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Behaviour of Light-Frame Wood Stud Walls Under High Strain Rates

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Abstract: This paper presents the methodology and preliminary results of an experimental program, where the behaviour of light-frame wood walls systems under blast loading was investigated. The walls were tested both statically and dynamically and material properties, such as the dynamic increase factor (DIF), were determined. Two different types and thicknesses of sheathing elements, namely OSB and plywood were studied. Preliminary results indicate that there is a significant increase in capacity when the walls were loaded under dynamic loading relative to their static capacity.

Keywords: High strain rate, blast loading, flexural response, wood light-frame, static capacity, dynamic capacity, shock tube testing.

1 Introduction

Advancements in analysis and design techniques have allowed for taller and safer light-frame wood buildings in the recent years. Timber structures have become a viable alternative in the non-residential building sector. Taller structures (e.g. 6-storeys in the province of British-Columbia) are emerging and hybrid structures (wood with steel and reinforced concrete) are becoming more common. Deliberate attacks (e.g. World Trade Centre 2001) and accidental explosions (e.g. Ronan Point 1968) have raised the awareness about the limited knowledge that currently exists on the behaviour of structures when subjected to blast loading. Where there has been significant advancement in research covering the behaviour of concrete and steel structures, research in wood has been very limited. The majority of the existing knowledge about the behaviour of wood under high strain rates stems from small clear specimens, free of defects (Wood 1951, Mindess and Madsen 1986, Jansson 1992) with only limited studies involving full scale testing (e.g. Lloyd et. al. 2011). Although wood structures may not be a direct target in the events of deliberate attacks, they may be located within a given radius of a target. The strain rates experienced by the material in such an event are much higher than those generated during earthquake and wind loading.

There are currently no explicit requirements in the building code to account for blast loading on structures, however, blast analysis and design requirements for structures are covered in the recently developed standard "Design and assessment of building subjected to blast loads" (CSA S850 2012).

Similar to other materials, such as concrete and steel, wood is expected to experience an increase in capacity under high strain rate loadings. The ratio of the dynamic to the static capacity is commonly known as the dynamic increase factor (DIF). Field tests were conducted on a number of wood frame houses (Kimbell and Fies 1953, Randall 1955, Marchand 2002) and they showed that under high pressure, the performance of the wood frame houses tested was greatly influenced by the performance of the rafters, joists, and studs and not the connections between them.

The overarching aim of the research is to mitigate hazards associated with blast loads on light-frame wood structures. This is done through establishing blast response limits for different damage levels under blast-induced shock waves. The current paper deals specifically with the experimental testing program aiming to determine the dynamic increase factor (DIF) for wood stud walls. The approach was holistic and involved investigating the behaviour of individual studs, and studs within fully sheathed walls.

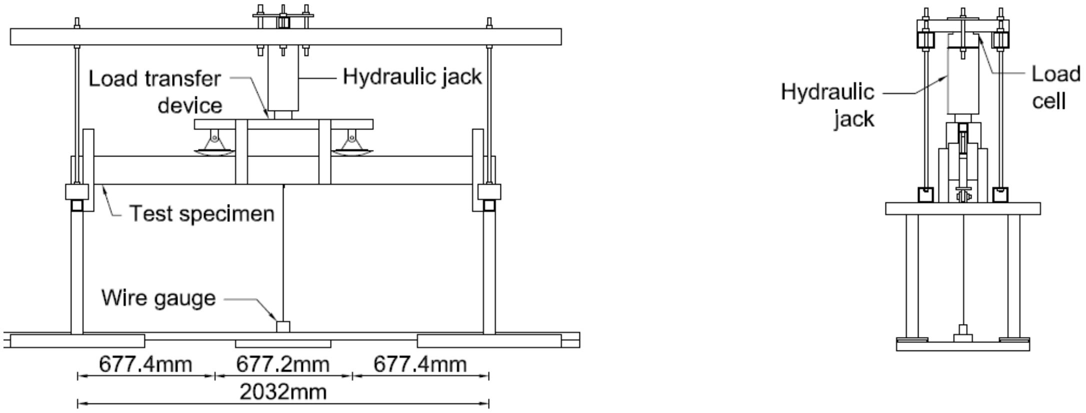
2 Experimental Program

Twenty walls consisting of 38 mm x 140 mm machine-stress-rated (MSR) studs, spaced 406 mm on center and with a single top and bottom plates were tested to failure under static and dynamic loading. The total height of the walls was 2159 mm. A total of ten walls were sheathed with 11 mm oriented-strand-board (OSB), attached to the studs with 64 mm long nails with a diameter of 3.25 mm. The other ten walls were sheathed with 19 mm plywood and attached with 76 mm long nails with a diameter of 3.33 mm. The nails were fastened using a grid pattern of 150 mm on center for all walls. The modulus of elasticity (MOE) was determined for each stud, using a preloading technique as well as a hand-held timber E-grader (Brookhuis Micro-Electronics). Forty studs were selected randomly from a total of 200 available stud elements and tested statically using four-point bending loading in accordance with ASTM D198. This helped determine the static capacity of the stud elements in isolation. A total of ten walls, half of them sheathed with OSB and the other half with plywood, were tested statically under loading pattern and boundary conditions similar to those of the individual studs. A matched sample of specimens was tested under uniformly distributed pressure simulating blast loading.

2.1 Stud Static Test Setup

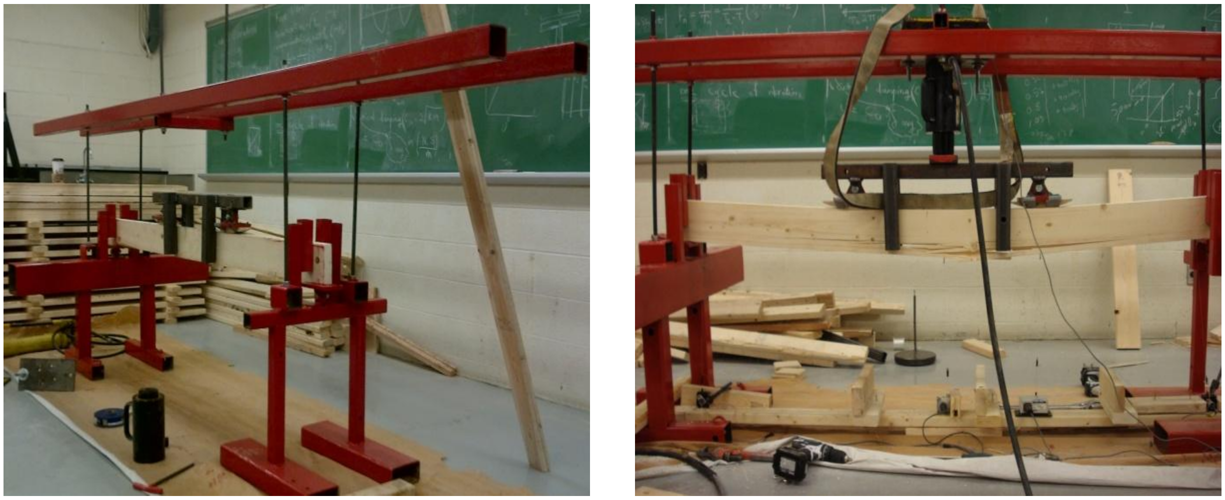
The test setup for the four-point bending tests on the stud elements can be seen in Figure 1. Bearing blocks consisting of a denser wood material were used to transfer the load to the test specimens. The displacement was measured at mid-span using a wire gauge, which was attached to the bottom of the test setup, and the applied load was measured using a load cell attached to the loading jack.

The measured force and mid-span displacement for each stud was recorded and information such as the modulus of elasticity (MOE) and modulus of rupture (MOR) were extracted. As shown in Figure 2, the test specimens were allowed to rotate at both ends while prevented from out-of-plane buckling at the supports and at the load application points.



(a) Profile (b) Side

Figure 1: Stud static test setup



(a) Before testing

(b) Typical failure of studs

Figure 2: Static testing of individual studs

Representative force-displacement curves obtained from the stud testing are shown in Figure 3. In general, the results for both the MOE and MOR were consistent with relatively small coefficient of variability (COV) of 0.11 and 0.23, respectively. It is expected to have such consistency in stiffness and capacity values for MSR lumber relative to those obtained from visually graded lumber.

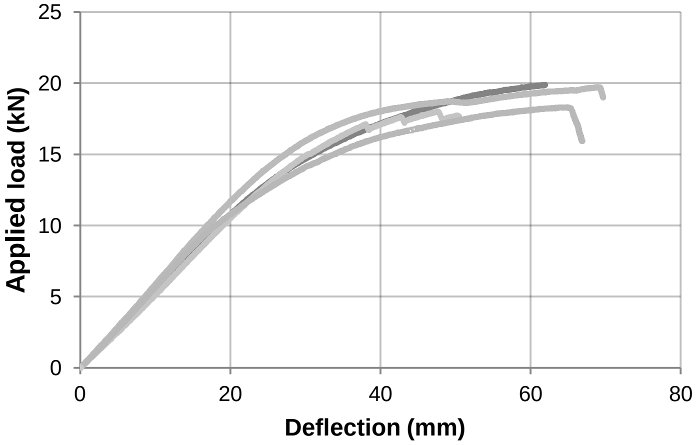
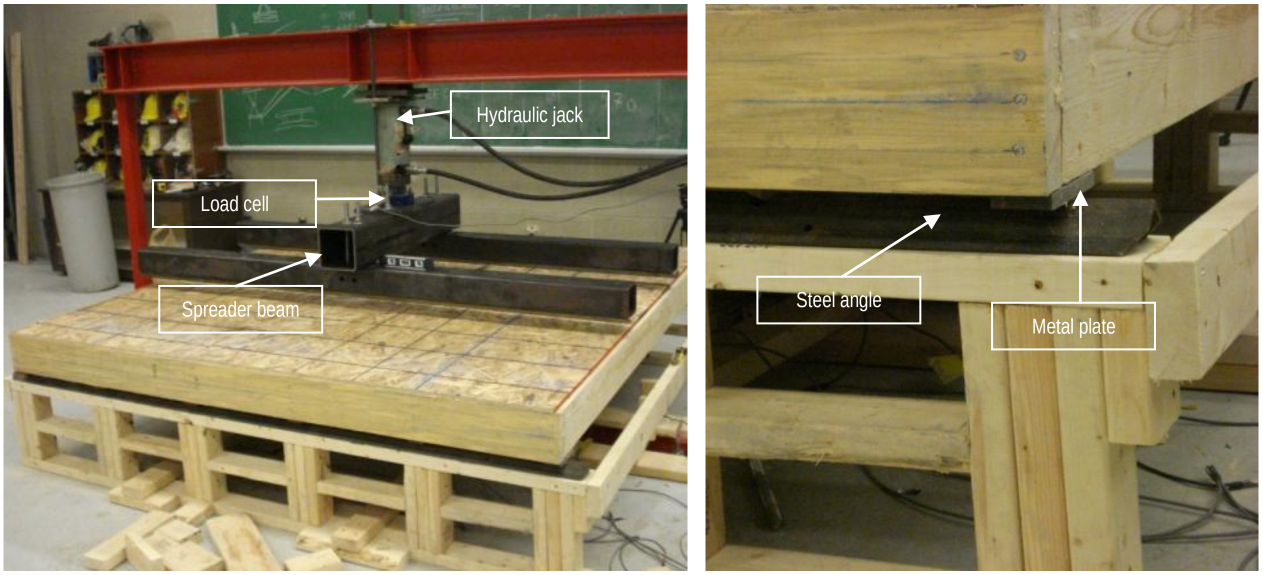


Figure 3: Force-deflection relationship of individual studs

2.2 Wall Static Test Setup

A static load was applied to the walls using a load spreader device as shown in Figure 4. The setup mimics the four-point bending setup used in the testing of individual studs. The load cell was placed between the spreader beam and the hydraulic jack. The displacements of the four middle studs were measured using wire gauges attached at mid-span. Simply supported conditions were provided by nailing a steel plate to each stud at the point of contact with the steel angle as shown in Figure 4.

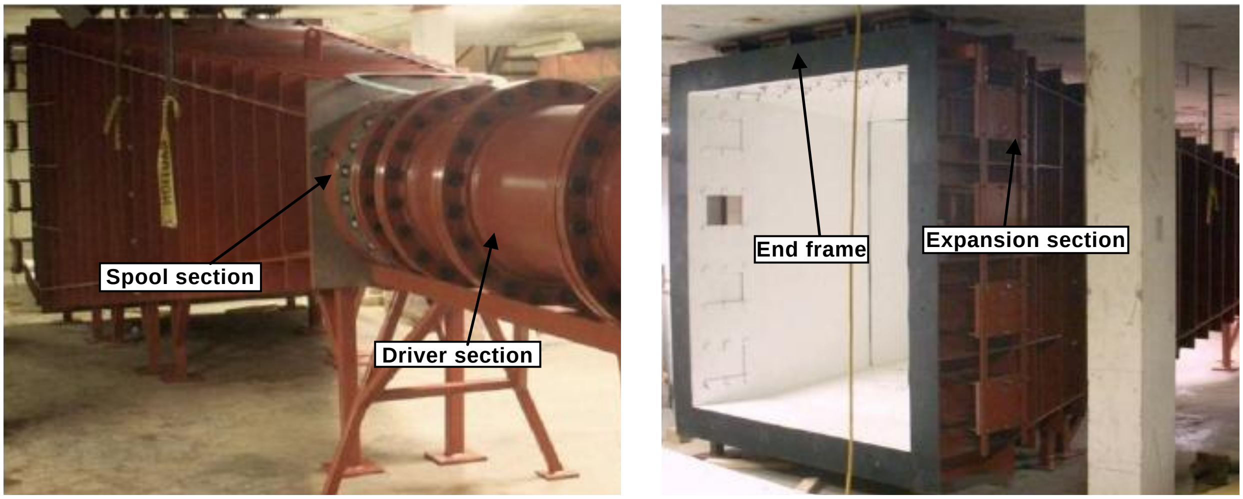


(a) Before testing (b) Typical failure

Figure 4: Wall static testing

2.3 Dynamic Test Setup

High strain rates in the stud walls were generated through shock wave loading using the University of Ottawa's Shock Tube. A shock wave, similar to that resulting from far-field detonations, is created by compressing the air in the driver section and then releasing it rapidly through the control of the spool section, as shown in Figure 5 (a). This mechanism is known as a double diaphragm firing system. Upon release, the compressed air travels through the 6096 mm expansion section and interacts with the specimen attached to the end frame, as shown in Figure 5 (b). The 2032 mm x 2032 mm opening of the end frame allows the testing of large scale specimens. Vents located near the end of the expansion section allows for a negative phase as the compressed air in the shock wave is released into the surrounding atmosphere.



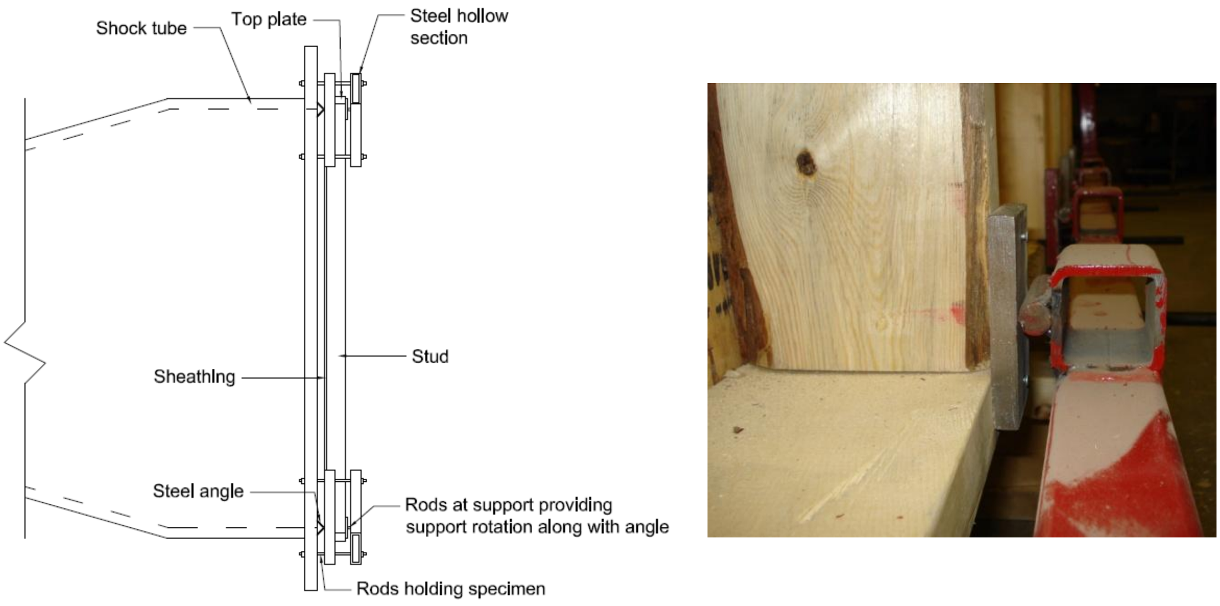
(a) Driver and spool sections (b) Expansion section and end frame

Figure 5: University of Ottawa's Shock Tube

The walls were subjected to various combinations of pressures and impulses to achieve different response levels. The reflected pressure was controlled by the driver pressure while the time duration was controlled by varying the driver length. The driver length was varied from one to sixteen feet. The reason for varying the driver length was to achieve pressure-impulse combinations in the impulsive, dynamic and quasi-static regions. The maximum reflected pressure and reflected impulse that can be achieved with the Shock Tube is 100 kPa and 2200 kPa-ms, respectively, while the range of time durations for the positive phase is 5 to 70 ms.

Strain gauges and linear variable displacement transducers (LVDTs) were placed at the mid-span of the four middle studs while two independent dynamic piezoelectric pressure sensors recorded the reflected pressure resulting from the shock wave. The strain gauges, LVDTs and the dynamic piezoelectric pressure sensors were connected to a data acquisition system which consisted of a digital oscilloscope with a recording capability of 100,000 samples per second. The data acquisition system and the high speed camera were triggered when the shock wave front passed one of the pressure sensors thus the response of the specimen was synchronized with the recorded data. The recording rate of the high speed camera was set to 500 frames per second.

The walls were attached directly to the end frame with end conditions that mimicked those used in the static testing as shown in Figure 6. The two angles were placed such that the clear span was equal to 2032 mm. Potential crushing of the wood due to the threaded rods was avoided by attaching a 50 mm x 100 mm metal plate at each point of contact (Figure 6 b).



(a) General setup details

(b) Support condition details

Figure 6: Dynamic experimental test setup

3 Preliminary Experimental Results and Discussion

The experimental work has been finalized and the data is currently under analysis. The following discusses representative data from the static and dynamic testing results. In order to compare the relative increase in capacity, it is necessary to determine the reflected pressure and reflected impulse as well as the displacement- and strain-time histories. Figure 7 shows an example of the reflected pressure- and impulse-time histories for a wall with 19 mm plywood sheathing. As it can be seen there is a sudden rise in pressure and a decrease that, in the analysis, is idealized as linear. The pressure diminishes to zero at 20 ms, which defines the positive phase duration. Also shown in Figure 7 is the negative phase with a small magnitude relative to the maximum positive peak pressure. An example of the displacement and strain time histories curves is shown in Figure 8.

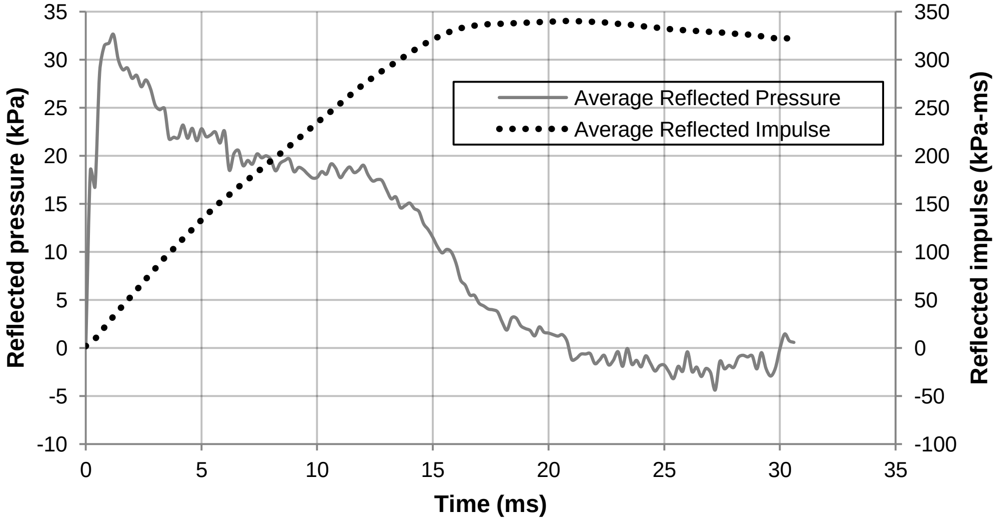


Figure 7: Typical reflected pressure and impulse time history

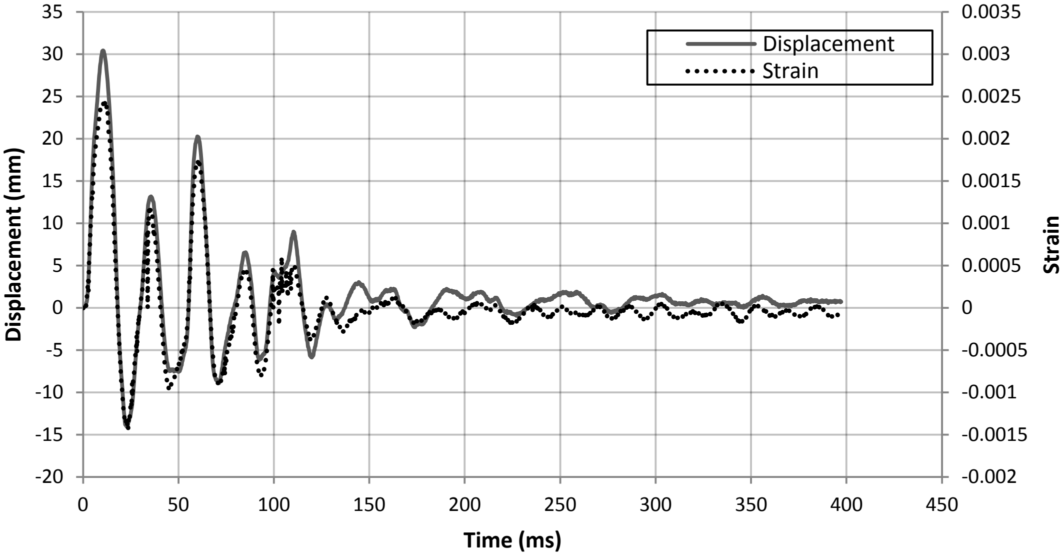


Figure 8: Typical displacement and strain time history

Flexure failure mode was observed both under dynamic and static loading, as shown in Figure 9. Identifying a unique failure mode was important especially for the purpose of simplifying the modelling analysis, which is presented in a companion paper.

(a) Typical plywood wall after dynamic testing (b)Typical plywood wall after static testing

Figure 9: Performance comparison between dynamic and static loading

Differences in the failure of the sheathing panels were observed between the OSB and plywood especially for the dynamic tests. In general, the walls sheathed with plywood resisted more load than the ones sheathed with OSB. This was expected, mainly due to the added mass and stiffness provided by the plywood panel. Some degree of tearing of the OSB panels was observed in almost every dynamic test. In all cases, the capacity of the OSB panel was reached around the same time as the studs reached their capacities. This observation is very important and has an implication on the design and detailing of such structural systems. In an explosion, the blast pressure is collected by the sheathing panels and transferred to the stud elements. In order for the studs to develop their full flexural capacity, the load distributing element, the sheathing, cannot fail before the main structural element, the stud. The observation made here suggests that sheathing panels with thicknesses of 11 mm or less may not be appropriate to use in a stud wall system designed to resist a blast load, because the anticipated capacity of the studs may not be achieved. Failure in the sheathing before the studs may also lead to fragments becoming projectiles and injuring the occupants. A detail that cannot be overlooked here of course is that the studs are slightly shorter than typical 8’ (2440 mm) walls, which means that the demand on the wall studs is less than would be anticipated in a full scale wall. The point to be made here is that the sequences of failure and load path are both important and this issue will be subject to further research. Damage on the plywood panels was limited to few cracks with no cases of flying debris.

While significant differences were observed between the two sheathing panels under dynamic loading, little to no difference was seen under static loading. The two wall types had similar ultimate capacities, with the plywood walls deflecting slightly less. This is expected given the slightly higher stiffness of the plywood.

The stiffness and capacity data from the static testing on studs and walls would serve as input in the analytical model currently under development. The material predictive model of the wall system would be based on the capacity and stiffness of a T-element consisting of a stud and a section of the sheathing width equivalent to its stud spacing. The model would also include an expression that reflects the composite action between the sheathing and the stud. The degree of composite action could enable the prediction of the behaviour under dynamic loading simply by testing individual studs. A companion paper describes the analysis techniques employed and provides a comparison between tests data and model results.

4 Conclusion

An experimental program investigating the behaviour of light-frame wood stud walls under blast loading was undertaken. Flexure failure mode was observed both under dynamic and static loading. Two different types and thicknesses of sheathing elements, namely OSB and plywood were studied. Differences in the failure of the sheathing panels were observed between the OSB and plywood especially for the dynamic tests. The performance of 19 mm sheathing panels was satisfactory and no sheathing failure was observed. Preliminary results indicate that there is a significant increase in capacity when the walls were loaded under dynamic loading relative to their static capacity.

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