Building Tomorrow's Society

Bâtir la Société de Demain

Fredericton, Canada

June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

EXPERIMENTAL DETERMINATION OF PULL- OUT STRENGTH OF THREADED STEEL RODS MECHANICALLY FASTENED INTO GLULAM BEAM SECTIONS

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Abstract: Threaded steel rods have been increasingly used as concealed connecting components in glued-laminated timber (glulam) frame connections. Embedding the rods in glulam beam ends has primarily been done with the use of adhesives. Connections for timber structures using concealed bonded-in steel rods offer a practical solution in the development of more efficient joining methods. However, the influence of adhesive type, specifically its properties and strength, are not yet fully understood and as such well-developed design criteria are lacking. For the research presented in this paper, instead of using adhesively-bonded rods, mechanically-fastened threaded steel rods were employed. The beam connection parameters investigated were rod embedment length and washer bearing area. A tensile force was applied to the steel rod, and linearly increased until the embedded connection failed. The strong steel rod in the connection resulted in the wood section failing every time, so a relationship between the embedment length and washer bearing area within the glulam section was observed. An understanding of this relationship would allow there to be a ductile failure mode of a weaker steel rod before any brittle failure occurred in the glulam section. Experimental results revealed that connections of 3/4-inch threaded steel rod mechanically fastened into black spruce glulam beam sections have pull-out strengths that range approximately between 66.2 kN for an embedment length of 150 mm and square washer size of 38.1 mm (1.5 inches), and 109.7 kN for an embedment length of 200 mm and square washer size of 50.8 mm (2.0 inches).

1 INTRODUCTION

Larger sawn lumber members are becoming increasingly difficult to obtain for heavy-timber construction because trees are limited in the size that they can grow. A way to negate this issue is to use glued-laminated timber (glulam) beams and columns. Glulam is manufactured by gluing together small sections of wood, known as lamina, to form a larger wood section. The lamina used are varied in size; 2" x 4", 2" x 6", and 2" x 8" are common sizes. Some manufacturers are using lamina as small as 25 x 50 mm (1" x 2") from wood that is normally wasted, such as wood sourced from the crown of trees, side cuts, or small branches (Nordic Structures 2015). These wood sections were previously ignored as a building material due to their small size or low mechanical properties individually, but when glued together they can form a larger, stronger, and more stable member than that from sawn lumber of the same species.

Glulam has been used in Canada in the construction of industrial, commercial, and institutional (ICI) buildings. Recently, amendments were made to the National Building Code of Canada (NBCC 2015) and several provincial building codes that allowed wood to be the primary building material in mid-rise buildings up to six storeys. These changes have increased the potential scope for glulam sections in Canadian construction, as glulam members can be made with much larger cross sections, lengths, and even be curved to support greater loads than sawn lumber members. As these changes have been recently made to building codes, there is still lack in technical design documentation providing adequate design guidelines for efficient heavy-timber beam-to-column connections.

The areas most lacking in the available design guidelines are embedded-rod connections (Hunger et al. 2016) and moment-resisting connections (Petrycki and Salem 2017). Glued in threaded steel rods have been in use and experimentally tested since the late 1980's, but there are no consistent design procedures for their application (Barillas 2014) (Fragiacomo and Batchelar 2012). Some design approaches and code models have been published; however, there are some discrepancies and even partial contradictions between the different models (Steiger et al. 2006). Experimental work has shown that threaded steel rods inserted into wood can provide a connection with certain degree of ductility that can prevent brittle failure modes from developing in the wood section (Tomasi et al. 2008). As these connections are composed of varied materials, they are considered hybrid connections. The interaction between wood, adhesive, and metal, introduces several variables that need to be considered, which has made it difficult to predict the connection's dominate failure mode (Oh 2016). Factors that have been found to affect the connection strength are: the rod embedment length, the size of the hole compared to the rod diameter, the type of adhesive used, and the species of wood (Hunger et al. 2016; Steiger et al. 2006). Steel rods can be epoxied into one member and secured with a nut and washer to the other member, or the same rod can be glued into two separate members making a connection (Fragiacomo and Batchelar 2012). A highlighted issue with connections composed of a glued rod in both members is that the connection has to be made on site; which has been shown to carry a high risk of being improperly bonded since the effectiveness of the grouting operation cannot be visually checked (Batchelar and McIntosh 1998). Therefore, it is highly recommended that the gluing process be done in a controlled environment where skilled workers can check their work and ensure a proper bond.

The use of embedded rods has the advantage of being superior in fire performance compared to other connections because the steel components are completely concealed inside the wood section. Even a connection where only a slight portion of the steel rod is exposed still has considerably high charring rate due to the fact that steel components quickly conduct heat into the connection (Barber 2017). Also, issues with the epoxy at elevated temperatures still need to be further investigated though. A study done by (Di Maria et al. 2017) shows that epoxy deteriorates, and thus the connection can easily fail when temperature reaches only 50 to 60°C.

A practical solution to the epoxy problem at elevated temperatures is to mechanically fasten the steel rods instead. The fastening can be done by cutting a small hole in the side of the beam section to meet the end of the rod, then a nut and washer can then be utilized to mechanically fasten the steel rod. Once the beam is connected, a small wood plug can be glued into the hole, covering the nut and washer, which will provide a fully-concealed connection just like the bonded-in rod connection. Such a connection can be easily assembled in the field, which eliminates the possibility of bond failure in the glued-in rods done in the field, as well as avoiding the epoxy deterioration issues at elevated temperatures. This paper presents the results of an experimental study undertaken to evaluate the behaviour of threaded steel rods embedded into glulam beam sections under tension. The embedded rods were mechanically fastened in the end of the glulam beam sections using nuts and square washers.

2 EXPERIMENTAL PROGRAM

Thirteen full-size test assemblies were experimentally examined in the research project presented in this paper. Four configurations were used for the rod-glulam connections. Test variables for the connection configurations included rod embedment length and size of the square washer.

2.1 Materials

2.1.1 Glulam Beams

The glulam beam sections (137 mm x 318 mm) used in the test assemblies was provided by Nordic Structures, Quebec. The wood species used in the sections was S-P-F, comprised of 90% black spruce. The beam sections were manufactured to meet the 24F-ES/NPG stress grade with architectural appearance grade. The individual lamina stocks that were used to build up the beam sections measured approximately 25 mm x 50 mm. The lamina stocks were finger jointed at their ends and glued together in horizontal and vertical layers. Since the glulam beam sections were symmetrical in width and depth and glued all around, they have uniform layup and their strength properties are the same regardless of orientation. The main mechanical design properties of the glulam sections are listed in Table 1 below.

Table 1: Mechanical properties of glulam beams (Nordic Structures 2015)

Property	Unit (MPa)
Bending moment, F_b	30.7
Longitudinal shear, F_v	2.5
Compression perpendicular to grain, F_{cp}	7.5
Compression parallel to grain, F_c	33.0
Tension parallel to grain, F_t	20.4
Tension perpendicular to grain, F_{tp}	0.51
Modulus of elasticity, E	13,100

2.1.2 Threaded Steel Rods

The threaded rods used in the experiments had a diameter of 3/4" (19.05 mm), length of 910 mm, and stress grade of SAE J429-Grade 5. Using a band saw, the rod was cut to 600 mm for the test assembly, while the other 310 mm was cut in half and both halves were tested on the Tinus Olsen Universal Testing Machine at Lakehead University's Civil Engineering Structures Laboratory to confirm the stress grade of the steel rods. The average of the yielding strength of the two pieces was 150 kN confirming the rods' stress grade.

2.1.3 Washers

The washers used in the experiments were fabricated from an 8-mm steel flat bar with a stress grade of 300W, as specified by (CSA G40.20-04/G40.21-13). There were six washers fabricated; three were 1.5" x 1.5" (38.1 mm x 38.1 mm), and three were 2.0" x 2.0" (50.8 mm x 50.8 mm). The washers were cut to rough length with a band saw, and then they were trimmed to final dimensions using the milling machine. A 3/4" (19.05 mm) hole was drilled in the centre of each washer.

2.2 Test Assembly Details and Fabrication Process

Four threaded-rod-in-glulam-beam connection configurations were tested: first, a rod embedment length of 150 mm with a 1.5" (38.1 mm) square washer; second, a rod embedment length of 150 mm with a 2.0" (50.8 mm) square washer; third, a rod embedment length of 200 mm with a 1.5" (38.1 mm) square washer; and fourth, a rod embedment length of 200 mm with a 2.0" (50.8 mm) square washer. Each connection configuration was tested three times, except for the first configuration which was tested four times.

The glulam beam sections with 150 mm embedment length were cut to a length of 450 mm; whereas the beam sections with 200 mm embedment length were cut to a length of 500 mm using a band saw. There was a small cut-off measuring 350 mm, which was used as the fourth test for the first connection configuration. A 13/16" (20.6 mm) hole was then drilled in the centre of one of the ends of the beam section to the required embedment length using a precise portable drilling station. Every beam section had a line marked perpendicular to the grain at the required embedment length, and a line marked parallel to the grain down the centre of the widest face of the beam section. A little rectangle was marked directly below the embedment length line and centred on the beam's face. Rectangles measured 1 5/8" (41.3 mm) wide for the 1.5" (38.1 mm) washer, and 2 1/8" (54.0 mm) wide for the 2.0" (50.8 mm) washer, with both measuring 30 mm thick to accommodate the washer and nut total thickness. All rectangles were then carved out into a rectangular prism using wood chisels to a depth where the centre of the washer hole would line up with the centre of the hole made through the end of the beam section. The depth of the hole chiselled out was approximately 87 mm for the 1.5" (38.1 mm) washer, and 93 mm for the 2.0" (50.8 mm) washer. The other end of the beam section had six 13/16" (20.6 mm) holes drilled on the widest face to match the holes in the tension attachment for the Universal Testing Machine (UTM). An example of a prepared beam section is shown in Figure 1a, and the tension attachment used in experiments is shown in Figure 1b.

(a) Prepared beam section

(b) Tension Attachment

Figure 1: A general prepared beam section and matching tension attachment

2.3 Test Assembly Design

The purpose of this research is to acquire the strength of the wood failures; therefore, a strong threaded steel rod was selected for the testing to make sure the failure happens in the wood, and not the steel. The anticipated failure mode of the glulam beam section is rod pull-out, similar to the failure mode in the case of glued-in threaded rods. Since there was no design clause for rod pull-out parallel to the grain in the Canadian Wood Design Manual 2015 (WDM 2015) (Canadian Wood Council 2016), the principles of mechanics were used. Like the failure mode of a glued-in threaded rod pull-out, the strength of the mechanically-fastened threaded-rod-in-glulam-beam connection is primarily dependent on the area of wood to be sheared. The glued-in threaded rod area to be sheared is the circumference of the rod multiplied by the embedment length; whereas, the area to be sheared by the mechanically fastened rod is determined to be the perimeter of the square washer multiplied by the embedment length.

According to Clause 12.2.1 in the WDM 2015, all connection formulas must take into account certain K factors to accurately predict their true strength values. These K factors include the load duration factor, K_D, the service condition factor, K_S, and the treatment factor, K_T. The glulam beam sections were tested under quick loading till failure (less than seven days); therefore, the load duration factor, K_D, equals 1.15 as per Clause 12.2.1.6 in the WDM 2015. The beam sections were under dry service condition and were untreated; therefore, the service condition factor, K_S, and the treatment factor, K_T, both equal 1.0 as per Clause 12.2.1.5 and Clause 12.2.1.7, respectively.

The specified shear strength for the glulam beam, f_v, equals 2.5 MPa according to a technical note published by Nordic Structures (Nordic Structures 2015). The final value to account for is a resistance factor due to the brittle nature of wood. In the WDM 2015, the most commonly used resistance factor for the different types of connections is 0.6, which has been adopted in this formula. Combining all these values resulted in development of Equation 1, as shown below.

$$[1]\ \mathrm{PR} = \phi\, \mathrm{f_v}\, (\mathrm{K_D}\, \mathrm{K_{Sv}}\, \mathrm{K_T})\, \mathrm{p}\, \mathrm{I}$$

Where; PR = Pull-out resistance of threaded rod in glulam (N), ϕ = 0.6 (resistance factor for brittle failure), f_v = specified shear strength (MPa), K_D = load duration factor, K_S = service condition factor, K_T = treatment factor, p = washer perimeter (mm), and I = embedment length (mm)

Using Equation 1, with and without the brittle failure factor of 0.6, the minimum and maximum expected pull-out strength values were calculated as shown in Table 2. The maximum expected pull-out tensile force of the glulam beam section for the strongest configuration was 116.8 kN, while the tested yielding tensile force resisted by the threaded rod was 150 kN; therefore, all failures should be rod pull-out, and not rod yielding.

Table 2: Threaded-rod-in-glulam-section connection tests matrix

Test configuration	Test replicates	Embedment length (mm)	Washer size (mm)	Minimum expected tensile force (kN)	Maximum expected tensile force (kN)
Test 150-1.5	4	150	38.1	39.4	65.7
Test 150-2.0	3	150	50.8	52.6	87.6
Test 200-1.5	3	200	38.1	52.6	87.6
Test 200-2.0	3	200	50.8	70.1	116.8

2.4 Tests Setup and Procedure

The tension attachment for the beam section was placed in the bottom jaws of the UTM. A small plate was attached to the end of the beam, and an attachment for a Linear Variable Differential Transformer (LVDT) was secured to the side of the beam section near the end, both of which were used to help with measuring the displacement using two LVDTs. The glulam beam section then had the threaded rod inserted through the end hole, and then was secured using a washer and nut through the small side rectangular cut off. The beam section was then placed on the tension attachment and secured using six A325M bolts, while the threaded rod was slipped up into the top jaws of the UTM. Both jaws were drawn tight, and a minimal initial load was applied to the test assembly to secure the machine jaws.

One draw-wire displacement transducer was attached to the cylinder head block and the stationary block to measure the displacement of the entire system; including the slippage in both sets of jaws, as shown in Figure 3a. Two LVDTs were attached at the top end of the beam section, as shown in Figure 3b. One was attached to a metal pole next to the small plate to measure the displacement between the pole and the small plate, while the other was attached to the side of the glulam section to measure the displacement between the beam section and the cylinder head block. Both were measuring the displacement between the beam section and the cylinder head block; therefore, their results should be the same. The two LVDTs measured the displacements of the beam section and the potential slippage of the top jaws. Once the displacement measuring instruments were in place and zeroed, the initially applied load was recorded, then the test assembly was loaded at a rate of about 8.0 kN per minute. The test was terminated when the glulam beam section achieved rod pull-out failure. A full test setup of a general assembly is shown in Figure 3c.

(a) Draw-wire displacement transducer

(b) Two LVDTs installed

(c) Test setup of a general assembly

Figure 3: Full test setup of a general test assembly

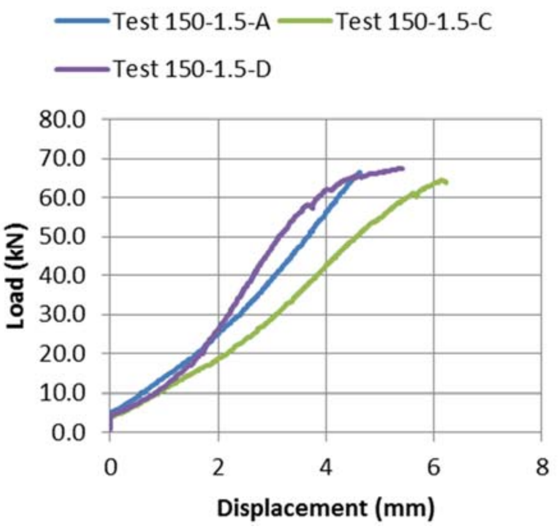
3 EXPERIMENTAL RESULTS AND DISCUSSION

The measurements of the two LVDTs installed on each test specimen were nearly identical, which confirmed the displacement between the cylinder head block and glulam beam section, as well as potential slippage in the top jaws. However, the draw-wire displacement transducer showed an increase in displacements by an average of 3 mm and up to 5 mm compared to the two LVDTs' measurements, which indicate that there was a slight slippage in the bottom jaws. Also, when the tested rod was removed from the top jaws, its threads were bent in the direction of the pulling jaws, which confirms that there was slight slippage in the top jaws as well. Accordingly, the experimental results showed slightly more displacements occurring in the pull-out of the rod than there should be. If the slippage was the same between the top and bottom jaws, the displacement results of the LVDTs should have the slippage in the bottom jaws subtracted from their results to give a more realistic result of the rod pull-out. However, since the exact slippage cannot be proven though; therefore, the current results remain unchanged and give more conservative values.

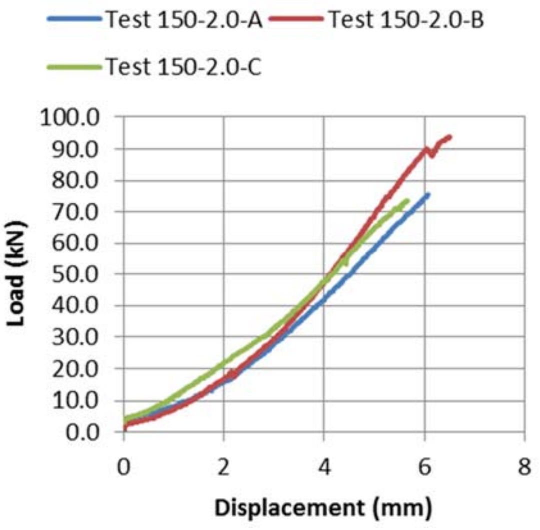
3.1 Load-Displacement Curves

Figures 4a through 4d show the load versus displacement curves for all test configurations. The displacements used in the development of these curves were the measurements of the LDVT attached to the metal pole. The displacement measurements of the LVDT attached to the glulam section were very similar to the measurements of the other LVDT, except for the end when the glulam failed under rod pull-out. The sudden jerk of the rod pull-out would slightly turn the installed LVDT and give a greater displacement value than what the actual value should be. The curves in Figures 4(a) through (d) were cut off at a point when a noticeable drop happened in the load, or a large displacement happened with minimal load gained. In some tests, the load would achieve a higher value afterwards; however, this was not allowed for safety reasons.

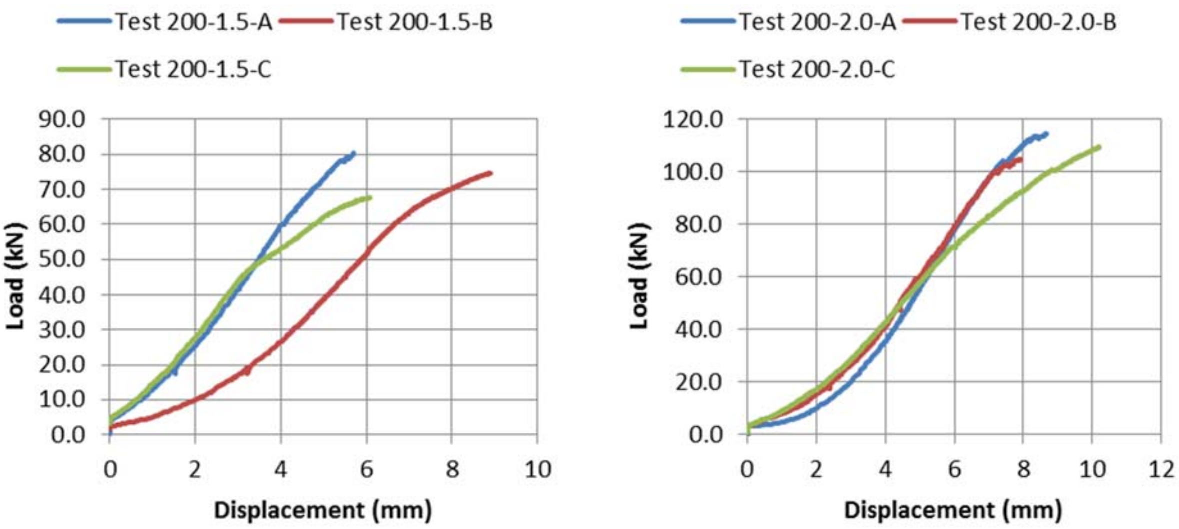
In Figures 4b and 4d, the curves are nearly identical as they are on top of one another. The consistency in these two figures is mostly because these test assemblies had larger bearing areas from the 50.8 mm (2 inches) washer to spread out the effects of imperfections, such as knots, in the wood. In Figures 4a and 4c, some parts of the curves are nearly identical in the beginning, but then certain curves experienced larger displacements at similar loads. The inconsistencies in these curves is most probably because these test assemblies had smaller bearing areas from the 38.1 mm (1.5 inches) washer to not spread out the effects of imperfections in the wood, unlike the configurations with larger washers. For Test 150-1.5 connection configuration, the three experiments used were A, C, and D, while test 150-1.5-B used the offcut beam section measuring 350 mm split down the middle, when tested, giving a much lower result compared to other similar tests. Therefore, this test was deemed unsatisfactory and given a null result.



(a) Test 150-1.5



(b) Test 150-2.0



(c) Test 200-1.5 (d) Test 200-2.0

Figure 4: Load versus displacement curves for the four tested configurations

Test 200-1.5 connection configuration had a different shape at the end of the curves as shown in Figure 5. While the other test configurations achieved rod pull-out failure almost immediately after their maximum load values were obtained, Test 200-1.5 connection configuration had the wood under the washer crushed before achieving rod pull-out failure. The wood crushing failure in this connection configuration was due to the smaller bearing area from the 38.1 mm (1.5 inches) washer, as well as the longer embedment length of 200 mm. In this configuration, the wood under the washer behaved like a short column and crushed before experiencing a large enough load to experience rod pull-out failure.

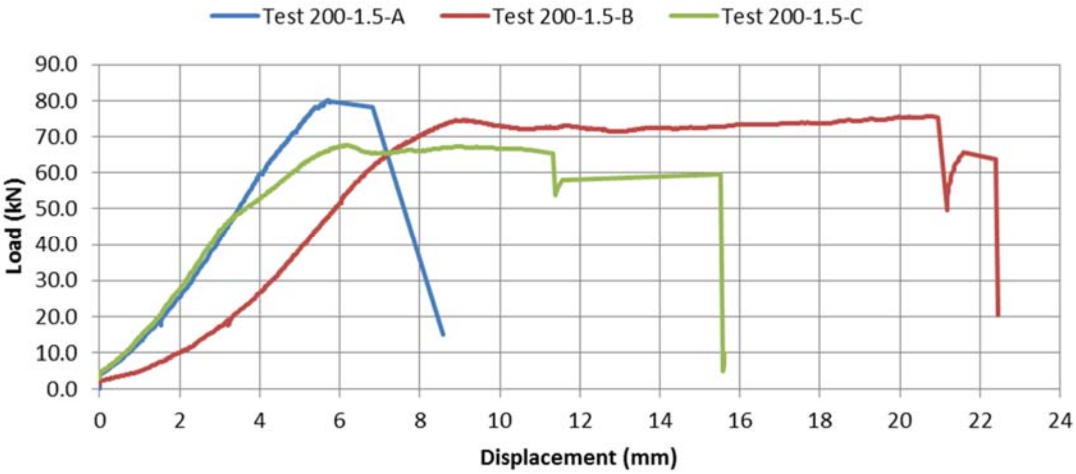


Figure 5: Test 200-1.5 load versus displacement (full curve)

3.2 Maximum Load Comparison

Shown in Figure 6 are the expected minimum, expected maximum, and the actual maximum loads of the tests for each of the four threaded-rod-in-glulam-beam connection configurations. All test results are either within the expected range or slightly above the expected maximum value; therefore, the range purposed by Equation 1, with and without the resistance factor, is plausible considering the number of test replicates for each connection configuration. The first connection configuration, Test 150-1.5 results have an excellent grouping that was around the maximum expected value of 65.7 kN. The last connection configuration's, Test 200-2.0, results have a good grouping as well that is close to the maximum expected value of 116.8 kN. While, the second and third test configurations' results are closer to the middle of their expected ranges and have their groupings more spread out. The larger spread of these two groupings is due to their embedment length and bearing area combination that added more stresses on the imperfections in the glulam sections causing them to fail before they can reach their maximum predicted pull-out capacities. Test 150-1.5 connection configuration had both, the smallest bearing area and the shortest embedment length, so the magnitude of force that stressed on the imperfections does not affect the overall strength of the glulam section. While Test 200-2.0 connection configuration had both, the largest bearing area and the longest embedment length, so the force developed until failure was much greater than that developed in Test 150-1.5; however, the stress put on the imperfections was still not as large to affect the strength significantly. Test 150-2.0 connection configuration had load-displacement curves directly on top of one another, but the spread of the maximum load is the largest which contradicts the expected predictability of this connection configuration. While Test 150-1.5 had a wide spread of load-displacement curves, but the closest spread of maximum load suggests that slippage of the top jaws could be affecting these results.

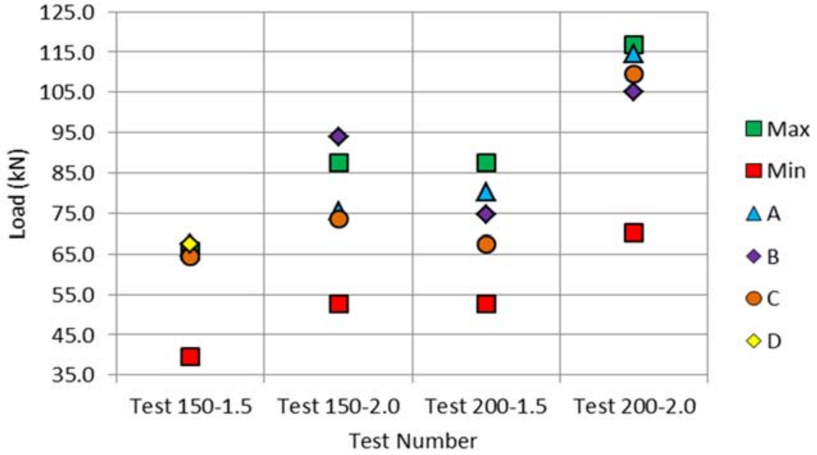


Figure 6: Maximum loads for the four configurations vs. their maximum and minimum predicted values

3.3 Failure Modes

The test connection configurations with the 38.1 mm (1.5 inches) washer size experienced two main failure modes, as shown in Figures 7a and 7b. In Figure 7a, the connection failure was due to rod pull-out taking out a wood cross-sectional area that is similar to the size of the washer. In Figure 7b, the failure was similar to that shown in Figure 7a, except that instead of shearing along the fourth side of the washer closest to the small side hole (used to insert the nut) it sheared along the three walls of the small hole that was chiselled out. As shown in Figure 7c, Test 150-2.0 configuration had a similar failure mode as that shown in Figure 7b, except that one or two 45-degree cracks also formed at the end of the beam section, at approximately where the washer corners were.

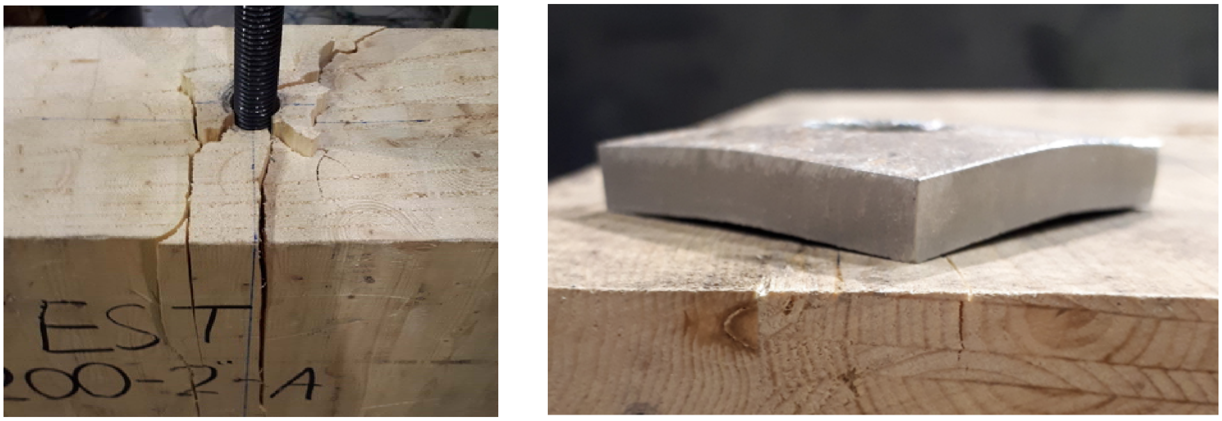
(a) Rod pull-out shearing along the washer edges

(b) Rod pull-out shearing along carved out hole edge

(c) Rod pull-out shearing along carved out hole edges with 45 degree cracks

Figure 7: Failure modes of first the three tested connection configurations

As shown in Figure 8a, Test 200-2.0 configuration had a more explosive failure, where a rod pull-out failure occurred like that shown in Figure 7b, as well as the 45-degree cracks formed similar to that shown in Figure 7c. In addition, the beam section in Test 200-2.0 had a clear split down the middle on the back side of the small hole, which did not form until the end, during around the last 5 kN before rod pull-out failure. The test configuration in this instance was much stronger than all other configurations, and caused the washer to yield slightly, as shown in Figure 8b. Since most of the yielding occurred at the corners of the washer; therefore, it can be assumed that more stresses happened at the corners to cause the 45-degree cracks to form at the end of the beam section.



(a) Rod pull-out shearing along carved out hole with 45-degree cracks and beam splitting

(b) yielded washer

Figure 8: Failure mode of Test 200-2.0

3.4 Summary of Test Results

Table 3 summarizes the results of all experiments presented in this paper. Test 150-1.5 displayed the closest average to the maximum expected load and had the smallest standard deviation of 1.24 kN. Test 200-2.0 had the second closest average to the maximum expected load and had the second smallest standard deviation of 3.92 kN. The other two configurations had their averages in the middle of the expected ranges, and their standard deviations were quite large. In general, it seems that keeping an embedment length to washer size ratio of 100 mm to 1” (25.4 mm) provides a more predictable failure load with the least amount of deviation.

Table 3: Summary of test results for the four threaded-rod-in-glulam beam connection configurations

Test No.	Minimum expected load (kN)	Maximum expected load (kN)	Test A load (kN)	Test B load (kN)	Test C load (kN)	Test D load (kN)	Average load (kN)	Standard deviation (kN)
Test 150-1.5	39.4	65.7	66.6	Null	64.5	67.5	66.2	1.24
Test 150-2.0	52.6	87.6	75.6	93.8	73.5	N/A	81.0	9.11
Test 200-1.5	52.6	87.6	80.3	74.6	67.6	N/A	74.1	5.20
Test 200-2.0	70.1	116.8	114.6	105.0	109.5	N/A	109.7	3.92

4 CONCLUSIONS

Based on the obtained experimental results and the analysis performed afterwards, the formula shown in Equation 1 is plausible; however, more test replicates need to be examined to confirm its validity. Also, keeping an embedment length to washer size ratio of 100 mm to 1” (25.4 mm) provides a more predictable failure load with the least amount of deviation.

According to the observations made out of the experiments presented in this paper, a few changes should be considered for future tests of this threaded-rod-in-glulam section connection. First, the top jaw of the UTM should be removed, and a fixed end should be attached to the cylinder head block instead, as this will guarantee no slippage to occur in the rod and that the displacement values will be more accurate. Second, more embedment lengths and washer sizes are to be tested, as this will help in confirming the validity of the developed formula, as per Equation 1. The final recommendation is to increase the washer thickness so that yielding in the washer does not happen for the tests with higher load capacities.

Acknowledgements

This research project was funded using NSERC Discovery Grant awarded to the second author. The authors would like to thank Conrad Hagstrom and Rob Timoon for their assistance in the Civil Engineering's Structures Laboratory at Lakehead University. Any opinions, findings, conclusions or recommendations are those of the authors and do not necessarily reflect the views of the funding agency.

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