

CLT Handbook

CROSS-LAMINATED TIMBER

U.S.  EDITION

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FC Handbook

CROSS-LAMINATED TIMBER



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FPInnovations
Pointe-Claire, QC
Special Publication SP-529E

2013



Forest Products
Laboratory



WoodWorks



*Funding for this publication
was provided by*



Publication

FPInnovations
570 boul. St. Jean
Pointe-Claire (QC)
H9R 3J9
www.fpinnovations.ca

Distribution of hard copies

AWC
222 Catoctin Circle SE
Suite 201
Leesburg, VA 20175
www.awc.org

Library and Archives Canada Cataloguing in Publication

CLT handbook : cross-laminated timber / edited by Erol Karacabeyli,
Brad Douglas. -- U.S. ed.

(Special publication, ISSN 1925-0495 ; SP-529E)

Co-published by U.S. Department of Agriculture, Forest Service, Forest
Products Laboratory, Binational Softwood Lumber Council (BSLC).

Includes bibliographical references.

Issued also in electronic format.

ISBN 978-0-86488-553-1

1. Laminated wood. 2. Laminated wood construction. 3. Engineered
wood construction. 4. Laminated wood--Standards. 5. Laminated wood--
Handbooks, manuals, etc. I. Karacabeyli, Erol, 1954- II. Douglas, Brad, 1960-
III. Forest Products Laboratory (U.S.) IV. FPInnovations (Institute)
V. Binational Softwood Lumber Council VI. Title: Cross-laminated timber.
VII. Series: Special publication (FPInnovations (Institute)) ; SP-529E

TA666.C57 2013

624.1'84

C2012-908154-X

Library and Archives Canada Cataloguing in Publication

CLT handbook [electronic resource] : cross-laminated timber / edited
by Erol Karacabeyli, Brad Douglas. -- U.S. ed.

(Special publication, ISSN 1925-0509 ; SP-529E)

Co-published by U.S. Department of Agriculture, Forest Service, Forest
Products Laboratory, Binational Softwood Lumber Council (BSLC).

Includes bibliographical references.

Electronic monograph in PDF format.

Issued also in print format.

ISBN 978-0-86488-554-8

1. Laminated wood. 2. Laminated wood construction. 3. Engineered
wood construction. 4. Laminated wood--Standards. 5. Laminated wood--
Handbooks, manuals, etc. I. Karacabeyli, Erol, 1954- II. Douglas, Brad, 1960-
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VII. Series: Special publication (FPInnovations (Institute)) ; Online ; SP-529E

TA666.C57 2013

624.1'84

C2012-908155-8

PREFACE

Expansion into mid-rise, high-rise and non-residential applications presents one of the most promising avenues for the North American wood industry to diversify its end use markets. This may be achieved by:

- Designing to new building heights with **Light Frame Wood Construction**
- Revival of **Heavy Timber Frame Construction**
- Adoption of **Cross-laminated Timber (CLT)**
- Facilitating **Hybrid Construction**

There are concerted efforts both in Canada and in the United States towards realizing that goal. In fact, the Canadian provinces of British Columbia and Quebec went even further and created specific initiatives to support the use of wood in those applications.

This Handbook is focused on one of these options – adoption of cross-laminated timber (CLT). CLT is an innovative wood product that was introduced in the early 1990s in Austria and Germany and has been gaining popularity in residential and non-residential applications in Europe. The Research and Standards Subcommittee of the industry's CLT Steering Committee identified CLT as a great addition to the “**wood product toolbox**” and expects CLT to enhance the re-introduction of wood-based systems in applications such as 5- to 10-story buildings where heavy timber systems were used a century ago. Several manufacturers have started to produce CLT in North America, and their products have already been used in the construction of a number of buildings.

CLT, like other structural wood-based products, lends itself well to prefabrication, resulting in very rapid construction, and dismantling at the end of its service life. The added benefit of being made from a renewable resource makes all wood-based systems desirable from a sustainability point of view.

In Canada, in order to facilitate the adoption of CLT, FPInnovations published the Canadian edition of the CLT Handbook in 2011 under the Transformative Technologies Program of Natural Resources Canada. The broad acceptance of the Canadian CLT Handbook in Canada encouraged this project, to develop a U.S. Edition of the CLT Handbook. Funding for this project was received from the Binational Softwood Lumber Council, Forestry Innovation Investment in British Columbia, and three CLT manufacturers, and was spearheaded by a Working Group from FPInnovations, the American Wood Council (AWC), the U.S. Forest Products Laboratory, APA-The Engineered Wood Association and U.S. WoodWorks. The U.S. CLT Handbook was developed by a team of over 40 experts from all over the world.

Both CLT handbooks serve two objectives:

- Provide immediate support for the design and construction of CLT systems under the alternative or innovative solutions path in design standards and building codes;
- Provide technical information that can be used for implementation of CLT systems as acceptable solutions in building codes and design standards to achieve broader acceptance.

The implementation of CLT in North America marks a new opportunity for cross-border cooperation, as five organizations worked together with the design and construction community, industry, universities, and regulatory officials in the development of this Handbook. This multi-disciplinary, peer-reviewed CLT Handbook is designed to facilitate the adoption of an innovative wood product to enhance the selection of wood-based solutions in non-residential and multi-storey construction.

Credible design teams in different parts of the world are advocating for larger and taller wood structures, as high as 30 stories. When asked, they identified the technical information compiled in this Handbook as what was needed for those applications.

A Renaissance in wood construction is underway; stay connected.

ACKNOWLEDGEMENTS

The great challenge with this U.S. Edition of the CLT Handbook was to gather experts from the United States, Canada and Europe to bring together their expertise and knowledge into a state-of-the-art reference document. The realization of this Handbook was made possible with the contribution of many people and numerous national and international organizations.

Such a piece of work would not be possible without the support from financing partners and, as such, we would like to express our special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to this project.

First and most of all, we would like to express our gratitude to AWC, APA, USFPL, FPIInnovations, U.S. WoodWorks and their staff for providing the effort and expertise needed to prepare this work. We would also like to express our special thanks to all chapter authors, co-authors, and reviewers who shared their precious time and expertise in improving this manual.

Our very special thanks go to Loren Ross at AWC and Sylvain Gagnon at FPIInnovations for their work as project leaders and for their special efforts in gathering the expertise of everyone into a unique document. Special thanks also go to the Working Group, Dr. Borjen Yeh from APA, Dave Kretschmann from the U.S. Forest Products Laboratory, and Lisa Podesto from U.S. WoodWorks. Thanks also to Madeline Leroux for her work on the drawings, Odile Fleury for her help with bibliographic references, and Marie-Claude Thibault for her support in editing and coordination work.

Erol Karacabeyli, P.Eng. and Brad Douglas, P.E.

Co-editors

CLT Handbook, U.S. Edition

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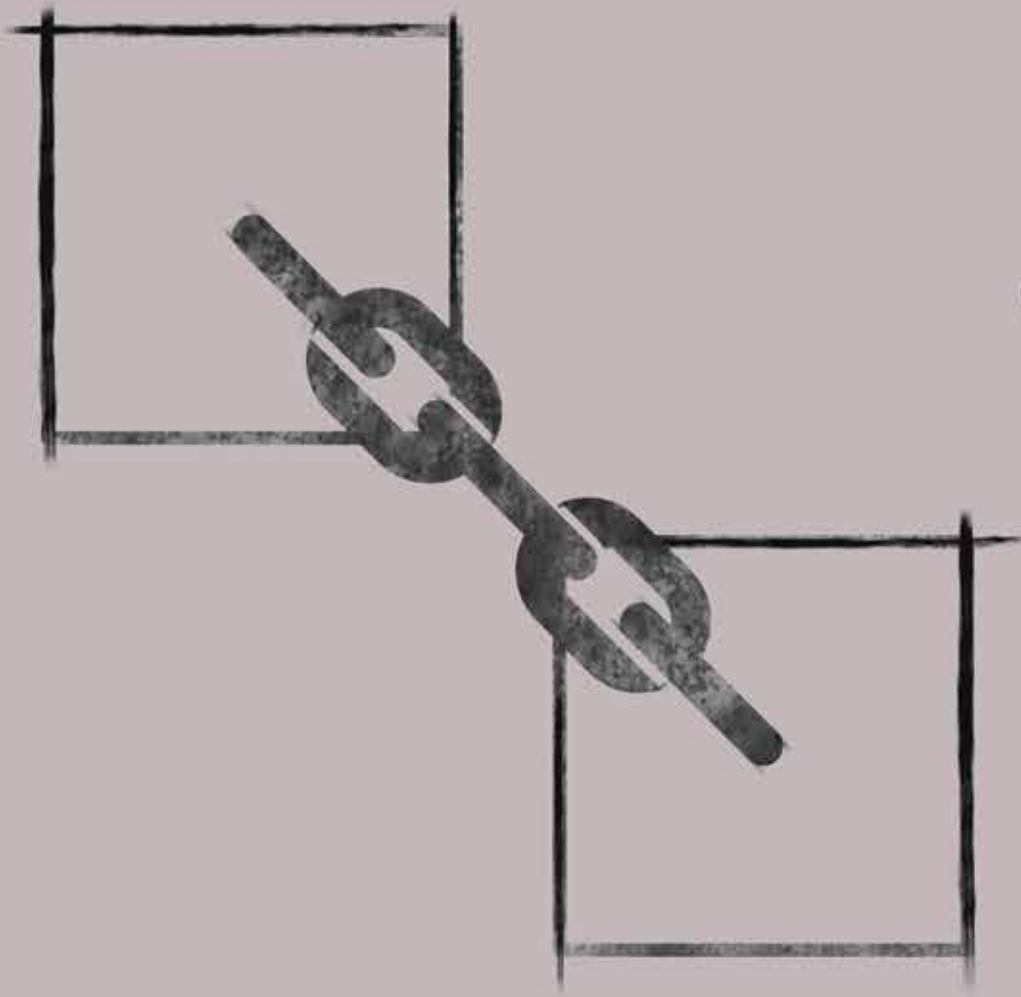
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ACKNOWLEDGEMENTS

The U.S. Edition of the CLT Handbook: *cross-laminated timber* combines the work and knowledge of American, Canadian and European specialists. The handbook is based on the original Canadian Edition of the CLT Handbook: *cross-laminated timber*, that was developed using a series of reports initially prepared by FPInnovations and collaborators to support the introduction of CLT in the North American market. A multi-disciplinary team revised, updated and implemented their know-how and technologies to adapt this document to U.S. standards.

The publication of this handbook was made possible with the special collaboration of the following partners:



The editing partners would also like to express their special thanks to Binational Softwood Lumber Council, Forestry Innovation Investment (FII), Nordic Engineered Wood, Structurlam, and CLT Canada for their financial contribution to studies in support of the introduction of cross-laminated timber products in the United States of America.



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ABSTRACT

The light weight of cross-laminated timber (CLT) products combined with the high level of prefabrication involved, in addition to the need to provide wood-based alternative products and systems to steel and concrete, have significantly contributed to the development of CLT products and systems, especially in mid-rise buildings (5 to 9 stories). While this product is well-established in Europe, work on the implementation of CLT products and systems has just begun in the United States and Canada. The structural efficiency of the floor system acting as a diaphragm and that of walls in resisting lateral loads depends on the efficiency of the fastening systems and connection details used to interconnect individual panels and assemblies together. A combination of metal brackets/plates and self-tapping screws or long self-tapping screws are typically recommended by the CLT manufacturers and are commonly used for connecting panels to panels in floors and floor-to-wall assemblies. However, there are other types of traditional and innovative fasteners and fastening systems that can be used efficiently in CLT assemblies.

This Chapter focuses on a few fastening systems that reflect present-day practices, some being conventional, while others are proprietary. Given the recent introduction of CLT into the construction market, it is expected that new connection types will be developed over time. Issues associated with connection design specific to CLT assemblies are presented. The European design approach is also presented and the applicability of the *National Design Specification (NDS) for Wood Construction* design provisions for traditional fasteners in CLT such as bolts, dowels, nails, and wood screws are reviewed and design guidelines are provided. Several design examples are also given at the end to demonstrate how connections in CLT can be established using current NDS design provisions.

The information given in this Chapter is aimed at U.S. designers, a group which expressed a strong interest in specifying CLT products for non-residential and multi-story applications. However, further studies are needed to assist designers in the development of U.S. engineering design specifications and procedures consistent with the U.S. material design standards and the International Building Code. The technical information will also be further used to facilitate code acceptance of CLT products in North America.

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1 CROSS-LAMINATED TIMBER IN CONSTRUCTION

Use of cross-laminated timber (CLT) panels in building construction has increased over the last few years. Several buildings have already been erected around the world, including North America, using CLT panels, which is a good testimony to the many advantages that this product offers to the construction industry. The light weight and the high quality of prefabrication of CLT result in quick erection times, especially in mid-rise construction (5 to 9 stories). While this product is well-established in Europe, work on the implementation of CLT products and systems has just begun in the United States and Canada.

The structural efficiency of the floor system acting as a diaphragm and that of walls in resisting lateral loads depends on the efficiency of the fastening systems and connection details used to connect individual panels and assemblies. This Chapter focuses on the design of connections for CLT construction based on current practices.



Figure 1
Typical CLT building with various components and connections

2

COMMON STRUCTURAL SYSTEMS IN CLT

There are several ways to design and construct CLT buildings. They all differ in the way the load-carrying panels/elements are arranged, the way the panels are connected together and by the type of wood and non-wood based materials used (such as the use of hybrid systems of construction). The most common forms of construction systems in CLT are:

Platform construction, where the floor panels rest directly on top of wall panels, therefore forming a platform for subsequent floors (Figure 2a). This is a typical North American light frame form of construction, except that CLT panels are used instead of stud wall systems with top and bottom plates. This is probably the most commonly used type of structural system in Europe for CLT assemblies, especially for multi-story buildings. This includes buildings constructed exclusively with CLT or mixing CLT with other types of wood-based products (e.g., CLT and glulam) or CLT with non-wood-based systems. There are several advantages to this system:

- it simplifies the erection of upper stories;
- simple connection systems can be used; and
- the load path is usually well-defined.

Balloon construction, a type of structural system where the walls continue for a few stories with intermediate floor assemblies attached to those walls. Due to the limitations in the length of the CLT panels and other design and construction issues, this system is often used in low-rise, commercial or industrial buildings. Connections are usually more complex in this form of construction. Balloon construction is generally less common compared to platform construction. As with platform construction, mixed CLT and other types of wood-based and non-wood-based products could also be used in the balloon type of systems.



(a)



(b)

Figure 2

Different types of CLT construction systems: (a) platform construction; (b) mixed CLT walls and light frame roof

3

INTRODUCTION TO CONNECTIONS IN CLT ASSEMBLIES - OVERVIEW

3.1 General

Connections in heavy timber construction, including those built with CLT, play an essential role in providing strength, stiffness, stability and ductility to the structure; consequently, they require careful attention by designers. Post-disaster surveys following strong earthquakes and hurricanes have shown that, among other reasons, structural failures often occur due to inadequately designed or improperly installed connections. The interruption of continuity in the timber structure caused by the presence of connections may result in a decrease in the overall strength and stiffness of the structure (i.e., if not properly designed or constructed) which in turn implies an increase in the cross-section of the assembled timber elements.

When structural members are attached with fasteners or some other types of metal hardware, such joints are referred to as “mechanical connections”. Typically, large fastener spacing as well as end and edge distances are required in most mechanical connections to avoid splitting and shear failures that are brittle in nature. The efficient design and fabrication of connections often determines the level of success of timber buildings when competing with other types of structural applications such as steel or concrete. This is particularly important for multi-story heavy timber structures and hybrid buildings, where CLT is used alone or could be used in combination with steel or concrete components.

The use of CLT panels enables a high degree of prefabrication at the plant. This is facilitated by the use of computer numerically controlled (CNC) machining technology to profile the panel for installation, at the plant, of conventional and sophisticated connection systems with a high degree of accuracy and efficiency. The dimensional stability of CLT products due to the use of kiln-dried (KD) source material is better for connection ‘stability’ prior to installation and ensures good accuracy at installation.

In this section, a very brief overview of connection types is provided. More detailed information is provided in Section 4 of this Chapter.

3.2 Connection Systems Commonly used in CLT Assemblies

Currently, there is a wide variety of fasteners and many different types of joint details that can be used to establish roof/wall, wall/floor, and inter-story connections in CLT assemblies or to connect CLT panels to other wood-based, concrete or steel elements in hybrid construction. While long self-tapping screws are typically recommended by CLT manufacturers and are commonly used for connecting panels to panels in floors and

floor-to-wall assemblies, traditional dowel-type fasteners such as wood screws, nails, lag screws, bolts and dowels can also be effectively used in connecting panel elements together. Other types of traditional fasteners, including bearing type fasteners such as split rings and shear plates, and tooth plates, may have some potential; however, their use is expected to be limited to applications where high loads are involved. Some interesting innovative connection systems are finding their way to the CLT construction market. These include glued-in rods, the KNAPP® system and other systems that adopt similar concepts. Such systems have good potential for use in CLT applications, especially those that employ a high degree of prefabrication using CNC machining technology. Fortunately, major CLT panel and glulam manufacturing facilities are equipped with CNC technology which could facilitate the rapid adoption of such connection systems. The choice of the type of connection to use depends largely on the type of assemblies to be connected (i.e., panel-to-panel, floor to wall, etc.), panel configurations, and the type of structural system used in the building.

The following sections provide some basic information on the most commonly used types of mechanical fasteners in CLT assemblies. Detailed applications of these fasteners are presented in Section 4 of this Chapter.

3.2.1 Wood and Self-tapping Screws

Wood and self-tapping screws are extensively used in Europe for the assembly of CLT panels (Figure 3). The ease of installation and the high lateral and withdrawal capacity of such screws make them quite popular among designers and builders as they can take combined axial and lateral loads. Wood screws and self-tapping screws come in a variety of sizes and specific features. Self-tapping screws are available in diameters up to 0.55 inch (14 mm) and lengths up to 59 inches (1500 mm), while common lengths are up to 39.4 inches (1000 mm). They do not require pre-drilling in most cases, unlike traditional wood or lag screws which require predrilled holes, the size of which depends on the density of the wood-based materials they are driven into and the diameter of the screws. The design capacity of screws in CLT must account for potential gaps in unglued cross plies and other artificially sawn grooves common in CLT fabrication.



Figure 3
Self-tapping screws used in CLT connections

3.2.2 Nails

Nails are not as commonly used in the assembly of CLT panels as wood screws. Nails with specific surface features such as grooves or helically threaded nails are mostly used with perforated metal plates and brackets and installed on the surface/plane of the panel (Figure 4). Most timber design standards do not allow the design of nailed connections in the end grain of wood-based products for withdrawal forces. Therefore, surface types of fasteners such as nails should not be driven in the edge of CLT panels (i.e., in end grain) to resist withdrawal forces. For lateral resistance, however, an end grain factor is usually applied to account for the reduction in the lateral resistance of nails driven in the end grain in most timber design standards, including NDS (AF&PA, 2005).



Figure 4

Pneumatically driven nails used in combination with perforated metal plates

3.2.3 Bolts and Dowels

Bolts and dowels are very common in heavy timber construction. They can also be used in the assembly of CLT panels, especially for lateral loading. If installed in the narrow face (on edge), care must be taken during the design, especially in CLT panels with unglued edges between the individual plank in a layer. This could eventually compromise the lateral resistance since there is a potential that such fasteners are driven in the gaps.

3.2.4 Bearing Types of Fasteners

While bearing-type fasteners such as split rings and shear plates are commonly used in connections of glulam, heavy sawn timber and structural composite lumber (SCL) such as parallel strand lumber (PSL), they are not widely used for the assembly of CLT panels. Bearing-type connections can be used in certain locations depending on the position of the fasteners with respect to the CLT layers and the type of service load.

3.2.5 Innovative Type of Fasteners

A new generation of fasteners, such as self-tapping screws and glued-in rods, are becoming increasingly popular in the assembly of mainstream heavy timber construction. This is driven by recent developments in CNC machining technology, wood materials and the desire for a high level of prefabrication to reduce assembly time and cost. With respect to CLT, glued-in rods in particular can be used for connections subjected to high longitudinal and transverse loads and to reduce the splitting potential (Augustin, 2008). More research work is needed in that area to evaluate the performance of such proprietary connection systems in CLT, especially for the American construction market.

4

CONNECTIONS IN CLT ASSEMBLIES - DETAILS

This section is focused on providing detailed information and schematics on traditional and innovative types of connection systems typically used in establishing connections between CLT panels, and those between walls and foundations and walls and floors. Figure 5 shows the various locations of such connections in a multi-story CLT building. While most of the commonly used types of fasteners and those with some potential for use in CLT assemblies are described hereafter, the list is not comprehensive. Other types of innovative proprietary fasteners, not mentioned under this section, could also be used, if found suitable.

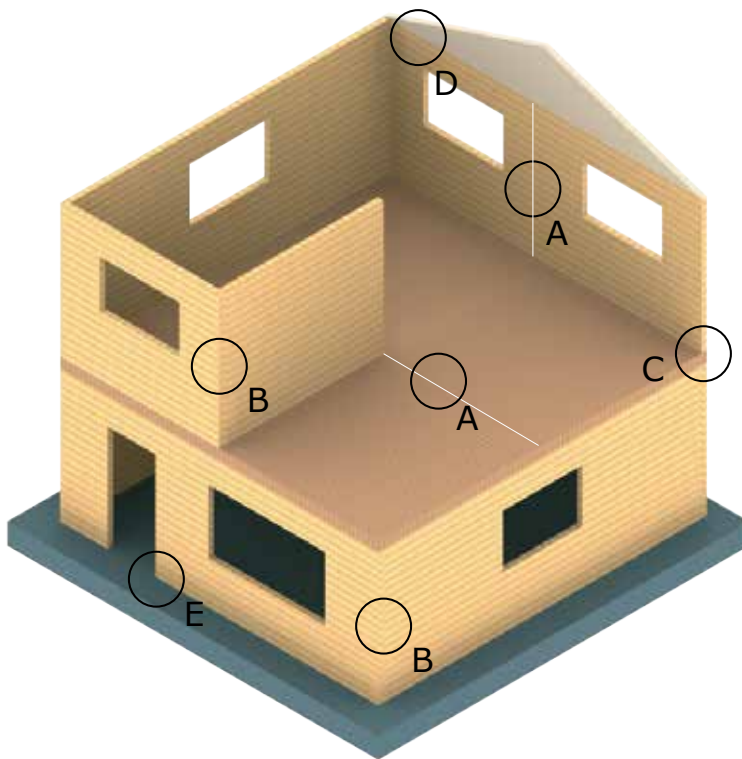


Figure 5

Typical two-story CLT building showing various connections between floor and wall panels

4.1 Panel-to-panel (Detail A)

This is the fundamental form of connection that is typically used to form wall and floor assemblies. It is used to connect panels along their longitudinal edges. Due to production and transport limitations related to the size of the panel that can be delivered to building sites, panel-to-panel connections are established mostly on site. Connection details must be easy to assemble and should facilitate quick fabrication. The panel-to-panel connection facilitates the transfer of in- and out-of-plane forces through the wall or floor assembly. For example, when panel-to-panel connections are used in wall assembly, the connection must be designed to resist in-plane shear and out-of-plane bending. When the connection is used in floor assemblies acting as diaphragms, however, the connection must be capable of transferring in-plane diaphragm forces in principle, and maintain the integrity of the diaphragms and the overall, lateral load resisting system. Several possible panel-to-panel connection details are described below.

4.1.1 Internal Splines

Single or double wooden splines/strips made of lumber, SCL such as laminated veneer lumber (LVL), thin CLT or plywood could be used to form this connection. Profiling of the panel at the plant is necessary prior to delivery on site. Connection between the spline(s) and the two panel edges could be established using self-tapping screws, wood screws or nails. One advantage of this detail is that it provides a double shear connection. However, it requires more accurate profiling and could be challenging in terms of fitting the different parts together on site. There are also other advantages regarding resistance to normal or out-of-plane loading. Structural adhesive could also be applied to the different parts in addition to the mechanical fasteners to provide more rigidity to the connection, if needed. Schematic of a single internal spline is shown in Figure 6 below. An example of a double internal splines commonly adopted by some CLT manufactures in Europe is shown in Figure 7.

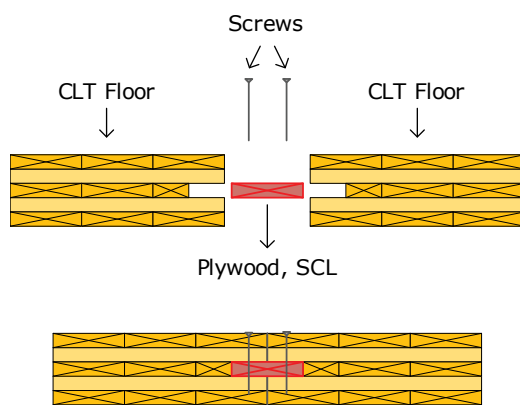


Figure 6
Single internal spline



Figure 7
Double internal splines (Courtesy of Kevin Meechan and U.S. WoodWorks)

4.1.2 Single Surface Spline

This is a rather simple connection detail that can be established quickly on site. Panel edges are profiled to take a strip/spline of lumber or SCL such as LVL, PSL or laminated strand lumber (LSL) (Figure 8). Traditional fasteners such as nails, wood screws and lag screws can be used for making the connection on site. Proprietary types of fasteners such as self-tapping screws are commonly used in Europe. Due to the single shear connection involved, this connection detail is typically inferior to the internal spline previously described. Structural adhesive could also be used in this type of connection detail.

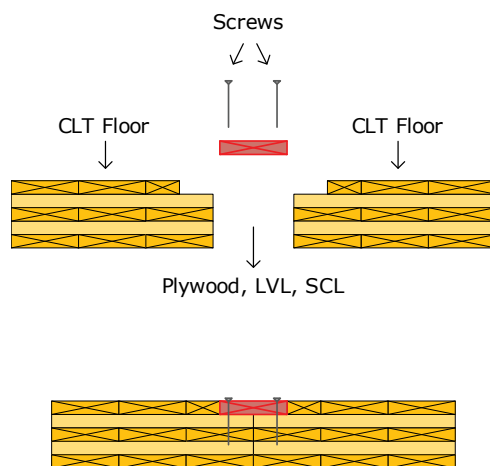


Figure 8
Single surface spline

4.1.3 Double Surface Splines

This connection detail is similar to that of the single surface spline previously described, except that a double spline is used here to increase the connection strength and stiffness (Figure 9). Since two sets of screws are used, which results in doubling the number of shear planes resisting the load, a better resistance can be achieved using this detail. However, this connection requires more machining and more time could be needed for erection since there is a need to attach the two splines from both sides of the panels during the insertion of fasteners, doubling the time needed for driving fasteners. According to Augustin (2008), if SCL is used as the splines, then the joint could be designed to resist moment for out-of-plane loading. Structural adhesives could be used to enhance the strength and stiffness.

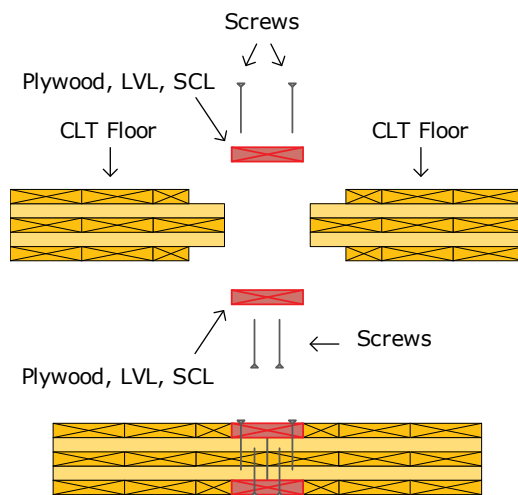


Figure 9
Double surface spline

4.1.4 Half-lapped Joint

This connection detail involves milling a half-lapped joint at the plant and is commonly used for panel-to-panel connections in wall and floor assemblies (Figure 10). Long self-tapping screws are usually used to connect the panel edges. The joint can carry normal and transverse loads but is not considered to be a moment resisting connection (Augustin, 2008). While this is a very simple connection detail that facilitates quick assembly of CLT elements, there is a risk of splitting of the cross section due to concentration of tension perpendicular to grain stresses in the notched area. This is particularly pronounced for cases where uneven loading on the floor elements occur (Augustin, 2008).

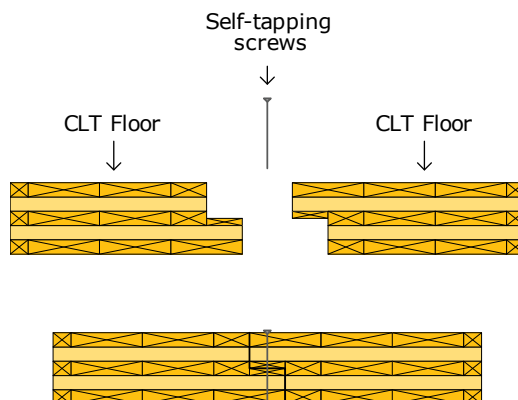


Figure 10
Details of half-lapped joints

4.1.5 Tube Connection System

This is an innovative type of connection system that has been developed and studied in Austria by G. Traetta (2007). This system incorporates a profiled steel tube with holes (Figure 11). Panel elements arrive on site with glued-in or screwed rods driven in the plane of the two panels to be connected and with holes machined in the panels at certain locations along the edges where the metal tubes could be placed. The tube connector is inserted at those locations along the panel elements and the system is tightened on site using metal nuts.

Tests were carried out at the Building Research Center in Graz, Austria to evaluate the capacity of this innovative system (Traetta, 2007). Usually no edge profiling along the panel is needed if this connection system is used as it relies principally on the pullout resistance of the screwed or glued-in rods.

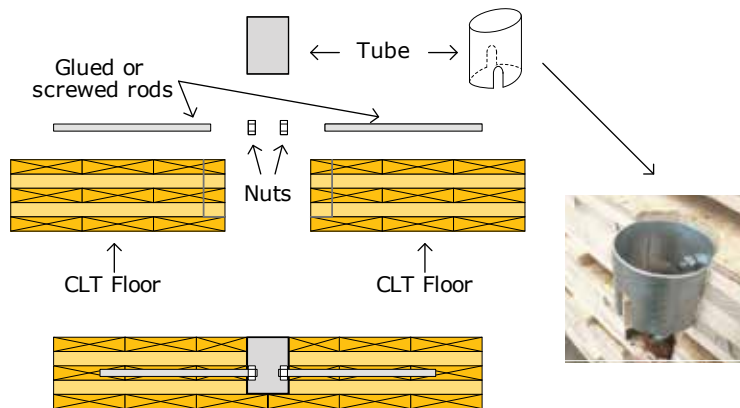


Figure 11
Details of the tube connection system

4.2 Wall to Wall (Detail B)

This section covers connection details for connecting walls to walls positioned at right angles (wall junction in the transverse direction). Such connection details include interior partitions to exterior walls or simple exterior corner walls. Walls connected in the same plane of the panels were covered previously under panel-to-panel connections (Detail A). Most of the connection details described hereafter are commonly used in the assembly of CLT walls. However, a few of these involve the use of innovative types of connection systems or details with some potential for use in such applications. The same connection systems adopted for connecting exterior walls in the transverse direction could be used for establishing connection between internal walls.

4.2.1 Self-tapping Screws

Several systems have been adopted to establish connection between walls at right angles (wall junction). The simplest form of connection relies mainly on self-tapping screws to connect the walls together (Figure 12). There are some concerns however related to this direct form of connection due to the fact that the screws are driven in the narrow side of panels, in particular if screws are installed in the end grain of the cross layers. While this may not be critical for small loads, it may not be suitable for walls subjected to high wind and seismic loads. Self-tapping screws could also be driven at an angle to avoid direct installation of screws in the narrow side of the panel (on edge) which would optimize the performance of the connection (i.e., toe screwing) (Figures 13 and 14).

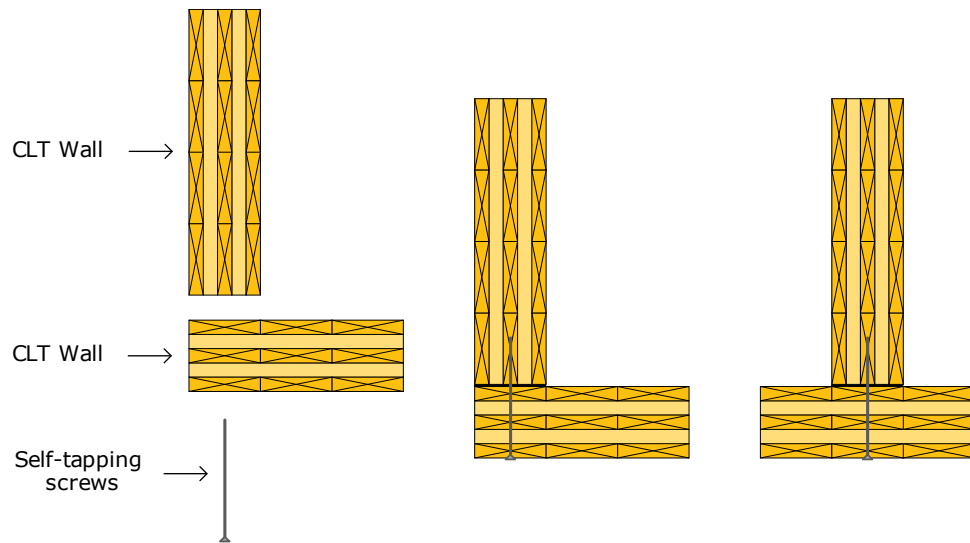


Figure 12
Self-tapping screws from the exterior



Figure 13
Installation of self-tapping screws from the exterior (courtesy of U.S. WoodWorks)

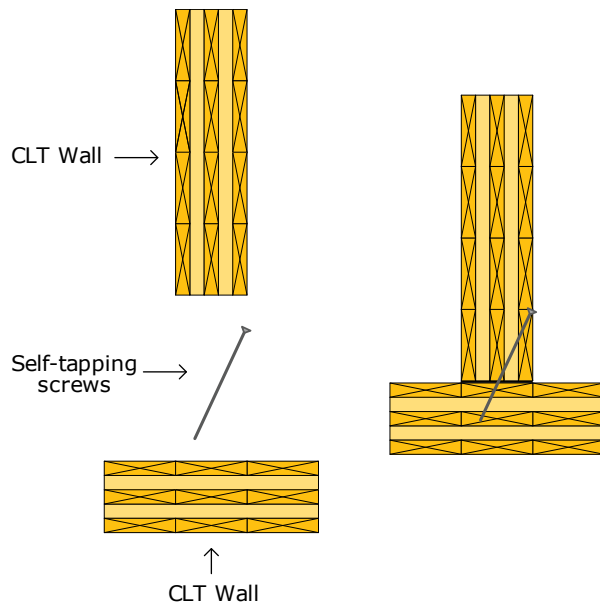


Figure 14
Self-tapping screws driven at an angle (toe-screwing)

4.2.2 Wooden Profiles

Concealed wooden profiles (keys) could also be used in a similar way, with self-tapping screws or traditional wood screws. The advantage of this system over the direct use of self-tapping screws is the possibility of enhancing the connection resistance by driving more wood screws to connect the profiled panel to the central wood profile/key which is in turn screwed to the transverse wall (Figure 15).

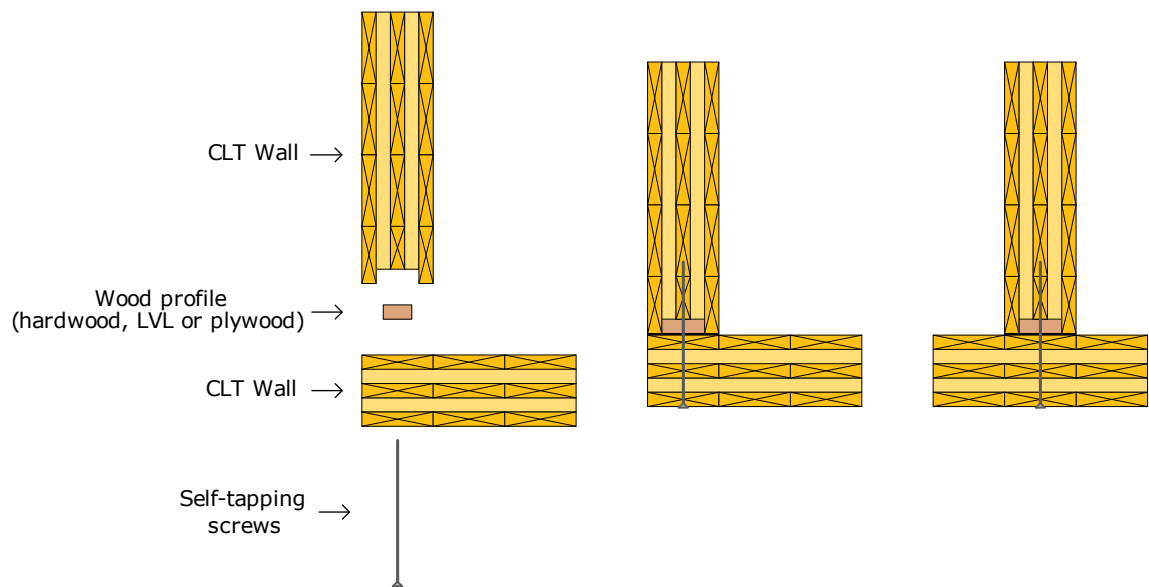


Figure 15
Concealed wooden profile

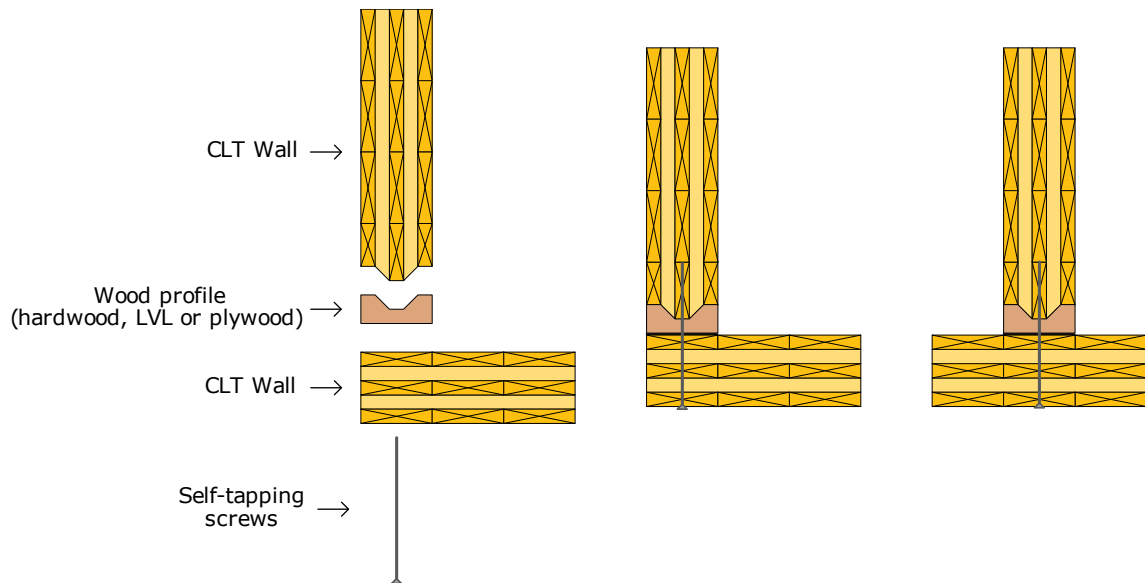


Figure 16
Edge protecting wooden profile

Other types of wooden profiles such as the one shown in Figure 16 could also be used to provide some form of reinforcement to the panel connected edges. Those are mainly made of high density hardwood or SCL. They are glued and screwed to the panel edge as mentioned earlier.

4.2.3 Metal Brackets

Another simple form of connecting walls in the transverse direction is the use of metal brackets with screws or nails (Figure 17). This connection system is one of the simplest and most efficient types of connection in terms of strength resulting from fastening in the direction perpendicular to the plane of the panels or recessed. Adding protective membrane (i.e., gypsum board) for improved fire resistance is required, however.

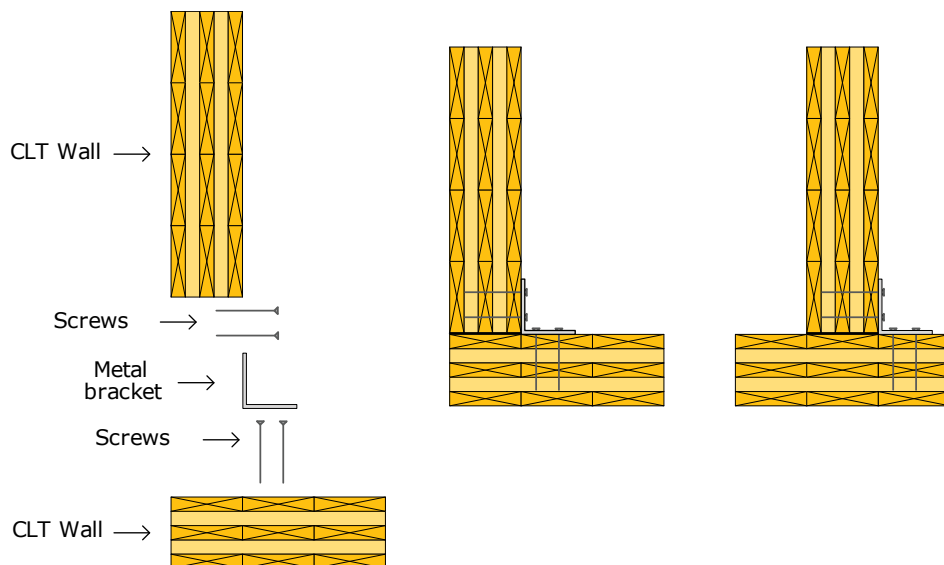


Figure 17
Interior metal bracket

4.2.4 Concealed Metal Plates

Concealed metal plates can also be used to establish wall-to-wall connection in the transverse direction. Metal plate thickness could range from 0.24 inch (6 mm) up to 0.47 inch (12 mm). As previously discussed, while this system has considerable advantages over exposed plates and brackets, especially when it comes to fire resistance, the system requires precise profiling at the plant using CNC machining technology (Figure 18). Proprietary self-drilling dowels that can penetrate through wood and steel (Figure 19) could also be used but design information on performance must be obtained from the manufacturer.

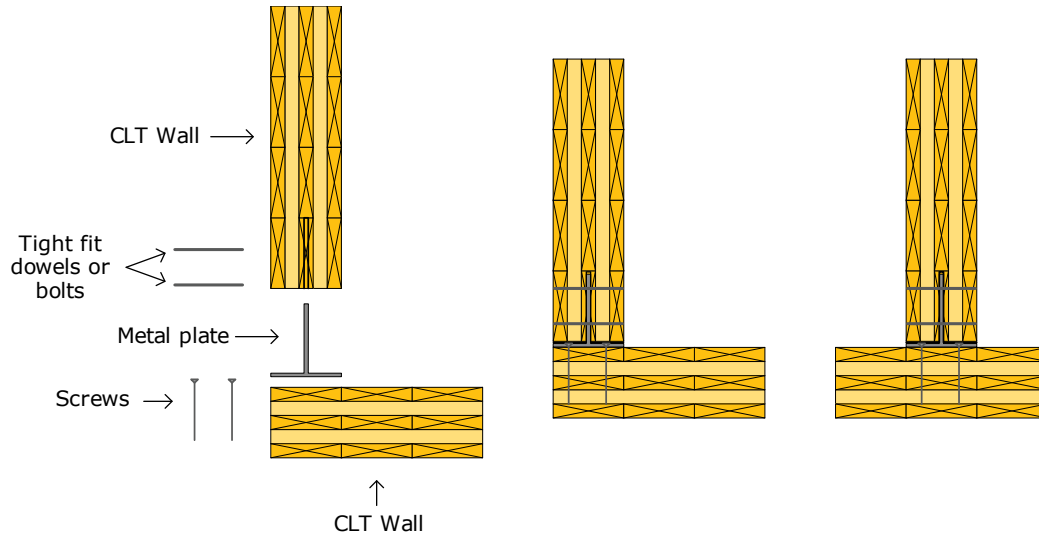


Figure 18
Concealed metal plate



Figure 19
Self-drilling dowel through steel and wood (Courtesy of SFS Intec)

4.3 Wall to Floor (Detail C)

Several possibilities exist when it comes to connecting walls to the floors above or connecting walls on the upper stories to floors, depending on the form of structural systems (i.e., platform vs. balloon), availability of fasteners and the degree of prefabrication. When platform construction is used, cumulative effects of bearing deformations should be addressed in the connection design.

4.3.1 Platform Construction

4.3.1.1 Self-tapping Screws

For connecting a floor or a roof to walls below, the simplest method is to use long self-tapping screws driven from the CLT floor directly into the narrow side of the wall edge, as shown in Figure 20. Self-tapping screws could also be driven at an angle to maximize the fastening capacity in the panel edge. The same principle could be applied for connecting walls above to floors below, where self-tapping screws are driven at an angle in the wall near the junction with the floor. Depending on the angle and the length of the screws, the self-tapping screws could reach the bottom walls, further reinforcing the connection between the upper and lower walls and the floor.

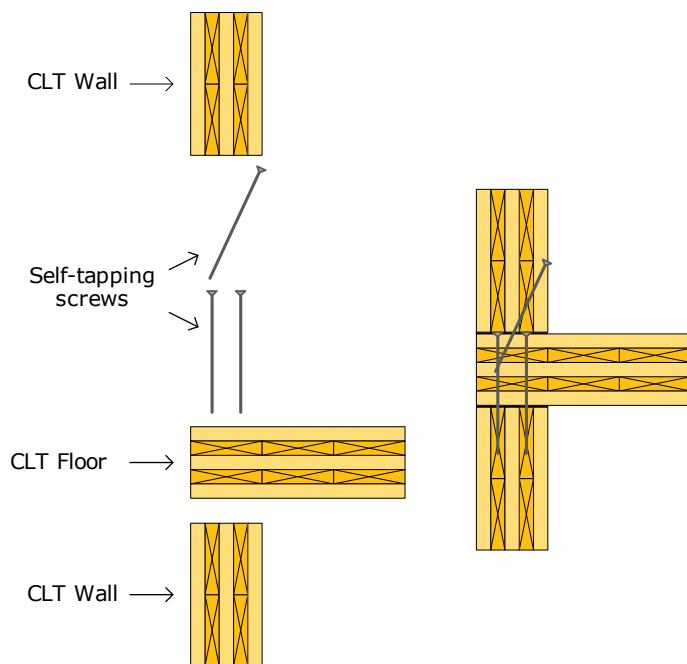


Figure 20
Self-tapping screws

4.3.1.2 Metal Brackets

Metal brackets are commonly used to connect floors to walls above and below to transfer, when required, lateral loads from one lateral load resisting system to another (e.g., from diaphragm to shearwalls). They are also used for connecting roofs to walls. Nails or wood screws could be used to attach the metal brackets to the CLT panels (Figures 21 and 22).

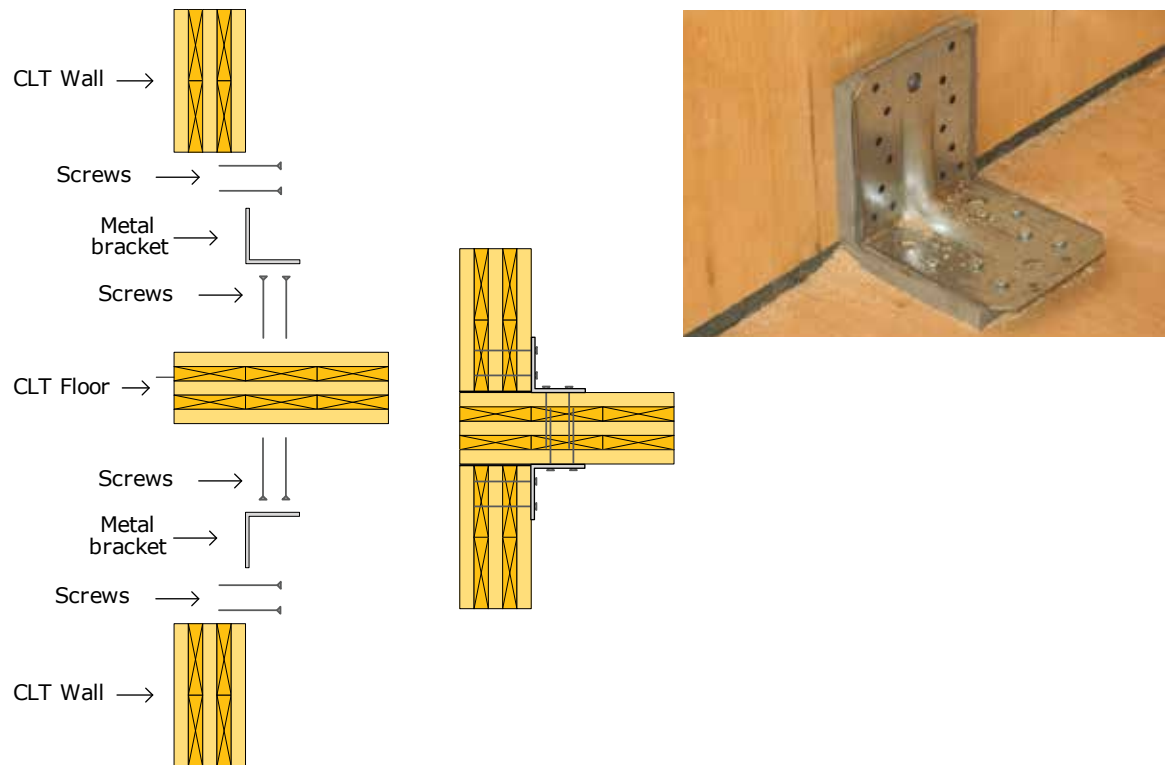


Figure 21
Metal brackets

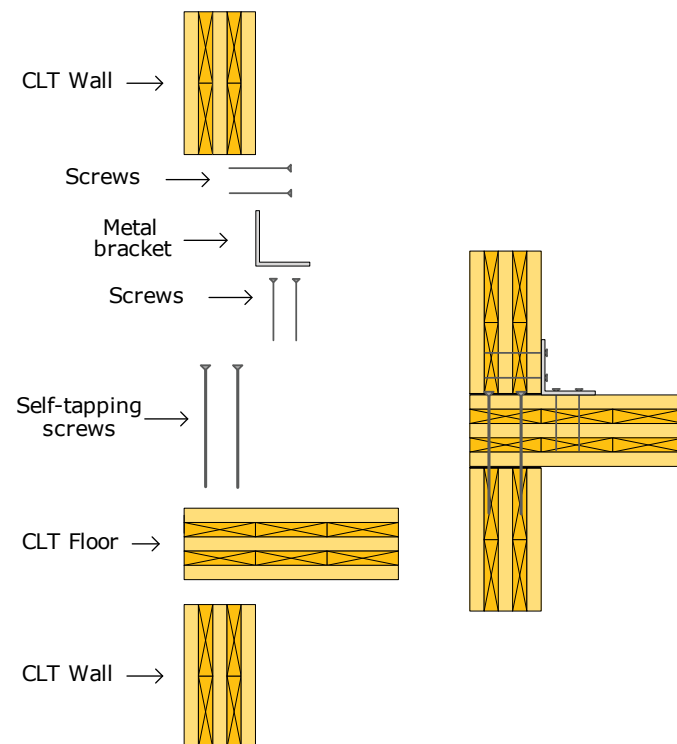


Figure 22
Metal bracket and self-tapping screws

4.3.1.3 Concealed Metal Plates

Concealed metal plates could also be used to establish wall-to-floor connections (Figure 23). As discussed above, while this system has considerable advantages over exposed plates and brackets, especially when it comes to fire resistance, the system requires precise profiling at the plant using CNC machining technology.

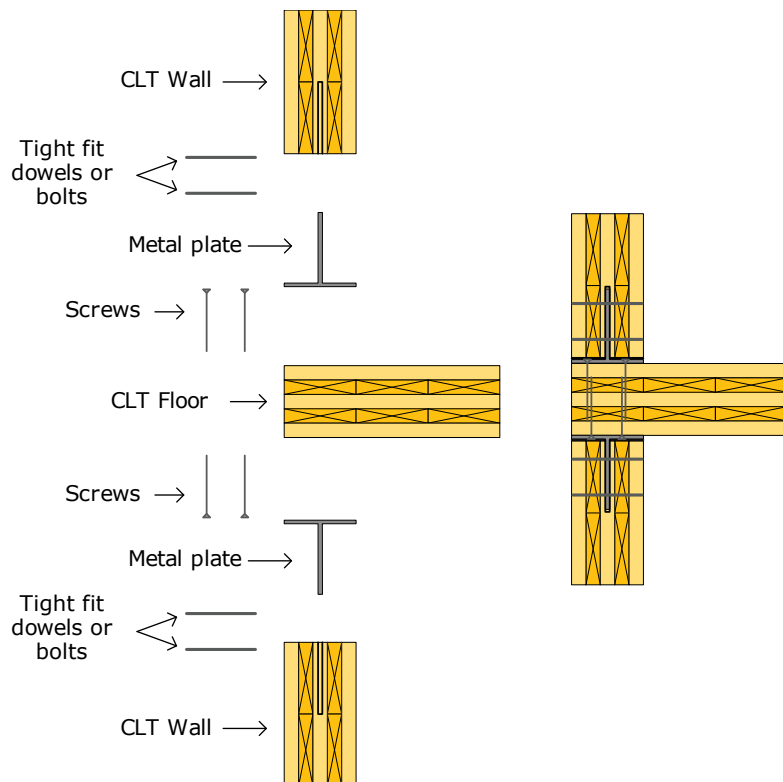


Figure 23
Concealed metal plates

4.3.2 Balloon Construction

The dominant type of structural form in CLT construction in Europe is the platform type of system due to its simplicity in design and erection. However, in non-residential construction, including farm and industrial buildings, it is common to use tall walls with a mezzanine which is an intermediate floor between the main floors of a building. A mezzanine floor is often located between the ground floor and the first floor; however, it is not unusual to have a mezzanine in the upper floors of a building.

To connect a typical CLT floor to a continuous CLT tall wall for such applications, several attachment options exist. The simplest attachment detail includes the use of a wooden ledger to provide a continuous bearing support to the CLT floor panels (Figure 24). The ledger is usually made of SCL such as LVL, LSL or PSL. CLT ledger could also be used. Another type of attachment is established with the use of metal brackets similar to the one shown in Figure 25 (a and b). Attachment of SCL ledger or metal brackets to the CLT wall and floor panels is established through the use of screws, lag screws or nails. However, out-of-plane bending due to wind suction could be an issue with this type of detail and designers need to take that into account.

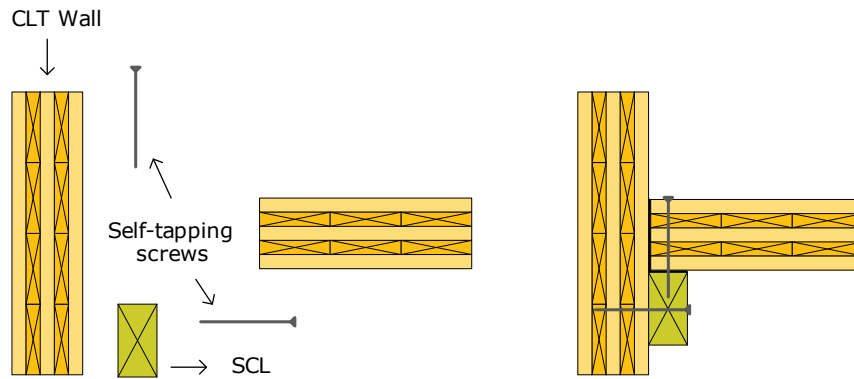
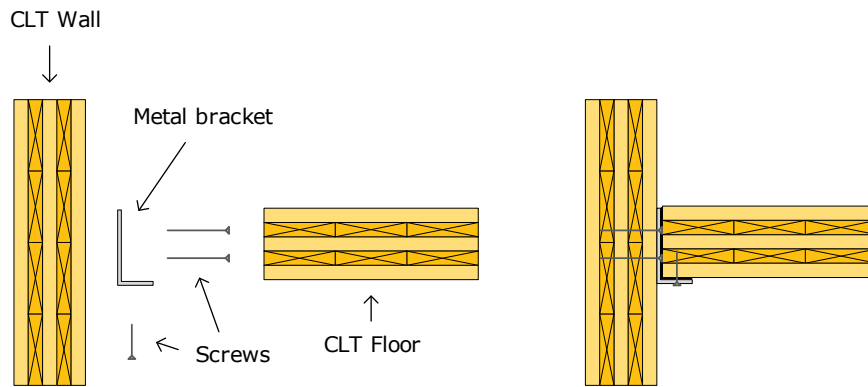
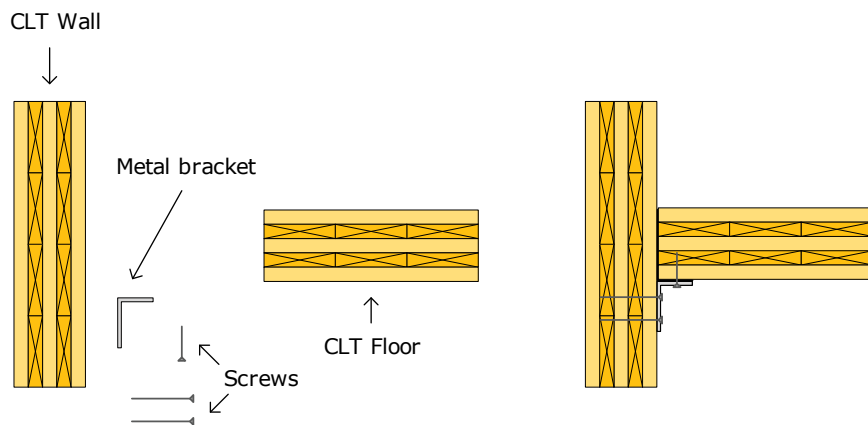


Figure 24

SCL components for bearing support (adapted from TRADA 2009)



(a)



(b)

Figure 25

Metal bracket used to provide bearing support (adapted from TRADA, 2009)

4.4 Roof to Wall (Detail D)

For sloping or flat roof to wall connections, a connection similar to those used for attaching floors to walls is used (Figure 26). Screws and metal brackets are the most commonly used fastening systems in this application (Figures 27 and 28).

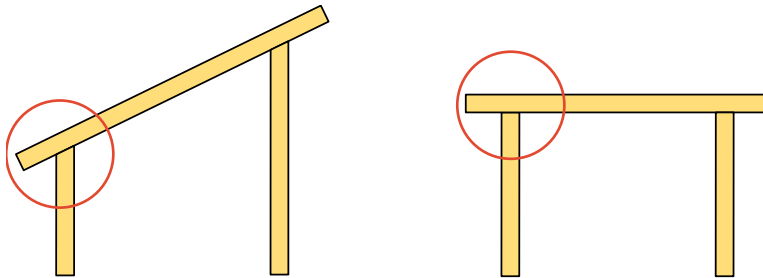
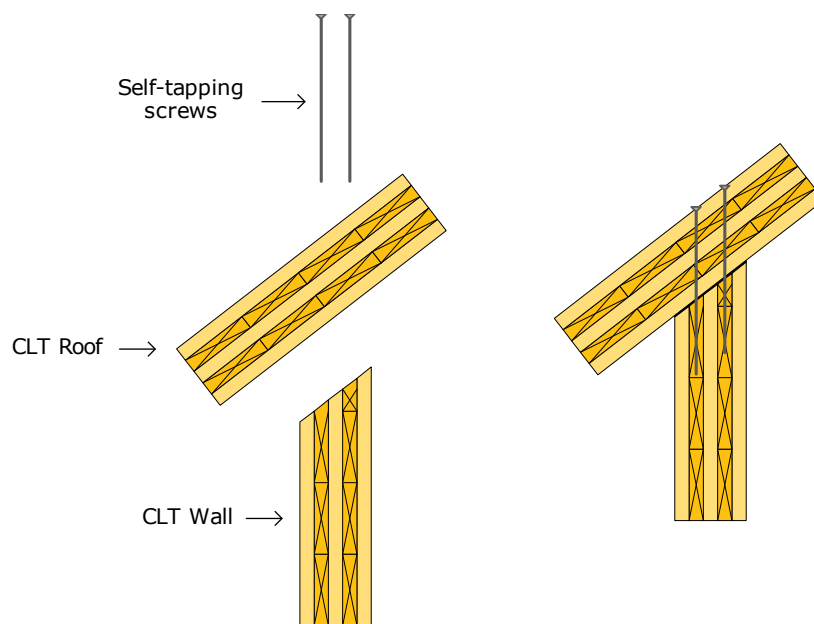
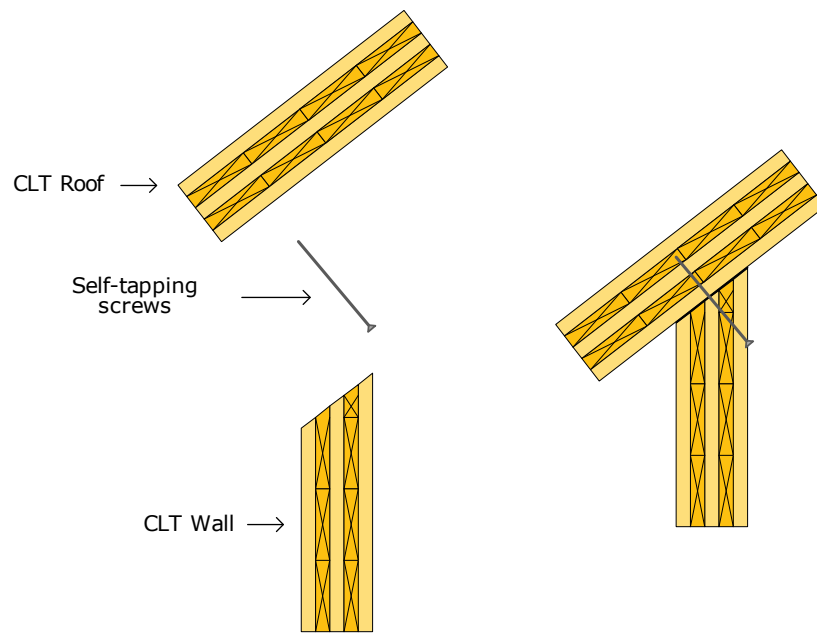


Figure 26
Possible roof-to-wall joints configurations



(a)



(b)

Figure 27
Self-tapping screws

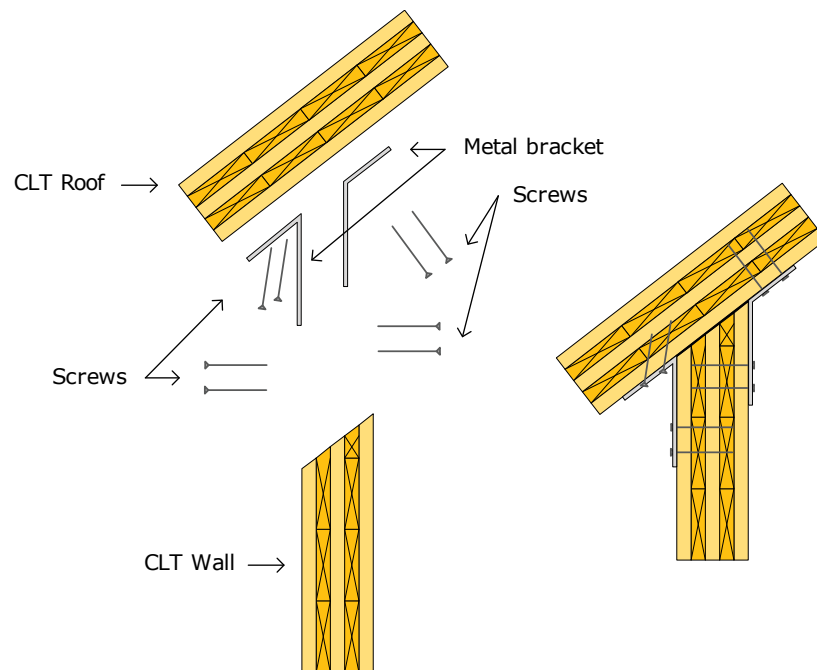


Figure 28
Metal brackets

4.5 Wall to Foundations (Detail E)

4.5.1 Visible/Exposed Plates

In connecting CLT wall panels to concrete foundations (common for the first story in a CLT building with concrete footing or with a multi-story CLT building with the first story made of concrete) or to steel beams, several fastening systems are available to establish such a connection. Exterior metal plates and brackets are commonly used in such applications as there is a variety of such metal hardware readily available on the market. Exposed steel plates similar to those shown in Figure 29 are probably the most commonly used in Europe due to their simplicity in terms of installation. When connections are established from outside, a typical metal plate is used (Figures 29 and 30). However, when access is provided from inside the building and where a concrete slab exists, metal brackets such as those shown in Figures 31 and 32 should be used. Lag screws or powder-actuated fasteners can be used to connect the metal plate to the concrete footing/slab, while lag screws or self-tapping screws are used to connect the plate to the CLT panel. It should be noted, however, that exposed metal plates and fasteners need to be protected against corrosive exterior environments. Galvanized or stainless steel should be used in such cases.

Direct contact between the concrete foundation and CLT panel should be avoided in all cases. To protect wood and improve the durability of CLT panels, a preservative-treated wood or SCL sill plate (or bottom plate) such as that shown in Figure 29 is installed between the concrete foundation and the CLT panels. This also simplifies the assembly. Contact can also be established through the use of special profiled steel brackets installed at the interface between the CLT panel and the concrete (Figure 30). Moreover, connection details should be designed to prevent potential moisture penetration between the metal plates and the CLT wall as water may get trapped and cause potential decay of the wood.

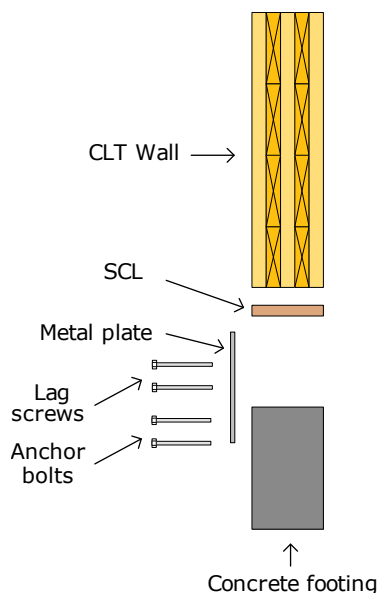


Figure 29
Exterior metal plate



Figure 30

Example of a connection detail with a gap between CLT wall and concrete foundation

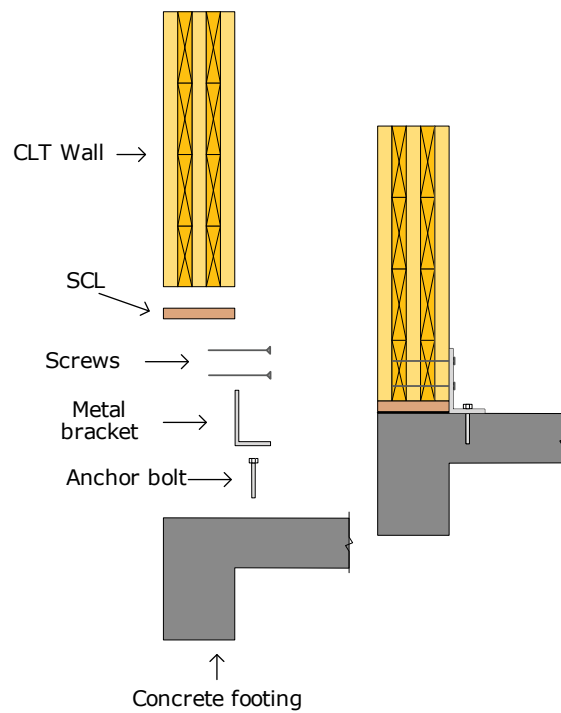


Figure 31

Metal brackets



Figure 32
Metal brackets installed on site

4.5.2 Concealed Hardware

To achieve better fire resistance and improve aesthetics, designers sometimes prefer concealed connection systems. Hidden metal plates similar to those shown in Figure 33 below can be used. However, some machining (sometimes precise CNC machining) is required to produce the grooves in the CLT panel to conceal the metal plates. Tight dowels or bolts could be used to attach the plates to the CLT panel. Some innovative types of fasteners that can be drilled through metal and wood or other types of screws that can penetrate through both materials can also be used for this purpose.

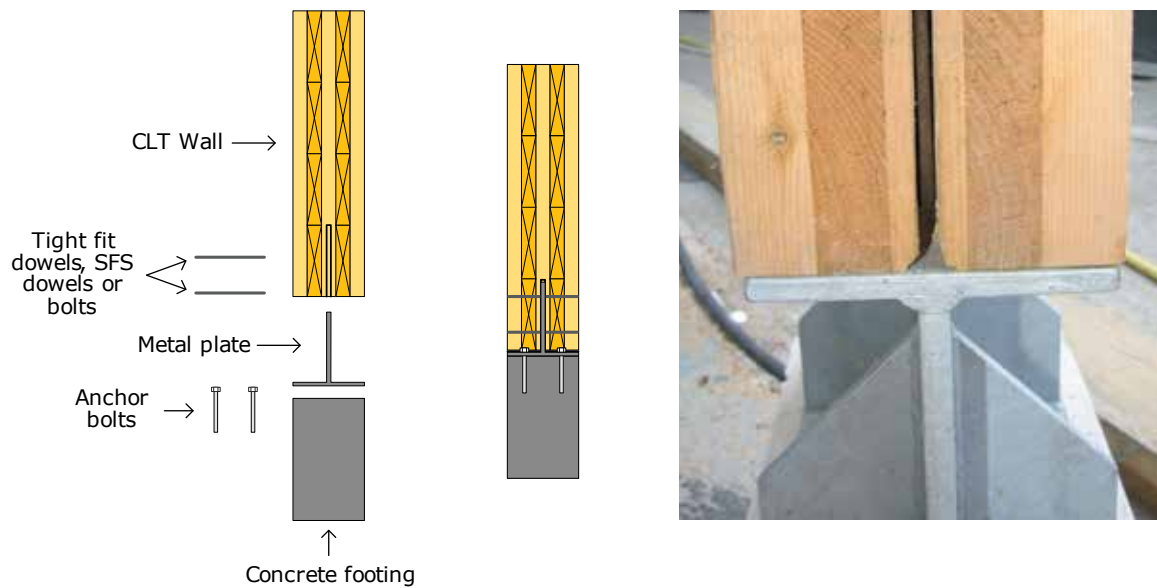


Figure 33
Concealed metal plates

4.5.3 Wooden Profiles

Wooden profiles are commonly used in connecting structural insulated panels (SIP) and other types of prefabricated wood-framed walls. It is important that such wooden profiles are fabricated from high density and stable materials. Engineered wood products or high density hardwood can generally be used for this purpose. The major advantage of this system is the ease of assembly. The wooden profiles are typically attached to CLT panels with wood screws or self-tapping screws. Structural adhesives are also used, sometimes in combination with mechanical fasteners since the wooden profile is installed in the panel. They are often used in combination with metal plates or brackets to improve the lateral load resistance as can be seen in Figure 34 below. CNC machining is needed at the CLT plant to produce the profiles in the panels. The use of wooden profiles is not limited only to wall-to-foundation applications. They can also be used for wall-to-wall or floor-to-wall connections. The wooden profiles could take several forms as can be seen in Figure 34, to provide additional protection and reinforcement to the bottom edge of the panel.

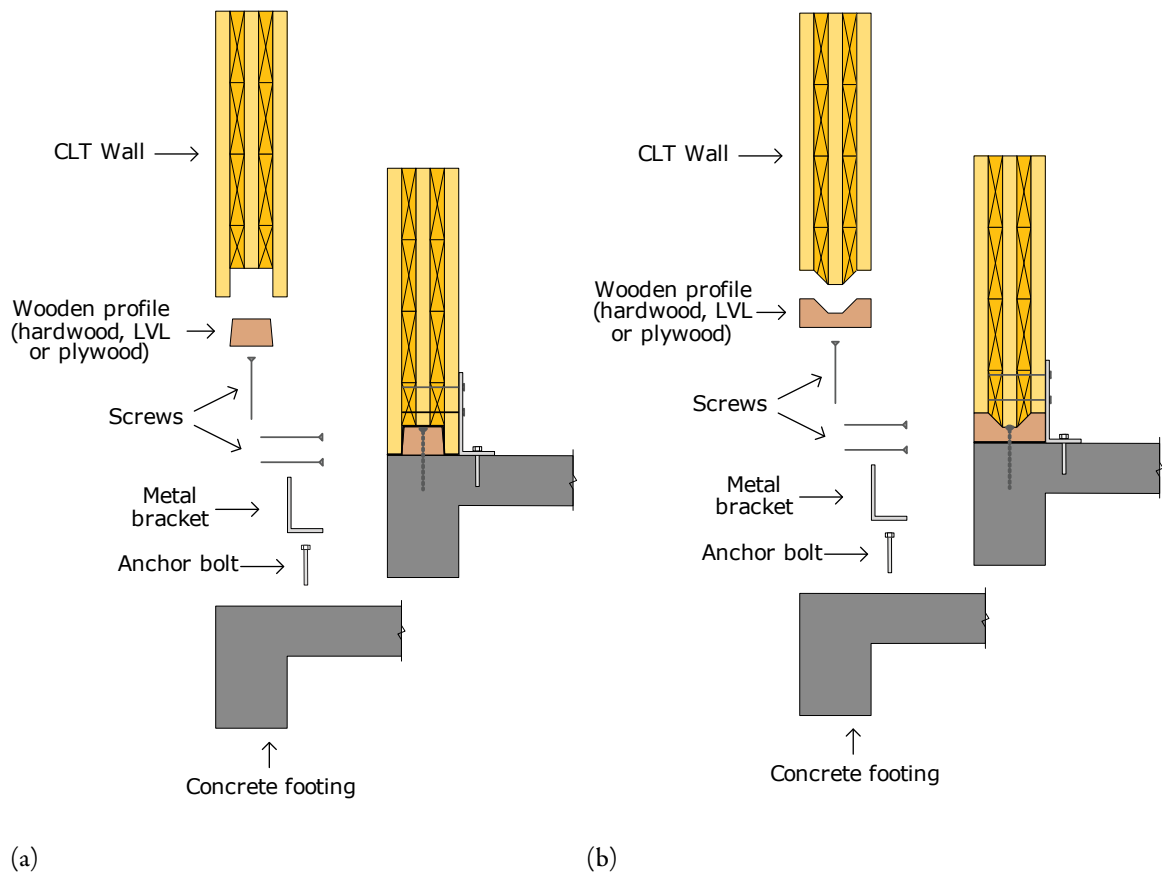


Figure 34
Concealed (a) and exposed (b) wooden profiles

5

CONNECTIONS IN MIXED HYBRID CLT CONSTRUCTION – DETAILS

Mixed systems using CLT with other types of wood-based materials such as glued-laminated timber (glulam) are common. Mixed systems are becoming increasingly popular in Europe as a way to optimize the overall design by capitalizing on the positive attributes of the various products. Mixing CLT with other types of construction materials such as concrete and masonry or mixing different types of structural forms is also common.

5.1 Mixed CLT with Other Wood-based Materials and Systems

In CLT assemblies, mixing different wood-based materials and different structural systems is done in such a way to optimize the design and to meet certain performance requirements. Therefore, it is not unusual to combine CLT wall assemblies with floor joist systems using glulam, wood I-joists, metal plated wood trusses or other types of engineered wood elements as the main floor support system, with either wood-based decking such as wood boards or wood structural panels. The following provides a brief summary of potential structural forms where CLT and other types of wood-based materials could be combined. Connection systems between those different materials are described.

5.1.1 Platform Construction

For platform-type construction, the main structural supporting elements of the floor system rest on top of the walls below. In mixed construction where walls are made of CLT panels, typical joisted floor system is placed on top of those walls as can be seen in Figures 35 and 36.

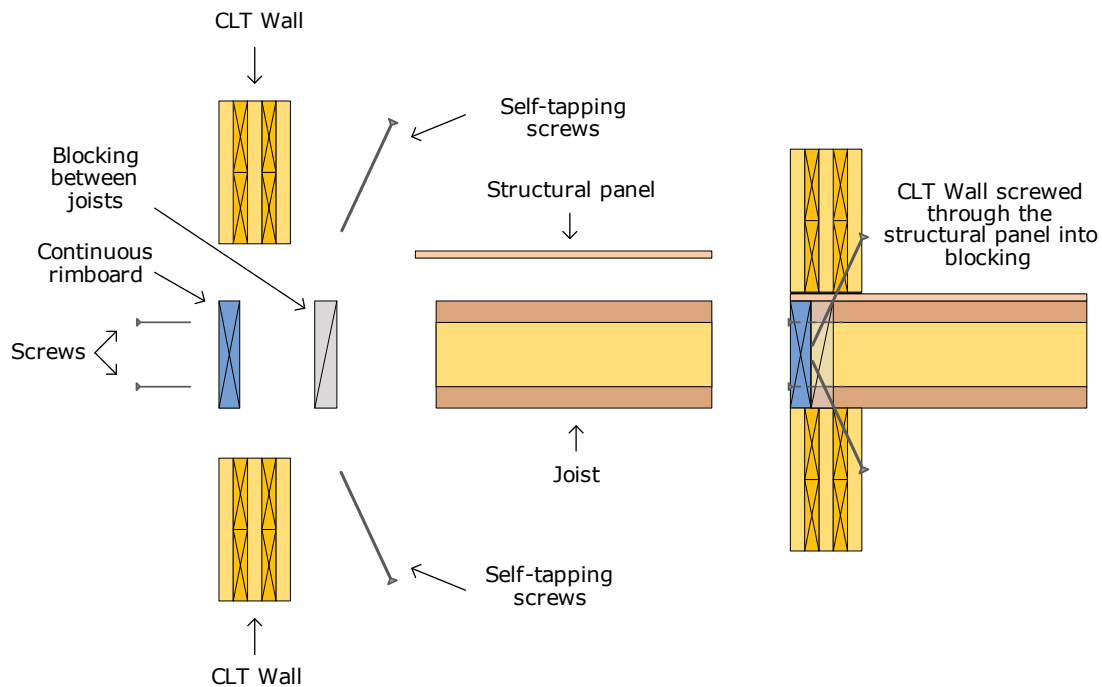


Figure 35
CLT wall – I-joist (adapted from TRADA, 2009)

A combination of rimboard and blocking elements made of SCL such as PSL, LVL or LSL between joists is generally used to ensure transfer of vertical and lateral loads from stories above to the CLT wall below. Differential shrinkage is not an issue here as the next story CLT walls are resting completely on the rimboard and blocking elements. In the case of a top chord bearing of wood floor trusses, it is necessary to provide wood-based blocking to prevent localized crushing of truss top chords and to have a uniform stress distribution along the wall perimeter (Figure 36). The wood blocking should be made with the same material as the truss top chord for dimensional stability.

Connection between walls above and below can be established using self-tapping screws driven at an angle or through one of the alternative methods of fastening previously described.

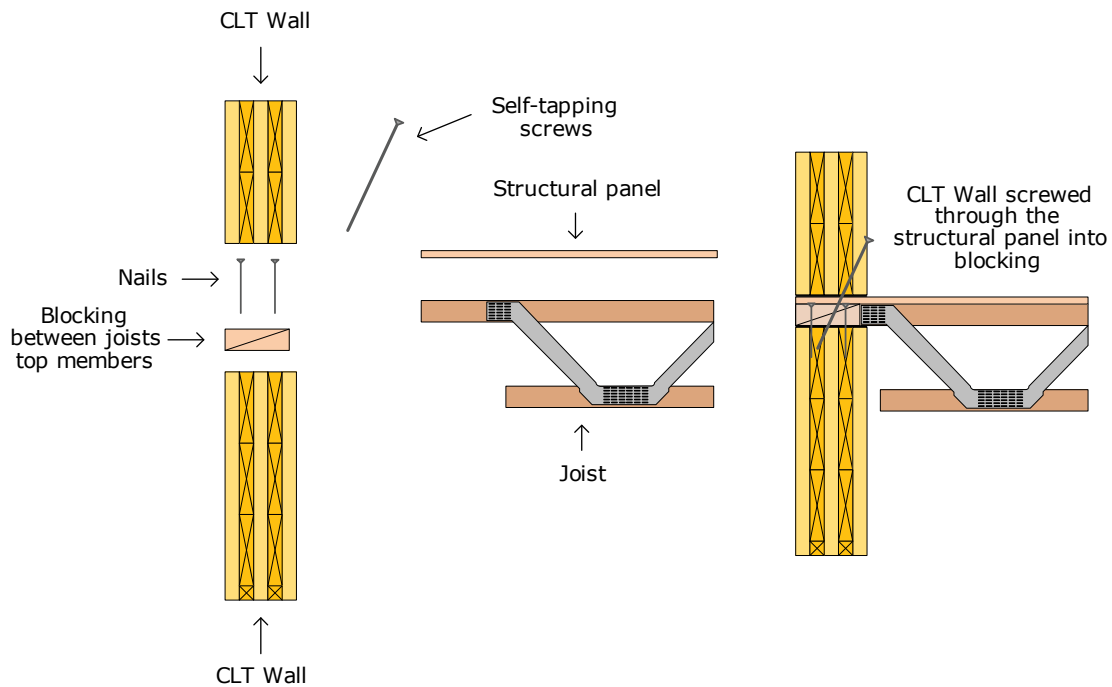


Figure 36
CLT wall – Engineered floor (adapted from TRADA, 2009)

5.1.2 Balloon Construction

Mixed CLT construction could also be used in buildings with a balloon structural form. In this type of construction, the joisted floor system which incorporates a variety of joist products such as sawn lumber, wood I-joists, and SCL can be attached to the CLT walls using traditional metal face mount hangers commonly used in light frame and heavy timber construction (Figures 37). The wall panels are continuous at the connection between the floor system and the wall and it provides support to the floor system.

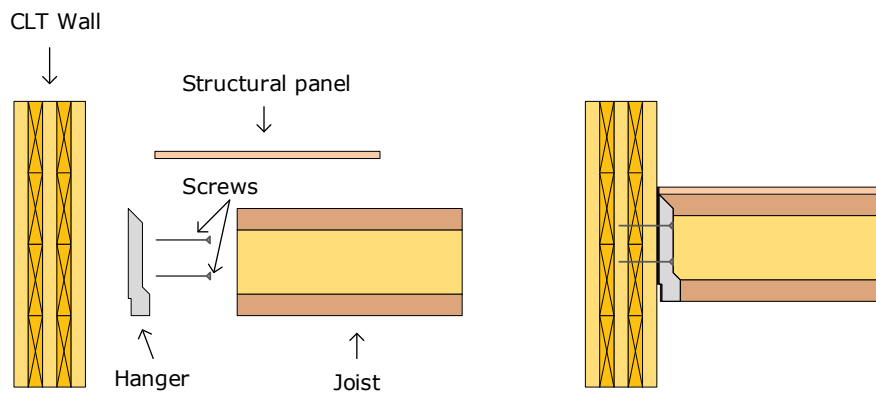


Figure 37
CLT wall – I-joist (adapted from TRADA, 2009)

6

DESIGNING CONNECTIONS IN CROSS-LAMINATED TIMBER

6.1 Why Connections in CLT are Different than those in Solid Timber or Glulam

CLT consists of layers of solid-sawn lumber or SCL where adjacent layers are cross-oriented and bonded with structural adhesive to form a solid wood element. The cross lamination and the built-up nature of the panel, in addition to certain unique panel features such as edge gluing (if any) and the potential presence of grooves sawn into the boards to relieve drying stresses, complicate the determination of the fastening capacity in CLT compared to traditional sawn solid lumber or SCL (Figure 38). Gaps between the longitudinal board as big as $\frac{1}{4}$ in. (6 mm) are not uncommon in some CLT products (Uibel and Blass, 2006). As a result, the remainder of this section will only be referring to CLT's manufacture without stress-relieving grooves and joints will be assumed to be tight-fitting.



Figure 38

CLT panel section with gaps and grooves sawn in the timber to relieve shrinkage stresses

It is well established that the loading direction relative to the grain direction of wood affects the connection capacity when relatively large diameter fasteners (with diameters equal to or greater than $\frac{1}{4}$ inch or 6 mm) such as bolts, lag screws and large diameter screws are used. However, connection capacities are relatively insensitive to grain direction when small diameter fasteners of less than $\frac{1}{4}$ inch (6 mm) are used. To account for the effects of load direction to grain orientation, timber design standards such as NDS specify different dowel-bearing equations for connections in timber loaded either in the direction parallel or perpendicular to grain for dowel-type fasteners with diameters of $\frac{1}{4}$ inch (6 mm) or more.

While yielding modes calculated using yield limit equations based on the European Yield Model (EYM) are the dominant limit for slender fasteners in CLT (Figure 39), there is a potential for developing wood strength limit states in CLT such as row shear, group tear-out, tension or splitting. According to tests conducted by Uibel and Blass (2006) in Europe with dowels and screws loaded perpendicular to the plane of the panel, the connections exhibited considerable ductility. Even when plug shear or splitting occurred in the outer layers, the load remained at the same level or showed a localized marginal drop. This could be attributed to the reinforcement effect provided by cross lamination in CLT; however, this finding is limited to the tested configurations. Fasteners loaded parallel to grain are more susceptible to these wood strength failure modes. Fasteners driven in end grain are very susceptible to splitting due to tension stresses perpendicular to the grain in small thickness panels when fasteners are loaded in shear. Therefore, there is a need to establish the conditions where wood strength failure modes may occur with large diameter fasteners and groups of fasteners used with CLT. General provisions are contained in NDS, Section 10.1.3 and Appendix E, to limit these types of wood strength failures.

Proprietary fasteners are often used based on information from the NDS in combination with connection testing and engineering analysis to establish prescriptive requirements and connection design values. When using proprietary fasteners, the user should contact the manufacturer for specific recommendations.



Figure 39

Ductile failure modes typically experienced during testing of self-tapping screws in CLT half-lapped connections

6.2 Design Approach for Lateral Connections in CLT

Extensive research has been conducted in Europe to evaluate the fastening capacity of different types of fasteners in CLT. Comprehensive research on the fastening capacity of CLT connections was conducted by Uibel and Blass (2006, 2007). The shear capacity of traditional fasteners in CLT was studied with the intent of developing a calculation methodology to establish the load carrying capacity of connections with dowel-type fasteners in the direction perpendicular to the CLT panel and on their narrow side (i.e., edge joints). Dowel-bearing tests were conducted using different types of CLT products and dowel-type fasteners. Empirical models expressed as a function of the fastener diameter, wood density and loading angle relative to the grain direction of the surface lamina were developed based on test results to establish the dowel-bearing strength under lateral loading. The results of these tests suggest that the dowel-bearing equations used in the NDS for dowel-type equations are applicable with minor adjustments.

6.2.1 Fasteners Driven Perpendicular to the Plane of the Panel

For dowel-type fasteners where the dowel diameter is equal to or larger than ¼ inch (6 mm), the dowel-bearing strengths, F_e , to use with the provisions of NDS 11.3 to calculate reference lateral design values for the two primary loading directions are:

Parallel to grain for the CLT ply at the shear plane:

$$F_{e\parallel} = 11200 G \quad [1]$$

Perpendicular to grain for the CLT ply at the shear plane:

$$F_{e\perp} = 6100 G^{1.45} D^{-0.5} \quad [2]$$

Where:

$F_{e\parallel}$ = dowel-bearing strength parallel to grain (psi) for fastener where $D \geq \frac{1}{4}$ inch

$F_{e\perp}$ = dowel-bearing strength perpendicular to grain (psi) for fastener where $D \geq \frac{1}{4}$ inch

G = minimum specific gravity of species used in CLT lay-ups

D = diameter (inches) of fastener penetration

Crossing layers will have different dowel-bearing strengths than the CLT ply at the shear plane. In most connections, the impact of this difference will be minimal; however, for connections using larger diameter fasteners or shorter dowel-bearing lengths, l_s or l_m , that is the “effective” length of the bearing length due to these layers should be reduced. For connections where the primary loading direction is parallel to grain for the CLT ply at the shear plane, the dowel bearing length should be reduced by multiplying the bearing length in the crossing plies (perpendicular to grain) by the ratio of $F_{e\perp} / F_{e\parallel}$. For connections where the primary loading direction is perpendicular to grain for the CLT ply at the shear plane, the dowel-bearing length can conservatively remain unadjusted or be adjusted by increasing the bearing length in the crossing plies (parallel to grain) by the ratio of $F_{e\parallel} / F_{e\perp}$. For connections loaded at an angle to grain, the procedures in NDS, Appendix J, for developing design values based on parallel and perpendicular to grain design values should be used with these adjusted “effective” lengths.

For dowel-type fasteners where the dowel diameter is less than ¼ inch (6 mm), the dowel-bearing strength, F_e , to use with the provisions of NDS 11.3 to calculate reference lateral design values loading at any angle to the grain is:

$$F_e = 16600 G^{1.84} \quad [3]$$

Where:

F_e = dowel-bearing strength (psi) for fastener where $D < \frac{1}{4}$ inch.

6.2.2 Dowel-type Fasteners Driven in the Narrow Side of the CLT Panel

For dowel-type fasteners installed in the narrow edge of CLT panels, the effects of inter-ply edge distance and end grain effects can be dramatic. For the purpose of developing design values for fasteners installed in this orientation, the dowel-bearing strength for fasteners with dowel diameters equal to or larger than ¼ inch (6 mm) should be limited to 0.55 times $F_{e\perp}$ from Equation (2), regardless of the actual grain orientation of the penetrated member. For fasteners with dowel diameters of less than ¼ inch (6 mm), the use of 0.67 times F_e from Equation (3) is adequate.

CLT connections using split rings and shear plates should be designed using principles and limitations of NDS Chapter 12. However, end distance, edge distance, and spacing limits are based on the use of split rings and shear plates installed in solid-sawn or glued-laminated lumber. For CLT, additional wood strength requirements should be checked to prevent unanticipated wood failures such as net section area tension, row tear-out and group tear-out addressed in NDS Appendix E.

CLT connections using timber rivets are beyond the application limits in the NDS and are not recommended at this time. Specific wood strength provisions must be developed for this application.

When using proprietary fasteners, the designer should contact the manufacturer for specific recommendations.

6.3 Design Approach for Withdrawal Connections in CLT

Withdrawal strength of large diameter self-tapping screws installed perpendicular to the plane of CLT panels or in CLT panel edges was also investigated by Uibel and Blass (2007). The withdrawal resistance was derived from tests using self-tapping screws with diameters ranging from ¼ inch (6 mm) to ½ inch (12 mm). The location of the screws was selected in such a way to have them installed at the joint between two boards within a lamina, or between one lamina and another (in the glue line). Comparative analysis studies using those proposed equations versus those given in the NDS suggest that the withdrawal equations provided in the NDS 11.2 for lag screws, wood screws, nails and spikes are also applicable to CLT installed perpendicular to the plane of the CLT and are as follows:

Lag screws:

$$W = 1800 G^{3/2} D^{3/4} \quad [4]$$

Wood screws:

$$W = 2850 G^2 D \quad [5]$$

Smooth-shank nails and spikes:

$$W = 1380 G^{5/2} D \quad [6]$$

Post-frame ring shank nails:

$$W = 1800 G^2 D \quad [7]$$

Where:

W = reference withdrawal design value (lb.) per inch of thread penetration as permitted in NDS

G = minimum specific gravity of species used in CLT lay-ups

D = diameter (inches) of fastener penetration

For the purpose of developing design values for fasteners installed in the narrow edge of CLT panels, the withdrawal equations and provisions in the NDS for fasteners installed in end grain should be followed. As a result, lag screw withdrawal values should be multiplied by the end grain factor (C_{eg}) of 0.75, as per NDS 11.5.2.1. Wood screws, nails, and spikes should not be loaded in withdrawal from end grain. When using proprietary fasteners, the designer should contact the manufacturer for specific recommendations.

6.4 Placement of Fasteners in Joints

Minimum requirements are given in the NDS for loaded end and edge distances, fastener spacing in a row and spacing between rows of fasteners for a variety of traditional fasteners with diameters equal to or greater than $\frac{1}{4}$ inch (6 mm) such as bolts, lag screws, and dowels. Recommendations for smaller fasteners such as nails, spikes, and wood screws are not explicitly provided in the NDS, which only details a requirement to avoid splitting. However, some guidance is provided in the NDS Commentary for these types of fasteners. These requirements can be applied conservatively to fasteners driven or placed in the direction perpendicular to the plane of the CLT panel since the cross laminations tend to reinforce the section. Fasteners placed in the narrow side (on edge) of the panel need special detailing requirements.

Realizing the importance of investigating the required end distances and spacing for fasteners driven or placed on edge, European researchers have developed minimum requirements for placement of self-tapping screws and dowels in CLT panels. This was done to avoid premature splitting and ensure the full bearing capacity of the dowels in the CLT is achieved. This is critical for CLT panels when they are connected at right angles (e.g., floor-to-wall or wall-to-wall corner connections) and where fasteners are driven in the narrow side (on edge) of a panel. In such situations, the fastener may tend to force plies apart across the panel thickness due to excessive tension perpendicular to grain stresses. This could initiate premature splitting in the vicinity of the fastener, thereby weakening the connection.

Recommendations on the end and edge distances and spacing for dowel-type fasteners driven on edge (adapted from Draft CEN CLT standard, 2010) are given in Table 1. Definition of end and edge distances and spacing are shown in Figure 40.

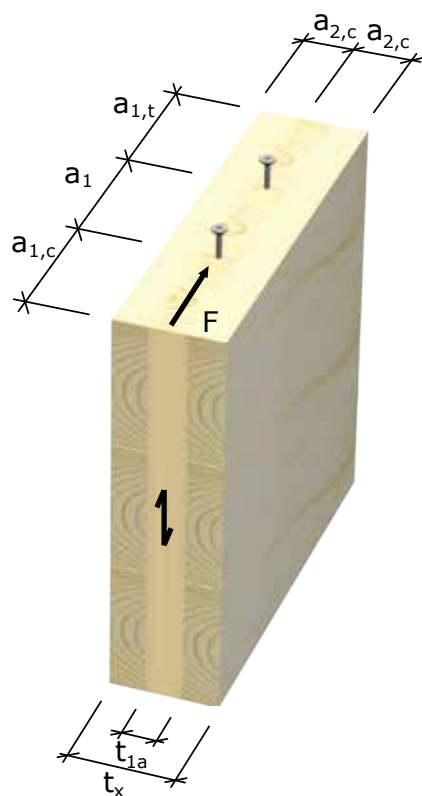


Figure 40

End and edge distances and spacing for dowel-type fasteners driven on edge (adapted from Draft CEN CLT standard, 2010)

Table 1

Minimum fastener spacing and distances in the narrow side of cross-laminated timber
(adapted from Draft CEN CLT standard, 2010)

Fastener	$a_{1,t}$	$a_{1,c}$	a_1 (in plane)	$a_{2,c}$	a_2 (perpendicular to the plane)
Dowels	5 d	3 d	4 d	3 d	3 d
Bolts	5 d	4 d	4 d	3 d	4 d

6.5 Detailing of Connections in CLT

In detailing and optimizing connections in CLT, it is important to consider not only the strength and stiffness performance of the connection system, but other performance attributes such as fire, sound insulation, air tightness, durability and vibration. Typically, sealant and other types of membranes are used to provide air tightness and improve sound insulation at the interfaces between the floor and wall plates (Figure 41).



Figure 41

Acoustic membrane inserted between walls and floors and underneath the metal bracket connector to provide air tightness (in exterior walls) and improve sound insulation

It is also critical to ensure tight fit between individual panels at the construction site. Special devices similar to what is shown in Figure 42 (i.e., beam grip with ratchet and hooks) have been developed by the various CLT manufacturers to facilitate the on-site assembly of floor and wall panels – see Sections 4.3 to 4.5 of Chapter 12, *Lifting and handling of cross-laminated elements*, for more details. This is a key component for providing:

- Structural integrity (adequate connections between panels for sharing loads);
- Improved fire resistance (tightness between panels to provide passage of flames);
- Sound insulation (for reducing flanking) and,
- Air tightness.

Shrinkage and swelling in CLT panels due to seasonal changes in the ambient environmental conditions need to be taken into account when designing connections. This is particularly important when other sealant products and membranes are incorporated as that might compromise the effectiveness of such products. Differential movement between CLT and other wood-based products or materials (in case of mixed materials and systems) need to be taken into account at the design and detailing stages due to potential shrinkage-induced stress that could undermine the connection capacity in CLT. More information and guidelines related to detailing will be provided in future versions of this document as additional studies need to be performed.



Figure 42

Tight fit between individual panels is ensured using special installation devices
(courtesy of U.S. WoodWorks)

7

DESIGN EXAMPLES

7.1 Example 1: Bolted Lateral Connection in CLT Face Lamination

7.1.1 Metal Plate Connection to CLT

Materials

3-ply grade E2 CLT (three times 1.5" plies = 4.5", see Figure), specific gravity (G) = 0.50

1/4" steel plate, ASTM A36 steel, $F_c = 87,000$ psi

1" bolt with washers on each end, $F_{yb} = 45,000$ psi

Design

Design for short-term loading ($C_D = 1.6$)

$C_M = 1.0$, $C_t = 1.0$, $C_g = 1.0$, $C_\Delta = 1.0$

From NDS Table 11.3.3:

$F_{e\parallel} = 5600$ psi

$F_{e\perp} = 2250$ psi

In this example, loading at the shear plane will be parallel to grain in the CLT.
The bearing length of the fastener must be reduced.

Bearing length in wood:

$$l_m = t_{1\parallel} + t_{2\perp} + t_{3\parallel} = 3(1.5) = 4.5'' \quad (\text{NDS 11.3.5})$$

Adjusted bearing length for lateral calculations:

$$l_{m-adj} = t_1 + t_2 (F_{e\perp} / F_{e\parallel}) + t_3 = 1.5 + (1.5)(2250/5600) + 1.5 = 3.6''$$

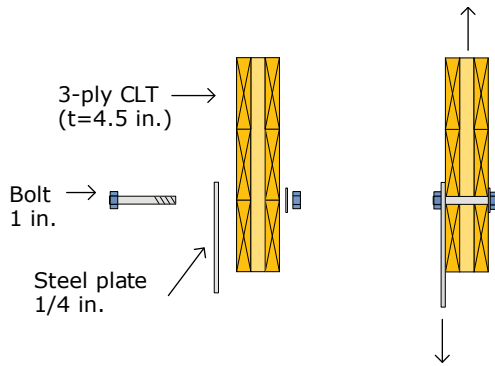


Figure 43

Bolted lateral connection in CLT face lamination

Calculation of ASD adjusted design value using NDS Yield Limit Equations (i.e., with k_1 , k_2 , k_3 , R_d and R_e values calculated based on traditional practice following the NDS):

$$\text{Mode } I_m: Z = \frac{D l_m F_{em}}{R_d} = \frac{(1.0)(3.6)(5600)}{4} = 5040 \text{ lb.}$$

$$\text{Mode } I_s: Z = \frac{D l_s F_{es}}{R_d} = \frac{(1.0)(0.25)(87,000)}{4} = 5438 \text{ lb.}$$

$$\text{Mode II: } Z = \frac{k_1 D l_s F_{es}}{R_d} = \frac{(0.3858)(1.0)(0.25)(87,000)}{3.6} = 2331 \text{ lb.}$$

$$\text{Mode III}_m: Z = \frac{k_2 D l_m F_{em}}{(1+2R_e)R_d} = \frac{(0.6106)(1.0)(3.6)(5600)}{(1+2(0.064))(3.2)} = 3410 \text{ lb.}$$

$$\text{Mode III}_s: Z = \frac{k_3 D l_s F_{em}}{(2+R_e)R_d} = \frac{(0.8682)(1.0)(0.25)(87,000)}{(2+0.064)(3.2)} = 2859 \text{ lb.}$$

$$\text{Mode IV: } Z = \frac{D^2}{R_d} \sqrt{\frac{2F_{em}F_{yb}}{3(1+R_e)}} = \frac{(1.0)^2}{3.2} \sqrt{\frac{(2)(5600)(45,000)}{(3)(1+0.064)}} = 3926 \text{ lb.}$$

Mode II controls and $Z_{\parallel} = 2331 \text{ lb.}$

$$Z'_{\parallel} = Z_{\parallel} C_D = 2331 (1.6) = 3730 \text{ lb.}$$

Alternatively, a slightly more conservative value can be interpolated from the NDS Table 11B (assuming $G=0.50$, $D=1"$, and $t_m=3.6"$):

$$Z_{\parallel} = 2309 \text{ lb.}$$

$$Z'_{\parallel} = 2309 (1.6) = 3695 \text{ lb.}$$

7.2 Example 2: Lag Screw Lateral Connection in CLT Face Lamination

7.2.1 Design of Half-lapped Joint for Shear Parallel to the Face Grain of the Panels

Materials

3-ply grade E1 CLT (three times 1.375" plies = 4.125", see Figure), specific gravity (G) = 0.42

3/8" lag screws, root diameter (D_r) = 0.265", lag screw length (L) = 4"

Tip length (E) = 0.22", F_{yb} = 45,000 psi

Design

Design for short-term loading ($C_D=1.6$)

$C_M=1.0$, $C_t=1.0$, $C_g=1.0$, $C_\Delta=1.0$

From NDS Table 11.3.3:

$F_{e\parallel} = 4700 \text{ psi}$

$F_{e\perp} = 2850 \text{ psi}$

$F_{es} = F_{em} = F_{e\perp} = 2850 \text{ psi}$

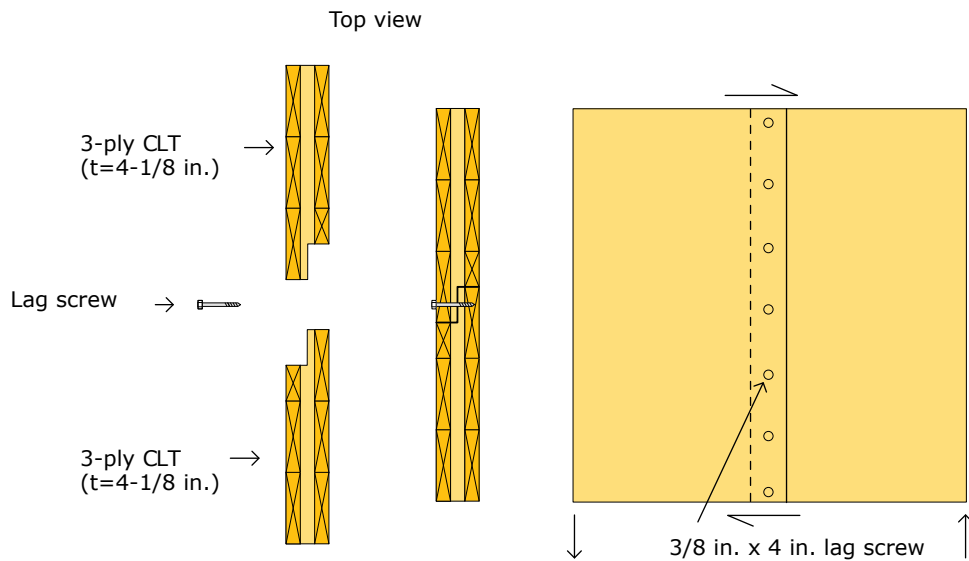


Figure 44

Lateral resistance of half-lapped joint using lag screws

In this example, the grain orientation at the joint is perpendicular to the face grain of the CLT; therefore, loading of the lag screw at the shear plane will be perpendicular to grain. While the bearing length of the fastener can be adjusted, it is not required. For purposes of the example, both solutions will be provided.

Bearing length in the lap joint:

$$l_s = t_{l\parallel} + t_{2\perp}/2 = 1.375 + (1.375/2) = 2.06'' \quad (\text{NDS 11.3.5})$$

$$p = L - l_s = 4 - 2.06 = 1.94''$$

$$l_m = p - E/2 = 1.94 - (0.22/2) = 1.83'' \quad (\text{NDS 11.3.5})$$

Check p_{\min} :

$$p_{\min} = p - E > 4D \quad (\text{NDS 11.1.4.6})$$

$$p_{\min} = 1.94 - 0.22 > 4 \cdot 0.265$$

$$p_{\min} = 1.72'' > 1.06''$$

Adjusted bearing length for lateral calculations:

$$l_{s\text{-adj}} = t_{l\parallel} (F_{e\parallel} / F_{e\perp}) + t_{2\perp}/2 = 1.375 (4700/2850) + (1.375/2) = 2.96''$$

$$l_{m\text{-adj}} = t_{2\perp}/2 + (p - t_{2\perp}/2)(F_{e\parallel} / F_{e\perp}) - E/2 = (1.375/2) + (1.94 - 1.375/2)(4700/2850) - 0.22/2 = 2.64''$$

Calculation of ASD adjusted design value using NDS Yield Limit Equations:

$$\text{Mode } I_m: \quad Z = \frac{D l_m F_{em}}{R_d} = \frac{(0.265)(2.64)(2850)}{5} = 399 \text{ lb.}$$

$$\text{Mode } I_s: \quad Z = \frac{D l_s F_{es}}{R_d} = \frac{(0.265)(2.96)(2850)}{5} = 447 \text{ lb.}$$

$$\text{Mode II:} \quad Z = \frac{k_1 D l_s F_{es}}{R_d} = \frac{(0.3942)(0.265)(2.96)(2850)}{4.5} = 196 \text{ lb.}$$

$$\text{Mode III}_m: \quad Z = \frac{k_2 D l_m F_{em}}{(1+2R_e)R_d} = \frac{(1.077)(0.265)(2.64)(2850)}{(1+2)(4)} = 179 \text{ lb.}$$

$$\text{Mode III}_s: \quad Z = \frac{k_3 D l_s F_{em}}{(2+R_e)R_d} = \frac{(1.062)(0.265)(2.96)(2850)}{(2+1)(4)} = 198 \text{ lb.}$$

$$\text{Mode IV:} \quad Z = \frac{D^2}{R_d} \sqrt{\frac{2F_{em}F_{yb}}{3(1+R_e)}} = \frac{(0.265)^2}{4} \sqrt{\frac{(2)(2850)(45,000)}{(3)(1+1)}} = 115 \text{ lb.}$$

$$Z_{\perp} = 115 \text{ lb.}$$

$$Z_{\perp}' = Z_{\perp} C_D = 115 (1.6) = 184 \text{ lb.}$$

Using the unadjusted bearing lengths, Mode IV still controls and $Z_{\perp} = 115 \text{ lb.}; Z_{\perp}' = 184 \text{ lb.}$

Alternatively, slightly more conservative values can also be taken from the NDS Table 11J assuming $G=0.42$ and a side member thickness greater than 2-1/2" and adjusted bearing length of at least 8D:

$$Z_{\perp} = 110 \text{ lb.}$$

$$Z_{\perp}' = 110 (1.6) = 176 \text{ lb.}$$

Example 3: Lag Screw Withdrawal Connection from CLT Face Lamination

Materials

5-ply grade V2 CLT (five times 1.375" plies = 6.875", see Figure), specific gravity (G) = 0.42

1/4" steel plate, ASTM A36 steel, $F_c = 87,000$ psi

1/2" lag screws, root diameter (D_r) = 0.371", lag screw length (L) = 7", thread length (T) = 4"

Tip length (E) = 5/16", $F_{yb} = 45,000$ psi

Design

Design for short-term loading ($C_D = 1.6$)

$C_M = 1.0$, $C_t = 1.0$, $C_g = 1.0$, $C_\Delta = 1.0$

Length of fastener penetration:

$$t_s = 0.25"$$

$$p = L - t_s - E = 7 - 0.25 - 0.31 = 6.44"$$

$$p_t = T - E = 4 - 0.31 = 3.69" < 6.44"$$

ASD adjusted withdrawal design value:

$$W = 291 \text{ lb./inch/lag screw} \quad (\text{NDS Table 11.2A})$$

$$W' = W C_D = (291)(1.6) = 466 \text{ lb./inch/lag screw} \quad (\text{NDS 11.2.1.3})$$

$$W' p_t = (466)(3.69) = 1720 \text{ lb./lag screw} \quad (\text{NDS 11.2.1.2})$$

Depending on the stiffness of the angle bracket and the position of the lag screw with regard to the bend angle, the withdrawal force loading the lag screw could be much larger than the vertical load on the angle bracket. Therefore, the strength of the metal bracket needs to be checked.

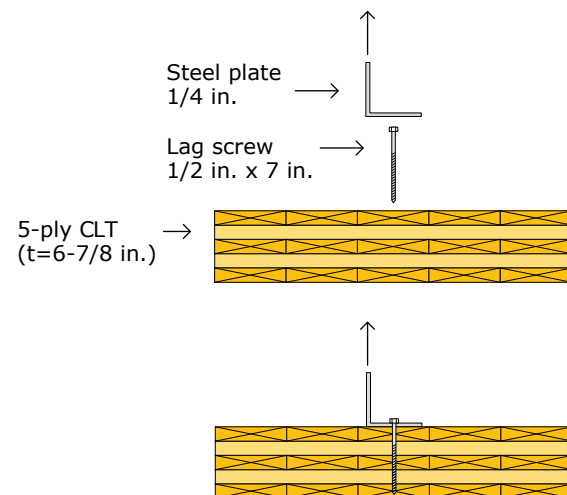


Figure 45

Withdrawal resistance of lag screws from CLT face lamination

Example 4: Design of Corner Joint (i.e. Wall Intersection) for Out-of-Plane Loads

Materials

5-ply grade E3 CLT (five times 1.375" plies = 6.875", see Figure), specific gravity (G) = 0.36

1/2" lag screws, root diameter (D_r) = 0.371", lag screw length (L) = 12", thread length (T) = 6"

Tip length (E) = 5/16", F_{yb} = 45,000 psi

Design for short-term loading (C_D = 1.6)

C_M = 1.0, C_t = 1.0, C_g = 1.0, C_Δ = 1.0

7.4.1 Lag Screw Lateral Connection in CLT Edge

From NDS Table 11.3.3:

$$F_{e\parallel} = 4050 \text{ psi}$$

$$F_{e\perp} = 1950 \text{ psi}$$

$$F_{es} = F_{e\perp} = 1950 \text{ psi}$$

$$F_{em} = 0.55 F_{e\perp} = 1073 \text{ psi}$$

Lag screw
(1/2 in. x 12 in.)

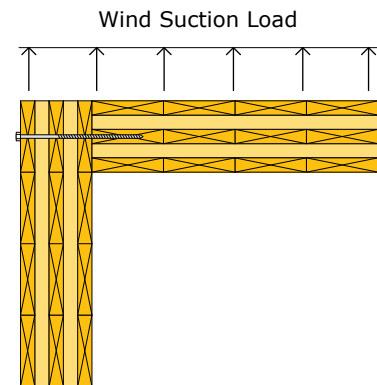
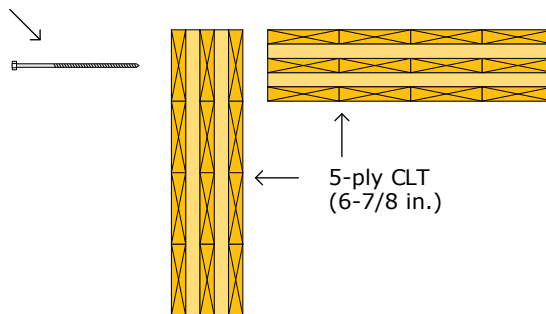


Figure 46

Corner joint: lag screw lateral resistance in CLT edge

In this example, the grain orientation at the joint is perpendicular to the face-grain of the CLT; therefore, loading of the lag screw at the shear plane will be perpendicular to grain. While the bearing length of the fastener can be adjusted, it is not required, so it will not be adjusted in this example. Bearing length in the lap joint:

$$l_s = 5t = 5(1.375) = 6.88" \quad (\text{NDS 11.3.5})$$

$$p = L - l_s = 12 - 6.88 = 5.12"$$

$$l_m = p - E/2 = 5.12 - 0.31/2 = 4.96" \quad (\text{NDS 11.3.5})$$

Check p_{\min} :

$$\begin{aligned} p_{\min} &= p - E &> 4D && \text{(NDS 11.1.4.6)} \\ p_{\min} &= 5.12 - 0.31 &> 4 \cdot 0.371 \\ p_{\min} &= 4.81'' &> 1.48'' \end{aligned}$$

Calculation of ASD adjusted design value using NDS Yield Limit Equations:

$$\text{Mode } I_m: Z = \frac{Dl_m F_{em}}{R_d} = 395 \text{ lb.}$$

$$\text{Mode } I_s: Z = \frac{Dl_s F_{es}}{R_d} = 995 \text{ lb.}$$

$$\text{Mode } II: Z = \frac{k_1 Dl_s F_{es}}{R_d} = 332 \text{ lb.}$$

$$\text{Mode } III_m: Z = \frac{k_2 Dl_m F_{em}}{(1+2R_e)R_d} = 200 \text{ lb.}$$

$$\text{Mode } III_s: Z = \frac{k_3 Dl_s F_{em}}{(2+R_e)R_d} = 380 \text{ lb.}$$

$$\text{Mode } IV: Z = \frac{D^2}{R_d} \sqrt{\frac{2F_{em}F_{yb}}{3(1+R_e)}} = 157 \text{ lb.}$$

Mode IV controls with $Z_{\perp} = 157 \text{ lb.}$

$$Z_{\perp}' = Z_{\perp} C_D = 157 (1.6) = 251 \text{ lb.}$$

It should be noted that the loaded edge is prone to splitting. A splitting check of the panel with the screws inserted in the edge may be required. Alternatively, reinforcing the panel with fully threaded self-tapping screws is advisable.

7.4.2 Lag Screw Withdrawal Connection in CLT Edge

Length of fastener penetration:

$$\begin{aligned} t_s &= 6.88'' \\ p &= L - t_s - E = 12 - 6.88 - 0.31 = 4.81'' \\ p_t &= T - E = 6 - 0.31 = 5.69'' > 4.81'' \end{aligned}$$

ASD adjusted withdrawal design value:

$$W = 231 \text{ lb./inch/lag screw} \quad \text{(NDS Table 11.2A)}$$

$$W' = W C_{eg} C_D = (231)(0.75)(1.6) = 277 \text{ lb./inch/lag screw} \quad \text{(NDS 11.2.1.3)}$$

$$W'p_t = (277)(4.81) = 1333 \text{ lb./lag screw} \quad \text{(NDS 11.2.1.2)}$$

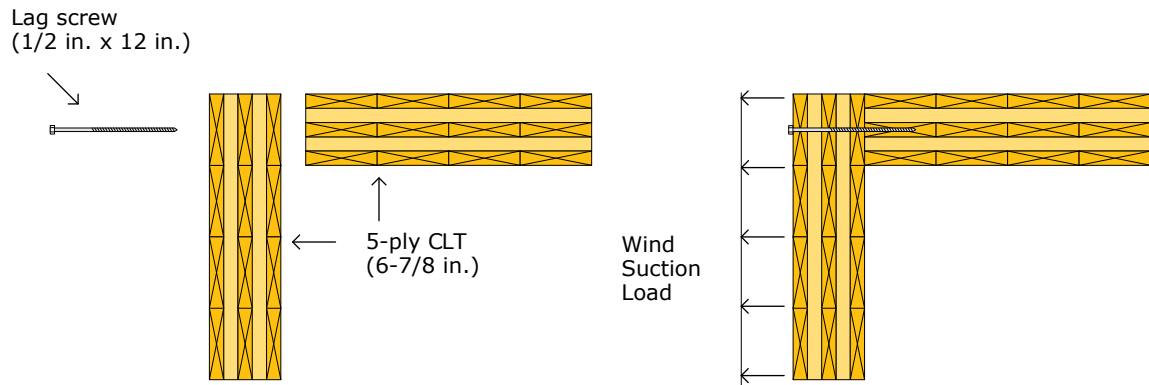


Figure 47
Corner joint: lag screw withdrawal resistance in CLT edge

7.5 Example 5: Design of Nailed Metal Plate Connection to CLT

Materials

5-ply grade V1 CLT (five times 1.375" = 6.875", see Figure), specific gravity (G) = 0.50

16 gauge (0.060" thick) steel plate, ASTM A653, grade 33 steel, $F_c = 61,850$ psi

10 8d common nails (0.131" x 2.5"), $F_{yb} = 100,000$ psi

Design for short-term loading ($C_D = 1.6$)

$C_M = 1.0$, $C_t = 1.0$, $C_g = 1.0$, $C_\Delta = 1.0$

Nailed lateral connection

Bearing lengths:

$$l_s = 0.060" \quad (\text{NDS 11.3.5})$$

$$p = L - l_s = 2.5 - 0.060 = 2.44"$$

$$l_m = p - E/2 = 2.44 - 2(0.131)/2 = 2.31" \quad (\text{NDS 11.3.5})$$

Check p_{\min} :

$$p_{\min}/D = 2.44/0.131 = 18.6 > 6D = 0.79" \quad (\text{NDS 11.1.5.5})$$

ASD adjusted lateral design value:

$$Z = 97 \text{ lb./nail} \quad (\text{NDS Table 11P})$$

$$Z' = Z C_D = 97 (1.6) = 155 \text{ lb./nail}$$

$$\text{Total } Z' = 155 * 10 = 1550 \text{ lb.}$$

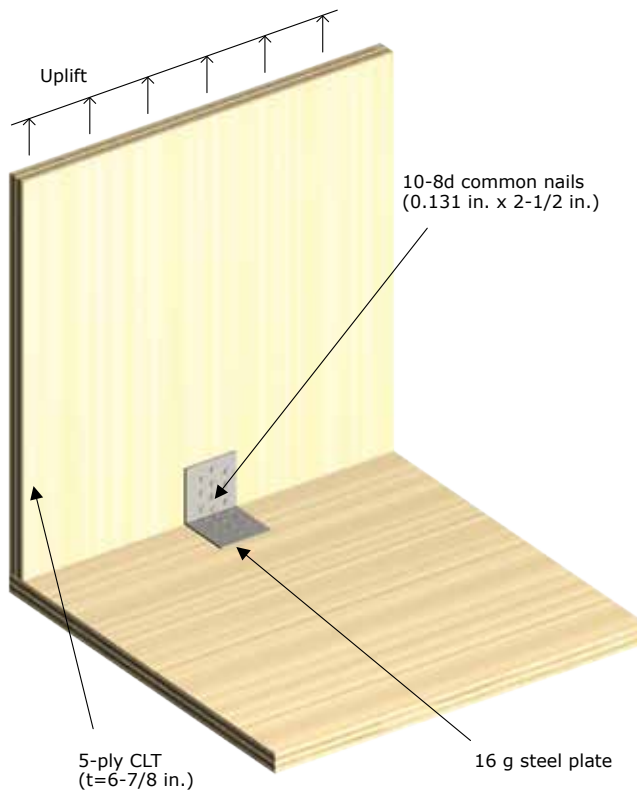


Figure 48

Nailed metal plate connection to CLT (lateral and withdrawal)

Note: The nails close to the bend line will be predominantly loaded, while the nails further away will be hardly loaded in withdrawal. This means that the connection capacity in withdrawal could be significantly less than the total withdrawal capacity of 10 nails.

While the total lateral capacity of this connection has been calculated to 1550 lb., in many cases, the size of the steel plate and spacing of the nails can lead to group failure modes of the wood member (brittle failure mode) or steel side plate which are not specifically addressed in the NDS. Provisions in Appendix E of NDS can be used to evaluate some of these modes, but testing of the connection should be undertaken to ensure that the connection capacity is not limited by wood failure.

Nailed withdrawal connection

Length of fastener penetration:

$$t_s = 0.060''$$

$$p_t = L - t_s = 2.5 - 0.060 = 2.44''$$

ASD adjusted withdrawal design value:

$$W = 32 \text{ lb./inch/nail}$$

(NDS Table 11.2C)

$$W' = W C_D = (32)(1.6) = 51 \text{ lb./inch/nail}$$

$$W' p_t = (51)(2.44) = 125 \text{ lb./nail}$$

(NDS 11.2.4)

$$\text{Total } W' p_t = 10(125) \text{ lb./nail} = 1250 \text{ lb.}$$

8

CONCLUSION

Connections in timber construction, including those built with CLT, play an important role in maintaining the integrity of the timber structure and in providing strength, stiffness, stability and ductility. Consequently, they require detailed attention by designers.

Traditional and innovative connection systems have been used in CLT assemblies in Europe. Several types of traditional and innovative connection systems for connecting CLT panels to panels, walls to walls and walls to floors are described in detail in this Chapter. They are mostly based on the European experience.

Researchers in Europe have developed design procedures for traditional connections in CLT, including dowels, wood screws and nails which are commonly used in Europe for designing CLT assemblies. The proposed design procedure deals only with ductile failure modes to determine the lateral load resistance of such connections. Expressions were developed for the calculation of characteristic dowel-bearing properties of each type of fastener, depending on its location with respect to the plane of the panel (perpendicular to or on edge). The expressions were verified and results seem to correspond well with predictions. European Yield Model equations for ductile failure modes as given in Eurocode 5 were adopted for design using CLT fastener dowel-bearing equations.

Due to the reinforcing effect of cross lamination in CLT, it is speculated that current minimum geometric requirements given in the NDS for dowels, screws and nails in solid timber or glulam are applicable to CLT. However, designers need to be cautious about this as further verification is required, considering the specific features of each panel. Brittle failure modes need also to be taken into account and have not yet been investigated. Further work is needed to verify possible brittle failure modes associated with each type of fasteners in CLT connections as well as their behavior for seismic design.

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