CSCE Annual Conference

Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)

June 12 - 15, 2019

INVESTIGATING THE RESPONSE OF BOLTED WOOD CONNECTIONS TO THE EFFECTS OF BLAST LOADING

Andrew, M^c^Grath[1,2], Christian, Viau[1], and Ghasan, Doudak[1]
[1] University of Ottawa, Canada
[2] amgr046@uottawa.ca

Abstract: The results of an experimental program designed to investigate the influence of high loading rates on the dowel embedment strength and stiffness of bolted connections are presented in this paper. A total of seventeen single bolt connections were tested under static and blast loading. Connections both parallel and perpendicular to the grain were tested. The dynamic increase factor for the dowel embedment strength and the connection stiffness were investigated. The results showed that parallel to the grain connections exhibited a significant loss in ductility under dynamic loading. Reinforcement used to supress splitting failure was shown to prevent this loss in ductility and further improve the performance of the connection.

1 INTRODUCTION

In recent decades, the mitigation of risk to structures and critical infrastructure associated with terrorist attacks and accidental explosions has become a topic of interest among researchers and engineers. This rise of interest largely stems from high profile incidents, including intentional attacks (e.g. World Trade Center, 2001; Oklahoma City Bombing, 1995) and accidental explosions (e.g. Texas City refinery explosion, 2005; Ronan Point, 1968; Lac-Mégantic rail disaster, 2013). Understanding a structure's response to blast loading and the material's behaviour under high rates of loading is an important step in the mitigation of the risk associated with such events. Past research regarding the behaviour of wood subjected to dynamic loading has focused on small clear specimens subjected to impact loading (Markwardt and Liska 1956; Reid and Peng 1997; Gilbertson and Bulleit 2013). Research studies on the response of full-scale lumber with idealized boundary conditions subjected to simulated blast loading, including individual studs (Jacques et al. 2014), light-frame walls (Lacroix and Doudak 2015), glulam beams (Lacroix 2017), and cross laminated timber panels (CLT) (Poulin et al. 2018), have all shown an increase in resistance under dynamic loading, but the magnitude of the reported increase varied for the different wood products. Recent research studies have investigated more realistic boundary conditions and their effects on the behaviour of stud walls (Viau and Doudak 2016) and CLT wall panels (Cote 2017). These studies revealed that the type of connections and detailing play a significant role in the performance of the wall systems. Typical connection details used to resist gravity and in plane shear loads were shown to cause premature failure of the wall system and were deemed inadequate for out of plane blast loads. While these studies highlighted the need to understand the behaviour of timber connections subjected to blast loading, little progress has been made to quantify the behaviour of the connections themselves under high rates of loading. Research into the rate of loading effects on nailed connections has been undertaken (Girhammar and Andersson 1988; Rosowsky and Reinhold 1999) but no effort has been made to establish the performance of bolted connections subjected to blast loading.

Described in this paper is the experimental investigation of the performance of single bolt connections aiming to establish a dynamic increase factor (DIF) value both parallel and perpendicular to the grain. Strength values obtained from static tests were compared to those determined from simulated blast loading. The DIF of both the strength and stiffness of the connections are presented and discussed.

2 EXPERIMENTAL PROGRAM

A total of 17 specimens, each consisting of a wood main member connected to two steel side plates with a single bolt, were tested. 12 specimens were tested parallel to the grain, 4 under static and 8 under dynamic loading. Five specimens were tested perpendicular to the grain, where three were tested under static and two under dynamic loading. The connections were specifically detailed to ensure a wood embedment (crushing) failure and to avoid yielding in the bolt. The connections consisted of 25.4 mm ASTM A307 hex bolts, 86 mm thick wood specimens, and two 6.4 mm steel side plates. This provided a length to diameter ratio for the bolt of 3.4, which ensured that wood crushing was the dominate failure mode. All specimens were 356 mm in length (14 times the diameter of the bolt) and were cut from 86x178 mm spruce-pine-fir glulam beams. For the parallel to the grain tests, both edge distances were 89 mm, and the loaded and unloaded end distances were 178 mm. For the perpendicular to the grain tests the loaded edge distance was 127 mm, the unloaded edge distance was 51 mm, and both end distances were 178 mm. All edge and end distances were selected to meet the minimum dimensions required by ASTM D5652 (ASTM 2015). Figure 1 and Figure 2 show an example of a parallel and perpendicular to the grain specimen, respectively.

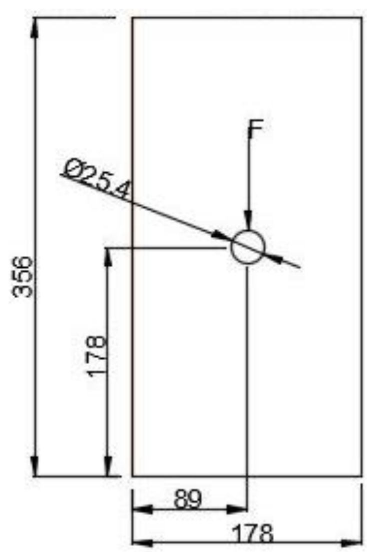

Figure 1: Parallel to the grain specimen (dimensions in mm)

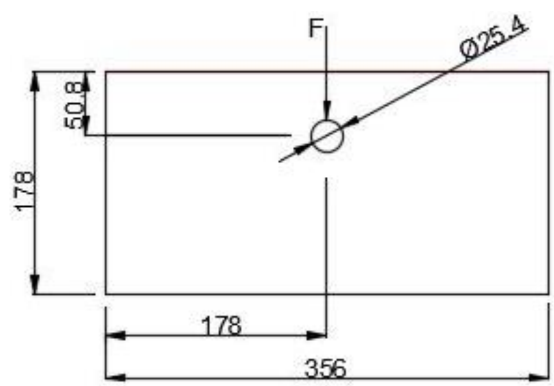

Figure 2: Perpendicular to the grain specimen (dimensions in mm)

In order to prevent splitting in the perpendicular to grain direction and to investigate the ability of self-tapping screws to reinforce the connection, three parallel to the grain specimens were reinforced with 8x120 mm Heco-Topix screws and tested dynamically. Four screws were driven into the loaded end distance, two from each side, and two were driven into the unloaded end distance, one from each side. An example of the screw used for the reinforcement can be seen in Figure 3. Figure 4 shows the reinforcement pattern used.

Figure 3: 8x120 mm Heco-Topix

Figure 4: Screw reinforcement detail

All static tests were performed using a Universal Testing Machine (UTM) in a displacement-controlled mode. The deformation rate was set at 2 mm/min for all tests. Figure 5 and Figure 6 show the static test set up for the parallel and perpendicular to the grain tests, respectively.

Figure 5: Parallel to the grain static test

Figure 6: Perpendicular to the grain static test

The dynamic tests were performed using the University of Ottawa's Shock Tube facility. Through the rapid release of compressed air, the shock tube is capable of generating a uniform shock wave that simulates a far-field detonation of high explosives. The driver section of the shock tube retains the compressed air before firing. The reflected pressure and impulse of the shock wave are varied by changing the combination of driver length and pressure. A load transfer device (LTD) was used to collect the pressure from the 2,032 x 2,032 mm shock tube opening and apply it to the two steel side plates of the connection. The LTD consisted of rigid steel panels that were connected at the top and bottom to the end frame of the shock tube with slotted hinges. These hinges allowed the entire LTD to freely translate up to 200 mm without transferring any forces through the hinges or adding to the stiffness of the tested specimen. The LTD, in its undeformed position and attached to the end frame of the shock tube, can be seen on the right side of Figure 7.

The connection specimens were supported by a steel reaction frame. This frame was designed to withstand the high dynamic loads produced by the shock tube. To reduce the deflection of the frame at the location of the connection specimen, the fame was braced against the laboratory floor and ceiling through four sets of diagonal bracing members. The horizontal restraint for the fame was provided through eight threaded rods at the top and bottom of the frame that were connected back to the end frame of the shock tube. The reaction frame can be seen in in the left of Figure 7.

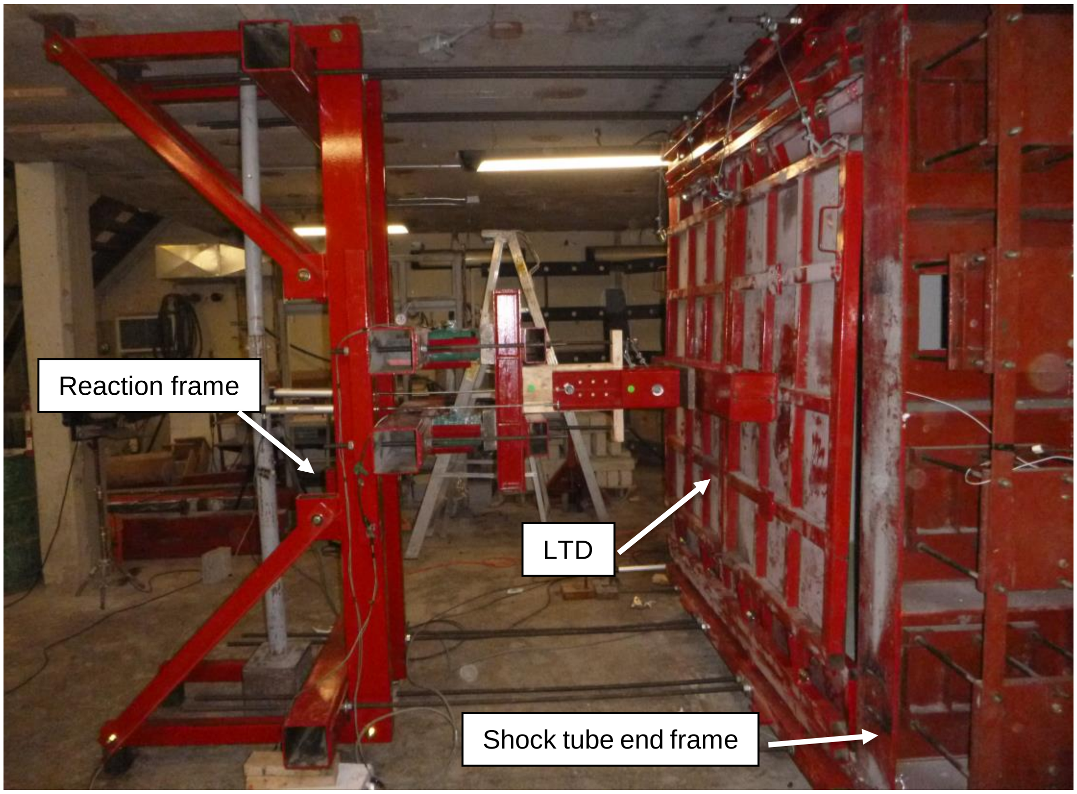

Figure 7: Dynamic test set up

The reflected pressure was measured using two dynamic piezoelectric sensors, one located at the bottom and one at the side of the shock tube. The load transferred through the connection was recorded using two load cells located between the specimen and the reaction frame. Linear variable displacement transducer (LVDT) were used to measure the movement of the steel side plates and the wood main member. The difference between the two measured displacements represents the displacement in the joint. Figure 8 shows the instrumentation used for the dynamic testing. All instrumentation was connected to a data acquisition system, which recorded data at a sampling rate of 100,000 sample per second. Two high speed cameras recording at 2000 frames per second were used to monitor the dynamic tests. The recording system was triggered when the shock wave passed over the pressure sensor.

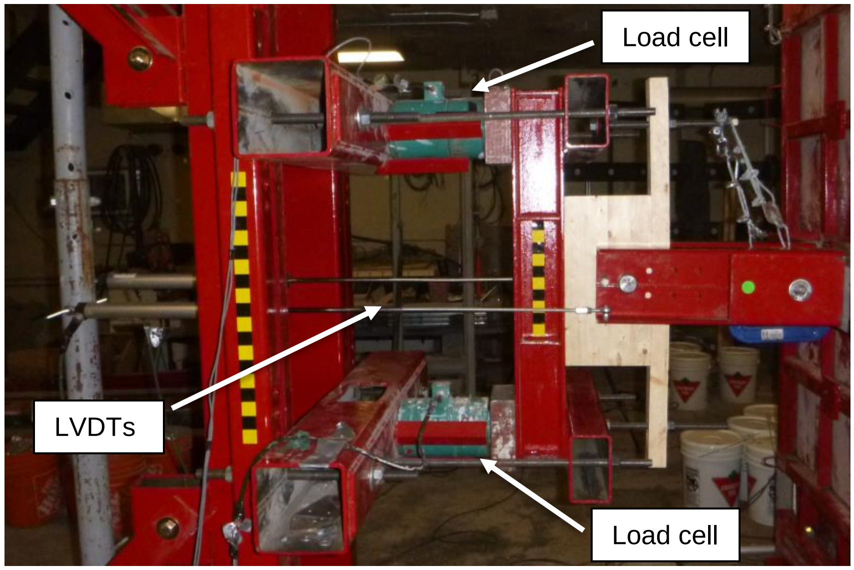

Figure 8: Instrumentation for dynamic tests

3 EXPERIMENTAL RESULTS

Typical load-deformation curves for the static parallel and perpendicular to the grain tests are shown in Figure 9. The parallel to the grain tests behaved in a linear elastic manner until yielding was reached. The post peak behaviour consisted of a sustained yielding (crushing) plateau with some strength degradation (Figure 9). The ultimate failure consisted of wood splitting that was initiated at the bolt hole. The perpendicular to the grain tests exhibited linear elastic behaviour up to a proportionality limit with lower stiffness than that observed in the parallel to the grain tests. After the proportionality limit, the resistance of the connections continued to increase, but with a lower stiffness than that of the initial linear elastic behaviour. At large deformations, splitting along the width of specimen was apparent. This splitting was not detrimental to the connections' load carrying capability because the bottom of the wood specimens were fully supported and the splitting was not in the direction of the applied load (i.e. splitting occurred in the tension perpendicular to grain direction).

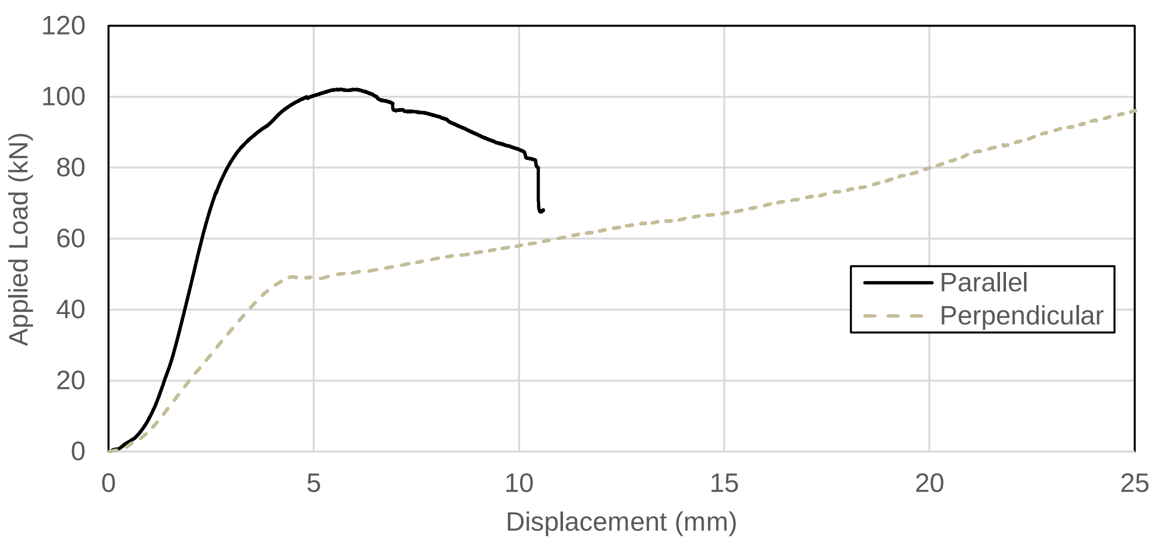

Figure 9: Typical static load-deformation curve

Tables 1 and 2 present the results of the static parallel and perpendicular to the grain tests, respectively. The yield load for each parallel to grain test was determined using the 5% offset method as presented in ASTM D5652 (2015). A straight line was fit to the initial linear portion of the load-deformation curve, which was then offset by 5% of the bolt diameter (i.e. 1.27 mm). The point of intersection between the offset line and the load-deformation curve was taken as the yield point. For the perpendicular to the grain tests a method presented in EN 12512 (2001) was used to define the yield point. This method was chosen because of its suitability to adequately describe load-deformation curves that have two well defined linear parts. The yield load was defined as the intersection between these two lines. The initial stiffness for all static tests was taken as the slope of a line fitted to the data between 10% and 40% of the yield load.

Table 1: Parallel to the grain static test results

Specimen	Yield Load (kN)	Stiffness (N/mm)	Deformation at Ultimate Failure (mm)
E0S[1]	99.7	35,200	9.7
E0S[2]	101.0	38,000	7.2
E0S[3]	89.8	40,800	11.5
E0S[4]	90.3	32,400	10.3

Table 2: Perpendicular to the grain static test results

Specimen	Yield Load (kN)	Initial Stiffness (N/mm)
E90S[1]	59.8	19,000
E90S[2]	46.0	14,500
E90S[3]	55.5	14,800

A typical reflected pressure-time history can be seen in Figure 10. The first two dynamic parallel to the grain tests, E0D[1] and E0D[2], were tested in the linear elastic range and as such, no permanent deformation was observed in the joint. Tests E0D[3] – E0D[5] were conducted with higher reflected pressures, and the results showed a small load plateau before the wood specimen split and was therefore incapable of resisting any additional applied load applied. The displacements that were observed before splitting were almost entirely from wood crushing, with some minor bending in the bolt. Failed specimen E0D[3] can be seen in Figure 11. Figure 14 shows a typical load-deformation curve for the unreinforced dynamic parallel to the grain tests.

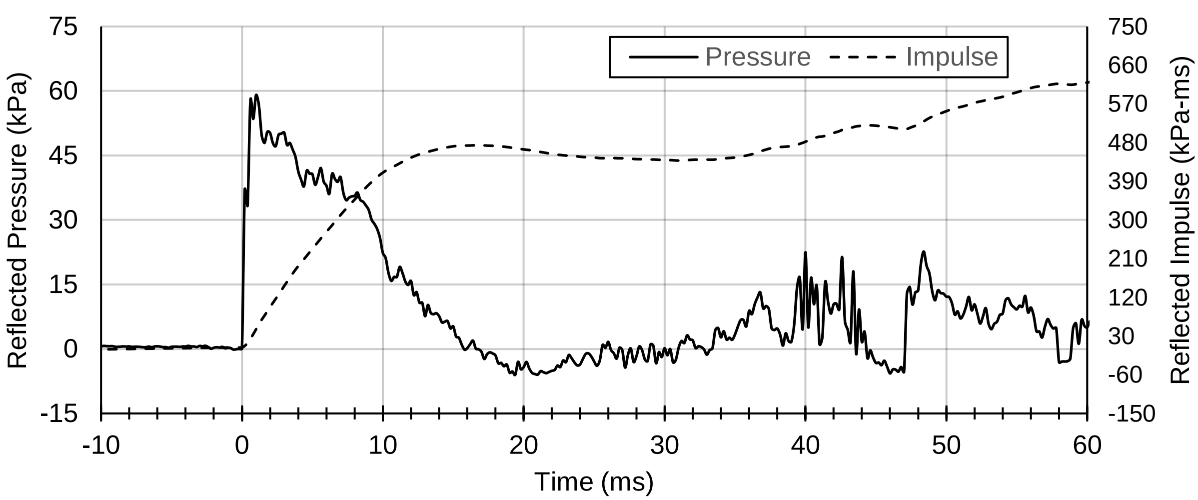

Figure 10: Typical reflected pressure and impulse time history

Tests E0D[6] – E0D[8] were reinforced with self-tapping screws in an attempt to prevent splitting failure and to improve the ductility of the connection. A pressure-impulse combination similar to that used in tests E0D[3] – E0D[5] was used in test E0D[6]. The specimen was pushed past its yield point and a small amount of permanent deformation was observed, but no splitting failure occurred. The shock wave did not contain enough energy to cause an ultimate failure in the connection. The permanent deformation observed consisted of mostly wood crushing with a small amount of bending in the bolt. Tests E0D[7] and E0D[8] were conducted with a higher pressure-impulse combinations. These tests showed similar responses to E0D[6], but the connections were pushed farther into the inelastic range. The connections exhibited a yield plateau with some minor strength degradation. E0D[7] ultimately failed when the self-tapping screws failed and allowed the specimen to split. As seen in Figure 12, E0D[8] showed evidence of splitting in the wood, but the screws did not fail and continued to hold the specimen together. Figure 14 shows a typical load-deformation curve for the reinforced dynamic parallel to the grain tests.

The two dynamic perpendicular to the grain tests, E90D[1] and E90D[2], showed similar results. The connections exhibited linear elastic response until the proportionality limit, after which the load continued to increase with a lower stiffness. Similar to the static testing, splitting of the wood specimens occurred at large displacements, but was not detrimental to the load carrying capacity of the connections. Figure 13 shows specimen E90D[2] after the dynamic testing. Figure 14 shows a typical load-deformation curve for the dynamic perpendicular to the grain tests.

Figure 11: Splitting of specimen E0D[3]

Figure 12: Specimen E0D[8] after dynamic test

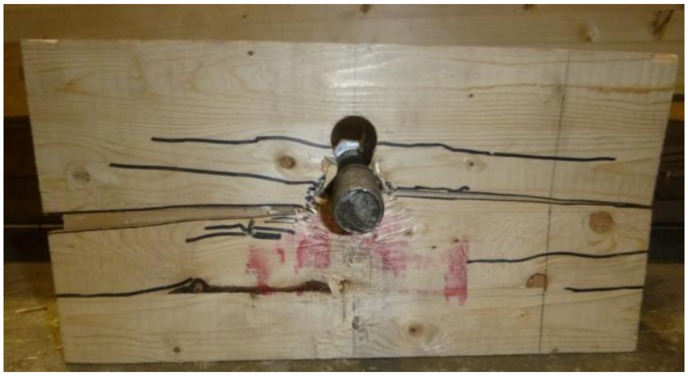

Figure 13: Specimen E90D[2] after dynamic test

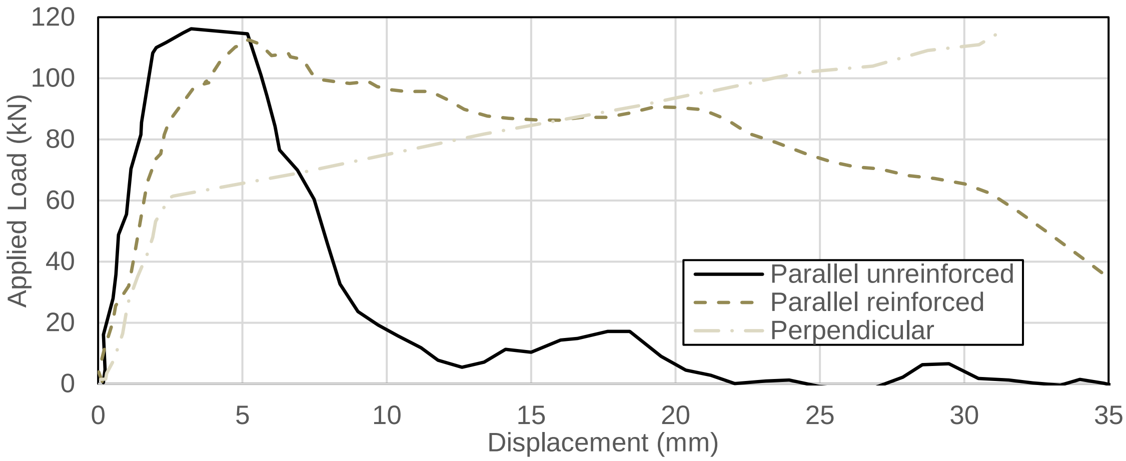

Figure 14: Typical load-deformation curves for dynamic tests

Tables 3 and 4 present a summary of the dynamic test results for the parallel and perpendicular to the grain tests, respectively. The yield loads were defined using the same method as the static loading. The initial stiffness was taken as the slope of the line of best fit for all the data before the proportionality limit.

Table 3: Parallel to the grain dynamic test results

Specimen	Yield Load (kN)	Stiffness (N/mm)	Deformation at Ultimate Failure (mm)
E0D[1]	-	35,500	-
E0D[2]	-	28,700	-
E0D[3]	117.2	57,400	5.9
E0D[4]	92.8	47,400	3.2
E0D[5]	103.2	55,200	5.9
E0D[6]	108.5	58,700	-
E0D[7]	97.8	34,700	30.0
E0D[8]	102.0	35,600	-

Table 4: Perpendicular to the grain dynamic test results

Specimen	Yield Load (kN)	Initial Stiffness (N/mm)
E90D[1]	62.3	28,700
E90D[2]	71.2	28,300

4 DYNAMIC INCREASE FACTORS AND REINFORCEMENT

Table 5 shows the average yield load and stiffness for both static and dynamic parallel to the grain tests. Table 6 presents these results for the perpendicular to the grain tests. These results show an average DIF for the yield load of 1.09 and 1.24 for the parallel and perpendicular to the grain direction, respectively. A DIF on the stiffness of 1.20 and 1.77 for the parallel and perpendicular to the grain direction, respectively, was also observed.

Table 5: Average results for static and dynamic parallel to the grain tests

Loading Type	Yield Load (kN)	Stiffness (N/mm)
Static	95.2	36,600
Dynamic	103.6	44,000
Difference	8.4	7,400
DIF	1.09	1.20

Table 6: Average results for static and dynamic perpendicular to the grain tests

Loading Type	Yield Load (kN)	Stiffness (N/mm)
Static	53.8	16,100
Dynamic	66.7	28,500
Difference	12.9	12,400
DIF	1.24	1.77

For the parallel to the grain static tests, the average deformation of the connection at failure was 9.7 mm, while an average deformation at failure of 5.0 mm was observed for the unreinforced dynamic tests. This represents a significant loss in ductility under dynamic loading and would be detrimental to the performance of a connection when subjected to blast loading. The reinforced dynamic tests showed much greater deformations at failure, with E0D[7] failing at 30.0 mm, while E0D[8] underwent deformations up to 41 mm without an ultimate splitting failure. While these results only represent one specific set of connection materials and geometry, they illustrate that reinforcing a connection to supress brittle failure modes, especially tension perpendicular to grain, can drastically improve the performance of the connection.

5 CONCLUSIONS

A series of static and dynamic tests were carried out on steel-wood-steel single bolt connections. The joint behaviour was investigated both parallel and perpendicular to the grain. The aim of the work was to investigate how the rate of loading affects the dowel embedment strength and stiffness. In addition, some connections were reinforced with self-tapping screws to investigate if the performance under dynamic loading could be improved. Based on this experimental work, the following conclusions can be drawn:

- In the parallel to the grain direction the yield load and stiffness experienced a DIF of 1.09 and 1.20, respectively.
- In the perpendicular to the grain direction the yield load and stiffness experienced a DIF of 1.24 and 1.77, respectively.
- Under dynamic loading, a reduction in the ductility of the parallel to the grain specimens was observed.
- Reinforcing a connection to supress the brittle tension perpendicular to grain wood failure modes significantly improves the ductility of the connection.

6 REFERENCES

ASTM. 2015. "ASTM D5652 - Standard Test Methods for Single-Bolt Connections in Wood and Wood-Based Products." American Society for Testing and Materials.

Cote, Dominic. 2017. "Effect of Realistic Boundary Conditions on the Behaviour of Cross-Laminated Timber Element Subjected to Simulated Blast Loads." Ottawa: University of Ottawa.

European Committee for Standardization. 2001. "EN 12512 - Timber Structures - Test Methods - Cyclic Testing of Joints Made with Mechanical Fasteners."

Gilbertson, Christopher G., and William M. Bulleit. 2013. "Load Duration Effects in Wood at High Strain Rates." *Journal of Materials in Civil Engineering* 25 (11): 1647–54.

Girhammar, Ulf Arne, and Hakan Andersson. 1988. "Effect of Loading Rate on Nailed Timber Joint Capacity." *Journal of Structural Engineering* 114 (11): 2439–56.

Jacques, Eric, Alan Lloyd, Abass Braimah, Murat Saatcioglu, Ghasan Doudak, and Omar Abdelalim. 2014. "Influence of High Strain-Rates on the Dynamic Flexural Material Properties of Spruce–Pine–Fir Wood Studs." *Canadian Journal of Civil Engineering* 41 (1): 56–64.

Lacroix, D. N., and G. Doudak. 2015. "Investigation of Dynamic Increase Factors in Light-Frame Wood Stud Walls Subjected to Out-of-Plane Blast Loading." *Journal of Structural Engineering* 141 (6).

Lacroix, Daniel Normand. 2017. "Investigating the Behaviour of Glulam Beams and Columns Subjected to Simulated Blast Loading." Ottawa: University of Ottawa.

Markwardt, L. J., and J. A. Liska. 1956. "The Influence of Rate of Loading on the Strength of Wood and Wood-Base Materials." In , 185:3–18. Atlantic City, N.J., USA: ASTM International.

Poulin, Mathieu, Christian Viau, Daniel N. Lacroix, and Ghasan Doudak. 2018. "Experimental and Analytical Investigation of Cross-Laminated Timber Panels Subjected to Out-of-Plane Blast Loads." *Journal of Structural Engineering* 144 (2).

Reid, S.R., and C. Peng. 1997. "Dynamic Uniaxial Crushing of Wood." *International Journal of Impact Engineering* 19 (5–6): 531–70.

Rosowsky, David V., and Timothy A. Reinhold. 1999. "Rate-of-Load and Duration-of-Load Effects for Wood Fasteners." *Journal of Structural Engineering* 125 (7): 719–24.

Viau, Christian, and Ghasan Doudak. 2016. "Investigating the Behaviour of Typical and Designed Wall-to-Floor Connections in Light-Frame Wood Stud Wall Structures Subjected to Blast Loading." *Canadian Journal of Civil Engineering* 43 (6): 562–72.