoke diminish the appeal of slash pile burning as a land management practice.

When mechanical thinning produces excess, non-merchantable biomass, land managers have several opportunities to safely store carbon in woody biomass and profit from it. Voluntary carbon offset markets provide anywhere from $15 per $MTCO_2e$ (metric ton of CO_2 equivalent) to $300 per $MTCO_2e$ for highly durable, verifiable carbon credits.[18]

To estimate the potential carbon in woody biomass residuals in US forests, the authors analyzed non-merchantable forest materials that decompose far more rapidly than other living or standing dead wood in forests. Using USDA Forest Service Forest Inventory and Analysis (FIA) datasets, the authors calculated that the annual flux of new woody biomass into the downed dead wood inventory is 65 million $MTCO_2e$.[19]

The authors focused on the US Pacific Northwest to understand how numbers play out at a regional level. More than 25 million acres (10 million hectares) of coniferous forests in this region are in moderate to high fire hazard conditions. Approximately 85.3 million acres (34 million hectares) of



△ Figure 4. Dowel Laminated Timber (DLT) panel types. (Credit: Carbon Containment Lab, 2023)

forestland across California, Oregon, and Washington potentially need thinning to reduce wildfire risk. Policy at the state level has begun to support thinning projects. California signed into law SB 904, which requires the state to double forest fuel removal. It is estimated that mechanical thinning could enable the profitable management of 800,000 acres (323,748.5 hectares) of forest land per year.[20] From these numbers, the authors assume that annual carbon-gathering treatments on 500,000 acres (202,342.8 hectares) in Oregon and Washington could remove approximately 10 million $MTCO_2e$ and yield $500 million at $50 per $MTCO_2e$.

Another regional case is the US Eastern Forest Products sector, which accounts for $167 billion annually and provides direct employment for over 540,000 people. The State of Maryland, not part of the traditional US West Coast, US Southeast, or Canadian wood basket regions, saw its forestry industry decline from $4.7 billion in 2005 to $3.5 billion in 2015. In 2020, 15,000 jobs in Maryland were supported by the forestry sector, a sharp decline from the 2005 BEACON report that estimated 29,000 jobs. Maryland has 74 sawmills, but only 12 are of significant size.

Maryland's forests are predominantly even-aged and mature, with an average tree age of 80 years. Forests in Maryland are experiencing a trend toward a slower annual net growth rate and increased natural mortality overall. The exception is the timberland, where harvesting has created tree densities that better withstand drought, disease, and pests.[21]

Investing in locally sourced products like wNLT could revitalize the small-scale forest product infrastructure on the Eastern Shore and in Western Maryland, where timber is a weak market. This investment could provide income for landowners who practice sustainable forest management. The flexibility of products like wNLT that can be made in small-scale facilities makes it easier to develop markets for underutilized local species, such as Loblolly pine (*Pinus taeda*) in the US Mid-Atlantic or Eastern hemlock (*Tsuga canadensis*) in the US Northeast. NLT and DLT panel layers can be aggregated to increase strength and improve thermal values for a building envelope. Increasing panel layers allows for the use of lower-grade timber left at log landings during industrial-scale timber operations.

Observing: Existing Commercial Products, Fabricator Interviews, and Literature Survey

Solid wood panelized construction is found worldwide in preindustrial buildings, including cedar plank houses of the Chinook and Tillamook people from the US Pacific Northwest, larch churches in the Chiloé Archipelago, cypress temples in Japan, and heart pine stave churches in Norway.

Industrial buildings in the early 1800s in the US used mechanically fastened solid timber frame construction, known as Heavy Timber (HT), according to the International Building Code (IBC) and fire codes. In the twenty-first century, mass timber emerged as an umbrella term for various engineered and glue-laminated solid wood products that have fire resistance comparable to traditional heavy timber frame posts, beams, and tongue-and-groove decking. Like HT, mass timber structures are categorized in the IBC as Type IV combustible construction.[22]

Early examples of Nail Laminated Timber (NLT) construction in the US include the Globe Grain Elevators, built up to 148 ft. (45.1 m) tall in Northern Minnesota in 1887. The walls consisted of horizontally stacked and staggered 2 in. (5 cm) thick old-growth heart pine fastened with iron fasteners.[23] In the 1970s, the German term "Brettstapel," meaning stacked planks, was used to describe a building technology developed in Central Europe that employed softwood lamellae and hardwood dowel fasteners that stay in place due to the strength of surface tension.[24] Dowel Laminated Timber (DLT) employs low-moisture hardwood dowels between lamellae instead of metal fasteners. DLT dowels are typically dried to 6–8% moisture content and expand once placed in softwood panels dried to 12–15% moisture content.[25]

In addition to understanding the history of mass timber technology in Europe and North America, the authors interviewed mass timber fabricators, sawmills, and managers of forestry operations to compile a list of all-wood mechanically fastened commercial products.[26] The Austrian company Thoma produces a premium product called Holz100/Wood100®, made with high-quality structural fir harvested at high altitudes during the waning moon of winter season.[27] Likewise, the fabrication of DowelLam™, a product by the Canadian company StructureCraft, controls quality through automation and certified testing.[28] Except for one bridge mat product, no North American manufacturers appear to fabricate medium- to low-grade all-wood mechanically fastened panel products at comparatively lower costs. Table 1 summarizes the commercial products explored.

The topic of wood waste from sawing dimensional lumber in the US was a recurring theme in interviews. The team conducted a quick study to compare yields from wood residuals to those from high-value commercial logs. In this exercise, wood residuals

Table 1. Survey of existing all-wood mass timber products manufactured in North America.

Company	Product Name	Product Type	Span	Fasteners	All-wood	Fabricated
StructureCraft	custom CLT	Cross-stacked DLT	Two-way	Hardwood Dowels	Yes	Canada
StructureCraft	DowelLam—DLT	Stacked DLT	One-way	Hardwood Dowels	Yes	Canada
International Timberframes	Wood100 DLT	Stacked DLT	One-way	Hardwood Dowels	Yes	Canada
International Timberframes	Wood100 DLT	Cross-stacked DLT	Two-way	Hardwood Dowels	Yes	Canada
Holz100	Wood100 DLT	Cross-stacked DLT	Two-way	Hardwood Dowels	Yes	Canada
Nur-Holz Rombach	NUR-HOLZ	Cross-stacked	Two-way	Wood Screw	Yes	Europe
Sterling Solutions	TERRALAM	Cross-stacked Bridge Mat	Two-way	Glue + Hardwood Screw	No	Canada
Beck Fasteners	LCLT	Cross-stacked NLT	Two-way	Hardwood Nails	Yes	Europe
Eder Holzbau	Eder NaturWand	Cross-stacked NLT	Two-way	Hardwood Nails	Yes	Europe
FraserWood	Key-Laminated Beam	Beam	One-way	Hardwood Key	Yes	Canada

Table 2. Comparison of Dimensional Lumber Yields from Residual Wood and High Value Saw Logs. (Credit: Carbon Containment Lab, 2022).

Residual Log Size	Cu. Ft.	Carbon Kg	% Total Volume
10' L x 10" dia	2.23	22.3	40.90%
10' L x 8-10" dia	1.51	15.1	34.01%
10' L x 4" dia	0.26	2.6	29.98%
10' L x 3-4" dia	0.16	1.6	23.88%
40' L x 10" w/ 1" char	7.07	70.7	39.90%

were defined as insect-damaged trees of any diameter, small-diameter trees (minimum 4 inches or 10 cm), fire-damaged logs with an outer layer of char, salvage logging, and timber log cut-offs. Once harvested, timber logs that remain at forest landings for twelve months lose their commercial value. If no mill receives the timber, its value drops after 30 days because moisture and varying temperatures cause logs to shrink and swell. Warping and checks in the wood make it susceptible to blue stain fungus, termite damage, and other forms of decay (Table 2).

Based on the interviews, wood fastener fabrication appears to be an opportunity to utilize domestic hardwoods, such as North American ash species, which are experiencing increased mortality due to the emerald ash borer (*Agrilus planipennis*) insect. As the warming climate shifts conifer forests north and favors mixed hardwood forests of oak, maple, and hickory, there will likely be more opportunities to use wood waste from precommercial forest thinning operations as a source for wood fastener production.

When lumber yields are relatively small, it is difficult to justify the increased labor required to gather, sort, grade, and mill residuals. However, upcycling wood residuals into products for wood building construction can close the loop by adding value to investments in forest management for carbon uptake, climate change resilience, durable methods for carbon storage for offset markets, growing markets for domestic wood, and increasing good jobs related to domestic forestry.

European sawmills that use precision automation and minimize wood waste provide an example of how wood residuals in North America can be transformed into viable wood products.[29] In addition, synced cut-to-length harvesters, log processing equipment, and machinery automation reduce the energy and labor needed to process residual wood and transport it to fabrication facilities.[30] Centralized logistics hubs can process residuals for biochar soil additives and negative emissions technologies. Development-stage Bioenergy with Carbon Capture and Storage (BECCS) systems have demonstrated the feasibility of generating green hydrogen and capturing concentrated streams of CO_2 from wood waste.[31]

Literature Comparing Metal Nail Fastened NLT with Wooden Dowel Fastened DLT

The authors conducted a literature survey of state-of-the-art testing. Much existing literature documents the structural performance of Nail Laminated Timber (NLT), which is most often described as vertically oriented lumber mechanically laminated with metal dowel-type fasteners. Documented structural properties include axial compression, bending performance, rolling shear, slip behavior, and brittle failures. The impacts of different joints and metal fastener types (threaded nail, screw, metal rod) on NLT performance have been studied. Several studies also compare NLT with DLT constructed with vertically oriented lumber. Key findings from the survey include:

Gap Formation

- NLT and DLT perform best for structural loads that are parallel to the board length. In vertical assemblies, gaps form between boards (called lamellae) due to differences in natural curvature or shrinkage from moisture loss. Fasteners transmit loads across these gaps.[32]

- Gaps negatively impact fire performance. Charring from fire tests was deeper in vertically stacked NLT than in cross-stacked timber (CLT). Even small gaps create pathways for flames and pyrolysis gases to travel. Eco-friendly fire coatings, as an alternative to intumescent materials and layers of gypsum board, are areas worth exploring.[33]
- Panel gaps impact acoustic performance: however, structure-born flanking transmissions (also present with cross-stacked timber panels that have no gaps) are essential, as are leaks, openings, and through-wall transmissions. Liners and routing acoustic profiles onto panels improve performance.

Moisture

- NLT installed outdoors with moisture content (MC) near the fiber saturation point (25–30%) lost up to 4% moisture post-installation and formed gaps between lamellae. Climate regions significantly impact moisture content. The strength and stiffness of panels are more significant in NLT with low moisture content. Pre-drying before installation could improve outcomes but would be more costly.[34]
- Water quickly penetrates the core of NLT panels. Installing permanent impermeable membranes or other low-permeance materials on NLT must be reconsidered due to the potential for moisture entrapment and wood decay. Post-installation heating is effective for thin members but not for thicker NLT.[35]

Fastener Performance

- Increasing the number of wood dowels or metal nails in a panel by lowering the spacing between fasteners does not necessarily improve panel performance. The interlaminar connection force and bending stiffness may improve, but stress concentrates near the fasteners, resulting in brittle failures such as splitting lamellae and fastener pull-out.[36]
- Withdrawal capacity, which is the ability of a fastener to resist pulling out of its wood substrate, limits the performance of metal nails and wooden dowels. Withdrawal resistance can be improved by increasing the diameters of fasteners or by using resins and coating nails.[37]
- Promising research documents the use of lower-grade lumber and fast-growing plantation species like poplar, eucalyptus, and bamboo for NLT and DLT. Splicing with a stepped pattern of butt joints is a method for incorporating smaller timber lengths from forestry residuals. These alternatives could decrease production costs and wood waste.[38]

Preference for Wooden Dowel Fastened DLT

In the existing literature, authors note the advantages of all-wood DLT over metal nail-fastened NLT. DLT has stronger fastener withdrawal resistance, better recyclability, is easier to route with CNC equipment, and has less embodied carbon for wooden dowels compared to metal nail fasteners. In 2017, the North American manufacturer StructureCraft constructed a new 50,000 ft.^{2} (4,645 m^2) facility in Abbotsford, British Columbia, with fully automated production of wooden dowel DLT as an alternative to its NLT product.[39]

Several articles cite the use of hardwood species like oak, maple, birch, ash, hickory, and aspen to make wood dowels. This fabrication is an exciting area of work because it relates to creating new markets for small-diameter forest residuals, fire-damaged logs with an outer layer of char, and insect-damaged trees like the ash species, which have experienced almost 100% mortality in response to the emerald ash borer insect in the US Midwest and East Coast.

Preference for Metal Nail Fastened NLT

In the existing literature, authors note that metal nail-fastened NLT remains a favored choice for mid-rise residential and commercial buildings. The ease of fabrication and the fact that NLT does not require a dedicated manufacturing facility or highly specialized labor are noted as primary factors. Pointed fasteners, such as screws or nails, are quick to install with inexpensive nailing equipment.[40] Because of this flexibility, NLT can be made from local, underutilized sources of lumber.

One paper analyzed Life Cycle Assessment (LCA) regarding Global Warming Potential (GWP), Embodied Energy, and Life Cycle Cost (LCC) by comparing metal nail NLT, wooden dowel DLT, and Cross-Laminated Timber (CLT). Hydraulic presses used in DLT and CLT fabrication increased energy use by a few percentage points compared to NLT. However, the actual wooden dowel or glue adhesive used in CLT and DLT had a few percentage points lower energy use than the metal nails in NLT. NLT seasoning accounted for 65% of the total embodied energy compared to 72% for CLT and 73% for DLT. End-of-life emissions for NLT were 30% higher due to the metal nails, which are not easily recycled because of the difficulty of removing them. The embodied energy of metal nails in NLT constituted 19% of the total system, while CLT adhesive was 3% embodied energy and wooden dowels in DLT was 5%.[41]

DLT had the lowest Life Cycle Cost (LCC) in the same study. The cost of steel nails in NLT was significantly higher than that of adhesive and dowels in the DLT. CLT's cost was higher overall, but it has the benefit of being a higher-performing structural product.[42]

Wood-Welding

Recent literature documents mechanically fastened NLT, DLT, and wood-welded connections. A rotary hydraulic press can insert a large-diameter hardwood dowel, with low moisture content, into a predrilled softwood substrate. Upon insertion, high friction and rotational speed create surface heat that solidifies the wood, forming a "weld." [43] Structural properties of hardwood dowels can be enhanced through thermal modification and wood densification via compression.[44]

Hardwood resin-coated nails driven at high speeds with hand-operated pneumatic nailing equipment into a softwood substrate create wood welds. More studies are needed to understand nail spacing and brittle failures in wood-welded NLT compared to metal nail-fastened NLT.

Defining a Point of View: Wood-Welded Nail Laminated Timber (wNLT)

The project team moved forward with durable wood-welded Nail Laminated Timber (wNLT) as a viable solution for better forest management. This approach offsets the cost of pre-commercial thinning and the need for innovative wood products to increase demand and timber sales. The project team also decided to apply for a US Forest Service 2024 Wood Innovation Grant to conduct structural testing.[45] The award was successful and this portion of the work is ongoing. The welded-wood NLT connection was optimal for the project team because, unlike DLT, it did not require a low-moisture wooden dowel, predrilling holes, or expensive pneumatic press equipment. Additionally, the builders on the project team had years of experience using nailing equipment with metal nails for light-frame wood construction projects.

Ideating and Prototyping: Dimensionally Stable NLT and DLT

A drill press and table saw were used to develop design ideas for two hybrid types of all-wood mechanically fastened mass timber panels made with industrial-grade 1 x 4 in. (1.9 x 8.89 cm) pine and 3/8 in. (0.95 cm) diameter ash dowels. Smaller diameter "nails" were simulated with thinner ¼ in. (0.64 cm) dowels driven manually. "NLT-Braced DLT" and "NLT Cross-stacked DLT" designs aimed to create a version of the vertically stacked DLT fabricated by companies like StructureCraft that could be dimensionally stable like CLT and span in two directions to resist lateral loads (Figure 4).[46]

Half-lap and butt joints were explored to extend panel lengths and make edge-to-edge connections. Tongue-and-groove lamella profiles seemed to improve the strength from friction between lamellae connections, and box joints strengthened corner joints. Repeated ideation using CNC milling equipment sped up the process and helped with the problem of fasteners splitting the wood lamellae.

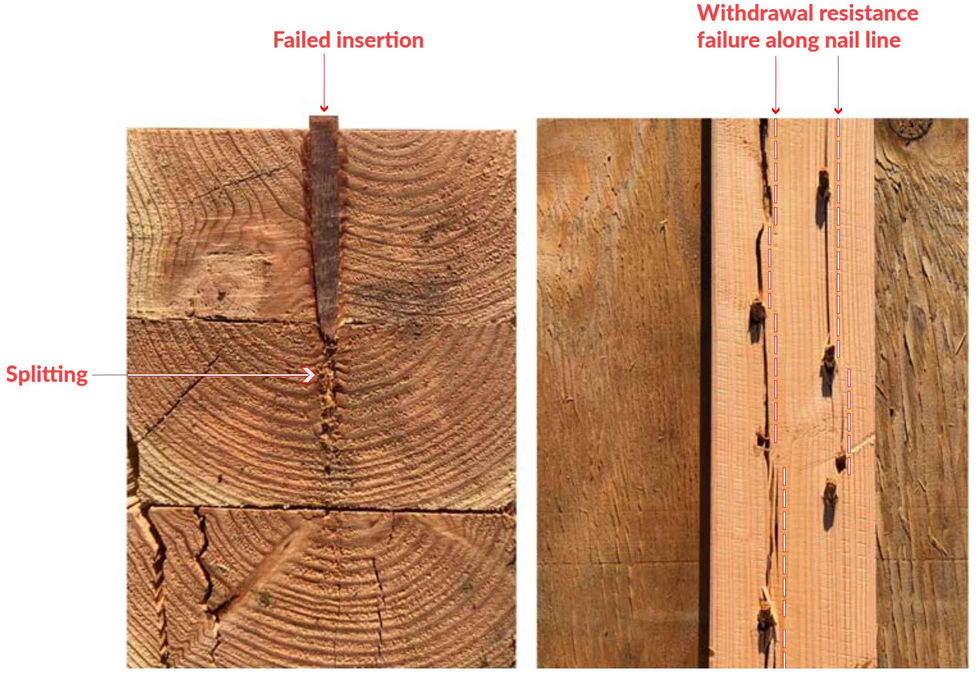
An early limitation was sourcing dimensional lumber made from residual or underutilized species. The authors proceeded with Douglas fir lumber, which was commercially available. The same applied to sourcing a stand-alone hardwood dowel product for DLT panel assembly. There were no wood dowel fasteners commercially available in North America, and the authors struggled to locate and translate design codes for wood dowel assemblies at the time. This lack of supply led to the decision to focus next on wNLT. Beck America distributes a European Lignoloc® product line that includes several types of beechwood nail fasteners and nailing equipment. Upon request, Beck provided essential structural design criteria, nailing patterns, panel layups, and use cases in building construction. The strength of the nails, equivalent to that of aluminum nails, is partly achieved due to the lignin weld produced when the nail is driven under pressure into a wood substrate (Figure 5).

wNLT Ease of Construction and Points of Failure

Later prototyping included constructing a 12 x 20 ft. (3.7 x 6 m)

△ Figure 5. Detail of lignin weld with Lignoloc® nail and softwood substrate.

△ Figure 6. Panel prototype with yellow pine and Lignoloc nails for Guilford Demonstration Building.



△ Figure 7. (left) Nailing failure; (right) pull-out test on two Douglas fir lamellae fastened with beech nails at 4" on center and no construction glue used.

wNLT demonstration building in Guilford, Connecticut. Between ideating and prototyping, permit drawings, pre-preliminary structural calculations, wall panel designs, and mock-up models were iterated many times (Figure 6).

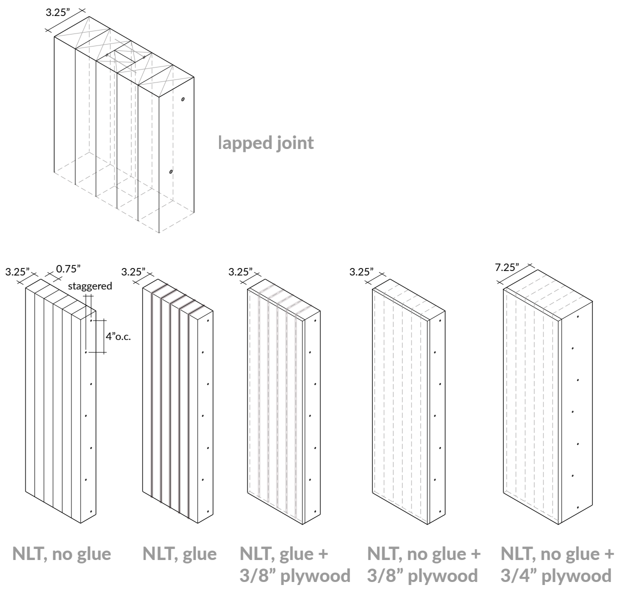
Although the Lignoloc® equipment functioned like many compressed air nail guns commonly used in light wood construction, there was a slight learning curve to gain precision. Based on the literature review and prototyping, the nail spacing for the wNLT panels in the demonstration building was set at 1.5 in. (3.8 cm) from the panel edges and 4 in. (10 cm) center-to-center in a staggered or zigzag pattern. Tighter spacing in early prototyping failed due to splitting the wood substrate. Nail insertion failed with initial panel mock-ups in yellow pine. Wood nails either did not form a solid lignin weld, or the nail head did not sink into the lamellae when encountering resistance, such as a wood knot or gap between lamellae. Adjusting the nail length, driver settings, and holding the device steadily in an orthogonal position improved the outcome.

Where metal nails fail on a curve when exposed to loads, wooden nails fail suddenly when they reach their shear limit. Testing highlighted that the nails perform well against pull-out forces. Brittle failure from withdrawal occurred in a longitudinal configuration that followed the nail line. Adding a small dab of construction glue at the top and bottom of wall panels improved the results (Figure 7).

A building permit was obtained by describing the structure as a heavy timber and light wood frame International Building Code Type IV structural system. The primary wind-resisting system elements were designed to withstand wind loads of 120 mph (193 kph) as prescribed by ASCE minimum loading requirements for buildings in this project area. Seismic risks in Guilford are minimal compared to the forces generated by wind. The snow load is 30 psf. The building foundation is bedrock. The basic 2 x 4 in. (3.81 x 8.89 cm) wNLT panels were defined as having a dead load of 10 psf (49 ksm). Adding 3/8 in. (0.95 cm) plywood sheathing increased the weight by 1.0 psf (4.9 ksm) and 15/32 in. (2.4 cm) sheathing increased it by 1.5 psf (7.3 ksm). The typical wall section for the building, which includes cork insulation and wood siding, was assumed to have a dead load of 20 psf (98 ksm).

The demonstration building included five wNLT panel types. A 5:12 pitched roof was designed with 2 x 4 in. (3.81 x 8.89 cm) wNLT and rated plywood sheathing based on SDPWS 2015 for wood-sheathed diaphragms. The 12 ft. (3.7 m) wide gable end shear wall facing north was designed with 2 x 4 in. (3.81 x 8.89 cm) wNLT. Instead of plywood sheathing, high-strength construction glue was applied at the top and bottom of each lamella. Rated plywood was added for the gable end shear wall facing south, and no glue was used. The 20 ft. (6 m) east and west walls do not use glue. The west wall, which includes windows and receives most of the coastal winds, was designed with wood nail spacing at 2.5–5 in. (6.4-13 m) and 3/8 in. (0.95 cm) plywood. The east wall was designed with 4–8 in. (10–20 cm) nailing spacing and has neither plywood nor glue (Figure 8).

The construction process involved prefabricating the wNLT panels with Douglas fir and Lignoloc® nails in a small-scale workshop off-site. The contractors noted that they greatly benefited from the improved working conditions while prefabricating the panels because they were away from the winter weather in a comfortable indoor environment. They also emphasized that avoiding lengthy daily commutes to the remote site saves time and minimizes gas mileage.



△ Figure 8. wNLT Panel Types, Demonstration Building, Guilford, Connecticut.

Simple, inexpensive fabrication tools and techniques were used to prefabricate the wNLT panels and 2 x 4 in. (3.81 x 8.89 cm) lamellae were bolted to a steel beam for rigidity and aligned at right angles. The lumber was not completely straight, so wood shims were placed on the back face of the wNLT panels between lamellae to create even joints and keep the panels plumb. Metal screws were used to ensure that the wood lamellae remained straight while the wood nails were inserted. Panels were fabricated in varying widths, with 2 x 8 ft. (0.6 x 2.4 m) panels serving as the standard for the 20 ft. (6 m) long walls. The 2 ft. (0.6 m) wide panels were manageable and could be easily handled by two people; however, in a pinch, one person could also slide them in and out of a pickup truck using 2 x 6 in. (5 x 12 cm) wood ramps. In minutes, the gable end walls were tilted into place by two people using hand cranks (Figure 9).

A strategy for moisture protection while the panels were installed was critical. Each panel was wrapped in a temporary waterproof membrane until the roof and rain-screen system could be applied. As moisture levels in the air fluctuated, the wood swelled. Half-lap joints were designed to accommodate both shrinking and swelling from panel to panel. Although the nails performed well during anecdotal pull-out tests, more information is needed to clarify how the nails will perform over time with the expansion and contraction of the wood. Tests were conducted with different lamella profiles fully submerged for 24 hours. Spline connections appeared to help stabilize the radial swelling expansion (Figure 10).

Conclusions

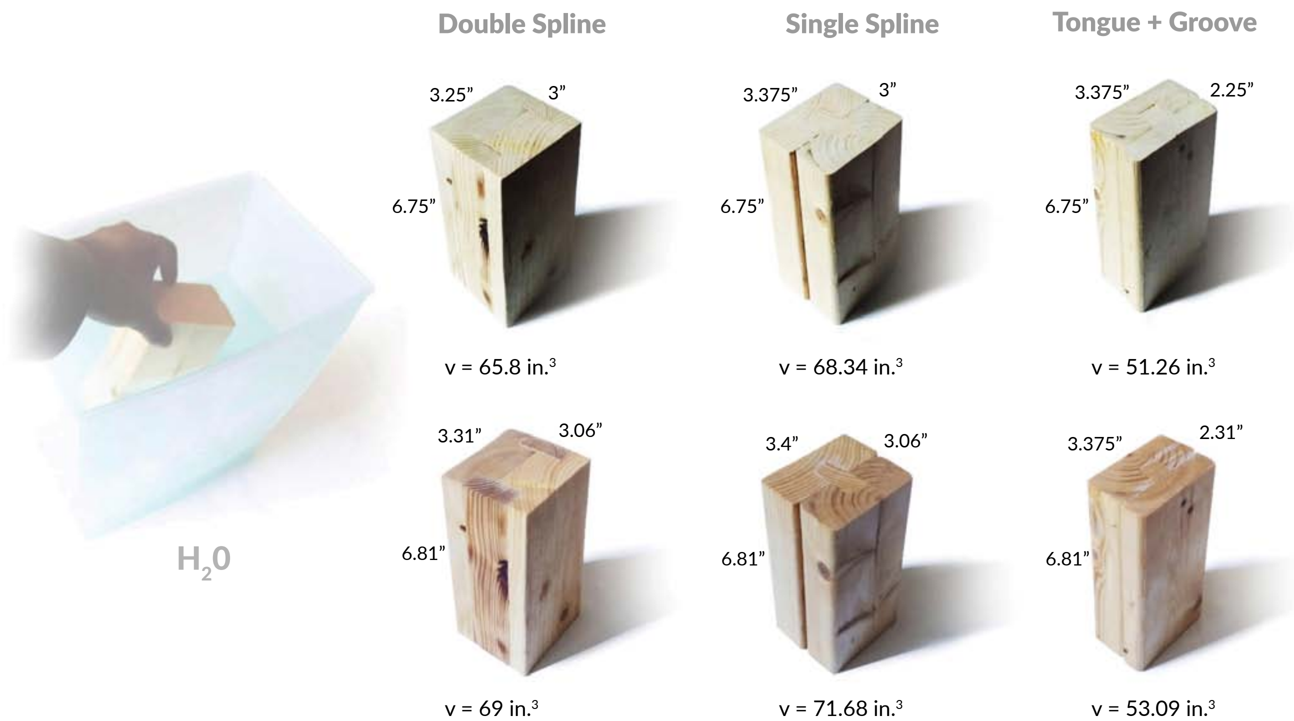
wNLT is a building technology accessible with a limited learning curve for contractors with conventional light-frame wood construction skills who seek jobs in small fabrication facilities with comfortable indoor working environments. Fabricating

△ Figure 9. (top) Prefabricated NLT panels delivered to site by one person in a pickup truck; (bottom) two people tilt-up north gable wall. (Credit: Carbon Containment Lab, 2023)

wNLT is like building a light-frame wall, one of North America's most common construction practices, using studs that are 1 in. (2.5 cm) apart instead of 24 in. (0.6 m) apart.

In North America, wNLT can address the need for affordable, high-quality single- and multifamily housing, as well as commercial buildings. wNLT can be used for structural systems, exterior walls, circulation cores, and fire-rated interior partition assemblies. The demand for locally produced building retrofit materials is high in metropolitan redevelopment areas, especially for upgrading multifamily residential buildings.

Many privately and publicly owned forestlands in North America produce underutilized tree species and non-merchantable wood residuals from forest thinning operations that prevent catastrophic wildfires and ecosystem damage caused by invasive species. While small-diameter trees thinned from forests currently have little commercial value, wNLT is an innovative product that demands hardwood dowels, wood nail fasteners, and lower-grade lumber that can be milled from small-diameter or fire- and insect-damaged logs. When used in well-maintained buildings, these products create opportunities



△ Figure 10. Moisture testing of different lamellae profiles for wNLT. (Credit: Abdureuf Mohammed Hussien, 2024)

for durable carbon storage. Further testing is needed for wNLT's potential to offer a more impact-resistant alternative to light-frame wood construction in areas where high-speed wind events are frequent.

The research on “design thinking and knowing” in this article provides a solid foundation for future testing and development of the North American Building Code. The resulting demonstration building offers an intuitive form of education and outreach to community stakeholders and serves as a valuable resource for further testing. Areas for further study include wNLT performance when exposed to moisture, thermal envelope testing, and the use of nontoxic, fire-resistant coatings such as lime or clay paints, which also help deter insects and prevent damage from wood decay. Future research could refine the structural performance of wNLT technology, for example by determining the largest diameter nail that can be driven for wNLT and whether the lignin weld increases the shaft diameter, making it act more like wooden dowels in DLT.

wNLT offers an alternative aesthetic and cultural story in North America.[47] More studies on the biophilic response to wNLT and the connections between wNLT and Indigenous building technologies of the Eastern Woodlands and Pacific Northwest have the potential to highlight suppressed cultures and support action around ethical land stewardship, tribal enterprises, land-based education, and community justice.

Increasing the presence of wNLT in North America involves maintaining open access to design, fabrication, and construction guidelines for these products. This openness requires a thoughtful, community-driven approach to patenting technologies. Funding to support third-party testing of wood fasteners as a basis for structural design guidelines for wNLT and wood-welded DLT is a critical next step. Perhaps most important, from an access and social equity standpoint, is the continued construction of demonstration buildings that can, in tangible and easy-to-understand ways, help a wider audience of affordable housing stakeholders envision what is possible.

Data Availability Statement

The data supporting this study's findings are available from the corresponding author, J. VanderGoot, upon reasonable request.

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