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EFFECT OF HIGH STRAIN-RATES ON HEAVY TIMBER CONNECTIONS

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Abstract: This paper reports on the experimental results from a research program investigating the blast performance of cross-laminated timber wall panels with idealized and realistic boundary conditions. Quasi-static and dynamic testing on component-level specimens was conducted in order to quantify the effects of simulated blast loads. Dynamic testing was conducted through the use of a shock tube; a test apparatus capable of simulating far-field blast explosions. Reported in this paper are the qualitative and quantitative results from the experimental portion of the program. Dynamic increase factors (DIFs) were calculated for the tested connections. A statistically significant DIF was observed when the failure mode was governed by wood crushing, while no significant increase was found in instances where rupturing of the screws was the dominating failure mode. Recommendations related to the analysis and design of wood connections subjected to blast loading are made based on the findings of the study.

1 INTRODUCTION

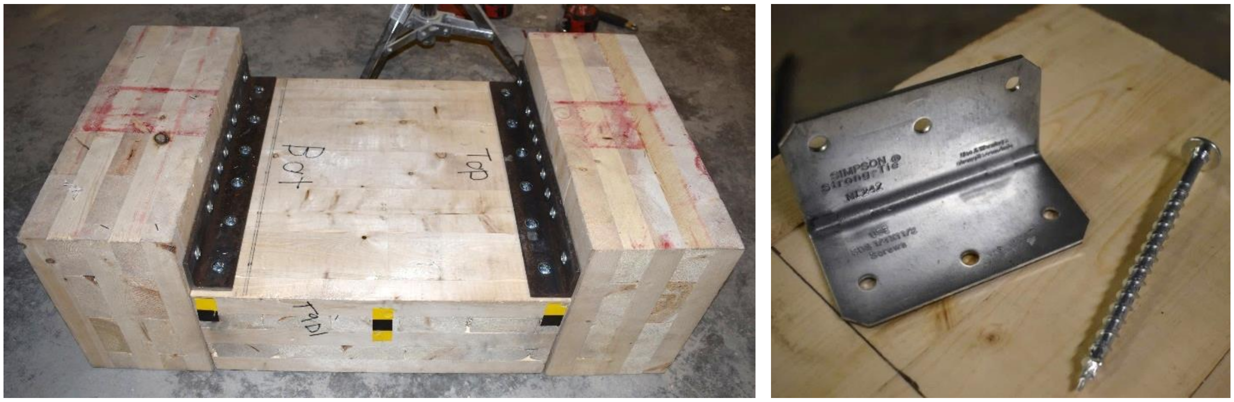
High-profile and tall timber structures are now prevalent, and include prominent examples such as the Richmond Olympic Oval in British Columbia, Canada, the Tianning Temple in Changzhou City, China, and the UMass Design Building in Amherst, Massachusetts. While designing such structures to resist gravity and in-plane lateral loads from winds and earthquakes has been well-established, adequate design and detailing to address potential blast threats are still lacking. Blast loading occurs during an extremely brief time period, generating high strain-rates in the materials exposed to the loading. This short duration loading often leads to an apparent increase in strength relative to the material's static strength. This increase, quantified as the ratio of the dynamic to the static strength, is termed the dynamic increase factor (DIF). DIFs for different materials can be found in literature and design codes (e.g. Unified Facilities Criteria Program 2008, CSA 2012). Recent full-scale testing on individual light-frame lumber elements (Jacques et al. 2014) and full-scale wood stud walls (Lacroix and Doudak 2015, Viau and Doudak 2016a, b) subjected to simulated blast loads established a DIF of 1.4 on the modulus of rupture (MOR) of dimensional lumber elements. Research by Poulin et al. (2017) on full-scale 3- and 5-ply CLT panels subjected to simulated blast loads reported a DIF of 1.28. Full-scale blast testing on glulam beams undertaken by Lacroix and Doudak (2018) reported a DIF of 1.14 for glulam beams when the outer tension laminate did not include closely aligned finger-joints. It is noteworthy to mention that all aforementioned studies dealt with structural elements under idealized simply-supported boundary conditions, in order to isolate the dynamic material properties.

Research on the blast performance of connections has primarily been limited to steel structures (e.g. Karns et al. 2007, Morrill et al. 2007, Crawford et al. 2012, Stoddart et al. 2014). Early research on timber connections under seismic loading has shown that strain-rate effects were heavily influenced by the failure mode of the connections (Girhammar and Andersson 1988, Daneff 1997, Rosowsky and Reinhold 1999). Viau and Doudak (2016b) investigated nailed and joist-hanger connections detailing for light-frame wood stud walls and showed that typical nailed connections, including those designed for high seismic regions, did not allow the studs to develop their full flexural capacity due to a premature failure in the connections. While significant damage in the joist hanger connections was observed, the studs were able to attain their ultimate flexural capacity. It was concluded that overdesigning the connection capacity based on the stud capacity may not be adequate and that proper understanding of the failure mechanism of the connection must be established. An experimental study by Côté and Doudak (2019) investigated the effects of realistic boundary conditions on the behaviour of CLT walls when subjected to simulated out-of-plane blast loads. The results from this study indicated that the detailing of the connections appears to significantly affect the behaviour of the CLT walls. Self-tapping screws in end-grain performed poorly and experienced brittle splitting failure whereas connections involving angle brackets performed well. Live blast tests were conducted on full-scale two-storey CLT structures with realistic construction detailing (Weaver et al. 2017). The main aim of the study was to evaluate the structure's ability to meet the prescriptive requirements for Department of Defense (DoD) structures (Unified Facilities Criteria Program 2012). The structures were anchored to a concrete slab with over-designed connections comprised of steel angles, in order to force the damage in the CLT panels. This approach is consistent with the current Canadian blast design provisions, which entails overdesigning the connection joints (CSA 2012). Additionally, these provisions currently provide no guidance on the high strain-rate effects in the connections themselves.

The current study aimed at investigating the effects of high strain-rate in typical CLT angle-type connections. The first phase of the study (reported in this paper) was to investigate the behaviour of the connections in isolation prior to incorporating them into the structural subsystem (i.e. walls).

2 EXPERIMENTAL PROGRAM AND RESULTS

As part of an ongoing research program conducted at the University of Ottawa to investigate the behaviour of mass- and heavy-timber assemblies subjected to blast loads, a total of sixteen 5-ply *Nordic X-Lam* E1 grade cross-laminated timber (CLT) specimens were tested statically and dynamically with the aim to quantify high strain-rate effects in the connections. Six specimens were tested under quasi-static loading and ten under simulated blast loading. The width and thickness of all panels were 445 mm and 175 mm, respectively. The specimens were cut to a length of 457.2 mm, in order to confirm with ASTM D7147 (ASTM 2011) and were fastened to CLT blocks of the same width (445 mm), as shown in Figure 1. Two types of CLT connections were investigated, namely a thin angle (ML24Z) manufactured by *Simpson Strong-Tie*, and a thicker custom-manufactured angle. Both connections were fastened using *Heco-Topix Tellerkopf* screws. The details of these fasteners and angles are presented in Table 1.



(a) (b)

Figure 1: Typical: (a) Custom-Manufactured Angle Specimen; (b) ML24Z Connection Subcomponents

Table 1: Details of Connection Subcomponents

Heco-Topix Tellerkopf Screw			*ML24Z* Angle			Custom-Manufactured Angle		
Total Length (mm)	Threaded Length (mm)	Diameter (mm)	Width (mm)	Height and Depth (mm)	Wall Thickness (mm)	Width (mm)	Height and Depth (mm)	Wall Thickness (mm)
120	70	8.0	101.6	53.4	2.6	431.8	50.8	6.4

For this paper, the specimens are identified first with M or C, denoting whether the specimen is tested with either the ML24Z angle (M) or custom-manufactured angle (C). The nomenclature following “M” or “C” conveys the quantity of connection variables, whether it was a static or dynamic test, and the test order sequence. For example, specimen M1D4 has one ML24Z angle at each joint, was tested dynamically, and was the fourth specimen to be tested. Table 2 summarizes all tested specimens.

Table 2: Summary of Experimental Specimens

Specimens	Loading Regime	Specimen End Conditions
M1S1, M1S2, M1S3	Static	1 x ML24Z
C6S1, C6S2, C6S3		Custom Angle w/ 6 screws
M1D1, M1D2	Dynamic	1 x ML24Z
M1D3, M1D4, M1D5		
M2D1, M2D2		2 x ML24Z
C3D1		Custom Angle w/ 3 screws
C6D1		Custom Angle w/ 6 screws
C9D1		Custom Angle w/ 9 screws

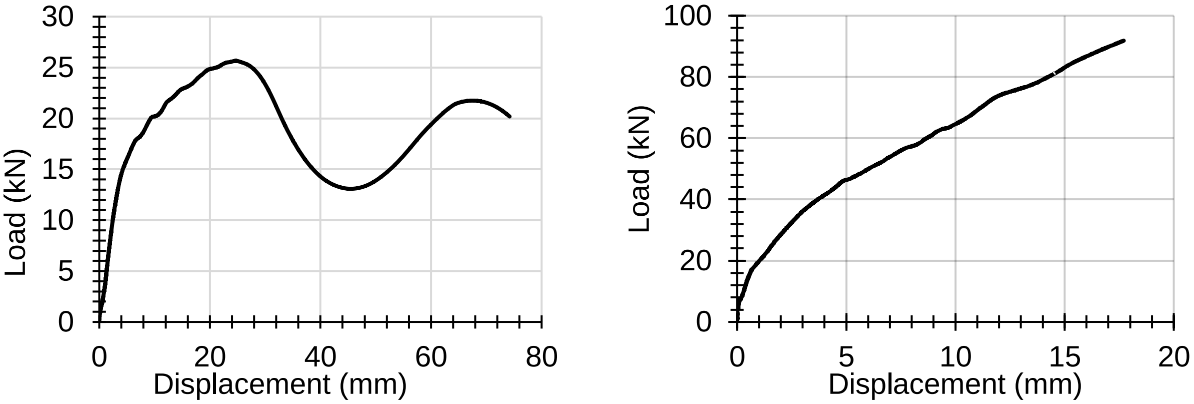
For connections consisting of the ML24Z angles, the capacity of the connections was scaled by adding or removing angles from the connection, while keeping the number of screws per angle constant at three. For connections with the custom-manufactured angle, the capacity was scaled by varying the number of screws used in the connection. To maintain a balanced load distribution in the screws, the number of screws was selected to be three, six, or nine screws.

2.1 Static Test Setup and Results

Static testing was performed in conformance with the ASTM D7147 standard for the testing of joist hangers (ASTM 2011). As shown in Figure 2, static loading was applied through the use of a hydraulic jack. Two wire gauges were connected to each panel end in order to measure the displacements, while a load-cell was used to measure the applied load. Both wire gauges and the load-cell were connected to a data acquisition system with a sampling rate of ten samples per second. Static testing was performed until failure of one of the two joints. In all tests, no damage to the intermediate panel was observed.

Figure 2: Static Test Setup

The baseline connection for the ML24Z angle consisted of a single angle per joint, whereas for the custom-manufactured angle consisted of an angle fastened with six screws. This scaling was used to normalize the experimental data in order to make inferences regarding high strain-rate effects and variability within the connection groups. Shown in Figure 3 are the representative static load-displacement curves for the baseline connections with ML24Z angle and custom-manufactured angle.



(a)

(b)

Figure 3: Representative Load-Displacement Curves of: (a) ML24Z; (b) Custom-Manufactured Angle

From the load-displacement relationship of the ML24Z angle (Figure 3a), an initial linear-elastic behaviour followed by drop in stiffness and a shift to a non-linear behaviour can be observed. Past the maximum load, the ML24Z angles deformed excessively and developed outward forces acting against the support blocks. The failure was dominated by bending in the ML24Z angle and significant wood crushing at the panel ends due to the perpendicular-to-grain compressive stresses caused by the ML24Z angles (Figure 4a). In cases where the specimens were overloaded, the ultimate failure occurred in shear rupture of the screws (Figure 4b).


(a) (b)

Figure 4: Representative Failure of ML24Z Connection: (a) Severe Angle Deformation; (b) Screw Failure

The thicker custom-manufactured angle connections exhibited early onset of stiffness degradation followed by an almost linear behaviour up to maximum load (Figure 3b). Ultimate failure of these joints occurred at significantly lower deformation levels when compared to the connection containing the ML24Z angles. Similar to the ML24Z angles, ultimate failure occurred in the screws in a combination of tension and shear failure, as shown in Figure 5. The extent of wood crushing in the case of the custom-manufactured angle was significantly less than that observed in the ML24Z angles and was limited to the area around the screw and near the face of the specimen.


(a) (b)

Figure 5: Representative Failure Mode of Custom-Manufactured Angle: (a) Specimen After Testing; (b) Screw Failure and Wood Crushing

2.2 Dynamic Test Setup and Results

Dynamic testing was performed at the University of Ottawa Shock Tube Facility. This state-of-the-art facility is capable of producing strain-rates similar to those observed during far-field blast explosions. As shown in Figure 6, a reaction frame was designed to support the specimens while a load transfer panel and beam were used to convert the pressure waves into a single concentrated load. The dynamic response of the connection specimens was captured using a data acquisition system with a sampling rate of 100,000 samples per second. Additionally, two high-speed cameras, recording at 2000 frames per second, were used in order to capture the dynamic response of each test, and provided the means to perform motion analysis for any desired point of interest on a given specimen. In tandem with the high-speed camera, load-cells and linear variable differential transducers were used to measure the load and displacements of the connections in each specimen, respectively.

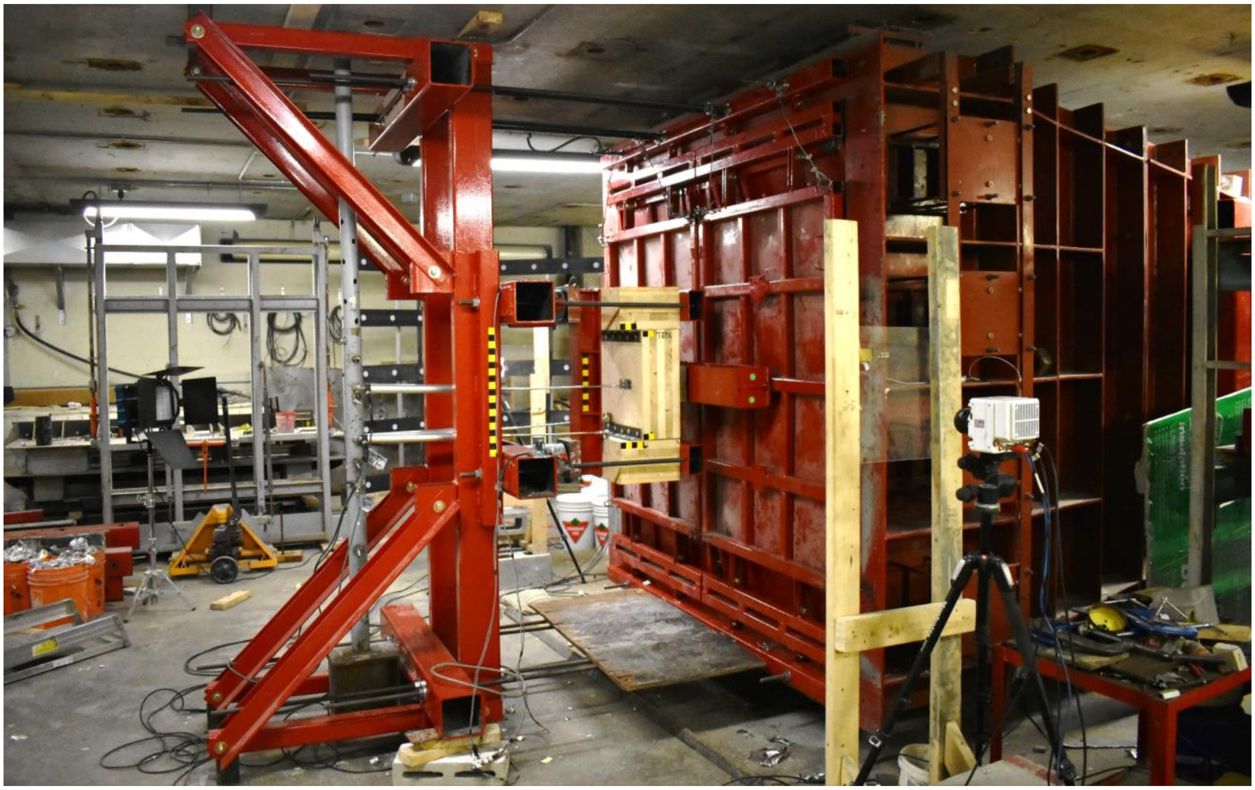
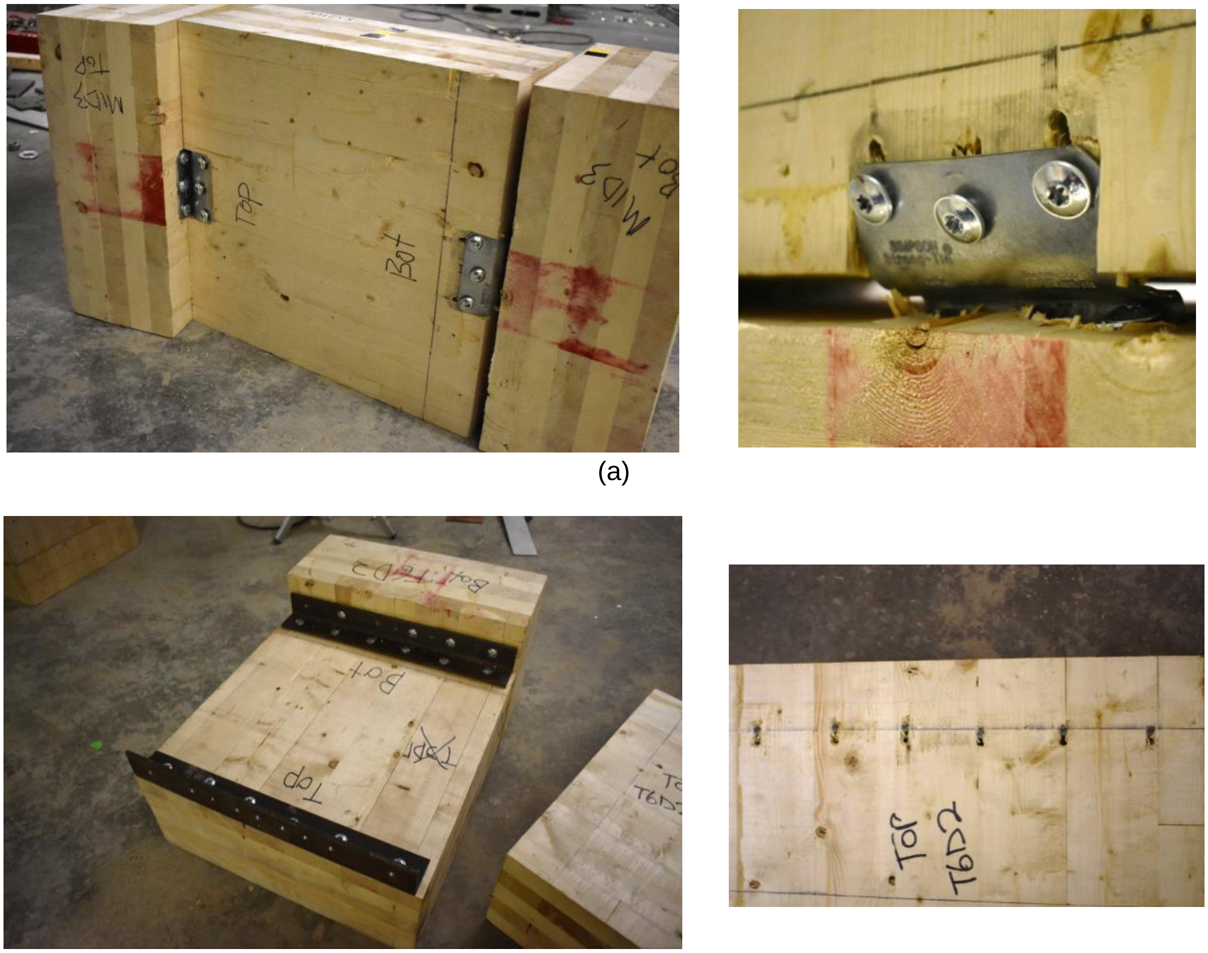


Figure 6: Shock Tube Test Setup

The observed failure modes under dynamic loading were, in general, similar to those observed during static loading. The predominant failure mode for specimens with the ML24Z angle and custom-manufactured angle was wood crushing and shear rupture in the screws, respectively. Examples of failed dynamic specimens are shown in Figure 7. From video review, rigid body motion of the intermediate panel was observed, with slight rotation at the supports occurring towards maximum displacement.



(a)

(b)

Figure 7: Examples of Failed Dynamic Specimens: (a) M1D3; (b) C6D1

3 DETERMINATION OF HIGH STRAIN-RATE EFFECTS IN CONNECTIONS

The use of identical spans and loading conditions during static and dynamic testing of the connections permitted direct comparisons between their load-displacement curves, which allowed for the quantification of the high strain-rate effects in the connections. The DIF on the maximum resistance was calculated using Equation 1:

[1] $\mathrm{DIF} = R_{\mathrm{Dynamic}} / R_{\mathrm{Static}}$

As shown in Figure 8, an average increase in resistance by a factor of 1.55 can be observed for the connections with the ML24Z angles, while only a slight increase can be observed for the custom-manufactured angle connections. These observations were corroborated by statistical analyses by using T-Tests, with a confidence interval of 95 %. These results are consistent with previous studies that reported a significant DIF when wood crushing failure was observed (e.g. Jacques et al. 2014, Lacroix and Doudak 2015, Poulin et al. 2017). Little-to-no strain-rate effects on the ultimate strength could be observed when the failure was dominated by steel yielding and rupturing as was the case in the custom manufactured angle. This is also consistent with the relatively lower DIF values associated with steel (CSA 2012). While the findings cannot be generalized for all heavy timber connections, they demonstrate the importance of further research into the area of timber connections under blast loads.

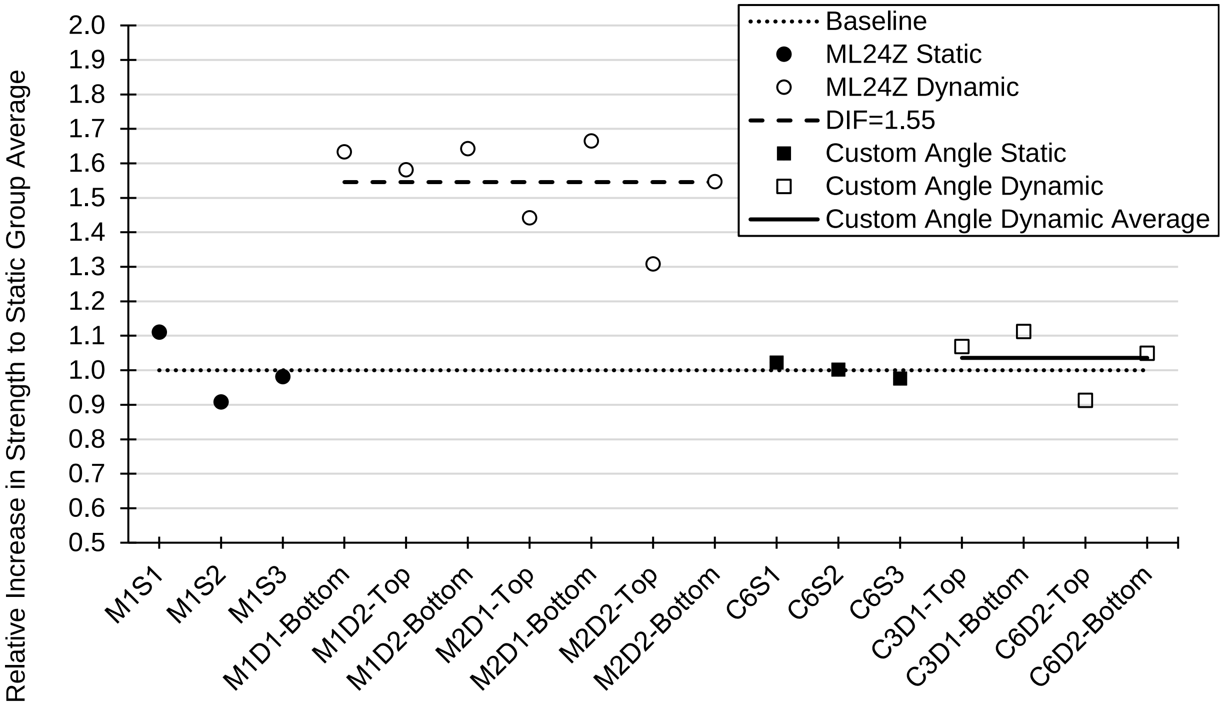


Figure 8: Dynamic Increase Factors on the Maximum Resistance of Both Tested Connections

4 CONCLUSIONS

A total of six static and ten dynamic tests were performed on connections in CLT using two types of angle-bracket connections; the ML24Z angle by *Simpson Strong-Tie* and an in-house custom-manufactured angle. A statistically significant DIF of 1.55 was observed for the ML24Z angle connections, which coincides with wood crushing failure. No increase of significance in the dynamic resistance of the connections was observed in the case of custom-manufactured angle bracket with screws. While these preliminary findings cannot be generalized for all heavy timber connections, they demonstrate the importance of further research into the area of timber connections especially when the behaviour of the entire CLT assembly is included.

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