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LESSONS LEARNED FROM A DECADE OF RESEARCH ON WOOD ASSEMBLIES UNDER BLAST LOADING

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ABSTRACT: A comprehensive research program, combining experimental and analytical research, has resulted in significant advancements of knowledge pertaining to the behaviour of various structural timber assemblies subjected to blast loads. The full paper will report on key findings obtained from investigating light-frame walls, mass timber elements, and boundary connections. Significant results on the effect of strain rate on the material behaviour, typical failure modes observed, as well as influence on connections will be discussed. The main outcomes from this decade-long research program have paved the way to the development of design methodologies and retrofit options.

KEYWORDS: Design, Blast, Timber, Glulam, CLT, Stud walls, Connections, Retrofits, Mitigation

1 INTRODUCTION AND RESEARCH NEEDS

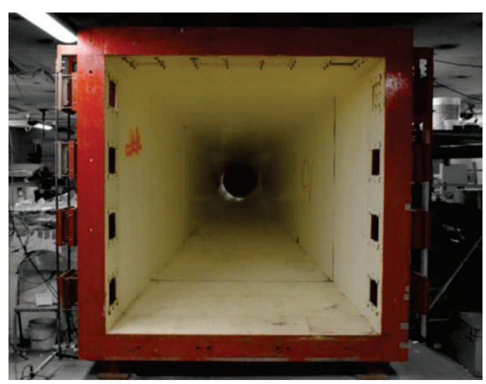
Targeted attacks or accidental explosions near civilian infrastructures have highlighted the need for developing reliable and robust design methodologies to address the behaviour of structural elements subjected to blast loading. With increasing number of timber structures built around the world, and evidence of their relatively poor performance when subjected to blast loads [1], there is a critical need to establish and enhance the behaviour of timber structural elements under high strain rates. Mid- and high-rise mass-timber structures comprised of engineered wood products (EWPs), such as glued laminated timber (glulam) and cross-laminated timber (CLT), are often accompanied by higher risk of being exposed to potential effects of blast loading.

American and Canadian blast standards (i.e., ASCE/SEI 59-11 and CSA S850) have been developed based on an experimental program on light-frame wood structures [1, 2], which focused on the overall qualitative behaviour of the structures. Since no in-situ properties of the structural members were measured during testing, published data was used to obtain the strength and stiffness of the specimens in order to conduct damage assessment, develop design provisions and propose response limits for wood structures [3]. Investigations into material behaviour under high strain-rate effects necessitates comprehensives experimental research programs, which can be accomplished through live explosion or simulated blast load testing (e.g., shock tube). While the former replicates the complete effects of a blast event (e.g., shock wave, fireball, fragmentation, debris throw, etc.) challenges arise with regard to the collection of reliable data. Conversely, the main benefit of laboratory experimentation simulating the shock wave over live arena testing is the richness of information generated.

A comprehensive research program has been established at the University of Ottawa to investigate the performance of light-frame stud walls, glued laminated timber (glulam) beams and columns, cross-laminated timber (CLT) slabs, and various connections (e.g., bolts, bearing angles, specialized energy-dissipative connections) when subjected to simulated blast loads. This paper presents key research results from the past decade including well over 200 tests conducted at the University of Ottawa Shock Tube Test Facility with the aim of establishing and improving the behaviour of several types of timber systems under blast loading.

2 EXPERIMENTAL PROGRAM

The Shock Tube (Figure 1), used in the experimental campaigns, is a test apparatus capable of simulating shock waves similar to those found in far-field explosions, on small-to-full-scale structural and non-structural components. A wide range of pressure and impulse combinations, representing different charge-weights and stand-off distances can be simulated.



***(a)** Expansion section and end-frame (front view)*

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(b) *Driver section (back view)*

Figure 1: *University of Ottawa Shock Tube*

The Shock Tube consists of three main components: driver, spool, and expansion sections. The shock wave is created by the release of compressed air stored in the driver section. This forms a shock front that travels along the 6096 mm expansion section and interacts with the specimen mounted at the end-frame (Figure 1b). The reflected pressure can be measured by two dynamic piezoelectric pressure sensors. Strain gauges are typically used to obtain strain data and determine the dynamic failure point for each test. Linear variable displacement transducers (LVDTs) are used to measure the specimen deflection. The data acquisition system is also connected to a full colour high-speed camera, capable of recording videos at a rate of 2000 frames per second.

3 KEY RESEARCH FINDINGS

3.1 MATERIAL PROPERTIES

Structural materials subjected to high strain rates during blast or impact loading tend to experience apparent increases in strength and sometimes stiffness [e.g. 4, 5-7], typically quantified as dynamic increase factors (DIFs). The current version of the Canadian blast design standard (CSA S850) assigns a DIF value of 1.4 to all wood element types [8]. Extensive static and dynamic experimental testing on full-scale studs, stud walls, glulam beams and columns, as well as CLT panels, has provided insight to values of DIFs for various wood products. As shown in Table 1, the current DIF value provided by the Canadian blast design standard [8] is clearly not sufficiently nuanced to capture the behaviour of different timber elements, and it may in several instances lead to a design that is not adequately conservative.

Table 1: *Observed and code DIF values*

	Experimentally Observed	CSA S850 [8]
Solid Sawn	1.40	
CLT	1.28	1.40
Glulam	1.14	

The values reported in Table 1 were based on testing of fifty-three light frame wood stud walls [6, 9, 10], seventy-one glulam beams [11-14], twenty-five CLT panels [7, 15, 16].

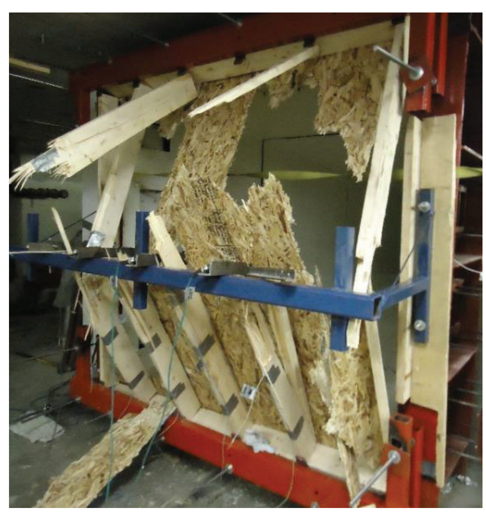
3.2 LIGHT-FRAME WOOD STUD WALLS

Light-frame stud walls of various configurations have been studied experimentally, involving various types and thicknesses of sheathing, stud size, and fasteners. Full-scale flexural tests on lumber elements have shown that the characteristics of the failure often shift from that of splintering failure when loaded under static loading to a brash "cut-through" failure when loaded dynamically (Figure 2).

(a) *Static* ***(b)*** *Dynamic*

Figure 2: *Representative failure modes for studs*

Results also showed indications of premature failure in some sheathing panels prior to achieving full flexural failure in the stud elements (Figure 3a). When sheathing failure occurred, debris was also produced, with some pieces being as large as the gap between the studs. Detachment of failed stud fragments was caused by the weak withdrawal capacity of the nail connections between the sheathing and the stud. While nails behave efficiently in shear when in-plane loads are imparted on the wall (i.e., shearwall), nails involved in out-of-plane motion are eventually loaded in withdrawal, where they are known to be very weak. The use of screws was found to significantly limit debris throw (Figure 3b), which has been shown to be the principal cause of injuries and deaths during blast events [17].



(a) *Sheathing failure and debris throw*

(b) Wall specimen with thicker sheathing and screws

Figure 3: *Light-frame wall specimens after testing*

3.3 GLUED-LAMINATED TIMBER

Failure of glulam members have been observed to consistently initiate at a tension-side finger joint or natural defect. In some instances, glulam specimens with localized concentration of finger joints on the tension-side laminate (Figure 4a) lacked the increase observed in specimens containing no finger joints in the middle one-third span (Figure 4b).

(a) *Concentrated* ***(b)*** *Staggered*

Figure 4: *Glulam finger joints*

The effect of axial load on the dynamic behaviour was also investigated. Three different axial load ratios were considered. The addition of axial load reduced the resistance of the column and contributed to concentrating the damage at midspan when compared to the case without axial load (Figure 5). It should be noted, however, that the contribution of axial loads in actual structures would highly depend on the connection detailing between the columns and the elements they support.

(a) *Without axial load* ***(b)*** *With axial load*

Figure 5: *Effect of axial load on glulam specimens*

3.4 CROSS-LAMINATED TIMBER

Two experimental programs investigating the out-of-plane behaviour of CLT under static and simulated blast loading of twenty-two panels, with different panel thicknesses was undertaken [7, 16]. The dynamic behaviour of CLT panels under bending consisted of a primarily flexural failure mode, accompanied by rolling shear damage in the transverse layers, particularly in specimens with low span-to-depth ratios. The overall behaviour of CLT panels can be generalized as a progression of failure of the longitudinal layers, initiating at the outermost longitudinal laminate, and crack propagation within the transverse laminates due to rolling shear (see Figure 6).

(a) *3-ply*

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(b) *5-ply* ***(c)*** *7-ply*

Figure 6: *Representative failure modes for CLT panels*

The CLT panels were observed to have significant post-peak resistance [7]. The initial drop in resistance represents the loss of the tension longitudinal and transversal laminates. For example, for a 7-ply specimen, which consist of four longitudinal and three transverse layers, this failure mechanism implies that the specimen would now behave as a 5-ply member, consisting of three longitudinal and two transverse layers.

4 CONNECTIONS

4.1 LIGHT-FRAME CONNECTIONS

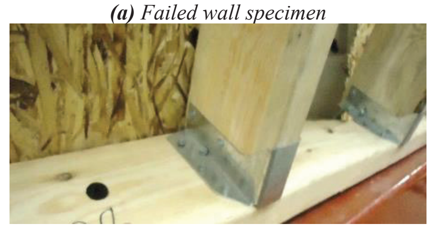
Premature failure of the wall connections to the roof and the foundation has been identified as the cause for most collapses [18]. A research study was undertaken to investigate the behaviour of typical nailed boundary connections, designed according to the National Building Code of Canada's prescriptive design guidelines [19]. The results showed that such detailing was not adequate to withstand the blast pressure and resulted in premature connection failure occurring at the top and bottom plates, as shown in Figure 7.

(a) *Arrival of blast wave* ***(b)*** *Top connection failure*

Figure 7: *Failure of nailed stud wall boundary connection*

Off-the-shelf joist hangers, typically used in light-frame wood floor systems, as well as simple angle brackets, were used to connect the studs to the boundary elements, as shown in Figure 8. The results showed that while overdesigned connections allowed the studs to achieve their flexural capacities, walls with connections designed to yield in a controlled manner could withstand greater blast pressures and impulses, and exhibit less damage.

(a) *Failed wall specimen*

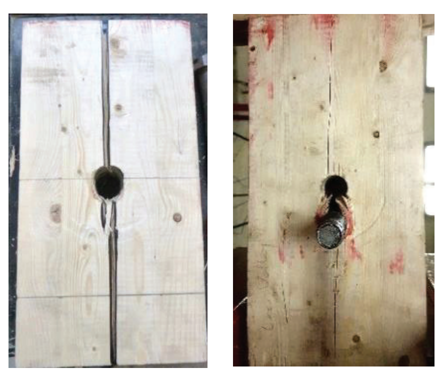


(b) *Relatively intact bottom plate connections*

Figure 8: *Wall specimen with joist hanger connections*

4.2 BOLTED GLULAM CONNECTIONS

A study was carried out on single-bolt joints of various slenderness ratios in both principal load direction (i.e., parallel- and perpendicular-to-grain), with the aim to investigated high strain-rate effects on the connections. An average dynamic increase ratio of 1.2 was observed on the yield load of connections designed to fail via wood crushing, while no significant dynamic increase on the yield load or stiffness was found for connections designed to fail in bolt bending and yielding. A loss in connection ductility was also noted when comparing static to dynamic loading, and the use of self-tapping screws (STS) as joint reinforcement was proved effective (see Figure 9).



(a) *Splitting failure (unreinforced)* ***(b)*** *Crushing failure (reinforced)*

Figure 9: *Dynamic stocky bolt specimens (parallel-to-grain)*

Glulam beams with bolted end connections with slenderness ratio of 10.8 were tested under shock tube simulated blast loads [12]. It was observed that bolted connections designed to yield and undergo significant inelastic deformations (Figure 10a) had enhanced overall energy dissipation when compared to specimens with overdesigned bolted connections, as required by the CSA S850.

***(a)** Yielding in connection* ***(b)** After blast test*

***Figure 10:** Full-scale bolted glulam specimen*

4.3 SELF-TAPPING SCREWS IN CLT

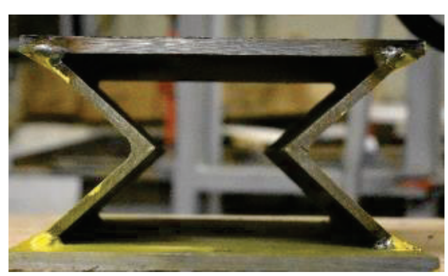
Self-tapping screws (STS) were used in end-grain with full-scale CLT specimens subjected to simulated blast loads. Significant damage was observed in the STS connections, where tension perpendicular-to-grain failure as well as combination of shear and withdrawal failure were prevalent. To take advantage of timber's relatively high capacity in bearing, the use of angle brackets with STS, which are traditionally used for in-plane loading for wind and seismic, were also investigated. Two angle brackets were tested, representing two distinct design philosophies; a thin and flexible angle bracket, designed to undergo significant yielding and wood crushing, and a robust and stiff angle bracket, designed to remain elastic and not cause significant wood crushing. The flexible angle bracket was found to fail in yielding and wood crushing. The overdesigned and stiff bracket exhibited a brittle failure mode when the capacity of the connection was exceeded, namely by rupturing the fasteners that connect the bracket to the base of the test assembly. As shown in Figure 11, full-scale test specimens with the flexible angle brackets were seen capable of absorbing more blast pressure and impulse prior to failure in the CLT panel.

***(a)** Flexible angle* ***(b)** Overdesigned angle*

***Figure 11:** Full-scale CLT specimens with angled connections*

4.4 ENERGY ABSORBING CONNECTIONS

The use of energy absorbing connections (EAC), which are purposefully designed to dissipate energy through controlled deformations of a steel fuse, were observed to improve the capability of a timber assembly to withstand blast explosions. Various configurations of EACs were investigated, all of which comprised of mild-steel shapes with various thickness and dimensions. The connections that were identified to perform optimally were found to exhibit a bi-linear elastic-perfectly plastic behaviour. The connection deemed the most efficient (Figure 12a) was implemented into full-scale glulam and CLT specimens. In comparison to specimens with simply-supported idealized boundary conditions, or overdesigned connections, the EACs were found to provide around 75%-115% increase in total impulse absorbed by the assembly prior to flexural failure of the wood element. A time lapse of a test is shown in Figure 12b.



***(a)** Tested EAC*

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(b) Time-lapse

Figure 12: *Full-scale CLT specimens with EACs*

5 WOOD ELEMENT RETROFITS

Identified deficiencies found during the research program were used as motivation for investigating possible retrofit options to increase the overall performance of various timber systems. This includes enhancing the performance of sheathing elements, load-bearing elements (i.e., stud, glulam column), boundary connections, as well as minimizing high-velocity flying debris. Stud walls designed according to typical prescriptive requirements often experienced premature failure of sheathing panels [9]. This not only caused flying debris but a loss in structure integrity, where the load-bearing elements cannot achieve their full flexural capacity. The use of thicker wood-based sheathing was found to shift the failures to the studs, while concurrently decrease the amount of sheathing debris. Corrugated steel panels were also tested (Figure 13) and the results showed that they provide significant increase in stiffness and strength.

Figure 13: *Corrugated steel panels as sheathing retrofit*

Welded-wire-mesh (WWM) was implemented as a sheathing retrofit, as well as a catcher system. In both applications, it was found to perform adequately well. As a sheathing reinforcement, the WWM acted similar to a skin reinforcement, thus reducing the demand on the panel in bending and minimizing overall damage and fragmentation (see Figure 14a), while as a catcher system, it adequately captured all debris of significant sizes (Figure 14b).

(a) *Sheathing reinforcement* ***(b)*** *Catcher system*

Figure 14: *Application of welded wire mesh (WWM) as retrofit*

Different retrofit configurations using fibre-reinforced-polymers (FRP) were investigated for light-frame stud walls, glulam columns, and CLT panels, as shown in Figure 15.

(a) *Stud wall*

(b) *Glulam column* ***(c)*** *CLT panel*

Figure 15: *Retrofits using fibre-reinforced polymers*

When adequate confinement in tandem with longitudinal tension reinforcement was provided, the application of FRP tended to delay and contain brittle tension parallel-to-grain failure and allowed for the compression-side longitudinal fibres to crush in a ductile manner [20-22]. In general, this allowed for the reinforced specimens to have sustained post-peak capacities, which would otherwise be limited, due to the inherent brittle nature of wood in flexure.

6 CONCLUSIONS

The key findings of a decade-long experimental and analytical research program investigating the behaviour of structural timber systems subjected to blast loads are summarized. High strain rate effects for various structural components and connections have been documented, paving the way for more accurate and resilient structural designs of wood assemblies. Mitigation strategies to improve the blast resistance of wood assemblies have been investigated, including boundary connections, sheathing reinforcements, and the use of fibre-reinforced polymers.

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