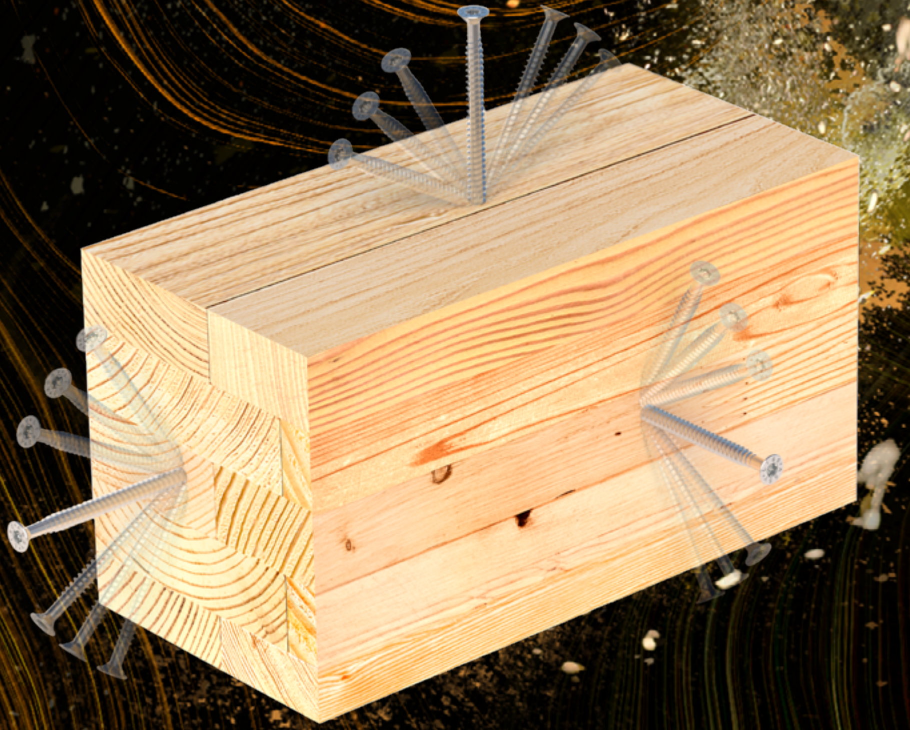
WHITE PAPER

MTC SOLUTIONS

WITHDRAWAL RESISTANCES OF ASSY SCREWS AT VARIOUS ANGLES TO THE GRAIN

How to Determine the NDS End-grain Adjustment Factor C_{eg} and Angle-to-Grain Reduction Factor R_{α}



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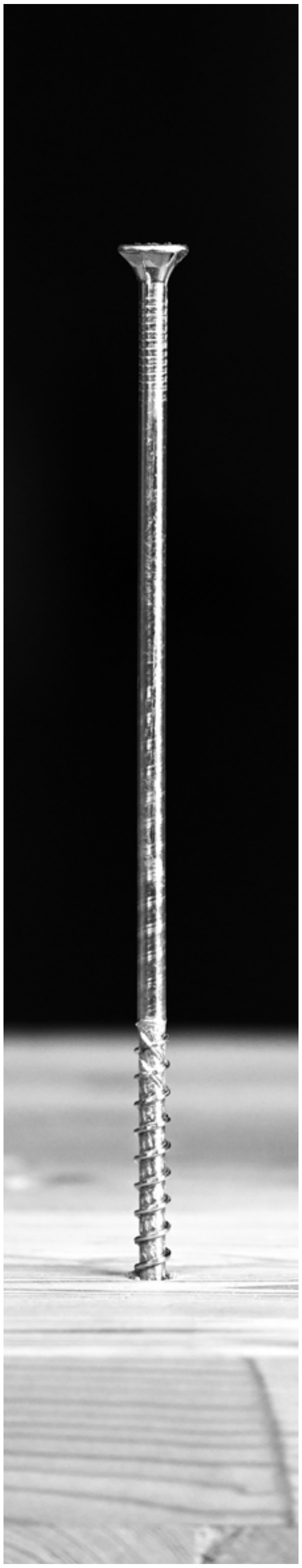
INTRODUCTION

MTC's ASSY self-tapping screws (STS) are commonly used to create axial or lateral connections in wood. Fully threaded STS provide the opportunity to design lateral connections by utilizing axially loaded inclined screws, where the screws are driven into the wood at an angle to the grain. This can provide a higher connection resistance and greater stiffness given a certain thread penetration. However, the withdrawal resistance of STS varies depending on the angle at which they are driven into the wood. This has significant implications for the strength and durability of the connection. In order to calculate design withdrawal resistance of MTC's STS, it is necessary to determine the reduction factor R_α when installing the screws at an angle to the grain, and the NDS end-grain adjustment factor C_{eg} when installing the screws in the end-grain. This paper delves into the theory behind end-grain withdrawal, the reduction factors, and provides practical guidance on how to determine these factors for various angles to the side-grain and end-grain in Glulam and CLT wood members.

Withdrawal Resistance in the End-Grain and NDS End-Grain Adjustment Factor C_{eg}



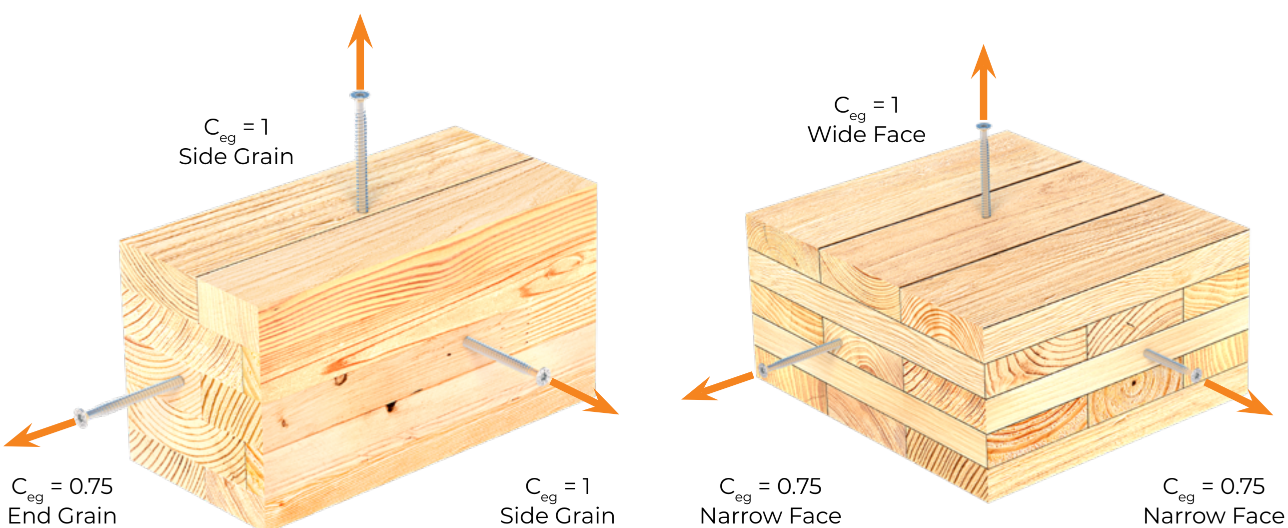
Withdrawal resistance of fasteners in end-grain applications is subject to a higher risk of capacity reduction when compared to side-grain applications due to several factors. One major factor is the natural susceptibility of wood in developing checks due to shrinking and swelling cycles caused by changes in moisture content over time. Checking is more common near the ends and surfaces of wood members due to tensile stresses caused by uneven drying. When a screw is installed in the end-grain, potential checks can develop along the length of the installed screw, thereby reducing the withdrawal resistance of the connection during the service life of the building. Additionally, potential surface checks may also reduce the withdrawal resistance of the connection when the screw is installed close to the edges and parallel-to-grain in the end-grain. To reduce the risk of checking and splitting due to changes in moisture content, wood members should be dried at a controlled rate and protected from moisture as much as possible. Furthermore, longer penetration lengths should be employed for screws installed in the end-grain and installation should be completed away from the edges to avoid potential surface checks that can trigger reduction in withdrawal resistance.

Another factor for the unpredictable behavior in withdrawal parallel-to-grain is the local density variation due to seasonal growth patterns in a wood member. A screw installed parallel-to-grain may penetrate low density early wood, reducing the withdrawal resistance. On the other hand, by inclining the screw at an angle or installing perpendicular-to-grain, the screw would penetrate multiple growth rings areas in the wood member and average out the impact of density variation.

Additionally in wide Glulam and CLT, often the wood plies are not edge-glued and during manufacturing, there is a possibility of voids between two plies placed side by side. This adds to the unpredictable behaviour of parallel-to-grain withdrawal as the screw may be installed along a void. The conservative approach is to apply reduction factors in calculating withdrawal resistance whenever there is possibility of voids, for example non edge-glued split-laminated Glulam members and all non edge-glued CLT members.

Besides other factors, the end-grain effects mentioned above reduce the withdrawal resistance in the end-grain. Withdrawal resistance is lowest when a screw is inserted parallel-to-grain. To account for the variability in potential checking and other end-grain related effects, the U.S. National Design Specification for Wood Construction 2018 (NDS-2018) recommends avoiding the application of lag screws loaded in withdrawal in end-grain surfaces. Where such application occurs, an end-grain adjustment factor C_{eg} is provided in the NDS-2018 to account for this less reliable failure mechanism.

According to Clauses 12.2.1.3 and 12.2.1.5 of the NDS-2018, a 25% reduction in withdrawal capacity is required where lag screws are loaded in withdrawal through the end-grain of wood, or through the narrow edge of CLT panels.



(a) Glulam *(b) CLT*

Figure 1. C_{eg} Values per the NDS-2018

It is important to note that the NDS-2018 recommendations are intended for lag screws rather than the use of STS in mass timber. Therefore, these provisions should only be used as a guideline for STS and need to be supplemented through technical reports and manufacturer guidelines.

MTC's ASSY STS and Proprietary Angle-to-Grain Reduction Factor R_α

At the moment, connection design using STS is not directly addressed in the NDS-2018. Designers rely on the provisions for traditional lag screws provided in the NDS-2018 when designing connections with STS. Significantly higher tensile strengths and availability of longer lengths allow STS to be used in axial connections at varying angles, unlike the traditional lag screws. As such, the provisions for lag screws do not entirely cover all STS application scenarios. For MTC's ASSY STS, an angle-to-grain reduction factor R_α for withdrawal applications is specified in Table 1.1 of the MTC's Structural Screw Catalog. At a 90° angle to the grain, the screw threads mechanically engage wood fiber in a way which produces the greatest withdrawal resistances while at a 0° angle to the grain, the screw threads mechanically engage wood fiber in a way which results in lower withdrawal resistances. This reduction is accounted for by applying the R_α.

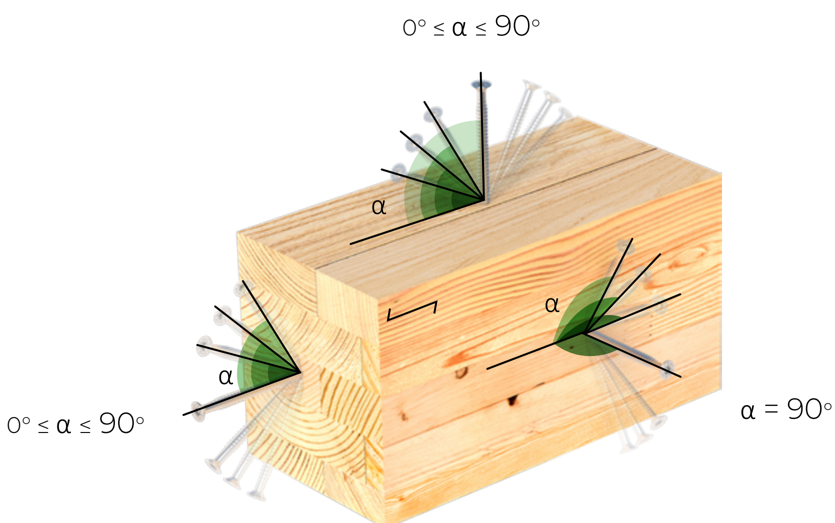


Figure 2. Angle α (measured as the angle between the fastener axis and the wood fiber grain orientation)

Table 1.1 Angle-to-Grain Reduction Factor R_α for Withdrawal at an Angle α

α	90°	85°	80°	75°	70°	65°	60°	55°	50°	45°	40°	35°	30°	25°	20°	15°	14°	10°	5°	0°
R_α *for Timber Products*	1	0.997	0.990	0.978	0.962	0.944	0.923	0.901	0.879	0.857	0.836	0.817	0.800	0.785	0.773	0.763	0.761	0.756	0.751	0.750
R_α *for LVL, MPP, Plywood*	1	0.997	0.990	0.978	0.962	0.944	0.923	0.901	0.879	0.857	0.836	0.817	0.800	0.785	0.773	0.763	0.656	0.611	0.556	0.500

Notes:

1. Timber Products are lumber, timber and mass timber elements such as Glulam and CLT.
2. For α < 15°, a minimum of four (4) screws are required per connection.
3. For α < 30°, the connection can be subjected to short-term loading only.

Which Factor Should be Applied to Calculate Withdrawal Resistance?

There appears to be a lack of clarity regarding the use of the end-grain adjustment factor C_{eg} and angle-to-grain reduction factor R_α. Common questions within the engineering community include: Do design engineers need to apply both the reduction factor and the adjustment factor in end-grain applications? How do design engineers determine each respective factor? The NDS-2018 C_{eg} factor only addresses simple cases of parallel-to-grain applications (i.e. end-grain where $\alpha = 0°$) and perpendicular-to-grain application (i.e. side grain where $\alpha = 90°$), but STS are often installed at varying angles to the grain. The angle-to-grain reduction factor R_α provided in MTC's catalog for ASSY fasteners addresses withdrawal applications with respect to a range of α values. Design engineers shall apply both C_{eg} and R_α, given the lack of explicit guidelines and scientific testing when fasteners are installed at varying angles into the *end-grain* of Glulam beams or columns, or into the narrow edge of CLT panels.

How to Determine Adjustment Factor C_{eg} and Reduction Factor R_α ?

Until STS are incorporated into North American design codes, additional guidance is available through technical papers, manufacturers' design guides, and technical approvals (or evaluation reports). The conservative approach is to apply both C_{eg} and R_α concurrently. The following guidelines provided to assist in determining the applicable adjustments/reductions.

1. Identify angle α in the wood member where withdrawal is being calculated
2. Determine R_α
   For both Glulam and CLT, determine R_α from Table 1.1 of MTC's Structural Screw Catalog as a function of α
3. Determine C_{eg}

In Glulam

C_{eg} = 1 if screw is loaded in withdrawal from the
- side-grain.

OR

- if screw is loaded in withdrawal from the end-grain, with α ≥ 30° and the beam is not split laminated or block laminated (i.e free of voids).

C_{eg} = 0.75 if screw is loaded in withdrawal from
- the end-grain, with α < 30°.

OR

- the end-grain and the beam is split laminated or block laminated (i.e. has the potential for voids).

Note:

1. Split laminated and block laminated Glulam (beams and columns) can contain manufacturing process related voids which may require the need for reduction in withdrawal capacity in the end-grain.

In CLT

C_{eg} = 1 if screw is inserted into the wide face of CLT panel

C_{eg} = 0.75 if the screw is inserted into the narrow face of the CLT panel regardless of the individual angle to grain relationship in each ply.

Note:

1. When fasteners are driven into the narrow face of CLT panels, various angle-to-grain relations can occur and conservative measures shall be taken.

A variety of examples for the application of adjustment and reduction factors is provided in the following section. In most connections with axially loaded inclined screws, α ranges between 30° and 60°. Connections with α < 30° are not recommended as a default application because of the outlined reduction factor requirements which typically result in long screws. Furthermore, installation where α < 30° is physically difficult as the drill chuck and drill body can interfere with the wood member prior to the wood screws being fully installed. The use of long bit holder extensions can mitigate this issue. However, installation precision typically declines.

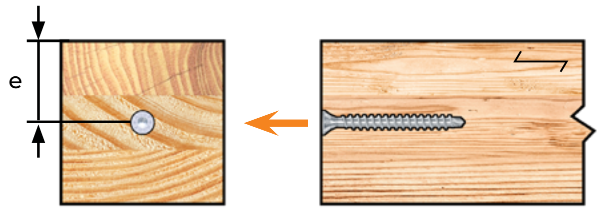
BOW RIVER PEDESTRIAN BRIDGE

Banff, Alberta

WORKED EXAMPLES

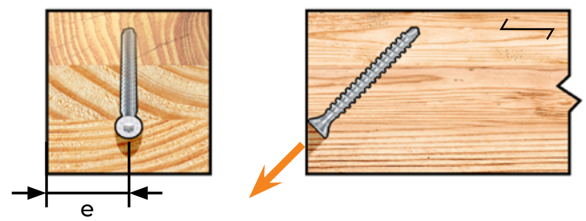
Examples of Withdrawal Applications in Glulam

Case (1)



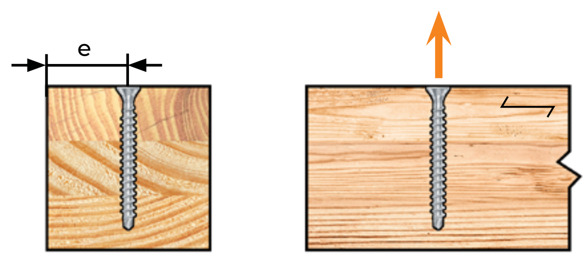
α	=	0°
R_α (From Table 1.1)	=	0.75
C_{eg} (end-grain, with α < 30°)	=	0.75
Minimum effective thread penetration, l_{eff}	=	20D
Load duration (α < 30°)	=	Short-term loading only
Minimum number of screws (α < 15°)	=	4
Minimum edge distance, e_{axial}	=	3D

Case (2)



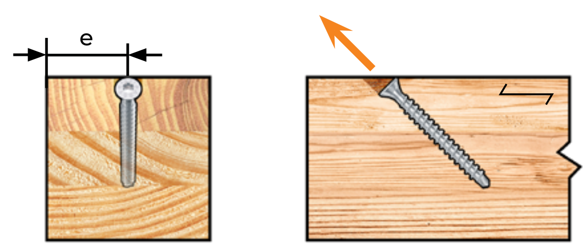
α	=	45°
R_α (From Table 1.1)	=	0.857
C_{eg} (end-grain, with $\alpha \geq$ 30° and the beam is not split laminated or block laminated)	=	1
Minimum effective thread penetration, l_{eff}	=	8.5D
Load duration	=	Short, Standard or Long-term loading
Minimum number of screws	=	2
Minimum edge distance, e_{axial}	=	3D

Case (3)



α	=	90°
R_α (From Table 1.1)	=	1
C_{eg} (side-grain)	=	1
Minimum effective thread penetration, l_{eff}	=	8D
Load duration	=	Short, Standard or Long-term loading
Minimum number of screws	=	2
Minimum edge distance, e_{axial}	=	3D

Case (4)



α	=	45°
R_α (From Table 1.1)	=	0.857
C_{eg} (side-grain)	=	1
Minimum effective thread penetration, l_{eff}	=	8.5D
Load duration	=	Short, Standard or Long-term loading
Minimum number of screws	=	2
Minimum edge distance, e_{axial}	=	3D

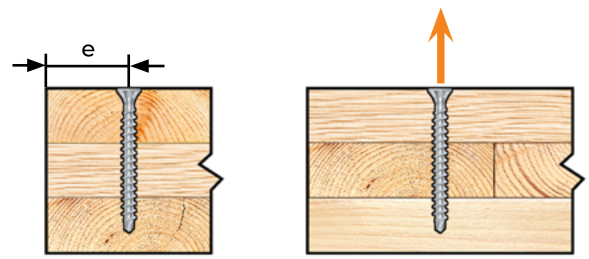
Notes:

1. D = Nominal Diameter of the fastener.
2. All Glulam beams are assumed to be non split or block laminated.
3. Case 2 and case 4 are representing similar conditions with a fastener installed at 45° to the wood grain. Only R_α shall apply and C_{eg} = 1, even though the screw is inserted through end-grain in case 2 ($\alpha \geq$ 30°).
4. Geometry requirements as per ICC ESR 3178 and ICC ESR 3179 apply.

Examples of Withdrawal Applications in CLT

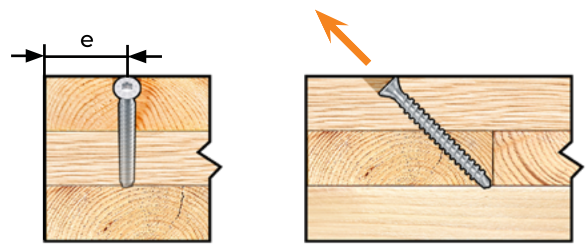
Case (1)

α	=	90°
R_{α} (From Table 1.1)	=	1
C_{eg} (wide face of CLT)	=	1
Minimum effective thread penetration, l_{eff}	=	8D
Load duration	=	Short, Standard or Long-term loading
Minimum number of screws	=	2
Minimum edge distance, e_{axial}	=	2.5D



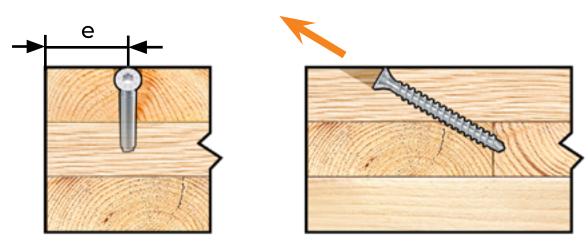
Case (2)

α	=	45°
R_{α} (From Table 1.1)	=	0.857
C_{eg} (wide face of CLT)	=	1
Minimum effective thread penetration, l_{eff}	=	8.5D
Load duration	=	Short, Standard or Long-term loading
Minimum number of screws	=	2
Minimum edge distance, e_{axial}	=	2.5D



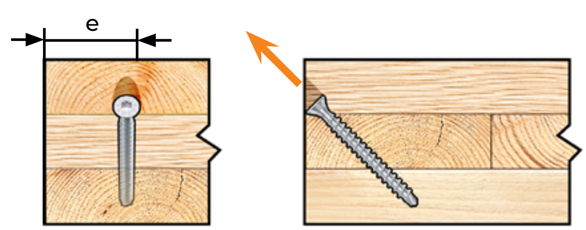
Case (3)

α	=	30°
R_{α} (From Table 1.1)	=	0.8
C_{eg} (wide face of CLT)	=	1
Minimum effective thread penetration, l_{eff}	=	12D
Load duration	=	Short, Standard or Long-term loading
Minimum number of screws	=	2
Minimum edge distance, e_{axial}	=	2.5D



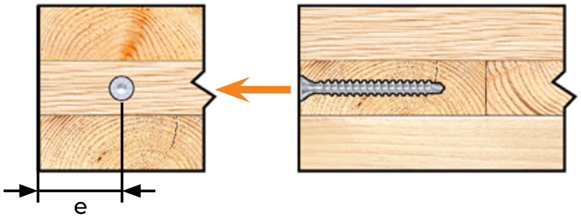
Case (4)

α	=	45°
R_{α} (From Table 1.1)	=	0.857
C_{eg} (narrow face of CLT)	=	0.75
Minimum effective thread penetration, l_{eff}	=	8.5D
Load duration	=	Short, Standard or Long-term loading
Minimum number of screws	=	2
Minimum edge distance, e_{axial}	=	3D



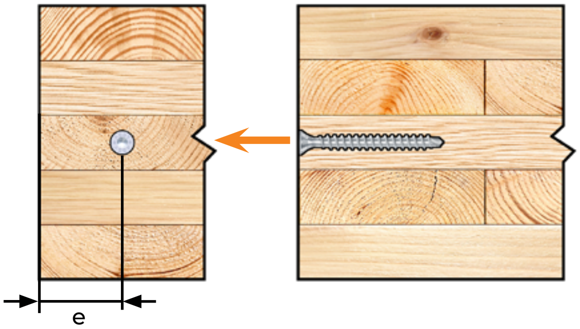
Case (5)

α	=	0°
R_{α} (From Table 1.1)	=	0.75
C_{eg} (narrow face of CLT)	=	0.75
Minimum effective thread penetration, l_{eff}	=	20D
Load duration (α < 30°)	=	Short-term loading only
Minimum number of screws (α < 15°)	=	4
Minimum edge distance, e_{axial}	=	3D



Case (6)

α	=	0°
R_{α} (From Table 1.1)	=	0.75
C_{eg} (narrow face of CLT)	=	0.75
Minimum effective thread penetration, l_{eff}	=	20D
Load duration (α < 30°)	=	Short-term loading only
Minimum number of screws (α < 15°)	=	4
Minimum edge distance, e_{axial}	=	3D



Notes:

1. D = Nominal Diameter of the fastener.
2. Case 2 and Case 4 are representing similar conditions of the fastener installed at α = 45°. R_{α} shall apply accordingly, but C_{eg} = 1 for case 2 (wide-face) and C_{eg} = 0.75 for Case 4 (narrow-face). This is attributed to the risk of fasteners being installed along a void in the narrow face of a CLT panel.
3. In case 5, due to the presence both the side-grain and end-grain in the narrow edge of the CLT panel and the necessity to maintain minimum geometry requirements, it is difficult to ensure that the screw will be perfectly installed into the side-grain ply as shown. Therefore, it is conservatively assumed that the screw will be installed in the end-grain.
4. The NDS-2018 Commentary for Cl.12.2.1.5 allows the design engineer to ignore the application of C_{eg} = 0.75, and use C_{eg} = 1 instead when the screw diameter is less than ¼", the lamination thickness is at least 2", and the screw is installed into the side-grain only.
5. Geometry requirements as per ICC ESR 3178 and ICC ESR 3179 apply.
6. Specific gravity of CLT panel is assumed to be ≥0.42.

SUMMARY

STS are modern versions of traditional lag screws and offer many advantages in connection design. Availability of larger diameters and longer lengths allow STS to develop higher withdrawal resistance. However, since connection design using STS is not covered in current North American codes such as the NDS-2018, the NDS-2018 provisions for lag screws and manufacturers' guidelines for STS can be used in conjunction to calculate withdrawal resistance at various angles to the grain.

The main points to highlight from this white paper are:

- Utilization of screws parallel-to-grain, especially near the edge of the end-grain is generally not recommended due to the non-homogenous nature of wood and its susceptibility to checking that makes end-grain applications sensitive to conditions which cannot be reliably controlled.
- End-grain applications are not always avoidable and the withdrawal resistance for STS should be decreased in accordance with the NDS-2018 and manufacturers' guidelines.
- Longer STS should be used in parallel-to-grain withdrawal in order to engage more wood deeper within the member.
- Fully Threaded STS have high axial capacities that should be taken advantage of via inclining the screws at an angle to the wood grain direction.
- Connections with STS where $\alpha < 30°$ must be subjected to short-term loading only.
- At $\alpha < 15°$, a minimum of four STS are needed for a reliable axial connection.

Due to the increasing popularity of STS in mass timber connection design, incorporation into the North American design codes is likely to occur in the near future. A standardised adjustment factor should, at that point be developed to calculate the withdrawal resistance that considers a wider range of angles to the grain. Meanwhile, the approach suggested in this paper should be employed for withdrawal calculations when using MTC's ASSY fasteners.

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