Tensile Strength Evaluation of Glulam Connection with Screw Fasteners

Bradley Sharpshair
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Tensile Strength Evaluation of Glulam Connection with Screw Type Fasteners

by Bradley Sharpshair

MS Project Report

Department of Civil and Environmental Engineering

Portland State University

June 2021

Abstract:

Multiple knife plate and external steel plate deep-beam glulam connections were investigated in a series of destructive tests within the Infrastructure Testing and Applied Research laboratory at Portland State University. The goal of these tests was to better understand the failure mode and ultimate load capacity of the large-scale glulam moment connections. Two different types of tests were performed on each connection; one with axial loading, and another loaded in flexure. The first, smaller, axial tests were conducted to inform the later, much larger, bending tests. The results of these tests helped to develop future designs as well as provide adequate proof of concept for an ongoing project.

Each of the failure types were cataloged and the ultimate loads of each tested connection were compared to estimated design capacities. Block shear and shear type splitting were the most observed failure types. The results demonstrated the knife plate connection consistently failing before the expected load was reached, whereas the external steel plate connection regularly exceeding the expected loads.
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Introduction:
With a push for more sustainable building methods and materials it is no surprise that mass timber is quickly becoming the focus of many new structures. The Portland International Airport broke ground in March 2020 on a new terminal core (TCORE), which will feature deep glulam beams supporting the roof of an open concept structure \(^{(1)}\). The new design will need to adequately handle gravity loads and also be seismically resilient in order to be safe for the public. The design calls for the glulam beam-to-column connections to have no rotation which is considered a moment resisting connection.

Moment resisting glulam connections are not widely used mainly because the National Design Specification for Wood Construction (NDS) design equations greatly limit the capacity of dowel type fasteners which are used in conjunction with steel plates to resist the tension component of an applied force couple \(^{(2)}\). Because moment resisting glulam connections are so uncommon, no design provisions have been adopted by the NDS as of yet. In order for the TCORE project to implement deep-glulam moment connections the NDS code limitations need to be bypassed. This is possible if independent studies and testing programs can prove adequate capacity in the new connection.

To help aid in the effort, Portland State University began a testing program September 2018, using their Infrastructure Testing and Applied Research (iSTAR) laboratory \(^{(3)}\), to test 12 full-scale deep glulam beams in bending and 24 partial scale glulam beams in pure tension. The first proposed connection design is a knife plate connection with MyTiCon Self-Drilling Dowels (SDD) \(^{(4)}\), and the second is a steel plate connection with Simpson Self-Drilling Screws (SDS) \(^{(5)}\). For each connection type, three sizes were investigated. The connection sizes correlate to the number of screws in each connection.

Prior to the full-scale bending tests 24, pure axial tests were performed to estimate the connection capacities and load-deformation relationship. These axial specimens were smaller, and based on the results of the tests, adjustments were made to the full-scale specimens. The results of both the axial and bending tests were used to develop allowable capacities for each connection as part of the TCORE project. The full-scale and axial tests aim to better understand the capacity and failure mode of the glulam connections with screw type fasteners.

Axial Tests:
Overview
24 axial tests were performed on smaller glulam beams with full scale connections; four tests for each connection type and size. The objective of the axial tests was to better understand the behavior of each connection before testing the larger, full-scale glulam specimens.
Table 1 shows the dimensions of each connection along with the size of the glulam beam it was paired with for the axial tests. Similar specimens are labeled by screw type (MyTiCon or Simpson) followed by the number of screws per connection (ex. M028 is a MyTiCon connection with 28 screws). The noteworthy connection parameters are the plate width (W), length (L), thickness (t), and separation (a) along with the screw edge distance (e). A subscript ‘r’ represents the use of reinforcing screws, which will be discussed later.

Each glulam beam was fitted with a connection on each end (Figure 1) and anchored into a steel frame (Figure 2, Appendix Photo 13) using 1-3/4” diameter threaded steel rods. The testing frame was designed to elongate the specimen with the use of four hydraulic cylinders (6) and can apply up to 800kips of tension. Local and global displacements as well as hydraulic cylinder load and pressure were monitored during each test with the use of LVDTs (7), load cells (8), and pressure transducers (9).

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<th>Glulam dimensions</th>
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<td>S432</td>
<td>18</td>
<td>40</td>
</tr>
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</table>

*Table 1: Axial Testing Specimen Details*
Figure 1: Axial Specimen Details

Figure 2: Axial Testing Instrumentation Plan
Instrumentation

Each specimen was fitted with 16 LDVTs and each hydraulic cylinder line was fitted with a pressure transducers and load cell (Figure 2: Axial Testing Instrumentation Plan). Each hydraulic line leading to a hydraulic cylinder had an accompanying pressure transducer. For specimens with estimated load capacity over 400 kips the load cells were removed.

LVDT’s 1 & 2 measure the total displacement, 3 & 4 measure any out-of-plane movement, 5 & 6 measure west end connection displacement, 7 & 8 measure east end connection displacement, 9 & 12 measure west end overall displacement, and 13 & 16 measure east end overall displacement.

The “connection displacement” measurement captures any movement within 3 feet of the glulam beam and the connection end plate. The “overall displacement” measurement captures any movement within 3 feet of the steel frame and the glulam beam, including anchor rod deformation.

The displacement, load, and pressure data were all collected at a sample rate of 50Hz using a data acquisition system (DAQ) (10). A visual instrumentation tool was then used to monitor the instrumentation remotely.

Loading Protocol and Testing

Each specimen was loaded to a predeteremined load and held for 10 minutes before continuing with the test. The predetermined load was to simulate the maximum service level loading the member would experience and was roughly half of the estimated connection capacity. The 10-minute hold time represents a short-term load duration as defined by the NDS. Once the 10-minute mark had passed the load was continually increased until the specimen failed.

Failure was defined for each of the specimens as the loss of at least half of the maximum applied load. If for any reason the test was deemed unsafe, the test was stopped.

Due to the hydraulic cylinder capacity the maximum applied load could not exceed a total of 800 kips. The maximum total displacement was limited by the hydraulic cylinder stroke length which was 5 inches.

Test Observations and Failure Mode

As each specimen was loaded, small creaking and popping noises could be heard as the steel fasteners settled into the glulam. Once the hold load was reached, it was uncommon for these small noises to continue. As the specimens were close to failure these noises could be heard once again, and were much louder than before. The most common noise was a large pop which was accompanied by a loss of axial load. During the hold load, it was common to see a gradual loss of load, which can be explained by the relaxation of the wood fibers and steel fasteners.

6
When the specimens reached their ultimate load, a sudden failure would reduce the axial load by more than 50% and a large amount of deformation was observed.

Of the 24 axial specimens tested, 22 failed in block shear failure or a shear type failure that spanned the length of the glulam beam. The connections typically ruptured in shear along the entirety of the outermost screw line and would then taper to a point toward the center of the specimen which left a distinct section that was permanently displaced approximately 0.25in from the rest of the glulam. Two specimens had a failure mode that included the shearing of fasteners along with a shear type failure through the glulam beam. On a few occasions there were tension failures seen across finger joints. Because the specimens were loaded parallel to the grain of the glulam, it was common to see shear failures follow the grain of the wood. It was common to see shear failures pass through weak points in the glulam such as knots, voids, and screw holes.

**Axial Results**

The maximum load, displacement at maximum load, displacement at failure, connection stiffness, and overall stiffness were calculated for each of the tests (Table 3: Axial Test Results). The overall stiffness and connection stiffness were calculated from the load vs displacement plots.

The “overall stiffness” is defined as the force required to displace the glulam beam relative to the testing frame one unit of length. The “connection stiffness” is defined as the force required to displace the glulam beam relative to the connection end plate one unit of length. To verify the accuracy of the stiffness calculations, a visualization of the calculated stiffness versus the collected data was created (Figure 4: Verification of Stiffness Value). A linear plot of the stiffness calculated is compared to the collected load versus displacement data.

As the reaction beam began to take large loads it was lifted slightly off of the ground supports. This out of plane movement will have an effect on the North-end overall displacement readings and therefore will affect the stiffness calculation. Because the steel wire used to connect the LVDT to the reaction beam was long, out of plane movement will only cause minimal in-plane displacement, and therefore should be neglected. No trends point to the stiffness or failure favoring the North end of the reaction frame.

The displacement at failure (Table 3: Axial Test Results) is defined as the failed-end displacement, post fracture, at 50% of the ultimate load. Due to the nature of failure, some of the reported values correspond to loads lower than 50% of the ultimate load. This was frequently observed when a specimen fractured, or split, and lost more than half of the ultimate load in under 0.02s. The testing
equipment samples data points at a maximum of 50Hz, and therefore could not capture the failure in its entirety.

Table 3: Axial Test Results reports the test values for each tested specimen. Table 2: Average Testing Results reports the average ultimate capacity, connection stiffness, and overall stiffness for each similar connection type.

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South Connection Load vs Displacement

![Graph](image)
Table 3: Axial Test Results

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Bending Tests:
Overview

Similar to the axial testing connections, the two connection types under investigation are a knife plate connection using MyTiCon SDD fasteners and a steel plate connection using Simpson SDS fasteners. The connections are identical to the ones seen from the axial test. Each connection has three sizes, which correspond to the number of fasteners used. The steel plates for each size have a different width (W), length (L), thickness (t), and separation of the connection plate (a). These parameters along with the number and edge distance (e) of screws used to fasten the connection, beam depth (d), moment arm (l), and lever arm (b) are given in Table 4: Bending Test Specimen Details.

Each glulam beam had dimensions of 240”x69”x 6-3/4” with the grain running parallel to the longitudinal axis. A total of 46 laminations were used to achieve the 69” depth. Multiple finger joints were used to achieve the 240” of length (Figure 7: Bending Specimen Parameters).

Table 4: Bending Test Specimen Details

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<th>Connection Type</th>
<th>Plate Dimensions</th>
<th>Glulam dimensions</th>
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<td>36</td>
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<tr>
<td>S432</td>
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</table>
The bending test frame consists of rolled steel members with additional web and flange stiffener plates, a load-applicator stand, and two 100-ton hydraulic rams. A compression bucket is secured to the frame and lateral supports are secured to the strong floor to prevent extensive out of plane movement. A specimen is first secured into the compression bucket, then the threaded rods are tightened to anchor the tension connection. The anchor holes in the steel frame have been oversized such that no shear can theoretically be transferred to the connection. Twenty feet from the connection, the load applicator stand is screwed to the bottom of the glulam beam using 2-1/2” SDS screws to prevent any slippage. Two hydraulic rams are placed underneath the load applicator stand and apply an upward force which translates to an applied moment at the connection. For the purpose of estimating applied moment, it is

*Figure 7: Bending Specimen Parameters*
assumed the connection is “fixed” to the frame and has a constant moment arm of 240 inches from the point of load application.

**Instrumentation**

Each bending test had 22 LVDTs, 2 load cells, and 2 pressure transducers. The load cells were fitted with a rounded cap so any load applied at an angle would be captured by the instrument. 10 LVDTs measured the displacements at the connection face, 6 LVDTs measured the vertical displacement of the beam relative to the strong floor, and 6 LVDTs measured the global movement of the testing frame. The hydraulic pump was connected to a manifold which split into 2 separate lines, in parallel, which then delivered equal pressure to the hydraulic rams.

Similar to the axial test, 4 LVDT’s measure the displacement of the glulam relative to the connection end plate, referred to as “connection displacement”. Likewise, 4 LVDTs measure the displacement of the glulam relative to the testing frame and are referred to as the “overall displacement”.

Unlike the axial test, a set of 2 LVDTs will measure any displacement in the glulam beam relative to the testing frame within the compression bucket.

**Loading Protocol and Testing**

Following the loading protocol from the axial tests, each test will be loaded to a predetermined moment and held for 10 minutes before continued loading. During the holding period, a constant load was maintained. Once the hold is complete, loading was applied until failure occurred. If the specimen lost half of the maximum load it was considered “failed”. If the test was deemed unsafe for any reason, the test was stopped.

If the test failure was localized, or did not destroy the whole beam, the beam was reused, and a second test was run on the opposite end. The beam was removed from the rig, flipped along the longitudinal axis, rotated 180 degrees, and reinserted into the rig.

In the event that the hydraulic cylinders reached their maximum stroke, a procedure was set in place to shim the load applicator, lower the cylinders, provide adequate extensions, and reload the specimen. Of the 12 tests, only 2 needed to be shimmed to provide enough cylinder stroke.

It is important to note that the testing rig was designed to fit specimens with a connection-centerline to extreme-compression-fiber dimension of 60 inches. Due to the placement of the small and medium sized specimens, this dimension was off by 2.5 inches and modifications had to be made to fit the specimen into the testing rig. A 2.5 inch by 12-inch notch was cut out of the top of the specimen.
**Test Observations and Failure Mode**

Similar to the axial tests, as each specimen was loaded small creaking and popping noises could be heard as the steel fasteners settled into the glulam. Because the loading apparatus was forced to push the specimen up the self-weight of the beam had to be overcome before significant loads were applied to the connection.

The most common failure was a block shear failure. Small cracks originated along the outermost fastener lines and extended toward the point of load application. The block shear failures often did not show a well-defined tension failure, but rather shear failures that tapered toward the other side of the specimen. However, when tension failure was seen, it was common to find failures across finger joints near the connection.

Each of the failures were preceded by loud creaking and popping, then, would fracture suddenly. It was common that after a large crack or pop that load would be lost and a significant positive displacement could be seen. Because the specimens were loaded parallel to the grain of the glulam, it was common to see shear failures follow the grain of the wood. Nearly all of the failures were localized to the connection.

*Figure 8: Bending Test Instrumentation*
Bending Results

Table 5: Bending Test Results summarize the ultimate load, displacement at ultimate load, connection and overall stiffness, and maximum displacement for each of the bending tests. Each variable is defined similar to the axial test parameters.

The ultimate load is calculated by first finding the applied moment at the connection (measured load multiplied by the moment arm), and dividing it by the lever arm (distance from centerline of connection to centerline of compression zone). This was done in an effort to compare the axial tests and bending tests.
### Table 5: Bending Test Results

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Comparison and Analysis:

In an effort to understand the large-scale moment connections, it is important to verify the axial tests perform similarly to the bending tests. The comparison of failure type, ultimate tension load, displacement and stiffness will be made between the axial tests and bending tests.

Common Failures

The most common failure seen in both the axial and bending tests was block shear in the glulam beam. The size and location of the failures were consistent between the axial and bending specimens with similar connection types and sizes. It was typical for the glulam to form a crack along the outermost fastener line which would then propagate the full length of the connection. These cracks propagated past the connection, it was common for them to converge to a single point. For a few cases, failures were seen to span the length of the beam to the point of load application. Every block shear failure occurred suddenly without warning, and can be described as being a brittle failure.

Second to block shear was a shear type failure that separated the connection from the rest of the specimen with a single failure plane. This was most common in the axial tests, but also was seen in the bending tests. This too can be described as a brittle failure.

Two tests, however, did not have a similar failure as the rest. The failure of these two tests was seen in the fasteners as well as in the glulam. The plate connection fastened with 108 Simpson SDS fasteners shows clear signs of steel yield. This was seen in one axial and one bending test with the small plate connections. These are the only two examples of somewhat ductile failures.

The failure plane for each specimen, axial and bending alike, followed the grain pattern of the glulam and would often pass through weak points such as knots or voids. Because the axial glulam beams were loaded in pure tension with one connection on either side, it was common to see failure start in one connection and extend into the other connection on the opposite side.

Ultimate Load

The objective of testing the smaller, more cost-effective, axial tests is to gain insight into the behavior of the large-scale connections, specifically the ultimate load capacity. To accurately compare the two types of test it is necessary to assume a lever arm to estimate the tension force in the deep beam of the bending tests. Secondly, it will be necessary to subtract the self-weight of the bending test specimens so the applied moment is not over-estimated. The approximate self-weight of each bending test specimen is 4,300 pounds.
Each connection type and size will be compared from the axial and bending tests. Each connection type and size will be compared to an estimated ultimate load capacity. The estimated load capacity was based on NDS equations and were performed by a separate party.

**M028**

Four axial tests configured with the M028 connection were successfully performed and average ultimate load was found to be 127.1 kips. The load vs displacement plot for each individual specimen all follow the same trend and therefore all were used for the analysis. The M028 connection from the axial test is 3% above the estimated capacity.

Two bending tests were performed on the M028 connection and the average ultimate load was found to be 141.8 kips. The first test had a significantly higher load than the second test, and therefore could potentially be an outlier for this connection and test type. The bending tests show an 11% increase in ultimate load when compared to the axial tests. The M028 connection from the bending test is 14% above the estimated capacity.

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**Axial(gray) and Bending(black) test results for M028 connection**
M063

The axial tests performed on the M068 connection are not as uniform as the smaller M028 connection, but still show a reasonable trend. One test however, had a significantly higher strength than the other three tests (17%-29%). This test was not excluded when determining the average ultimate load of 174.9 kip for the axial tests. The M068 connection from the axial tests is on average 37% lower than the estimated load capacity.

The bending tests performed on the M068 connection were uniform and no outlier should be excluded from the analysis. The average ultimate load of the bending tests performed on the M068 connection is 237.0 kip. This is a 35% increase in ultimate load compared to the axial tests. The M068 connection for the bending tests were on average 14% lower than the estimated ultimate capacity.

Axial(gray) and Bending(black) test results for M063 connection
M120

Four successful axial tests were performed on the M120 connection and the average ultimate load was found to be 491.8 kip. One test shows a higher ultimate load than the other three, but will not be excluded in the analysis. The M120 connection from the axial tests is on average 20% lower than the estimated ultimate capacity.

Two bending tests performed on the M120 connection show uniform behavior with an average ultimate load of 358.6 kip. This is a 37% decrease in the ultimate load when compared to the axial tests. The M120 connection for the bending tests were on average 41% lower than the estimated ultimate capacity.

Axial(gray) and Bending(black) test results for M120 connection
S108

A total of four tests were performed on the S108 connection. It is important to note that none of these tests included transverse reinforcement, which will be discussed later. All of the tests were extremely uniform, and an average ultimate load of 148.0 kip. The S108 connection from the axial tests is on average 16% higher than the estimated ultimate capacity.

Two bending tests performed on the S108 connection show an average ultimate load of 187.8 kip. It is important to note the first test has an ultimate load that is 28% higher than the second test, but is not excluded from the analysis. When compared to the axial tests, the average ultimate load is 26% higher. The S108 connection for the bending tests were on average 47% higher than the estimated ultimate capacity.

Axial(gray) and Bending(black) test results for S108 connection
S234

Two tests were performed on the S234 connection. After these tests an average ultimate load was determined to be 221.2 kip. Because the ultimate load was significantly lower than the estimated value (12%-28%), another four specimens were fabricated with transverse screws and were named S234r. No bending tests were performed on this connection without transverse reinforcing screws.

\[ \text{Axial(test results for S234 connection)} \]

S234r

Four tests were performed on the S234r connection, which included 10 transverse screws in each connection (Appendix: Photo 14). An average ultimate load was determined to be 325 kip. The S234r connection from the axial tests is on average 18% higher than the estimated ultimate capacity.

Two bending tests were performed on the S234r connection, and the ultimate load was determined to be 440.1 kip. This is a 35% increase in the ultimate load when compared to the axial tests. The S234r connection for the bending tests were on average 60% higher than the estimated ultimate
capacity. Note that for one of the bending tests, shimming of the load applicator was required to reach failure. This is represented by the dramatic decrease, then increase, in load just before failure.

*Axial (gray) and Bending (black) test results for S234r connection*
S432r

Four tests were performed on the S432r connection, which included transverse reinforcing screws. The average ultimate load was determined to be 677.2 kip. The S432r connection from the axial tests is on average 33% higher than the estimated ultimate capacity.

Two bending tests were performed on the S432r connection and the ultimate load was determined to be 584.2 kip. This is a 16% decrease in ultimate load when compared to the axial tests. The S432r connection for the bending tests were on average 15% higher than the estimated ultimate capacity.

Axial (gray) and Bending (black) test results for S432r connection
Expected Ultimate Load
Each specimen had an estimated ultimate load calculated by the appropriate NDS equations for dowel type fasteners. Each of the steel plate connections with Simpson SDS fasteners exceeded the expected ultimate load capacity, except for S234 which was not reinforced with transverse screws. The only knife-plate connection to exceed the expected ultimate capacity was M028, all others failed to meet this value.

Transverse Screws
After the first two tests of the S234 connection, it was determined that the connection needed to be supplemented with transverse screws. To accommodate for the new screws, three rows of SDS fasteners had to be relocated to the end of the connection plate. Five rows of two 18-inch screws were driven perpendicular to the glulam laminations. The objective of adding these screws was to help the glulam resist shear parallel to grain, which was the leading failure in the previous tests.

No transverse screws were added to any of the knife plate connections because the already reduced section would make it extremely difficult to properly drive the screws. Likewise, removing more of the glulam fibers to drive the screws would further reduce the capacity of the wood. No transverse screws were added to the S108 connection because the initial testing showed adequate strength without them.
With the transverse screws added the S234r connection experienced, on average, a 47% increase in ultimate load capacity when compared to the S234 connection with no transverse reinforcement. The main failure type was still block shear, but was less pronounced than before. The permanent deformation in the specimens with added reinforcement was 39% less than those without the transverse screws.

Moving forward from this, the S234 and S432 connections would now have transverse reinforcement added and will be designated as S234r and S432r. No testing of the S432 connection (no transverse reinforcement) was performed in the axial or bending setups. No testing of the S234 connection (no transverse reinforcement) was performed in the bending test setup.

**Moisture Modifications**

Four axial test specimens (M028, M063, S108 and S234) were moisture treated off-site prior to testing. The objective of the moisture modification was to investigate if the moisture content of the glulam would have any effect on the ultimate capacity.

The average moisture content of the specimens without treatment was 8.3% with a high of 10.9%. The moisture treated specimens had a moisture content of approximately 6.3%. All moisture modifications and readings were performed by a third party.

Comparing specimens with similar connections and different moisture contents shows no difference in ultimate capacity. There appears to be no correlation between moisture content and the ultimate capacity of these connection types.

**Connection and Overall Stiffness**

Every specimen, both from the axial and bending tests, were analyzed and their stiffness values were reported. Two stiffness values were reported for each specimen; connection stiffness and overall stiffness. As previously mentioned, the overall stiffness is the tension force required to move the glulam one unit of measurement relative to the testing frame whereas the connection stiffness is the tension force required to move the glulam one unit of length relative to the connection end plate. The objective of taking two stiffness measurements is to better understand where the displacement of the connection is coming from.

For the axial tests, connection stiffness tends to be on average 77% higher than the overall stiffness. This shows us that a large part of the overall deformation is coming from the anchor rods rather than the connection. Because of testing frame limitations, it was not possible to pretension the anchor rods without applying a tensile load into the axial specimens. The bending test frame allowed for the anchor rods to be tightened with the use of a lever arm leading to the connection stiffness to be on average 19% greater than the overall stiffness.
Summary:

Two deep beam glulam tension connections, external steel plate and knife plate, were extensively tested at Portland State University’s Infrastructure Testing and Applied Research laboratory. The steel plate connection consists of two external steel plates that are connected to the glulam beam with Simpson SDS fasteners. The knife plate connection consists of two steel plates imbedded into the glulam beam and are connected by MyTiCon SDD fasteners from one side. Each connection has 3 different sizes correlating to the number of fasteners used. For each connection and size, an estimated load was calculated based off of current NDS equations.

The main objective of testing the large-scale connections is to better understand the ultimate load capacity and to categorize the failure types for each connection. In total 38 tests were completed, 26 axial tests and 12 bending tests.

The M028 connection’s ultimate tensile load was on average 3%(axial) and 15%(bending) greater than the estimated capacity. For the M063 connection, the ultimate tensile load was on average 37%(axial) and 15%(bending) less than the estimated capacity. The M120 connection’s ultimate tensile load was on average 24%(axial) and 42%(bending) less than the estimated capacity. In summary, 2 of the 3 sizes of the knife plate connection with MyTiCon fasteners did not meet the estimated tensile load capacity.

The S108 connection’s ultimate load capacity was on average 17%(axial) and 48%(bending) greater than the estimated capacity. The S234 connection was not reinforced with transverse screws and had an ultimate tensile load capacity 20%(axial) lower than the estimated value. Because the connection did not meet the estimated load value, transverse screws were added to connections that could accommodate them and include an ‘r’ at the end of their name. The S234r connection’s ultimate load capacity was on average 18%(axial) and 60%(bending) greater than the estimated capacity. The S432r connection’s ultimate load capacity was on average 33%(axial) and 15%(bending) greater than the estimated capacity. All of the external steel plate connections with the Simpson SDS fasteners, except for the S234 connection, exceeded the estimated tensile load capacity in every size.

The vast majority of connections tested failed in block shear, in which the shear failure plane was along the outermost fastener lines and the tension failure plane was not well defined. The average displacement of the ‘block’ was approximately 0.25in and in some cases was as large as 0.5in. The second most prominent failure type was a shear-type failure that originated at the fastener line closest to the extreme tension fiber. In this case a single failure plane was observed and often spanned the length of the beam. Two failures were observed in the S108 connections that involved the yielding and shearing of
several fasteners in combination to a shear-type failure in the glulam. These failures were more ductile than all of the other failures observed.

The moisture content was taken for each axial specimen and compared to the ultimate load. Four specimens, one M028, one M063, one S108, and one S234, were moisture treated. It was concluded that there was no correlation between the moisture content and the ultimate load capacity.

The deformation of each connection was represented in the stiffness values calculated from the collected data. It was found that the stiffness of the glulam-to-connection-endplate was higher than the glulam-to-testing-frame. This leads to the conclusion that on average 77%(axial) and 19%(bending) of the overall deformation comes from the deformation of the steel anchor rods that tie the connection to the testing frame.

**Recommendations for Future Research:**

Though the inherent variability of wood makes designing glulam moment connections difficult, it is important to continue the research within this field so sustainable construction can thrive. With the conclusion of the bending and axial tests, a few topics for future research would be helpful to investigate.

One area of focus could be the development of a finite element model to help describe the strain profiles in the connections. This could lead to an explanation of why the axial and bending tests had different results, both in their capacity and in the failure mode.

The development of a finite element model or a numerical model could then lead to guidance on the placement of transverse reinforcement. Many of the observed failures originated from the splitting of the wood perpendicular to the grain. Therefore, understanding the effect of the placement of these screws could help better develop these connections.

Lastly, in an effort to make these connections accepted at large, the connections should be redesigned such that a ductile failure occurs in steel, rather than a brittle failure in the glulam. The redesign of these connections could focus on the spacing of the fasteners, or the thickness of the connection plate to ensure a more consistent and ductile failure.
References:


(3) iSTAR Laboratory; [accessed 2021 Jun] https://istarlab.cee.pdx.edu/


Appendix:

Photo 1: Knife Plate connection M028; Axial specimen

Photo 2: Knife Plate connection M028; Bending specimen
Photo 3: M028 bending test block shear failure
Photo 4: Knife Plate connection M063; Axial specimen
Photo 5: Knife Plate connection; Bending specimen
Photo 6: M063 bending test block shear failure
Photo 7: Knife Plate connection M120; Axial specimen
Photo 8: Knife Plate connection M120; Bending specimen
Photo 9: M120 block shear failure
Photo 10: M120 block shear failure
Photo 11: S108 Connection, Axial Specimen
Photo 12: S108 Connection, Bending Specimen Failure
Photo 13: Axial Testing Frame Overview
Photo 14: S234r Connection, Axial Specimen
Photo 15: S234r Connection, Bending Specimen Failure
Photo 16: S432r Connection, Axial Specimen
Photo 17: S432r Connection, Bending Specimen
Photo 18: S432rConnection, Bending Specimen Failure
Photo 19: S432r Connection, Bending Specimen Failure, Plate Removed