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DEVELOPING AN APPLICATION FOR MASS PLYWOOD PANELS IN SEISMIC AND ENERGY WALL RETROFITS

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University of Oregon and Oregon State University are collaborating through the TallWood Design Institute (TDI) to upgrade aging multi-family housing, which is energy inefficient and does not meet current code lateral force resistance, by developing a mass ply panel (MPP) façade retrofit panel assembly that employs digital workflows and small diameter logs (down to 127mm) to create an economically viable energy/seismic retrofit model for the West Coast of the United States (U.S.) and beyond. The design and testing of the retrofit panelised system for upgraded energy and seismic resilience of existing light-wood-frame multi-family housing stock were completed at TDI's Emmerson Laboratory for a full-scale one-story mock-up. The research program includes structural and energy performance design, and benchmarking of digital to physical workflows and construction methods. The next iteration is a three-story prototype fabricated by a commercial contractor to validate the design, scanning techniques, fabrication, construction, and cost models resulting from the initial prototype construction, with the intent of commercializing designs for immediate adoption.

KEYWORDS: Seismic Resilience, Energy Upgrades, Retrofits, Mass Plywood Panels

1 INTRODUCTION

In the past decade, humans have witnessed the convergence of global, regional, and local natural and human-made crises. On the U.S. West Coast, extreme weather events, forest fires, and power outages have exposed millions of Americans to the loss of life, property, and livelihood. Skyrocketing housing prices have depleted the market of available housing that is affordable, exacerbating social inequities and homelessness [1]. Moreover, reductions in timber harvest have depressed rural manufacturing and economic development. Therefore, the building design and construction industry, manufacturing, and government agencies are working to respond to multiple crises simultaneously by developing creative solutions to multifaceted problems.

The U.S. Forest Service has responded to extreme forest fires with healthy forest initiatives [2] that include selective harvesting of small-diameter trees to reduce fuels and wildfire risk; however, this form of harvesting is labour intensive, costly, and the resulting harvest of small-diameter logs has low market value [3], resulting in this wood fibre being commonly sold for products that have only short-term biogenic carbon storage (e.g., paper, biomass fuel), thus, reducing the climate benefit of wood to sequester carbon dioxide. Thus, there is great interest in finding higher value utilization of small-diameter logs that provide long-term carbon sequestration in building materials.

At the same time, local, state, and federal investments in energy efficiency and decarbonization have been increasing. At the local level, the City of Portland, Oregon created and approved in 2018 a unique funding stream to support climate action by providing clean energy home upgrades and associated jobs to vulnerable communities [4]. The fund, called the Portland Clean Energy Fund (PCEF), initially anticipated local investments of USD 44-61 million annually [5]; however, in 2022, the fund made its largest award of USD107 million to 65 projects fighting climate change [6]. The State of California is also aggressively pursuing an energy code to achieve zero net energy to mitigate climate change. The California Energy Commission is advancing novel energy efficient technologies through Electric Program Investment Charge (EPIC) funding to develop and commercialize

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deep energy retrofit solutions for existing buildings [7]. In August 2022, the U.S. Congress passed the Inflation Reduction Act, which includes USD369 billion for energy and climate resilience, targeted at building decarbonization, energy efficiency, and affordability [8].

In the U.S., buildings account for approximately one-third of carbon dioxide equivalent emissions each year [9]. Moreover, existing low-rise multifamily building stock is ubiquitous and much of it is affordable but also aging and not climate resilient. According to the Northwest Energy Efficiency Alliance (NEEA) Residential Building Stock Assessment, 88% of this housing stock in the Pacific Northwest is one- to three-story light-wood-frame and was constructed between 1960-1994 with very low wall insulation levels (64% had R8-R12 wall insulation) [10].

While urgent, the focus on building energy and decarbonization does not address the other critical West Coast need for seismic retrofits for pre-1990's era buildings [11]. In Oregon, the building seismic code has evolved since the 1970s to include a better understanding of seismic risks and associated base shear forces, beginning at 5% in the 1973 Uniform Building Code (UBC) [12], slowly ramping to 16.41% in the 1997 UBC following an initial understanding of the Cascadia Subduction Zone risk, and back down to 11.30% in the 2003 International Residential Code (IRC) [13]. Unfortunately, the preponderance of existing multifamily housing units in the Pacific Northwest was constructed well before the increased base shear code requirements ramped up in the 1990s [10]. Moreover, many low-rise multifamily buildings typically found in this housing group include a soft story, such as open bays without horizontal bracing or shear walls to accommodate parking at the ground level, further escalating the urgency of seismic retrofit.

Although there is increased recognition of the need to address multifamily housing climate and seismic resilience in the Pacific Northwest, the states of Oregon and Washington currently do not require these upgrades and there has been resistance to making these retrofits mandatory due, in part, to their construction costs and potential for tenant displacement. Prevailing seismic upgrade techniques often require extended building vacancy or at least significant occupant disturbance, which cannot be tolerated in an environment of housing scarcity. In fact, due to years of housing underproduction on the U.S. West Coast, Oregon alone predicts that it will need 584,000 new homes over the next 20 years [14]. To meet that goal, existing housing must be maintained, in addition to creating new housing units. Therefore, there is an urgent need for cost-effective, low-impact energy and seismic upgrades to extend the useful life of this critical housing stock.

Housing projects in Europe have begun to address deep energy upgrades with minimal tenant disturbance using prefabricated façade retrofits. For example, the *Energiesprong* [15] method developed in the Netherlands employs a technique of digital scanning of existing facades and using these scans to fabricate new façade systems off-site, complete with insulation, high-performance windows, doors, and cladding. Since the panelised systems are manufactured in a factory, fabrication can employ digital workflows, such as computer numerical control (CNC) machining, with high environmental and quality control over the manufacturing process. The resulting products are then applied over the existing facade with minimal time and occupant disruption on site.

While the *Energiesprong* method provides many lessons for the U.S., deep energy façade retrofits on the West Coast must also contend with seismic activity; adding an increase of 10% to an existing building's weight in an insulative wall system triggers seismic upgrade requirements in many jurisdictions. The mass ply panel (MPP) system that is described in this paper is a building assembly that could provide for both energy and seismic resilience while minimizing occupant disturbance with few necessary interior disruptions through off-site prefabrication. MPP, developed in rural Oregon by Freres Engineered Wood, is a veneer-based mass timber panel that utilizes small diameter logs (down to 127 mm), which can be sourced from healthy forest initiatives, thereby making forest restoration products more economically viable while providing a building product that supports the housing industry. Since panels are available in nominal sizes as large as 3.7 m x 14.6 m with thicknesses starting at 52 mm and increasing by additional lamella thicknesses of 26 mm, there is a wide range of flexibility for their use as secondary facade systems.

The estimated total available U.S. multifamily market for the MPP panel system is close to 18 million housing units [16]. Even narrowing this to the serviceable available market (California/Oregon/Washington region, pre-1990 construction in a high seismic zone, not previously upgraded seismically), there are slightly more than 3 million housing units. By employing MPP that are 52 mm to 78 mm thick using an efficient process of prefabrication with digital workflows, retrofit wall panels spanning one- to three-stories can be efficiently constructed and provide both energy upgrades and seismic resilience to aging multifamily housing.

The project is a collaboration between the University of Oregon (UO)'s Energy Studies in Buildings Laboratory and Oregon State University (OSU) through the TallWood Design Institute (TDI), a collaboration between UO's College of Design and OSU's College of Forestry and College of Engineering that advances engineered timber products and their application through research and testing. This project demonstrates a system of prefabricated panels built with MPP that can be rapidly applied onsite over existing building cladding to upgrade older light-wood-frame one- to three-story buildings to meet or exceed current energy and seismic codes.

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2 METHODS

To develop the panelised wall system, we divided the project into discrete phases: *predesign, structural design, envelope design*, then created an existing condition mock-up to test digital workflows during *panel fabrication and construction.* Structural connection and envelope details were developed over a series of iterations and a full-scale mock-up resulting in construction and assembly details.

2.1 PRE-DESIGN

At the outset of the project, we surveyed the morphologies of pre-1990 multifamily housing in Portland, Oregon USA to characterize common aspects of building, site, and existing utility infrastructure that would impact or even preclude a façade retrofit. We found predominantly two-story light-wood-frame structures with repeated stacked housing units and regular façade elements, such as window size and placement. Concrete stem wall foundations with a shallow crawlspace were most common, though slab-on-grade was found as well.

Often units were sited with priority given to on-site vehicle surface parking, leaving limited lot building setbacks and minimal landscaping. Access to upper-floor units is typical via exterior stairs with circulation zones occurring either between sets of units or by incorporating an outdoor walkway in front of units.

Electrical service in the area is from overhead power lines but is brought to larger multifamily structures below grade from the street. On-site distribution usually incorporates an exterior façade-mounted electric meter for each unit. Natural gas service is not typical for this housing typology in this location in Portland, Oregon. Additional façade penetrations may include exhaust fan venting, which predominantly occurs through the roof, but can be found located at the façade for ground floor units.

Figure 1: *Visualization of case study multifamily building used for façade retrofit study, pre-retrofit*

The case study building selected, pictured in Figure 1 and detailed in Figure 2, offers an example of typical existing multifamily construction found in the study region while also representing a reasonable candidate for façade retrofit. Exterior circulation occurs between units, leaving the façade unobstructed by walkways or other large overhangs. Window openings are large, but sufficient two-story wall area remains between openings to locate full-height shear panels. Furthermore, the building is set back sufficiently far from the property line, so additional wall thickness will not encroach into the setback zone.

The central on-site parking area offers a straightforward staging and crane location, eliminating the need for crane access from multiple street frontage locations or over other structures not involved in the retrofit. The location of electric meters, distribution conduit, and exhaust vents, though spread across the structure, are all found on the façade opposite the parking area, which minimizes the continuous lineal footage of the façade where services will need to be factored into more complex retrofit panel design and installation.

2.2 STRUCTURAL DESIGN

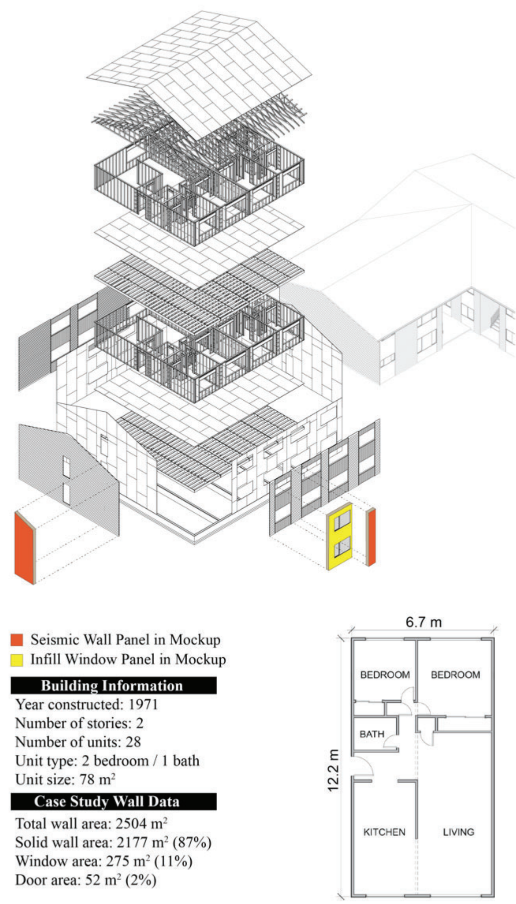

Figure 2: *Case study multifamily building: building information, typical unit design, exploded view of existing light-wood frame structural system, wall area data and panels tested during mock-up.*

With the focus of structural design on the development of a façade retrofit lateral force resisting system (LFRS) which incorporates the use of MPP, a foundation upgrade

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was identified early on as a requirement to both account for the added gravity load of the MPP and new façade elements, but also to help resolve concentrated seismic loads delivered through the stiffer and stronger MPP as compared to the conventional plywood shear walls found in existing light-wood-frame structures.

The MPP could be attached to this additional concrete footing which would be tied back into the existing foundation, but a solution would also be required to transfer lateral loads between the existing wood structure and the MPP. At the elevation of each floor diaphragm, as well as at the roof diaphragm, a transition joist was planned to wrap the entire existing building and be securely fastened to the building's existing load-carrying elements. The MPP would then be attached to these transition joists to accomplish the load transfer between the existing structure and the retrofit LFRS.

The entire façade would not need this type of LFRS; infill panels could be used in between these panels and would not require the same level and type of connection. Infill panels could still be designed with MPP to simplify the material palette and assembly complexity.

The lateral resistance provided by an MPP LFRS is expected to significantly reduce inter-story drifts and overall building deformation in the event of a seismic event. This should limit overall damage to the building, including interior finishes, and could shorten the timeline for re-occupancy of light-wood-frame multifamily housing, therefore providing for a more resilient design.

2.3 ENVELOPE DESIGN

The wall insulation of existing pre-1990 multifamily housing in the study region can be assumed to be below the current code requirements of RSI-3.7 for new construction, and the degree to which the walls are insulated is a primary design criterion for a façade energy upgrade. Leaving the existing wall in place minimizes renovation disturbance, and adds the existing insulation value to the overall effective insulation value of the retrofit solution.

With the MPP façade retrofit panel, insulation can be included on either or both sides of the MPP. A natural insulation cavity is created behind the MPP where the depth of the transition joist at each diaphragm location holds the MPP off the existing façade everywhere else. A compressible insulation allows for managing some of the inevitable construction irregularities of the existing façade, such as areas with trim elements protruding or an area being out of true. It also offers a location for new services to be run, should they be required. The depth of insulation added outboard of the MPP can be easily modified in the design phase to meet the energy code needs of a different climate zone or to increase the thermal performance target of the envelope. Table 1 lists a range of performance criteria by level of retrofit target.

Table 1: *Range of Energy Retrofit: Comprehensive, Moderate, Low-Cost and Current Energy Code Standard. [1]Indicates typical existing conditions per NEEA Residential Building Stock Assessment.*

RETROFIT ENERGY PERFORMANCE LEVEL				
	1 (Comprehensive)	**2** (Moderate)	**3** (Low-cost)	**0** (No retrofit)
STANDARD	**PHIUS**	**DOE - ZERO ENERGY READY HOME (ZERH)**	**OREGON CODE (2021 ORSC)**	**TYPICAL EXISTING CONDITIONS[1]**
WALLS	**RSI-8.3**	CZ 4-5: **RSI-3.5** OR **RSI-2.3 + RSI-0.9** CZ 6: **RSI-3.5 +0.9** OR **RSI-2.3 + 1.8**	**RSI-2.6** (EXISTING) **RSI-3.7** (NEW)	**RSI-1.4 – RSI-2.1**
CEILING	**RSI-15.7**	CZ 4-6: **RSI-8.6**	(EXISTING) **RSI-3.7 – RSI-8.6** (NEW) **RSI-5.3 – RSI-8.6**	**RSI-5.3+**
FLOOR	**RSI-9.0**	CZ 4-6: **RSI-5.3** SLAB CZ 4,5:**RSI-1.8,** 61cm CZ 6:**RSI-1.8,** 122cm	(EXISTING) **RSI-4.4 – RSI-5.3** (NEW) **RSI-5.3** (SLAB EDGE) **RSI-2.6**	**UNINSULATED SLAB**
WINDOWS	**U-0.91** OR LESS	CZ 4-6: **U-1.53** CZ 4C & 5: **U-1.70**	**U-1.48** OR LESS	**SINGLE PANE ALUMINUM TYPICAL**
DOORS	**RSI-1.8**	**NO REQUIREMENT**	**U-1.14** WITH <= 0.23 m^2 GLAZING **U-2.27** WITH >= 0.23 m^2 GLAZING	**NO REQUIREMENT**
INFILTRATION	**0.30** L/s50/m2 ENVELOPE AREA	LESS THAN **3 ACH 50**	LESS THAN **3 ACH 50**	**NO REQUIREMENT**

New windows offer the most tangible feature of energy upgrades for occupants through perceptibly improved thermal comfort. Installing them in the MPP retrofit panel in the factory as part of a prefabricated façade assembly allows for greater quality control and speed of on-site installation. Existing windows would be removed just prior to retrofit panel installation, and interior finish carpentry would immediately follow the panel installation, minimizing occupant disturbance. The precision CNC fabrication of the MPP also achieves a very predictable tolerance for window rough openings in the panels so that gaps between the window and MPP can be far smaller than site-built rough openings.

Air tightness or infiltration is another key envelope criterion for reducing operational energy use in buildings for heating and cooling. The large format, multi-story MPP limits the number of joints where air leakage can occur. Panel-to-panel joints closed in the field become critical details that need to be executed precisely to achieve anticipated performance.

One concern in covering the existing envelope with new additional enclosure layers is that moisture could become trapped in the combined wall assembly. For this reason, we used WUFI 2D (version 3.4) moisture transmission simulation [17] and analysis for the proposed retrofit solution over an existing wall assembly. All materials were assumed to have an elevated starting water content

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equivalent to 80% relative humidity and the simulation was run for one year with modelled climate and weather. For each material in the assembly and every hour over one year, the duration at a given water content is converted to mould index ranging from 0 - no growth to 6 - 100% coverage with visible growth [18]. Results for all materials demonstrate that moisture is not being trapped in the overall wall assembly at any time, which translates to <1% coverage of microscopic growth. At the conclusion of the one-year simulation, all materials have dried, having a mould index of 0, or no growth.

2.4 EXISTING CONDITION MOCK-UP, PANEL FABRICATION AND CONSTRUCTION

We constructed a full-size mock-up using a corner and window condition from the case study building (Figures 2, 3) to test design, detail, fabrication, and installation assumptions. Research questions addressed with the mock-up included: 1) how much data generated from the scan of an irregular building topography can and should we ignore with the high tolerance capabilities of CNC; 2) what digital actions can minimize our time on site through the use of a digital model compared to simple physical interactions with the existing physical object; 3) what are the out of plane tolerances of an existing building; 4) how do we make structural connections while prefabricating and closing as much of the panel as possible; and 5) how do we rig and lift the panel in a vertical orientation to not damage foundation connections and navigate the eave. We used video and still photography to capture key elements and events during the testing process.

First, we created a mock existing condition. Although the shear panel foundation connectors were sized for the two-story case study building, we determined that a one-story section of the existing structure was sufficient to allow us to test the foundation, roof eave, rake details, and a panel-to-panel field and corner condition. The existing structure included plywood T1-11 siding, a typical vinyl frame sliding window, gutter, downspout, dryer vent, and trim.

Next, we scanned the existing condition as in Figure 3a. We evaluated different scanning techniques, including Matterport Pro2, Leica BLK360, and Artec Ray. The Matterport Pro2 camera is a professional, high-resolution 3D camera. Both the Leika BLK360 and the Artec Ray are Light Detection and Ranging (LiDAR) equipment. The Leica BLK 360 provides 3D captures with indoor and outdoor capabilities and excellent measurement accuracy for an extended range of 20 m. However, the Artec Ray is designed for large objects with up to 110 m distance and proved to work well with the large scale of a building façade, yielding clean, complete scans. The point-cloud software, Artec Studio, was used to merge Artec Ray scans into a singular model (Figure 3b) and to fit planes through the existing T1-11 wall surface (Figure 3c). Once planes were established, we could develop a topographical map of wall surface tolerance (Figure 3d) and use Autodesk ReCap Pro (Figure 3e) to link the model into Autodesk Revit 2022, in which we modelled the new facade. The façade models were exported from Revit and imported into DDX EasyWOOD for the generation of CNC toolpaths. CNC processing (Biesse Uniteam UT-9) of MPP occurred at TDI's Emmerson Laboratory at OSU (Figure 3f) along with the subsequent addition of weather barrier, window, flashing, insulation, and cladding (Figure 3g).

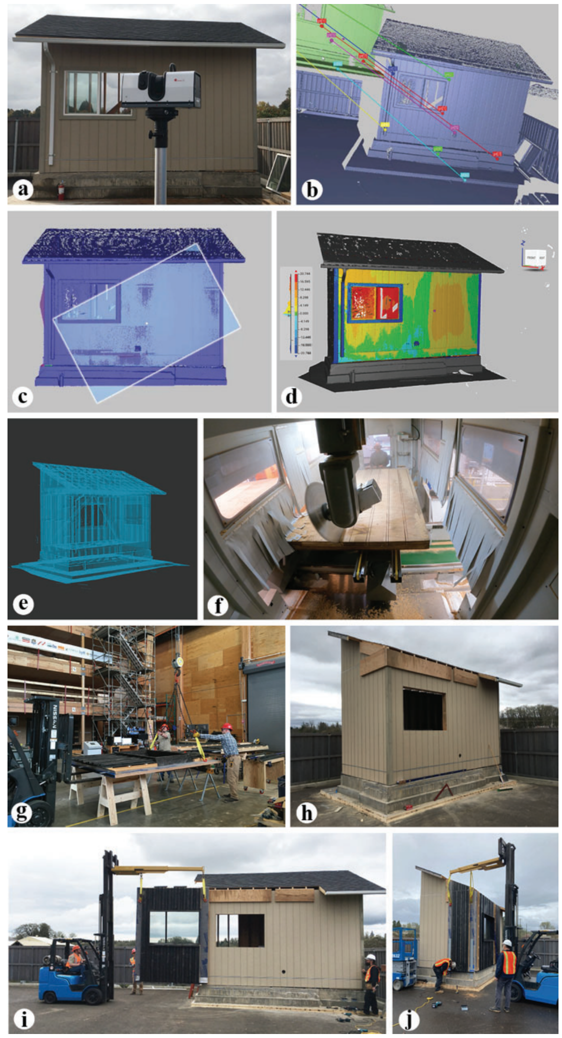

Figure 3: *Process for facade energy + seismic panelized retrofit: a) LiDAR scan existing building; b) process multiple scans into singular digital model; c) fit plane to wall surface; d) surface irregularity establishes tolerances; e) digital scan to Autodesk ReCap Pro; f) digital CNC fabrication of MPP structural core for facade panel assemblies; g) factory pre-assembly of facade panels with weather barriers, insulation, windows and cladding; h) site preparation including removing eave, trim, existing window and installation of MPP transfer joists at roof diaphragm; i) individual panels lifted into position on existing façade; j) panel connections completed at foundation beam and transfer joists. Panel-to-panel joints completed with elastomeric sealant, WRB, connector plates, insulation, and cladding.*

Finally, we tested prefabricated panels for ease of installation. On-site work included the installation of a 52 mm MPP transfer joist at the roof diaphragm, removing the existing eave for ease of installation, then gutter, downspout, trim, dryer vent, and existing window (Figure 3h). Once the existing condition was prepared, we flew panels into position, beginning with the infill window panel to align the window with a framed rough opening (Figure 3i) and continued with the seismic shear panels at the corner and panel-to-panel location with approximately 6 mm tolerance between panels. After completing all structural connections, we closed the joints with sealant, weather barrier, in-plane panel-to-panel plates, insulation, and cladding (Figure 3j). Lastly, we installed the roof blocking, sheathing, shingles, and the foundation rigid insulation with cementitious board over the newly installed seismic connections.

3 RESULTS

The main structural components of the system include an upgraded foundation system using a new 102 mm concrete beam and footing bonded to the existing stem wall and footing using epoxy rods. Wall panels consist of a rocking shear wall panel that resists panel flexural and shear forces, two hold-downs connected to an upgraded concrete foundation, resisting design forces induced by rocking of the wall either in tension (T) or compression (C), and a shear plate that transfers the horizontal base shear (V_b) between the wall and the concrete foundation. Forces between the shear wall panels are transferred to steel plates through fasteners (screws). Forces between the steel plates and the concrete foundation are transferred by the concrete shear anchor bolts (Figure 4b). At floor levels, shear wall panels are connected to the MPP transfer joist via eight fasteners at each edge of the panel, transferring diaphragm forces between the building and the shear wall (Figure 4a). Infill wall panels are connected to the MPP transfer joist via slotted steel plate connections (not shown in the figure).

The MPP walls selected for the two-story case study building are 1.22 m in width, 6.10 m in height, and 78 mm thick. The design of the shear wall panel followed existing standards, including ASCE 41-17 [19] and ASCE 7-16 [20], and consisted of determining (1) the tributary seismic weight to be resisted by the shear wall panel, (2) the seismic base shear, (3) forces and verification of the design of the main elements of the wall lateral force resisting system, (4) a drift analysis, and (5) capacity-based design of elements that are designed to remain essentially elastic. For a total base shear of 7.88 kN, tension and compression forces equalling 36.61 kN are generated at the base of the wall. Further description of the structural analysis of the system, and details on connections are described in the structural retrofit paper of the project [21].

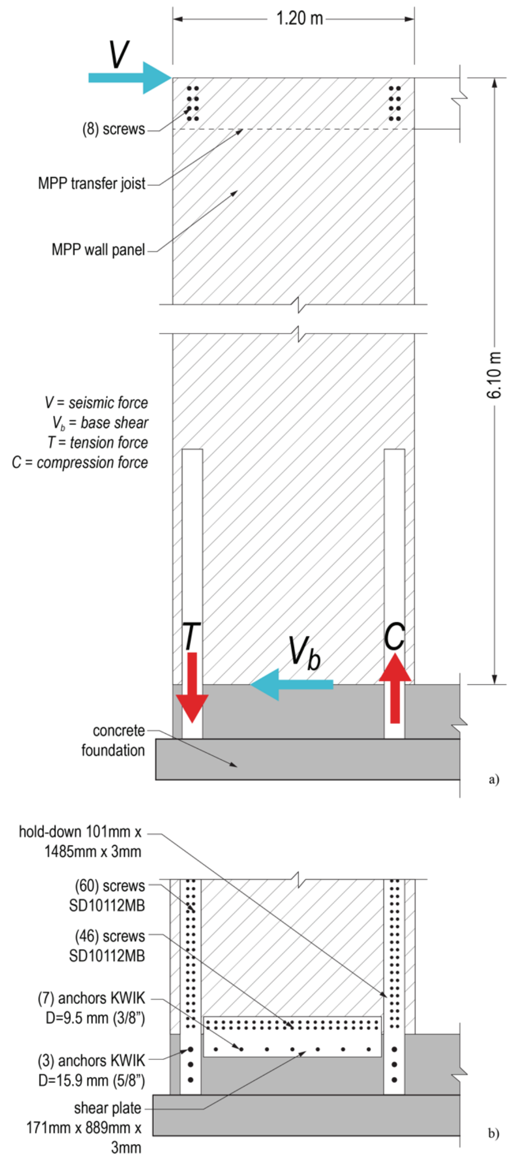

Figure 4: *a) Panel dimensions and reaction forces for connection design, b) foundation connection design*

Due to the MPP structural core, the panel system is designed to accept a wide range of outboard insulation levels, thus, a wide range of energy performance possibilities for a given climate. The existing case study wall assembly included (from inside to outside) 13 mm gypsum board, 89 mm stud frame with fiberglass batt insulation, and 13 mm T1-11 plywood siding for an insulation value of RSI-2.5. The retrofit system developed for the case study included (from inside to outside) 60 mm Steico flex wood batt insulation, 78 mm MPP, 60 mm Steico special dry board insulation, Soprema VP Sopraseal weather barrier, 19 mm ventilated cavity and 16

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mm T1-11 plywood siding for an insulation value of RSI-3.1 (Figures 5-7). The combined system (existing condition and retrofit assembly) insulation value exceeded code in Portland, Oregon for a wall insulation value of RSI-5.6.

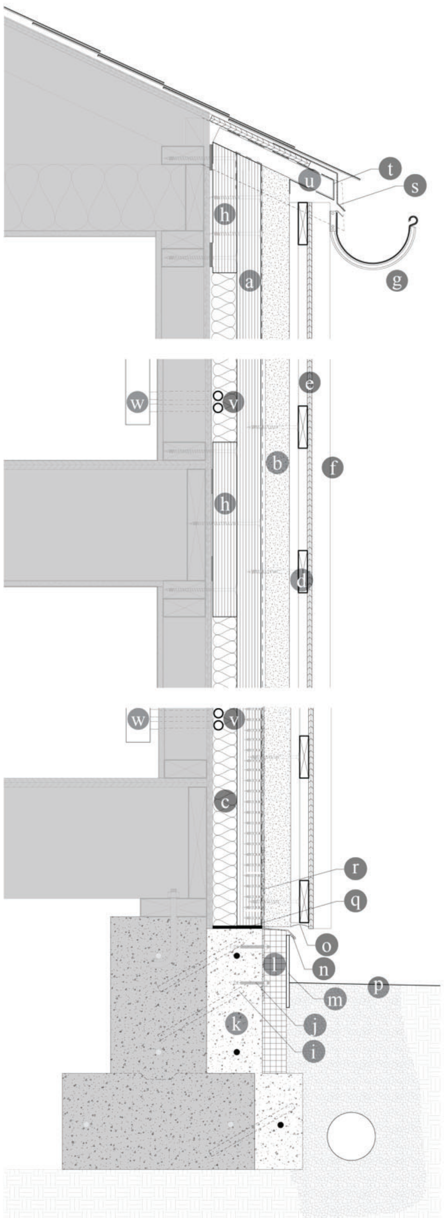

Figure 5: *Detail section view of façade retrofit assembly: a) 51mm MPP panel b) shop-applied mineral wool board; c) shop-applied 51mm mineral wool batt; d) horizontal batten; e) rough-sawn T1-11 plywood f) reclaimed wood batten; g) half-round gutter; h) 51mm MPP transfer joist; i) epoxy rod; j) steel expansion anchor; k) new 102mm concrete beam and footing; l) 51mm XPS insulation; m) cementitious board; n) flashing; o) insect screen; p) existing grade; q) neoprene pad; r) foundation seismic connector; s) flashing; t) insect screen; u) vented attic intake; v) hydronic retrofit piping; w) hydronic fan coil unit*

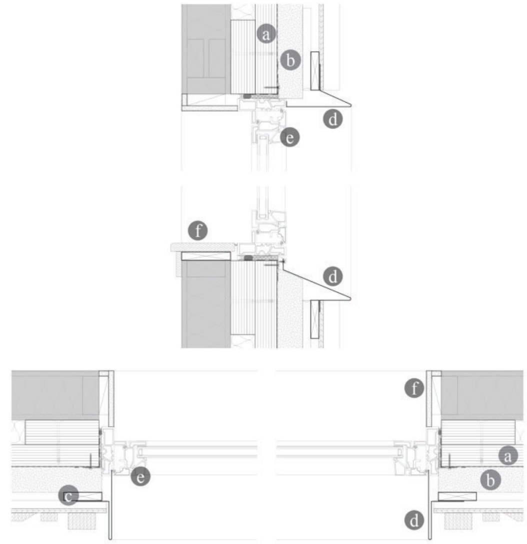

Figure 6: *Detail section and plan views of façade retrofit at window: a) 51mm MPP panel; b) shop-applied mineral wool board; c) vertical batten; d) brake-form steel window enclosure; e) fiberglass window; f) new interior finish.*

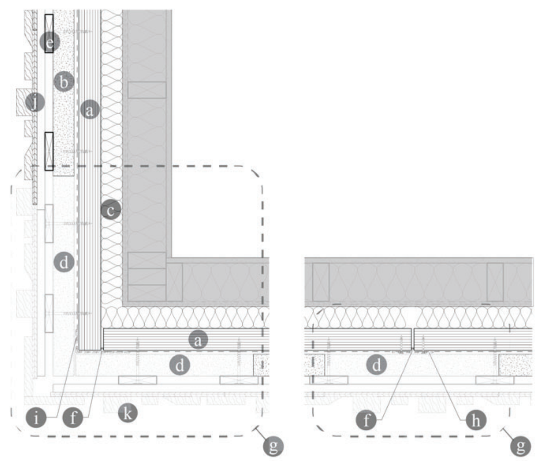

Figure 7: *Detail plan view of façade retrofit at panel-to-panel corner and field joint condition: a) 51mm MPP panel; b) shop-applied mineral wool board; c) shop-applied 51mm mineral wool batt; d) field-applied mineral wool board; e) vertical batten; f) elastomeric sealant; g) panel-to-panel field joint; h) panel-to-panel field connector plate; i) panel-to-panel corner connector plate; j) rough-sawn T1-11 plywood; k) reclaimed wood batten*

4 DISCUSSION

4.1 CONSIDERATIONS FROM MOCK-UP

Several light detection and ranging (LiDAR) scanning technologies are commercially available with a wide range in both capability and cost. Of the three systems we tested for this project, we found the Artec Ray (Artec 3D, Senningerberg, Luxembourg) to provide a suitable solution for our intended use case. This three-dimensional scanner is intended for large objects and in our experience

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captured high quality dimensionally accurate information of building facades. In addition, the ease and sophistication of post-processing into one clean usable model and compatibility with other software required for panel design and fabrication was an important consideration in developing the digital workflow used in the project. The scan resolution allowed irregularities in the finish of the retrofit concrete foundation to even be translated to a cut file and milled into the bottom edge of the MPP for an exact fit when installed.

Figure 8: *Mock-up pre-retrofit (top image) and Mock-up post-retrofit (bottom image).*

Where deep overhangs from existing eaves impede retrofit façade panel installation, two methods are possible. Some *Energiesprong* projects in Europe have employed specialty lifting attachments for crane-assisted positioning of panels that keep the attachment clear of the eave while allowing the suspended panel to be placed flush against the existing wall. We chose the other method: removing the existing eave so retrofit panels can be placed by conventional lifting attachments (Figure 8).

Though the scope of the current project is limited to façade retrofit only, it is reasonable to assume that if a building were to undergo such a retrofit the roof may also be considered for an upgrade. In this case, a parallel chord roof truss may be selected to span the existing roof while adding space for additional roof insulation and transferring the added load to the perimeter walls where façade retrofit panels can be designed to accommodate this. In this whole building retrofit scenario, the removal of existing eaves would be advantageous for more than just ease of placing retrofit wall panels.

Figure 9: *Reflected view of installed seismic retrofit panel.*

In rigging the panels for lifting and installation two Dragon lifting belts (Rothoblaas, Cortaccia, Italy) were used suspended from a boom (Figure 3i). This method required 35mm through-holes to be drilled through the MPP panel. The method was successful from an installation perspective, with the lifting belts easily retrievable and reusable once the panels were secured. However, the two holes are large envelope penetrations that must be properly sealed in the field as part of completing the panel-to-panel joints. An alternative approach to rigging attachments that eliminates these through holes would be desirable as a future installation refinement to avoid any possibility of these penetrations being missed or improperly finished.

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Some elements of façade panel assemblies are best accomplished with panels oriented flat. For example, bonding wood fibre insulation to the MPP prior to CNC milling of the composite panel was piloted and proved a successful means of reducing the overall fabrication labour. The panels not only need to be rotated in the factory for fabrication, but also for transportation, and again while being lifted into place. The panel stiffness, factoring in window openings and added weight from the built-up façade assembly, must be sufficient to allow for panel rotation in any configuration. Panel flex is also undesirable for machining operations. If the panel must be stiffened or attached to a spoil board to be accurately cut, this will add time and in turn cost.

One important consideration concerning the positioning of steel seismic connectors on each panel is that some of each connector must be left exposed for attachment to the building and to adjacent panels during installation. The plates must then be covered as part of the process of sealing and finishing panel-to-panel joints once attached to the building. Limiting the size and location of these areas to be finished in the field reduces installation time and complexity. It also should be part of a cohesive design strategy focused on how panels and seams are conceived to work visually with the overall completed façade aesthetic. Seismic connectors were intended to be limited to exposed vertical edges of each panel (Figure 9), with field-installed vertical siding elements used to conceal panel-to-panel joints on the completed façade. However, the seismic connection to the foundation is best accomplished with the inclusion of a horizontal steel plate at the base of the MPP panel (Figure 4b). This area, if left exposed for installation, needs future consideration for how it will be detailed to be incorporated into the overall façade design.

4.2 FUTURE RESEARCH DIRECTION

We are now planning to construct and test a three-story prototype fabricated and installed by a commercial contractor to test the validity of design, scanning techniques, fabrication and construction methods, and cost models resulting from the initial prototype construction. Construction-ready documents will be made publicly available and given the potential market for these retrofits, a significant market increase for mass timber products is anticipated.

Along with this project, the team is exploring mass timber façade retrofits for energy and seismic resilience in low-rise commercial buildings. Other future related research may include designs for a prefabricated MPP roof retrofit with insulation and integrated photovoltaics.

5 CONCLUSIONS

This project produced a physical demonstration mock-up of a seismic/energy panelised retrofit, utilizing MPP as the structural core, with performance upgrades to meet U.S. Department of Energy Zero Energy Ready Home (ZERH) Standard [22] and current seismic code, that is capable of initially being rolled out across U.S. West Coast markets and beyond. The desired result is to use the innovative design solution produced by UO/OSU as a demonstration and cost model for industry adoption, including manufacturers, developers, and contractors.

Figure 10: *Visualization of case study multifamily building using the façade retrofit system developed.*

We recognize that each retrofit project will need this prototype design adapted for each existing building. In particular, the seismic design will vary depending on the existing conditions in the building, including its size and shape. Some buildings may need additional structural interventions across floors to connect to exterior walls and these will have to be designed to cause minimal interior disruption. However, using scans of existing buildings, translated into digital files for fabrication and panel assembly in a factory setting, we believe that the custom solutions can be more efficiently accomplished than with each project constructed on-site. With the substantial need for upgrading this existing stock of housing for energy and seismic resilience, this solution can have a significant impact on lowering carbon emissions and extending the useful life of much-needed existing housing.

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