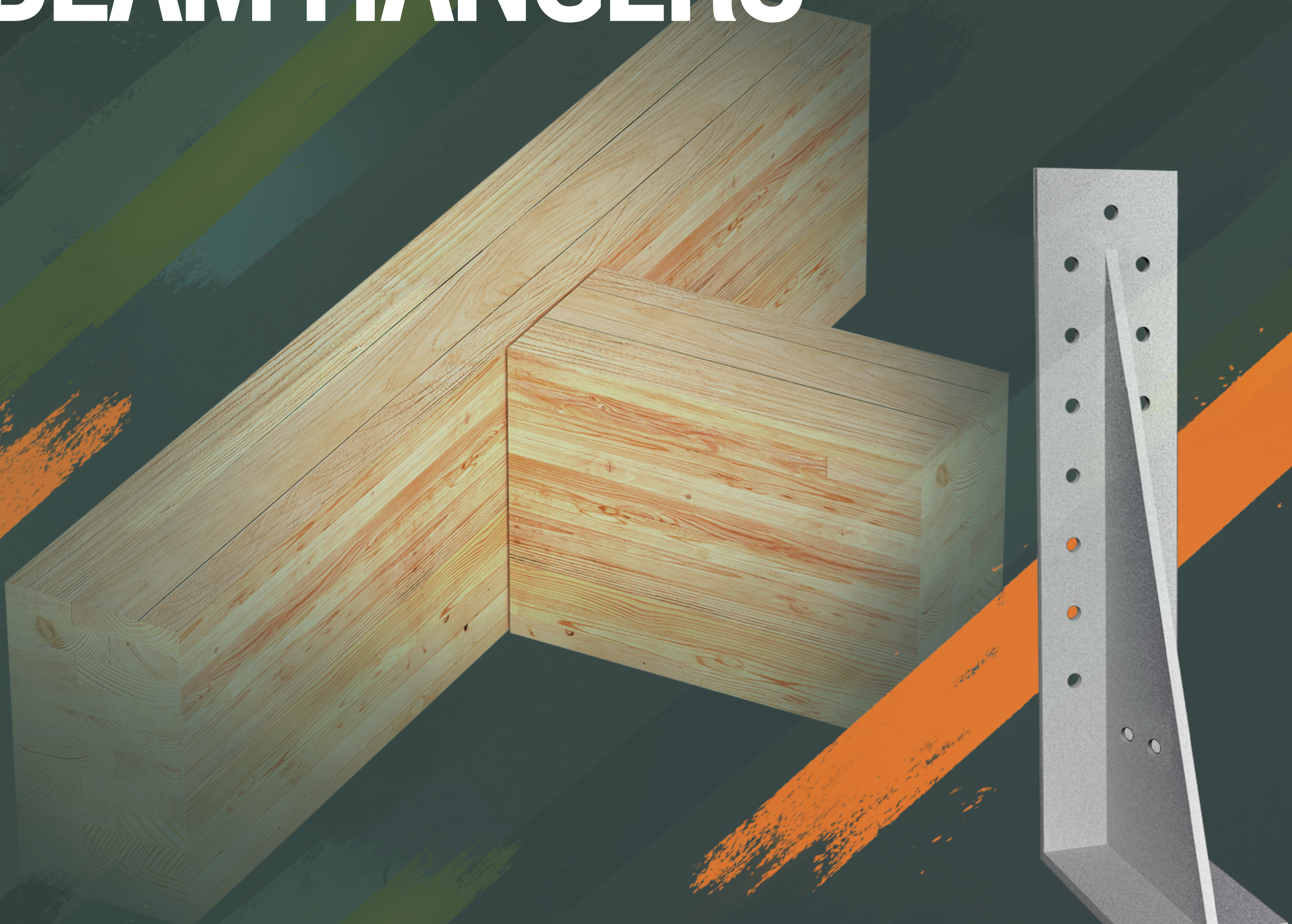
WHITE PAPER

MTC SOLUTIONS

STIFFNESS CONSIDERATIONS FOR CUSTOM BEARING BEAM HANGERS



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INTRODUCTION

Given the growing popularity of post and beam framing systems for high rise mass timber buildings, there is a greater need for designing high-capacity beam hanger connections that are both cost-effective and safe. Custom connections are designed to meet the specific needs of the structure and building location and are typically designed with bolts using wood design codes such as the CSA O86 for Canada and the NDS for the United States. However, designing custom connectors using exclusively code values may pose some challenges including meeting serviceability limit requirements.

Serviceability requirements rely on the stiffness of the system which is highly dependent on the system's fastener configuration: the quantity, placement, size, and embedment of the fasteners acting in the connection. A beam hanger system may be designed to have enough capacity for the ultimate applied load, but these designs may not account for any additional permanent deformations that the connection may experience and may not have the required stiffness to withstand sustained loads throughout its life cycle.

Most mass timber beam hanger connection suppliers test their connectors to verify the system's ultimate capacity and overall stiffness behavior. The testing of these connections and discrepancies between expected and actual results, have shown that verifying the stiffness of a beam hanger connection is crucial in confirming the actual design capacity and deformation behavior of the system. Proper testing of a beam hanger connection is essential because system stiffness and deformation cannot be accurately predicted using theoretical formulas.
In extreme cases, the omission of stiffness criteria when designing a custom beam hanger connection may lead to premature failure of the connection during high displacement events such as high seismic or wind scenarios. This omission could also lead to serviceability issues in the structure, such as cracks in beams, bent beam hangers, sagging connections, etc. When designing a custom beam hanger connection, it is highly recommended to perform additional testing on the system to accurately predict the system's displacement and deformation under the desired load.

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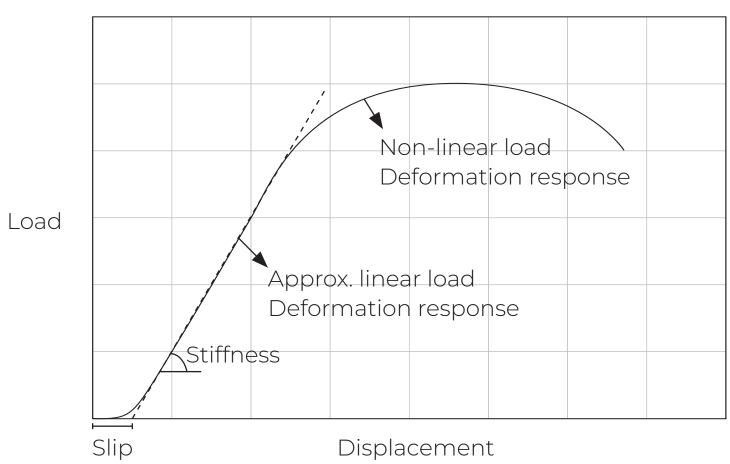
CONNECTION STIFFNESS THEORY

Currently, when designing a custom mass timber connector system using the relevant North American standards, only the design capacity of the system can be calculated. When designing a simple bearing beam hanger, the designer is only required to complete wood and bearing failure checks, steel checks and calculate the connector system's vertical shear capacity. Stiffness or possible deformation are not considered in the design capacity of the connector and no accurate formulas are provided to estimate the potential level of deformation in the connection itself.

Figure 1 represents a simplified load-displacement curve response for a typical steel-to-wood connection in shear using dowel type fasteners. The load-displacement curve includes an initial slip region prior to the linear elastic response. The stiffness response of a connection is typically approximated using the linear elastic zone of the load-displacement curve. After the linear elastic region, the connection will experience a non-linear plastic response, then ultimate failure. In the non-linear region, the stiffness response is non-constant and decreases as displacement increases (Jockwer & Jorissen, 2018).

Table 1. Specimen Dimensions



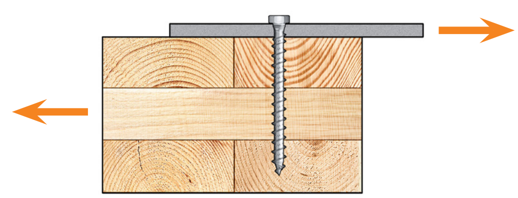


Figure 1 Typical Load Displacement Curve (Steel-to-Wood Connection in Shear)

The plastic behavior of the system makes it difficult to predict the overall stiffness and deformation response of a connection system. When using dowel type fasteners, current design codes do not offer an adequate prediction of system stiffness and suggest testing must be done to confirm the actual behavior of the connector (Jockwer & Jorissen, 2018). This is partially due to the simplified assumptions made and the non-linearity of the system's plastic response under load.

Accurately predicting the system stiffness is especially important in maintaining a connection's serviceability limits while ensuring the connection remains functional when subjected to different loading scenarios such as seismic or high wind events (Kolb, 2008, p.160). Testing can confirm whether a system performs softer/more ductile under these loading cases or if it exhibits a more brittle failure performance. Excess deflection can also damage the load-bearing capabilities of the system and affect the connection's appearance. Concrete toppings used for fire protection of CLT floor panels can experience cracking if the serviceability limits of the supporting connections are exceeded. This is also true for any window features as they cannot sustain any excessive deformation.

TESTING CODE REQUIREMENTS

In Canada, the CSA O86 design code only includes stiffness criteria for tested beam hanger solutions. The USA wood design codes do not offer any stiffness guidelines for tested solutions. However other testing criteria specific to Load and Resistance Factor Design (LRFD) and Allowable Stress Design (ASD) can be used to analyze beam hanger testing data.

The following summarizes the analysis criteria for a tested custom beam hanger connector in both Canada and USA.

CSA O86 - Limit States Design

Chapter 16 of CSA O86-19, while referencing ASTM D7147, provides detailed requirements on calculating the ultimate resistance of joist hangers. Clause 16.5.3 of CSA O86-19 states that if less than 10 pairs of beam hangers are tested, the ultimate capacity of the system is the lesser of

1. the corrected ultimate load per hanger calculated in accordance with Clause 16.5.4, multiplied by 0.91 and a resistance factor (ø) of 0.6 per Clause 12.6; or

2. the average load per hanger at which the vertical movement between the joist and the header is 3 mm, multiplied by 2.42 and a resistance factor (ø) of 0.6 per Clause 12.6

NDS - Allowable Stress Design

The NDS does not include a direct reference to stiffness provisions for calculating the ultimate capacity of beam hanger systems, however the ICC-ES Acceptance Criteria for Joist Hangers and Similar Devices (AC 13) is used to calculate the ultimate capacity of beam hangers in the United States and includes details on connection stiffness. This criteria references ASTM D7147: Testing and Establishing Allowable Loads of Joist Hangers, for testing and performance requirements while providing more detailed analysis provisions. ASTM D7147and AC 13 state that the ultimate capacity of a beam hanger system where six or less tests are conducted, is the lesser of

1. The lowest ultimate vertical load for a single device from any test divided by 3 (where three tests are conducted); or

2. The average from all the tests of the vertical load that produces a vertical movement of the joist with respect to the header of 0.125 inch (3.2 mm)

In both the Canadian and USA standards, the design capacity of a beam hanger system is limited either by the strength or stiffness requirement that must be confirmed with proper testing.

Bearing Beam Hanger Testing

MTC Solutions has conducted a series of tests on a simple custom bearing beam hanger connector to identify the system deformation response and highlight the unpredictability of system stiffness.

This project was developed with the goal of testing a custom bearing beam hanger concept that is common on the market. To mimic typical office building glulam sizes and loading scenarios, the beam hanger was designed for a standard beam size of 8-3/4” x 24” [222mm x 610mm]. ASSY Kombi 1/2” x 3-1/8” [12mm x 80mm] self-tapping screws, specifically designed for high performance steel-to-wood connections, were used to fasten to the primary member (Figure 2). The hanger includes a 0.24” [6mm] stiffener and a 6” [160mm] bearing plate (Figure 3).

Testing was done in accordance with ASTM D7147 where the secondary wood member was reinforced under the bearing plate with fully threaded self-tapping screws to prevent premature compression failure of the wood.

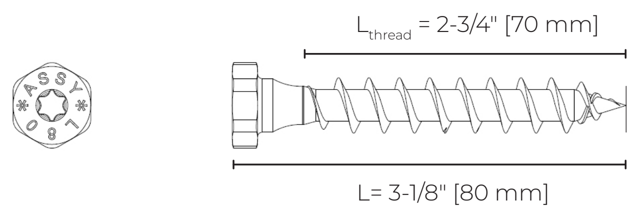


Figure 2 ASSY Kombi Self-tapping Screw Dimensions

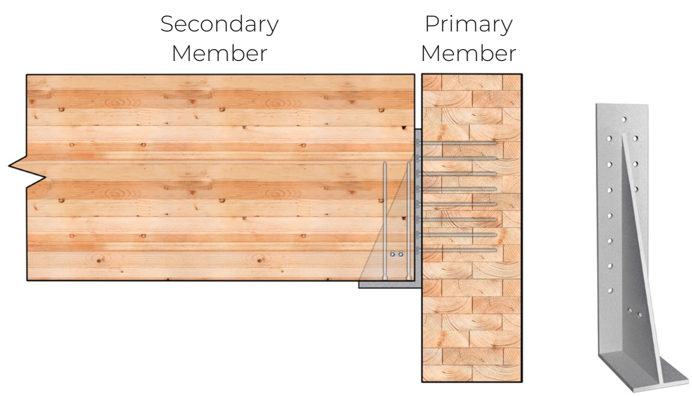


Figure 3 MTC Solutions Custom Bearing Beam Hanger

RESULTS

The following section summarizes the results obtained from the testing, beginning with the design capacity of the system.

As previously explained, the system capacity of a tested beam hanger system is calculated using Chapter 16 of CSA O86 which provides detailed requirements on calculating the ultimate resistance of joist hangers. MTC Solutions' test results are as follows:

1. The corrected ultimate load per hanger calculated in accordance with Clause 16.5.4, multiplied by 0.91 and a resistance factor (ø) of 0.6 per Clause 12.6 was calculated to be 98kN
2. The average load per hanger at which the vertical movement between the joist and the header is 3 mm, multiplied by 2.42 and and a resistance factor (ø) of 0.6 per Clause 12.6 was calculated to be 51.4kN

Therefore, taking the lesser result, the design capacity of the tested bearing beam hanger is 51.4 kN [11.55 kips] in LSD.

As previously stated, the ICC-ES AC 13 is used as a reference to calculate the ultimate capacity of tested beam hangers in the United States. MTC Solutions' test results are as follows:

1. The lowest ultimate vertical load for a single device from any test divided by 3 was calculated to be 13.1 kips
2. The average from all the tests of the vertical load that produces a vertical movement of the joist with respect to the header of 0.125 inch (3.2 mm) was calculated to be 8.11 kips

Therefore, taking the lesser result, the design capacity of the tested bearing beam hanger is 8.11 kips in ASD.

The results for both Canada Limits States Design and USA Allowable Stress Design are summarized in Table 1.

Unpredictable Connection Response

Analyzing the testing data shows that displacement and system deformation play an important role in identifying the bearing beam hanger's design capacity as it was the governing factor for both Canada and USA analyses. This outcome can be further supported by the load-displacement curve of the connector during the test. Figure 4 outlines the load-displacement curve of the connector during trial one of testing, which includes an initial 25% pre-loading imposed at the beginning of the test to minimize the effect of the connector's initial slip.

The bearing beam hanger exhibited the following behaviors during testing:

1. Between points A and B, there is a small initial slip in the system
2. Between points B and C, the load deformation curve is non-linear which is typically associated with permanent plastic deformation of the connection
3. Between points C and D, the elastic deformation occurs
4. Between points D and E, there is the expected plastic deformation of the system after reaching the elastic limit of the connection
5. At point F, the system fails completely

As with most beam hanger connections, the initial slip of the system, the elastic region, the long ductile region and eventual ultimate failure were all expected. In contrast, the early permanent plastic deformation of the connection between points B and C was not predicted. This response greatly affects the design capacity of the system and must be accounted for in the overall design of the connection. One or more design components of the connector appear to be the cause of this premature deformation.

The following section and Figure 7 summarize the four factors potentially contributing to this behavior.

Table 1 Custom Bearing Beam Hanger - Tested Design Capacity

Country	Tested Bearing Beam Hanger Design Capacity
	[Kips]
Canada (LSD)	11.55
USA (ASD)	8.11

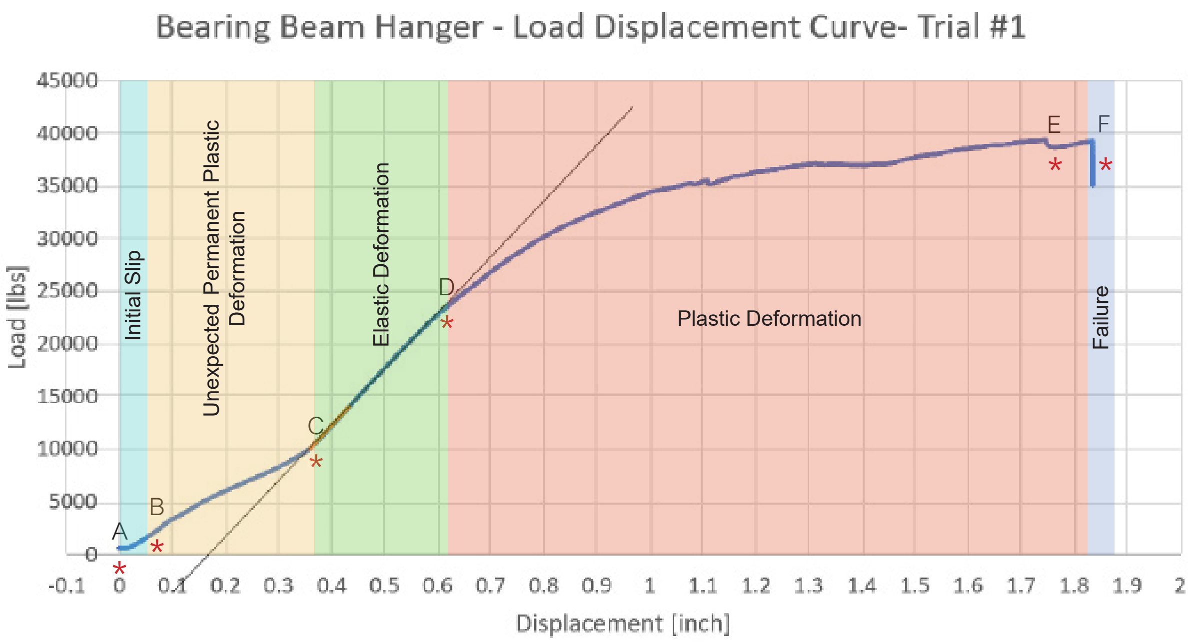


Figure 4 Custom Bearing Beam Hanger - Test Load - Displacement Curve

[1] Deformation of the Screws in Shear

The self-tapping screws in the primary member were removed for inspection after the testing trials (Figure 5). These connecting self-tapping screws barely deformed for all test series even when the connector reached its ultimate capacity. Although it can be assumed that the minimal deformation of the connecting screws is likely not significantly contributing to the premature deformation of the connection between points B and C, the cumulative effects of deformation in the system will contribute to the total displacement criteria set in the testing criteria.

Figure 5

Deformation of Self-tapping Screws in Primary Member

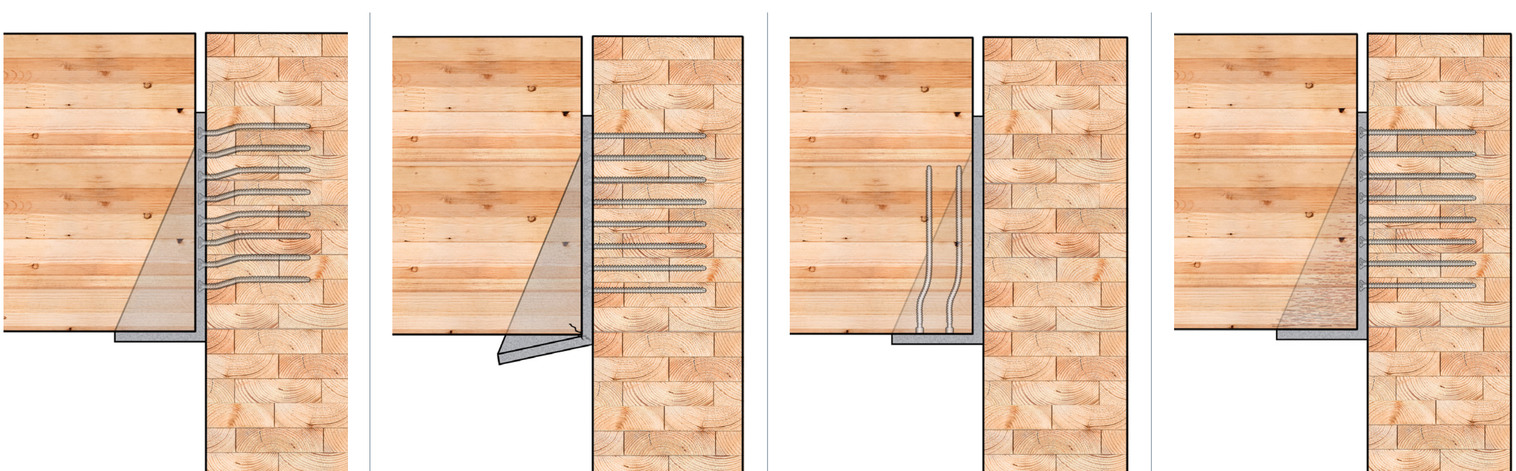
[2] Deformation of the Bearing Plate

The bearing plate of the connector does not seem to have undergone a significant permanent deformation during testing, as shown in Figure 6. It is important to note that a small deformation of the bearing plate in addition to the overall deformation response of the system (Figure 7) will accumulate and will affect the displacement requirement set in the testing criteria.

Figure 6

Deformation of the Bearing Plate

Figure 7 Potential Causes for Premature Deformation of the Custom Bearing Beam Hanger



[1] Deformation of self-tapping screws in primary member

[2] Deformation of bearing plate

[3] Buckling of reinforcing screws

[4] Compression failure of secondary member

[3&4] Compression Failure Deformation

Compression perpendicular-to-grain is one of the weakest responses in a wood member and can lead to premature failure of the wood. To limit the risk of wood failure, reinforcing screws were installed under the bearing plate in the secondary timber member. Figure 8 shows the bearing failure of the wood and the reinforcing screws after the completion of the test. The compression failure of the bearing area can be associated to the possible buckling of the reinforcing screws, reinforcing screw pushing-in capacity or the compression failure of the wood at the screw tip by having the compression stress released into the wood.

As seen in Table 2, the design bearing capacity of the system without reinforcing screws was predicted to be 72kN per CSA O86 and 13kips per NDS, which are slightly lower than the testing capacity governed by the ultimate load. The design capacities based on codes do not account for the loss of stiffness and excess deformation of the connection. The reinforcing screws in the testing have prevented a more severe bearing failure by evenly distributing the stress created by the bearing forces into the beam section (Table 2). This concept is further confirmed by Bejtka and Blaß using both theoretical calculations and testing that concluded fully threaded self-tapping screws are a good method of "increasing the load-carrying capacity of stiffness perpendicular-to-grain of the wood member or to minimize the elastic displacement perpendicular-to-the grain" (2006).

Most modern bearing connections designed for the mass timber industry do not include reinforcing screws in their design as it is not required by North American standards. The lack of reinforcement in the bearing area can lead to even more unpredictable displacement response in these connections. It is also troubling since most custom bearing beam hangers are not tested, and standards used for designing these connectors do not require reinforcement in the bearing area. Additionally, these standards do not include adequate deformation response criteria for very high-capacity beam hanger connectors (in the order of 300kN in LSD or 36kips in ASD).

Further research must also be done to investigate the influence of the knife plate kerf on the strength reduction of the bearing area. The concealed housing for the connector stiffener may promote buckling of the bearing timber by contributing to the compression perpendicular-to-grain failure.

Table 2 Custom Bearing Beam Hanger - Tested and Code Standard Design Capacity

Country		Tested Design Capacity		Code Standard Design Capacity
		Governed by Ultimate Load	Governed by Displacement	Unreinforced Bearing Resistance
Canada	**[KN]**	**98.0**	**51.4**	**72.0**
USA	**[Kips]**	**13.1**	**8.1**	**13.0**

Figure 8

Compression Failure of the Wood in the Bearing Area

CONCLUSION

The design of custom mass timber post and beam connections according to North American standards does not account for deformation or stiffness, two of the most important serviceability requirements. Underestimating the importance of connection stiffness and behavior under the load may lead to unpredictable damages to the structure or in extreme cases, a premature failure of the connection altogether.

When designing custom connections, designers expect to achieve a typical load-displacement curve. The testing of the custom bearing beam hanger system presented in this white paper shows that due to the complexity of each component, it is difficult to accurately predict the actual response of the system using only theoretical formulas. Bearing beam hanger connections will typically include an initial plastic deformation prior to its elastic response and ultimate failure. This unpredictable deformation response is attributed to many unique components of the connection, including yielding of screws, bearing plate deformation, deformation of timber in compression, and buckling of reinforcing screws.

As higher capacity beam hangers are required in high rise mass timber buildings, verifying the deformation criteria with testing becomes even more crucial. It is understandable that not every project can verify the behavior of their custom-designed hangers with testing. In this situation, it is suggested to use pre-engineered beam hanger systems that have been tested and capacity verified. Most mass timber connection suppliers including MTC Solutions, test their connection systems and analyze their data according to the appropriate acceptance criteria for usage in both the USA and Canada. This ensures quality and compliance with North American standards, bringing peace of mind to engineers and builders alike.

Additionally, using pre-engineered beam hangers can reduce the research and development costs associated with additional testing, effectively reducing project budgets. The use of pre-engineered connections can greatly reduce the challenges that an engineer may face when designing custom connections such as fire design, fastener geometry requirements and even estimating the proper ultimate load. These modern proprietary connecting systems can also be designed for higher capacities and are easier to install than traditional systems.

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