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OVERVIEW OF THE BEHAVIOUR OF MASS-TIMBER MEMBERS SUBJECTED TO CONTACT CHARGE DETONATIONS AND NEAR-FIELD BLAST LOADS

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ABSTRACT: Research on the performance of timber structures subjected to near-field blast loads and contact charge detonations is lacking, and a holistic approach is required in order to develop effective design guidelines and retrofits. A comprehensive research programme is currently underway to investigate the performance of mass-timber structural elements subjected to extreme dynamic loads using full-scale experimental testing and high-fidelity modelling. This paper provides an overview on some of the initial experimental results of an ongoing research programme investigating cross-laminated timber (CLT) panels. Key results on the effect of these loads on the material behaviour, including localized and global failure modes, are discussed. The overarching results of this research programme will provide the knowledge required to develop design methods for mass-timber structures subjected to contact charge detonations and near-field blast loads, as well as develop and validate simplified analytical and high-fidelity modelling tools.

KEYWORDS: blast loads, contact charge, near-field, mass-timber, force-protection

1 – INTRODUCTION & BACKGROUND

Mass-timber elements have become a cost-competitive construction form for a variety of infrastructure projects, particularly in regions possessing an abundance of trees and sustainably-managed forests. Engineered wood products (EWP), such as cross-laminated timber (CLT), provide greater control on variability, strength and stiffness properties, and provide a greater level of design flexibilities, as EWP can be manufactured to almost any dimension and specification. With recent geopolitical instabilities and ongoing conflicts, the need for effective hazard mitigation against extreme loads are needed. Whether intentional or accidental, threats from explosives and blast loading can lead to catastrophic damage to structures, as well as mass casualties.

Current design standards relating to the mitigation of explosion effects on structures are used to prevent human casualties and building collapse by assessing potential threats and evaluating whether structural elements and members can satisfy acceptable damage levels. These provisions are provided in blast design standards in Canada (CSA S850) [1] and the United States of America [2, 3], which can be used to conduct blast design and assessment, including determining whether a damage level can be attained, or whether retrofitting is needed.

A blast load is generated from an instantaneous release of chemical, physical, or nuclear energy. The detonation of high explosives creates a blast wave that expands at supersonic speeds from the initiation site resulting in significant overpressures (i.e. pressures greater than atmospheric). Depending on the location of the explosion, relative to the element of interest, blast loads can be divided into three categories: contact, near-field, and far-field loading. The delineation between these categories is often quantified through the scaled distance

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factor, Z, which takes into consideration the charge weight in Trinitrotoluene (TNT) equivalent, W, and stand-off distance, R, based on the Hopkinson-Cranz Scaling Law [4, 5]:

$$Z = \frac{R}{\sqrt[3]{W}} \quad (1)$$

Contact charge detonation events occur when the explosive charge is detonated in contact with or very close to a structure (i.e. $Z \approx 0$ m/kg$^{1/3}$). This type of event tends to generate localized high-intensity non-uniform loads, that are difficult to quantify analytically. Near-field detonations are characterized by highly non-uniform and temporally varying loading. These events tend to occur when $Z < 1.2$ m/kg$^{1/3}$. Finally, far-field blast loads, characterized by the planarity of the shockwave at time of arrival to the target, occur when $Z \geq 1.2$ m/kg$^{1/3}$.

Little is known about the behaviour of mass-timber elements subjected to near-field blast loading and contact charge detonations. As a result, current blast design standards [1, 2] are limited in scope to far-field blast loads. Other existing guidance pertaining to near-field blast loads and contact charges relates to other materials [e.g., 6, 7-10]. Most of the work done on wood assemblies has pertained to far-field blast loading on structural elements and connections, such as light-frame wood stud walls [e.g., 11, 12-15], glued-laminated timber elements [e.g., 16, 17-21], and CLT panels [e.g., 22, 23-26]. Of these studies, the majority were conducted through shock tube testing, which simulates the effects of a far-field blast through the use of compressed air. While live arena blast testing has been conducted to investigate the response of CLT panels under axial load exposed to a uniformly distributed blast load [27, 28], these have primarily focused on overall structural performance and load distribution under controlled conditions. However, this approach has limitations in capturing localized damage and failure mechanisms that occur under near-field and close-in conditions. Qiu, et al. [29] investigated the performance of parallel bamboo strand lumber (PBSL) and cross-laminated bamboo (CLB) subjected to near-field blast loading and contact charge detonations. Both panels exhibited significant blast resistance, albeit with different performances due to structural anisotropy. In near-field explosions, two failure modes were observed between CLB and PBSL specimens. Under contact charge detonations, both PBSL and CLB panels experienced breaching failure, forming a through-hole at the centre of the plate. However, the CLB panel exhibited noticeably smaller breach dimensions than the PBSL. These results highlight the efficiency of the cross-laminated system in reducing damage and improving protective performance in blast-resistant scenarios exposed to close-in explosive loads.

Research on laminated bamboo plates (LBPs) has demonstrated the application of wood-based panelised construction for near-field and contact explosive loading conditions [30]. Three types of LBPs were investigated: flat-pressed one-way plates, flat-pressed orthogonal plates, and side-pressed one-way plates. Experimental results revealed distinct damage patterns, including matrix cracking in the form of a through-thickness crack, fibre fracture, spalling, and breaching. Overall, LBPs retained good elasticity, structural integrity, and residual bearing capacity, with orthogonal and side-pressed structures enhancing load-carrying performance. These findings highlight the role of lamination and fibre orientation as key parameters in improving blast resistance [30]. This paper reports on an ongoing overarching research programme aiming to investigate the behaviour of CLT panels subjected to near-field blast loading and contact charge detonations in order to provide guidance for force protection design and analysis of mass-timber elements under these extreme load events.

2 – EXPERIMENTAL PROGRAM

The experimental phase of the ongoing research programme on CLT specimens subjected to live near-field blast loads and contact charge detonations was conducted at the Canadian Explosives Research Laboratory (Ottawa, Canada). Due to the proximity of the test site with residential neighbourhoods, a blast tank was utilized in order to conduct the tests (see Figure 1).

Figure 1: Blast tank

The CLT specimens measured 1,050 mm in width by 2,100 mm in length, with a clear span of 1,900 mm. The specimen dimensions correspond to the maximum dimensions that can be accommodated by the blast tank. 3-, 5-, and 7-ply specimens were investigated, corresponding to panel thicknesses of 105 mm, 175 mm, 245 mm, respectively. As shown in Figure 2a, a steel reaction frame was designed to provide the specimens with simply supported end conditions at the two narrow panel edges, whilst preventing the panels from any vertical displacement and rebound uplift, but permitting rotation at the ends. The behaviour of the CLT panels subjected to near-field blast loads was investigated by varying the charge weight, range, and inherently, the scaled distance *Z*, which remained under 1.2 m/kg$^{1/3}$ throughout testing. The behaviour of the specimens under contact charge detonations was investigated by varying the quantity of explosives.

Explosions are quantified by the amount of energy released during detonation and, in order to compare explosions, they are standardized to an equivalent unit of TNT. The majority of published data uses TNT explosives for predictions and in analysis methods and thus, TNT is often used as a standard unit for explosives. Composition 4 (C4) high explosive was used as the testing explosive. For the purpose of near-field testing, the C4 charges were shaped into spheres (Figure 2b) using 3D-printed moulds, with appropriate volume to achieve consistent and near-ideal density in order to obtain representative results, whilst hemispherical 3D-printed moulds were used to shape the contact charges (Figure 2c). Conventional duct tape was used to maintain the charges in their shape, representative of a bare explosive charge.

Each specimen was instrumented with three strain gauges on the tension side, along with two linear potentiometers (LP) and two high-speed laser sensors to provide mid-span displacements. The laser sensors were positioned to take measurements at mid-width of the panel, while the linear potentiometers took displacement measurements at quarter-width. This displacement instrumentation arrangement was used to capture the transverse deflection profile of the specimens. Four load cells were utilized to measure the end reaction-time histories. Reflected pressures along the surface of the specimen were not measured during testing as this would entail the installation of sensors within the body of the specimens. Instead, a piezoelectric pressure sensor (i.e. “lollipop” gauge) was placed perpendicular to the shock front near the end of the specimen in order to provide a singular measurement point of the blast tank incident pressures and impulses. This will be used for validation purposes later, particularly when estimating blast parameters using established empirical means (e.g. Kingery and Bulmash) and computational fluid dynamics (CFD).

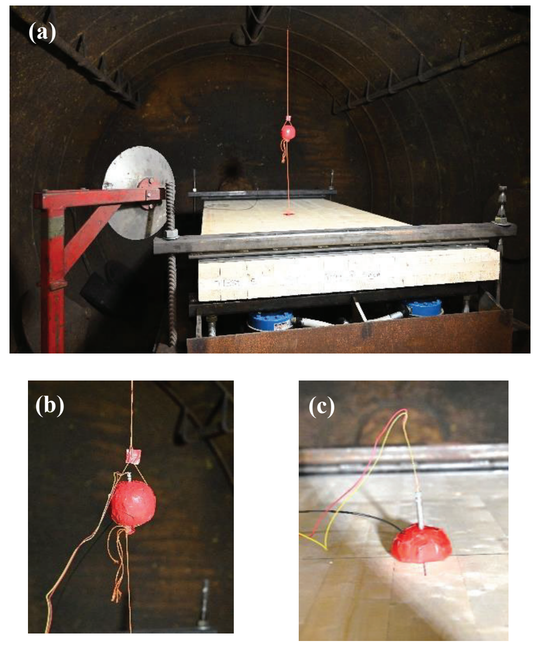

Figure 2: (a) Experimental test setups (b) near-field C4 charge (c) C4 contact charge

Figure 3 presents a representative incident pressure-time history recorded in the blast tank. Using the Kingery-Bulmash curves [31], good agreement can be seen between the experimental and predicted pressure-time histories. The relatively small variances signify that established empirical methods can be used to accurately compute blast parameters for near-field events. Significant secondary blast pressures and impulses were observed following the initial positive phase duration, as a result of blast tank confinement and reflections of blast pressures.

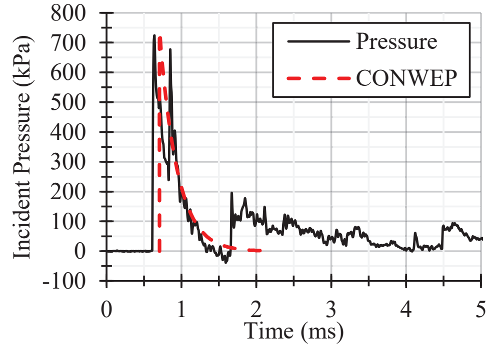

Figure 3: Pressure-time history

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3 – DISCUSSION OF KEY RESULTS

3.1 NEAR-FIELD BLAST LOADING

Unlike far-field blast loads, whereby a uniform pressure distribution is applied onto the specimen, the imparted near-field blast loads, upon impacting the specimens, were of a spherical nature. The middle of the specimens received the highest amount of reflected pressure, and the front face of the specimens being loaded with varying arrival times across the front face as a function of the geometric position, owing to the non-planar nature of the shockwave. This was observed in the displacement-time histories, as shown in Figure 4, where the displacement-time history at the centre of the specimens were observed to deflect prior to the quarter-width points. This is a result of the non-uniform loading across the length and width of the panel, creating two-way bending action during the specimens' initial response. For each specimen, the time at failure was determined using the dynamic reaction data obtained from the load cells, whereby a significant drop in dynamic reactions was attributed to failure of the outer tension laminates and/or rolling shear. The nature of the laser sensors used to measure the mid-span centre-width displacement-time histories left them susceptible to interference through debris and fireballs, resulting in data that would no longer be representative of specimen behaviour. However, this tended to occur after failure of the test specimens.

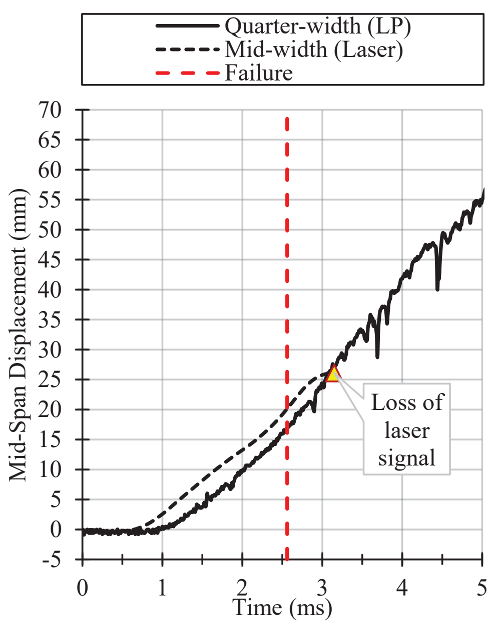

Figure 4: Representative near-field blast displacement-time history

As shown in Figure 5a, flexural failure was the dominant failure mode, with failure initiation occurring on the outermost tension-side laminate. Due to the small space and lack of light within the blast tank, high speed cameras could not be used to observe and document dynamic response of the specimens as a function of time. However, it became apparent that failure tended to occur near or at localized natural defects and finger joints located on the tension side (Figure 5b).

Figure 5: Representative (a) flexural failure (3-ply specimen) (b) finger joint failure

Due to characteristic non-uniformity of the blast loads investigated throughout this research programme, localized finger joint failures on the tension side of the panel, as shown in Figure 6, were prominently observed. While this behaviour has been observed in other studies investigating CLT panels of the same grade and species subjected to simulated far-field blast loads [32], the frequency and extent of finger joint damage and failure was noted to be significantly higher throughout the current study. This points to the high likelihood of strain-rate sensitivity of the CLT panel and finger joints. In instances where the applied blast loads were enough to cause initial failure in the tension laminates but not a complete failure of the specimens, high concentrations of finger joint failure were observed, as shown in Figure 6. This may point to instances where a highly concentrated blast load applied over a small area relative to the total exposed area of the CLT specimens could cause premature finger joint failures, and thus causing subsequent failure to take place across the specimen.

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Figure 6: Prominence of finger joint failure

As shown in Figure 7, 5-ply and 7-ply specimens experienced rolling shear failure when subjected to loading that did not cause complete blowout failures. For larger charge sizes, however, complete flexural failure of the specimens occurred, in tandem with rolling shear, however, it could not be discerned whether the latter occurred prior to, simultaneously with, or following the former, due to the lack of high-speed cameras. This was expected, however, since the span of the test setup (1,900 mm) could not be modified to accommodate the increase in specimen thickness.

Localized wood material failure characterized by severe warping of the wood fibres and superficial charring was observed in the loaded areas closest to the point of detonation for specimens tested with $Z \leq 0.6$ m/kg$^{1/3}$. Throughout testing, combustion of failed debris was observed, however, these were quickly extinguished by the blast tank post-test ventilation system. These fires, however, point to possible instances during a near-field or close-in blast event whereby material auto-ignition could potentially lead to post-blast fire hazards.

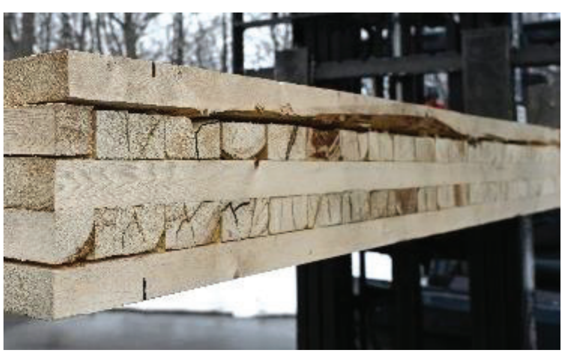

Figure 7: Rolling shear failure in 5-ply specimen

Figure 8: Charring and warping of fibres

3.2 CONTACT CHARGE DETONATIONS

All specimens subjected to contact charge detonations experienced breaching damage. Representative damage patterns for the tested CLT panels, including breaching and spalling damages, are shown in Figure 9. As expected, the thickness of the CLT panel played a significant role whether full breach could be reached. Spalling of the laminates at the top and bottom of the panel in the areas adjacent to the breach hole was observed in the majority of the test specimens, with the breach dimensions on the protected side being consistently larger than the loaded side of the panels. It is noteworthy to mention that the results of CLT panels under contact charge detonations, demonstrating a breaching failure mode at the location of the explosive with spalling surrounding the breach at the top and bottom of the panel, is consistent with previous studies on bamboo panels under contact charge detonations [13, 14]. In addition, the loading mechanism of the contact charge detonations would inherently create a stress-wave travelling through the depth of the panel, which upon reaching the end of the specimen (i.e. wood-air interface) would reflect and travel back towards the compression side. These stress waves lead to delamination of the wood near, as evident from finger joint failures and the failure plane lying between laminates. This phenomenon was observed in the majority of the CLT specimens under contact charge testing (see Figure 9).

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Figure 9: 200g C4 contact charge on (a) 3-ply panel (full breach) (b) 7-ply panel (no breach and localized cracking and FJ failure)

Due to the combustibility of wood, charring hazards were noteworthy throughout contact charge testing, with significant burning and charring taking place within the breaching hole, due to the high temperatures and energy dissipation mechanism during the detonation. Debris throw was also significant, in some instances damaging instrumentation and causing secondary fires in the blast tank. This latter point again raises the issue of post-blast fires and their associated risks, similar to those observed during near-field blast loads. Overall, these results indicate that conducting analysis and design for both near-field blast threats and contact charge threats may require that a multi-hazard be adopted.

4 – CONCLUSIONS AND NEXT STEPS

An overview on an ongoing research programme investigating the behaviour of mass-timber elements subjected to near-field blast loads and contact charge detonations was presented. Experimental testing on full-scale CLT panels was conducted at the Canadian Explosives Research Laboratory (Ottawa, Canada) through the use of a blast tank. Preliminary results showed significant differences in overall behaviour, structural properties, and failure modes when compared with published results pertaining to far-field blast loads, which represents the overwhelming majority of published research on blast loads on timber structures.

Work is ongoing as part of this research programme with the overarching aim to develop design and analysis guidelines for mass-timber elements subjected to extreme near-field and contact loading. This includes conducting quasi-static characterisation of the CLT panels, which will be used to quantify high strain-rate effects and failure. The experimental test results, both dynamic and quasi-static, will be used in the development and validation of simplified modelling tools and high-fidelity numerical models, such as using the finite element method.

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