Strategies for the Repair and Re-use of Unreinforced Masonry in Eastern Canada

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Keywords: Retrofit, Timber, Masonry, Building Structures

Unreinforced masonry (URM) buildings constitute a substantial percentage of existing structures across the Northeastern United States and Eastern Canada. While some of these structures have remained in continuous use as residential structures, many of those built for non-residential purposes do not conform to contemporary building guidelines or design codes. They often have inadequate resistance to lateral loading due to low-intensity earthquakes or settlement. With progressive material deterioration over decades and a frequent lack of maintenance, retrofitting of these structures is often necessary for continued occupancy and adaptation for new uses.

Many retrofit systems use steel and concrete to supplant existing masonry walls and create auxiliary or substitute loadbearing systems to handle both vertical and lateral loads. In such cases, masonry elements are retained for historic or aesthetic value, but they are largely superseded by a new structural frame. This approach is invasive, materially intensive and costly, and it is seldom suitable for most URM buildings, particularly the workaday (non-listed) buildings that are frequently taken out of use. By taking an alternative approach, the research here aims to repurpose existing masonry buildings that are unlikely to be preserved for architectural value alone. These anonymous structures account for a large quantity of the material and energy embodied in current building stocks, and extending their service life has substantial benefits from carbon emissions and urban regeneration to heritage and housing supply.

Across North America, a widespread shortage of housing continues to be a defining feature of many cities, and in Canada, the situation has grown especially severe. Rental and ownership costs have risen substantially in recent years, leaving many citizens in financially precarious circumstances and contributing to increased rates of homelessness in major cities. Unfortunately, the root causes of this crisis go well beyond building design. While architects and engineers work to improve affordability through spatial efficiency, material reductions and streamlined construction, the costs of new construction are often governed by forces beyond our control. In this context, even well-intentioned efforts at new housing development can lead to sprawling development, low-quality construction and characterless design.

However, improving the affordability and quality of housing need not be limited to new construction. The potential of existing buildings in many cities remains significant, and strategies for repair and re-use have potential to expand housing supply and reduce costs by capitalizing on investments in material and energy that were made decades ago. Here the authors introduce the first phase of a continuing research project funded by the Canada Mortgage and Housing Association to develop and experimentally validate strategies for retrofitting existing buildings across Eastern Canada. Led by specialists in architecture, building physics, structural design and computational analysis, the project focuses on masonry buildings that are often underutilized or vacant due to changes in use, location and lack of compliance with current codes. As such, the work has broad applicability to cities in Eastern Canada and the Northeastern United States. Extending the working life of these existing buildings for even a few decades has the potential to increase the number of housing units in urban areas and supports the wider effort to improve quality and affordability of housing.

REPAIR, RECONSIDERED

The research here focuses particularly on the eastern provinces of Québec and Ontario, where more than 60% of the Canadian population lives (22% Quebec, 39% Ontario), many of them in the metropolitan regions of Montreal, Ottawa, Toronto and Québec City.[1] Not only are these some of the densest urban agglomerations in the country, they also contain the nation's oldest building stock.[2] The majority of these aging structures remain in active use and are subject to regular repair and maintenance, but thousands have fallen into disrepair and now sit partially or fully vacant. In Montréal alone more than 3000 buildings are unoccupied and awaiting demolition or refurbishment.[3] Many of these structures are built from unreinforced masonry (URM), bearing walls of stone or clay brick that have been assembled without supplemental steel or iron. As such, they are vulnerable to natural hazards like earthquakes, floods and differential settlement,[4] many of which are exacerbated by the elastic properties of local subgrade soils present across the region.[5] Along the

Ottawa and St. Lawrence river valleys, these risks are especially concerning given the threat of moderate seismic activity[6] and changing patterns of seasonal precipitation.[7]

The URM buildings in this area are generally *no-code* or *low-code* structures, meaning that they were constructed long before the introduction of robust national seismic provisions in 1960.[8] These broad categories accounts for a wide range of buildings with varying degrees of architectural and historical significance. Most remarkable examples have already been recognized, protected and restored, but many workaday structures remain in a state of ambiguous definition. While these buildings do not rise to a level of historical significance demanded for conservation, they are recognized – and sometimes protected – for their important role in the urban milieu. Rather or not such buildings remain in use, obtaining permission to demolish them can be difficult, and repurposing them poses significant challenges. With small footprints and modest spans, URM residential buildings such as the duplex and triplex types common throughout the region have a low likelihood of failure. Structural collapses can occur, but periodic maintenance, repair and upgrades allow these buildings to continue playing an important role in housing for urban centers.[9] However, the large floor areas, wider spans and taller floors of industrial and commercial buildings are more challenging.

The National Building Code of Canada (NBCC 2020) requires that major renovations and/or changes of use to existing buildings bring them up to contemporary standards for both structural and energy performance. Partly for this reason, current practices for the conversion of non-residential URM buildings are labor and material intensive. Typical approaches often use a steel or reinforced concrete frame to supplant existing masonry walls and create a new loadbearing structure withing the existing building envelope. In such cases, new systems are designed to accept all vertical and lateral loads while masonry facades are retained only for historic or aesthetic effect.

This approach is less a matter of repair or re-use than a means of creating a new building within an existing shell. Setting aside concerns of authenticity or *façadism*, the practice poses substantial economic challenges. Building a new building inside an existing shell is costly and is only carried out in sites where the value of the existing land or building is very high. As such, it is rarely applicable to buildings and sites of modest value, where the possibility for return on such an investment is limited. This paradigm leaves few options for owners of buildings on less valuable sites. In many such cases, buildings are left to sit empty, initiating a downward spiral of deterioration that leads eventually to demolition.

Given this state of affairs, it seems reasonable to ask if this is the only path available? Life safety remains paramount, but it need not be confused with the structural longevity. New buildings should be designed to resist and recover from structural damage, but this is not necessarily the case for older structures that have already existed for more than a century. In these cases, it may be more useful to consider repair as an interim solution. The American Society of Civil Engineers recognizes multiple categories for structural performance, including S-3 (ASCE 41-23) which defines safety in relation to a post-calamity state in which a structure has damaged components but retains a margin against the onset of partial or total collapse. Framed in this way, it may be possible to extend the useful life of URM buildings and ensure the safety of their occupants while accepting that they may no longer be recoverable after a seismic event or major settlement.

The Canadian Commission on Building and Fire Codes has already recognized that current frameworks limit the number of renovations undertaken in Canada and is seeking to make building renovation a priority for the 2020-2025 development of the National Building Code of Canada. Following the guidelines set out by their report, the repair and alteration of buildings should prioritize affordability, life safety and sustainability. Rather than supplanting existing systems with a new structural frame, the solution we propose is to capitalize on the vertical load-bearing capacity of URM walls and supplement these with a low-stiffness system of reinforcement that increases in-plane lateral resistance and controls the mode of failure under lateral loading. If this alternative approach can be achieved at lower cost than typical solutions, it has the potential to be applied to a broad range of existing buildings and contribute substantially to their re-use for residential purposes.

CASE STUDY: 3558 RUE SAINT PATRICK

Departing from the ambitions outlined above, the team set out to locate a building that could serve as a viable test case for the material, architectural, structural and urban conditions of the project framework. This lead to the identification of a former industrial building in Montreal, now owned by the City of Montreal and used as a part-time office space. Located on Saint Patrick Street, near the Lachine Canal, the building sits in a developing area of the city alongside similar industrial buildings with comparable brick construction. The largest of these buildings have already been converted to office and housing via extensive renovation, but many structures of smaller size remain vacant or partially in use.

The team initiated work by characterizing the spatial and material composition of the building. Using a stationary drill and carbide coring bit, samples were extracted from the masonry walls of the structure and transported to the lab for analysis. Values for compressive strength of the brick and mortar then served as reference points for the construction of test walls in the lab.

At the same time, the team conducted an extensive laser scan of the interior and exterior of the building, collecting data was then used to create point cloud models. In addition to these high-resolution scans for the geometry of the walls, openings and

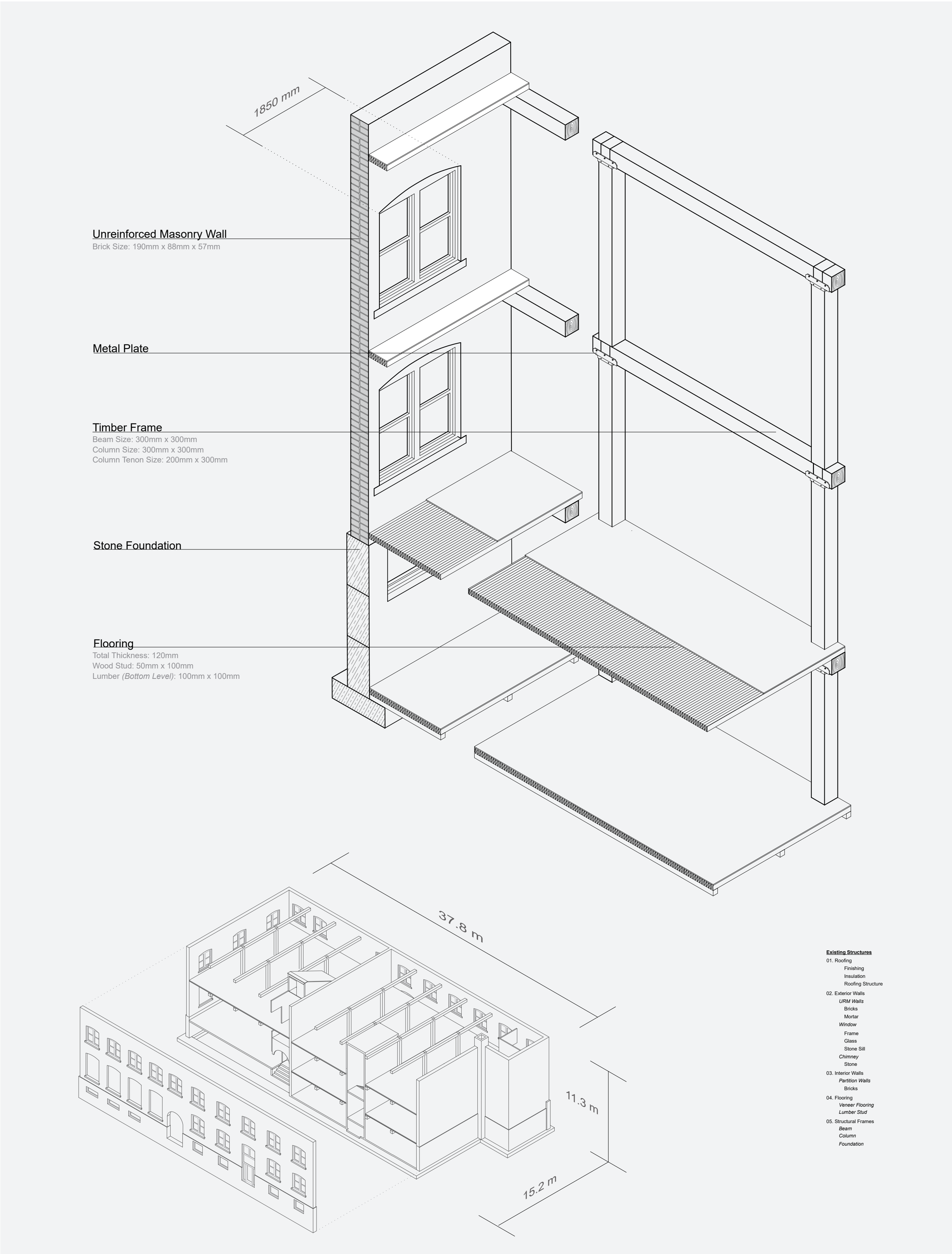

Figure 1. Case study building at 3558 Rue Saint Patrick in Montreal, QC. Drawing by Yifan Xie.

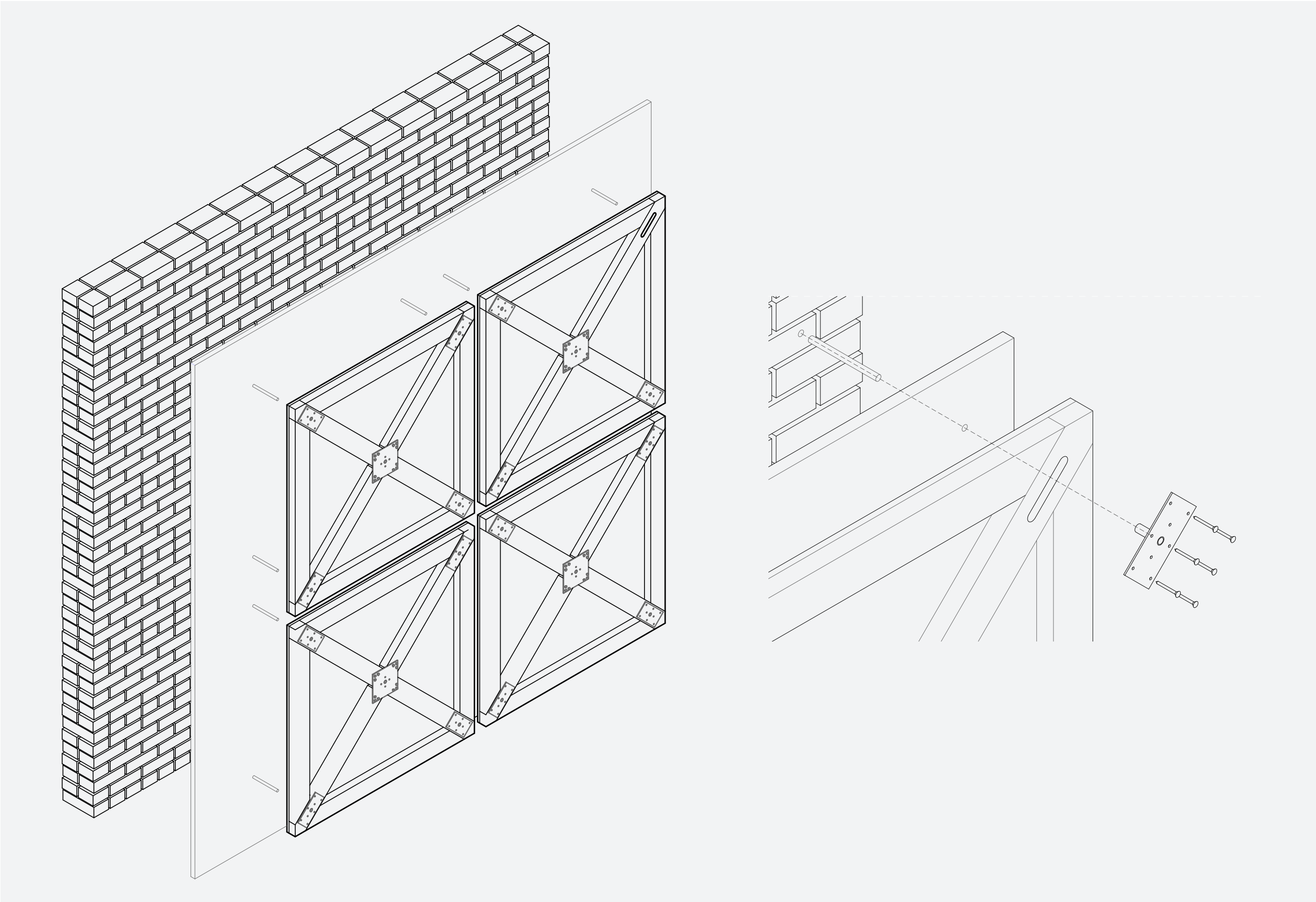

Figure 2. Application of panels to the URM wall using custom connector plate. Drawing by Philip Tidwell.

structural features, photography and photogrammetry were used to survey the interior and document notable conditions including pocketed beams and structural connections between the heavy timber framing and masonry walls. Synthesis of these various forms of information proved challenging. Although laser scanning was able to produce a highly detailed study of the walls and interior, materials differences were not always legible and structural features such as beams and walls were not always distinguishable from furnishings such as lockers and cabinets. While useful as a reference, the point cloud models were supplemented with a more conventional 3d NURBS model that incorporated critical points and dimensions while eliminating unnecessary features and inaccuracies from scanning.

PANEL DESIGN

Based on the dimensions of the existing building and on assumptions of structure performance, the system is based on a series of prefabricated panels based on standard plywood which are combined with dimensional lumber to improve lateral loading and out-of-plane buckling. Standard modules of 1.2 x 2.4 m (4 x 8 ft) and 1.2 x 1.2 m (4 x 4 ft) serve as the basis for the design, but can be adjusted to accommodate geometric conditions such as corners, windows and beams. In this way, the system aims to maximize the use of standard sheet materials while fitting comfortably within the fenestration pattern of the existing building.

The patterns for lateral bracing position are dimensions so that the sawn timber bracing elements are positioned between 35 and 55° to the panel edge, maximizing their resistance to lateral load. In the center of the panel, four diagonal members are discontinuous with and aim to limit buckling under compression. The bracing and perimeter profiles are fixed to the base plywood using adhesive and screws (#8 @ 4-5 in OC). This allows for fabrication using standard dimensions and equipment, and the use of interchangeable components allows for rapid production in large quantities. At the scale of the building, the panels are placed adjacent to one another across the interior surface of the perimeter walls, forming a nearly continuous surface across the URM structure.

In order to strengthen the wall, the panel must be firmly engaged with at least two wythes of brick through chemically fixed steel anchors. To distribute force through these anchors to a large area of the panel, a steel washer or plate is used to fix the panel to the anchor. Initially, a standard sawtooth washer was meant to be pressed into the wood panel before it was attached to the wall. However, this system allowed minimal tolerance when

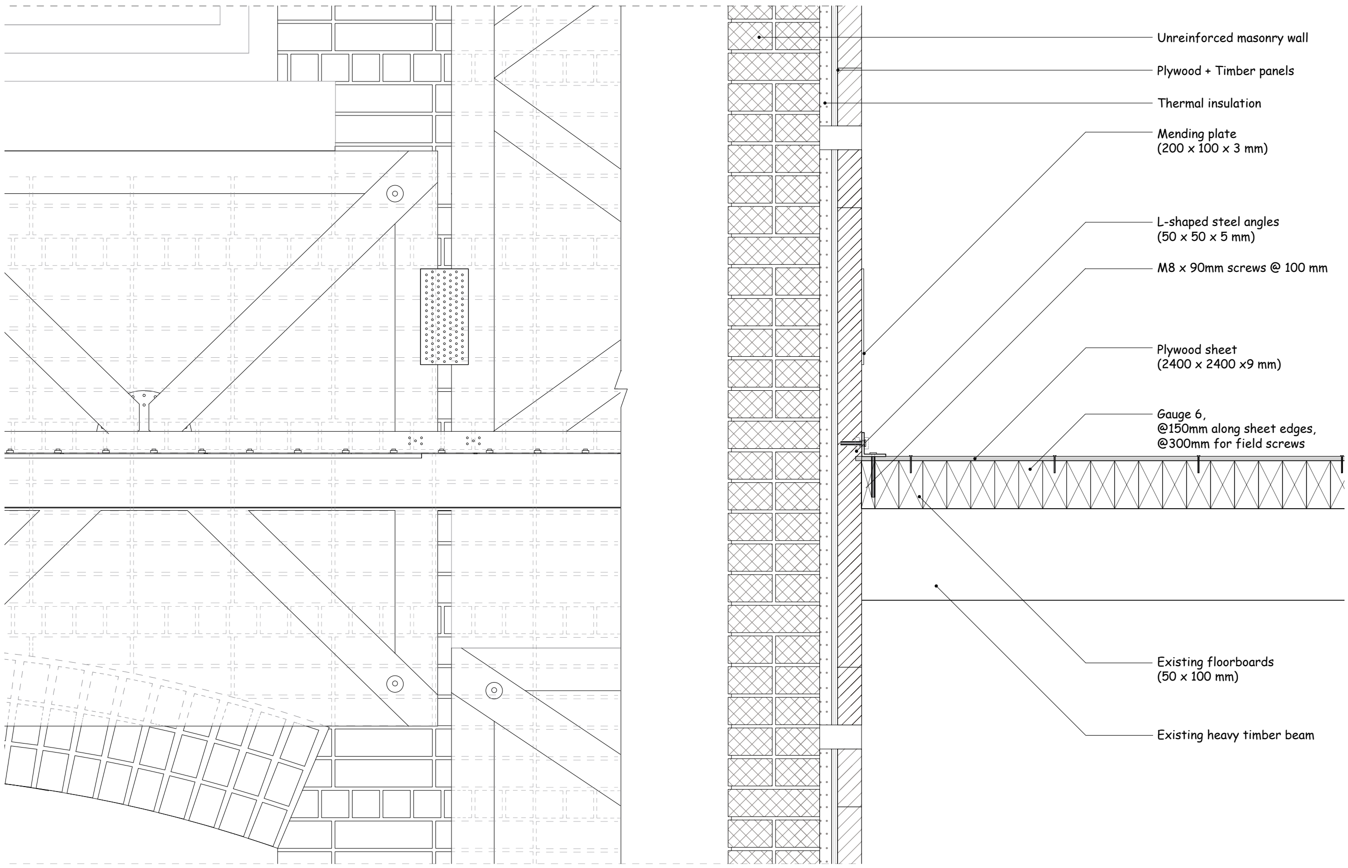

Figure 3. Elevation and section showing the attachment of structural panels to URM walls and timber floors. Drawing by Yifan Xie.

mounting the panels. A new plate connection was devised so that the connectors could be applied after the panel was hung on the wall. The revised connection allowed a slot to be cut in the panel to increase tolerance when mounting. Rather than being pre-installed in the panel, this plate is screwed in place after the panel is hung on the wall anchor.

STRUCTURAL TESTING AND SIMULATION

Preliminary structural tests were performed on six URM walls (1.2 x 1.2 x 0.2 m3) built to identical specifications. The specifications for the walls were based on data from earlier surveys and analysis of samples taken from the Saint Patrick Street building. The physical properties of 100-year-old clay bricks could not be easily matched, but approximate specimens were selected based on contemporary samples. Matching the properties of the lime mortar proved more challenging. Historical data could give a rough approximation of the original mixture, but 100 years of environmental exposure would be difficult to approximate. To overcome this problem, the team developed an analogous sample using cementitious mortar (Type-O), which was weakened incrementally through the addition of sand until its physical characteristics were comparable to sampled specimens. The final mix used 15% additional sand.

All test walls were constructed by professional masons using Glen-Gery solid handmade clay bricks, then cured for a minimum of 28 days. Two walls were used as control specimens while two walls were fitted with wood panels and two more were fitted with wood panels and surface-mounted steel rods for additional reinforcement. Following the testing standard ASTM E519, structural tests were performed to simulate the effect of earthquake or settlement condition by applying diagonal compressive load to each wall on opposing corners. For practical reasons, the setup departs slightly from the test standard, which calls for a 45° rotation of the walls. Overall, a total of 58 characterization tests on masonry, bricks and mortar were carried out, plus 45 on timber. Detailed descriptions of testing methods and related standards are provided in a separate paper.

Typically, this sort of diagonal tension failure yields at minimal drift capacity, which is to say the smallest amount of lateral displacement that the wall can withstand before significant damage is incurred. The test is thus characterized by a sudden drop in force as the specimen reaches its ultimate lateral load. In practical terms, this sort of failure provides little warning before catastrophic collapse, leaving insufficient time for occupants to evacuate. Notably, in these tests, walls to which the retrofit had been applied demonstrated progressive sliding failure, and

Figure 4a. Construction of test walls in the McGill lab.

Figure 4b. Panel and diagonal test rig applied to test wall.

avoided the explosive collapse that was seen in all un-retrofitted specimens. This delay of abrupt failure in lateral resistance is desirable for building evacuation and is promising in terms of life-safety goals per ASCE 41-17.

Following laboratory tests, the team developed computational simulations of the same configuration using Distinct Element Method (DEM) in the commercial analysis platform 3DEC. This approach was chosen over Finite Element Method (FEM) for a number of reasons. While FEM models are effective in dividing large components into smaller shapes for analysis, the structural behavior of a URM wall is far less consistent than large elements in wood, concrete or steel. By contrast, DEM models allow for discontinuum-based analysis, which represents the wall as a system of discrete blocks that interact along individual boundaries. The forces between these separate blocks are predicted following the point-contact hypothesis, in which three orthogonal springs are defined at each point of contact, one in the normal and two in the shear direction.

THERMAL ANALYSIS

In addition to improving structural performance, the retrofit system is meant to concurrently improve thermal capacity (per the National Energy Code of Canada for Buildings) with an aim of bringing existing brick walls up to a thermal resistance of +/- R22. In the cold regions of Eastern Canada this is no simple task. As anyone who has engaged with brick buildings and wood structures knows, moisture damage with interior retrofitting is a common problem, and full-scale testing is necessary to prove that the system can withstand extended exposure to cold and humid conditions.

To address these issues, preliminary tests of the retrofit were designed and tested using wood fibreboard insulation panels. After the structural panels are anchored to the masonry wall, wood fibreboard is installed directly against the plywood/timber panel and air sealed with caulk and tape. Two layers of wood fibreboard are then applied, each layer 38 mm (1.5”) thick with a thermal resistance of 0.713 m2·K/W (4.05 ft2·°F·h/BTU). As the wood framing is also 38 mm (1.5”) thick the first layer of wood fibreboard is in-serted into the triangular cavities created by the frame and installed to be coplanar with the wood framing. The second layer of wood fibreboard is installed over both the wood framing and first layer of wood fibreboard to reduce thermal bridging. 12 mm (1/2 in.) thick gypsum wall board is installed over the wood fibreboard as the interior surface. The unreinforced original masonry wall is estimated to have a total thermal resistance value of 0.3667 m2·K/W (2.0822 ft2·°F·h/BTU). The retrofitted wall assembly with wood reinforcement, 76.2 mm of wood fibreboard insulation, and gypsum wall board is estimated to have a total thermal resistance of 1.8667 m2·K/W (10.6028 ft2·°F·h/BTU).

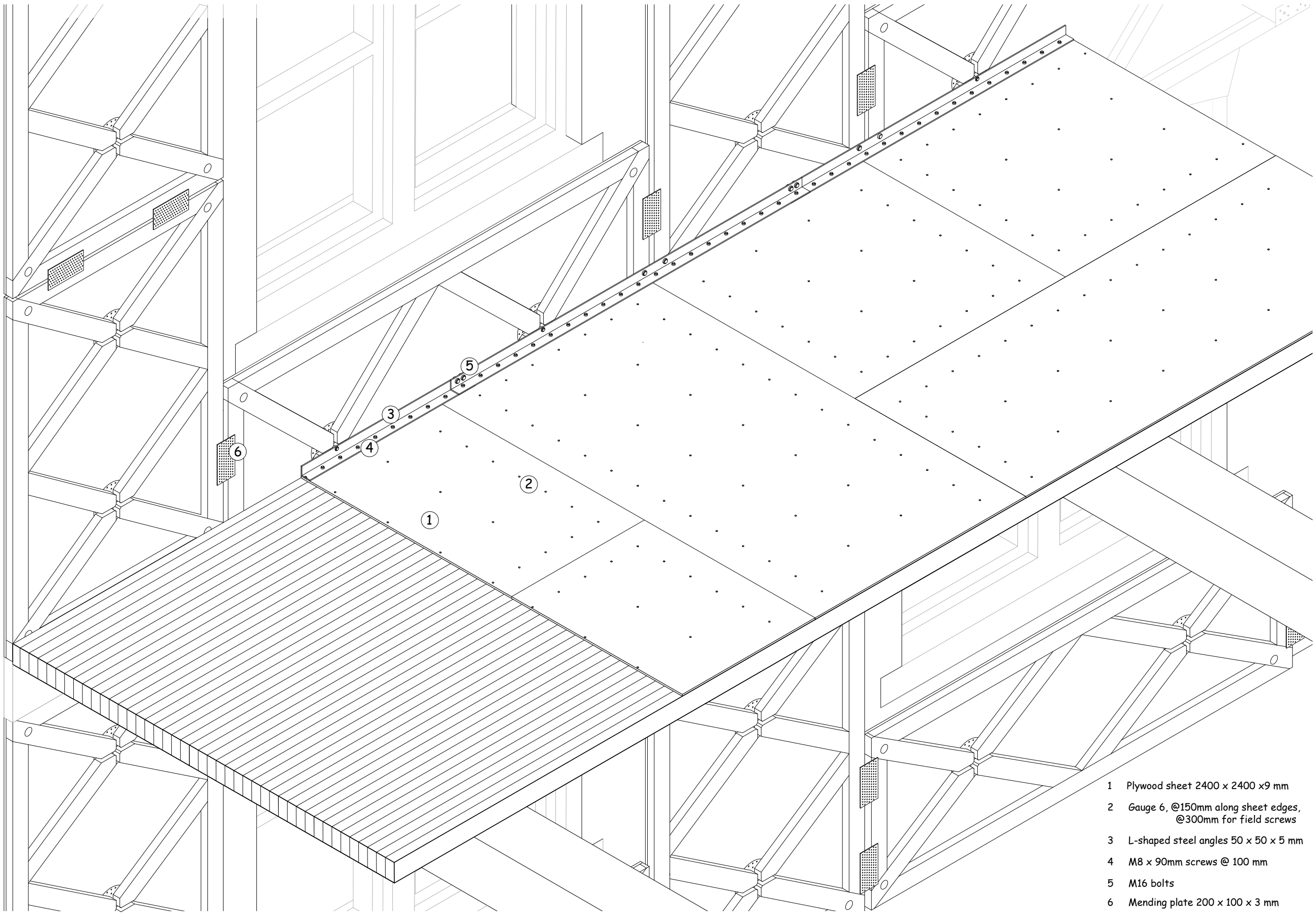

Figure 5. Implementation of the system including connection to existing floor plates. Drawing by Yifan Xie.

These thermal resistance values were determined through physical testing with a guarded hot box (ASTM C1363) and simulation modelling using THERM 7.8. The physical and modelled results demonstrated that the retrofit with two layers of fibreboard insulation improves the thermal resistance of the assembly by over 400%. Further design, analysis, and testing is now underway, with an ambition to achieve an assembly thermal resistance of ca. 4.0 m2·K/W (22.7 ft2·°F·h/BTU) and meet moisture performance criteria (ASHRAE standard 160-2021).

CONCLUSIONS

Preliminary investigations into this novel method of light-timber retrofitting of unreinforced masonry (URM) buildings have been fruitful and yielded many encouraging results. Both numerical and experimental validation demonstrate that potential exists for a low-cost system that can effectively prevent catastrophic failures during seismic events, without wholesale replacement of the building structure. Experimental results show a significant increase in structural performance compared to un-retrofitted walls, and an ability to meet life-safety goals per ASCE 41-17. Structural modeling further validates the retrofitting approach, with good agreement between the Distinct Element Method (DEM) models and the experimental findings for both retrofitted and un-retrofitted masonry walls. In terms of thermal performance, the use of wood fibreboard insulation panels in the retrofit is shown to substantially improve the overall thermal resistance of the URM walls. Both physical testing and simulation modeling confirm the effectiveness of thermal retrofit, with a notable increase in thermal resistance.

Ongoing research and testing will aim to further optimize the retrofit design and confront the evident challenges of applying the system at building scale. These findings contribute valuable insights to the field of conservation and re-use with potential for widespread implementation that may improve structural integrity and energy efficiency while potentially allowing a lower barrier to entry for re-use and repair of existing buildings.

P A P E R

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