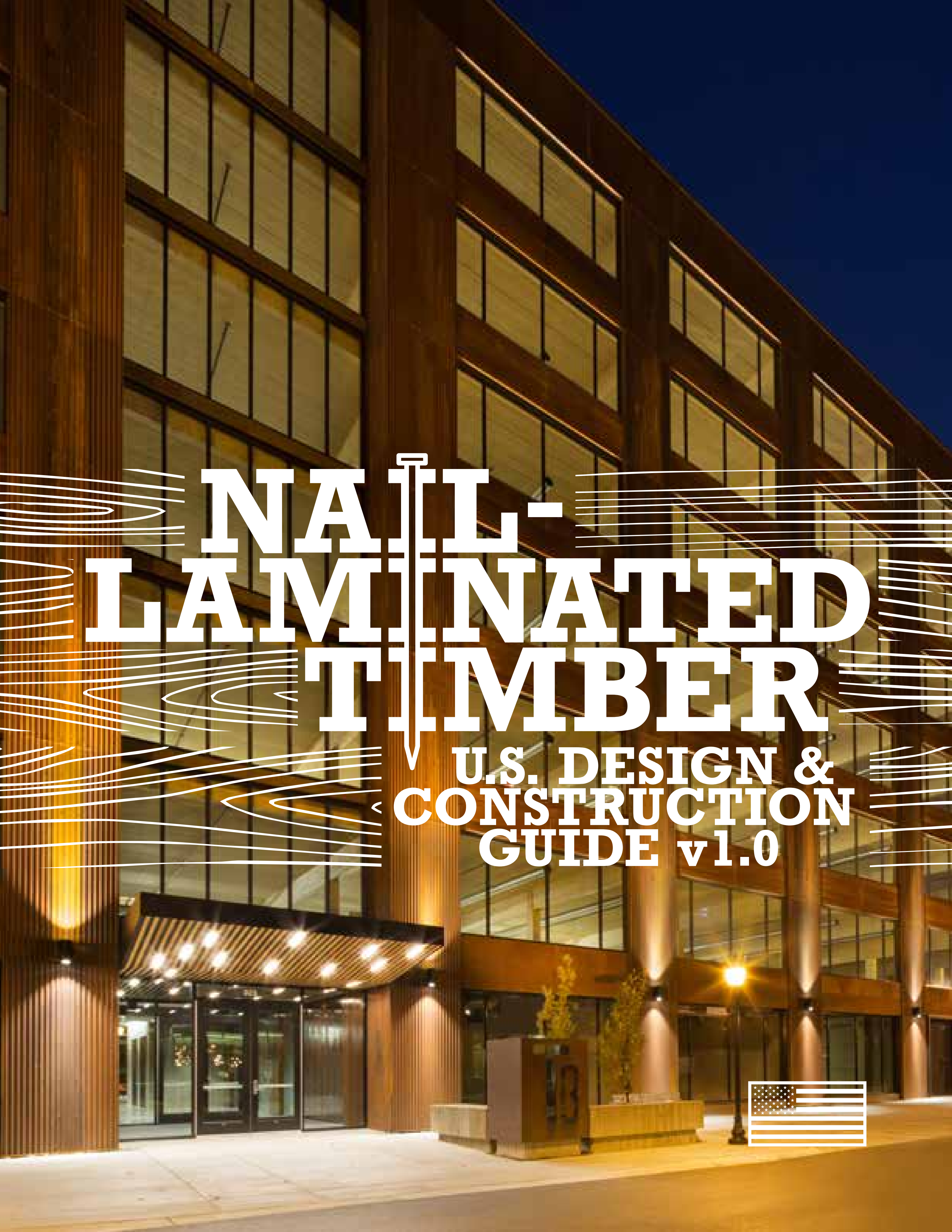

NAIL-LAMINATED TIMBER

U.S. DESIGN & CONSTRUCTION GUIDE v1.0

BSLC

Binational Softwood Lumber Council

Cover Image: *T3, Minneapolis, MN. Architecture: Michael Green Architecture. (Photo credit: Ema Peter)*

Acknowledgements

The NLT Design and Construction Guide was conceived and prepared by skilled practitioners who are each extraordinarily dedicated to advancing high-quality timber construction across industries, typologies, and geographies. We are grateful for the support of the Binational Softwood Lumber Council for funding this work, and for their ongoing partnership as we advocate for responsible use of timber in the built environment. Each author listed here contributed essential content and expertise; we wish to acknowledge their effort, time, and dedication with much gratitude.

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Above *Lansdowne Station, Richmond, BC. Architecture: Perkins+Will. (Photo credit: Martin Tessler)*

Glossary

Absorption
Gain of moisture.

Aesthetic Grading
Additional grading done to select lumber with a higher quality appearance. This form of visual grading does not allow higher structural design values than typical visually graded lumber.

Anisotropic
Having different physical properties along different axes. For example, wood is stronger parallel to the grain than it is perpendicular to the grain.

Appearance Grading
See Aesthetic Grading.

Bound Water
Water held within the cell walls of the wood.

Butt Joint
Individual laminations within a course aligned end-to-end, generally without a direct connection between the laminations (i.e. no toe nails, glue, or connection plates).

Checking
See Lumber Checking.

Computer Automated Drawing (CAD)
Software used to create 2D drawings, 3D models, and sometimes 4D (including sequencing) engineering, architectural, or shop drawings for construction.

Computer Numerically Controlled (CNC)
A machine, usually a router, used to cut materials into specific forms defined within a computer. Different machines will have varying numbers of axes on which it can move. For example, a three-axis CNC can typically move along two linear axes and one rotational axis.

Course
Multiple laminations within a single lamination line.

Cross Laminated Timber (CLT)

A wood pannel typically consisting of three, five, or seven layers of dimenion luber oriented at right angles to one another, and then glued to form structural panels with exceptional strength, dimensional stability, and rigidity.

Curved-In-Plan NLT

Planar NLT with a curve or profile for in-plan only, generally formed by cutting the edges of the panel after layup.

Curved NLT

NLT curved in section, perpendicular to the laminations, generally created on a curved jig to follow the curve of a supporting perpendicular beam. This fabrication process does not produce a true curve but a faceted surface, with each facet being the width of one lam.

Desorption

Loss of moisture.

Dimension Lumber

Visually graded or mechanically graded sawn lumber cut into planks from 2 in. to 4 in. thick (nominal thickness) and a minimum of 2 in. wide (nominal width). Refer to NDS tables 4A to 4C for design values.

Dowel-laminated Timber (DLT)

A solid wood structural element, created by placing dimension softwood lumber (nominal 2x, 4x, etc., thickness) on edge and friction-fastening them together with hardwood dowels.

Dunnage

Scrap wood or disposable material placed below construction material to raise it off the ground or truck bed.

Equilibrium Moisture Content (EMC), %

A moisture content at which wood neither gains nor loses moisture to the surrounding air.

Fiber Saturation Point, %

The moisture content at which the cell walls are saturated with water (bound water) and no water is held in the cell cavities by capillary forces. It usually is taken as $25^{\%}$ to $30^{\%}$ moisture content, based on weight when oven-dry.

Firestop

A fire protection system made of various components used to seal openings and joints in a wall or floor assembly.

Fire Separation

A fire resistant separation that separates or divides a building to prevent fire spread, such as a fire wall.

Flanking

The passage of sound around, over the top, or under the primary partition separating two spaces.

Flashover

The near-simultaneous ignition and sustained burning of most or all of the exposed combustible material in an enclosed area.

Flame Spread Rating

A standardized rating system used to describe the surface burning characteristics of a building material. One common rating systems is the ASTM E-84.

Finger-joined Lumber

Lumber manufactured by bonding two pieces of lumber with ends machined to mated finger-like profiles.

Free Water

Water that is not bound within the cells walls of the wood.

Forest Stewardship Council (FSC) Certified Wood

Wood from responsibly managed forests evaluated by the Forest Stewardship Council to meet environmental and social standards which may be required by projects pursuing certification under some green building rating systems (www.fsc.org).

Glued-Laminated Timber (GLT)

Sometimes known as Glulam, composed of individual wood laminations, specifically selected and positioned based on their performance characteristics, and then bonded together with durable, moisture-resistant adhesives. The grain of all laminations runs parallel with the length of the member.

Hi-Line Grade

An appearance grade of SPF lumber, often for export, and generally kiln-dried. It generally meets visual grading standards (white, bright, straight), however a visual grading standard must also be specified. Also known as Home Center Grade.

Home Center Grade

An appearance grade of SPF lumber, often for export, and generally kiln dried. It generally meets visual grading standards (white, bright, straight), however a visual grading standard must also be specified. Also known as Hi-Line Grade.

Hygroscopic Material

A material that tends to adsorb or desorb water from the air.

Impact Isolation Class (IIC)

An integer rating describing how well a floor reduces impact sounds, such as footsteps. A larger number means more attenuation. ICC ratings are provided on a logarithmic scale (similar to the decibel scale) with larger numbers representing a higher reduction in sound.

J Grade Lumber

The preferred appearance grade of wood in the Japanese market. This grade of lumber meets high visual grading standards (minimal defects, white, bright appearance) and is kiln-dried for dimensional stability. This is generally the most selective appearance grade of lumber.

Jig

A temporary structure that assists with a specific task in the manufacturing process.

Kerf

A slit made by a saw cut. Kerf width is equal to saw blade width.

Kiln-Dried (KD) Lumber

Lumber dried in a wood-drying kiln to meet lower moisture content values, generally around 12%.

Lamination/Lam

Individual dimension lumber component.

Laminated Strand Lumber (LSL)

A structural composite lumber made of wood strand elements with wood fibers primarily oriented along the longitudinal axis of the member. The strands are selected to meet specific strength requirements.

Laminated Veneer Lumber (LVL)

A structural composite lumber made of wood veneer sheet elements with wood fibers primarily oriented along the longitudinal axis of the member. The veneers are selected to meet specific strength requirement.

Layout

Placement, orientation, and location of prefabricated NLT panels in plan view.

Layup

Individual lamination pattern within NLT.

Leadership in Energy and Environmental Design (LEED)

A third party verified green building rating system managed by the US Green Building Council that provides a method of measuring environmental benefit of buildings and communities (www.usgbc.org).

Lumber Checking

A separation of the wood along the fiber direction that usually extends across the rings of annual growth, commonly resulting from stresses created in wood during seasoning/drying.

Mass Timber

A category of framing styles typically characterized by the use of large solid wood panels for wall, floor, and roof construction.

Machine Stress Rated (MSR) Lumber

Lumber graded using machine stress rating equipment instead of being visually graded. Each piece is non-destructively evaluated and assigned to a bending and modulus of elasticity class.

Moisture Content, %

The ratio of the total mass of water within the wood relative to the total mass of wood at its oven-dried state. Living trees can have a moisture content between $30^{\%}$ and $200+^{\%}$.

Nail-laminated Timber (NLT)

A solid wood structural element created by placing dimension lumber (nominal 2x, 3x, or 4x thickness and 4 in. to 12 in. width) on edge and fastening the individual laminations together with nails.

Nail Penny Weight (6D, 8D, 10D, 12D)

A trade designation used in commercial practice to describe nail size. In this Guide, nail type, penny weight, diameter and length are specified for clarity.

Nominal Size

As applied to products such as lumber, traditionally the approximate rough-sawn commercial size by which it is known and sold in the market. Actual rough-sawn sizes may vary from the nominal. Reference to standards or grade rules is required to determine nominal/actual finished size relationships:
2 in. nominal thickness = 1-1/2 in. actual finished thickness
3 in. nominal thickness = 2-1/2in. actual finished thickness
4 in. nominal thickness = 3-1/2in. actual finished thickness

Noise Reduction Coefficient (NRC)

A scalar representation of the amount of sound energy that can be absorbed by a specific surface, ranging from 0 to 1 where 0 represents no noise absorption and 1 represents complete noise absorption.

Premium Grade Lumber

An appearance grade of lumber generally square edged and virtually wane and warp free. These are not code standardized grades and may vary from mill to mill. Also known as Prime Grade Lumber.

Prime Grade Lumber

See Premium Grade Lumber

Programme for the Endorsement of Forest Certification (PEFC)

An international non-profit, non-governmental organization dedicated to promoting Sustainable Forest Management (SFM) through independent third-party certification. PEFC certified wood may be required by projects pursuing certification under some green building rating systems (www.pefc.org).

Sawn Lumber

Visually or mechanically graded wood cut/sawn to typical construction sizes as described in NDS Chapter 4. The term applies to a variety of sizes and species as defined in the NDS Supplement Tables 4A through 4F.

Seasoned Lumber

Lumber that has been either air-dried or kiln-dried to lower the moisture content not in excess of 19%.

Sound Transmission Class (STC)

An integer rating provided in ASTM E413 and E90 describing the average amount of airborne sound stopped by a building partition/wall/floor at 18 different frequencies. STC ratings are provided on a logarithmic scale (similar to the decibel scale) with larger numbers representing a higher reduction in sound.

Spruce-Pine-Fir (SPF)

A specific wood species group as described by the NDS.

Specific Heat Capacity

The rate at which heat diffuses through a material, measured as the amount of energy needed to increase one unit of mass by one unit in temperature. Expressed as Btu/lb-°F.

Stickers

Narrow strips of scrap wood or disposable material placed between layers of construction material to provide a gap between layers.

Sustainable Forestry Initiative (SFI)

A non-profit organization that manages the SFI Forest Management and Certification Standard which may be required by some projects pursuing green building rating systems (www.sfiprogram.org).

Thermal Conductivity

Rate of heat flow through a material for a given unit temperature difference, expressed as Btu-in/h-ft^2-°F.

Thermal Diffusivity

The thermal conductivity of a material divided by the product density and specific heat capacity.

Thermal Resistance (R-Value)

The resistance of heat transfer across a unit thickness expressed as h-ft^2-°F/Btu.

Temporary Moisture Management System (TMMS)

TMMS may include applied membranes, panel joint treatments, or both used to control construction phase moisture.

Visually Graded Lumber (No.1, No.2, or Select Structural)

Lumber graded by visual evaluation in accordance with the grading rules of the applicable grading or inspection agency.

Volatile Organic Compound (VOC) Content

Organic chemicals that have high vapor pressure/low evaporation points causing large numbers of molecules to evaporate or sublimate into the air at ordinary room temperature. Maximum VOC content for composite wood products may be specified by projects pursuing certification through green building rating systems such as LEED.

Warped NLT

NLT forming undulating or warped surface out of plane, generally by staggering the NLT courses up or down from the adjacent courses to create curvature in section perpendicular to the laminations.

Wood Structural Panel (WSP)

A wood-based panel product bonded with a waterproof adhesive. Included under this designation are plywood, oriented strand board (OSB), and composite panels.

Above *Clay Creative, Portland, OR. Architecture: Mackenzie. (Photo credit: Christian Columbres Photography)*

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Above *UBC Bookstore, Vancouver, BC. Architecture: office of mcfarlane biggar architects + designers. (Photo credit: Ema Peter)*

1 Introduction

Part of the family of mass timber products, Nail-laminated timber (NLT) is mechanically laminated to create a solid structural element. NLT is created by placing dimension lumber (nominal 2x, 3x, or 4x thickness and 4 in. to 12 in. width) on edge and fastening the individual laminations together with nails. Typically used as floors and roofs, NLT can also be used for walls, elevator shafts, and stair shafts. Plywood/OSB added to one face can provide in-plane shear capacity, allowing the product to be used as a shear wall or diaphragm.

NLT is an old method of construction with a range of modern opportunity to create compelling architecture. Used in many historic applications, it is enjoying renewed interest as we rediscover the many benefits of mass timber and advance wood technology and manufacturing. Lightweight, low-carbon, and very compatible with high-performance buildings, innovation with NLT is inspiring new opportunities for large- and small-scale buildings across sectors and around the world.

The mass timber product range available in North America includes Glued-laminated Timber (GLT), Cross-laminated Timber (CLT), Dowel-laminated Timber (DLT) and Nail-laminated Timber (NLT). While this wide range of products affords many options for specific design applications, each has different design challenges, performance characteristics, and construction advantages.

NLT is significant in the range of available mass timber options given the relative ease of fabrication and access to material; NLT requires no necessarily unique manufacturing facility and can be fabricated with local dimension lumber for use in applications across sectors and structure types. While products like GLT and CLT have modern publications and resources aimed at assisting designers and builders with specification, detailing, and installation, NLT resources are dated and focus on prescriptive rather than engineered applications.

This Design and Construction Guide (the Guide) provides the U.S. design and construction community with guidance to ensure safe, predictable, and economical use of NLT. It is intended to offer practical strategies, advice, and guidance, transferring knowledge and lessons learned from NLT project experience.

This Guide focuses on design and construction considerations for floor and roof systems pertaining to U.S. construction practice and standards. While NLT is being used for vertical elements for walls, stair shafts, and elevator shafts, this Guide provides the greatest depth of direction for more common horizontal applications. The information included here is supplemental to wood design and construction best practices and is specific to the application of NLT. Built examples are included to illustrate real application and visual reference as much as possible. This Guide is consistent with the following codes and standards, and these should be referenced as accompanying documents:

- 2015 International Building Code [1]
- ASCE 7-2010, Minimum Design Loads for Buildings and Other Structures [2]
- ANSI/AWC NDS-2015 National Design Specification (NDS) for Wood Construction [3]

Other relevant resources are referenced throughout as necessary for more details.

References

[1] International Code Council. 2014. *International building code 2015*. Country Club Hills, Ill: ICC.

[2] American Society of Civil Engineers. 2010. *Minimum design loads for buildings and other structures*. Reston, VA: American Society of Civil Engineers.

[3] American Wood Council. 2014. *NDS national design specification for wood construction*. Leesburg, VA: American Wood Council.

Above *Clay Creative, Portland, OR. Architecture: Mackenzie. (Photo credit: Christian Columbres Photography)*

Above *T3, Minneapolis, MN. Architecture: Michael Green Architecture. (Photo credit: Ema Peter)*

2 Architecture

2.1 Conceptual Considerations

2.1.1 Form

Nail-laminated timber (NLT) allows the creation of a monolithic "slab" of wood from off-the-shelf dimension lumber, supporting a broad range of architectural opportunities. Historically, NLT was primarily used for the construction of warehouses and other large buildings (refer to Figures 2.1 and 2.2). While flat floors and roofs remain the most common NLT building elements, more expressive and dynamic forms are being explored.

IN THIS CHAPTER

Figure 2.1: *Vancouver Urban Winery, part of the Settlement Building Brand Collective which also houses Postmark Brewing and Belgard Kitchen. Dating from the 1920's, the building was originally used as a steel manufacturing foundry. (Photo courtesy of Vancouver Urban Winery. vancouverurbanwinery.com)*

Figure 2.2: *Renovated space at Vancouver Urban Winery. The building dates from the 1920's, used originally as a steel manufacturing foundry. (Photo courtesy of Vancouver Urban Winery. vancouverurbanwinery.com)*

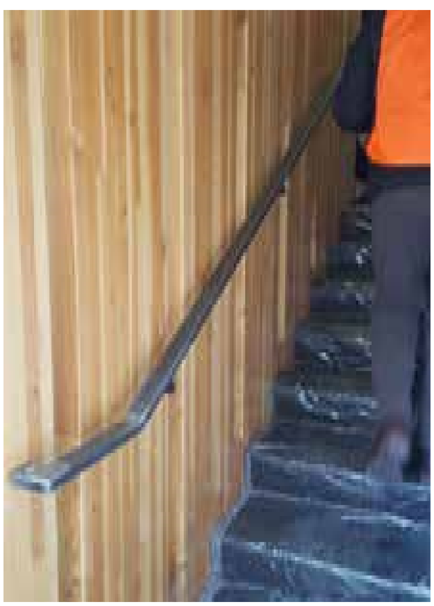


Figure 2.3: *NLT Stair Core. (Photo courtesy of WoodWorks)*

The examples here are intended to inspire and illustrate the breadth of possibilities as they pertain to NLT. Although NLT floors and roofs can be covered by finishes, it is often left exposed as a key design element. NLT is most commonly exposed at the ceiling, where it is protected from wear and the elements.

NLT may also be used as walls where exposing it for aesthetics is desirable, or for elevator and stair cores to meet higher loading or solid wall requirements (refer to Figure 2.3).

Figure 2.4: *Aberdeen Canada Line Station, Richmond, BC. Architecture: Perkins+Will. (Photo credit Left: Enrico Dagostini; Photo credit Right: Martin Tessler)*

Creating simple curves from NLT is relatively easy. The roof of Aberdeen Station, shown in Figure 2.4, is composed of gently curving steel channels which support the lumber, creating a modular, prefabricated panel that was craned into place. The channels were bolted to the adjacent panel channels.

Figure 2.5: *Brentwood Station, Burnaby, BC. Architecture: Perkins+Will. (Photo credits: Nic Lehoux)*

Figure 2.6: *Samuel Brighouse Elementary School. Richmond, BC. Architecture: Perkins+Will. (Photo credit: Nic Lehoux)*

The atrium at Samuel Brighouse Elementary School, shown in Figure 2.6, advances the same concept with integrated steel struts and tension cables, turning the NLT into a truss system to create a whimsically undulating roof.

Compound curves are also possible. The NLT at Brentwood station is curved perpendicular to the laminations, and used a combination of curved NLT, curved-in-plan. Figure 2.5 (left) shows the NLT curved to follow the shape of the glued-laminated beams, and Figure 2.5 (right) shows the form of the NLT curved-in-plan to accommodate the overall form of the station. The NLT spans between the curved glued-laminated beams set at varying angles, resulting in a building form with compound curvature.

Figure 2.7: *Tsingtao Pearl Visitor Center, Qingdao, China. Architecture: Bohlin Cywinski Jackson. (Photo Credit: Nic Lehoux)*

More dramatic, freeform curvatures are also possible. Gradual curves achieved with large radii help to mitigate the visual impact of faceting and stepping between adjacent laminations as demonstrated by the Tsingtao Pearl Visitor Center shown in Figure 2.7.

Compound curvature NLT with tight radii in the direction parallel to laminations requires the use of short lumber segments and results in noticeably faceted surfaces. Computer Numerical Control (CNC) milling of the faceted surface can be used to achieve a smooth surface. This is a labor- and material-intensive process typically reserved for specialty applications. Refer to Figure 2.8 for prototype examples.

Figure 2.8: *CNC milled compound curve prototype. (Photo courtesy of Perkins+Will)*

2.1.2 Surface Characteristics

Whether in flat or curved building elements, the components that form NLT remain distinguishable within the final product, allowing for considerable flexibility and freedom for the designer to define the appearance of the surface. Visible surface characteristics that must be considered include:

Species: Any species of wood can be used to fabricate NLT; this Guide assumes the use of species listed in the National Design Specification (NDS) for Wood Construction. Availability of species will vary by region, and offer different coloration and variation in appearance. For example, Douglas Fir appears to be more red or orange, compared to Pine, which appears more yellow or white. Refer to Appendix A for an NLT Appearance Chart.

Lumber Grade: Specify lumber grade and any other desired characteristics of the timber if the product will be visible in the finished building. For example, one project may require a ceiling that is free from knots, while another may demand a rougher look. Specifications should use regional appearance grading nomenclature to ensure lumber will achieve the desired surface aesthetic. Refer to Appendix A for an NLT Appearance Chart.

Eased or Sharp Edges: Typical North American dimension lumber is milled with slightly rounded corners in cross section, giving NLT a distinctive grooved or ribbed texture. To achieve a smooth face, the entire surface may be planed after layup, or specifications may call for individual laminations to be planed on one side prior to layup, as shown in Figure 2.9. If the NLT is assembled first, and then planed or sanded smooth, the gaps between the boards will become more obvious; the grooves tend to hide these imperfections. Both approaches will impact cost, and not all fabricators will have the ability to plane NLT smooth. Refer to Chapter 6 for more on fabrication.

Cross Section Size: Another way to modify the surface of NLT is by incorporating different sizes of dimension lumber. This technique achieves a unique aesthetic and can modify the acoustic properties of NLT (refer to Section 2.5.1). While the number of unique cross sections is theoretically infinite, most NLT is fabricated as illustrated in Figures 2.10, 2.11, and 2.12. Where NLT depth is staggered, lumber depths that vary by two inches are the most common combination: for example, alternating 2x4s with 2x6s. Larger variations in depth are less efficient structurally, owing to a large stiffness discrepancy. Structural considerations are addressed in depth in Chapter 4. The visibility of grade stamps on the sides of boards in staggered cross section NLT should be addressed in the design and fabrication processes.

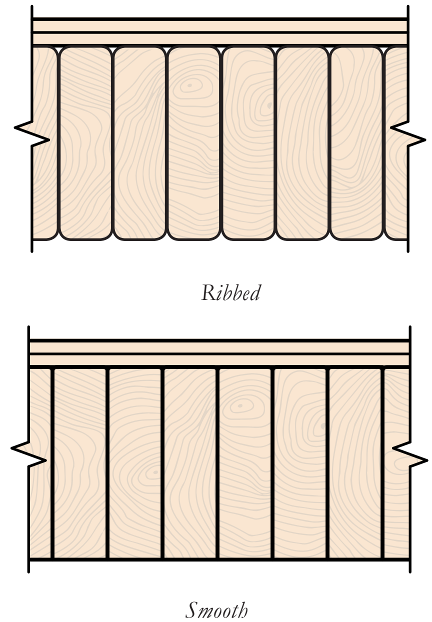


Figure 2.9: *Ribbed and smooth surfaces on NLT from un-planed and planed laminations.*

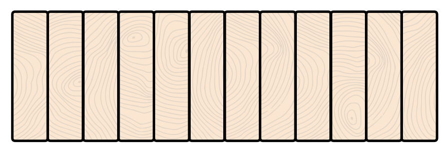


Figure 2.10: *Uniform Depth Cross Section.*

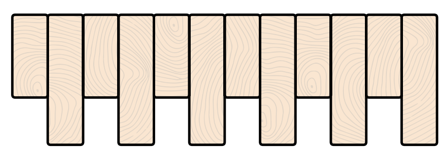


Figure 2.11: *1:1 Alternating Staggered Depth Cross Section.*

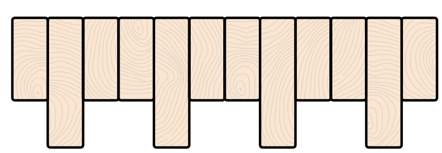


Figure 2.12: *2:1 Alternating Staggered Depth Cross Section.*

Figure 2.13: *NLT samples used as visual reference. (Photo courtesy of StructureCraft Builders Inc.)*

Set expectations for NLT appearance using physical samples, reference images, and clear specifications with regionally appropriate nomenclature. These should be provided to the fabricator and discussed in detail to ensure that the design intent is delivered. Refer to Chapter 6 for more on fabrication and Appendix A for an NLT Appearance Chart. All construction materials and systems are susceptible to damage during transportation, installation, or by other construction activities after installation. For wood, this includes staining from water, rust, and paint; mechanical damage; and burning. Restoring damaged NLT may be accomplished by sanding, refinishing, and patching. NLT can tolerate heavy sanding and refinishing due to its thickness; however, heavy sanding tends to degrade the even appearance of the ribs and grooves of NLT. Patching poses an even greater aesthetic challenge to the ribs and grooves. When reviewing construction deficiencies and repairs, all NLT should be compared with a sample as shown in Figure 2.13 or a mockup. Detailed considerations on fabrication and installation are provided in Chapter 6 and Chapter 7. Refer to Appendix B for a sample specification including requirements for finish and mock-up requirements.

2.2 Planning Considerations

NLT is a combustible material and a code-compliant structural system for buildings with varying heights, areas, and occupancies that allow for Type III, Type IV, or Type V construction. (For Type III and IV construction, it cannot be used for exterior walls unless it is fire-retardant treated.) For Type IB and Type II construction, NLT can be used as a heavy timber element for unoccupied roofs in accordance with IBC Table 601, footnote c. Refer to Chapter 3 for more information.

Structurally, NLT is a system that spans only in one direction, which has implications for the layout of the structural grid. NLT requires linear support and cannot be supported on columns alone. Typical spans for NLT of various depths are given in Table 2.1; linear supports such as load-bearing walls or beams should be spaced accordingly. These maximum spans may be governed by vibrations rather than strength. Where changes in the column grid or load-bearing wall locations from floor to floor are necessary, load transfers should be accomplished through supplementary framing rather than placing large concentrated loads on the NLT itself. Refer to Section 4.4.1 for more on point loads.

TABLE 2.1 TYPICAL NLT FLOOR SPANS

NLT DEPTH	TYPICAL SPAN RANGE
4 in. nominal	up to 12 ft.
6 in. nominal	10 to 17 ft.
8 in. nominal	14 to 21 ft.
10 in. nominal	17 to 24 ft.
12 in. nominal	20 to 26 ft.

Spans will vary and may fall outside these ranges depending on use, loading, and vibration criteria.

To reduce floor/ceiling assembly thickness, NLT can be mounted flush with the top of beams. NLT can also be suspended below the bottom of beams, with a raised floor system concealing the beams.

Cantilevers in the direction of the NLT span are feasible. A useful rule of thumb for concept design is that NLT can cantilever one quarter of its backspan length, although larger cantilevers may be possible depending on loading conditions. Cantilevers projecting through the building envelope create additional design and detailing considerations; refer to Sections 4.4.3 and 5.2.1.

Planning should also carefully consider tolerance for swelling and shrinkage with NLT. To achieve a consistent aesthetic, NLT expansion joint widths should be considered in parallel with structural detailing requirement, fabrication tolerances, and installation tolerances. Finish applications and MEP anchorage requirements should be designed to accommodate swelling and shrinkage of NLT. Refer to Section 4.3.1 for more guidance.

Figure 2.14: *Office partition walls in Mountain Equipment Co-Op Head Office. Vancouver, BC. (Photo courtesy of Fast+Epp)*

2.3 Detail Considerations

The architectural details for NLT carry the same considerations as for other building materials and systems. Wood construction detailing practices should be followed, but details may resemble those used for other materials. For example, when NLT is used as a non-bearing exterior wall it will bypass the floor slab, similar to a steel curtain wall system. Detailing in these situations are typically very similar despite the material.

In addition to affecting the appearance of the surface of NLT, the grooves at eased edges of laminations and gaps between laminations can affect the appearance and the performance of construction details. When a wall, door frame, or other linear element butts up against the underside of NLT, the gaps created by the grooves and the space between laminations must be considered for fire, acoustics, and aesthetics. Situations requiring airtight construction must be carefully detailed. For example, Figure 2.14 shows enclosed offices with interior partition walls that extend to the underside of an NLT floor structure above. Careful consideration of the interface between the walls and the ceiling is required to mitigate sound travel between spaces.

Due to the difficulty in sealing linear elements to the underside of NLT, it is good practice to keep NLT from penetrating the building envelope. If a continuous soffit is desired from interior to exterior, a detail should be devised that accommodates continuity of air, vapor, and weather barriers. Refer to Figures 5.3 and 4.20 for example section details.

2.4 Mechanical, Electrical, and Plumbing Considerations

Services such as pipes, conduits, and cables in an NLT building are usually either suspended from the ceiling or contained within a raised floor system.

Where services are suspended and the NLT is supported on beams rather than load-bearing walls, the direction of service runs should be carefully considered. Service runs that are parallel to the beams allow for the most efficient use of space, because the services can be contained between the NLT soffit and the beam soffit. Where services must run perpendicular to the beams, they must either penetrate the beams or be routed beneath them. If penetration is required, coordinate carefully with the structural engineer. Where routing services beneath, floor-to-floor heights may be affected if a minimum overhead clearance is required.

Another strategy for suspended services is to create a service chase in the face of the NLT and then insert a cap once the conduit, piping, and/or cabling has been installed. Refer to Figure 2.15. This approach creates a concealed space. Refer to Section 3.4.5 for details on protecting concealed spaces.

Vertical distribution of services through NLT must be coordinated with the structural engineer to ensure any openings have a maximum diameter the width of two laminations. Larger openings must have additional reinforcing or framing for support. Refer to Section 4.4.2 for detailed framing requirements at openings. For both vertical and horizontal distribution of services, typical care must be exercised to isolate piping and ducts from the structure so as to avoid the transfer of noise generated by the flow of water, waste, or air.

When using NLT as walls, keep in mind that there is no wall cavity within which to route services after the fact. All pipes, conduit, cables, and so forth must be accounted for and accurately located during fabrication.

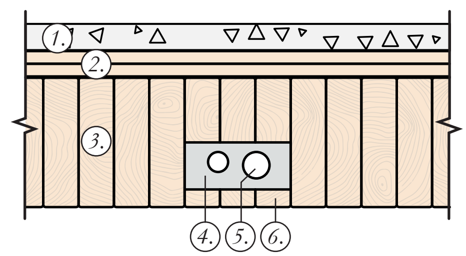


Figure 2.15: *Service chase in NLT.*

Key

1. *Concrete topping*
2. *Plywood/OSB*
3. *NLT*
4. *Gap for mechanical fire stopped as required*
5. *Mechanical services*
6. *Wood cover to hide services as required*

2.5 Acoustical Considerations

Acoustics is a complex field, and an expert should be consulted in the design of floor/ceiling and wall assemblies. This is particularly important for specialized spaces or spaces with low tolerances such as a performance or recording space. In general, the acoustic considerations for an NLT structure are the same as for any other structural system. Consider how sound reflects from the NLT surface and how sound passes through it.

Initial testing done by FPInnovations indicates that NLT performs in ways similar to CLT with respect to acoustics. Assemblies and values published in the CLT Handbook [1] can therefore be used as a starting point of reference for designers. Although their acoustic performance may be similar, unlike CLT, NLT typically has small gaps between laminations, which can provide flanking paths for sound to travel. The addition of plywood/OSB and/or a concrete topping over NLT may address this, by limiting passage of air and sound.

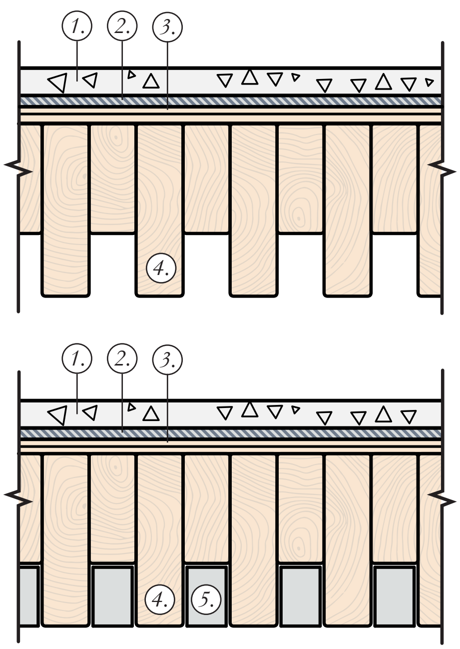


Figure 2.16: *Alternating 2x4 and 2x6 lumber with and without sound absorbing material.*

Key

1. *Concrete topping*
2. *Acoustic mat*
3. *Plywood/OSB*
4. *NLT*
5. *Sound absorbing material*

2.5.1 Interior Space Acoustics

An NLT surface is generally hard, flat, and smooth, making it inherently sound-reflecting, with properties similar to a concrete slab system. Where NLT is exposed, an uneven surface is required to diffuse reflection of sound waves. To create such a surface, use an alternating staggered cross section layup. To improve the sound absorption of the NLT, introduce openings or add a material with dissimilar acoustic properties. Refer to Figure 2.16 showing NLT made of alternating 2x4 and 2x6 dimension lumber with a strip of sound-absorbing material glued betweeen the deeper laminations. The surface of such an assembly is composed of 50% lumber and 50% sound-absorbing material, with a Noise Reduction Coefficient (NRC) approximately 50% of the NRC of solid wood, plus 50% of the NRC of the sound-absorbing material. However, given that the depth of the sound-absorbing material is limited, the actual overall value for the assembly is likely lower than this oversimplified calculation might indicate. Always consult an acoustics expert for project-specific advice.

2.5.2 Inter-Space Sound Control

Transfer of sound between adjacent spaces takes two forms. The first is the transfer of airborne sound such as speech or music. The ability for a building element such as wall or floor/ceiling to prevent the transfer of airborne sound is measured by Sound Transmission Class (STC) ratings. The second form is the transfer of impact sound such as footfall. The ability of a floor/

ceiling assembly to prevent the transfer of impact sound is measured by Impact Isolation Class (IIC) ratings. Designers should determine the most appropriate rating to satisfy codes, regulations, and owner requirements; indicative STC and IIC ratings are included in Table 2.2 for reference only.

Airborne Sound

Airborne sound can travel through NLT for two reasons. First, similar to other mass timber panel products, NLT does not have enough mass to mitigate airborne sound on its own. Also, because it is composed of linear elements which are fastened together mechanically, gaps often develop between the laminations as a result of minor swelling and shrinkage which penetrate the full depth of the NLT. Any gap through which air can pass is also a path for airborne sound. Accordingly, bare NLT without continuous plywood or OSB sheathing will not provide effective attenuation airborne sound.

Airborne sound also travels along NLT; the grooves on the surface provide potential paths for airborne sound. Pay special attention to interface details when using NLT. Where a wall running perpendicular to the laminations meets the underside or top-side of the NLT, an acoustic sealant should be applied between the NLT and the plates of the abutting wall to fill the gaps.

Impact Sound

Impact sound is often more disruptive than airborne sound. For example, if a residential building is constructed of concrete, an eight-inch slab will effectively block the sound of voices from the suite above, but the sharp reports of someone walking in hard-soled shoes will be clearly audible. Attenuation of impact sound is therefore typically what governs for a floor assembly. As with most structural floor systems, floor finish material can have a significant effect on an NLT floor assembly's IIC rating. For horizontal applications (floors and roofs), additional materials will typically be applied on top of the NLT, below it, or both.

As with all construction types, careful control of flanking paths is required. Field-tested ratings (FIIC and FSTC) are typically lower than those achieved in laboratories (IIC and STC).

Table 2.2 provides STC and IIC testing data completed for NLT floors. Included in the table for comparison is the acoustic performance of bare NLT (with plywood topping) and bare CLT. It is always important, however, to contextualize the results and the applications in which systems are typically used. For example, STC and IIC ratings are derived from 1/3 band octave data that occurs over a range of frequencies. In order to understand better the comparison of one assembly's acoustic performance to another, the differences over that entire range should be evaluated, keeping in mind what common frequencies occur in typical occupied spaces.

TABLE 2.2 STC AND IIC TESTING DATA COMPLETED FOR NLT FLOORS

	FLOOR ASSEMBLY (TOP TO BOTTOM)	STC	IIC
1	1/2 in. plywood + 2x6 NLT **(baseline measurement)**	34	32
2	Bare CLT (5-ply, 6-7/8 in. thick)	39	25
3	4 in. normal weight concrete topping + Pliteq GenieMat FF06 acoustical mat + 1/2 in. plywood + 2x6 NLT	51	44
4	Carpet + 4 in. normal weight concrete topping + Pliteq GenieMat FF06 acoustical mat + 1/2 in. plywood + 2x6 NLT	51	58
5	4 in. normal weight concrete topping + Pliteq GenieMat FF25 acoustical mat + 1/2 in. plywood + 2x6 NLT	54	50
6	4 in. normal weight concrete topping + Pliteq GenieMat FF50 acoustical mat + 1/2 in. plywood + 2x6 NLT	56	52
7	4 in. normal weight concrete topping + Pliteq GenieMat FF06 acoustical mat + 1/2 in. plywood + 2x6 NLT + RC + 5/8 in. Type C Gypsum	55	49
8	4 in. normal weight concrete topping + Pliteq GenieMat FF06 acoustical mat + 1/2 in. plywood + 2x6 NLT + Pliteq GenieClip RST Clip + R8 Fiberglass batts + 5/8 in. Type C Gypsum	60	59

While the industry builds a more complete database of tested assemblies for NLT, designers may opt to use other mass timber assembly tests as a guide to predict the performance of NLT. For example, there are a number of CLT acoustic assemblies listed in the CLT Handbook [1] as well as others available from acoustical mat product manufacturers; some provide STC/IIC values and some provide FSTC/FIIC values. If an NLT deck of a similar thickness was used in place of the CLT, the assembly performance could be estimated by subtracting three from either the STC/IIC or FSTC/FIIC values.

2.6 Durability Considerations

Durability considerations for any wood product also apply to NLT; ultraviolet (UV) light and moisture are primary concerns. Where NLT is exposed to UV light, its color will fade unless the wood is protected with a suitable coating. Coatings with higher pigment amounts typically resist UV longer than clear coatings. Consult manufacturers to assist with selecting coatings, and weather test options to help select the appropriate product. A continuous film coating applied to NLT after fabrication will likely develop cracks between laminations, causing the film to fail. A penetrating finish may not crack, but concealed faces of laminations will not be exposed to receive the coating.

Where wood is exposed to moisture, there is a significant risk of decay. Exposed end grain at the edges of NLT is most susceptible to moisture, leading to swelling and distortion of the laminations. However, moisture exposure on any part of the NLT, including moisture trapped between adjacent laminations or between laminations and sheathing, can have a significant impact on the durability and lifespan of the NLT. Enclosure elements must be designed to avoid trapped water and moisture build up. Refer to Chapter 5 for more on enclosure. Construction phase moisture must be managed through a moisture protection plan established in consultation with the design team. Unplanned moisture exposure during the construction phase can delay project schedules and negatively impact the quality of the work. Refer to Section 7.6 for more on construction phase moisture management.

References

[1] Karacabeyli, Erol, and Brad Douglas. 2013. *CLT handbook: Cross-laminated timber*. Pointe-Claire, Québec: FPInnovations

Above *Mountain Equipment Co-op Head Office, Vancouver, BC. Architecture: Proscenium Architecture+Interiors. (Photo credit: Ed White Photographics)*

3 Fire

This chapter provides guidance on using nail-laminated timber (NLT) in accordance with the 2015 International Building Code (IBC) and assumes a general level of familiarity with the IBC. Requirements for NLT floors and roofs are prescriptively incorporated into the IBC Type IV construction provisions; where wood assemblies are permitted in other construction types, NLT can also be used. Refer to the joint publication of the American Wood Council and the International Code Council entitled 2015 Code Conforming Wood Design [1] to learn more about where wood can be used in accordance with the IBC.

In This Chapter

3.1 Fire and Life Safety in Timber Buildings

The fire and life safety performance requirements of IBC Section 101.3 include:

- Safety to life;
- Safety to property; and
- Safety to fire fighters and emergency responders during emergency operations.

Methods to satisfy these performance requirements include:

- Compliance with prescriptive requirements;
- Approval of alternative means and methods; and
- Performance-based design.

Prescriptive requirements of the IBC are based on construction type, which are linked to use and occupancy classification, as well as building height and area. While NLT is listed as a prescriptive heavy timber assembly in Type IV construction, the perscriptive building code allows NLT in all types of construction, with the greatest flexibility for use in Type III, IV and Type V construction. Use of NLT is limited in Type I and II construction, as well as high-rise and underground buildings, and larger Institutional and High Hazard occupancies.

IBC Section 104.11 allows design flexibility beyond prescriptive requirements through alternative means and methods, which are intended to demonstrate to the Authority Having Jurisdiction (AHJ) that the fire and life safety objectives of the code are achieved. Alternatives could range in scope from specific details, such as addressing void spaces in Type IV construction, to a whole performance-based building design based on guidance documentation such as the ICC Performance Code for Buildings and Facilities (ICCPC) [2]. Refer to Section 3.4.7 for more on alternative means and methods and performance based design.

3.2 NLT in Type IV (Heavy Timber) Construction

IBC Section 602.4 describes Type IV construction as having exterior walls of noncombustible construction, having internal building elements of solid and/or laminated wood without concealed spaces, and meeting certain minimum size requirements. While NLT in a Type IV building is most often used in roofs, floors, and interior walls, two code exceptions permit combustible material in exterior walls:

- IBC Section 602.4.1, where fire retardant treated wood (FRTW) is used; or
- IBC Section 602.4.2, where cross laminated timber (CLT) is used and covered with FRTW sheathing, gypsum board or a noncombustible material.

These provisions can be applied to NLT in exterior walls, most directly when laminations are fire retardant treated, but also when approved as an alternative method equivalent to encapsulated CLT.

Additionally, the following prescriptive descriptions apply to NLT structural assemblies in Type IV construction:

IBC Section 602.4.6: Floors Without concealed spaces, planks not less than 4 in. nominal in width (this dimension refers to the depth of the plank/board which is the depth of the panel, in this case, set on edge close together, well-spiked, and covered with 1 in. nominal flooring or 15/32 in. wood structural panel sheathing). Refer to Figure 3.1.

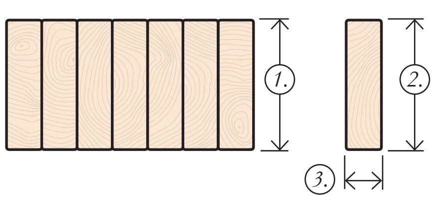


Figure 3.1: *Width and Depth Definitions for NLT in IBC Section 602.4.*

Key

1. *Panel Depth*
2. *Board Width*
3. *Board Thickness*

IBC Section 602.4.7: Roofs Without concealed spaces, planks not less than 3 in. nominal in width (this dimension refers to the depth of the plank/board which is the depth of the panel in this case), set on edge close together and laid as required for floors. Refer to Figure 3.1.

IBC Section 602.4.8.1: Interior walls and partitions Solid wood construction formed by not less than two layers of 1 in. matched boards, OR laminated construction of at least 4 in. depth (this is referring to panel depth as shown in Figure 3.1), or one hour fire-resistance-rated construction.

IBC Sections 602.4.1, 602.4.8.2 and 2303.2: Exterior walls NLT depth not less than 6 in. if pursuing a CLT equivalence OR constructed of fire-retardant-treated wood to comply as a non-combustible alternative.

3.3 NLT in Other Types of Construction

Besides Type IV buildings, NLT may be readily used in Type III and Type V construction, with limited applications in Types I and II construction.

Type III Construction

IBC Section 602.3 defines Type III construction as having exterior walls of noncombustible materials and interior systems of any type of construction allowed per code, including combustible and noncombustible materials. Type III may have light frame structural elements and concealed spaces, where fire resistance ratings are prescribed for building elements (walls, floors, roofs) in accordance with IBC Table 601. Refer to Section 3.3.1 for further discussion of fire resistance ratings.

IBC Table 601 further separates Type III construction into III-A and III-B, where:

- Type III-A is of fire resistance rated construction throughout; and
- Type III-B has fire resistance ratings for exterior walls.

For Type III construction, fire resistance ratings can be achieved via calculation as opposed to depth as in Type IV construction. In addition, Type III permits concealed spaces and can provide greater flexibility for use of exposed NLT, especially with non-rated building elements (III-B). Similar to the exception in Type IV construction, fire-retardant-treated wood is allowed in external wall assemblies with required fire-resistance ratings of up to two hours.

Type V Construction

While the typical Type V building is often light frame construction, IBC Section 602.5 indicates that Type V construction allows structural elements, exterior walls and interior walls to be constructed of any materials permitted by the code, including NLT.

IBC Table 601 further separates Type V construction into V-A and V-B, where:

- Type V-A is of fire resistance rated construction, and
- Type V-B does not require a fire resistance rating.

Accordingly, Type V-B provides greater flexibility for use of NLT.

Type I and Type II Construction

IBC Section 602.2 defines Type I and Type II as construction in which building elements consist of noncombustible materials.

While the use of combustible materials such as NLT is relatively limited in Type I and Type II construction, IBC Section 603.1 provides exceptions, which include:

- Fire-retardant-treated wood used in most roofs and non-loadbearing wall applications; and
- Heavy timber roof construction in a Type I-B or Type II building.

In applications where heavy timber is permitted, NLT is not required to be fire-retardant treated. NLT may also be used as permanent formwork for a concrete slab in a Type I or Type II building.

3.3.1 Fire Resistance Rating

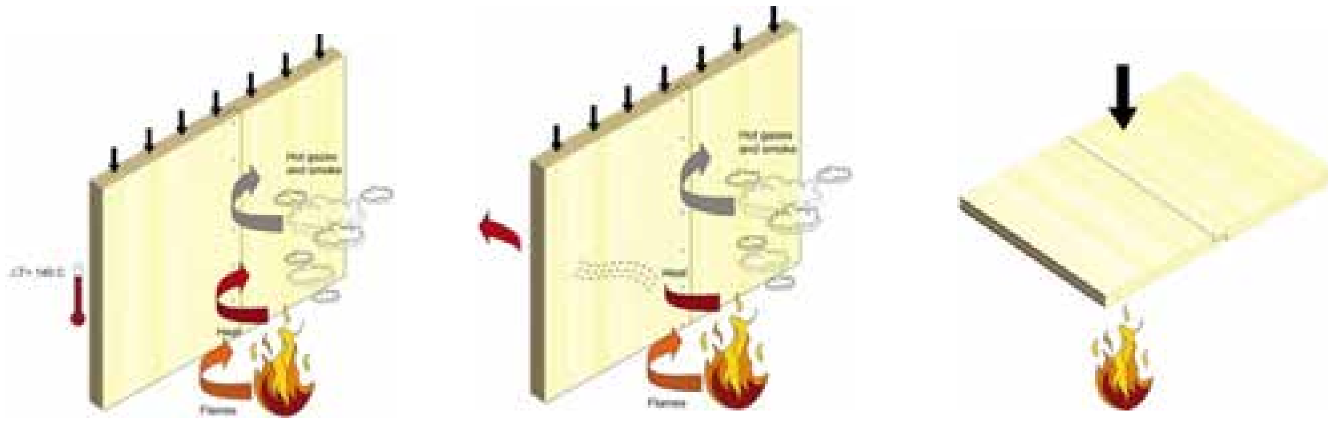
Fire resistance ratings are based on the following criteria, illustrated in Figure 3.2:

Structural stability: resistance of the assembly or member to structural collapse or exceedance of deformation limits.

Integrity: ability of the assembly to limit the spread of smoke or fire to the unexposed side.

Insulation: ability of the assembly to limit the rise of temperature on the unexposed side.

The applicable criterion to determine the fire resistance rating for a specific element or assembly depends on its intended purpose. For example, a



Structural Stability *Integrity* *Insulation*

Figure 3.2: *Functions of Fire Resistance. (Adapted from the CLT Handbook [3])*

structural column is expected to meet the stability criterion, but not integrity or insulation, as it is not a separating element. A structural floor or wall, acting as both a structural component and a fire separation, is required to meet all three criteria. NLT used in fire resistive applications are typically required to meet all three criteria.

There are two primary methods to determine a fire resistance rating:

Tested assemblies: Wood-framed floor systems that have been tested to the ASTM E119 [4] or UL 263 [5] standard fire and are listed in publications such as the UL Fire Resistance Directory [6] or the Gypsum Association Fire Resistance Design Manual [7] and are typically membrane-protected. A wood joist floor in these tested assemblies can easily be replaced by an NLT floor of equal depth (i.e. joists with zero spacing). Exposed NLT may have to use the alternate methods presented in 703.3 until more tested assemblies are available.

Calculated fire resistance: NLT systems that are shown to meet the minimum fire resistance ratings using prescribed calculations methods. IBC Section 722.1 references NDS Chapter 16 for calculating fire resistance of wood members. Additional information is also provided in the American Wood Council's TR-10 [8]. These methods are based on char behavior, discussed in Section 3.3.2.

Figure 3.3: *Wood Charring. (Photo courtesy of Holmes Fire)*

3.3.2 Char

The cross sectional dimensions of a wood element have a considerable impact on fire performance due to the development of char on the surface of a burning member, as shown in Figure 3.3. Charring occurs when wood is exposed to temperatures exceeding approximately 550°F (290°C) [8] and delays heating through the depth of the wood element. Extensive testing of wood exposed to the ASTM E119 standard fire test time-temperature curve has allowed char rates of wood to be predictably estimated under the standardized ASTM E119 exposure [9], [10], [11]. Both charred and uncharred wood act as a good insulator to delay heating of unexposed wood.

NLT has an inherent fire resistance due to its thickness, and is recognized as a heavy timber element in the building code as defined in Type IV construction, which does not require fire resistance calculations. Where NLT is used in other construction types, fire resistance calculations can be used to determine the structural stability of elements exposed to the ASTM E119 standard fire for the required fire resistance period. This process involves calculating the char rate, determining the char depth, and evaluating the loadbearing capacity of the remaining structural element.

Calculated Char Rate

The char rate is the speed at which solid wood burns and creates char through the depth of a wood member. It is expressed in units of length divided by time:

Char rate = char depth [inches] / time [hours]

The char rate can be expressed as a nominal or an effective value, and is generally consistent between types and species of wood. NDS Chapter 16 defines the nominal char rate based on a 1-hour fire ASTM E119 standard fire exposure as 1.5 in./hour.

The effective char rate is calculated by adjusting the nominal char rate to account for the following:

- Delayed heating over the fire duration due to the insulating properties of char;
- Loss of strength and stiffness in the elevated temperature zone ahead of the char layer; and
- Rounding at the corners where two-dimensional charring occurs (Arris rounding)

The effective char rate is calculated per NDS Chapter 16 and ranges from approximately 1.8 in./hour for one hour exposure to 1.58 in./hour for two hour ASTM E119 standard fire exposure.

NDS and TR10 provide additional fire design guidance regarding the application of nominal and effective char rates.

Calculated Effective Char Depth

The effective char depth is the distance that the char layer has progressed through the wood cross section after the required fire resistance duration:

Effective char depth = Effective char rate [in./hour] * fire exposure duration [hours]

The effective char depth represents only the volume of wood that has charred or heated; this wood is assumed to have no mechanical strength. The effective char depth should be applied to all surfaces that are expected to be directly exposed to fire. The resulting “cold” wood below the char is assumed to maintain full strength and is used to evaluate structural stability. Refer to Figure 3.4, and to Chapter 4 for evaluation of the residual capacity of the remaining structural element(s).

Figure 3.4: *Representative Example of Effective Depth. Photo adapted from the CLT Handbook [3]*

Key

1. *Residual Section*
2. *Calculated Charring Line*
3. *Calculated Depth of Charring*
4. *Profile of Orignal Section*
5. *Radius of Arris Rounding*

Topping Continuity and Char Behavior

Where fire resistance rated construction is required, the topping used over NLT may have a considerable impact on char behavior and resulting fire resistance, as shown in Figure 3.5. Existing documentation suggests where hot gases pass between NLT laminations, bi-directional char may occur [12], i.e. char may occur on the sides of the individual laminations as well as the bottom. Where NLT is provided with a monolithic topping layer such as concrete, gypsum or similar, char behavior has been shown to be primarily uni-directional, limited to the exposed bottom surface in one direction, as airflow is restricted through the structural assembly.

3.4 Additional Considerations

Additional fire-related considerations and their impact on NLT assemblies and buildings are provided in this section.

3.4.1 Active and Passive Fire Protection

For code-compliant NLT systems, active fire protection measures (such as automatic sprinklers or smoke detection systems) will generally be the same as for non-combustible buildings; passive fire protection measures may be required based on design features such as the building height and area, number of occupants, and occupancy type. Incorporating active fire protection systems allows greater flexibility for creative, passive protection of NLT systems.

Active Protection

An active fire protection system is often referred to as the 'first line of defense' in a building's fire-protection approach. Common examples include automatic sprinkler and smoke detection systems. These types of systems are typically required for all residential occupancies and larger buildings. The installation of an automatic sprinkler system reduces the finish requirements, and can sometimes reduce the fire resistance rating, due to the increased safety afforded by the active protection.

Passive Protection

Passive protection is provided for loadbearing building elements of structure such as walls, floors, and roofs to control the spread of fire, mitigate the risk of exposure for occupants, and provide structural stability. In combustible buildings, a common passive strategy is to apply a non-combustible membrane protection over combustible elements of structure, often referred to as encapsulation.

Passive protection systems are designed as integral elements of the building, protecting both structural and non-structural elements, including their connections, as discussed in Section 3.4.3. The extent of passive fire protection is generally expressed in terms of an hourly fire resistance rating; where required resistance ratings typically increase for larger and taller structures.

In addition to fire resistance for structural elements, passive protection is also used to control the spread of fire and smoke at penetrations and openings, as discussed in Section 3.4.4.

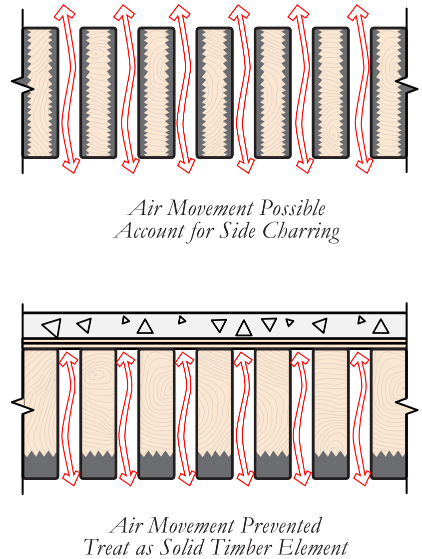


Figure 3.5: *Air Movement Through NLT*

3.4.2 Fire Spread and Smoke Development

To control the risk of fire spread and smoke development at early stages in a fire, the building code regulates the materials and finish surfaces that can be used in different buildings based on occupancy classification and installation of sprinkler protection. Limitations on finishes are intended to delay ignition and flame spread, to mitigate the risks of untenable conditions and flashover. For exposed NLT (acting as both structure and finish), finish classification requirements may apply in addition to fire resistance requirements.

Finish material classifications are evaluated based on testing in accordance with ASTM E841 [13] to determine flame spread ratings, which are divided into Classes A, B, and C. Class A is the highest rating with the least amount of flame spread, and Class C is the lowest permitted rating. The smoke-developed index must be 450 or less for all classifications.

Most softwood species achieve a Class B rating, which is generally permitted in sprinkler-protected buildings. Refer to IBC Table 803.11 for interior finish requirements. For NLT, the species of wood used will determine the appropriate flame spread rating, and in some cases, may provide a better (Class A) or worse (Class C) rating. The American Wood Council publishes a list of reported flame spread ratings that distinguishes between various species of wood [14]. Note that the code allows a relaxation in required rating where automatic sprinkler systems are installed.

In accordance with IBC Section 803.3, exposed portions of heavy timber elements in Type IV construction are not required to meet interior finish requirements.

3.4.3 Connections

Where the building code requires a fire resistance rating for elements of the structure, vertical-load-resisting (i.e. gravity) connections are required to be protected to the rating of the elements they connect. The NDS requires connectors and fasteners for exposed wood structural members to be protected from fire exposure for the required fire resistance time using additional wood, gypsum board, or other approved materials [15].

Any connection where a steel plate, fastener, or portion of the wood member in the connection is exposed to fire or elevated temperatures should be evaluated for strength loss, and the results reviewed with the AHJ. In such cases, fire protection could be approved using an alternative means and methods assessment, discussed in Section 3.4.7.

Applied protection for NLT connections may not be necessary. Fasteners between laminations or between prefabricated panels are considered to be protected by adjacent laminations, and NLT gravity loads are often transferred to supports through direct bearing rather than through fasteners. In some cases, where connection failure will not cause collapse, protection of the connection may not be required. For example, connections associated only with the lateral load path are not required to be fire rated.

Additional information on the fire performance of connections is provided in the following resources:

- NDS Chapter 16
- TR 10 - Calculating the Fire Resistance of Exposed Wood Members [8]
- Fire Safety Design of Mid-Rise Timber Buildings, Wood Solutions [16]

3.4.4 Penetrations

Modern buildings typically contain an array of services which penetrate fire-rated elements of the structure such as walls, floors and shafts. Where penetrations exist in fire resistance rated construction, the IBC requires them to be protected with through-penetration or other systems installed as tested in an approved fire resistance rated assembly. More commonly, the code alternative to a tested assembly is the use of an approved fire-stop system tested to ASTM E814 [17] or UL 1479 [18]. For wood construction in general, fire testing has shown the importance of insulating the wood from metal penetrations, as hot metal can cause unpredictable charring and allow passage of hot gasses and smoke [19].

For NLT specifically, fire-stopping guidance is relatively limited, but engineered alternatives can be developed from available CLT testing. For example, an engineered alternative for metal pipe penetrations of 5 in. to 8 in. thick could be proposed on the basis these have been tested and approved for CLT insulated by 1 in. of mineral wool. Additional listings for fire-stopping are expected for CLT in the near future. Refer to the CLT Handbook [3] for additional details on penetration protection. Joints built into NLT to accommodate swelling during construction, as discussed in Chapter 4, should be fire stopped.

3.4.5 Concealed Spaces

As indicated in Section 3.2, the IBC specifically prohibits concealed spaces in Type IV construction. While NLT assemblies may not typically include voids or concealed spaces, concealed spaces are likely to exist where NLT is used with dropped ceilings, furred walls, or raised floors. Accordingly, the presence of a concealed space in Type IV construction can often complicate the design and additional protection should be considered.

In general, concealed spaces require sprinkler protection under the following conditions, as outlined by NFPA 13 [20], unless an engineered alternative solution is approved:

- When sprinkler protection is required per code (based on the height, area, number of stories, fire resistance requirement, etc.); or
- When a cavity does not contain fire-blocked or draft-stopped space to a volume of 160 ft^3 or less.

Notable exceptions include:

- Certain residential buildings where NFPA 13R [21] is the permitted sprinkler standard; and
- Where fire stop is equal to material used in NLT.

To address concealed spaces not permitted by the prescriptive code, the AHJ must approve an alternative solution to achieve equivalent fire performance. Potential strategies could include installation of an approved sprinkler system within the space, filling the space with noncombustible insulation, or lining the space with gypsum wallboard.

3.4.6 Exposed Wood Surfaces

IBC Section 803.3 allows exposed wood surfaces for Type IV construction. Where combustible material is permitted for other construction types, exposed wood construction is allowed as long as the proper fire resistance rating and interior finish requirements are met. See previous discussions in Sections 3.3.1 and 3.4.2.

Where the code restricts exposed wood surfaces, such as in Types I and II construction, alternative means and methods may be proposed to justify exposure of wood surfaces within a fire compartment. A successful strategy may demonstrate an equivalent level of safety with a limited amount of exposed wood for a given compartment, including demonstrating that NLT is self-protecting based on the depth of solid wood.

3.4.7 Alternative Means and Methods and Performance-Based Design

Where NLT conforms to the prescriptive requirements of the IBC, such as for Type IV and Type V construction, the approvals process is usually simple. Generally, the more familiar the AHJ is with wood and heavy timber construction, the simpler the approvals process will be, keeping in mind familiarity with wood construction may vary widely with geography.

Designers are increasingly using NLT in modern buildings beyond prescriptive parameters; IBC Section 104.11 provides a mechanism for code approval through alternative means and methods and performance-based design. This provision reflects the intent of the code to not prohibit materials, design approaches or construction methods not covered by prescriptive requirements.

Figure 3.6: *Example of exposed wood structure at T3, Minneapolis, MN. Architecture: Michael Green Architecture. (Photo courtesy of StructureCraft Builders Inc.)*

Alternative Means and Methods

In general, an “alternative means and methods” approval is a compliance strategy which would permit a material, design, or method of construction, that is not specifically prescribed by the code, to still be used in accordance with the requirements of Section 104.11.

Section 104.11 states that the code is intended to allow the installation of any material or use of any method of construction not specifically prescribed by the code, as long as it can be shown that the use of the material or method can be done in such a way as to provide equivalent safety. This strategy often involves working with a building authority to identify a potentially non-compliant condition, and demonstrate that the intent of the code is achieved through the use of the desired material or method, along with other protective features that may offset the potential non-compliance. For example, where Type IV construction prohibits void spaces, early discussion with the AHJ on the need for such spaces, including the proposed approach to provide acceptable performance (e.g. through the use of sprinkler protection, filling with noncombustible insulation or other methods) may be valuable.

Designers may consider enhancing certain fire safety features of a building in order to use NLT where it may not be prescribed by the code, such as in

Type I or II construction. Such an enhancement could involve providing protection for the NLT in the form of covering or additional fire resistance. Code officials may choose to approve other building safety "trade-offs" if it is determined that overall fire safety is not diminished, such as:

- Installation of a sprinkler system that may not be otherwise required (i.e. an enhanced system);
- Enhanced fire resistance for structural elements;
- Enhanced compartmentalization within the building;
- Enhanced protection for exit enclosures; and
- Advanced analysis to demonstrate safety and/or robustness.

Performance-Based Design

Within the IBC, performance-based designs can be proposed as one method to achieve the intent of the code through alternative means and methods. Performance-based design is an engineering approach based on agreed performance goals and objectives, engineering analysis, and assessment of alternatives against design goals and objectives using accepted engineering tools, methodology and performance criteria. It often involves a third-party peer review and will require approval from the AHJ. It is a comprehensive approach to building safety, and where permitted by the code official, code officials should be engaged early in the design process.

While performance-based design for NLT is currently uncommon in the U.S., the principles and features of such an approach may be helpful to designers and code officials when considering when alternative means and methods approaches in general.

Examples of performance-based design guidance [22] include the following:

- ICC Performance Based Code [25]
- International Fire Engineering Guidelines [23]
- National Performance Based Design Guide [24]
- SFPE Engineering Guide to Performance Based Fire Protection Analysis and Design of Buildings[25], [26]

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Above *Mountain Equipment Co-op Head Office. Vancouver, BC. Architecture: Proscenium Architecture+Interiors. (Photo credit: Ed White Photographics)*

Above *East Village Presentation Centre, Calgary AB. Architecture: James KM Cheng Architects (Photo courtesy of StructureCraft Builders Inc.)*

4 Structure

Nail-laminated timber (NLT) is a system that spans in one direction to resist out-of-plane loading. Although its monolithic nature makes it a mass timber system rather than a joist system, it can be conceptualized structurally as dimension lumber joists spaced at the joist width (e.g. for 2x material, joists spaced at 1-1/2 in.). NLT can consist of any species, grade, and size of dimension lumber. Floors and roofs are typically sheathed on the top side with plywood or OSB to carry in-plane shear caused by lateral loads. The strength and serviceability of the NLT for both gravity and lateral loads must meet the minimum requirements of applicable codes and standards. Given timber's high strength-to-weight ratio, serviceability requirements such as deflections and vibrations often govern the design of NLT floors. Designing for fire resistance may also be a governing factor.

IN THIS CHAPTER

4.1 Gravity Design Procedures

To design for gravity loads, treat NLT as a built-up beam as shown in Figure 4.1. Follow the provisions in the National Design Specification for Wood Construction (NDS). Where NLT contains butt-jointed laminations, additional adjustment factors are required beyond those given in the NDS.

Although the NDS does not address vibrations, this serviceability limit state can govern the design and should be checked when NLT is used for floors or occupied roofs.

Where NLT is exposed and required to meet certain fire ratings, determine post-fire capacities in accordance with NDS Chapter 16.

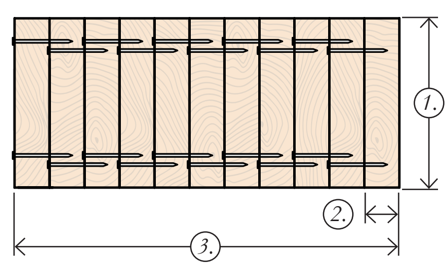


Figure 4.1: *NLT Cross Section*

Key

1. *NLT depth (d)*
2. *Lamination thickness (b_{lam})*
3. *NLT panel width (b)*

4.1.1 NDS Adjustment Factors

Use adjustment factors for the design of NLT from NDS Chapter 4. Factors that require clarification for NLT in lieu of individual sawn lumber joists are discussed in this section. Apply the remaining adjustment factors directly per the NDS provisions.

Beam Stability Factor (C_L)

Use a beam stability factor of 1.0 except in rare cases where edge conditions or large openings may create narrow sections of NLT with only a few laminations.

Size Factor (C_F)

Develop the size factor based on the individual lamination thickness (b_{lam}), analogous to the typical design approach for built-up sawn lumber members.

Repetitive Member Factor (C_r)

NLT is similar to decking; use a repetitive member factor of 1.15.

4.1.2 Additional Adjustment Factors

Additional adjustment factors are required in cases where NLT laminations are butt jointed in between supports and/or NLT is fabricated from laminations of varying depths.

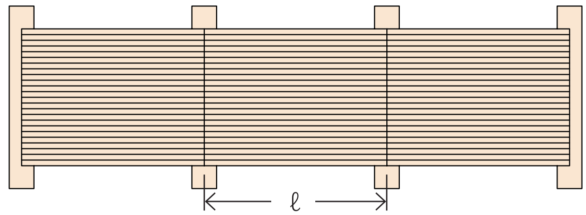
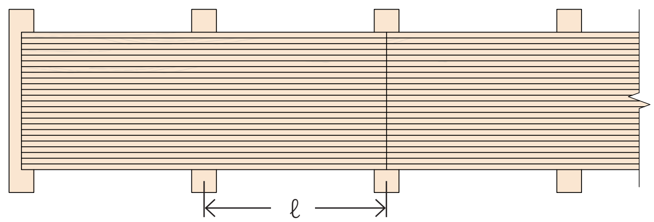
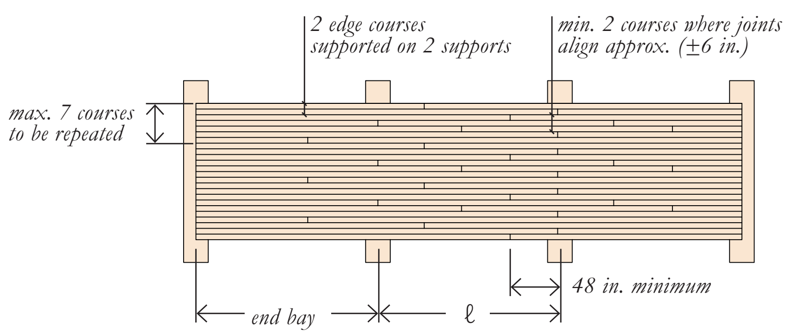
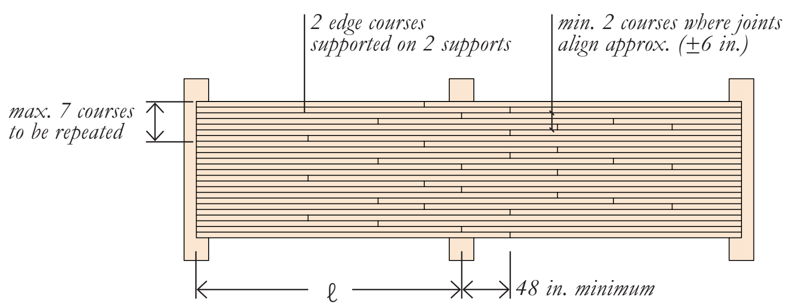
Layup Factor (K_{layup})

Butt jointing laminations between supports is a common approach to reduce the cost of NLT, because it permits use of a variety of lumber lengths. However, these modified layups result in reduced strength and stiffness that must be accounted for in design.

Table 4.1 provides a number of layup types and the associated adjustment factors for bending strength and stiffness. These factors provide a simplified way to account for stress redistribution between the laminations. Some have been derived based on IBC Table 2306.1.4; others are based on European research [1], [2], [3].

Above *Chilliwack Secondary School, Chilliwack, BC. Architecture: Dialog. (Photo courtesy of StructureCraft Builders, Inc.)*

TABLE 4.1: NLT LAYUP TYPES AND ADJUSTMENT FACTORS

<table>
<tr><th colspan="2">LAYUP TYPE</th></tr>
<tr><td>Laminations continuous and single span</td><td>
</td></tr>
<tr><td>Laminations continuous and multi-span</td><td>
</td></tr>
<tr><td>Laminations with controlled random butt joints over 4 or more supports</td><td>
</td></tr>
<tr><td>Laminations with controlled random butt joints over fewer than 4 supports</td><td>
</td></tr>
</table>

ADJUSTMENT FACTOR		NOTES
Bending Strength ($K_{layup.b}$)	**Stiffness ($K_{layup.E}$)**	
$K_{layup.b} = 1.0$ $M = \frac{w\ell^2}{8}$	$K_{layup.E} = 1.0$ $\Delta = \frac{5w\ell^4}{384E\,(d^3/12)}$	Maximum strength for a given depth. Typical maximum length for laminations of 16 to 20 feet. Longer laminations can be fabricated with structural finger joints (certified exterior joints or certified end joints).
$K_{layup.b} = 1.0$ $M = \frac{w\ell^2}{8}$	$K_{layup.E} = 1.0$ $\Delta = \frac{w\ell^4}{185E\,(d^3/12)}$	Maximum strength and stiffness for a given depth. Typical maximum length for laminations of 16 to 20 feet. Longer laminations can be fabricated with structural finger joints (certified exterior joints or certified end joints).
$K_{layup.b} = 0.67$ $M = 0.10w\ell^2$	$K_{layup.E} = 0.69$ $\Delta = \frac{0.0069w\ell^4}{E\,(d^3/12)}$	Maximum stiffness for a butt-jointed system. Rules for joint locations are given in IBC 2304.9.2.5 and 2304.9.3.3, and illustrated in the adjacent figure.
$K_{layup.b}=0.202\frac{(\ell/d)^{1/4}}{s^{1/9}}$ $M = \frac{w\ell^2}{8}$ $K_{layup.E}=0.0436\frac{(\ell/d)^{9/10}}{s^{1/5}}$	for single span: $\Delta = \frac{5w\ell^4}{384E\,(d^3/12)}$ for double span: $\Delta = \frac{w\ell^4}{185E\,(d^3/12)}$	Based on European research, rules for joint locations per IBC should be amended as follows: • Where butt joints occur in the same general line (±6 in.), they must be separated by a minimum of three intervening laminations. • Each lamination must extend over a minimum of one support. • See Section 4.3.1 for minimum nailing requirements.

Where:

d = NLT depth

E = modulus of elasticity

ℓ = span

s = nail spacing in direction of span, in inches

w = uniformly distributed line load

Use consistent units, except where specific units are noted

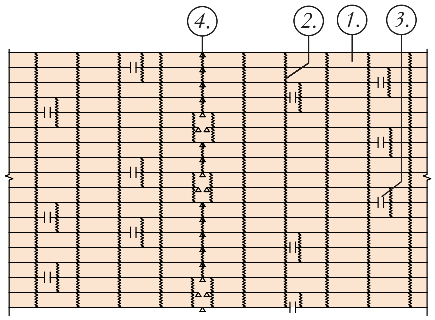


Figure 4.2: *Grillage Model*

Key

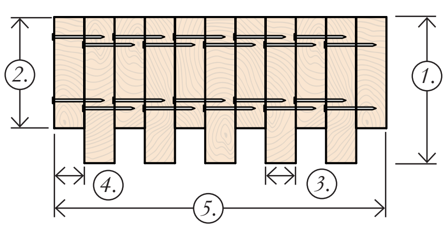
1. *NLT lamination (modeled as beam element)*
2. *Spring between lams representing nails (model stiffness to match nail shear behavior)*
3. *Break in lamination at butt joint (modeled without connection to lam within the course)*
4. *Support location (modeled as pinned supports at each lam)*

Additional layup types are also possible; options such as combination simple/two-span and mixed cantilever are described in IBC 2304.9.2. For these layups and others not addressed here, or where the requirements noted are not met, appropriate adjustment factors can be developed through a finite element analysis using a grillage model. Figure 4.2 is an illustration of a grillage model, where the laminations, modeled as beam members, are connected with shear springs representing the nails. For more detail on the development of this kind of model, including appropriate nail spring stiffness values, refer to Kramer [1], Kramer [2] and Haller [3].

Cross Section Factor ($K_{section}$)

Staggered NLT cross sections, as illustrated in Figure 4.3, can be used for architectural or acoustic effect or to accommodate finish requirements, as discussed in Chapter 2. In some cases they can also be used to accommodate venting as discussed in Chapter 5.

For these cross sections, the variation in depth of the laminations is more structurally complex than it initially appears. The nails do not provide sufficient stiffness to create a fully composite system with all laminations reaching their maximum bending capacity. Summing the capacity of all the laminations (deep and shallow) is therefore not conservative. Instead, when the deeper lams reach their full capacity, only a portion of the shallower lams' strength is engaged, based on their relative stiffnesses. The section strength and stiffness can be determined based on flat NLT of full depth (d_1) modified in accordance with Table 4.2. For NLT using more than two lamination depths, the shallowest laminations, with the smallest contribution, can be ignored, or a similar approach based on relative stiffnesses can be developed.



$$x_i = \frac{n_i b_{lam\,i}}{b_{panel}}$$

Figure 4.3: *Staggered NLT Cross Section*

Key

1. *NLT deep lamination depth (d_1)*
2. *NLT shallow lamination depth (d_2)*
3. *NLT deep lamination thickness (b_{lam1})*
4. *NLT shallow lamination thickness (b_{lam2})*
5. *NLT panel width (b)*
6. *Ratio of lamination depths (x_i), where n_i = the number of laminations of depth d_i*

TABLE 4.2 STAGGERED NLT ADJUSTMENT FACTORS

STIFFNESS ($K_{section.E}$)	BENDING ($K_{section.b}$)	SHEAR ($K_{section.v}$)
$K_{section.E} = X_1 + X_2 \left[\frac{d_2}{d_1}\right]^3$	$K_{section.b} = X_1 + X_2 \left[\frac{d_2}{d_1}\right]^3$	$K_{section.v} = X_1$

Note that $K_{section}$ is always less than 1.0 for staggered NLT and is intended to modify stress and stiffness calculations based on the deeper laminations (i.e. flat NLT with a constant depth of "d_1").

The factor provided for shear strength is simplified to account only for the deeper laminations. This approach is conservative, but shear rarely governs the design.

4.1.3 Strength

Strength design of NLT floors and roofs is based on NDS provisions for flexure, shear, and bearing.

Flexure

Design NLT for flexure using NDS provisions, ensuring the applied bending stress (f_b) is less than the bending capacity ($F_{b.NLT}$'). Calculate the applied bending stress in the NLT assuming linear elastic behavior per NDS Section 3.3, with peak stresses occurring at the extreme fibers of the NLT section. Determine the bending capacity by calculating the individual lamination capacity (F_b') according to NDS Section 4.3 and then modifying by additional factors to account for layup type (K_{layup}) and cross section type ($K_{section}$) as described in Section 4.1.2. Refer to Table 4.3 for NDS equations with additional factors.

TABLE 4.3 BENDING DESIGN EQUATIONS

NLT STRESS	NLT CAPACITY
$f_b = \frac{6M}{b_{panel} d^2}$	$F_{b.NLT}' = F_b' K_{layup.b} K_{section.b}$

Shear

Shear rarely governs the design of uniformly loaded NLT, but a review of the design approach is provided for completeness. Design NLT for vertical shear using NDS provisions, ensuring the applied shear stress (f_v) is less than the shear capacity ($F_{v.NLT}$'). Calculate the shear stress in the NLT assuming linear elastic behavior, with the maximum stress occurring at the centroid of the NLT depth in accordance with NDS Section 3.4. For shear design of NLT with controlled random butt joints, calculate shear at interior supports as if all laminations are continuous multi-span, calculate shear at exterior supports as if all laminations are single-span. Determine the shear capacity by calculating the individual lamination capacity (F_v') according to NDS Section 4.3 and then modifying by additional factors to account for cross section type ($K_{section}$) as described in Section 4.1.2. Refer to Table 4.4 for NDS equations with additional factors.

TABLE 4.4 SHEAR DESIGN EQUATIONS

NLT STRESS	NLT CAPACITY
$f_v = \frac{3V}{2b_{panel} d}$	$F_{v.NLT}' = F_v' K_{section.v}$

Bearing

Bearing rarely governs the design of uniformly loaded NLT. Design NLT for perpendicular-to-grain bearing using NDS provisions, ensuring the applied bearing load is less than the bearing capacity of the NLT. For NLT with a staggered cross section that requires a fire rating, consider blocking within the gaps where bearing occurs to address char on the top side of the support.

4.1.4 Deflection

Analyze NLT deflections using a simplified beam analogy, and compare the results to code-prescribed and/or project-specific limits. Base stiffness properties on NDS reference values, modified in accordance with NDS adjustment factors and additional factors described in Section 4.1.2.

$$EI = E_{NLT}'\,I = E'\,K_{layup.E}K_{section.E}\,\frac{b_{panel}d^3}{12}$$

Long-term Loading

Creep deflections from long-term loading are an important consideration for the design of any wood member, as they can easily exceed short-term elastic deflection values. The NDS addresses long-term loading in Section 3.5.2 and provides further discussion in Appendix F.

Moisture Service Condition

Use NLT only in dry service conditions as defined in NDS Section 4.1.4. Wet service conditions will create problems with durability and will impact strength properties and long-term deflections. Examples of dry service conditions may include wood that is exposed to the atmosphere but sheltered from direct rain exposure.

Even if NLT is detailed for dry service conditions, the wood may still be exposed to moisture during construction, particularly if moisture is not well-managed on site and the NLT is not allowed to dry after rain exposure. If the NLT becomes wet, consider measures such as temporary shores to control creep deflections that may occur, particularly in deflection-sensitive areas such as cantilevers. In cases where creep during construction has already occurred, take particular care with concrete topping slabs for the following reasons:

Concrete Ponding: Creep deformations developed prior to casting the topping will result in ponding effects if the topping is poured to a fixed elevation rather than a constant thickness.

Desorption: The topping prevents moisture evaporation from the top surface of the NLT, reducing the drying rate of the NLT.

Increased Creep Loading: The concrete topping is a long-term load which will increase the creep deflections.

Refer to Chapter 7 for more on moisture control during construction.

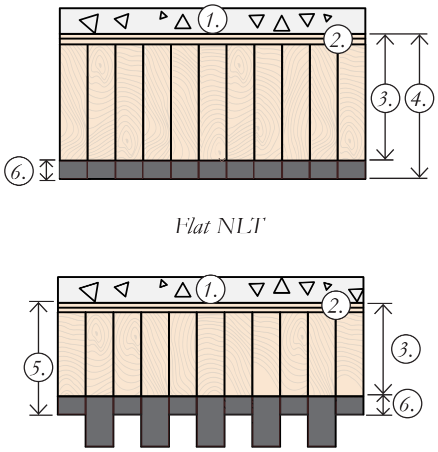
4.1.5 Vibration

Because of NLT's high strength-to-weight ratio, vibrations become more likely to govern floor design as spans increase. The stiffness of an NLT floor with butt-jointed laminations should be calculated as discussed in Section 4.1.2. Beyond this modification, basic vibration design procedures for NLT are based on loads, mass, damping, and stiffness, similar to any other type of floor system. Discuss vibrations early in the project to determine the end users' expectations and set appropriate design criteria. Limits on vibrations can vary widely, because occupancy and individual sensitivity to vibration impact what a person views as "acceptable."

Vibration-controlled floor spans have historically been designed using simple approximations such as upper limits on elastic live load deflection (e.g. L/480 or L/600) or lower limits on the fundamental frequency of the floor system (e.g. 6 Hz or 8 Hz). The typical span ranges given in Table 2.1 also factor vibrations into account for occupancies that are not especially vibration sensitive, such as offices. These rules of thumb and span ranges are useful for preliminary design but should not be relied on exclusively. In some cases, these guidelines may be too stringent, and in others they may be insufficient.

For any NLT floor with potential vibration concerns, perform a detailed design by calculating maximum accelerations, which are a better performance measure than deflections or frequencies. Pay particular attention to structural supports and their effect on the overall performance of the floor. For example, NLT supported on walls will perform better than NLT with the same span supported on beams, because the beam will also contribute to vibrations. Non-structural components such as floor build-ups and partition walls can also have a major influence on performance because of their effects on mass, stiffness, and damping. In the absence of more specific information, assume a damping value in the range of 2% to 4% for bare NLT.

AISC's design guide on vibrations of steel-framed structures provides a useful overview, and most of the content can be applied directly to NLT systems by using the appropriate stiffness values in the equations [4]. ISO 10137 [5] provides additional recommendations.



Staggered NLT

Figure 4.4: *Charred NLT Cross Section*

Key

1. *Continuous air barrier such as concrete topping*
2. *Plywood/OSB diaphragm sheathing*
3. *Remaining NLT depth (d_{fire})*
4. *Initial flat NLT depth (d)*
5. *Intial staggered NLT depth of shallower lams (d_2)*
6. *Char Depth (a_{char})*

4.1.6 Fire Design

As described in Chapter 3, NLT with an exposed surface can be designed to meet fire resistance ratings by allowing the wood to char, which occurs at a predictable rate. The char layer will develop on any exposed surface, effectively reducing the member size. This remaining NLT member is then checked for strength using a similar procedure to the base design. (Serviceability checks are not required.) Because NLT is often governed by deflections or vibrations, the overall depth may not need to increase in order to achieve a certain fire resistance rating.

After determining the depth of char as described in Chapter 3, perform strength and stability checks using the revised section depth and adjusted capacities to determine the remaining capacity of NLT. Compare this capacity to the imposed stresses determined with applicable load combination(s). Although fire is an "extraordinary event" in accordance with ASCE 7, the load combinations given in ASCE 7 Section 2.5 for LRFD cannot be used in conjunction with NDS Chapter 16 calculation procedures, which determine ASD structural fire resistances. For ASD fire design, use full service loads (1.0D + 1.0L).

The ASD strength design provisions of NDS Chapter 16 include a "design stress to member strength" factor ranging from 2.03 to 2.85. This factor converts the NDS reference design strength (F_b, F_c, etc), which is based on a 95% non-exceedance, to an average ultimate strength. The average ultimate strength is used to predict fire resistance for the required ASTM E119 fire exposure. If LRFD design is preferred, adjustments in accordance with ASTM E119 Appendix A can be used to provide equivalent structural fire resistance.

The layup factor for bending strength ($K_{layup,b}$) described in Section 4.1.2 is still applicable for NLT with butt-jointed laminations in the fire case. The cross section factor ($K_{section,b}$) need not be applied for staggered NLT cross sections in the fire case. The post-fire section is based on the char depth occurring on the shallowest lams as illustrated in Figure 4.4. This simplified approach accounts for the char that occurs on three sides for the portion of the deeper lams projecting below the shallower lams.

If the NLT is supported on an exposed wood member, such as a glued-laminated beam, check bearing based on the reduced bearing length of the NLT as shown in Figure 4.5.

4.2 Lateral Design Procedures

NLT is typically used in floor and roof applications; lateral design for NLT is therefore often limited to providing diaphragm action. Though less common, NLT can also be used for shear walls. In both cases, a separate layer of structure takes in-plane shear loads. Design shear walls and diaphragms based on the Special Design Provisions for Wind and Seismic (SDPWS), with additional guidance provided in the following sections.

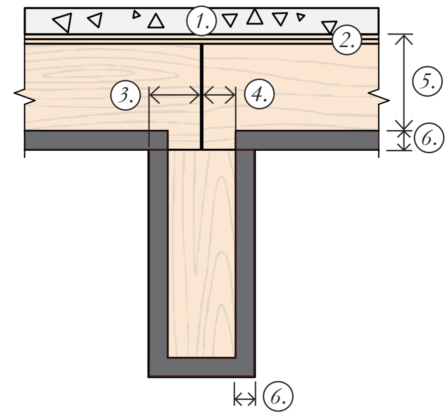


Figure 4.5: *Bearing Reduction where Supported on Exposed Charred Timber Beam*

Key

1. *Topping*
2. *Plywood/OSB diaphragm sheathing*
3. *Initial bearing length (l_b)*
4. *Remaining bearing length ($l_{b,fire}$)*
5. *Remaining NLT depth (d_{fire})*
6. *Effective char depth (a_{char})*

4.2.1 Diaphragms

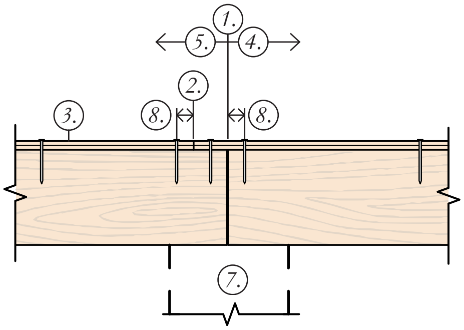
In-plane load transfer across lamination joints is not well researched, nor is the contribution of those joints to the in-plane shear and bending stiffness of NLT. Relying on diaphragm capacities given in the SDPWS for a fully blocked plywood/OSB diaphragm is an appropriate, conservative approach. The SDPWS also recognizes lumber diaphragms, with the lumber applied either diagonally or perpendicular to the NLT span direction. This system is more common in historic structures and is not addressed here.

Where over-framing or an inverted staggered cross section is provided to accommodate venting as discussed in Chapter 5 the connection between the plywood/OSB diaphragm and the NLT is provided in only one direction, and the diaphragm should be designed as unblocked. Where additional blocking between the staggered lams or the over-framing is provided, a fully blocked diaphragm design is appropriate. Ensure continuity of the load path between the diaphragm and the vertical lateral-resisting elements.

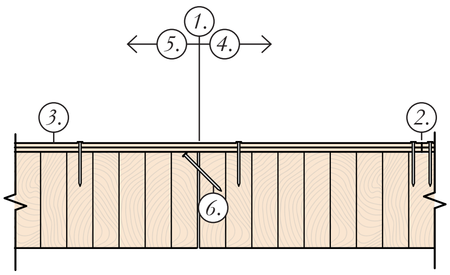
Distributing shear to the vertical lateral-resisting elements is more complex than for typical joist floors. The connections between laminations likely create a stiffer diaphragm than a typical plywood/OSB diaphragm, but calculating a semi-rigid diaphragm stiffness is difficult to do accurately; the analysis will be highly sensitive to assumptions about nail stiffness and load transfer between laminations. A simplified approach to determine load distribution is to perform two separate analyses, one assuming flexible diaphragms and one assuming rigid diaphragms. A full envelope design (taking the worst case from both analyses) may be overly conservative; use engineering judgment to determine final design forces.

Plywood/OSB

Follow the approach provided in the SDPWS for fully blocked diaphragms to design plywood/OSB. For all diaphragms except high load diaphragms, plywood/OSB panel joints parallel to the direction of the NLT span should



Panel Joint Perpendicular to NLT Span



Panel Joint Parallel to NLT Span

Figure 4.6: *Prefabricated NLT Panel Sheathed on Site*

Key

1. *NLT panel joint location*
2. *Plywood/OSB panel joint location with panel edge nailing*
3. *Field-installed plywood/OSB diaphragm with intermediate support nailing*
4. *Prefabricated NLT panel A*
5. *Prefabricated NLT panel B*
6. *Toe nail at NLT interface where no expansion gap is required*
7. *NLT support element*
8. *Diaphragm nail edge distance requirements per SDPWS*

TABLE 4.5 CHORD STRESS EQUATIONS

LAMINATION COMPRESSION	LAMINATION TENSION
$f_c = \frac{P}{b_{lam}d}$	$f_t = \frac{T}{b_{lam}d}$

always be centered on an individual lamination to allow for proper load transfer across the joint, as shown in Figures 4.6 and 4.7. For high load diaphragms, where multiple rows of fasteners are required at panel edges and boundary elements, the NLT laminations must have sufficient nailing to transfer the shear load across the joint. A simple approach is to provide equal nailing between the laminations at the plywood/OSB panel splice locations to that provided between the plywood/OSB and the NLT at the diaphragm panel edges. Another common approach is to provide long screw reinforcement (typically self-tapping screws) at the NLT edges near plywood/OSB splices, as shown in Figure 4.7.

Chords and Collectors

Tension and compression forces in the diaphragm chords or collectors can be resisted in a number of ways. Using beams as axial force members is one option. If the design does not include beams at the edges of the diaphragm, chord forces must be resisted within the floor assembly. One approach is to assume the NLT laminations act as discrete tension and compression elements that resist the full chord force at the extreme edges of the diaphragm[1]. Design the NLT laminations in this case as combined axial and bending members, with the axial forces due to lateral loads and the bending forces due to gravity loads in a given load combination; use the adjustment factors outlined in Sections 4.1.1 and 4.1.2. This approach requires careful consideration of load transfer across the lamination joints within the discrete chord element, as shown in Figure 4.8.

The design of NLT chords in the direction of the NLT span is relatively straightforward. Design individual laminations as tension or compression elements, laterally restrained about the lamination weak axis (i.e. column stability factor C_P=1.0) in accordance with NDS Chapters 3 and 4. Ensure the chord stress (f_c and f_t) is less than the individual lamination strength (F_c' and F_T') developed in accordance with NDS Section 4.3. Refer to Table 4.5 for NDS equations.

If the outermost single lamination does not meet the strength requirements, spread the load among multiple laminations as required. In such cases, ensure the laminations are sufficiently nailed together and nailed to the plywood/OSB, as shown in Figure 4.8. A simple approach is to provide equal nailing

1 This approach ignores the potential contribution of laminations further inward and therefore is conservative, but a pure linear elastic stress distribution in the NLT laminations would be inaccurate. Load transfer from the sheathing to the laminations occurs at discrete locations, primarily at the plywoods/OSB panel edges, rather than uniformly across the full diaphragm.

between the edge laminations to that provided in the plywood/OSB at the diaphragm boundary. Compression force transfer across the lamination butt joints is provided by direct bearing. Transferring tension across a butt joint is possible by transferring the force into the adjacent lamination and then back into the original lamination on the other side of the joint, using nails in shear. This load path becomes complicated where multiple laminations are needed to resist the tension force and for layups with frequent butt joints in between supports. Consider using light-gauge steel straps as a simpler approach.

For chords perpendicular to the direction of the NLT span, one option is to provide a rim board to take both the tension and compression forces. Where a single rim board does not provide sufficient tension strength, consider using light-gauge steel straps. Where a single rim board does not provide sufficient compression strength, another option is to resist the force with perpendicular-to-grain bearing in the NLT laminations. Calculate the width required to resist the compression force in accordance with NDS Chapters 3 and 4, and evaluate the result for reasonableness. Widths of over 6 in. may result in excessive crushing at the extreme edge of the diaphragm. This approach increases the flexibility of the chord, which must be considered in overall diaphragm flexibility as described in the SPDWS.

Design collector elements using the same approach. Where additional nailing is difficult to locate accurately (for example interior shear walls) consider using separate elements such as beams, straps, or wall top plates as the collectors.

4.2.2 Shear Walls

NLT is not as commonly used for walls but can be designed as a vertical lateral-resisting element. Similar to diaphragms, lateral capacity is provided by plywood/OSB, which can be applied to either side of the wall. Follow the approach provided in the SDPWS for blocked shear walls.

4.3 Connections

A complete NLT design includes details and specifications for connections, both within the NLT and from the NLT to its supports.

4.3.1 NLT Connections

Provide requirements for NLT lamination-to-lamination nailing in the structural contract documents. Where NLT is prefabricated in panels, also include requirements for panel-to-panel connections.

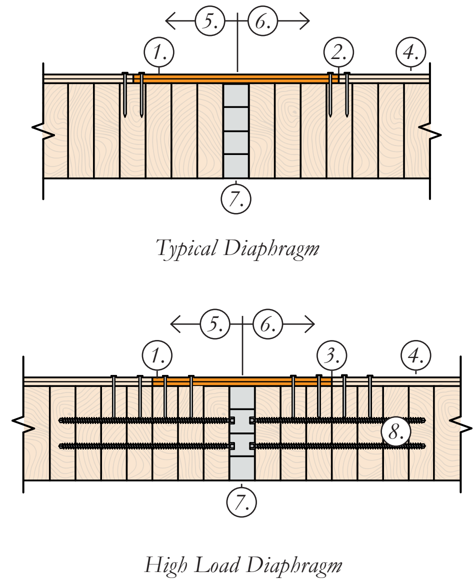


Figure 4.7: *Prefabricated Pre-sheathed Panels*

Key

1. *Field-intalled Plywood/OSB*
2. *Plywood/OSB splice location with typical diaphragm nailing*
3. *Plywood/OSB splice location for high load daiphragm nailing*
4. *Shop-installed plywood/OSB diaphragm sheathing*
5. *Prefabricated NLT panel A*
6. *Prefabricated NLT panel B*
7. *NLT expansion gap location fire stopped as required*
8. *Self-tapping screw pairs crossing plywood/OSB splice location*

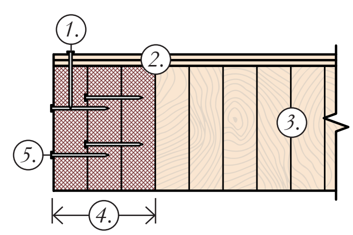


Figure 4.8: *Effective Discrete Chord Element*

Key

1. *Diaphragm perimeter nailing*
2. *Plywood/OSB diaphragm sheathing*
3. *NLT*
4. *Built-up chord width*
5. *Chord fastening for load transfer*

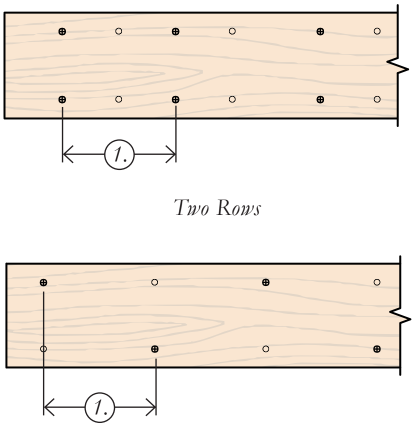


Figure 4.9: *Lamination Nailing*

Key

1. *Nailing spacing*
- ⊕ *Nailing in face layer*
- ○ *Nailing in layer beyond*

Lamination Nailing

Lamination-to-lamination nailing provides vertical shear transfer, forces the laminations to deflect equally, and pulls the laminations tight together. Recommended nailing for NLT fabricated with 2x lamination stock (1-1/2 in. actual thickness) is provided in Table 4.6 and Figure 4.9.

TABLE 4.6 MINIMUM LAMINATION NAILING

NLT TYPE	NLT DEPTH (NOMINAL)	NAILING PATTERN	
		3 in. long, 0.148 in. diameter nails (staggered)	3 in. long, 0.128 in. diameter nails (staggered)
Continuous Laminations	Less than 6 in.	One row @ 7 in. o.c.	One row @ 5 in. o.c.
	More than 6 in.	Two rows @ 14 in. o.c.	Two rows @ 10 in. o.c.
Butt-Jointed Laminations*	Less than 6 in.	One row @ 7 in. o.c.	One row @ 5 in. o.c.
	More than 6 in.	Two rows @ 10 in. o.c.	Two rows @ 10 in. o.c.

Note: *Nails are smooth shank galvanized steel nails.*

**Provide two additional nails on each side of every butt joint.*

The use of 3 in. nails for 2x laminations is a departure from the 2015 edition of IBC (2304.9.3.2), which requires nail lengths of 2.5 times the lamination thickness in every other lamination. Revisions to the 2018 edition of IBC will allow a variety of alternate nails sizes with revised nailing patterns, including the patterns given in Table 4.3. These revisions were accepted based on demonstrating equivalent lateral strength, shear stiffness, and withdrawal capacity to the nailing patterns given in the 2015 IBC. Prior to adoption of the 2018 IBC, the use of 3 in. nails should be approved by the authority having jurisdiction.

Panel-to-Panel Connections

For prefabricated NLT, panel-to-panel connections are provided by the plywood/OSB. In order to maintain diaphragm continuity and in-plane shear transfer, plywood/OSB joints must be located a sufficient distance from NLT panel splices. For plywood/OSB joints parallel to the NLT span, the distance must be sufficient to prevent differential gravity deflection between NLT panels. Refer to Figures 4.6 and 4.7 for examples of panel-to-panel connections.

For large areas of NLT, make allowances for swelling due to changing moisture content during construction; these allowances are needed to avoid inducing large stresses and deformations into the supporting structure. An effective strategy is to leave a 1-1/2 in. gap (one lam) approximately every 20 ft., as shown in Figure 4.7. After the building is operational and the NLT reaches its equilibrium moisture content, as discussed in Chapter 7, the gap can be filled if desired for aesthetics or to maintain fire separation between floors, as discussed in Chapter 3. Alternatively, if larger gaps in the NLT are being provided for sprinklers, electrical, or mechanical services, these gaps can be used to accommodate swelling.

For prefabricated NLT panels, support conditions may create discontinuities in deflection between adjacent panels. In such cases, additional panel-to-panel connections should be provided to create continuity in the overall deflected shape of the floor or roof and to prevent withdrawal of the plywood/OSB nails at the NLT panel joint. For example, one panel could be clear spanning 16 ft. while the adjacent could be supported on wood stud walls every 4 ft. for closets. At the center of the 16 ft. span, the first panel will deflect more than the second panel if the two are not sufficiently connected. Similarly, if a wall support is parallel to the NLT span, as illustrated in Figure 4.10, the adjacent unsupported panel will experience a larger deflection unless the two panels are tied together.

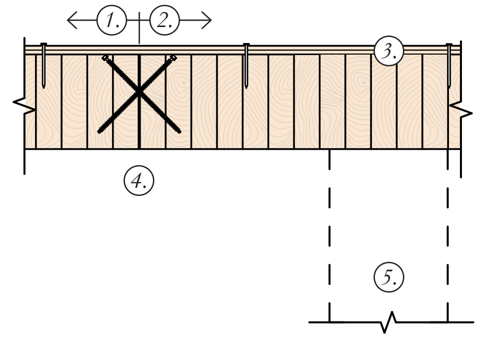


Figure 4.10: *Prefabricated NLT Panels with Varying Support Conditions*

Key

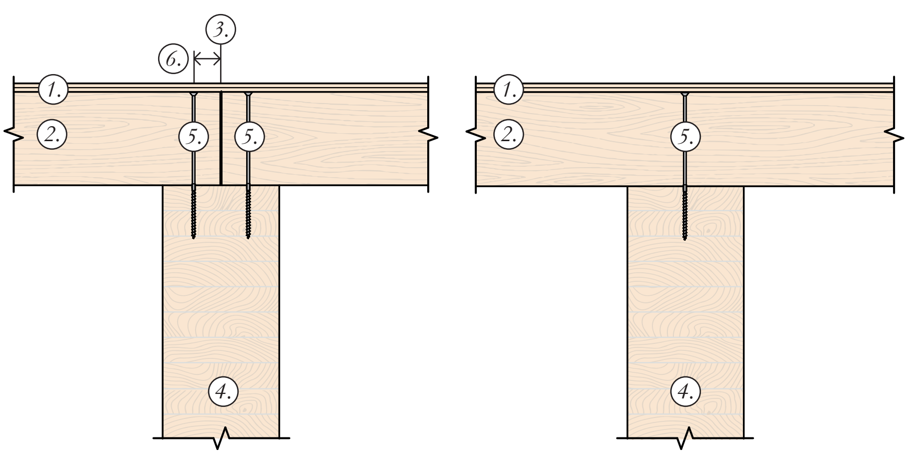
1. *Prefabricated NLT panel A*
2. *Prefabricated NLT panel B*
3. *Plywood/OSB diaphragm sheathing over screw heads*
4. *Self-tapping fully threaded screws inclined at 45⁰*
5. *Proximate support*

4.3.2 Support Connections

Detailing of connections between NLT and its supports varies with the type of load being transferred (gravity, uplift, lateral) and the type of support. Common supports include wood shear walls, wood beams, steel beams, and concrete walls.

Gravity Connections

For gravity cases, direct bearing of the NLT on the supporting element is the most common approach for transferring load. If net uplift is not a concern, which is typical for floors and some roofs, nominal connections with either self-tapping screws or nails ensure the NLT stays in place, as shown in Figures 4.11 through 4.16. For NLT built in place, minimum toenail requirements are given in IBC



Key

1. *Plywood/OSB installed over countersunk screws*
2. *NLT*
3. *Prefabricated NLT panel joint*
4. *Wood support beam*
5. *Self-tapping partially threaded screws with countersunk heads*
6. *Self-tapping screw fastener end distance*

Figure 4.11: *NLT Connection to Wood Beam*

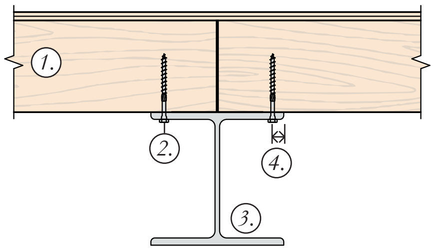
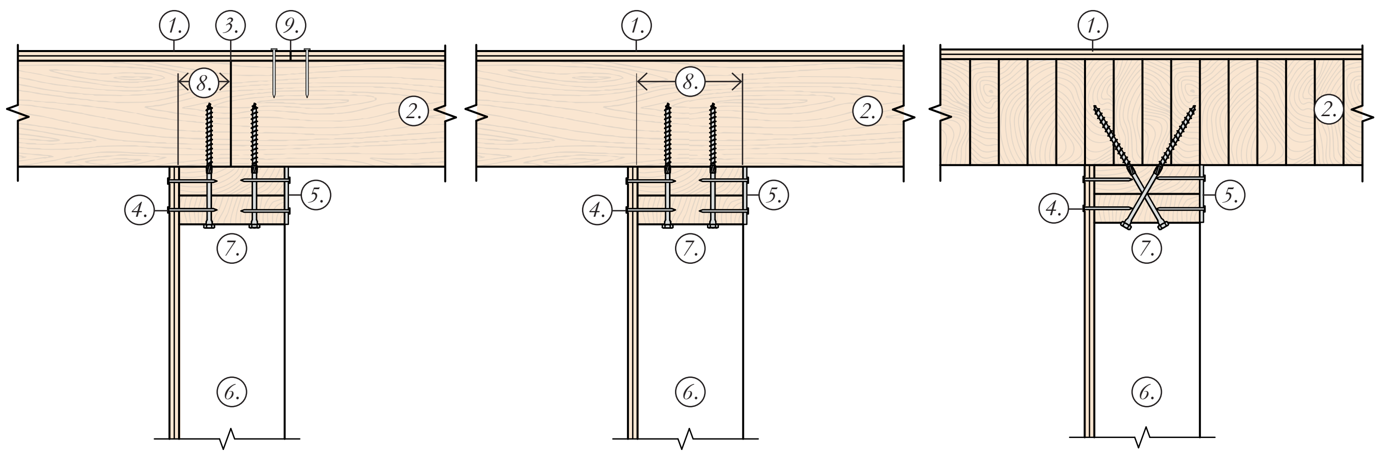


Figure 4.12: *NLT Connection to Steel Beam*

Key

1. *NLT*
2. *Partially threaded screws*
3. *Steel support beam*
4. *Minimum edge distance for ease of screw installation*

2304.9.3.2. Prefabricated NLT panels, however, cannot be toenailed. One common approach is to provide partially threaded self-tapping screws through the NLT at support beams, as shown in Figure 4.11. Alternately, at steel beam supports, provide screws up through the steel top flange into the NLT from below, as shown in Figure 4.12. Screws installed vertically should be centered on laminations; another option is to install self-tapping screws on an angle so that multiple laminations are engaged and the screws need not be located with precision. For inclined self-tapping screws installed through steel beam flanges, 45-degree washer heads are an economical way to accommodate the angle while ensuring proper bearing of the screw head on the steel. Design support connections at minimum to provide equal lateral strength, shear stiffness, and withdrawal capacity to the IBC toenail requirements, calculated in accordance with NDS provisions. If wind forces are sufficient to cause net uplift on the NLT, the fasteners must be designed to resist the uplift in withdrawal, subject to the minimum requirements listed previously. If beams are used as drag elements, design the screws to transfer the necessary forces into the beam.

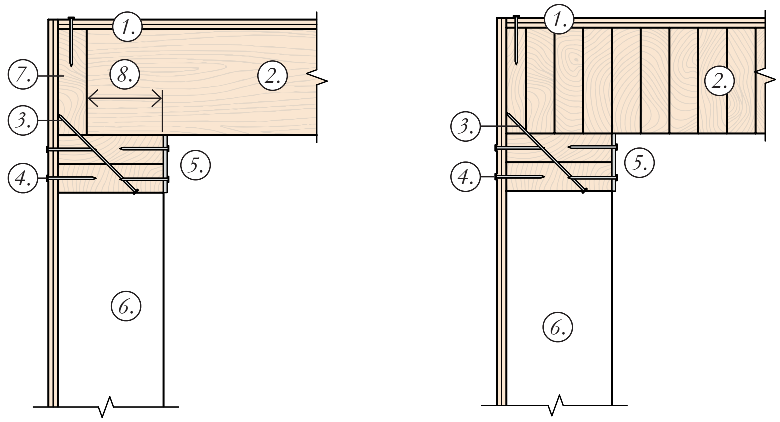


NLT Span Perpendicular to Shear Wall at Panel Joint — *NLT Span Perpendicular to Shear Wall* — *NLT Span Parallel to Shear Wall*

Figure 4.13: *NLT Connection to Interior Wood Shear Walls*

Key

1. *Diaphragm Plywood/OSB sheathing*
2. *NLT*
3. *Prefabricated NLT panel joint*
4. *Shear Wall Plywood/OSB edge nailing to top plate*
5. *Shear Wall top plate with straps to act as drag*
6. *Wood Shear Wall*
7. *Screws through top plate to NLT*
8. *NLT bearing length*
9. *Diaphragm Plywood/OSB sheathing joint with diaphragm nailing*



NLT Span Perpendicular to Shear Wall *NLT Span Parallel to Shear Wall*

Key

1. *Diaphragm plywood/OSB sheathing*
2. *NLT*
3. *Toenail of edge lam/rim board to shear wall*
4. *Shear wall plywood/OSB edge nailing to top plate*
5. *Shear wall top plate with straps to act as drag*
6. *Wood shear wall*
7. *NLT rim board*
8. *NLT bearing length*

Figure 4.14: *NLT Connection to Exterior Wood Shear Wall*

Shear Walls

Where NLT is continuous over a wood shear wall below, the lateral load path between the plywood/OSB and the shear wall must past through the NLT lams. Typical connections where NLT passes over an interior shear wall are shown in Figure 4.13. Connections between NLT and perimeter walls are shown in Figure 4.14. For interior shear walls, provide screws from the underside of the top plate through the NLT. Similar to connections at beams, the screws should be either installed vertically and centered on the laminations, or installed on an angle to engage multiple laminations. For large lateral forces, inclined self-tapping screws will provide higher capacities by loading the screws in tension rather than pure shear. Where drag elements are required beyond the wall, use the same approach discussed for chords and collectors in Section 4.2.1.

Where NLT connects to a perimeter shear wall, make a direct connection between the horizontal and vertical plywood/OSB wherever possible. The lateral load path should pass through the rim board, similar to any typical light-frame wood building. Ensure that the vertical plywood/OSB is sufficiently nailed to both the wall framing and the NLT or rim board for the shear transfer.

In cases where a perimeter shear wall continues past the NLT (balloon frame), wood ledgers are an option, as shown in Figure 4.15. Provide a ledger connection to the shear wall designed for full transfer of the gravity and shear forces with either nails or screws. In addition, provide tension ties between the top of the NLT and the shear wall to resist out-of-plane loading. Ensure the studs are blocked in line with the ledger to provide a direct load path to the plywood/OSB.

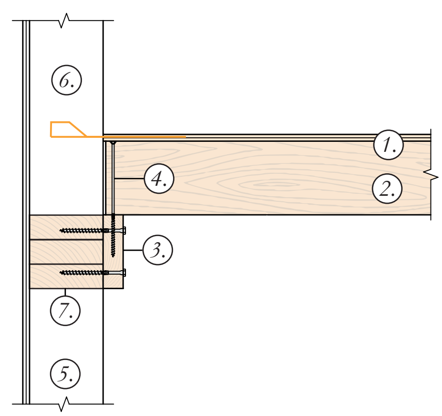


Figure 4.15: *NLT Support at Balloon-Framed Wood Shear Wall*

Key

1. *Plywood/OSB diaphragm sheathing*
2. *NLT*
3. *Wood ledger connected to shear wall studs*
4. *Self-tapping screws from NLT to ledger support*
5. *Double height wood shear wall (Balloon framed)*
6. *Tension tie at top of NLT*
7. *Wood blocking for diaphragm shear transfer into wall*

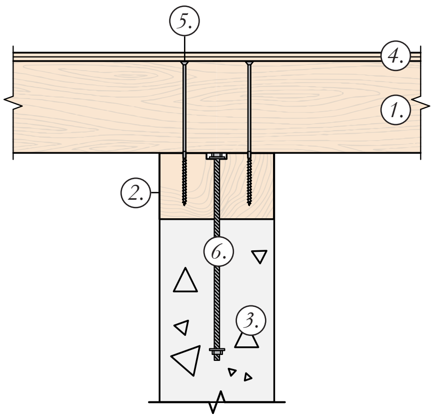


Figure 4.16: *NLT Connection to Concrete Wall*

Key

1. *NLT*
2. *Sill plate, depth to accept screws*
3. *Concrete wall*
4. *Diaphragm plywood/OSB over screw heads*
5. *Self-tapping partially threaded screws into sill plate*
6. *Sill plate anchors to concrete wall*

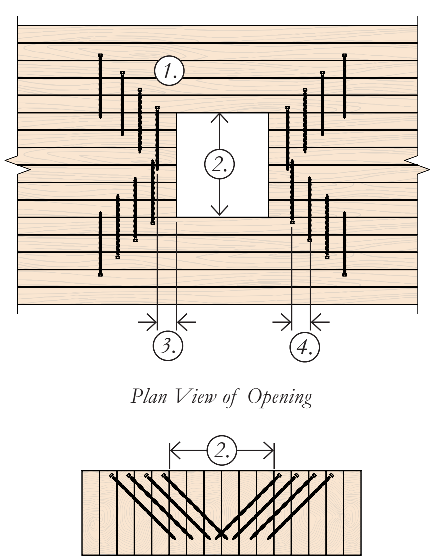


Figure 4.17: *Small Opening with Fully Threaded Screw Reinforcing*

Key

1. *Self-tapping fully threaded screws inclined 45°*
2. *Opening width*
3. *Fastener edge distance*
4. *Fastener space*

For NLT connecting to a concrete wall, install a continuous wood ledger at the top of the wall. For site-built NLT which is toenailed to the ledger, a single 2x is sufficient. For prefabricated NLT, install a thicker ledger to accommodate self-tapping screw connections as show in Figure 4.16.

4.4 Additional Design Considerations

Give special consideration to NLT systems with concentrated loads, openings, and cantilevers.

4.4.1 Point Loads

Point loads on NLT will be shared by multiple laminations but must be checked independently from uniform loads. A reasonable assumption for the effective width of NLT resisting a point load is 12 in. or the actual width of the load plus half the panel depth (d/2) on each side, whichever is greater. Treat line loads parallel to the NLT span in a similar fashion. For large point loads or line loads near supports, shear or bearing may govern the NLT design.

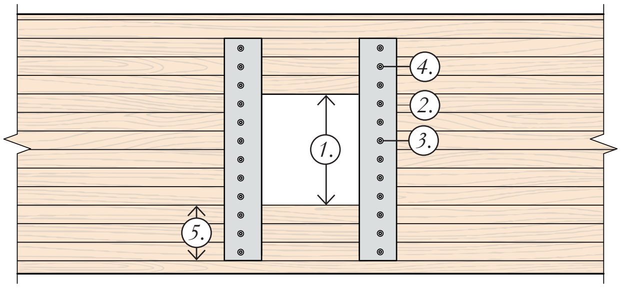
4.4.2 Openings

NLT is a one-way system, which means that openings often require additional analysis and reinforcement. This Guide defines small openings as 9 in. wide or less (up to 6 laminations for NLT fabricated from 2x material); other openings are considered large.

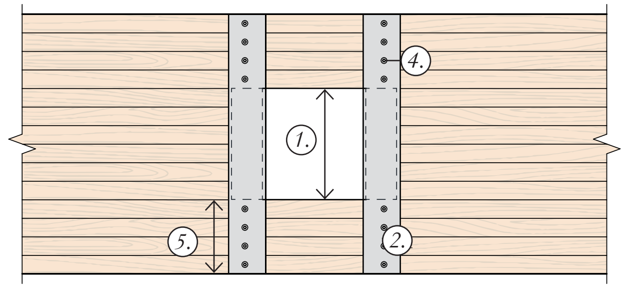
Small Openings (9 in. wide or less)

Small cores up to 3 in. diameter, such as for conduit or small pipes, can often be accommodated without reinforcing. For larger openings up to 9 in. wide, provide reinforcing with fully threaded self-tapping screws or supplementary steel framing.

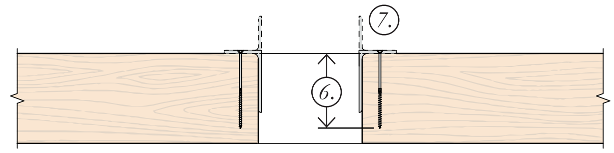
Fully threaded self-tapping screw reinforcing is a simple way to transfer shear around an opening. Installing screws at a 45-degree angle allows the screws to act primarily in withdrawal, which is a stiffer and stronger load path than the screws acting in shear. Design each screw for the appropriate withdrawal force associated with the lamination it supports. In addition to the "basic" shear from the terminated lams, which is calculated based on design loads, shear is also generated due to imposed deformation. The terminated lams must deflect equally to the adjacent full-length courses, which creates shear proportional to the equivalent uniform load required to deflect the terminated lams the same amount as the continuous courses. In grillage model studies, the additional shear can be significant. Refer to Figure 4.17 for an example of an opening reinforced with fully threaded screws.



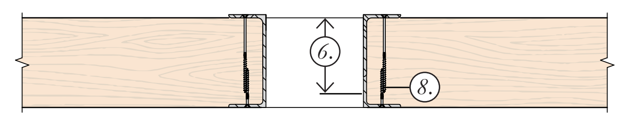
Plan View of Opening with Steel Angle Framing



Plan View of Opening with Steel Channel Framing



Section of Opening with Steel Angle Framing



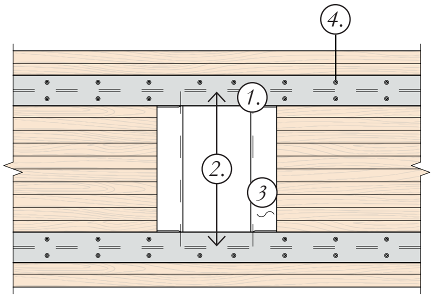
Section of Opening with Steel Channel Framing

Figure 4.18: *Supplementary Steel Framing at Small Openings*

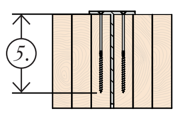
Key

1. *Opening width*
2. *Steel support framing coped at edge of opening to extend top plate only*
3. *Self-tapping screws in withdrawal at opening*
4. *Nominal screws away from opening*
5. *Bearing over supporting continuous laminations*
6. *Screw length of 80% of NLT depth*
7. *Upturn leg to close concrete topping pour if required*
8. *Nominal screws from underside of NLT at opening*

Steel reinforcing of small openings, as shown in Figure 4.18, is another option. The steel framing acts as a beam, taking the end reactions from the terminated laminations and spreading it to the adjacent continuous courses. Extend the supplementary framing at least half the width of the opening on both sides, and check the laminations supporting the steel framing for the additional load. Where exposed steel on the underside of the NLT is undesirable for either architectural or fire resistance purposes, an angle can be provided as shown in Figure 4.18 (left). If the vertical leg can be embedded in a topping slab or other floor build-up, orient the leg upward for easier fabrication and installation. If projection above the NLT cannot be accommodated, the vertical leg can be oriented downward but will need to be coped at the edges of the opening. Use self-tapping screws that penetrate a minimum of 80% of the NLT depth. Alternately, Figure 4.18 (right) shows a steel channel supporting the terminated lams through a simple bearing connection with nominal screws provided. For this approach, the terminated lams are supported by partially threaded self-tapping screws installed through the horizontal leg and centered on each lamination. In either case, only the top flange/horizontal leg is extended over the continuous courses to provide support through bearing on each lamination; provide nominal attachment with screws to each lamination.



Plan View of Opening



Section Beyond Opening

Figure 4.19: *Supplementary Steel Framing at Large Openings*

Key

1. *Steel T-section spanning between supports*
2. *Opening width*
3. *Steel framing at opening (channel or angle)*
4. *Nominal screws into NLT laminations*
5. *Screw length of 80% of NLT depth*

Large Openings (Greater than 9 in.)

Larger openings require additional framing in both directions to support the terminated laminations, because the adjacent laminations are insufficient to carry the load. If added beams below the NLT are not desired, consider framing the opening within the depth of the NLT with steel members as shown in Figure 4.19. The members parallel to the NLT span extend from support to support and can be concealed by providing a T-section with the vertical web extending between laminations; provide nominal screws between the top flange and the continuous courses. The steel members supporting the terminated lams can be detailed similar to those for small openings.

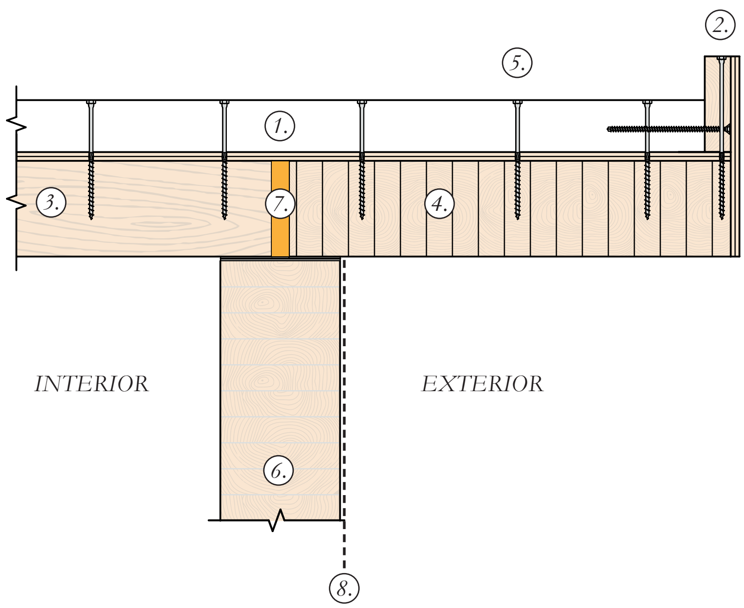
4.4.3 Overhangs

NLT cantilevers in the direction of the span are structurally straightforward; cantilevering in the weak axis direction is more challenging. Short cantilevers can be accommodated using fully threaded self-tapping screws installed at a 45-degree angle, similar to the screw-reinforced openings shown in Figure 4.17. A weak-axis cantilever of 9 in. (six lams for 2x material) is a reasonable limit for this type of detail.

NLT cantilevers that cross the building enclosure, such as eaves and entrance canopies, require special attention. As discussed further in Chapter 5, best practice is to extend the enclosure to encapsulate the overhang. However, this strategy does not allow the NLT to remain exposed, which is often desirable for aesthetic reasons. In cases such as these, ensure enclosure continuity in one of two ways: provide some type of flexible sealant between each lamination at the enclosure line, as discussed in Section 5.2.1, or provide a continuous break in the NLT and hang the cantilevered portion from outriggers installed above (refer to Figure 4.20).

Providing sealant between each lam requires careful coordination with the fabricator and installer. One option is to leave all the laminations fully intact and use a thin sealant tape at each interface. Although preferable from a structural strength and stiffness perspective, this strategy will create a "bulge" in the NLT at the enclosure line. Products are available with less than 1/8 in. thickness, but even these will add up. Another option is to kerf each lamination over its full height at the enclosure line and inject sealant into the kerfs. This approach eliminates the "bulge" problem but reduces the structural strength and stiffness of the NLT, which must be accounted for in the design.

Where NLT is hung from outriggers using self-tapping screws, as shown in Figure 4.20, the NLT can span in either direction. Details with upstand outriggers such as these are especially susceptible to moisture and must be designed accordingly: if improperly detailed, the increase in tensile stress in the screw resulting from moisture-induced wood swelling could cause brittle fracture of the screw. Where wood outriggers are provided, the screw threads should engage only in the NLT and not in the outrigger, as shown in Figure 4.20. This approach will ensure that extreme cases of swelling will result in crushing below the head of the screw, preventing excess tensile stress in the screws. Capacity can be increased somewhat by providing washer head screws or using separate washers below the screw heads. If steel outriggers



Key

1. *Intermittent outrigger*
2. *Perimeter/Parapet member at outer edge*
3. *Interior NLT*
4. *Exterior overhang NLT*
5. *Self-tapping partially threaded washer or hex head screws supporting NLT overhang*
6. *Structural support*
7. *Insulation and air/vapor barrier*
8. *Building enclosure*

Figure 4.20: *Wood Outrigger Supports for NLT Overhang*

are necessary, provide a compressible material between the outrigger and the plywood/OSB. The material should be strong enough to resist the design loads on the connection but weak enough to crush or deform sufficiently at a load below the screw's tensile strength.

4.5 Specifications

NLT does not have an accepted standard for production, so project specifications must help address this gap. The raw material is standardized via the American Lumber Standards Committee (ALSC), and some requirements for assembly (such as minimum nail spacings) are contained in IBC and the NDS, but these standards are not sufficient to ensure proper quality control on NLT projects. Issue stand-alone NLT specifications as a complete resource for the fabricator and contractor teams. In particular, require the general contractor to submit a weather protection plan appropriate to the local climate and the specific project. Also outline all special inspection requirements in accordance with local codes and the authority having jurisdiction.

Refer to Appendix B for a sample NLT specification section. This section is intended for projects with prefabricated NLT panels but can be adapted for site-built NLT.

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[5] International Organization for Standardization, and Technical Committee ISO/TC 98, Bases for design of structures. 2007. *Bases for design of structures--serviceability of buildings and walkways against vibrations*.

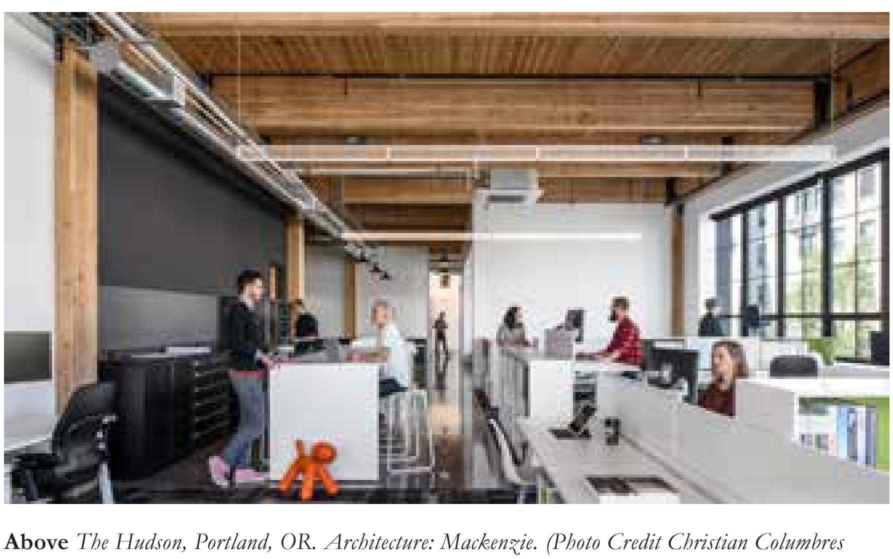
Above *Pitt River Middle School, Port Coquitlam, BC. Architecture: Perkins+Will. (Photo Credit: Latreille Delage Photography)*

5 Enclosure

The building enclosure is a system of materials, components, and assemblies physically separating conditioned and unconditioned spaces. It controls heat flow, air flow, and moisture in the form of both water vapor and liquid water, in addition to providing other functions as described throughout this Guide. This chapter focuses on the enclosure's performance during a building's service life. Refer to Chapter 7 for guidance on moisture management during construction.

Where NLT is used as part of the building enclosure, it works together with several other components to manage heat flow, air flow, and moisture loads. To ensure good enclosure performance with NLT, designers should carefully consider the NLT assembly and thoroughly detail enclosure interfaces and transitions. In addition, accounting for climate-specific conditions and building occupancy conditions both during construction and throughout the service life of the building is key. Climate conditions across the United States vary widely (refer to Figure 5.1). Accordingly, properties and placement of control layers and components used with NLT will vary by project location.

In This Chapter



Above *The Hudson, Portland, OR. Architecture: Mackenzie. (Photo Credit Christian Columbres Photography)*

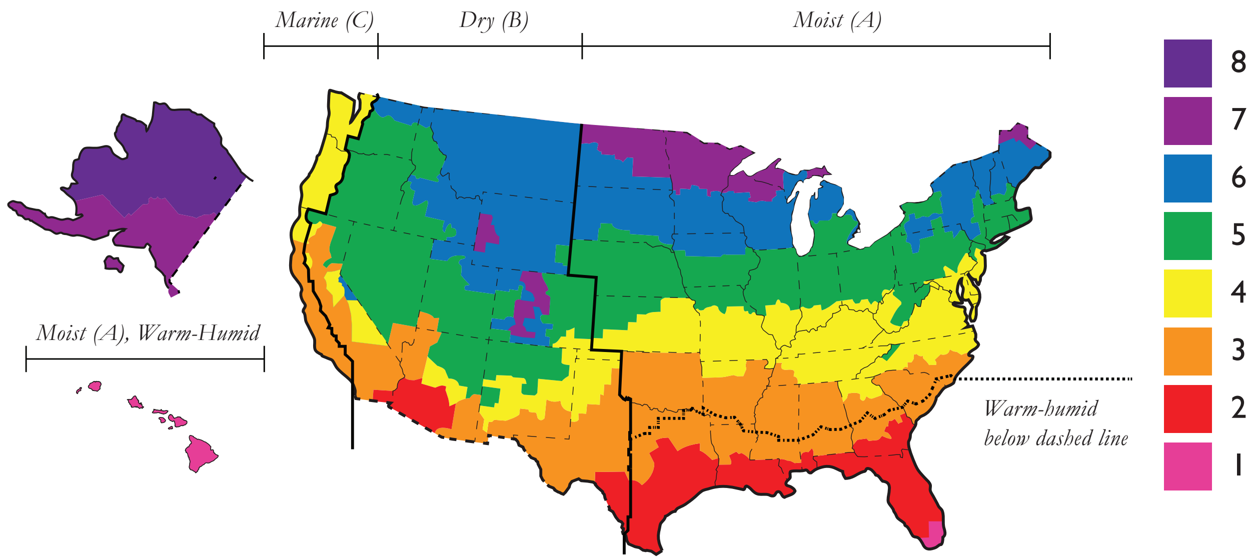


Figure 5.1: *U.S. climate map adapted from Figure C301.1 of the 2015 International Energy Conservation Code [1]*

5.1 Heat Flow

Managing heat flow across the enclosure is important to reduce energy consumption, minimize condensation risk, and increase occupant thermal comfort. The 2015 International Energy Conservation Code (IECC)[1] or project-specific energy targets will dictate the required thermal resistance (R-value) or thermal transmittance (U-factor) for the enclosure assembly. For horizontal NLT assemblies, the heat flow path is across the grain of each lamination and is controlled by the inherent thermal resistance of the wood and thermal insulation; other enclosure layers and surface air films provide some additional resistance to heat flow, but the overall contribution of the wood is minimal in well-insulated buildings.

Wood has a relatively low thermal conductivity compared to other structural building materials. Thermal conductivity and resistance values for common NLT sheathing types are provided in Table 5.1A through Table 5.1C. Where the NLT lamination species is unknown, the thermal conductivity and thermal resistance per inch of thickness may be approximated as 0.8 Btu-in/h-ft^2-°F and 1.25 h-ft^2-°F/Btu, respectively [2].

1 Local energy codes are typically an adopted or amended version of the International Energy Conservation Code (IECC) [1] or ASHRAE 90.1 [2].

TABLE 5.1 THERMAL CONDUCTIVITY AND R-VALUES OF COMMON NLT SOFTWOOD LAMINATIONS AND SHEATHING

A. THERMAL CONDUCTIVITY VALUES FOR COMMON NLT SOTWOOD SPECIES		
SPECIES	THERMAL CONDUCTIVITY (Btu-in/h-ft²-°F)	THERMAL RESISTANCE PER INCH (h-ft²-°F/Btu)
Hem-Fir / Spruce-Pine-Fir	0.74-0.90	1.11-1.35
Douglas Fir-Larch	0.95-1.01	0.99-1.05
Southern Yellow Pine	0.9	1.1

B. TYPICAL SHEATHING R-VALUES		
SHEATHING TYPE	THICKNESS (INCHES)	THERMAL RESISTANCE PER INCH (h-ft²-°F/Btu)
Plywood	1/2	0.79
Plywood	5/8	0.85
Plywood	3/4	1.08
OSB	7/16	0.62

C. TYPICAL NLT LAMINATION R-VALUES		
WOOD LAMINATION NOMINAL DIMENSION	ACTUAL THICKNESS (INCHES)	THERMAL RESISTANCE PER INCH (h-ft²-°F/Btu)
2x4	3.5	3.5-5.0
2x6	5.5	5.5-7.9
2x8	7.25	7.3-10.4
2x10	9.25	9.3-13.2

Wood also has a low thermal diffusivity due to its relatively low thermal conductivity (high R-value per inch of thickness) and moderate specific heat capacity and density. Accordingly, in some climates, NLT may contribute to moderating or potentially reducing heating and cooling loads. NLT may also contribute to overall thermal comfort as demonstrated in modeling exercises performed for CLT, a mass timber product of similar mass [3].

To meet the minimum insulation R-value or maximum assembly U-factor method requirements of the 2015 IECC Commercial provisions [1], thermal insulation with NLT is usually required. In all climate zones, it is best practice to locate the thermal insulation of NLT assembly on the outboard side of the NLT to best protect the wood from temperature fluctuations and related changes in moisture content. This will increase long-term durability and provide better thermal conductivity. Placing insulation on the outside also allows the NLT to remain exposed on the interior as discussed in Chapter 2.

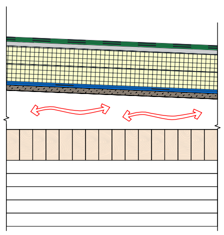
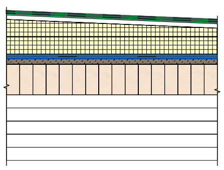
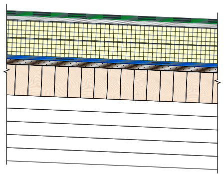
Above *T3, Minneapolis, MN. Architecture: Michael Green Architecture. (Photo credit: Ema Peter)*

In a circumstance where all or a portion of the thermal insulation is located on the interior side of the NLT, carefully evaluate the project-specific assembly for long-term moisture performance and durability.

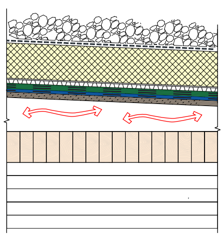
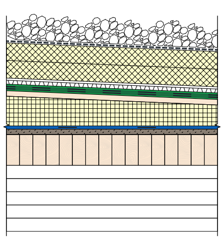
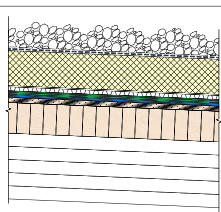
Table 5.2 describes conventional and inverted roof membrane assemblies commonly used with NLT. Where tapered roof insulation is used, calculating the assembly's effective thermal performance becomes more complex. Refer to RDH Technical Bulletin No. 005 for additional discussion for effective R-value design tables [4]. For a simplified, conservative approach, the tapered insulation could be neglected in the roof assembly calculation. Table 5.3 describes common NLT floor/soffit assemblies.

TABLE 5.2 ROOF MEMBRANE ASSEMBLIES

CONVENTIONAL ROOF MEMBRANE ASSEMBLIES

	DETAILS	TYPICAL ASSEMBLY LAYERS (TOP TO BOTTOM)	ASSEMBLY AND CLIMATE ZONE CONSIDERATIONS (REFER TO FIGURE 5.1)
SLOPED OVER-FRAMING		Roof membrane Coverboard Rigid insulation Air/vapor control membrane/TMMS Structural Plywood/OSB Sloped over-framing, Air cavity, vented to interior. (Refer to section 5.4.1) NLT Roof support (beyond)	Assembly Considerations: The air and vapor control membrane may also serve as a temporary moisture management system (TMMS), as further discussed in Section 7.6. The vapor permeance of all assembly layers should be carefully considered relative to the NLT and interior/exterior environmental conditions. Typical Climate Zone Considerations: **Climate Zones 1, 2, 3:** A fully adhered roof membrane will typically serve as the air and vapor control membrane. In this case, the air and vapor control membrane over top of the structural sheathing is often not necessary; however, a TMMS membrane may still be needed. **Climate Zone 4:** The air and vapor control membrane is an applied membrane and typically exists on the warm side of the insulation; if the membrane is otherwise located or omitted, carefully evaluate the assembly relative to interior and exterior conditions and construction phase moisture. **Climate Zones 5, 6, 7, 8:** The air and vapor control membrane is an applied membrane and exists on the warm side of the insulation.
TAPERED INSULATION		Roof membrane Coverboard Tapered rigid insulation Air/vapor control membrane/TMMS Structural Plywood/OSB NLT Roof support (beyond)	
SLOPED STRUCTURE		Roof membrane Coverboard Rigid insulation Air/vapor control membrane/TMMS Structural Plywood/OSB NLT Sloped roof support (beyond)	

INVERTED ROOF MEMBRANE ASSEMBLIES

	DETAILS	TYPICAL ASSEMBLY LAYERS (TOP TO BOTTOM)	ASSEMBLY AND CLIMATE ZONE CONSIDERATIONS (REFER TO FIGURE 5.1)
SLOPED OVER-FRAMING		Overburden/ballast Extruded polystyrene insulation Drainage composite Roof membrane/TMMS Structural Plywood/OSB Sloped over-framing Air cavity, vented to interior NLT Structural support (beyond)	Assembly Considerations: The roof membrane and TMMS may be the same assembly component where they occur within the same location in the assembly. Some structural sheathing substrates or TMMS (where separate from the roof membrane) may not provide an appropriate roof membrane substrate; an additional sheathing layer may be required. Evaluate the risks of construction phase moisture where the TMMS is not located directly on the structural sheathing. The vapor permeance of all assembly layers should be carefully considered relative to the NLT and interior/exterior environmental conditions. Climate Zone Considerations: For all climate zones, the fully adhered roof membrane typically serves as the primary air and vapor control membrane.
TAPERED INSULATION		Overburden/ballast Extruded polystyrene insulation Drainage composite Roof membrane Coverboard Tapered rigid insulation Air/Vapor Control Membrane/TMMS Structural Plywood/OSB NLT Structural support (beyond)	
SLOPED STRUCTURE		Overburden/ballast Extruded polystyrene insulation Drainage composite Roof membrane/TMMS Structural Plywood/OSB NLT Structural support (beyond)	

Impermeability: Air barrier systems must be impermeable to air flow. Typically, NLT laminations alone are not part of the air barrier system. While individual laminations may have a very low air permeability, the spaces or gaps between each lamination and between laminations and sheathing allow the passage of air. To address this, an air barrier system independent of the NLT is needed. Often, continuous sealed sheathing or membranes which meet air transmission rates in the governing energy code are used as part of the air barrier system.

Continuity: The materials within the air barrier system must form a continuous boundary. Ensure that the air barrier system of the NLT assembly is continuous at all joints and penetrations and interfaces with other assemblies. Refer to Figure 5.2 for example details. Where the NLT is part of the air barrier system as shown in Figure 5.3, refer to Section 5.2.1 for guidance on special considerations.

Stiffness: The air barrier system must withstand the air pressure forces acting on it without deforming or deflecting in such a way that inhibits the system's ablity to perform as intended. In a horizontal NLT assembly, this is overcome by providing a fully adhered or constrained air barrier membrane.

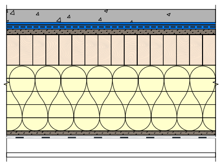
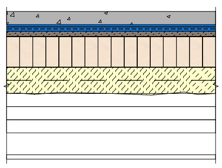
Strength: The air barrier system must be strong enough to transfer air pressure differentials back to the structure. Whereas the NLT structure is strong enough to carry this load, the membrane and components that serve as the air barrier system should be fully adhered or mechanically attached to the NLT, alternatively sealed sheathing may also be considered.

Durability: The air barrier system must perform over the service life of the building. In a horizontal NLT assembly, the air barrier system must withstand temperature fluctuations, building movement, air pressure differentials, and environmental exposures (e.g. UV and site contaminants) which may occur during the building's service life.

The five attributes detailed above are specific to building service life; however, if installed as part of the TMMS air barrier system materials must also be strong and durable during the construction phase to ensure long-term performance of the system. UV exposure, moisture exposure, wind pressures/gusts, and trade activities must all be considered.

The location of the air barrier membrane within typical NLT assemblies is referenced in Tables 5.2 and 5.3.

TABLE 5.3 CONVENTIONAL FLOOR/SOFFIT ASSEMBLIES

FLOOR/SOFFIT ASSEMBLY			
	DETAIL	TYPICAL ASSEMBLY LAYERS (TOP TO BOTTOM)	ASSEMBLY AND CLIMATE ZONE CONSIDERATIONS (REFER TO FIGURE 5.1)
AIR PERMEABLE INSULATION		Interior finish and acoustic components TMMS Structural Plywood/OSB NLT Air-permeable or -impermeable thermal insulation (structure beyond) Air barrier membrane (vapor-permeable water-resistive barrier membrane optional) Furring and vented cavity Exterior vented soffit panel	<u>Assembly Considerations:</u> Air-impermeable flooring or NLT sheathing (e.g. concrete topping or fully taped/sealed sheathing) may provide an alternative air barrier system when continuously detailed at all penetrations, assembly transitions, and interfacing details. A waterproof floor coating should be considered where wet conditions or risk of plumbing failures exist at interior space. The vapor permeance of all assembly layers should be carefully considered relative to the NLT and interior/exterior environmental conditions. <u>Climate Zone Considerations:</u> The Air-permeable insulation assembly is not recommended in hot/humid climates.
AIR IMPERMEABLE INSULATION		Interior finish and acoustic components TMMS Structural Plywood/OSB NLT Air- and vapor-impermeable thermal insulation (structure beyond) Exterior vented soffit panel	

5.2 Air Flow

NLT enclosure assemblies have very unique air-flow management considerations. Managing air flow across the building enclosure is a requirement of the 2015 IECC [3], and is key for reducing energy consumption, increasing thermal comfort, and minimizing the movement of water vapor into an assembly (refer to Section 5.3 for more on managing water vapor transport). Addressing air flow also minimizes the transfer of sound, smoke, fire, and contaminants between environments.

Managing air flow across the building enclosure is accomplished by using an air barrier system: a three-dimensional system of materials designed and constructed to control air flow across the building enclosure. An air barrier has five basic requirements as described by Straube [4]; consider these requirements specific to NLT assemblies as follows:

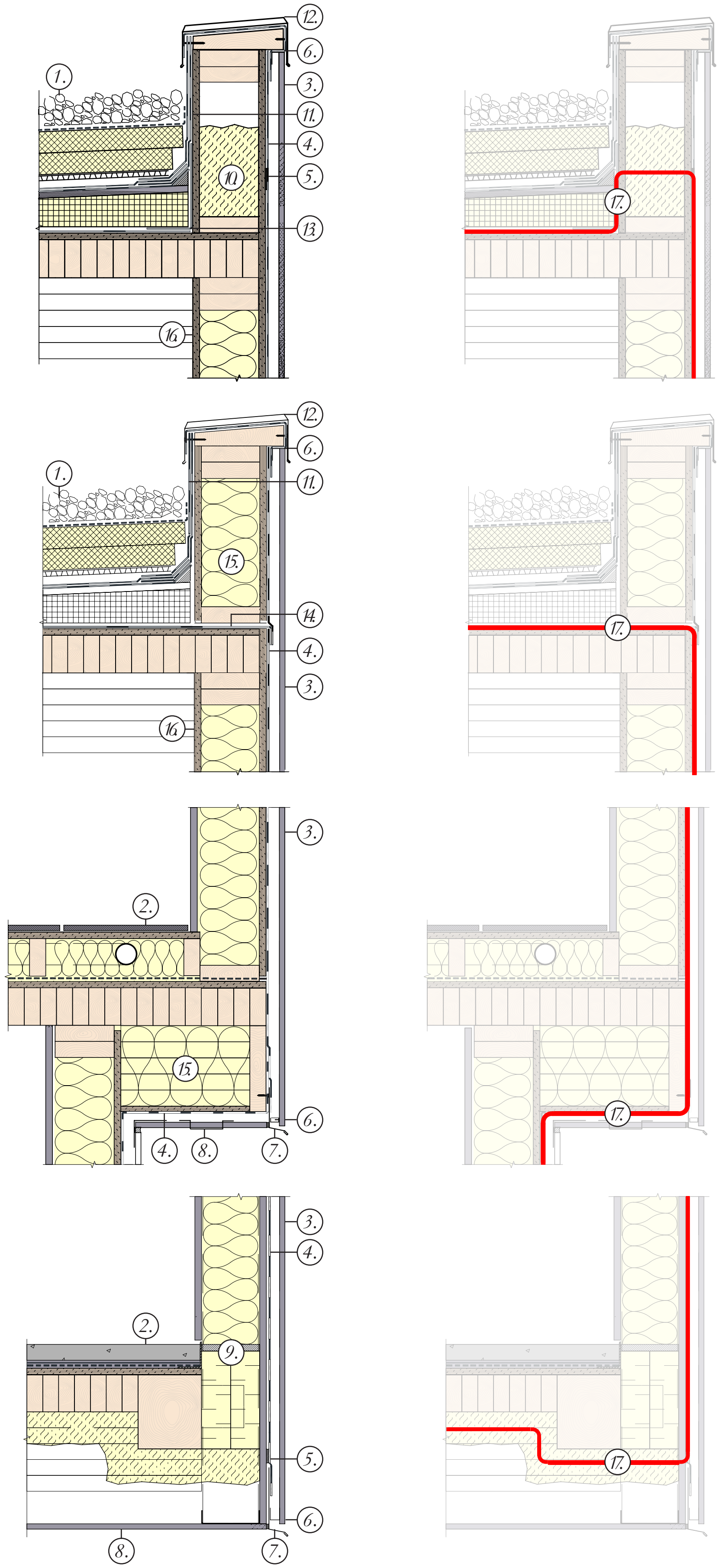


Figure 5.2: *Example Horizontal NLT Assembly Details*

Key

1. *Typical roof assembly - Refer to Table 5.2.*
2. *Typical soffit assembly - Refer to Table 5.3.*
3. *Typical exterior wall assembly with drained (and often vented) cladding.*
4. *Water-resistive and air barrier membrane, shingle lapped and continuously taped/sealed*
5. *Air barrier transition seal*
6. *Insect screen*
7. *Sheet metal drip flashing, shingle lapped by Item 4*
8. *Soffit panel (often vented)*
9. *Approved smoke seal*
10. *Continuous air impermeable insulation*
11. *Roof base flashing*
12. *Sheet-metal coping over high temperature membrane and sloped treated blocking*
13. *Air/vapor control membrane, upturned at parapet*
14. *Air/vapor control membrane, continuous under parapet with a sealed lap over Item 4*
15. *Air permeable insulation*
16. *Drywall*
17. *Continuous air barrier system. Details may vary on climate zone and building use.*

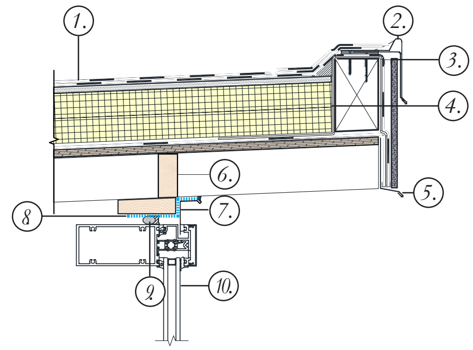
5.2.1 Special Detail Considerations

In some instances, the NLT may become part of the air barrier system, such as in a cantilevered condition as shown in Figure 5.3. In this instance, the NLT extends through the primary enclosure plane and can allow air flow across the enclosure, resulting in heat loss and movement of water vapor. To manage this, carefully detail gaps between each lamination, between NLT and structural sheathing, and between NLT and continuous blocking (e.g. a fenestration or wall head). Successfully sealing these gaps for long-term air barrier system performance can be challenging. The protruding NLT shown in Figure 5.3 also creates a thermal bridge at the wall and/or window head that should be considered.

The air sealing materials used within the Figure 5.3 detail need to withstand mechanical pressures between each layer while maintaining continuity and adhesion throughout shrinkage/swelling (refer to Appendix C). Preformed butyl tape and expanding foam tape products shown in Figure 5.4 may provide better performance when installed between laminations and between sheathing and NLT interfaces. While preformed tapes are easier to control throughout the fabrication process, they increase the overall gap dimension between laminations and distort alignment. To maintain straightness, it may be necessary to install tape or shims throughout the NLT.

Most sealants and spray foam products should be avoided for air sealing this transition; they have a limited ability to accommodate movement when sandwiched between materials, and can be difficult and messy to install during the fabrication process.

Alternate soffit transitions, such as the outrigger support concept presented in Section 4.4.3, may be considered. However, the NLT roof and soffit panel interface, as shown in Figure 4.20, can also allow air to infiltrate, requiring careful detailing with air barrier tape or membrane products. Designers should be aware that this transition can also be difficult to execute due to construction sequencing and material limitations. Furthermore, as discussed in Chapter 4, outrigger support connections can be sensitive to moisture.



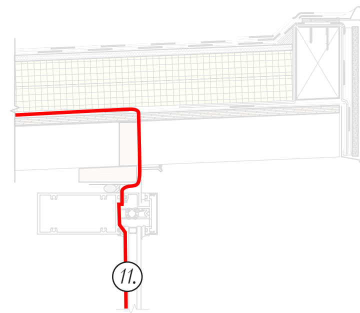
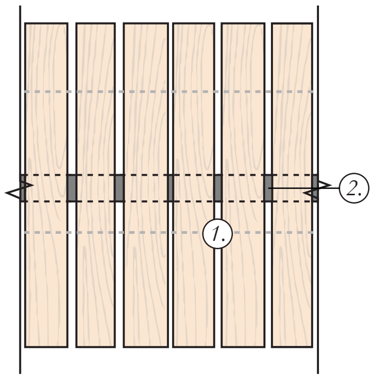


Figure 5.3: *Example Horizontal NLT Roof Assembly to Soffit Transition Detail at Window Head*

Key

1. *Typical roof assembly. Refer to Table 5.2*
2. *Typical roof temination detail*
3. *Insect screen*
4. *Air/vapor control/TMMS membrane*
5. *Sheet metal flashing with hemmed drip edge*
6. *NLT panel air seal*
7. *Sheet metal closure flashing, sealed to underside of exposed NLT*
8. *Water-resisitive and air barrier flashing membrane*
9. *Continuous air barrier selant and backer rod joint*
10. *Window system*
11. *Continuous air barrier system.*

Note: Details may vary on climate zone and building use.



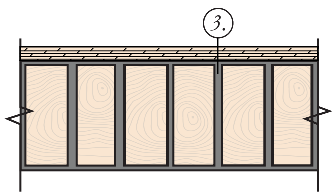


Figure 5.4: *NLT Panel with Preformed Tape*

Key

1. *Line of Exterior Wall Beyond*
2. *Preformed Tape*
3. *Preformed Tape Beyond*

5.3 Water Vapor Transport

Managing water vapor transport across an NLT assembly is accomplished with a water vapor control layer (e.g. vapor barrier), and by managing air flow with an air barrier system. Air flow transports significantly larger amounts of water vapor than vapor diffusion alone; however, both transport mechanisms should be carefully considered relative to the building's interior and exterior climatic conditions.

At thicknesses used for NLT laminations, wood has a water vapor permeance value of less than 0.1 perm-inch, which classifies the NLT laminations as a Class I vapor retarder as per the IBC. Although NLT laminations are relatively vapor impermeable, gaps and checks within the laminations minimize the effectiveness of the NLT to manage water vapor transport; air flow can still occur through the joints as noted in Section 5.2.

To avoid water vapor accumulation within NLT and to ensure long-term durability, consider the vapor impermeability of the NLT relative to the assembly's insulation and air barrier system layers and locations. The location of the vapor control layer will vary with climate (and building occupancy) and is generally discussed in Table 5.2 and Table 5.3.

Be aware that a vapor control layer and air barrier system in an NLT assembly can limit the ability of the NLT to dry, should it become wet during construction. Other low-permeability assembly layers and components can also limit drying. As such, it is important that NLT laminations and sheathing are sufficiently dry prior to installing any enclosure layers, or that the assembly is specifically designed to allow for drying of construction moisture.

5.4 Liquid Water

NLT exposure to liquid water can occur both during construction and over the service life of the building. Exposure can increase risks of dimensional changes from shrinking and swelling (refer to Appendix C), and can disrupt gaps between the NLT laminations and/or between NLT and penetrating or surrounding elements such as columns or wall structures. Rapid dimensional changes can also cause warping and checking to occur, and exposure to liquid water can cause corrosion of mechanical fasteners. Minimizing moisture exposure and maintaining an NLT moisture content consistent with the in-service equilibrium moisture content is critical for the integrity of the NLT assembly performance and the long-term service life of the building.

Liquid water at the roof is managed by the roof membrane; the location of this membrane and additional considerations are discussed in Tables 5.2 and 5.3. To help ensure the long-term performance of the NLT roof during building occupancy, a durable, fully adhered (e.g. multi-ply) roof membrane installed on the NLT roof is recommended, especially where a TMMS is not used (refer to Section 7.6). Refer to the National Roofing Contractors Association Manual for more on best practices [6].

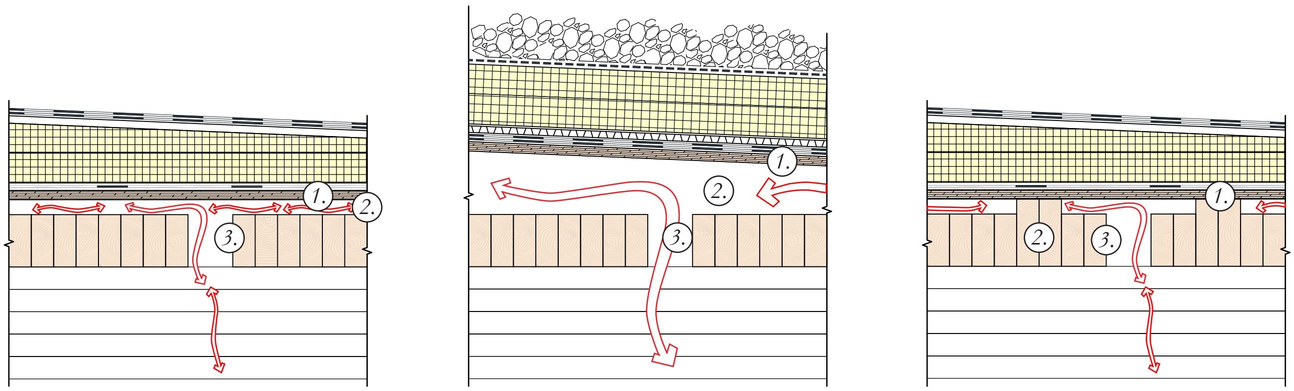
Floor assemblies generally not exposed to liquid water during a building's service life except for plumbing and appliance failures and wet in-service building conditions. Where the risk of wet interior conditions exists, consider a waterproof floor coating and drainage. Managing liquid water at NLT soffit assemblies is also accomplished by managing water at the adjacent perimeter wall interfaces.

When concrete toppings are to be installed at floor assemblies, the moisture content of the NLT should be maintained below approximately 16% prior to concrete placement. Some concrete toppings trap moisture within the NLT for extended periods of time, so coatings or membranes on the top side of the NLT may be necessary prior to concrete placement. Refer to Chapter 4 for structural considerations for the placement of concrete topping.

5.4.1 Leak Detection and NLT Venting

Detecting a leak through the roof membrane can be difficult to identify because the NLT can absorb moisture, and structural sheathing can further mask the presence of water. The use of a leak detection system within the roof assembly, or vented NLT as described in Figure 5.5, can help identify and locate leaks, minimizing the risk of exposing the NLT to long-term moisture and mitigating the associated effort and cost to dry it.

An active electronic leak detection system or vented panel is recommended when a temporary roof membrane over the NLT is not provided or when a green roof system is used. Locate the leak detection system below the roof membrane or as recommended by the roof manufacturer. Alternatively, consider venting to facilitate drying the topside of the NLT to the interior. When venting is used, locate the structural plywood/OSB on top of battens or sloped over-framing. Either omit the TMMS within the assembly or locate it on top of the structural plywood/OSB. Carefully consider the implications of omitting or relocating the TMMS against the project specific climate conditions discussed in Section 7.6. Finally, the air cavity vented to the interior may exclude the NLT from the from the assembly effective thermal



Vented Battens

Key

1. *Structural sheathing installed over intermittent battens*
2. *Intermittent battens, beyond*
3. *NLT panel, vented*

Sloped and Vented Over-Framing

Key

1. *Structural installed over intermittent sleeper framing*
2. *Intermittent sleeper framing beyond*
3. *NLT panel, vented*

Staggered Lamination Depths

Key

1. *Structural sheathing*
2. *NLT laminations, staggered lamination depth*
3. *NLT panel, vented*

Figure 5.5: *Venting options for NLT roof assemblies.**

**In all cases venting occurs between the NLT laminations and sheathing and is vented to the building interior.*

performance calculations however, confirm with the local jurisdiction for energy code compliance requirements.

Where a clear air cavity vent space is not possible, another means of leak detection or NLT drying will need to be considered. In such instances, consider the following potential limitations:

- Fire code may require the air cavity to be filled with insulation, negating the purpose of the vented cavity. Where this is required in cold climates, consider limiting the cavity insulation R-value to less than one-third of the total assembly insulation R-value, to minimize the risk of condensation within the assembly.
- Some applications may not allow structural sheathing to be located on top of the over-framing; if sheathing is located directly on top of the NLT laminations, air from the vent will not be able to effectively dry the NLT.
- Structural sheathing boundary and edge nailing requirements may block the air cavity connection to the interior, negating the benefit of venting the NLT to the interior.

References

[1] International Code Council. 2015. *International energy conservation code 2015*. Washington, D.C.: International Code Council, Inc.

[2] American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2016. *2016 ASHRAE handbook: fundamentals*. Atlanta, GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers.

[3] Karacabeyli, Erol, and Brad Douglas. 2013. *CLT handbook: cross-laminated timber*. Pointe-Claire, Québec: FPInnovations.

[4] RDH. "Effective U-values (R-values) for Tapered Insulation." *RDH Technical Bulletin No. 005 (2011): Feb. 2011*. Web. 2 May 2017. http://rdh.com/wp-content/uploads/2015/09/TB-5-Tapered-Insulation-wAppendix1.pdf

[5] Staube, John. "BSD-014: Air Flow Control in Buildings." Building Science Digests, October 15, 2007. https://buildingscience.com/documents/digests/bsd-014-air-flow-control-in-buildings.

[6] National Roofing Contractors' Association. 2016. *The NRCA roofing manual*.

Above *T3, Minneapolis, MN. Architecture: Michael Green Architecture. (Photo courtesy of StructureCraft Builders, Inc.)*

6 Supply and Fabrication

6.1 Materials

IN THIS CHAPTER

Material selection and fabrication techniques will affect the finished aesthetic and performance of any project. Understanding material attributes and the NLT fabrication process helps inform all aspects of design and construction. Material supplies for NLT production include wood materials (lumber and plywood/OSB) as well as fasteners and coatings.

6.1.1 Lumber

The primary factors in determining wood species and grades for NLT are availability, cost, structural performance, and aesthetics. Consider the following to inform lumber choices for NLT.

Lumber Grades and Species

Lumber species and grade affects both strength and appearance of NLT. Color, uniformity of appearance, and presence of visual defects differ between species. In addition to aesthetic or structural considerations, species also vary in other important ways. Species absorb and release water at different rates, which should be considered if NLT will be exposed to significant moisture during construction. Workability and hardness also differ between species and generally relate to density; for instance, Douglas Fir is more dense than SPF, which can result in more resistance when nailing or cutting, although only slightly.

Grade also matters where NLT is exposed as an interior finish. For instance, although visually graded No. 2 lumber may meet structural requirements, a higher appearance grade can minimize visual defects (wane, holes, large

Figure 6.1: *NLT showing blue staining from beetle-killed wood. (Photo Courtesy of Perkins+Will)*

knots) to better address aesthetic criteria. Using Select Structural grade lumber will provide improved structural properties while reducing visual defects compared to No. 2 lumber, but availability may be limited, and Select Structural is typically more expensive. Although visually graded lumber is more common than Machine Stress Rated (MSR) lumber, MSR lumber can improve the strength and stiffness of NLT.

Research and consider locally available lumber grades before ordering lumber for NLT. In some regions, SPF includes a significant supply of beetle-killed wood, which typically has blue stain through the grain, refer to Figure 6.1. While staining is often acceptable and sometimes even desired as an aesthetic feature, distributing it evenly throughout the NLT can be challenging.

Where high-quality, exposed NLT is desired, fabricators ordering No. 2 and better material should expect to visually cull it for consistent quality and anticipate a typical waste factor of 15% to 20%. To assist with visual culling it may be helpful to identify visual characteristics of acceptable lumber in

Figure 6.2: *Example of aesthetic grade boards for NLT panels. (Photo Courtesy of StructureCraft Builders Inc.)*

advance to facilitate a consistent look. Refer to Figure 6.2 for an example of board selection criteria for NLT panels used in the T3 project in Minneapolis. Some lumber mills offer specific appearance grades in addition to visual grading for structural performance. Request information on availability and differences between appearance grades from local lumber suppliers. Some higher appearance grades of lumber include Premium (or Prime) grade, Hi-Line (or Home Center) grade, and J Grade. J Grade is generally the highest quality of these options. A waste factor of 5% to 10% is typical for higher appearance grades, which may offset the increased cost of the lumber. The NLT Apperance Chart in Appendix A provides further examples of different levels of visual quality.

Other important considerations for selecting grade and species include fabrication efficiency and cost, such as labor required to grade and handle extra material, and space required to store additional material and culled lumber. Some lumber yards may agree to buy back culled lumber at a reasonable rate if negotiated in advance.

Spliced Panels and Finger Jointing

Prefabricated panels less than than 20 ft. in length are typically made with continuous boards cut to the panel length. Where longer panels are needed, there are two ways to build them: creating splices in the panel with a layup specific pattern or using finger-jointed lumber.

For panels created with layup patterns, often called "spliced" panels, shorter length boards can be used, but fabrication complexity and cost will increase. Refer to Section 4.1.2 for further discussion on structural design for spliced panels and Section 6.3.1 for more on layup pattern fabrication.

Finger-jointed lumber is used widely for manufacturing other mass timber products such as GLT and CLT; it can also be used for NLT where butt joints are undesirable for structural or aesthetic reasons. Finger-jointed lumber typically represents a 15% to 20% cost premium in some markets. Moreover, it can impact the amount of material required, as the thickness of finger-jointed lumber will generally be 1/16 in. narrower than typical dimension lumber. Structural requirements for the type of finger joint should be assessed and specified by the structural engineer as not all finger joints are intended for use in bending applications as per the ALSC finger jointing standards. Appendix B provides a sample specification noting acceptable finger joints. If finger-jointed lumber is used, the joints should be staggered from one course to the next.

Material Certification and Chain of Custody

Verification of environmentally responsible lumber and wood products is managed by several third-party programs which require certification of forest management, chain of custody, or both. Forest Stewardship Council (FSC), Sustainable Forest Initiative (SFI), and Programme for the Endorsement of Forest Certification (PEFC) are a few of the common certification standards. Projects pursuing LEED or other green building rating systems may require wood certified by one of these programs. Certified lumber may be more costly and can affect availability. Proof of chain-of-custody of the material is usually required by most rating systems, and may include certification of the manufacturing facility and supplier and/or installer.

Plywood/OSB

Standard construction grades of plywood or OSB are generally used over NLT floors or roofs and on one or both sides of NLT walls. The plywood/OSB provides vertical or horizontal diaphragm capacity and connects prefabricated panels together with a continuous substrate. Requirements for plywood/OSB thickness and layout should be described in the contract documents.

6.1.2 Fasteners

Assemble exposed NLT using galvanized nails to join laminations and for fastening plywood/OSB. If non-galvanized nails are used, iron staining will occur when exposed to moisture during construction. The structural drawings and specifications will specify nail types and nailing patterns. If nails longer than 3 in. are specified, they will require more expensive pneumatic nailers and potentially a larger compressor. Although 8D (0.131 in. diameter) nails are commonly specified, engineers may specify 10D (0.148 in. diameter) nails; in such cases, expect a cost premium.

Self-tapping screws are often used to connect NLT to its supports and can be used to reinforce panels at other conditions in panel assemblies such as openings, overhangs, or weak-axis cantilevers. Where self-tapping screws are needed, use zinc-plated screws to prevent iron staining; galvanizing this type of screw reduces the strength of the steel, and is rare and expensive. Although self-tapping screws have much higher structural capacity than nails, requiring fewer per NLT panel, using screws will increase fabrication time, increasing labor costs. For example, adding one pair of screws to every course at a spacing of 12 in. on center increases assembly time by a factor of approximately three.

6.1.3 Coatings

Coatings include sealers and stains often applied to exposed faces of NLT floors, roofs, and walls for aesthetic purposes. They can be applied in the shop, on site, or both. While coatings can mitigate water staining, they will not prevent swelling and are not an effective construction moisture control system. Water staining is typically minimal for horizontal NLT even without coatings, as the laminations create a natural drip edge every 1-1/2 in. Site-applied coatings can be cost effective depending on size and complexity of the project. Many different types of coatings are available, and the appropriate product is generally coordinated between the coating manufacturers and the project architect. Penetrating coatings are usually preferred over film-building coatings, because the natural movement in the NLT over time can lead to shrinkage or expansion and cracking in the film. For exterior NLT, carefully consider coating specification and maintenance requirements.

Figure 6.3: *NLT fabrication set-up. (Photo courtesy of StructureCraft Builders Inc.)*

6.2 Tools and Equipment

The mechanisms for handling NLT panels in the shop are often the same ones used on site. Consider lifting and handling strategies early, as the chosen approach will impact shop setup and required equipment. Refer to Chapter 8 for more on lifting and handling.

6.2.1 Jigs

The best way to assemble NLT is on jigs made from pony walls, back and end stops, and back fences as shown in Figure 6.3. Consider the following tips for an efficient and comfortable setup:

Jig: Build pony walls at typical waist height (30 in. to 34 in. tall) to provide a comfortable position for using a pneumatic nailer for long periods of time. Different setups can be used to create NLT that is curved in plan or warped in elevation.

Back Stop: Ensure a straight, sturdy back stop, built on top of the jig to withstand continuous battering over the course of manufacturing. Consider engineered wood (LSL or LVL) or steel angles. Unless the backstop is too thick, fasten the first board of a panel from the back side of the backstop for ease of panel removal after completion.

End Stop: Make the end stop straight and square with the back stop, built on top of the jig similarly to the back stop.

Back Fence: Build a back fence where nailing stations are set up back to back, to protect workers from misfired nails.

6.2.2 Fastening

It is important to choose the appropriate nailer for the nails specified in the drawings. For typical 3 in. pneumatic power nailers, a single compressor with air volume of 5 CFM should be used for every two pneumatic nailers. To prevent tripping hazards and protect equipment, run air hoses overhead, allowing them to drop down only over work stations wherever possible.

Where large self-tapping screws are used, high-torque drills capable of driving large screws are required. Never use an impact drill to install these screws; doing so may overdrive or damage the screws, compromising the strength of the connection. Where predrilling is required (for example with larger diameter screws) take care to drill the correct sized pilot hole.

Where possible, identify zones where the NLT is expected to be cut after fabrication, for example at panel ends and openings; do not put nails in these zones. Where plywood/OSB is shop installed, nail the plywood/OSB to the NLT as specified in the structural drawings with a pneumatic nailer. Where self-tapping screws are required, install them after cutting or take special care to ensure no screws are present in the zones where cutting will occur as they are difficult to cut through.

6.2.3 Cutting

After fabrication, cut NLT panels to length and provide other cuts that can be coordinated in advance such as notching panel corners at column locations and cutting mechanical openings. Cutting panels in the shop helps prevent erection delays on site. While it may be possible to identify zones without nails in advance of cutting (refer to Section 6.2.2), the steel nails located throughout NLT do present a challenge for cutting. For this reason, NLT panels are not well suited for CNC fabrication.

Some circular saws can handle cutting through nails, however it is best to consult a blade sharpening professional and select a blade that will cut through small amounts of steel. Even specialized “nail-cutting” blades will become dull and chipped but will last longer than standard wood blades. Circular beam saws range in cutting depth, accordingly deep NLT panels may

TABLE 6.1 SAW TYPES AND CUTTING DEPTH

SAW SIZE AND TYPE	MAXIMUM VERTICAL DEPTH
10 in. beam saw	3-1/2 in.
16 in. beam saw	6-1/2 in.
18 in. beam saw	7-3/8 in.
Carpenter's chainsaw*	16 in.

* *A chainsaw is not recommended due to high probability of cutting through nails*

need to be cut from both sides. Refer to Table 6.1 for saw types and sizes with corresponding cut depths.

Cutting notches and penetrations is similar to cutting for length. Square penetrations will need plunge cuts with a circular saw or a combination of drilling holes and cutting with a reciprocating saw. Circular penetrations are easily cut with a hole saw. If needed, custom hole saw manufacturers can create saws up to 13 in. diameter; while custom saws are expensive, they may be a worthwhile investment if many identical penetrations are required.

6.2.4 Coating Application

Coatings are applied to the underside of NLT to add aesthetic quality to exposed soffits or where NLT is used in exterior conditions. They typically do not provide weather protection. The performance of coatings will vary with species, along with resistance to decay.

Coatings may be applied in the shop or on site after the building is enclosed. If applied on site, the most important considerations are accessibility and coating ingredient attributes. Adequate ventilation may be difficult on some sites so coatings with high VOC content may present a challenge for on-site application. If coatings are applied in the shop, account for added lead time and more stringent panel storage requirements. Avoid placing stickers and dunnage on exposed sections of a panel, to ensure they do not affect the final appearance.

When applying coatings in the shop, pony walls or scaffolding built to a height of between 6 ft. and 6-1/2 ft. make an effective coating jig (refer to Figure 6.4). Assemble jig walls to mimic the final bearing condition for panels so uniform coating can be achieved, avoiding exposed stripes of uncoated panel. Rolling on coatings is easy and cost effective, but spraying may also be considered. Where coating is applied on site, it is typically done after the NLT is in place over the structural supports.

6.2.5 Temporary Moisture Management System Installation

Where a temporary moisture management system (TMMS) requires partial shop installation (refer to Section 7.6), allow additional time for application and curing of the adhesive where necessary. The TMMS may require an independent qualified installer; this should be coordinated with the supplier.

Figure 6.4: *Shop applied coating on NLT.(Photo courtesy of StructureCraft Builders Inc.)*

Take care during storage and shipping to ensure the pre-installed TMMS is not damaged prior to panel installation. Refer to Chapter 7 for more on storage and shipping approaches.

6.2.6 Panel Handling

After fabrication, panels may be handled in the shop using either an overhead crane or forklifts and telehandlers.

Overhead Crane

Ensure an engineered lift plan is in place. Where overhead cranes are used in fabrication, consider the site lifting strategy early, allowing the same lifting plan to be re-used. Refer to Chapter 8 for more on lifting requirements.

Forklifts and Telehandlers

Ensure that forks are clean and covered to prevent damage to the panels. Use plastic covers are recommended, not carpet or cardboard covers. Keep panel widths to a maximum of 6 ft. where overhead cranes are not available.

Figure 6.5: *Combined NLT and support beams being installed as one. (Photo courtesy of Fast+Epp)*

6.3 Fabrication Process

The pattern of individual boards within a panel, the presence or absence of shop-applied plywood/OSB, and the layout of panels within a floor plate all affect the fabrication process.

6.3.1 Board Placement and Splice Pattern

When placing boards, pay close attention to the board lengths and orientations. Where NLT will be exposed in the finished space, choose the exposed face of each lam with care. For boards with grading stamps present on the faces, ensure the stamps are present on the non-exposed side of the NLT.

Panels longer than 20 ft. can be created from shorter sections of boards butt jointed to create continuous courses. The pattern of these joints is called a splice or layup pattern. Different layup patterns affect the efficiency of material usage as well as the structural capacity of the NLT. (Refer to Section 4.1.2 for examples of layup patterns). The structural drawings may supply a pattern or ask the fabricator to propose a pattern based on specified requirements. In cases where the pattern is proposed by the fabricator, it must be reviewed and approved by the structural engineer and architect before production. Incorrect splice patterns can impact deflection and strength.

6.3.2 Plywood / OSB Installation

Plywood/OSB can be installed in the shop or on site. Shop installation provides a limited amount of moisture protection and adds stiffness to the panels, which can aid lifting. If plywood/OSB is installed in the shop, hold it back from the NLT panel edges, allowing infill strips to be installed on site to provide diaphragm continuity as shown in Figure 4.7. Site-applied plywood/OSB requires less pre-planning and is most efficient with narrow panels. Take care with site installation to place plywood/OSB joints per the structural drawings. Refer to Sections 4.2.1 and 4.3.1 for more.

6.3.3 Plan Layout of Panels

Panels can be arranged in various ways within a roof or floor plate, with short spans offering more options. Consider combining a single-span NLT deck with its supporting beams in the shop. The combined beam/deck shipping piece can be provided at every other span, and simple NLT panels can infill the gaps as shown in Figure 6.5. This strategy will reduce the overall number of crane picks required on site and can add out-of-plane stability to the panels, though transporting the combined beam/deck pieces to site is less efficient than shipping NLT panels alone.

6.4 Manufacturing Standards

Industry-wide manufacturing standards and tolerances for NLT do not exist. The following criteria are based on past experience and provide an acceptable, achievable level of quality. Refer to Appendix B for a sample specification with additional quality control and assurance requirements.

6.4.1 Pre-Manufacturing Checks

Prior to fabrication, check moisture content, fastener type, and jig setup:

Moisture Content (MC): The moisture content of kiln-dried (KD) lumber is usually 12%-16% but must be below 19% before NLT fabrication. Assess the moisture content of purchased material soon after it is received, and again before fabrication.

Fastener Type: Incorrect nail diameter is the most common mistake. Also ensure that nails are galvanized.

Jig Setup: Even with solid back and end stops, check frequently to ensure the jig remains square.

Figure 6.6: *4D sequencing with Navisworks for T3. T3, Minneapolis, MN. (Image courtesy of StructureCraft Builders Inc.)*

6.4.2 Tolerances

Reasonable manufacturing tolerances on panel width, length, and squareness help speed erection and maximize the benefit of prefabricated NLT panels. Refer to Appendix B for example tolerances for panel fabrication. Consider the following:

Panel Width: To maintain a consistent panel width, it is important to check width frequently during assembly, and use localized shimming or board planning.

Panel Length: Tight tolerances on length are easily met with accurate cutting after the panel is nailed.

Out-of-Square: Square panels are easy to achieve by constructing and maintaining a sturdy, square jig.

6.4.3 Quality Control and Documentation Review

Shop drawings are an important tool to communicate fabrication criteria between the shop, the site, and the design team. Quality Control (QC) checklists should supplement shop drawings. Panel mock-ups are also usually required for architectural review and approval and can be the best way to communicate finish quality.

Shop Drawings

To create 3D models and 2D shop drawings, CAD platforms such as AutoCAD can be used, but timber-specific software packages such as cadwork, hsbCAD, Dietrichs, and SEMA provide advantages when automating shop drawing production. In most cases, 2D shop drawings will be sufficient, but for larger and more complex projects, 3D and occasionally 4D modelling (including construction sequencing) is critical to schedule work and ensure coordination with other trades. Simulation platforms such as Navisworks may be helpful to merge models from different trades and support clash detection (refer to Figure 6.6).

Accurate and efficient installation requires good shop drawings that clearly communicate part numbering, placement, plan layout, and construction details. Sequencing panels for installation should be considered in the pre-construction phase. Identify panels required on site first, and work backwards to plan and coordinate speed of manufacturing, panel storage, and truck loading. Shop drawing packages, at a minimum, should include the following:

- Overall panel dimensions (including cuts and openings);
- Lumber species, size, and grade;
- Splice pattern (if applicable); and
- Fastener specifications and fastening pattern.

In some cases, fabricators may also be required to provide their own engineering of the panels, including gravity and lateral design, which would require an engineer's stamp on the shop drawings. In all cases, shop drawings require review and approval by the architect and engineer of record.

Quality Control Checklists

Quality Control (QC) checklists should include information regarding appearance and tolerances.

Samples and Mock-up Panels

Samples or larger mock-up panels are often required by the architect for review and approval to ensure aesthetic requirements are met where NLT is exposed. Mock-ups can often be incorporated into the main structure. Where this is done, take care to protect the panel during storage until it can be installed. Refer to Appendix B for sample specifications for mock-up requirements.

Above *The Bullitt Center, Seattle, WA. Architecture: The Miller Hull Partnership (Photo credit: John Stamets)*

7 Construction and Installation

7.1 Organization

The most appropriate panel organization strategy depends on the size, location, and complexity of the project, but there are three common approaches for the most efficient installation:

- Just-in-time delivery;
- Sorting and staging on site; and
- Off-site storage.

Just-in-time delivery offers the greatest advantage. Where it is possible to organize delivery just-in-time, load panels to allow for installation directly from trailers, and use truck stacking diagrams to ensure correct loading sequences for larger or more complex projects.

7.2 Shipping

Consider shipping constraints carefully to ensure the width, length, height, and weight limitations of transporting loads can be accommodated.

Width

Optimum panel width are 4 ft. or 8 ft. wide. Loads wider than 11 ft.-6 in. require permits and generally have time-of-day restrictions at the discretion of local transportation authorities.

Length

Panels up to 60 ft. long can usually be transported without restriction. Longer panels may require special trucks or permits.

IN THIS CHAPTER

Figure 7.1: *Shipping with dunnage and stickers. (Photo courtesy of StructureCraft Builders Inc.)*

Height

Maximum shipping height for a loaded truck is generally 13 ft.-6 in. above the ground. Over-height permits may be allowed up to 14 ft.-2 in., but are generally not granted on loads that can be divided to reduce height.

Weight

Trailer capacities and local transport authorities also impose limits on shipping. Typical tandem-axle trailers have a capacity of 45,000 to 50,000 lbs., and typical triple-axle trailers have a capacity of 55,000 to 60,000 lbs. Local transport authority truck weight limits are usually 45,000 lbs. Most softwoods have a density of 30 to 35 lbs./ft.^{3}, which can be used to estimate panel weights with reasonable accuracy. For more precise density values of specific species, refer to the NDS Supplement.

It is best practice is to use clean, dry lumber as dunnage and stickers, to raise the panels off the truck bed and separate them to allow air circulation, as shown in Figure 7.1. To avoid staining, dunnage and stickers should be free of grade stamps. Placing plastic, lumber wrap, or wax paper on the underside of panels to protect them from dunnage and stickers is usually ineffective and can cause moisture to accumulate.

Reducing the thickness of the dunnage and stickers can maximize the number of panels that fit on a truck. Ensure the thickness of the dunnage is sufficent to allow a fork between the panels. Most forklifts with fork extensions require a minimum of 4 in. of clearance. Other lifting devices may require the same consideration, or additional clearance between loaded panels to avoid damage to the undersides.

7.3 Storage

Where NLT panels must be stored outside, panels should be stored off the ground and properly tarped for moisture protection. At least two forms of weather protection, such as lumber wrap and tarps, is highly recommended. Where lumber wrap is provided around the entire panel, slit the underside of the wrap to prevent moisture from being trapped inside the wrap. Ensure the lumber wrap or tarps are opaque to prevent light from penetrating, as UV light will fade the panels where exposed, leaving visible discoloration where dunnage and stickers were in contact with the panels. Slope the top of panel stacks to assist with drainage.

Renting trailers can be a good way to gain storage space during manufacturing and to protect the panels from the elements, but the cost may add up quickly for multiple trailers or in cases of schedule delays. Wherever the panels are stored, the panel stacking sequence should match the install sequence to prevent inefficiencies with repeat handling (refer to Figure 7.2).

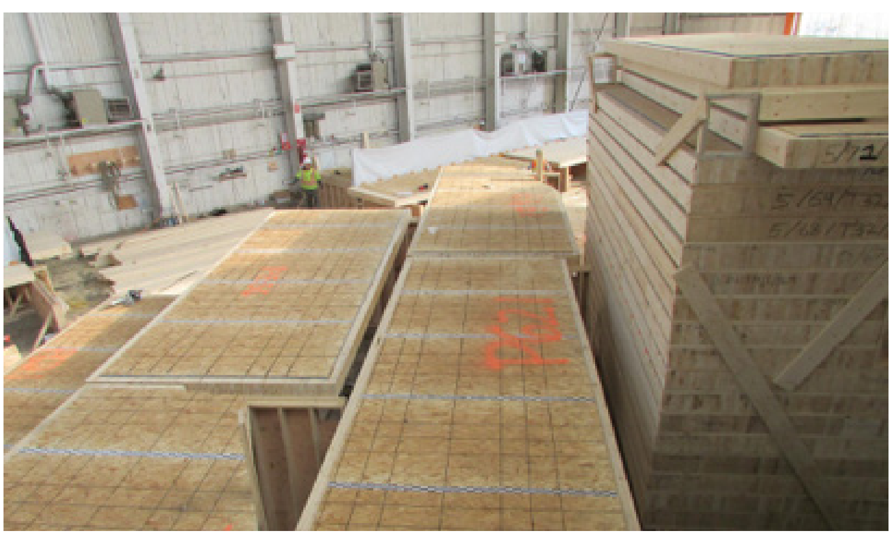


Figure 7.2: *Storage set up with dunnage and stickers. (Photo courtesy StructureCraft Builders Inc.)*

7.4 Unloading

When clean, dry forklift forks are used, no additional protection during unloading should be required. If fork protection is desired, shrink wrap over fork attachments offers the best fork protection without adding too much thickness. Forklift damage to NLT panels can be costly and difficult to remediate. Where cranes are used to unload/erect the panels, refer to Chapter 8 for erection engineering guidance. In either case, NLT-specific safety requirements would follow standard safety rules for loading, offloading, and general material handling.

7.5 Installation

The complexity of planning and coordination for NLT projects will vary with the scale and size, which can range from small-scale residential buildings to large multi-story commercial projects. The typical installation sequence involves placing the panels, support attachment, panel-to-panel connections, and sheathing, and then installing integrated mechanical/electrical/plumbing and other service runs within the NLT if necessary. A sequencing model is shown in Figure 7.3. Refer to Chapter 4 for structural details and to Chapter 8 for more on erection requirements for stability.

Ensure the panels are placed per the structural drawings and details, which may include gaps as shown in Figures 7.4 and 7.5. NLT panels are an engineered system; no notching or cutting is permitted without approval. Where high-strength screws are used for the connection to supporting structural elements, never use an impact drill, to avoid stripping the wood. Refer to Section 6.2.2 for more on high-strength screw installation.

Figure 7.3: *NLT panel installation sequencing model for T3 office building, Minneapolis, MN. (Image courtesy of StructureCraft Builder Inc.)*

Figure 7.4: *Installed roof panels with gaps for expansion. (Photo courtesy of StructureCraft Builders Inc.)*

Figure 7.5: *NLT install of prefabricated pre-sheathed panels. (Photo courtesy of StructureCraft Builders Inc.)*

Access to panels on top of a truck needs to be provided for safe rigging and lifting. Certified riggers should be involved in the lifting process, particularly with some of the panel lifting methods requiring carefully attached and installed lifting mechanisms.

Lifting Station and Devices

Selecting a lifting device is critical for safe handling and panel protection. More than one lifting device may be required depending on the project size and complexity. Consider the positioning of panel stacks or trucks and ensure the lifting device is able to handle all loads and reaches required throughout the project. Lifting devices may be re-used as required, although new fastners for attaching the device to the panel are typically recommended by lifting device manufacturers. Refer to Chapter 8 for more on erection engineering with cranes.

Consideration of the ground conditions and soil bearing capacity is important, and a geotechnical engineer should be retained if required to assess conditions and capacity. Stability of lifting devices is critical, and careful choice of device and positioning is imperative. Safety-related requirements are specified by OSHA standards.

7.6 Construction Phase Moisture Management

NLT has high potential for moisture entrapment at multiple locations: prefabricated panel interfaces, lamination interfaces, splices, exposed end grain, and the interface between NLT and plywood/OSB [1]. Moisture can be properly managed during construction with the right design and construction techniques, but a lack of proper care can affect aesthetics, structural capacity, dimensional tolerances, enclosure integrity, and even indoor air quality.

Sources of construction phase moisture include rainfall and snow melt, night-sky condensation, and plumbing leaks. Because moisture absorption is not instantaneous, long-term or persistent exposure is likely to be more problematic than the overall quantity of water [2]. When NLT assemblies are subjected to long-term exposure or standing water, moisture can penetrate deep within the wood, significantly slowing drying [1]. Attempting to fix this problem retroactively with tenting or large-scale drying is costly and can delay the construction schedule.

Consider the following strategies alone or in combination to minimize the risks associated with construction phase moisture:

- Provide a temporary moisture management system (TMMS) over NLT (refer to Section 7.6.1 for more);
- Schedule NLT installation during dry seasons;
- Coordinate shipping for just-in-time delivery and installation of NLT panels;
- Increase the speed of erection including the installation of the roof and roofing membrane;
- Minimize schedule delays between constructions of adjacent floor levels;
- Maximize panel size to decrease the number of site-installed TMMS joints, which are most susceptible to leakage; and
- Install enclosure components (e.g. temporary roof membranes, wall WRB) in parallel or shortly following the structure.

The intent of any moisture management approach is to maintain a moisture content of less than 16% on average, with a maximum of 19%. Temporary or permanent membranes should not be applied unless the moisture content of both the NLT laminations and the plywood/OSB is a maximum of 16%. Refer to The Guide for On-Site Moisture Management of Wood Construction [3] for more on moisture management.

Figure 7.6: *Horizontal NLT floor panel subjected to snow during the winter months in Climate Zone 6. Snow melt was later cleared from the NLT TMMS to minimize moisture exposure. (Photo courtesy of StructureCraft Builders Inc.)*

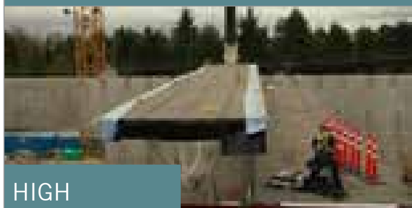
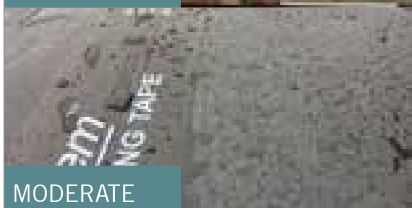
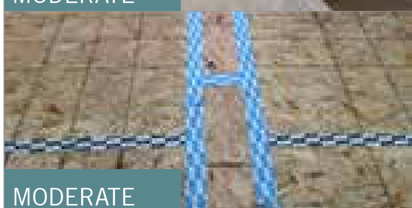
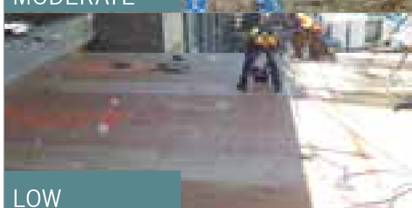
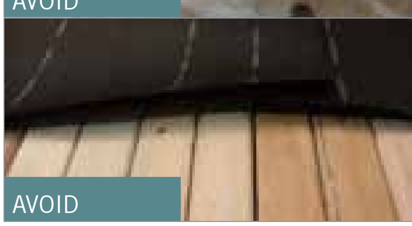
7.6.1 Temporary Moisture Management Systems

Roof assemblies may receive the greatest amount of moisture exposure during the construction phase; however, floors are also susceptible to wetting risks, such as shown in Figure 7.6, especially if construction schedule delays occur. The use of temporary moisture management systems (TMMS) and additional moisture management strategies at both roof and floor assemblies can limit the exposure to moisture during construction.

TMMS may include applied membranes, panel joint treatments, or both to control construction phase moisture. Membrane and joint treatment products used in the system should be UV stable throughout the expected exposure period.

The need for a TMMS will vary by project and is impacted by both seasonal temperatures and frequency of rain events. One approach to determine an effective TMMS is to use a climate index such as the Scheffer Climate Index Map [2], [4]. Refer to Figure 7.7 for the four categories of climate indices across the United States, and Table 7.1 for suggested temporary moisture management systems for each climate index category.

TABLE 7.1 TEMPERATURE MOISTURE MANAGEMENT SYSTEMS

PROTECTION LEVEL	TMMS MEMBRANE / JOINT TREATMENT	BENEFITS
 HIGH	**Field Membrane:** Fully adhered, vapor-impermeable waterproof membrane on sheathing. **Joint Treatment:** Fully adhered or welded field membrane laps.	Factory applied field membrane prior to shipping minimizes errors and weather limitations of onsite application. Field membrane may serve as part of permanent roof membrane or flooring underlay. Allows for immediate installation of joint treatment following panel installation (if skilled workers are available). High durability of membrane laps where torched or welded (avoid self-adhered laps).
 MODERATE	**Field Membrane:** Precoated, moisture-resistant bonded water-repellent coating on sheathing. **Joint Treatment:** Taped and/or sealed (e.g. flexible flashing membrane or tape).	Precoated sheathing minimizes need for experienced membrane installers. Sheathing and TMMS field membrane are combined into a single fabrication step. Allows immediate installation of joint treatment following panel installation.
 MODERATE	**Field Membrane:** Fully adhered, vapor-permeable and moisture-resistant membrane on sheathing. **Joint Treatment:** Taped and/or sealed (e.g. flexible flashing membrane or tape).	Factory applied field membrane prior to shipping minimizes errors and weather limitations of onsite application. Allows for immediate installation of joint treatment following panel installation if field membrane is pre-applied to sheathing.
 MODERATE	**Field Membrane**: None. Exposed plywood or OSB sheathing. **Joint Treatment:** Taped and/or sealed (e.g. flexible flashing membrane or tape).	Allows for immediate installation of joint treatment following panel installation. Skilled/experienced workers not required for joint treatment installation. Additional applications of water sealer may further increase water resistivity of the sheathing. Cost effective compared to options with field membrane.
 LOW	**Field Membrane:** None. Exposed plywood or OSB sheathing **Joint Treatment:** None. Exposed sheathing joints.	Cost effective. May minimize schedule impacts.
 LOW	**Field Membrane:** None. Exposed NLT laminations. **Joint Treatment:** Not applicable.	Accommodates sheathing installation at a later date or following site installation of overframing. May minimize schedule impacts. Cost effective.
 AVOID	**Field Membrane:** Loose laid sheet over sheathing. **Joint Treatment:** Taped and/or sealed (e.g. flexible flashing membrane or tape).	Serves as short-term temporary protection for isolated areas.
 AVOID	**Field Membrane:** Membrane under sheathing and over NLT laminations. **Joint Treatment:** Varies.	Sheathing protects membrane from trade damage.

CHALLENGES / LIMITATIONS	RECOMMENDED CLIMATE INDEX / SEASON
Requires pre-coordination with subcontractor installing TMMS.	All Climate Indices / All Seasons
Sheathing attachment penetrates through TMMS field membrane; taped/seal over fasteners. May be susceptible to damage and/or adhesion failure due to trade activities. May have limited exposure time; ponding water may result in water absorption and slow drying.	Climate Index ≤ 70 / All Seasons
Requires pre-coordination with subcontractor installing TMMS. TMMS may be susceptible to damage and/or adhesion failure due to trade activities. May require skilled/experienced installer.	Climate Index ≤ 70 / All Seasons
Some joint treatment products may not bond to damp or wet sheathing substrate. Joint treatment may be susceptible to damage and/or adhesion failure due to trade activities.	Climate Index ≤ 35 / All Season Climate Index ≤ 70 / Dry Seasons
System permits water migration between sheathing joints and into the NLT in wet weather conditions.	Climate Index ≤ 35 / All Season
Option permits water migration between NLT in wet weather conditions.	Climate Index ≤ 35 / All Season
Low durability. Difficult to seal. Typically slippery and dangerous to walk on. Allows lateral moisture movement beneath membrane.	Isolated Conditions (evaluate for project specific appropriateness)
TMMS is inaccessible for quality control review. TMMS below sheathing is difficult to drain and dry; traps moisture within NLT.	Avoid

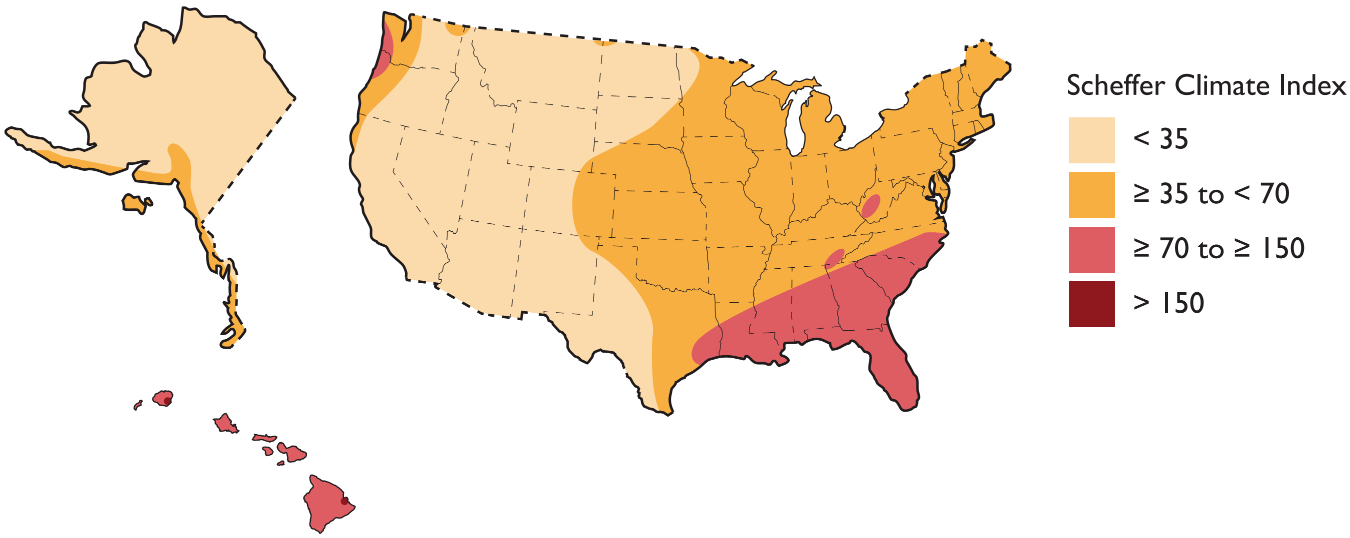
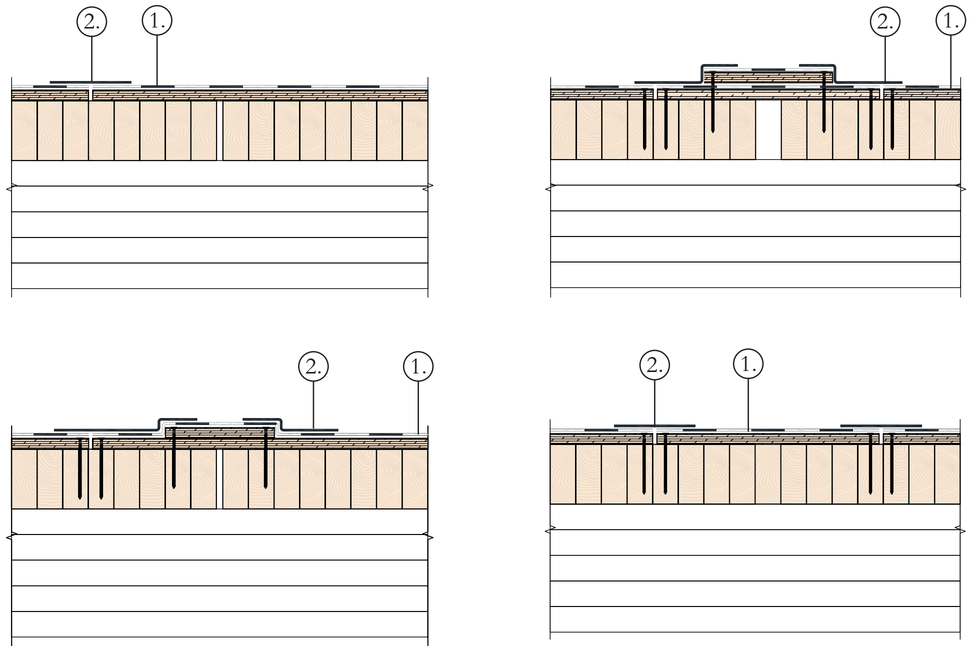


Figure 7.7: *Scheffer Climate Index as updated by Morris and Wang [6] and modified by RDH Building Science Inc.*

In general, temporary moisture management systems are recommended in areas with a climate index of 35 or greater, especially when construction is scheduled during wet weather seasons. Areas with a climate index less than 35 may also benefit from a temporary moisture management membrane system, and should be considered as a risk control strategy, as even mild moisture exposure can cause swelling and shrinkage. It may be tempting to use a less robust TMMS than the options presented in Table 7.1 as an initial cost saving measure; however, be careful to also consider the increased risk of exposing the NLT to moisture and associated cost of moisture mitigation.

Scheffer Climate Indices (SCI) may vary based on local climates and geographic features. Where specific conditions merit, calculate a project-specific SCI using recent weather data acquired from the closest available weather station. Refer to Morris and Wang [4] for more information and city-specific indexes.

In addition to the guidelines provided in Table 7.1, consider the ability of the TMMS to accommodate construction activity without undue risk of workers slipping, the system's compatibility with any interfacing roof membranes or flooring systems to be installed later in construction, and the TMMS sensitivity to UV exposure relative to the project schedule. Where the TMMS is also to be used as the permanent air barrier system and vapor control layer, ensure the TMMS has the appropriate properties to function as these elements and is repaired as needed prior to cover.



Field Applied TMMS and Joint Treatment *Shop Applied TMMS with Field Applied Joints*

Figure 7.8: *Temporary moisture management system joint treatment concepts.*

Key

1. *TMMS Membrane*
2. *Joint Treatment*

Take care where fasteners penetrate through the TMMS at elements such as fall arrest anchors (refer to Chapter 8), scaffolding supports, or structural outriggers (refer to Chapter 4). Detail fastener penetrations through the TMMS and consider additional protection for high rainfall areas. Any removed fasteners or damaged TMMS areas should be promptly repaired.

7.6.2 Additional Strategies

Consider the following strategies to supplement or replace the chosen TMMS:

TMMS Joint Treatment: Install sheathing, field membrane, and/or joint treatment (where used) at panel connections as soon as possible after installation. This connection is critical for protecting against moisture intrusion and providing a continuous TMMS. Example TMMS joint treatment concepts based on panel-to-panel sheathing details are shown in Figure 7.8. In all cases, the TMMS should extend continuously across the surface of the NLT. Regardless of TMMS type, always design the system to accomodate possible swelling during construction, as discussed in Chapter 4.

Figure 7.9: *Fixed tenting installation. (Photos courtesy of Fast+Epp)*

Water Deflection/Diversion Mechanisms: On all project sites where rain or snowmelt may occur, temporary drains sealed to the TMMS will divert water away from the NLT assemblies and supplement the TMMS.

At the building perimeter, provide protection to minimize water ingress through openings and penetrations, which may cause puddling on the horizontal assemblies. Close off perimeter wall cavities at the top; leaving the cavities open may divert water onto lower floor areas. Install temporary protection at roof parapets as well as at perimeter wall elements to avoid directing water into the building.

Tenting: For construction during the wet season or in wet climates, consider a temporary tent until the building is enclosed as an alternative to a TMMS. Tents may be fixed or movable (refer to Figure 7.9). Tenting represents the lowest risk in terms of moisture impacts but they can be costly and may hinder installation strategies.

Drying: If NLT moisture content exceeds recommended limits in spite of the TMMS applied, a strategy to dry the wood will be necessary. The overall depth of the NLT and the extent of water intrusion will determine the most effective strategy; deep assemblies require more aggressive tactics and more time to dry. Where large dimension wood panels require drying, it is also important to control the rate of drying to minimize checking.

Using natural ventilation to dry wet NLT is not effective; drying typically occurs slowly and relies on natural heating from sun exposure, and air flow from wind [3]. Active heating and dehumidifying are more effective but have limited benefit in cases where there is a membrane on top of the assembly.

In these instances, heating and dehumidifying can lower the moisture content of wood close to the underside of the NLT, but research suggests the membrane slows the overall rate of drying; heat may be ineffective at drying the plywood/OSB or moisture trapped just below it. Heating and dehumidifying is most effective in combination with ventilation. Membranes and plywood/OSB should therefore be removed whenever possible to allow drying of both the top and bottom sides of the NLT. Tenting, as described previously, can also help speed the process.

References

[1] Wang, Jieying. 2016. *Wetting and Drying Performance and On-Site Moisture Protection of Nail Laminated Timber Assemblies*. Publication 173-644. Vancouver, B.C., Canada: FPInnovations.

[2] Sheffer, Theodore C. "A Climate Index for Estimating Potential for Decay in Wood Structures Above Ground." Forest Products Journal, Vol. 21, No. 10. (1971), 25-31.

[3] Wang, J. 2016. *Guide for on-site moisture management of wood construction*. Publication 173-525. Vancouver, BC: FPInnnovations.

[4] Morris, P.I.; Wang, J. 2008. *A new decay hazard map for North America using the Scheffer Index*. Document IRG/WP, 08-10672. Stockholm, Sweden: International Research Group on Wood Protection.

Above *T3 Minneapolis, MN, (Photo Courtesy of StructureCraft Builders Inc.)*

8 Erection Engineering

NLT projects usually require specialty erection engineering for panel lifting, fall arrest, and temporary structural stability. This engineering can be performed by the structural engineer but is more often carried out by the supplier's or installer's temporary works engineer.

For larger structures, an engineered, stamped, and sealed set of erection drawings should be in place prior to the start of work on site.

IN THIS CHAPTER

8.1 Design Loads

Successful systems for lifting and temporary stability are based on accurate design load calculations. Consider the following:

- IBC and OSHA requirements for temporary stability, construction loads per ASCE 37-14, and fall arrest loads;
- The impact of wind to increase forces in lifting systems. Maximum wind speeds for panel lifting should be specified by the erection engineer;
- Accurate panel weights, considering wood species and moisture content of the NLT panel;
- Appropriate dynamic amplification factors related to the lifting mechanism being proposed (refer to Table 8.1.); and
- Accurate calculation of the panel's center of gravity and any impact of asymmetric lifting.

Take care before specifying a specific load rating for any engineered lifting system. Once a rating is stated, others may assume it to be valid even under significantly different circumstances.

TABLE 8.1 DYNAMIC ACCELERATION FACTORS (F) [1]

LIFTING DEVICE	DYNAMIC COEFFICIENT OF ACCELERATION F
Fixed crane	1.1 ~ 1.3
Mobile crane	1.3 ~ 1.4
Bridge crane	1.2 ~ 1.6
Lifting and moving on flat terrain	2.0 ~ 2.5
Lifting and moving on rough terrain	3.0 ~ 4.0 and +

8.2 Panel Lifting

Many systems for lifting NLT panels are available, ranging from simple lifting with slings to pre-engineered systems using screws. Lifting drawings sealed by a professional engineer are required for many of these systems. Typical stamped lifting drawings can be re-used across projects, if they are reviewed for applicability with a registered professional engineer prior to re-use.

8.2.1 Engineering Considerations

Lifting capacities depend on many project-specific factors including wood species, moisture content, panel shape or openings, and crane type. Specify and include the following information on panel lifting or erection drawings:

Weight: Loading and panel weights

Lifting Mechanism: Slings, spreader bars, and chain hoists can all be components of the rigging system which attaches to pick points on panels. Specifying allowable sling angles and required sling or chain capacities is critical to a safe lifting plan. Specify use of tag lines to safely guide the panel during lifting.

Lifting Point Connection Details: specifiy associated reinforcing screws if required.

Lifting Point Capacities and Assumptions: Acount for wood species, moisture content, panel build-up, type of lifting device, factor of safety, and assumed dynamic amplification factor related to the specific lifting device or crane being used.

Location of Lifting Points: Notches and non-rectangular panel shapes modify the position of the center of gravity; in these cases, typical lifting point patterns must be rearranged to ensure panel stability during lifting. Some panels may require so-called strong backs or reinforcement atop the panel during lifting to avoid excessive deflection or damage to the panel until it is fully supported in its final installed condition.

Screw Installation: Screws should never be installed with an impact drill. Do not remove or reinstall screws. Do not reuse holes.

Stability of Support Structure: The support structure must be adequately braced and connected prior to landing NLT panels, both to ensure sufficient load-bearing capacity and to maintain panel alignment once set.

Minimum Connection from Panel into Support Structure: Prior to walking on panels or attaching fall arrest anchor points, a minimum level of connectivity is required between the NLT panel and the support structure.

8.2.2 Lifting Mechanisms

Many different lifting mechanisms are possible, and a registered professional engineer should design an appropriate lifting mechanism for the project and panel configuration.

Refer to Table 8.2 for some common approaches to lifting horizontal NLT panels for floors or roofs, many of which include high-strength self-tapping screws. Where these screws are used, place them centered on NLT laminations. Screws of larger diameter should be predrilled.

Use the right tools, correctly calibrated to prevent stripping of the wood during screw installation. Never use impact tools to avoid overdriving the screw, breaking the screw, or stripping the holes. Generally these screws cannot be re-used; consult with the supplier to confirm.

NLT wall panels with vertically oriented laminations and a horizontal top plate require special lifting techniques. Consider the use of choked slings or screws fastened through the top plate, or D-ring plates fastened to the sides of the panel. It is important to consider load transfer between lams, although where plywood/OSB is pre-installed on at least one side this is usually straightforward.

8.2.3 Pick Points

Distribute pick points such that the resulting lifting hook position lies over the panel center of gravity, minimizing eccentricities and any tendency for the panel to tip in one direction. For asymmetric panels, a stable arrangement of pick points can be determined by placing two, three, or four pick points on a radius drawn from the panel center of gravity. This radius should not be less than one-quarter of the overall panel length.

When picking more than two lifting points from a single hook, use appropriate compensation systems to ensure proper load distribution between all pick points, and carefully consider effective loads on each pick point.

TABLE 8.2 LIFTING MECHANISM OPTIONS

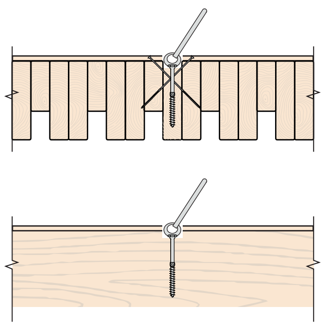
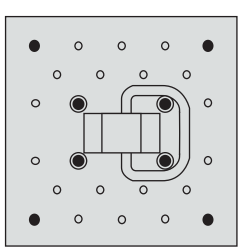
LIFTING MECHANISM	USE AND LOAD RANGES	CONSIDERATIONS
Screwed in Quick-Release Anchors 	Common system for mid-range panel weights. Load is dependent on the withdrawal capacity of high-strength screws.	Quick-connect system reduces cycle times. Screws must be installed at correct angle. Local reinforcement of panel is required. For higher loaded connection, provide timber blocking fastened to the top of the panel or a counterbore into the panel to ensure lifting screws are loaded in withdrawal only. Screws penetrate pre-installed TMMS.
Slings  *(Photo courtesy of Seagate Structures Ltd.)*	Simple system common for narrow panels or tight spaces (ex: shops). Load is governed by sling capacity and rigging configuration.	Slings can be re-used. Hook-up and release of panels is slow. Typical max width is 4 ft. (use of a spreader bar can increase the sling angle). Sling angles less than 60° increase lifting anchor force (impacts lift rating). Difficult to remove slings, so panels must be landed apart and pulled together. Potential for instability of the panel if slings slip. No penetration through the TMMS (where applicable).
Screwed Plates with Lifting Rings 	Governed by plate dimension and number of screws installed. Used for higher load panels (or reduced number of pick points).	D-ring plates and screws can be re-used. Can be time consuming to install. Consider impact to dunnage during shipping for pre-installed plates. Multiple plates required for a project will impact the cost. Provide either swivel lift ring or orient d-ring to pivot in same direction as chains/slings. Large number of penetrations into the TMMS.

Figure 8.1: *Point arrest and lifelines. (Photo courtesy of StructureCraft Builders Inc.)*

8.3 Fall Arrest and Horizontal Lifelines

Temporary fall arrest systems atop horizontal NLT are an important part of any installation plan, in addition to any fall arrest anchors required for permanent conditions. Both of these systems can be fastened directly to the NLT and provide sufficient capacity to meet OSHA requirements. They require specific engineering, which is usually provided by the installer's engineer. Give special consideration to load transfer requirements from the NLT to the supporting structure.

Panels that are covered with lumber wrap or adhesive membrane for weather protection also become very slippery when wet, posing an additional hazard during construction. For temporary fall arrest systems, D-plates can be fastened directly to the NLT and used for both point arrests and life lines; refer to Figure 8.1. Note that not all lifting systems are designed for fall arrest. Fall arrest engineering should be done in addition to lift engineering.

Permanent fall arrest anchors typically impose larger loads on the structure than temporary systems, because minimum clearances above the finished roof increase the height of the anchors. Local reinforcement of the NLT may be required at anchor locations to distribute the load to a sufficient number of laminations. If the anchor locations are coordinated early enough, reinforcing screws can be preinstalled in the NLT. In other cases, 45-degree screws attaching the anchor base plate to the NLT can function both as anchorage and as reinforcing. If fasteners for fall arrest anchors penetrate either the permanent or temporary waterproofing membrane, consider their impact on the integrity of the membrane.

8.4 Temporary Stability

To ensure proper alignment of elements before and after NLT installation, temporary stability supports may be applied to the structure supporting NLT floor panels as shown in Figure 8.2. NLT is heavier than light-frame wood construction and therefore less susceptible to wind uplift, but lateral loads such as horizontal fall arrest loads or seismic loads during construction must be considered. Install a limited number of fasteners between the NLT and its supports immediately to secure each panel in place.

If panels are stacked on the structure during installation, be sure to check the weight of the panel stacks against the design loads for the structure.

Wall panels require restraint for temporary construction loading such as wind. Shores are common and may take several forms, from bespoke built-up 2x6 braces with adjustable turnbuckles at either end, to pre-manufactured and adjustable metal shores.

References

[1] Karacabeyli, Erol, and Brad Douglas. 2013. *CLT handbook: cross-laminated timber*. Pointe-Claire, Québec: FPInnovations.

Figure 8.2: *Temporary stability supports. (Photo courtesy of StructureCraft Builders Inc.)*

Above *The Hudson, Portland, OR. Architecture: Mackenzie. (Photo credit: Christian Columbres Photography)*

Appendices

APPENDICES

Appendix A: NLT Appearance Chart

Figure A.1: *Significant wane and knots, inconsistent coloration. Loose vertical tolerance on placement of laminations.*

Figure A.2: *Minimal wane, some knot holes, variable coloration. Tight vertical tolerance on placement of laminations.*

Figure A.3: *No wane, minimal knot holes, variable coloration. Tight vertical tolerance on placement of laminations.*

Figure A.4: *No wane, no knot holes, consistent coloration. Tight vertical tolerance on placement of laminations.*

Appendix B: Sample Specification

PART 1 - GENERAL

1.1 RELATED DOCUMENTS

A. Drawings and general provisions of the Contract, including General and Supplementary Conditions and Division 01 Specification Sections, apply to this Section.

1.2 SUMMARY

A. Section includes nail-laminated timber (NLT) floor and roof decking, prefabricated in panels.

B. Related Sections:

1. Section 01 81 13 "Sustainable Design Requirements" for LEED requirements.
2. Section 05 12 00 "Structural Steel Framing" for custom-fabricated steel connection brackets.
3. Section 06 10 00 "Rough Carpentry" for dimension lumber framing.
4. Section 06 16 00 "Sheathing" for floor and roof sheathing.
5. Section 09 91 00 "Painting" for sealing and finishing requirements.

C. References:

1. ALSC, American Lumber Standard Committee Board of Review.
2. ALSC DOC PS20-15 American Softwood Lumber Standard.
3. APA, The Engineered Wood Association.
4. ASTM A153/A153M-16a Standard Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware.
5. ASTM E488/E488M-15 Standard Test Methods for Strength of Anchors in Concrete Elements.
6. ASTM F1667-15 Standard Specification for Driven Fasteners: Nails, Spikes, and Staples.
7. ICC-ES ESR-1539 Power-Driven Staples and Nails.
8. NDS 2015 National Design Specification for Wood Construction.
9. 2015 International Building Code.
10. For Projects overseen by a Construction Manager or Design-Build Contractor in lieu of a General Contractor, references to "Contractor" shall apply to the relevant Subcontractor(s).

1.3 ACTION SUBMITTALS

A. Product Data: For each type of factory-fabricated product. Submit proposed sealer for review and approval.

B. Shop Drawings: Connections and details, joint patterns, material specifications, and finishes, including an erection layout.

C. Provide a letter outlining steps to be taken during construction to ensure adequate weather protection of wood structures.

D. Sustainable Design Submittals: Per Section 01 81 13.

1.4 INFORMATIONAL SUBMITTALS

A. In lieu of grade stamping lumber exposed to view, submit manufacturer's certificate certifying that products meet or exceed specified requirements.

B. The fabricator and erector shall submit a QA/QC log of items such as but not limited to:

1. Environmental conditions at all stages, such as during fabrication, storage, transportation, erection, and ideally until building is completely finished.
2. Actual length, thickness, and width of the NLT panels. Length, width, thickness, and diagonal measurement are to be noted on the top surface of the panels.
3. Site deliveries, including verified load manifests with notes of damaged or missing materials and elements.
4. Material and element install with sign off for QC on hardware/fastener installation.
5. Equipment used, such as but not limited to torque drills (with torque clutch) for screw installation through steel plates etc.
6. Any changes or modifications.

The inclusion of representative pictures within the log is required.

1.5 QUALITY ASSURANCE

A. Perform Work in accordance with NDS and the following agencies:

1. Lumber Grading Agency: Certified by ALSC.
2. Plywood Grading Agency: Certified by APA.

B. Build mockups to demonstrate aesthetic effects and set quality standards for materials and execution.

1. Build one complete NLT panel with a minimum width of 48 inches.
2. Mockup must illustrate typical wood appearance, coating, and finish.
3. Keep mockup available to view as the standard of Work for remaining fabrication.
4. Approved mockups may become part of the completed Work if undisturbed at the time of Substantial Completion.

C. Build NLT panels in a shop environment for quality control. Shop fit panels during fabrication. Review with Consultant prior to proceeding further.

1.6 DELIVERY, STORAGE, AND HANDLING

A. Store all materials and assembled NLT panels under cover with proper drainage. Take particular care to protect exposed end grain. Protect from staining and damage at all times during fabrication, transportation, and installation.

B. Take all necessary precautions to keep NLT dry during and after installation, including temporary sloping tarps and UV protection.

PART 2 - PRODUCTS

2.1 DIMENSION LUMBER

A. Lumber Grading Rules: DOC PS20 and applicable rules of grading agencies indicated. If no grading agency is indicated, comply with the applicable rules of any rules-writing agency certified by the ALSC Board of Review. Grade lumber by an agency certified by the ALSC Board of Review to inspect and grade lumber under the rules indicated.

B. Do not grade stamp lumber exposed to view. Deliver to site with certificates as to species, grades, stress grades, seasoning, moisture content, and other evidence as required to show compliance with the Specifications.

C. Dress lumber, S4S, unless otherwise indicated.

D. Maximum Moisture Content: 19% unless noted otherwise.

E. Wood Members: SPF #1/#2 unless noted otherwise on the Drawings.

F. Finger-Jointed Lumber: Certified Exterior Joints, Heat-Resistant Adhesive (HRA), in accordance with ALSC.

2.2 CONNECTORS

A. Provide fasteners of size and type indicated that comply with requirements specified in this article for material and manufacture. Provide fasteners with hot-dip zinc coating complying with ASTM A153 or of Type 304 stainless steel.

B. Nails, Brads, and Staples: ASTM F1667.

C. Power-Driven Fasteners: ICC-ES ESR-1539.

D. Screws, Tight-Fit Pins and Bolts, Through-Bolts, Glued-In Rods, and Specialty Connectors: As specified on the Drawings.

E. Expansion Anchors: Anchor bolt and sleeve assembly with capability to sustain, without failure, a load equal to six times the load imposed when installed in unit masonry assemblies and equal to four times the load imposed when installed in concrete as determined by testing per ASTM E488 conducted by a qualified independent testing and inspecting agency.

F. Metal Straps and Ties: Galvanized Simpson Strong-Tie connectors or approved equal where required.

G. Structural Steel Connectors: As specified in Section 05 12 00. All steel and connectors shall be hot dip galvanized unless noted otherwise. Fabricate steel hardware and connections with joints neatly fitted, welded, and ground smooth. Test fit in shop.

2.3 MISCELLANEOUS MATERIALS

A. Moisture Barrier: Light gauge metal, asphalt-impregnated building paper, 1/4-inch-thick closed-cell foam gasket material, saturated felt roll roofing, or 6 mil polyethylene.

B. Wood Sealer: As specified in Section 09 91 00. Sealer shall be compatible with indicated finish. End sealer shall be effective in retarding the transmission of moisture at cross-grain cuts.

C. Specialty and/or proprietary products shown on the Drawings have been selected and specified based on the manufacturer's representation. The Consultant shall not become guarantor of the product. Install specialty products in strict conformance with the manufacturer's recommendations. Contractor is responsible for proper workmanship during installation.

NAIL-LAMINATED TIMBER – SAMPLE SPEC 06 15 29 - 3

2.4 PREFABRICATION

A. Hand select members to ensure straightness and architectural-quality appearance.

1. No wane, knot holes, grade stamps, or stains are permitted to be visible in the completed structure.
2. Where pine beetle kill wood is specified, hand select all members to ensure beetle staining is visible. Ensure staining is spatially distributed throughout NLT panels; avoid clusters of stained boards.
3. Assume a minimum of 30% - 40% lumber rejection rate to achieve acceptable appearance with #2 grade material. Higher grade material (e.g. J-grade or MSR lumber) will reduce the rejection rate and may be substituted for #2 grade material at Contractor's option.

B. Place soffits of timbers so the least number of checks and knots will be visible in the completed structure.

C. Arrange laminations in staggered pattern or aligned joint pattern as indicated on the Drawings.

1. For staggered pattern, stagger and nail together as indicated on the Drawings.
2. For aligned joint pattern, place laminations with joints centered over support members below. No joints are to be visible from below. Nail together as indicated on the Drawings.

D. Use common steel wire nails unless noted otherwise. Make tight connections between members. Install fasteners without splitting wood. Drive nails snug but do not countersink nail heads unless noted otherwise.

E. Substitution of common nails with power-driven nails of the same length and diameter is acceptable. Substitution of power-driven nails of smaller diameter is permitted only with the Consultant's approval.

F. Clearly mark top surface of NLT panels for identification during erection.

G. Apply a saturation coat of end sealer to ends and other cross-cut surfaces, keeping surfaces flood coated for not less than 10 minutes.

H. After end-coat sealing, apply a heavy saturation coat of penetrating sealer on surfaces of each NLT panel, or seal every lam prior to assembling.

2.5 FABRICATION TOLERANCES

A. Soffit Elevation of Individual Laminations: plus or minus 1/32 inch.

B. Panel Width: plus or minus 1/4 inch.

C. Panel Length: plus or minus 1/8 inch.

D. For rectangular panels, the corner-to-corner diagonal measurements should not deviate from each other by more than 1/8 inch.

PART 3 - EXECUTION

3.1 EXAMINATION

A. Confirm all dimensions prior to fabrication. Coordinate with shop drawings of other trades.

B. Examine supporting construction in areas to receive NLT, with Installer present, for compliance with requirements, installation tolerances, and other conditions affecting performance of the Work.

C. Proceed with installation only after unsatisfactory conditions have been corrected.

3.2 INSTALLATION

A. Provide temporary shores, guys, braces, and other supports during erection to keep NLT secure and in alignment against wind loads, seismic loads, temporary construction loads, and loads equal in intensity to design loads. Any failure to make proper and adequate provisions for stresses during erection shall be solely the responsibility of the Installer. Fasteners required for erection purposes are the responsibility of the Contractor and are to be included in the bid.

B. Fit NLT panels closely and accurately to required levels and lines without trimming, cutting, or other modifications, unless approved in writing by the Consultant.

C. Securely attach NLT to supports as indicated on the Drawings.

D. Site cutting or boring of NLT, other than shown on the shop drawings, is not permitted without written consent of the Consultant. Coat all field-cut openings with minimum two coats of clear sealer.

E. Provide sill gaskets below laminations and non-rigid vapor barrier sealant between laminations where assembly passes over exterior walls.

F. Provide moisture barrier at all locations where NLT abuts concrete or masonry construction. Acceptable barriers include light gauge metal, asphalt-impregnated building paper, closed-cell foam gasket material, saturated felt roll roofing, or 6-mil-thick polyethylene.

G. Provide gaps as required for construction tolerances and swelling. Details and locations shall be discussed with and approved by the Consultant in writing prior to construction. Gaps on the interior of the building are to be filled after the building is fully enclosed and temperature-controlled.

3.3 REPAIRS AND FINISHING

A. Prior to finishing, remove any stains, marks, or other damage that may have occurred during construction.

B. Provide field finish of NLT as specified in Section 09 91 00.

C. Final approval by Architect will be after installation of all NLT. Remove and replace all Work that does not conform to the standard of the approved mockup, at Architect's request. Replacement of defective Work is at Contractor's expense.

3.4 ERECTION TOLERANCES

A. For rectangular areas, the corner-to-corner diagonal measurements should not deviate from each other by more than 1/2 inch or 0.25% of the length of the shortest side of the rectangle, whichever is greater.

B. Overall Surface Levelness (Floors and Flat Roofs): 1/4 inch in 10 feet maximum.

C. Elevation: plus or minus 3/8 inch from theoretical.

D. Joints: 3/16 inch maximum gap between NLT panels or individual laminations unless noted otherwise.

END OF SECTION 06 15 29

Appendix C: Swelling & Shrinkage of Wood

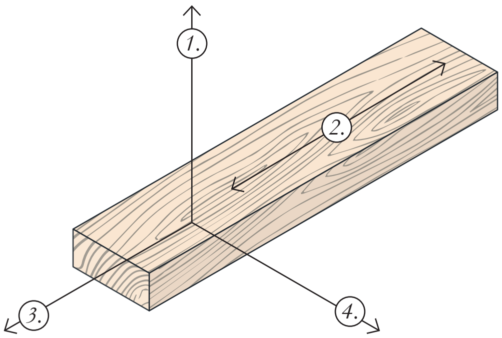


Figure C.1: *The three principal axes of wood grain*

Key

1. *Radial*
2. *Fiber direction*
3. *Longitudinal*
4. *Tangential*

Wood is a natural material, therefore its properties vary with the direction of the wood grain. As shown in Figure C.1, three directions of grain are identified: radial, longitudinal, and tangential.

Although there are no prescribed manufacturer standards for NLT, typical softwood species used to construct NLT include Douglas Fir (DF) and Spruce-Pine-Fir (SPF). Different species have different physical properties, including density and water vapor permeability.

As a natural hygroscopic material, wood experiences sorption and desorption; thus, its moisture content will change with exposure to both liquid water and water vapor within the surrounding environment. Changes in moisture content at or below fiber saturation point affect wood dimensions and structural properties. With regard to water vapor, the equilibrium moisture content (EMC) of wood will change with the temperature and relative humidity of the surrounding environment. The relationship of EMC and relative humidity at a given temperature is expressed as a sorption isotherm as shown in Figure C.2.

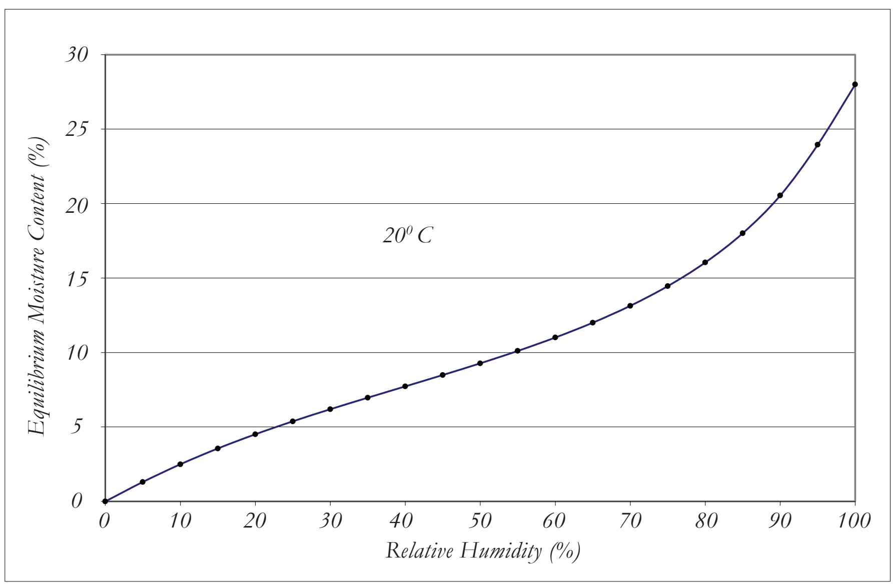
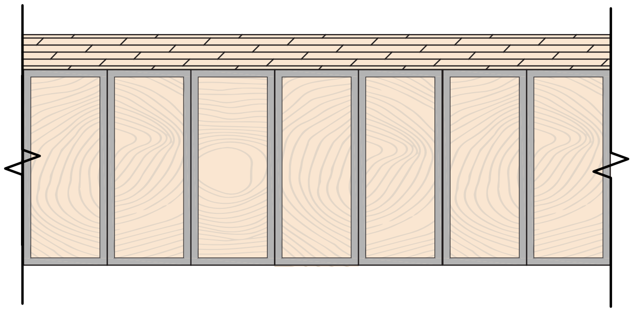
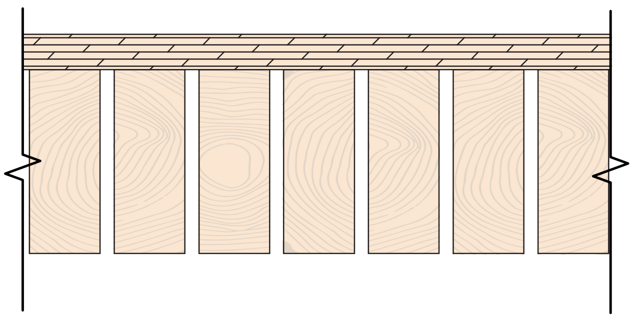


Figure C.2 *Wood moisture sorption isotherm at 68⁰F.*

Based on data from Forest Products Laboratory, USA. FPL (Forest Products Laboratory). 1999. Wood Handbook--Wood as an Engineering Material. Gen. Tech. Rep. FPL-GTR-113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory



Lamination expansion due to swelling



Lamination position after NLT has returned to lower moisture

Figure C.3: *Swelling and shrinkage in individual laminations (scale exaggerated to show general effect).*

Wood will change dimensionally with changes in moisture content most in the tangential direction, half as much in the radial direction, and a minimal amount (0.1% to 0.2%) in the longitudinal direction (United States Departement of Agriculture Forest Service, 2010). As longitudinal shrinkage/swelling is so small, it is generally ignored in the design and construction of NLT panels. Expected values of swelling can be calculated by estimating the material's installation moisture content and the maximum expected moisture content during a heavy rain event. Typically these values range from 12% to approximately 28% respectively. Values of shrinkage can be calculated by estimating the material's installation moisture content and the building's equilibrium moisture content. Typically, equilibrium values range from 8% to 12%.

When NLT gets wet, the wood fibers will fill with water and begin to swell. When NLT dries out and finds stable humidity and temperature levels, the individual laminations will shrink in cross section. When detailing NLT, consider both swelling during the construction phase and shrinkage during the first few years of building service life. This cycle can result in small gaps between the NLT laminations as shown in Figure C.3.