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BLAST PEROFRMANCE OF CROSS-LAMINATED TIMBER PANELS WITH REALISTIC BOUNDARY CONDITIONS

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Abstract: This paper presents a recent study which investigated the effects of realistic boundary conditions on the behaviour of cross-laminated timber (CLT) panels when subjected to out-of-plane blast loads. Experimental testing was conducted at the University of Ottawa Blast Research Laboratory, where shock waves were generated and applied through the use of a shock tube test apparatus. Connection configurations with seismic detailing were considered, in order to evaluate whether existing structures have adequate capacities to resist a given blast load with desired damage in the primary structural elements. Typical connections used in construction to resist gravity and lateral loads, as well as connections designed specifically to resist a given blast load, were also investigated. The results indicate that the detailing of the connections appears to significantly affect the behaviour of the CLT panel. Bearing type connections performed better than those composed of only wood screws, which tended to fail in a brittle manner. It was observed that under-designed steel angles provided significant energy dissipation through steel yielding and wood crushing, resulting in reduced panel damage. The study also concluded that using simplified tools such as single degree-of-freedom (SDOF) modelling together with current available material models for CLT may not be sufficient to adequately describe the behaviour and approximate the damage.

1 INTRODUCTION

Over the past decades, the effect of blast loads on structural members has steadily been gaining research interest due to high-profile deliberate attacks and accidental explosions, such as the September 11 attack in New York and the Oklahoma City Bombing. Coincidentally, the recent interest in developing and utilizing massive wood panels in construction and the advancement in technology to produce high-performance connections has pushed the boundaries for what can be achieved in timber construction. Despite the meticulous effort to produce complete design requirements for CLT panels under gravity, seismic and wind loads, little information on how to design such members for blast loading currently exists.

Recent research efforts have established key dynamic characteristics of CLT including strength increase factor (SIF) and dynamic increase factor (DIF), both of which are key parameters used in design and research to develop suitable material predictive models (Poulin et al. 2017). Although this study has significantly contributed to understanding the behaviour of the material, it was conducted on CLT panels with idealized simply supported boundary conditions. Connections between the wall and the floor systems above and below are critical to fully describe the overall behaviour of CLT structures when subjected to blast loads. The end conditions used in the construction of cross-laminated timber structures may affect the failure mode of the elements, where the boundary connection elements could fail prematurely, and thereby prevent the wall panel from reaching its intended maximum flexural capacity. Alternatively, a failure in the connections, when adequately detailed, may yield ductile failure and limit the damage to the CLT wall panel. Both design approaches are investigated in the current study and outcomes from the experimental investigation is reported.

This paper reports on the effects of realistic boundary conditions on the behaviour of cross-laminated timber wall panels when subjected to simulated out-of-plane blast loads. Both typical connection details as well as connections that are expected to perform well under blast loading are evaluated experimentally. Analytical modelling methodologies for blast design are discussed and their appropriateness for timber systems with connections is evaluated.

2 EXPERIMENTAL PROGRAM

Dynamic testing was undertaken using a shock tube, which is a testing apparatus capable of generating pressure waves to simulate far-field detonations created by high explosives. An example of such test setup is shown in Figure 1 (a). In order to simulate floor diaphragms as part of creating the boundary conditions for the panels, pieces of CLT specimens were cut and clamped at the panel ends to the shock tube, as shown in Figure 1 (b). These end blocks were then attached to the wall panels using the connection detail being investigated, simulating the connection at the ends of a CLT wall and the in-plane stiffness of the floors above and below.

A total of eleven dynamic tests were performed on five-layer Nordic X-Lam Cross-Laminated Timber panels with varying connection detailing. The specimens comprised of spruce-pine-fir (SPF) plies measuring 35 mm by 80 mm with 1950Fb machine stress rated lumber used in layers oriented in the major direction and No. 3/Stud lumber in layers oriented in the minor direction. Heco-Topix screws were used to connect the panel ends to the end blocks directly or through two different types of steel angles. Three types of screws were used, including 300 mm long screws, with 6 mm and 8 mm in diameter; 120 mm long screws, with 8 mm and 10 mm diameter; and 350 mm long double-threaded screws, with 8.5 mm diameter. Two steel angle types were used; one consisted of ML24Z steel angles from Simpson Strong-Tie®; and the other of 6.6 mm thick manufactured steel angle. For some of the configurations, the connections were designed based on the capacity of the CLT panels. For the purpose of this research project, the designed connections were selected by considering a 20 % increase on the dynamic reaction obtained from tests on CLT panels with simply supported boundary conditions (Poulin et al. 2017).

Table 1 presents a summary of the specimens which were tested dynamically, including the type of connection tested, specimen identification (ID), and construction details of the top and bottom connections. The nomenclature of each specimen conveys type of connection (i.e. EG – End-Grain; DT – Double-Threaded; DA – Ductile Angle, and; SA – Stiff Angle), and a numerical indicator representing the order of which the specimen was tested within its group (e.g. DT3 was the third specimen tested with double-threaded screw connections).

(a) (b)

Figure 1: (a) Experimental test setup; (b) Boundary condition

Table 1: Outline of Experimental Program

Connection Group	Specimen ID	Bottom Connection	Top Connection
End-grain screws	EG1	4 – ML24Z angle	25 – 6x300 Heco-Topix Zn Gelb A2L
	EG2	2 – ML24Z angle	12 – 6x300 Heco-Topix Zn Gelb A2L w/ reinforcement
	EG3	27 – 8x300 Heco-Topix Zn Gelb A2L w/ reinforcement	27 – 8x300 Heco-Topix Zn Gelb A2L w/ reinforcement
Double-threaded screws at 60°	DT1	2 – 8.5x350 ZnA2K+DS-Beschichtet	2 – 8.5x350 ZnA2K+DS-Beschichtet
	DT2	8 – 8.5x350 ZnA2K+DS-Beschichtet	8 – 8.5x350 ZnA2K+DS-Beschichtet
Ductile angles	DA1 – DA4	2 – ML24Z angle	2 – ML24Z angle
Stiff angles	SA1 – SA2	Manufactured angle	Manufactured angle

3 EXPERIMENTAL RESULTS

3.1 Screw Connections

End-grain screw connections are typically used in construction to resist gravity loads. The purpose of this set of tests was to investigate whether typical connections have any inherent blast resisting capabilities and ductility. The connection capacity of specimens EG1 and EG2 was calculated using the blast standard requirements, which requires overdesigning the connections by a factor of 1.2. The connection of specimens EG3 was intentionally overdesigned using an additional factor of 1.25, for a total overdesign ratio of 1.5.

Significant damage was observed in the connection, where tension perpendicular to grain failure occurred at the row of screws closest to the tension face. Little-to-no damage occurred in the angled connections nor the CLT panel. In an attempt to strengthen the end-grain connection joints, reinforcing screws were installed normal to the panel face. This reinforcement provided a slight increase in the connection capacity by shifting the location of splitting towards the compression face. Figure 2 (a) and (b) show the failure modes for the unreinforced and reinforced end-grain connections, respectively.

Double-threaded screws, which have a discontinuity at the middle of the screw thread, were installed at 60° from horizontal. The number of screws in the first specimen tested under this connection group (DT1) was selected based on seismic design. It was ensured that the point of thread discontinuity was located at the interface between the panel and end block. No damage to the CLT panel was observed in any of the tests, however, the screws at the top and bottom connections all failed in combination of shear and withdrawal, as shown in Figure 2 (c).

The same double-threaded screws were used in a similar test specimen (DT2), which contained connections designed based on the Canadian blast design standard (CSA 2012). This was an attempt to increase the connection capacity beyond what was deemed adequate for the purpose of seismic design of the panel. Whereas fracturing of the screws was observed in the test with only two screws per joint (DT1), the additional screws in DT2 caused rolling shear and tension perpendicular to grain failure, as shown in Figure 2 (d).


(a) (b) (c) (d)

Figure 2: Screw connection failure modes: (a) EG1; (b) EG2; (c) DT1; (d) DT2

3.2 Angle Connections

The connections tested in this group consisted of bearing type connectors in order to reduce the perpendicular to grain stresses and failure. Two types of angles were tested: a relatively thin prefabricated steel angle, and an in-house-designed heavy angle.

Four tests were replicated using the ductile angles. In these tests, the connection at both the top and bottom floors consisted of two ML24Z angle brackets. The capacity of this connection was sufficient for seismic detailing, however, was under-designed based on the dynamic out-of-plane capacity considerations. The aim of this test was to try to achieve ductile damage in the connection without causing complete failure in the panel or connections. The thin angles (D1 to D4) resulted in a ductile behaviour, where bending in the angles helped absorb the energy of the blast, with very little to no visible damage in the CLT panel. All four angle brackets deformed significantly and in a similar manner, as shown in Figure 3 (a).

In order to investigate the possibility of attaining flexural failure in the CLT panels, a 6.6 mm thick steel angle bracket was manufactured and tested. No permanent yielding in the angles was observed, but screw deformation and crushing of wood allowed the ends of the panel to rotate and displace slightly. Signs of rolling shear were apparent near the end supports, which is consistent with the level of loading present in specimens S1 and S2. Unlike the specimens with ductile angles, the two specimens tested with the stiff angle caused flexural failure in the panel (Figure 3 (b)).

(a) (b)

Figure 3: (a) Crushing of wood and yielding of ductile angle; (b) Flexural failure of CLT panel

4 DISCUSSION

4.1 Effect of Connections

The goal of the experimental program presented in this paper was to qualitatively determine the effects of realistic boundary connections on the response of CLT panels to blast loads. While this paper presents the case where realistic connections are present, identical five-ply CLT panels were tested under idealized pin-ended conditions in order to establish their behaviour (Poulin et al. 2017). The results from that study serve as a reference to the measurements made in the current study since the material in both studies consists of the same CLT size, grade, and was obtained from the same manufacturer. The ultimate failure observed for the CLT panels with pin-ended support was consistently characterized by flexure failure. The ultimate failure occurred at an average reflected pressure and impulse of 54.8 kPa and 596.2 kPa-ms, respectively (Poulin et al. 2017). Using these experiments as an average baseline for comparison with the current study's results, the effects of realistic boundary conditions on CLT panels subjected to blast loads is evaluated in the following section.

The end-grain connections used in specimens EG1 to EG3 were observed to cause premature failure in the system at the connections, where the CLT panels were not able to reach their complete flexural capacity. Although it is well-known that wood is weak in tension perpendicular to grain and that splitting failure should be avoided even when the structural element is subjected to static loading, failure in the connections was not expected because the connection was designed to resist 20% more loads than the expected dynamic reaction. The observed behaviour is of great concern due to the fact that it may lead to collapse of the structure and loss of life. Although based on very limited data, such connection detailing is strongly cautioned against for blast design considerations.

In an attempt to improve the behaviour observed in the specimen with end-grain connections (EG1), screws were installed from the tension face to reinforce the connection joints, a practice that has shown promising results in terms of improving connection capacities and behaviour (Trautz and Koj 2009). Additionally, the number of screws in the end grain was reduced to emphasize the positive effect of the reinforcing screws. Without the reinforcing screws, this connection would be under-designed according to the Canadian blast design standard (CSA 2012). Although the connection was under-designed, the failure shifted towards the compression face, engaging more wood material and thereby increasing the splitting capacity. Despite this, the brittle failure obtained in this test emphasizes the fact that end grain screw connections are not suitable for blast design. This is further underlined in the test conducted on specimen EG3, where the number of screws was increased to resist 50% more load compared to the unreinforced specimen. Despite such effort, splitting failure was still observed. Based on these findings, it can be concluded that providing reinforcing screws only slightly enhances the behaviour of the CLT panels. It is therefore not advisable to employ such retrofit technique to existing CLT wall systems for platform type construction. In general, it can be noted that end grain connections are vulnerable to out of plane dynamic pressure waves, and should be avoided in new construction where a risk of blast is present.

The use of double-threaded screws resulted in little improvement in the performance. Tension perpendicular to grain splitting and shear failure in connections were observed in this group of connectors. Seismic design detailing was found to be insufficient to resist the applied blast load, with the screws at the top and bottom supports failing near the shear plane between the blocks and the test panel. The brittle failure observed at the connections is hazardous and can lead to potential collapse of the structure. Based on the results it can be concluded that angled screws with sufficient capacity to resist in-plane seismic loading would likely fail in a brittle manner during a blast event. This would completely eliminate the wall's ability to carry loads from floors above and also increase the risk on injuries of the building occupants. Even when the number of screws was increased by a factor of four in specimen DT2 compared to DT1 in order to meet the requirements for connection design following the Canadian blast design code (CSA 2012), brittle tension perpendicular to grain failure was still observed.

In an attempt to improve the behaviour observed with the screw connections, bearing type connections were investigated. This is in principle similar to those used in the context of light-frame wood stud walls (Viau and Doudak 2016b). The choice of bearing type supports was meant to promote compression rather than tension perpendicular to grain failure and thin angles were meant to deform and provide energy dissipation in the system. In order to show consistency in behaviour, multiple tests were conducted with the only difference being the pressure and impulse combinations to which the specimens were subjected. This also allowed to establish the limit to which the connection could be pushed without any catastrophic failure occurring.

In all tests involving the ML24Z ductile angles, significant deformation and crushing in the wood on the tension face was observed. No significant failure was observed in the CLT panel itself. This type of failure mode goes against the design philosophy outlined in the Canadian blast design standard (CSA 2012), where the connections are typically over-designed to allow the member to fully develop its capacity and ductility. For a material like wood, relying on the connection to yield is essential in enhancing the ductility and overall performance of the system. The difficulty, of course, lies in finding the balance between yielding the connections to obtain adequate ductility while preventing complete failure which will compromise the performance of the building and the safety of the occupants. Ideally, the connections would provide the desired ductility ratio and not reach failure before the panel reaches its ultimate flexural failure. In order to investigate and optimize this concept further, more research needs to be done on ductile type connections, where the yielding is isolated in connections with large enough deflection capacity to allow the wood member to fully develop its capacity.

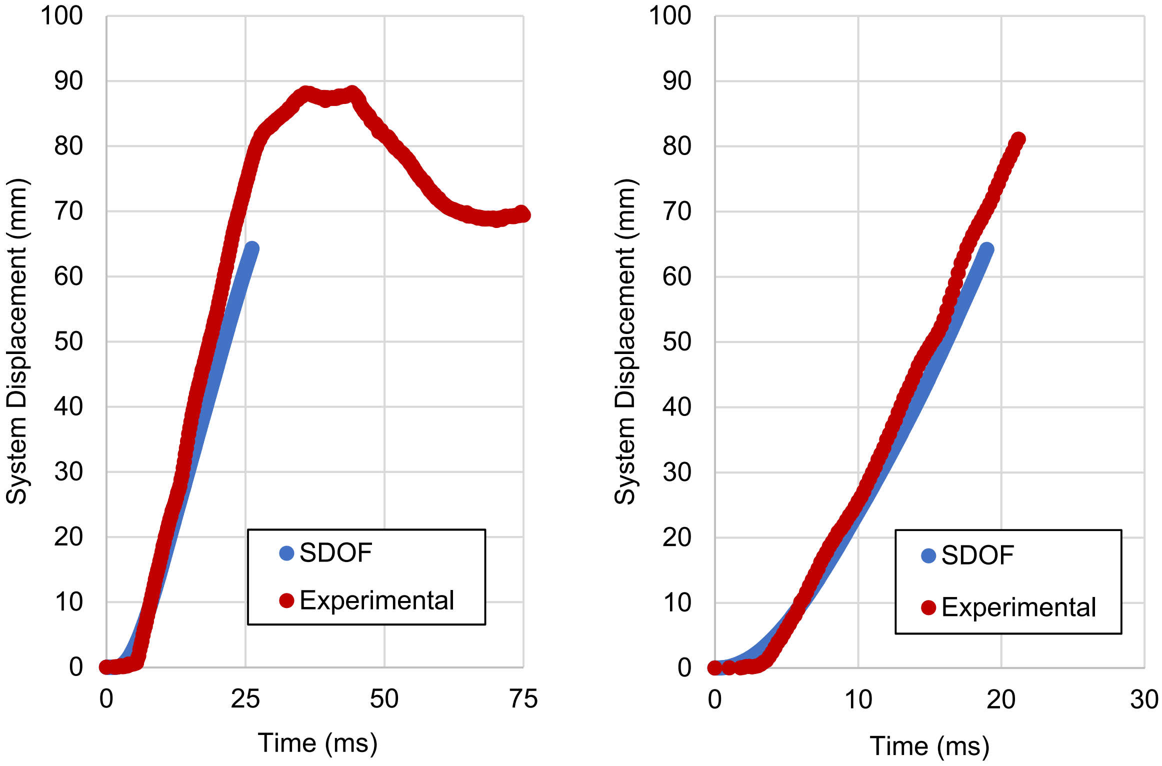
The thick steel angle was another bearing type connection with sufficient capacity to meet the requirements in the blast design standard. This approach could be considered as a viable alternative to that of ductile angles. The screw connection with the stiff steel angle provided some rotational restraint as observed through the small amount of separation between the panel and the block simulating floors. While some translation in the connections was observed, which would imply that some energy was indeed transmitted and absorbed in the connections, the stiff angle connections provided enough capacity that allowed the CLT panels to reach their ultimate capacity in both tests.

4.2 Validity of Simplified Modelling Techniques

Work conducted on simply supported CLT panels identical to those tested in the current study resulted in the development and validation of a material predictive model for CLT panels with simply supported boundary conditions (Poulin et al. 2017). This section aims at investigating the validity of using such a model for CLT members with realistic boundary conditions. Timber systems are generally assumed by designers to have simply supported end conditions because the tension perpendicular to grain capacity is typically insignificant to develop moment resistance at the connection. Some of the test configurations failed prematurely in splitting such as the ones with screws in end grain (EG1 – EG3, and DT1 – DT2). Although designers may still assume that such connections can be idealized as simply supported, the test results clearly show that a model developed for the flexural behaviour of the simply supported CLT panel would likely not be suitable to model such configurations.

Single degree-of-freedom (SDOF) analysis was conducted using the material-predictive model developed and validated by Poulin et al. (2017) to predict the deformation-time response of the CLT panels while using the actual pressure-time histories generated during the tests. SDOF modelling is widely used in blast design and has shown to predict the behaviour of structural elements to blast with good accuracy (Jacques et al. 2013, Jacques et al. 2012, Lacroix and Doudak 2015, Parlin 2010, Viau and Doudak 2016a). This methodology consists of lumping the system in a single mass and spring system, and solving the equation of motion for a given pressure-time history. The main shortcomings of using SDOF analysis are the assumed deflected shape and failure mode that must hold true for the predictions to be accurate. As mentioned earlier, not all connection types are suitable for the comparison with SDOF analysis since it can be confirmed through observation of the failure mode that the shape function for simply supported condition is not applicable. This includes the end-grain screw connections and angled double-threaded screws, which resulted in tension perpendicular to grain failure at the connection.

The tests in which failure did not ultimately occur in the connections were modelled using SDOF analysis in order to verify the validity of using the assumption of simply supported end conditions, which is a typical assumption in wood design. Presented in Figure 4 are the analytical results for two specimens, namely DA4 and SA2. It can be seen from the figure that the SDOF model tends to underpredict the displacement of the system. This is due to the fact that the energy absorbed by the angles is not considered in the model, due to the limitations of assuming simply supported boundary conditions. It can be concluded that the contribution of the connections must be included in the model in order to conduct accurate modelling and obtained reasonable results. One possible way of including the contribution of the end connections would be by the development of composite curves for the purpose of performing SDOF analysis. This entails combining the resistance and stiffness relationships of all the system components into one equivalent resistance curve. Such methodology has been utilized in previous studies on, for example, retrofitted masonry walls subjected to blast (Ciornei 2012, Knox et al. 2000) and has shown to provide accurate numerical predictions. The development of such a model is currently underway. If proven to provide inaccurate predictions, the use of more refined modelling techniques, such as multi degree-of-freedom modelling or finite element analysis, will be explored.



(a) (b)

Figure 4: SDOF modelling results: (a) DA4; (b) SA2

4.3 Code Considerations

The current blast design codes provide simplistic guidelines, which consist of overdesigning the connection based on the capacity of the structural element. The design philosophy aims at allowing the main structural element, in this case the CLT panel, to reach its ultimate capacity prior to failure in the connections. This approach is unsuitable for wood, due to the fact that it fails in a brittle manner in flexure. Additionally, the results presented in this paper show that overdesigning the connections may not be sufficient to prevent the unwanted failure in the boundary conditions. Fuse-based design of connections, similar to what is the design philosophy in seismic engineering, entails allowing only a certain aspect of a structural system to experience inelastic strains. In timber structures, the connections may act as the fuse, since they are typically made of ductile steel mechanical fasteners. Given that the primary objective of blast codes is to protect the lives of building occupants, for which progressive collapse prevention plays an important part, this fuse-based approach may provide an alternative approach to that included in the current blast design standard guidelines.

The results from the testing reported in this paper show that simply relying on the assumption of flexural failure of the CLT slab may not be adequate since unwanted brittle and premature failure in the connection may occur. Controlled failure of ductile connections with high levels of displacement capacity seems promising. The authors are in the process of exploring and optimizing such connection systems.

5 CONCLUSIONS

A total of eleven tests were performed using a shock tube test apparatus on five-ply CLT panels using various realistic connections. An emphasis was placed on damage levels and failure modes in comparison to previous CLT tests which only looked at the behaviour of CLT under idealized boundary conditions. It was found that even when designed according to the specifications of the current blast design standard, connections involving end-grain and double-threaded screws experienced brittle failure that corresponded to a load level inferior to that of the panel flexural capacity. Two bearing type angle connections showed that the higher capacity angle effectively allowed the CLT panel to reach its ultimate capacity, while the more flexible angle acted as an energy dissipater, which allowed the panel to remain elastic. Discussions on the ability of simplified SDOF models to predict the behaviour of wall systems consisting of panels and connections showed poor match between predicted and experimental displacements, due to the fact that the model assumes simply supported end conditions and takes no account for the connections' displacement, nor their ability to dissipate energy. Finally, current design philosophies and code guidelines, where connections are simply required to be overdesigned, may not be adequate. A better understanding of the connection behaviour is required before further guidance can be provided for their design under the effects of blast loading.

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