Innovative and Cost Effective Blast Strengthening of Wood Framed Structures

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Introduction

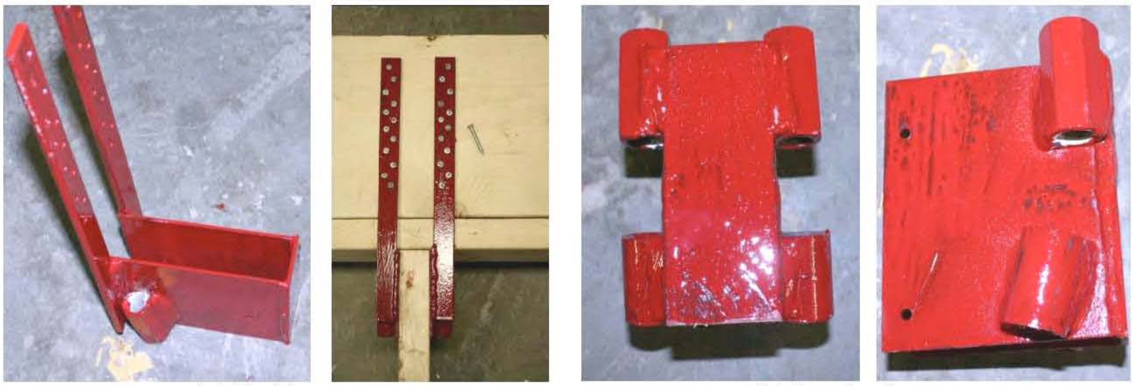
Typical timber construction, used extensively throughout North America, is not generally regarded as having inherent blast-resistance. However, timber framed structures are so widespread that many of these structures face a real risk of being subjected to blast-induced explosive loading. The advantages of timber construction – ease of construction, cost and adaptability – results in structures which are lightweight, yet relatively weak. Such structures are vulnerable to high pressure-short duration blast loads. The blast threats facing timber structures come from malicious terrorist attacks or accidental industrial explosions. In other cases, timber structures and their occupants are placed at an unacceptable level of risk by simply being located within the blast-radius of other high-risk high-profile infrastructure.

Wood framed buildings rely on exterior load bearing stud walls to carry gravity loads and resist in-plane seismic lateral loads. These exterior walls are only designed to resist relatively small lateral wind pressures. Timber construction is generally regarded as blast deficient as it does not have sufficient lateral load capacity to survive the blast event and prevent progressive collapse of the structure. We have developed a novel approach to strengthen blast-deficient wood frame buildings. This approach involves using a specially designed hanger and tension rod system to provide the necessary strength and continuity to increase the blast resistance of exterior stud walls.

Technical Analysis

Exterior stud walls are load bearing elements that form the envelope of the structure. These walls are constructed using vertical studs that sit on a bottom plate and support a top plate. The floor diaphragm system is comprised of joists and floor sheathing which bears on the top plate of the wall. Stud walls are typically constructed from *2”×6”* (*38 mm × 140 mm*) boards spaced every *24” (576 mm)* with a span of approximately *7’-9”* (*2.36 m*) [1]. Studs are end-nailed to the top and bottom plate with two *3”* (*76 mm*) nails per stud. The out-of-plane capacity of this method of construction is a function of stud length, stud spacing and the end-connection of the studs to the floor system. Pull-out of the nails connecting the wall to the floor system is a primary failure mode. Flexural failure of the studs – when the bending stress in the stud exceeds the material rupture capacity – can also be a dominant failure mechanism. Both failure modes are characterised as brittle failures. These failures would result in a collapse of all or part of the structure without allowing sufficient time for the structure to be safely evacuated following a blast event.

We designed a strengthening system to address the blast-deficiencies of typical timber construction. This system consists of a steel hanger and tension rod system. It is designed to limit the stresses in the wood studs and enhance the continuity between the wall and floor systems. The entire system is designed to be contained entirely within the wall itself. Furthermore, it is lightweight, and installation does not require any specialized labour. The system consists of three main components; end hangers, interior hangers and threaded steel rods. End hangers, shown in Figure 1 (a), are designed to connect the top and bottom of individual studs to the high mass floor diaphragm systems. These hangers are installed at the ends of the studs and extend into the rim joist. Twenty-four off-the-shelf bearing fasteners are used to connect each end hanger to the rim joints. The number and type of fastener was designed according to standard wood design practice [2]. Coupler nuts are welded to the side plates to facilitate the connection of the threaded tension rods. Interior hangers, shown in Figure 1 (b), are installed at 1/3 and 2/3 distances along length of the stud. The interior hangers also have connectors welded to the side plates to allow for the connection of the tension rods. *5/8”* (*15.9 mm*) diameter high-grade steel- threaded rods run along the length, and on both sides, of the stud. They are threaded into the couplers welded to either side of the hangers.



(a) End hanger (b) Interior hanger

Figure 1: Close-up of Hangers Used to Strengthen Timber Stud Walls.

The prototype hangers are constructed from welded *1/8”* (*3.12 mm*) and *1/4”* (*6.35 mm*) steel plates. They are designed to provide sufficient bearing area for the studs while ensuring that none of the hanger plates yield under the design blast loads. The plate thickness and geometry of the hanger system has been selected with mass production in mind. Common machining technology can be used to stamp and bend the hanger shapes with minimal need for expensive welding. The use of commercially available 5/8” threaded rod further reduces costs associated with large scale production.

Figure 2 shows the strengthening system installed on a typical stud wall. The system is designed to react passively to the lateral displacement of the stud caused by blast loading. The blast-induced displacement of the stud causes the steel rods to be stressed and elongate. This elongation applies two natural restoring forces at the locations of the interior hangers. These restoring forces counteract the blast-induced wall displacements. The magnitude of the restoring forces applied by the system is in direct proportion to wall displacements: larger wall displacements initiate larger restoring forces. The tensile restoring forces in the steel rods are transferred to the high mass diaphragm floor systems through the end hangers attached to the rim joints.

We developed an analytical model of both the strengthened and as-built stud walls prior to performing experimental testing. The strength and stiffness of the two walls were calculated based on the known dimensions and material properties of the wood [3], as well as the crosssectional area of the threaded rods and geometry of the strengthening system. It was found that the strengthened wall could withstand *5.3* times more lateral load and was *7.6* times stiffer than the as-built wall. Furthermore, the model predicted that the strengthened wall would remain relatively undamaged when subjected to explosions that would cause catastrophic failure of the as-built wall.

(a) Profile of a strengthened stud

(b) Strengthened wall (left) and as-built wall (right) prior to shock tube testing

Figure 2: Timber Strengthening System as Installed on a Stud Wall.

The effectiveness of the strengthening system was verified experimentally by subjecting near full scale segments of exterior walls to simulated explosions. Two walls, each consisting of three *2"×6"* spruce-pine-fir studs spaced at *16"* (*406 mm*) were constructed. The walls were sheathed with standard *½"* (*12.7 mm*) plywood and the studs were attached to *2"×6"* top and bottom plates which were then nailed to *2"×10"* top and bottom joists. The wall segments were each *3'- 4"* (*1016 mm*) wide and *6'-10"* (*2082 mm*) tall. These wall segments were designed to fit sit-byside within the loaded area of the University of Ottawa Shock Tube, as shown in Figure 2 (b).

The shock tube was used to generate shock wave pressures which are analogous to the shock waves produced by the detonation of high explosive [4, 5]. The strengthening system was applied to one of the wall segments, shown on the left in Figure 2 (b), while the other wall segment remained as-built. The strengthening procedure itself was straightforward and took two people approximately *1.5* additional hours to perform. Construction and testing the two identical wall segments side-by-side allowed for direct comparison of results.

Both walls were subjected to a shock wave with a peak reflected pressure of *8.70 psi* (*60 kPa*), positive phase duration of *15 milliseconds* (*ms*), and reflected impulse of *43.54 psi-ms* (*300 kPams*). This is equivalent to the hemispherical detonation of *74.8 lbs* (*34 kg)* of TNT at stand-off distance of *69.3 ft* (*21 m*). Figure 3 shows a series of frames taken from the high speed video of the test. Each frame is labelled by the amount of time, in milliseconds, after the arrival of the shock front. As predicted in the analytical model, the strengthened wall was undamaged during the test and retained its crucial load bearing capacity. The strengthened wall did not form any projectiles and the timber studs and end connections did not suffer any appreciable damage. The as-built wall failed in a combined flexure and fastener pull-out failure mode. This caused the majority of the wall to form a single projectile, shown in Figure 3 (d), which traveled over *19.8 ft* (*6 m*) before impacting the concrete wall of the test laboratory. The wall velocity was measured as approximately *26.5 ft/s* (*8 m/s*) at *100 ms* after the shock front arrival. Clearly, the results of this test have confirmed that this strengthening system can effectively increase the blast-resistance of exterior stud walls.

(a) *0 ms* (b) *14 ms* (c) *46 ms* (d) *100 ms*

Figure 3: Response of Strengthened (left) and As-Built (right) Walls at Various Times After Shock Front Arrival.

Market Analysis

It is difficult to place a dollar figure on the market size of blast resistant retrofit technologies due to the classified nature of national defence. However, a large number of civilian and government timber structures in North America are at an elevated level of risk of being subjected to blast loading. As timber does not have the requisite mass, strength or stiffness, no economically viable retrofit system can be designed to mitigate the effects of contact or close in explosive threats to these structures. Our technology is aimed at timber structures that are threatened by distant explosions. It is useful in situations where the defined threat level does not warrant the high cost of a complete structural reconstruction and/or reconfiguration. This strengthening technology gives developers the option to construct or retrofit blast-resistant facilities out of standard, economical and environmentally friendly timber products without sacrificing life safety and protection.

Our expertise and credibility is in research and development of structural and blast engineering technology. We will be applying for patent protection of this technology. The commercialization plan involves partnering with larger, more established engineering firms. Our role in this partnership would be to offer exclusive expertise and technology rights of this strengthening system. Our partner would benefit as they can leverage the exclusive use of this economical and effective technology to obtain more business. Facilities protected by this system will have abated their blast risk at minimum cost while still being able to employ traditional construction methods.

As innovators, we benefit financially from this business relationship by charging a fee (either on a per unit or per job basis, or perhaps as a general technology license) for the use of our technology.

Industry Analysis

Currently there are two alternatives for strengthening existing wood construction: replace wood components with alternate materials, such as steel; or use composite materials, such as fibre reinforced polymers (FRP), to retrofit individual studs. The first option is time consuming, expensive and invasive. The second option has several challenges including: the need for specialized labour; difficulty providing continuity between the wall and the floor; limited strength gains; high cost; and the high likelihood of damage to the fibres during placement of drywall and interior finishing. For new construction, if there is a need for blast resistance, the structure will likely be built out of a different material. It is possible to achieve high levels of resistance using reinforced concrete or structural steel. Both of these building materials are substantially more expensive, require more time for construction, and require more specialized labour than wood construction. Other techniques for mitigating the risk to life safety in the event of a blast include limiting access to the structure and increasing the standoff distance between the source of the explosion and the facility. One of the primary benefits of our strengthening system is that timber building materials can now be used to construction effective blast-resistant structures.

We anticipate that this technology will be ready for use in actual structures within one to two years time. A prototype has been developed and successfully tested under realistic conditions. Further shock tube testing will be performed in rapid succession, with up to three full scale tests per week. This testing, coupled with strong analytical modeling techniques, will fully validate the use of this technology within six months time. Once the technology has been fully developed, the expected raw material and manufacturing costs will be between *$60* and *$100* per strengthened structural member. This cost can decrease with large scale manufacturing. The design methodologies have already been established and present no real per unit cost.

Recommendations

Continued research and development is required to bring a safe and effective technology to market. To date, this project has been funded by the Government of Canada, although further sources of capital are required to continue development. One source of funds actively being explored is to partner with the University of Ottawa's Office of Technology Transfer and Business Enterprise. This office has a mandate to facilitate the commercialization of technology developed using university facilities and can assist in securing funding sources. We anticipate that approximately *$50,000* to *$100,000* is required to complete experimental research to the degree that this technology would be ready for implementation. This research cost includes modifying the hanger-tension rod system so that other wood products, such as double or triple studs and laminate beams, may be strengthened. Concurrent with the continued experimental research, we will apply to patent the technology. The cost of this patent will be shared amongst the researchers and the University of Ottawa.

References

[1] Burrows, J. "Canadian Wood-Frame House Construction," Third Edition. Canadian Mortgage and Housing Corporation (CMHC); 2005.
[2] CSA O86-09, "Engineering Design in Wood," Canadian Standards Association, Mississauga, Ontario, Canada; 2009.
[3] Lloyd, A., Jacques, E., Abdelalim, O., Saatcioglu, M., Braimah, A., and Doudak, G. "High Strain-Rate Effects on the Dynamic Material Properties of Wood Beams," 2nd International Engineering Mechanics and Materials Specialty Conference, Canadian Society for Civil Engineering, Ottawa, Ontario; 2011 (Accepted to proceedings).
[4] Lloyd, A. "Performance of reinforced concrete columns under shock tube induced shock wave loading," Master's thesis, University of Ottawa, Ottawa, Ontario; 2010.
[5] Lloyd, A., Jacques, E., Saatcioglu, M., Palermo, D., Nistor, I., Tikka, T. "Capabilities and Effectiveness of using a Shock Tube to Simulate Blast Loading on Structures and Structural Components", ACI Special Publication on Performance of Structures Subjected to Blast. American Concrete Institute; 2010 (Accepted for Publication).