FOREST TO FACADE

Developing an Application for Mass Plywood Panels in Seismic and Energy Wall Retrofits

TALLWOOD
DESIGN INSTITUTE

Developing an Application for Mass Plywood Panels in Seismic and Energy Wall Retrofits

Prepared for

United States Forest Service & The Wood Innovations Grant Program

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Cover Image

Multifamily retrofit concept rendering, by Isaac Martinotti

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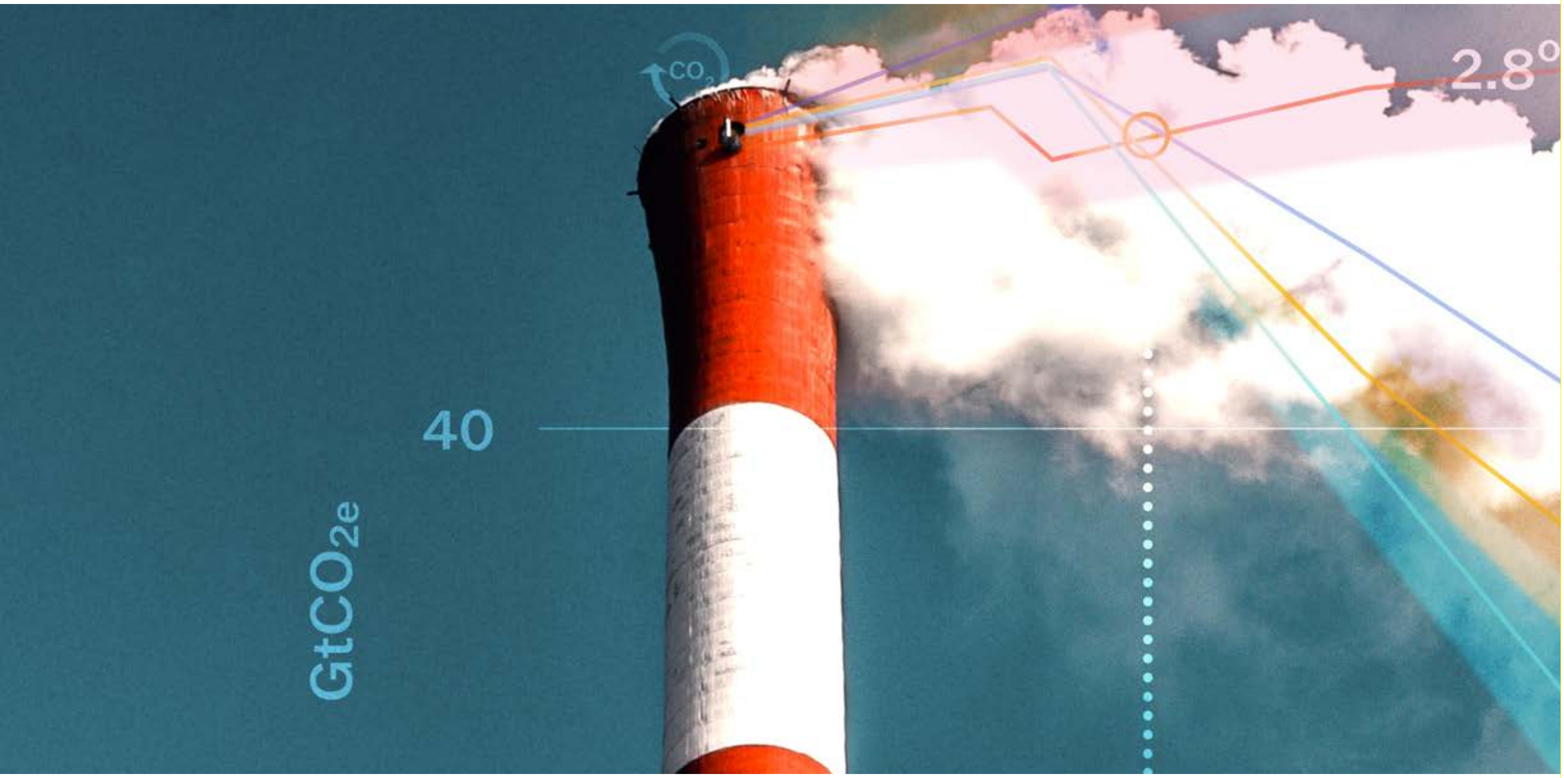


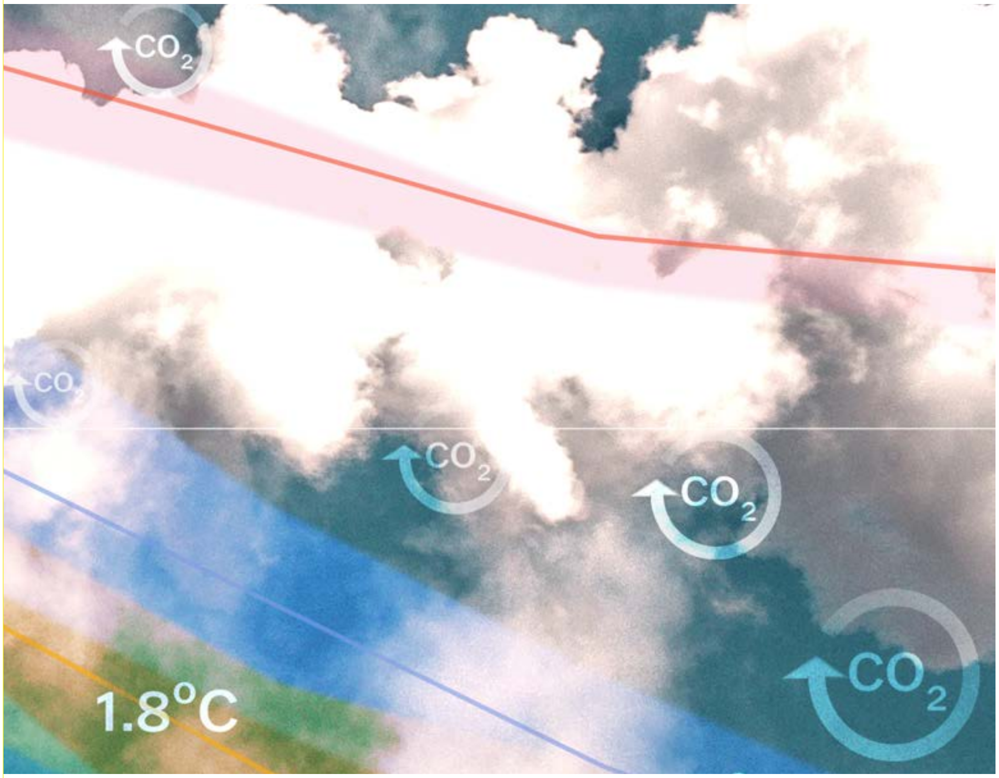
Introduction

Brief

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. 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 that include selective harvesting of small-diameter trees to reduce fuels and wildfire risk; however, this form of harvesting is labor intensive, costly, and the resulting harvest of small-diameter logs has low market value, resulting in this wood fiber 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. The fund, called the Portland Clean Energy Fund (PCEF), initially anticipated local investments of USD 44-61 million annually; however, in 2022, the fund made its largest award of USD107 million to 65 projects fighting climate change.



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 deep energy retrofit solutions for existing buildings. 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.

In the U.S., buildings account for approximately one-third of carbon dioxide equivalent emissions each year. 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).

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. 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), 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). 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. 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. To meet that goal, existing housing must be maintained, in addition to creating new

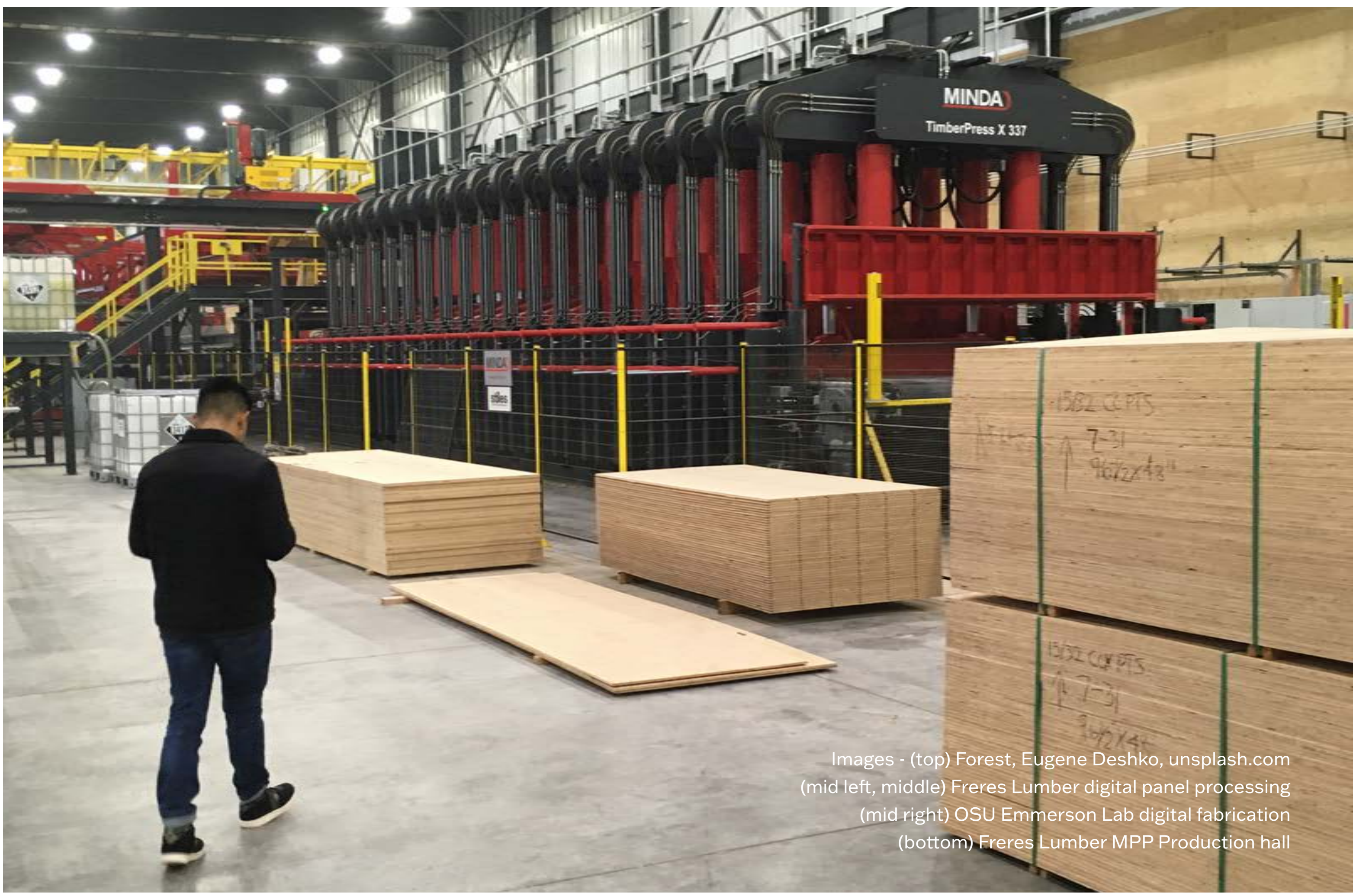
housing units. Therefore, there is an urgent need for cost-effective, low-impact energy and seismic upgrades to extend the useful life of this critical housing stock.

Housing projects in Europe have begun to address deep energy upgrades with minimal tenant disturbance using prefabricated facade retrofits. For example, the Energiesprong method developed in the Netherlands employs a technique of digital scanning of existing facades and using these scans to fabricate new facade systems off-site, complete with insulation, high-performance windows, doors, and cladding. Since the panelized 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 facade 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. 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 on-site over existing building cladding to upgrade older light-wood-frame one- to three-story buildings to meet or exceed current energy and seismic codes.



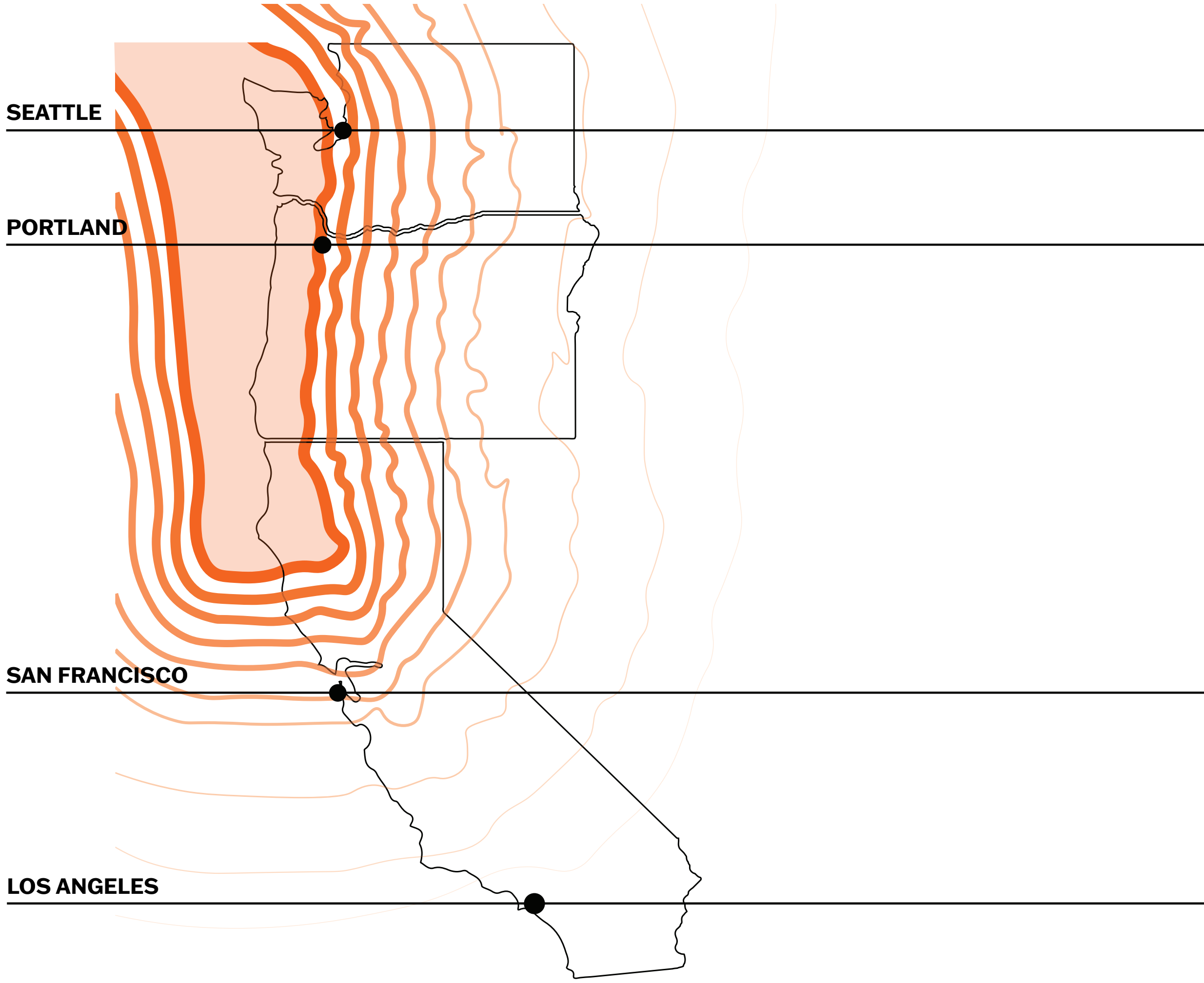
Images - (top) Forest, Eugene Deshko, unsplash.com
(mid left, middle) Freres Lumber digital panel processing
(mid right) OSU Emmerson Lab digital fabrication
(bottom) Freres Lumber MPP Production hall

01. PRE-DESIGN

Predesign (Goal 1)

Define the design criteria and document. This will include energy, structure, attachments, moisture, constructibility, geometry, and materials.

To develop the panelized 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.

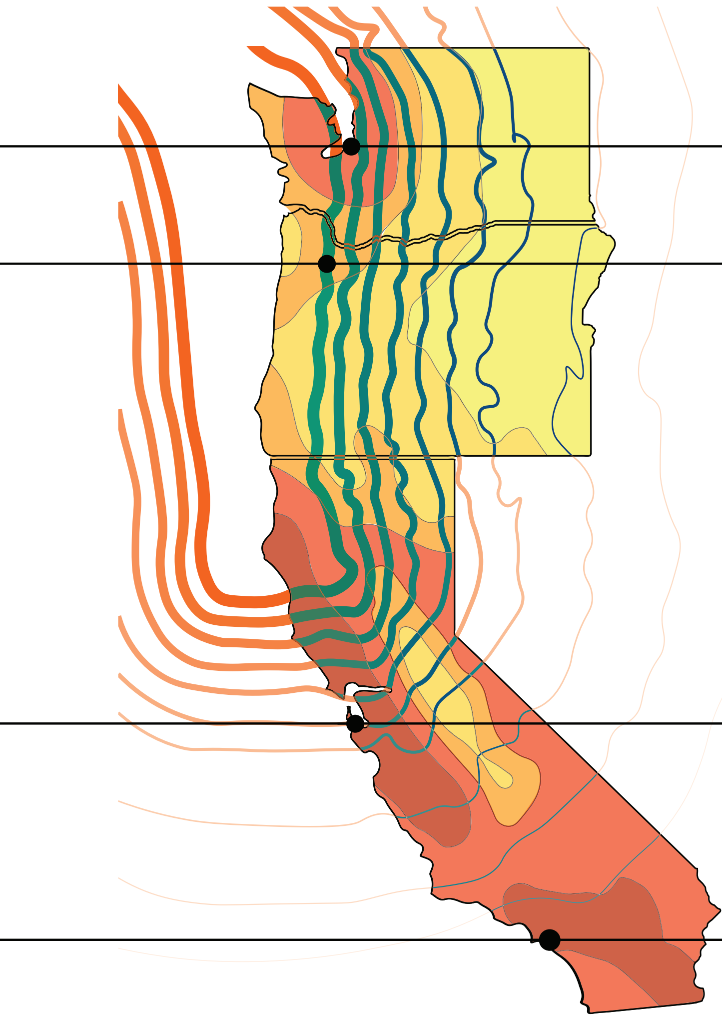


Cascadia Subduction Zone Intensity

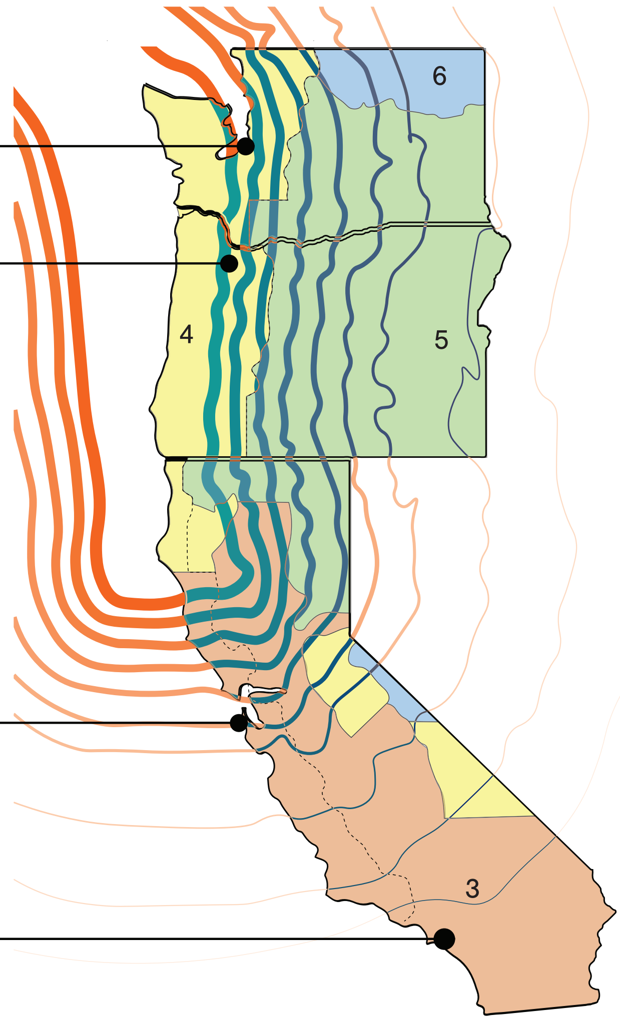
Regional Conditions

Climate and Seismic

The eventuality of a large magnitude earthquake from the Cascadia Subduction Zone is now common knowledge in the Pacific Northwest. Population centers like Portland, Oregon and Seattle, Washington are positioned to experience some of the highest seismic intensity during such an event. Oregon is expected to have less frequent earthquakes in the coming centuries relative to other areas of the West Coast, however, with some of those earthquakes coming from the Cascadia Subduction Zone, significant steps toward preparedness and seismic resilience are warranted throughout Oregon. Much of the region's population is located in a relatively mild climate zone influenced by its proximity to the Pacific Coast and onshore weather patterns. This is one reason typical construction practices over the preceding decades hasn't prioritized envelope insulation and air sealing. Instead, meeting heating demand in buildings with energy and carbon intensive systems. With climate change and increasing summer cooling demand throughout the region, envelope improvements will have nearly year-round impact.



+ **Frequency of Earthquakes**



+ **West Coast Climate Zones**

EXPECTED NUMBER OF DAMAGING EARTHQUAKES IN 10,000 YEARS

- >250
- 100-250
- 50-100
- 20-50
- 10-20

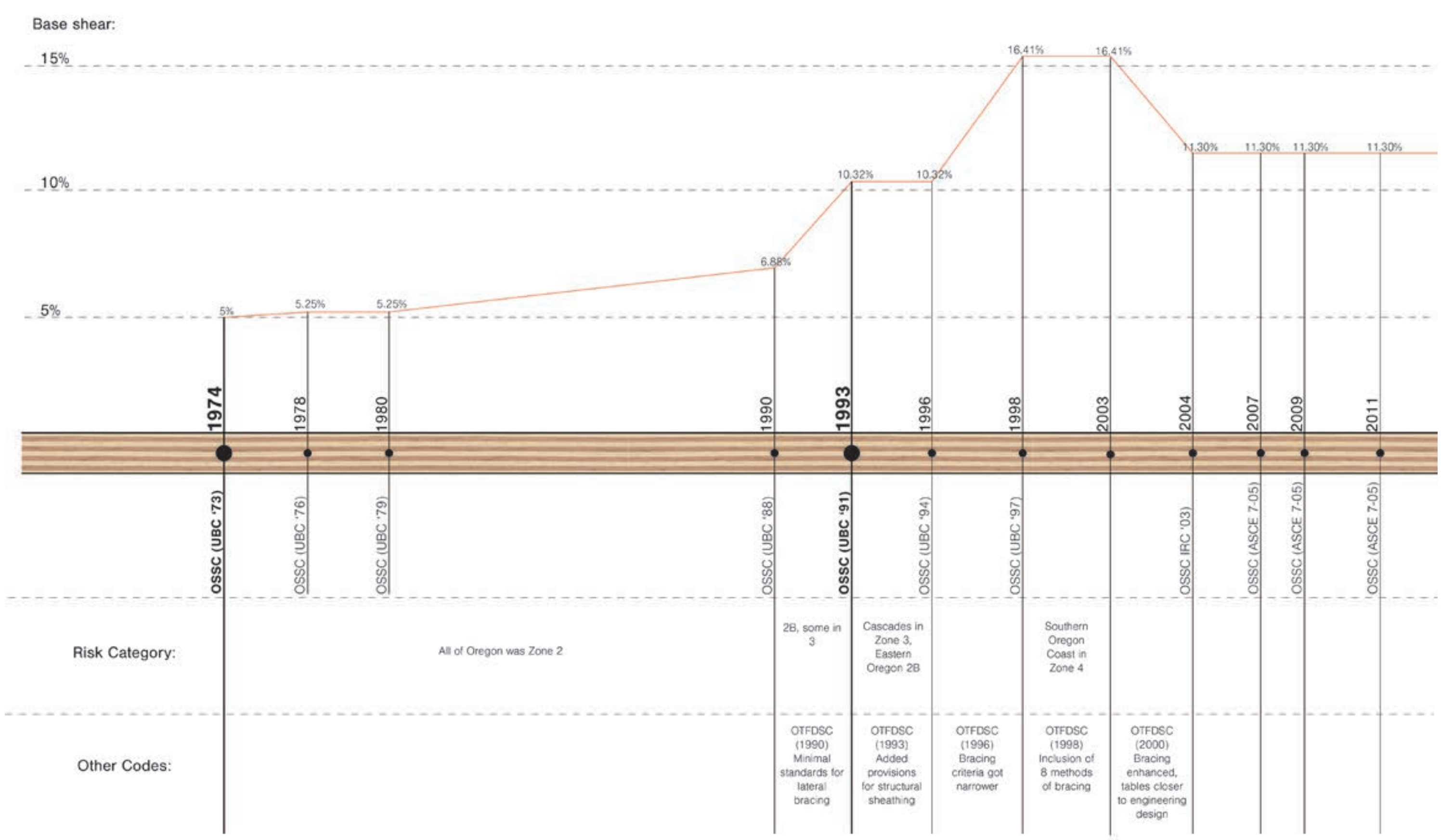
WEST COAST CLIMATE ZONES

- WARM
- MIXED MARINE
- COOL, DRY
- COLD

Evolving Seismic Code

Challenges and Opportunities

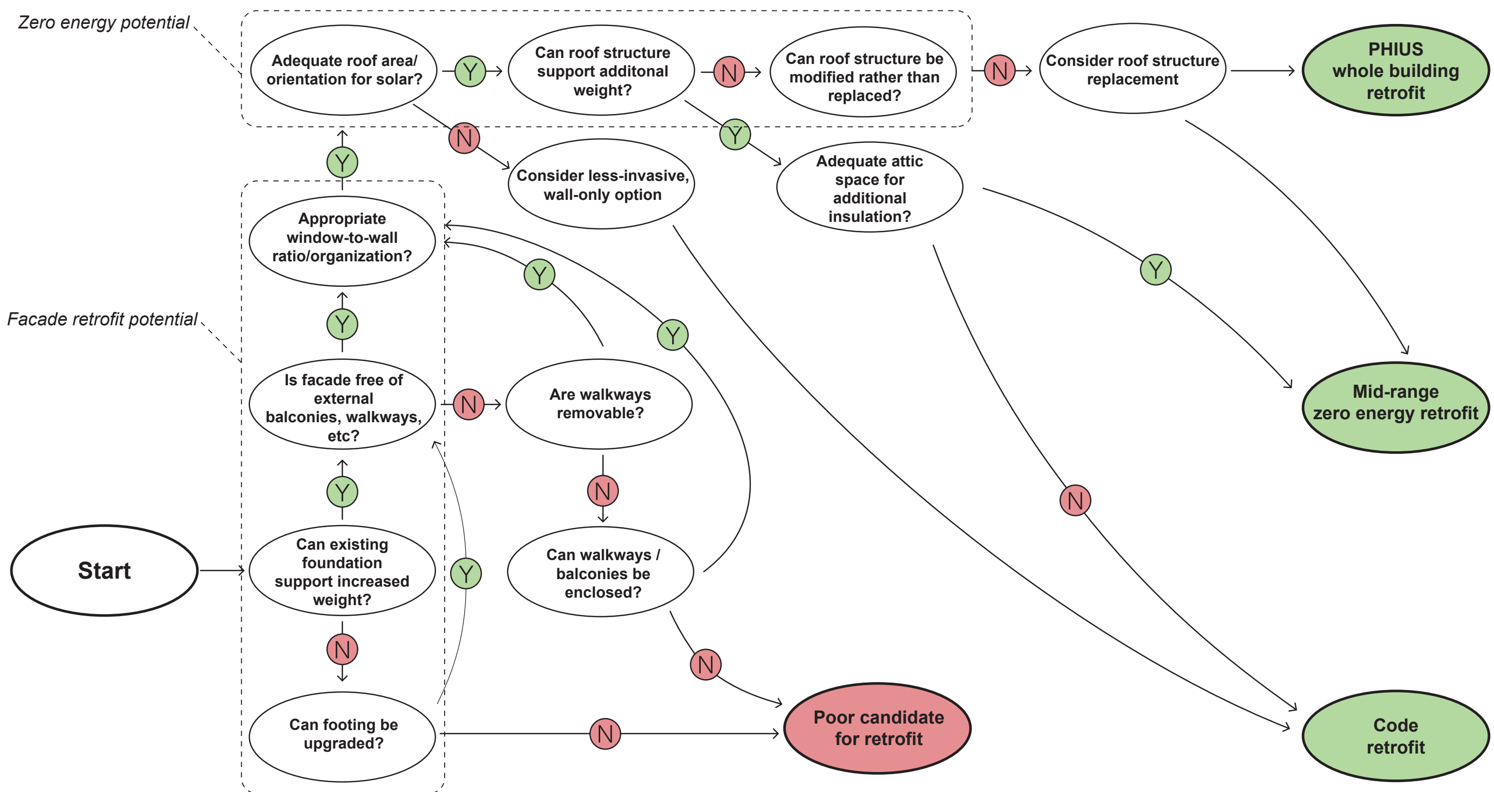
In Oregon, the building seismic code has evolved since the 1970s to include a better understanding of seismic risks and associated base shear forces, beginning at 5% in the 1973 Uniform Building Code (UBC), slowly ramping to 16.41% in the 1997 UBC following an initial understanding of the Cascadia Subduction Zone risk, and back down to 11.30% in the 2003 International Residential Code (IRC). 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.



Building Suitability

Challenges and Opportunities

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 facade retrofit. We found predominantly two-story light-wood-frame structures with repeated stacked housing units and regular facade 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.

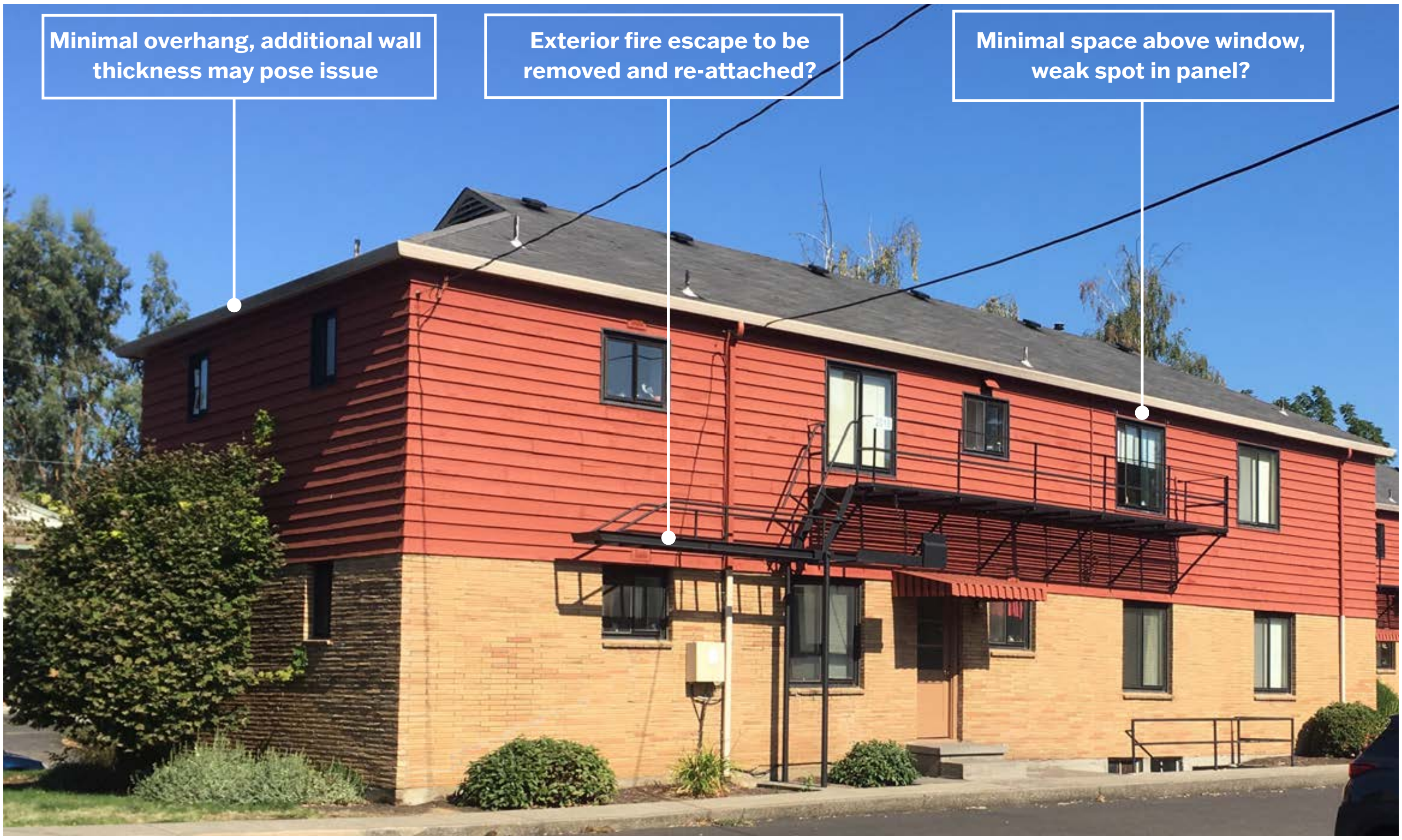


Building Selection

Retrofit Candidates

Not every mulitfamily builing is a suitable candidate for a panelized energy + seismic retrofit. The research team developed a decision tree workflow to sort potential candiates based on desired retrofit level and potential for achieving. 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 facade-mounted electric meter for each unit. Natural gas service is not typical for this housing typology in this location in Portland, Oregon. Additional facade penetrations may include exhaust fan venting, which predominantly occurs through the roof, but can be found located at the facade for ground floor units.


Minimal overhang, additional wall thickness may pose issue
Exterior fire escape to be removed and re-attached?
Minimal space above window, weak spot in panel?

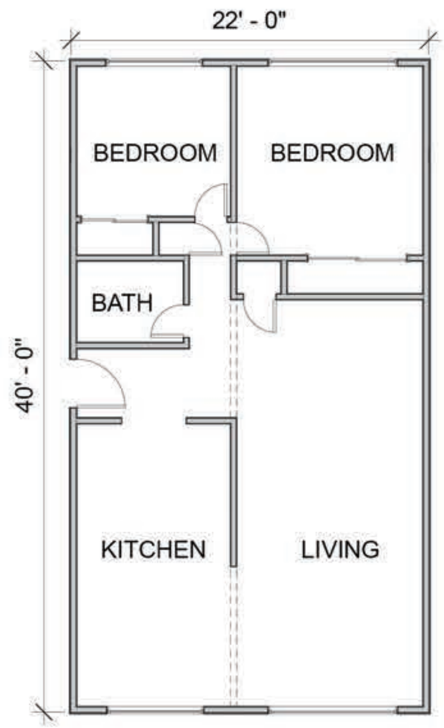

Too many openings- much of MPP panel will be waste
Walkway on cantilevered joists- presents possible structural challenges.

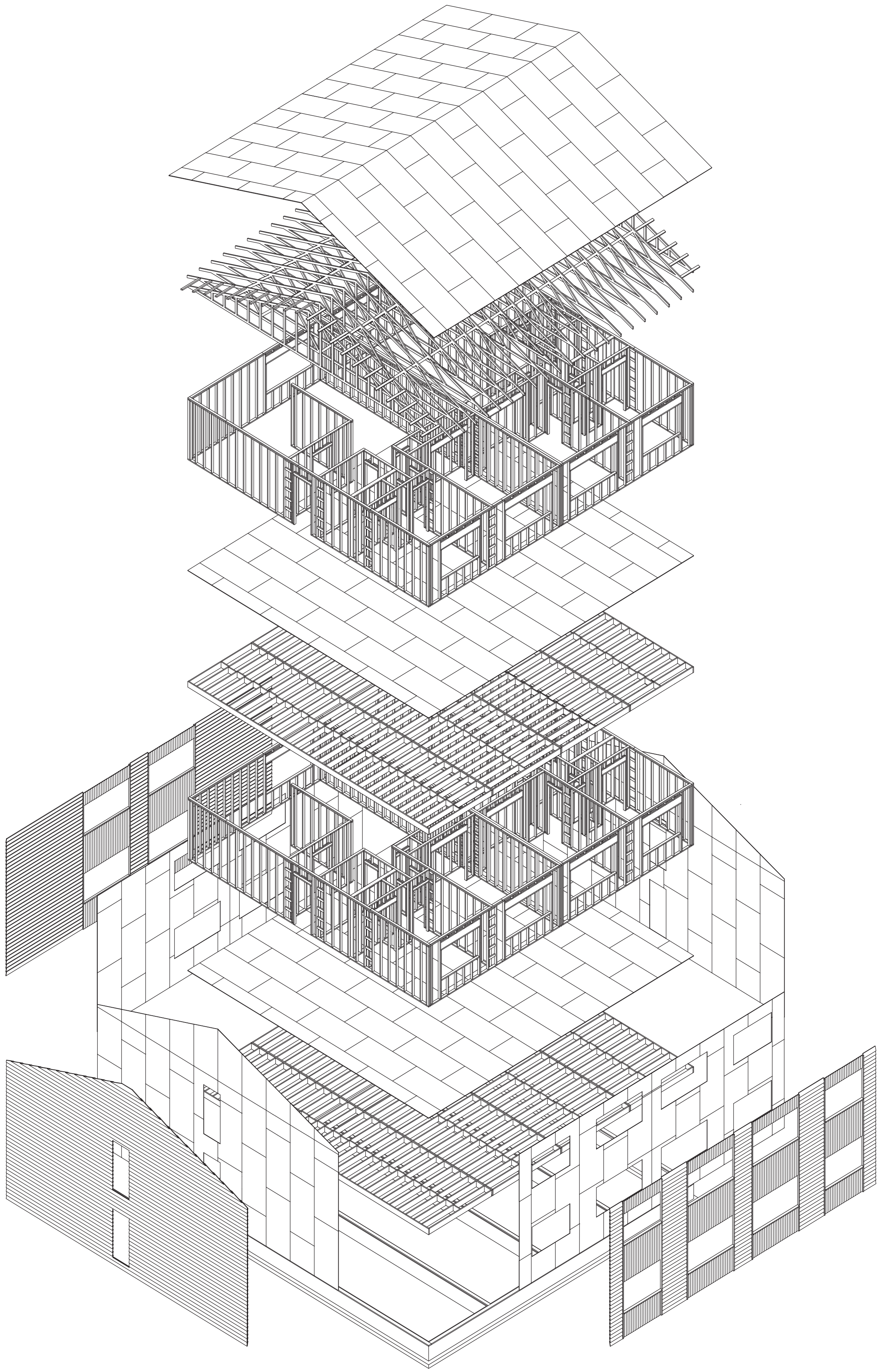
Case Study

27 East Apartments - Portland, Oregon

The case study building selected, offers an example of typical existing multifamily construction found in the study region while also representing a reasonable candidate for facade retrofit. Exterior circulation occurs between units, leaving the facade 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 facade opposite the parking area, which minimizes the continuous lineal footage of the facade where services will need to be factored into more complex retrofit panel design and installation.

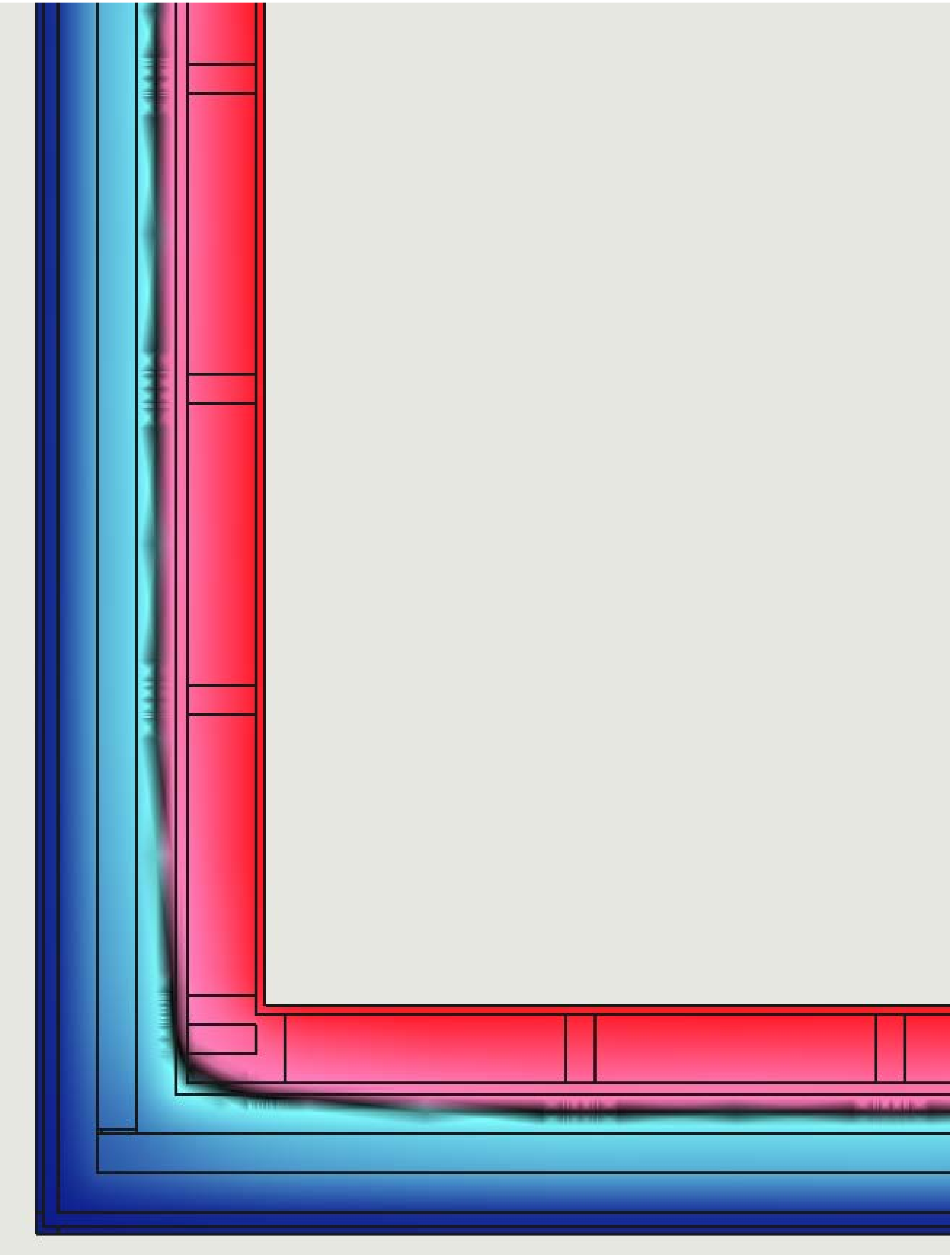




02. ENVELOPE DESIGN

Envelope design (Goal 1, Obj. 1.1)

Develop the panels to meet the thermal and moisture requirements while considering cost and constructibility. This design will consider windows and doors as well as prototypical panel-panel, panel-foundation, and panel-roof details.

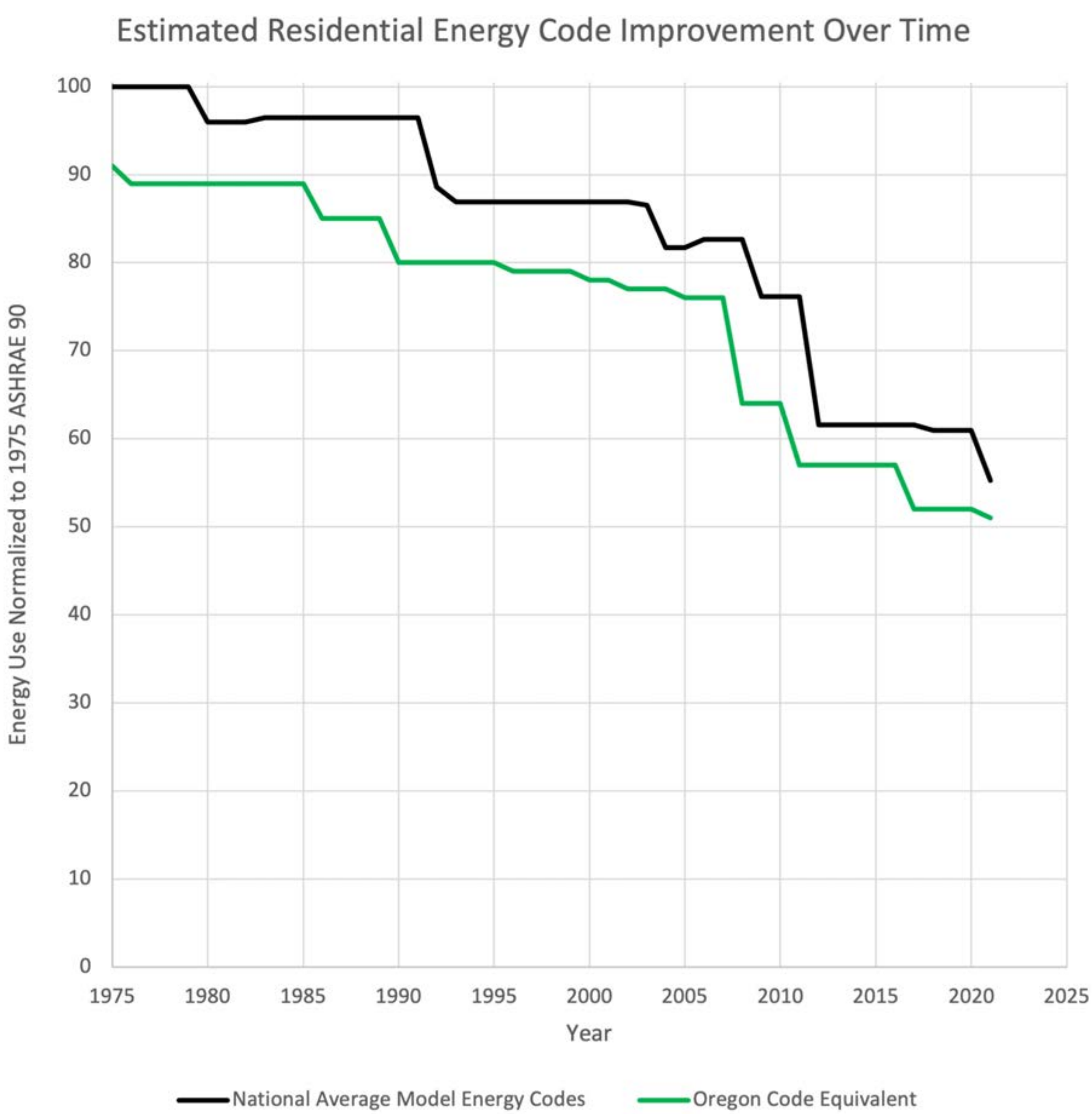


Energy Retrofit Levels

Current Code to Passive House

In Oregon, the structural building code evolved significantly from the 1970s to the 2000s to include a better understanding of seismic risks and associated base shear forces. From that same starting point of adopting a statewide Oregon building code 50 years ago, energy code provisions have also seen periodic advancement toward higher efficiency building systems and lower resultant energy use for new construction, however, energy codes continued to see step changes beyond the 2000s, and that trend is projected to continue into the future. This means regardless of the vintage of the structure, a facade energy retrofit to current code is likely to result in improved energy performance. The level of retrofit for individual measures and how comprehensive the set of building-wide measures is will dictate overall reduction of future energy use for that building and it's occupants.

RETROFIT LEVEL	STANDARD	WALLS	CEILING	FLOOR	WINDOWS	DOORS	AIR INFILTRATION
1 (COMPREHENSIVE)	PHIUS	R-47	R-89	R-51	U-0.16 OR LESS	R-10	0.06 CFM50/FT2 ENVELOPE AREA
2 (MODERATE)	DOE - ZERO ENERGY READY HOME (ZERH)	CZ 4-5: R-20 OR R-13+R-5 CZ 6 R20 +5 or R13+10	CZ 4-6: R-49	CZ 4-6: R-30 SLAB: CZ 4,5 R-10, 2 FT CZ 6 R-10, 4 FT	CZ 4-6: U-0.27 CZ 4C & 5: U-0.30	NR	LESS THAN 3 ACH 50
	ASHRAE 90.2-2018	CZ 4-5: U-0.060 CZ 6: U-0.045	CZ 4-6: U-0.026	(FLOOR) CZ 4-6: U-0.033 (SLAB) CZ 4-5: R-10, 2FT CZ 6: R-10, 4 FT	CZ 4-6: U-0.32	CZ 4-6: U-0.32	CZ 4-6: LESS THAN 3 ACH 50
	NORTHWEST ENERGY EFFICIENCY ALLIANCE (NEEA) ORSC RECOMMENDATIONS	R-21+R-5	R-60	R-38 (FLOOR) R-10 (SLAB)	U-0.24 OR LESS SHGC 0.27	NR	LESS THAN 2 ACH 50
3 (LOW-COST)	OR CODE (2021 ORSC)	R-15 (EXISTING) R-21 (NEW)	(EXISTING) R-21 - R-49 (NEW) R-30 - R-49	(EXISTING) R-25 - R-30 (NEW) R-30 (SLAB EDGE) R-15	U-0.26 OR LESS	U-0.2 WITH <= 2.5 SF GLAZING, U-0.4 WITH >= 2.5 SF GLAZING	LESS THAN 3 ACH 50
	CA CODE (2019) TABLE 150.1-B CAL CZ 1,2,14-16	U-0.051	R-38	(FLOOR) R-19 (SLAB) CAL CZ 1,2,14 - NR; CZ 16 R-7	U-0.30 OR LESS SHGC 0.23 MAX MAX AREA 20% MAX WEST 5%	U-0.20	NR
(NO RETROFIT)	TYPICAL EXISTING CONDITIONS	R-8 - R-12	R-30+	UNINSULATED SLAB	SINGLE PANE ALUMINUM TYPICAL	NR	NR



Data source: Pacific Northwest National Laboratory, US Department of Energy (National Average Model Energy Codes); Oregon Building Codes Division (Oregon Code Equivalent)

Retrofit Panels

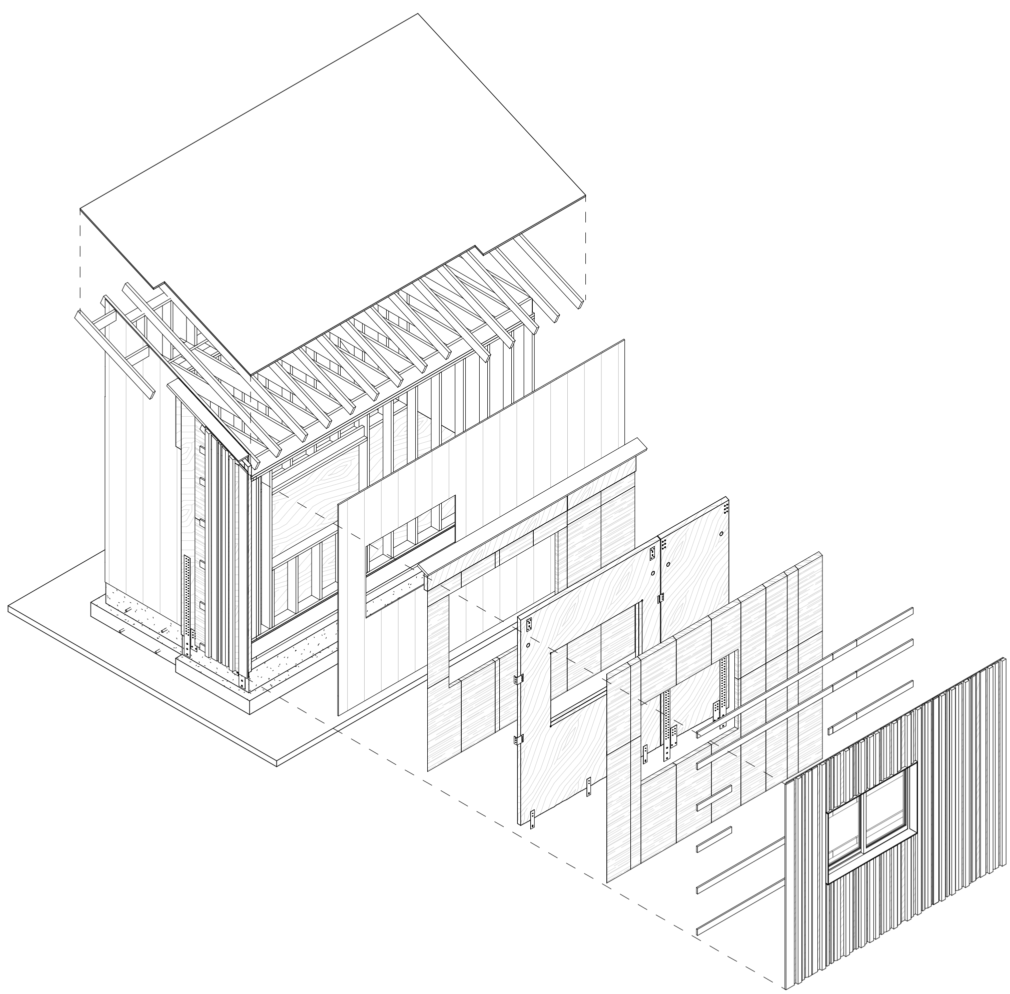
Layup and installation principles

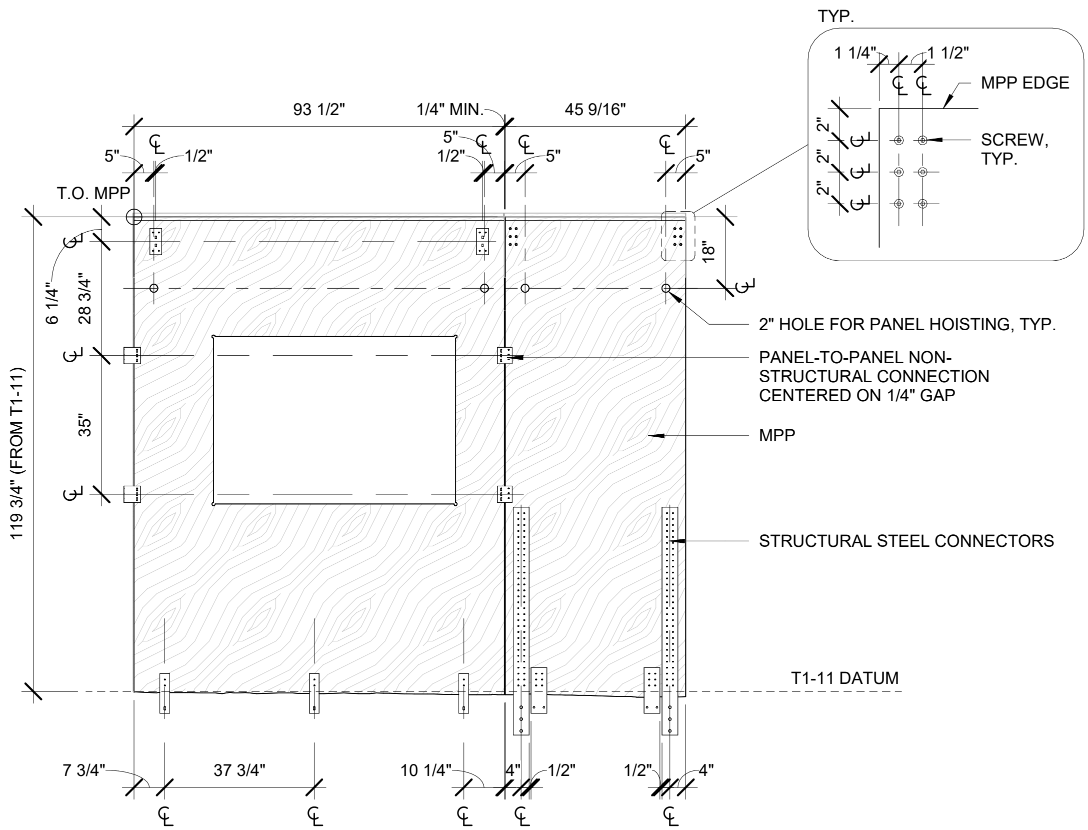
The intent of this project is to challenge the cultural conventions of building construction in the United States; buildings in the U.S. are generally constructed with minimal off-site work. Off-site construction in factories has a variety of advantages that this project capitalizes on.

Pre-assembled panels mitigate weather-driven issues during construction. Because the panels can be waterproofed and clad before they are brought on-site, the assembly is better protected from the elements than it would be during conventional construction methods. Maintaining a dry assembly, especially during wetter months, prevents damage and mold from growing within the wall. As a result, construction does not necessarily need to be limited to drier months, but rather can be achieved year-round due to its built-in protection.

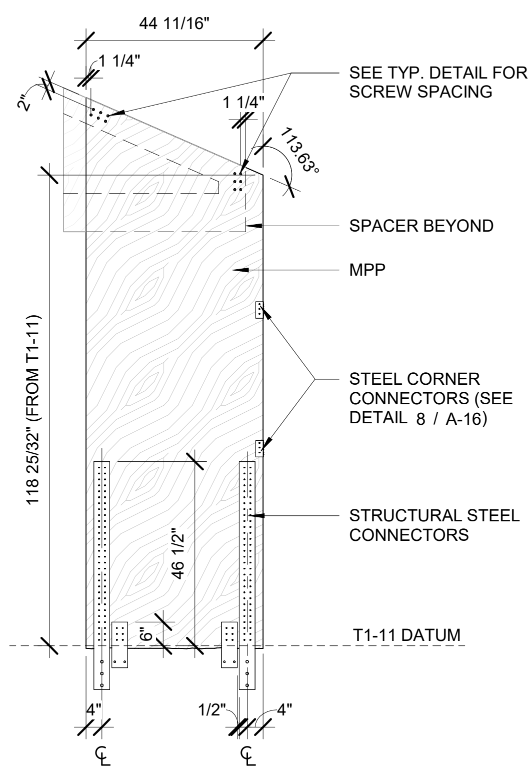
On the other hand, prefabrication is still a growing industry within the U.S. which translates to higher construction costs. In order for these panelized facade systems to be implemented at a larger scale, they would need to be manufactured in a factory setting.

The MPP spacers that are attached first to the building prior to panel installation serve to level the existing surface and to provide space for insulation and services. Prefabricated facade panels are installed over these MPP spacers which ultimately serve as a transfer joist connection between existing structure floor and roof diaphragms and retrofit facade panels.

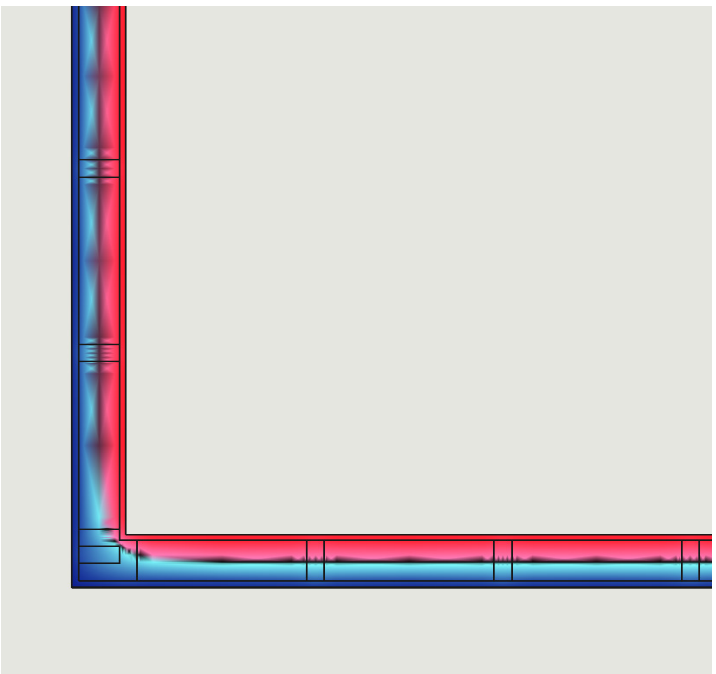


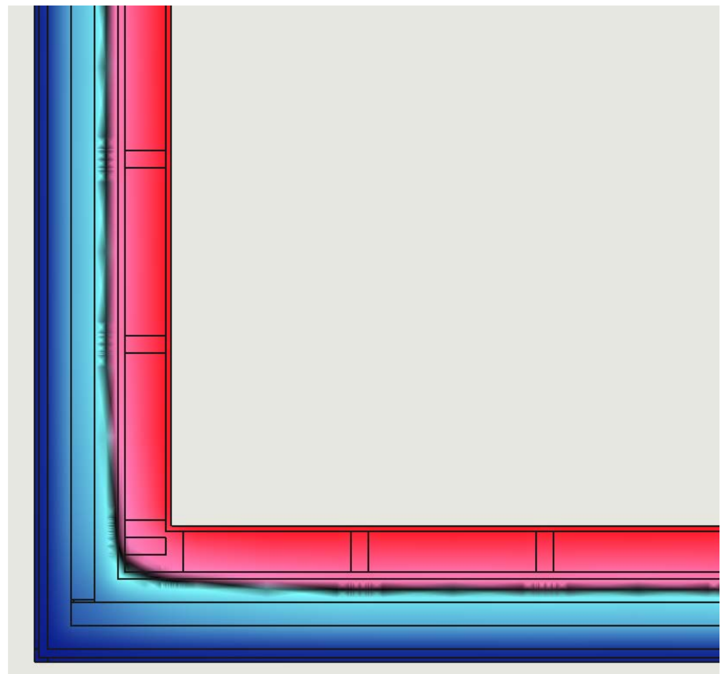


8 South Layer 2 - MPP
3/8" = 1'-0"



2 West Layer 2 - MPP
3/8" = 1'-0"





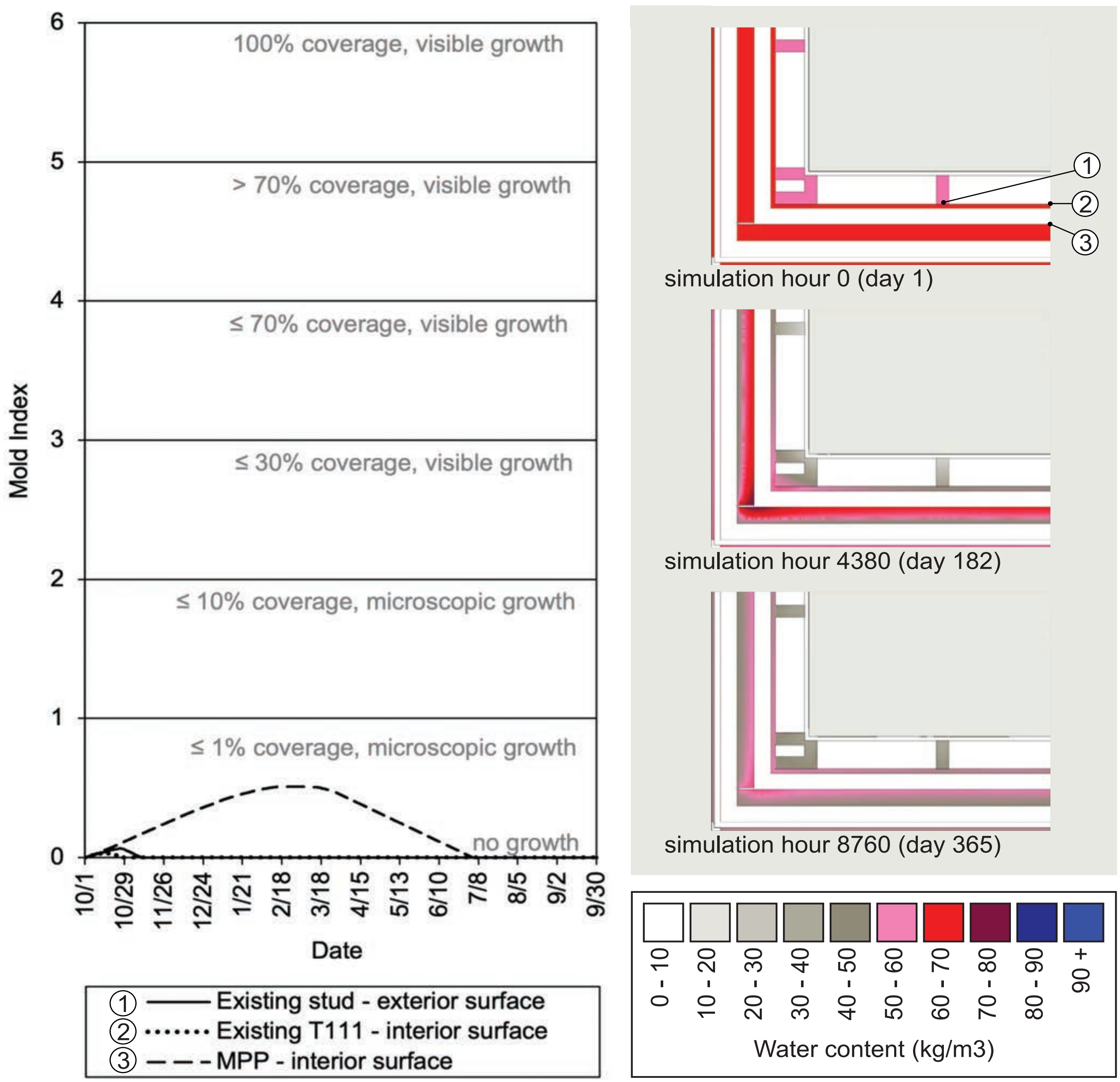
Hygrothermal Assessment

Simulation results

New windows offer the most tangible feature of energy upgrades for occupants through perceptible improvements in thermal comfort. 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 and analysis for the proposed retrofit solution over an existing wall assembly. All materials were assumed to have an elevated starting water content equivalent to 80% relative humidity and the simulation was run for one year with modeled 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 mold index ranging from 0 - no growth to 6 - 100% coverage with visible growth. 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 mold index of 0, or no growth.

In separate steady state temperature simulations, where warm indoor and cold outdoor air temperatures are maintained and the simulation is run until steady state temperature is reached throughout the wall assembly depth, the location of the transition point between the two conditions remains outboard of the existing envelope with the addition of the retrofit panels and the added insulation they provide.



Mold Index
6
5
4
3
2
1
0
100% coverage, visible growth
> 70% coverage, visible growth
≤ 70% coverage, visible growth
≤ 30% coverage, visible growth
≤ 10% coverage, microscopic growth
≤ 1% coverage, microscopic growth
no growth
10/1
10/29
11/26
12/24
1/21
2/18
3/18
4/15
5/13
6/10
7/8
8/5
9/2
9/30
Date
1 Existing stud - exterior surface
2 Existing T111 - interior surface
3 MPP - interior surface
simulation hour 0 (day 1)
simulation hour 4380 (day 182)
simulation hour 8760 (day 365)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 +
Water content (kg/m3)

Envelope Details

Drawings

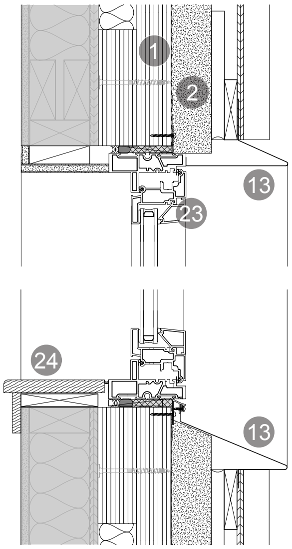
An eaveless roof detail was chosen for two primary reasons: architectural expression and constructibility limitations. Buildings that are eligible for this type of seismic and energy upgrade are also typically neighborhood eyesores. An eaveless roof, in addition to a full facade upgrade, modernizes the existing building to achieve a more seamless design. Furthermore, due to construction limitations, an eaveless roof was necessary in order to mount the new facade panels. European projects that employ a similar pre-fabricated facade system use mounting technology specifically created for lifting panels underneath roof eaves. For the purposes of this research project, only tools available at the Emmerson Lab were used for hoisting the panels and, thus, the roof eave was removed so that the panels could be lifted into place with no interference during installation.

A flange window was chosen so that the window could be face screwed into the MPP rather than screwed into the end grain. We acknowledge that flange windows potentially have issues with condensation build-up at the flange, but, in order to mitigate this issue, it is advised that the outboard insulation is placed over the flange where possible.

The retrofit concrete foundation, anchored to the existing footing and stem wall and prepared prior to panel installation, is a key element of the overall system. Not only would seismic forces transmitted through the panels be resolved at this connection, the additional foundation also carries the substantial new gravity load of the MPP panelized system.

Callout Key:

1. 2” Mass Plywood Panel (MPP)
2. shop-applied rigid mineral wool
3. shop-applied mineral wool batten
4. field-applied rigid mineral wool
5. 1x4 horizontal furring
6. 1x4 vertical batten
7. elastomeric sealant
8. panel-to-panel field joint
9. panel-to-panel field connector plate
10. panel-to-panel corner connector plate
11. rough-sawn T1-11 rainscreen
12. reclaimed wood batten
13. brake-form steel enclosure
14. half-round gutter
15. 2” MPP transfer joist
16. epoxy rod
17. steel expansion anchor
18. new 4” concrete beam and footing
19. 2” XPS insulation
20. cementitious board
21. flashing
22. insect screen
23. fiberglass window
24. interior finish
25. existing grade
26. vented attic intake
27. neoprene pad
28. foundation seismic connector
29. hydronic retrofit piping
30. HVAC hydronic fan coil unit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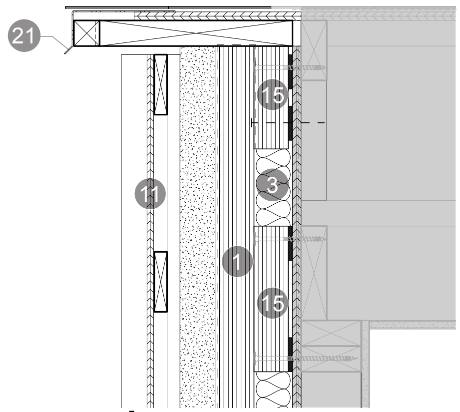
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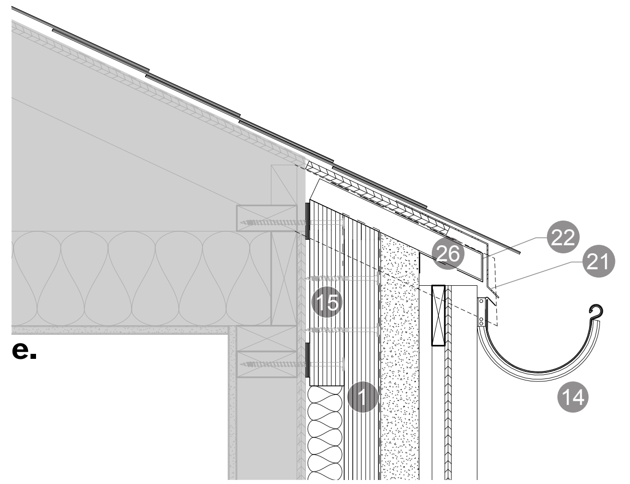
d.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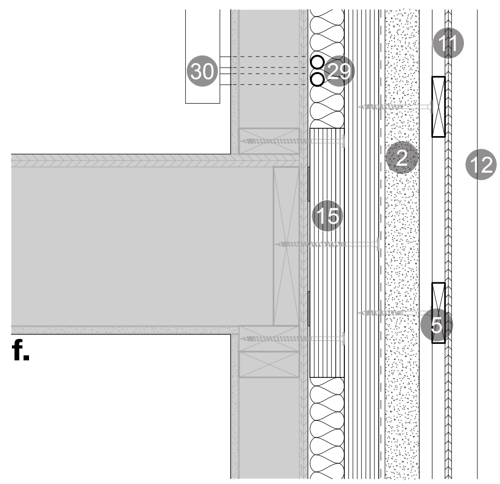
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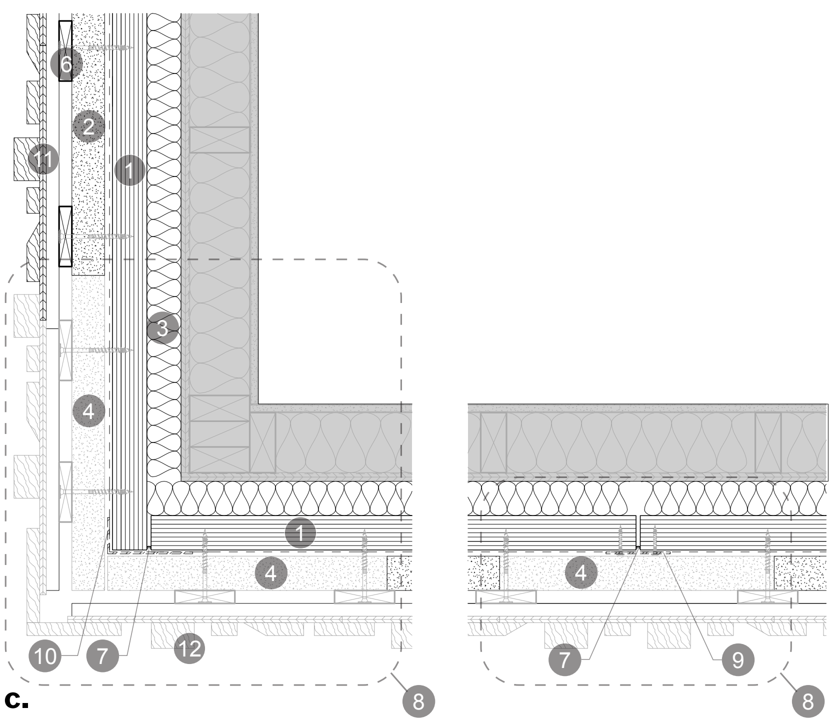
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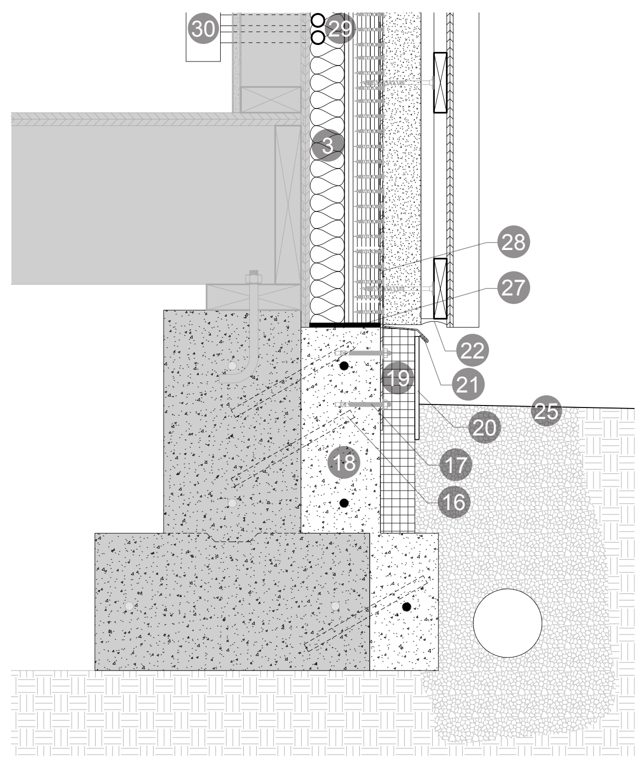
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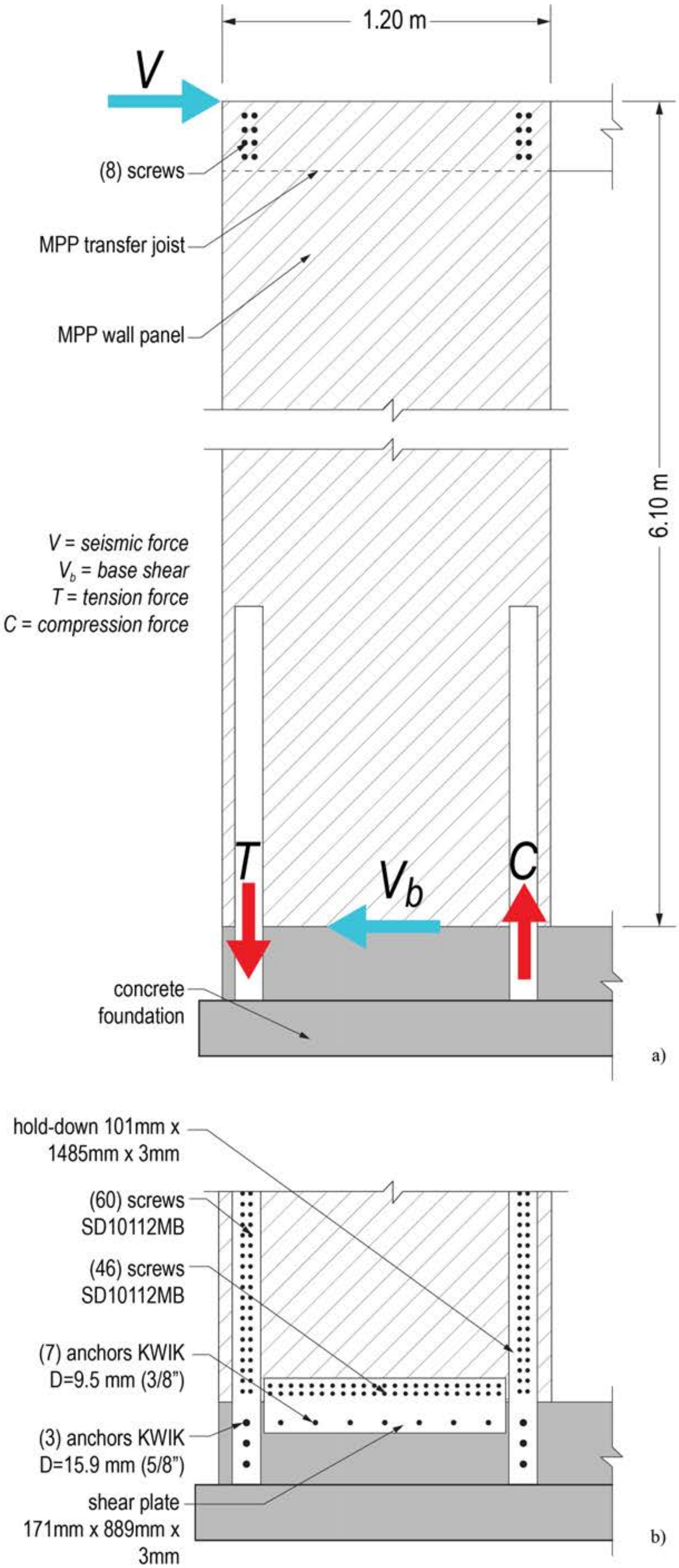
03. STRUCTURAL DESIGN

Structural design (Goal 1, Obj. 1.2)

Develop an attachment system to transfer vertical and lateral loads between the existing structure and the panels. Also develop panel joints to transfer loads between panels and between panels. Five to ten small scale structural tests will be performed.



Single Wall Analysis

Brief

In a single structural wall, lateral design forces are calculated and distributed assuming a triangular distribution of forces. Tension and compression reaction forces generated at the base of the wall, T and C, respectively, are determined.

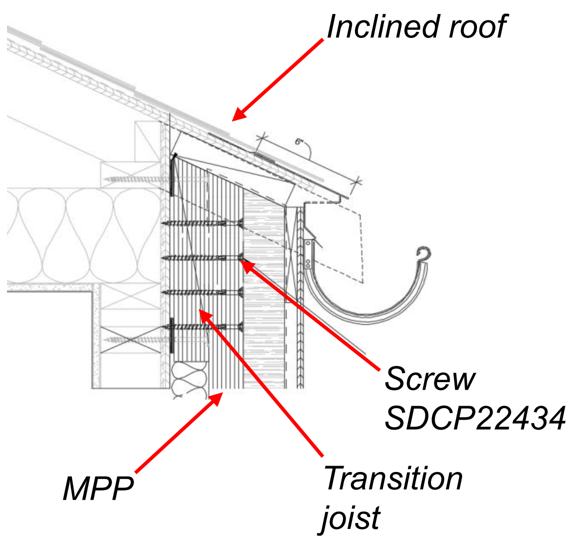
The foundation will most probably need to be retrofitted since typical stem walls in existing buildings will not have the bearing area needed to support the new facade panels. Also, due to the addition of extra walls on the facade, the existing diaphragm needs to be evaluated to verify if additional retrofit elements are needed to resist added capacity provided by the facade panels.

Upon determination of the diaphragm forces, it may be necessary to provide additional floor sheeting and/or steel coiled straps that may work as collectors or diaphragm tension chords. The need for these elements will vary from project to project, and are therefore not detailed here. Example cross-sections on how the MPP is attached to the existing facade and additional non-structural insulation materials are shown or a foundation and roof eave connection. Additional details on other necessary considerations are provided elsewhere.

Lateral Deformation Analysis

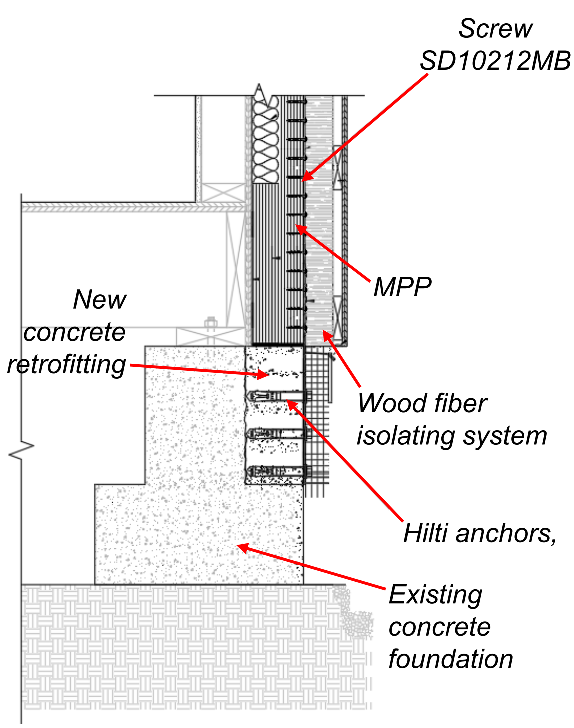
Lateral deformations of the new LFRS can be verified using a nonlinear analytical model, that considers three types of deformation types in the wall: (1) lateral deformation due to the rocking of the panel, (2) lateral deformation due to the flexural deformation of the panel, (3) lateral deformation due to the shear deformations of the panel.

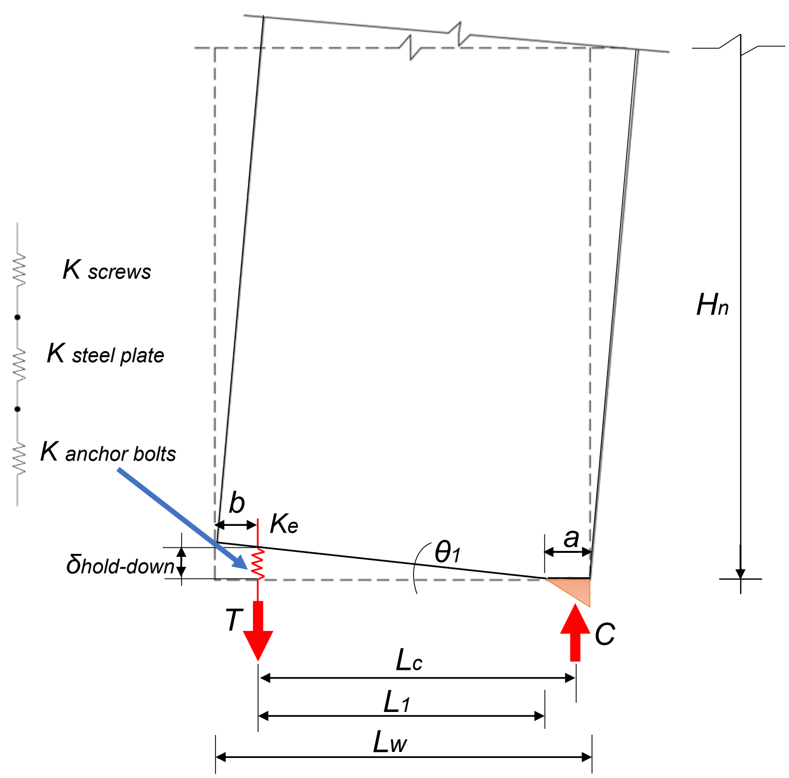
A simplified model illustrates the effects induced by the rocking of the wall. As the wall rocks about one end, the opposite end tends to uplift resulting in compression and tension of either hold-down.

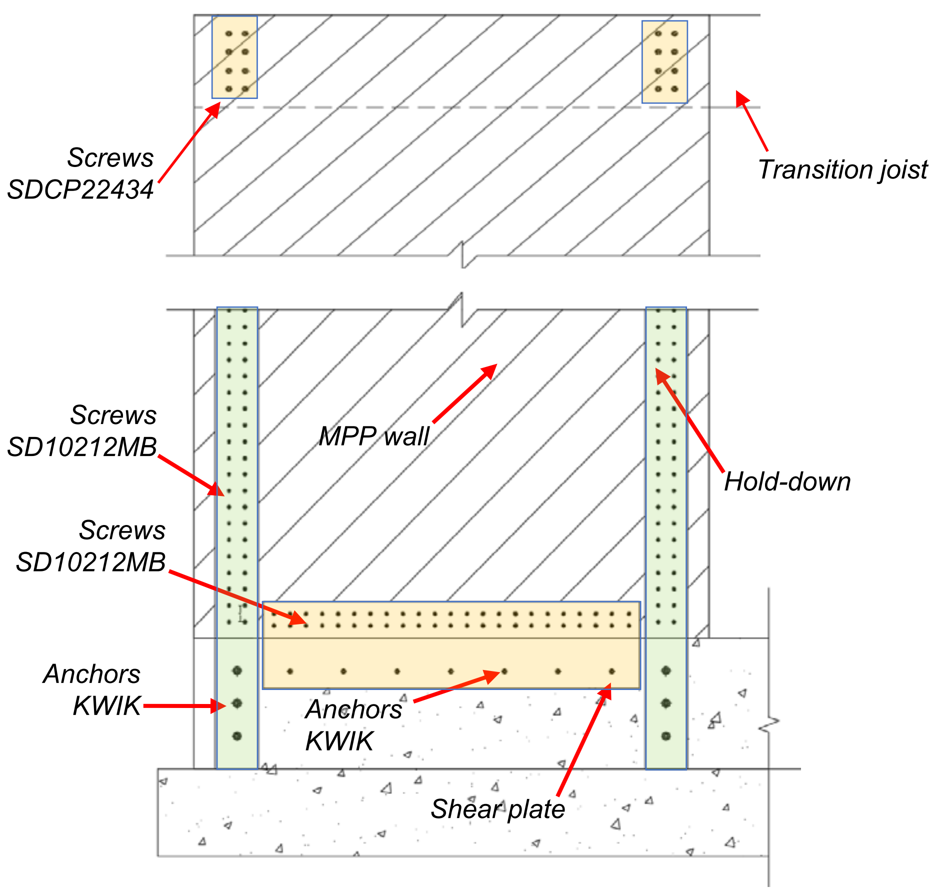


Non-Linear Capacity

The capacity-based design methodology requires the calculation of any source of over-strength that can affect the new LFRS. In the present application, the main contributor for over-strength in the system is the existing LWF structure. To obtain the lateral stiffness of these walls, simplified backbone curves can be calculated from experimental tests, considering different types of sheathing and length of walls. Infill walls are not considered in the lateral resistance of the exiting LWF, and are only considered for over-strength factor calculation.



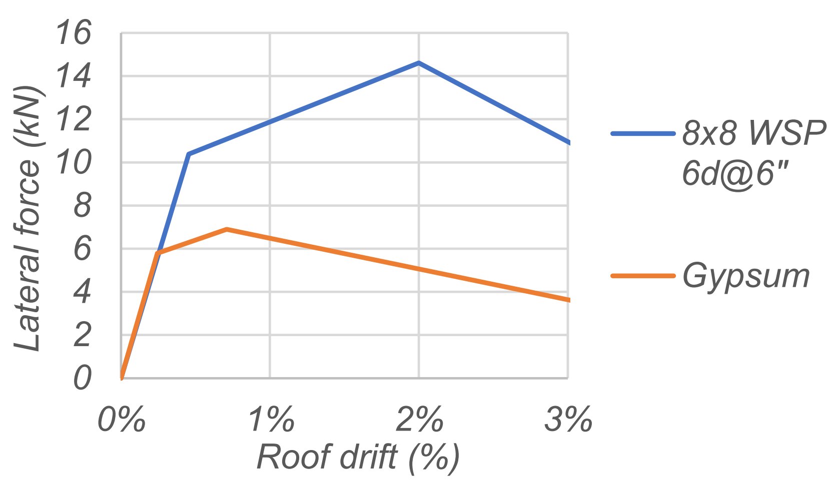




Shear Transfer Connections

For this example, an overstrength factor, Ω, of 4 is initially considered. Based on this assumption, the ASTM 572 shear plate connection is 3.2 mm thick, 171 mm wide, 889 mm long, and requiring a total of 46 SD10212MB screws, and seven carbon steel KWIK expansion bolts with a diameter of 9.5 mm.

For the transition joists, 16 screws type SDCP22434 are needed. Note that these are designed with slotted hole connections that allow the wall to rock relative to the transition joist without inducing uplift forces on the joist.

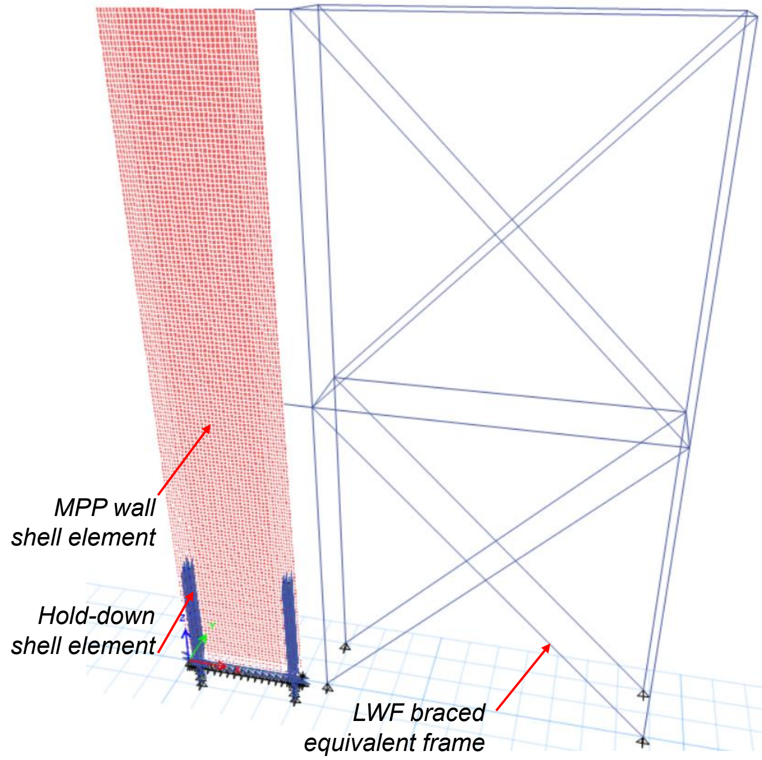


LWF Contribution

The exterior and interior walls of the existing structure contribute to the performance of the building, by increasing its apparent strength and stiffness. For each MPP structural wall, a tributary length of existing exterior and interior walls and type of sheathing are considered in the determination of the contribution of the existing walls to the apparent strength and stiffness. For the interior gypsum board walls, a tributary length of 3 m is assumed. For the exterior walls, which are assumed to be wood structural panels with 6d nails spaced at 150 mm on-center (8x8 WSP 6d @ 150 mm) a length of 1.20 m (4 feet) is assumed, thus neglecting the contribution of the existing walls with window or door openings. The resulting backbone curves are based on these considerations.

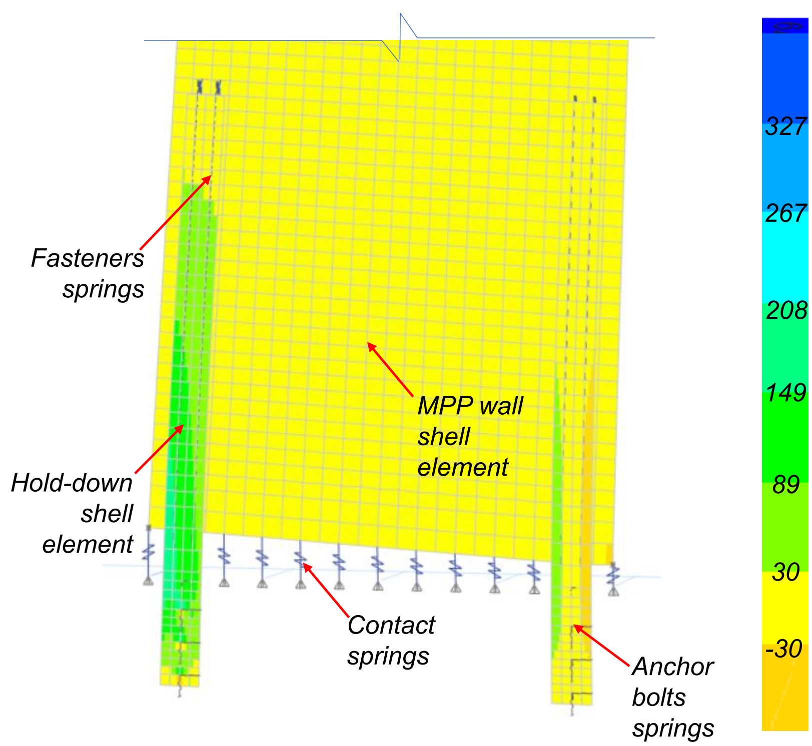
Finite Element Model

A detailed Finite Element Model (FEM) was developed to predict the response of the retrofitted building and validate the analytical methodology described in the previous sections. The FEM software used was ETABS. The MPP structural walls are modeled using elastic shell elements for the panel and nonlinear fiber shell elements for the steel plate, both with a mesh size of 50 mm x 50 mm. Orthotropic material properties for the MPP are assumed, based on experimental data, using 12362 MPa for Ex, 2979 MPa for Ey, 206 MPa for Ez, 861 MPa for Gxy, 820 MPa for Gyz, and 145 MPa for Gzx. Multilinear elastic links are used to model the nonlinear behavior of screws and bolts. Compression-only nonlinear elasto-plastic contact springs are assigned to the FEM to simulate the uplift/contact behavior of the panel with the foundation, considering a yield stress for MPP of 42.95 MPa, a corresponding yield strain of 0.0032, and ultimate strain of 0.007, with the tributary area for each spring and a plastic hinge length of twice the panel width (152.4 mm).



The existing LWF structure is modeled using X-braced frames that can deform axially only and capture the horizontal story force-displacement response. Compression and tension plastic hinges are assigned for two braced frames acting in parallel to capture the shear response of the exterior and interior walls. The vertical and horizontal elements are assumed to be nearly rigid elements with moment releases at the ends.

A nonlinear static analysis is performed, using a displacement-controlled analysis, with 200 saved steps until reaching a target displacement at the top of the MPP wall of 254 mm. The nonlinear parameters used in the software are: Newton-Raphson for positive iterations, Constant-Stiffness for negative iterations, solution scheme is Event-to-Event Only, event lumping tolerance (relative) of 0.01, maximum events per step of 200, minimum event step size of 0.001, and the maximum number of null events per step of 5.



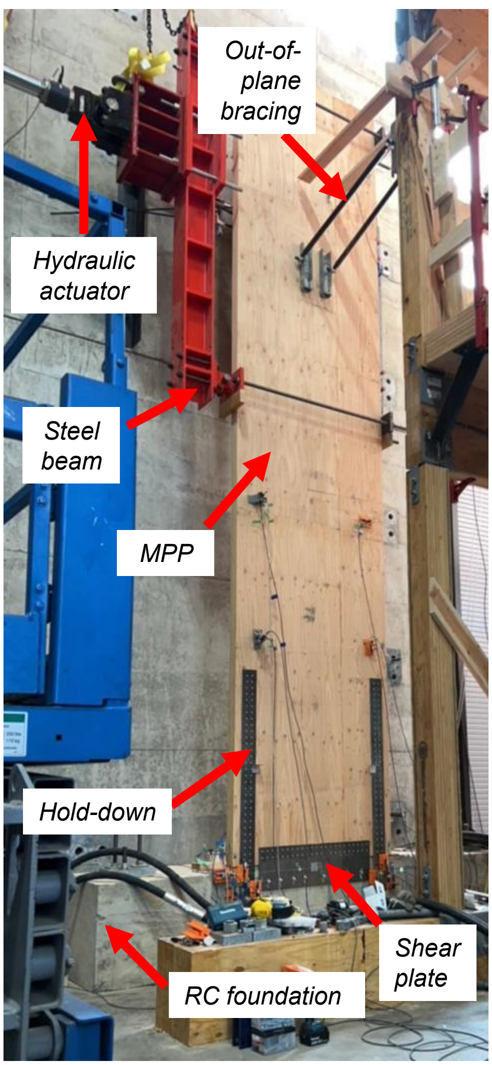
Structural Test

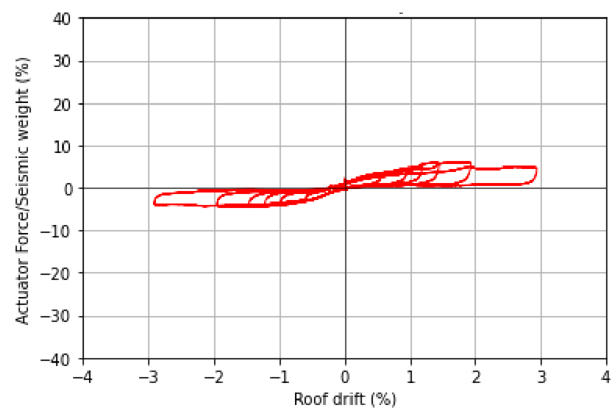
Experimental program and results

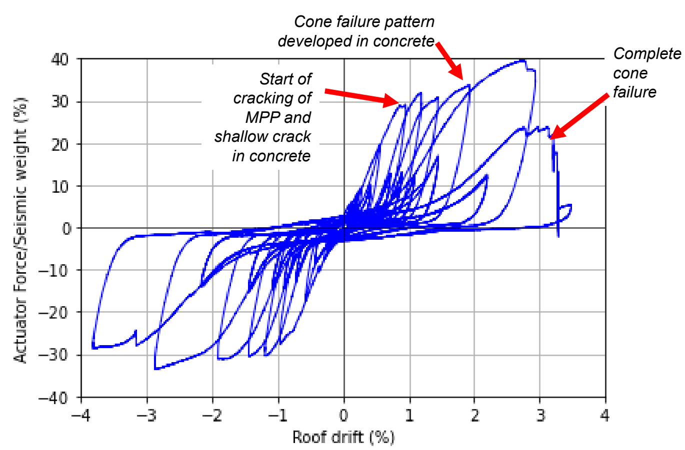
An experimental setup for the retrofit solution, consisting of a single MPP wall, F16-3 layup with dimensions 1.20 m wide, 6.10 m high, and 76.2 mm thick, attached to a reinforced concrete foundation via custom-designed steel plate connections (hold downs and shear plates). The experiment contemplates a two-story building where the first story is 3.05 m, and the second story is 2.58 m in height. The reinforced concrete foundation is designed with closed hoop stirrups every 15 cm, designed to resist the maximum shear force from the rocking system. Pryout analysis of the bolt connections should be performed following ACI 318-19 requirements.

The experiment consisted of two phases. Phase 0, which includes the shear plate at the base of the wall only and the lateral bracing for stability, and Phase 1 with the addition of hold-down connections installed in the wall to provide an increased over-turning moment capacity. By separating the experiment into two phases, the overstrength capacity of the system due to the shear plate and minimal impact of the out-of-plane bracing can be assessed.

The key findings from the experimental test are: (1) the overstrength capacity of the shear plate connection is minimal, due to the slotted holes used to attach the steel plate to the expansion bolts. (2) Phase 1 of the experiment showed an increased in-plane over-turning capacity of the wall due to the hold-down connections. (3) The energy dissipated in the hold-down connection is highly dependent on the degradation of the anchor bolts and the concrete around them. Pryout failure limited the capacity of the test, reaching a maximum drift of 3% in one of the directions.



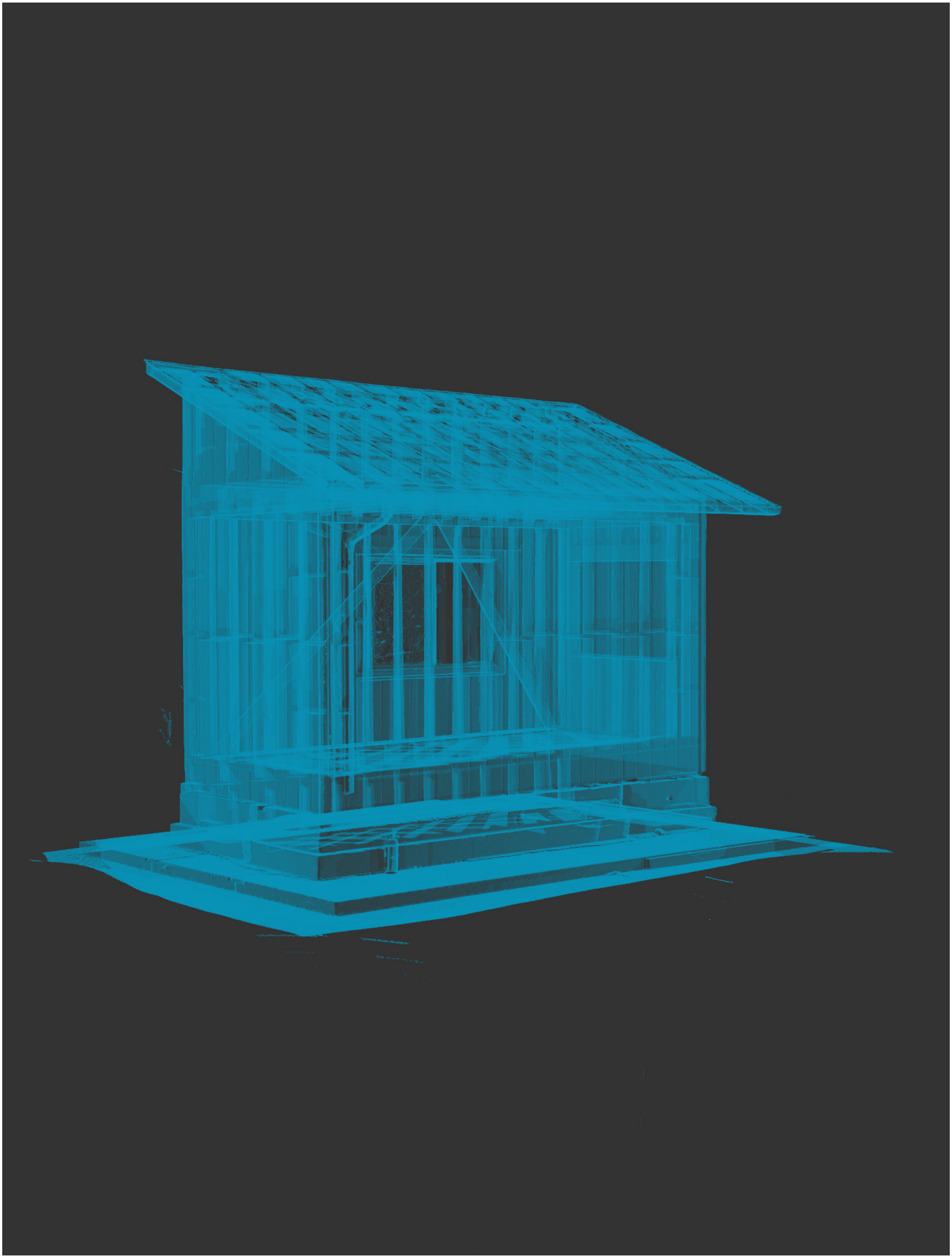




04. FULL-SIZE TEST DEMONSTRATION

Full-size test and demonstration
(Goal 1, Obj. 1.3)

Mockup a portion of a building to mount panels onto; this structure will model an older structure as expected to be found in the field. Test the ease of installation of each of the key attachment and joint details. Install sensors to monitor performance during testing. We will apply forces to simulate seismic loads to better understand and verify performance in a real-world situation. We will use video and still photography recording to capture key elements and events of the testing process. Quantitative results will be compiled, analyzed, and compiled into a technical report.

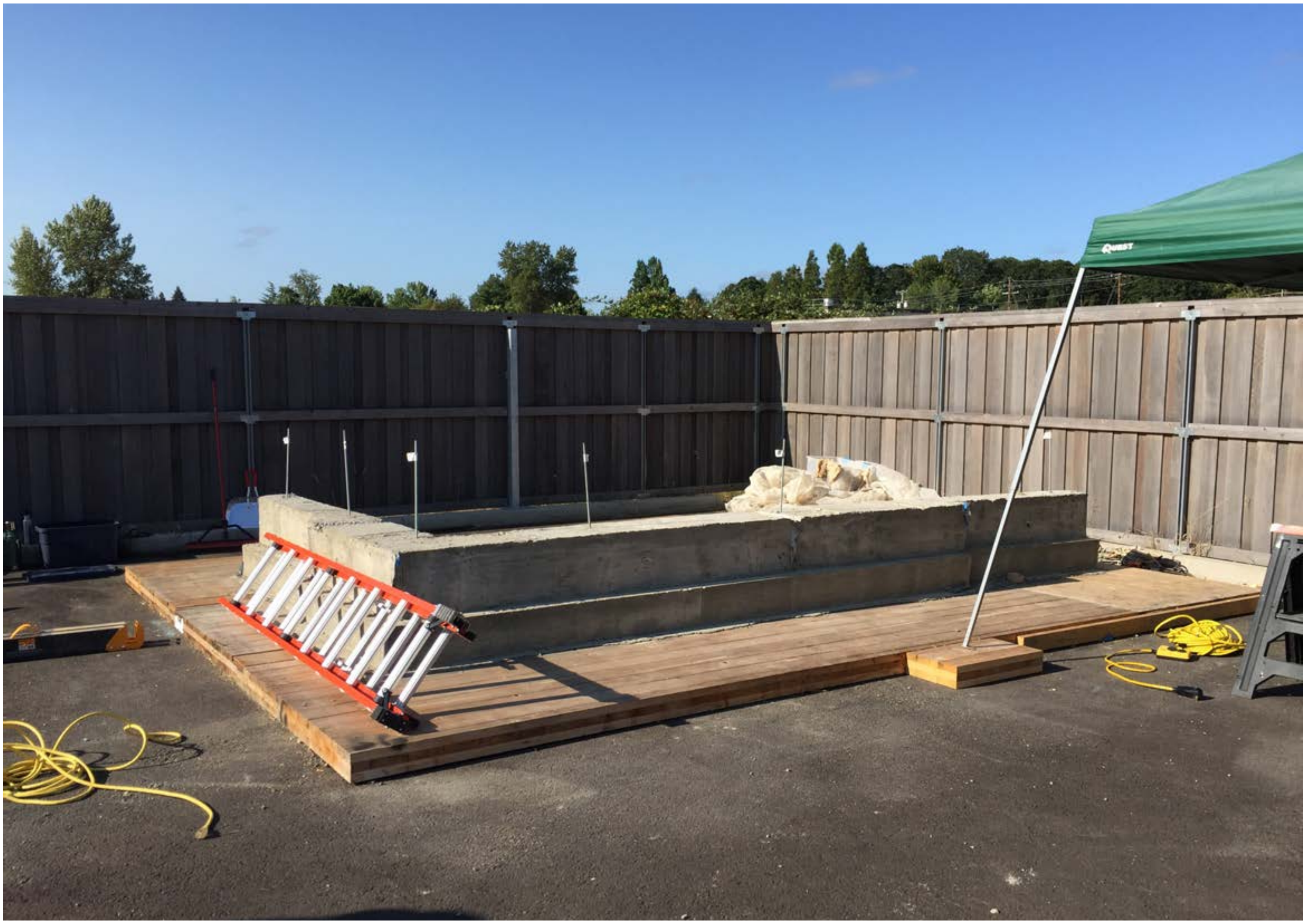


Step 1: Create Existing Condition

We constructed a full-size mock-up using a corner and window condition from the case study building 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.

First, we created a mock existing condition. The panel to foundation connectors were sized for the two-story case study building, but 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.




DEWALT
FRAMING

Step 2: Scan Existing Building

A critical aspect to the fabrication of the panels is the digital workflow that occurs before physical construction can begin. Existing building conditions pose a variety of challenges such as uneven wall surfaces, existing window and door openings, roof overhangs, irregular foundation surfaces, and other out-of-plane details that can affect the design of the panels. As a way to mitigate the effects of imperfect conditions, LIDAR scanning is a helpful tool that can identify defects on the existing building and provide accurate measurements that can be used to digitally fabricate the panels. As part of this research, three different LIDAR scanning methods were used to identify challenges and advantages of different scanners and softwares.

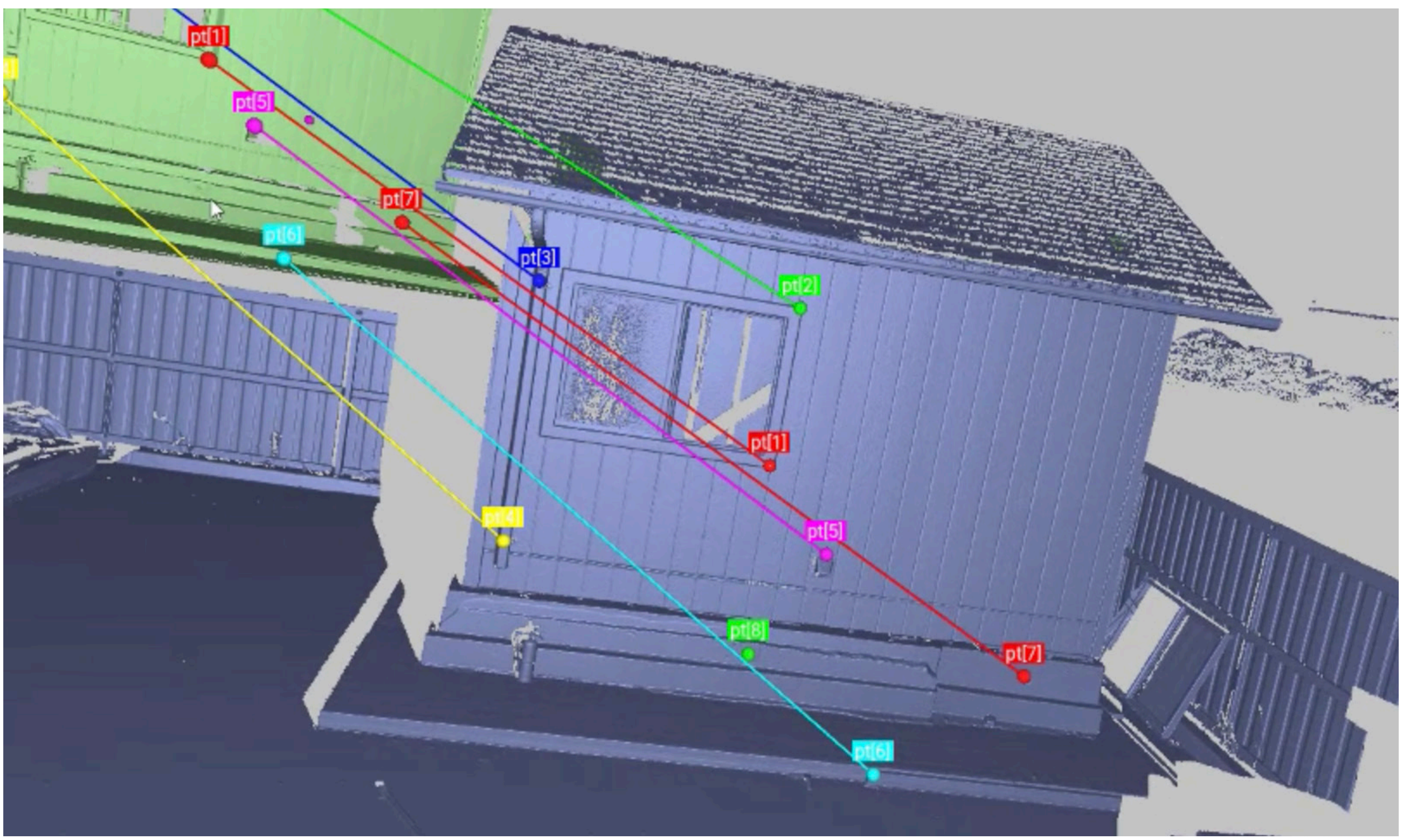
The first scanner used was the Leica BLK360 accompanied by its proprietary software Cyclone 3DR. This scanner achieved accuracy within 2mm; however, the final output of the point cloud files proved to be cumbersome and Cyclone 3DR was not only difficult to use, but also expensive. Based on this evaluation, the Leica scanner and its Cyclone software, although accurate, may not be the most accessible to designers due in part to its lack of user-friendly design.

The second scanner used was Matterport. Given the nature of the uses for this scanning method, it is not intended for accurate architectural documentation, but rather for virtual experiences. Therefore, point cloud data was inaccurate with substantial gaps within the data points. This method was not viable for extracting the necessary information to fabricate the panels.

The third scanner used was the Artec Ray, courtesy of Hawk Ridge Systems. This scanning method proved to be the most versatile and accurate of the three scanners. This process involved using a combination of a tripod camera and a handheld camera to capture all of the necessary details. In addition, Artec's proprietary software, Artec Studio, was user-friendly and has features that enable surface analysis. The surface analysis tool was especially useful for determining deviations on the surface of the existing walls. This allowed us to determine where the wall surfaces had the greatest amount of variation. Furthermore, Artec Studio had the greatest compatibility with architectural software; exporting file formats enabled the point cloud data to be imported into Autodesk Recap Photo which then could be exported as an .obj file into Autodesk Revit and Rhinoceros.

During the process, both Revit and Rhino were evaluated for their panel modeling uses. Rhino proved to be an effective tool for analyzing surface deviations (using the contour tool); however, modeling panels to the existing conditions was not effective due in part to Rhino's inability to handle large data files (in this instance, the .obj file from Recap Photo). Revit was better suited for both handling large point cloud data files and the panel modeling itself. With Revit, as-built conditions were able to be easily modeled using the LIDAR scan as an underlay and, thus, panels could be modeled with both the LIDAR scan and as-built 3D model as bases. A major challenge we were presented with was a highly irregular foundation stem wall face. The jagged edges offered the opportunity to experiment with the digital 3D model to investigate whether or not the MPP could be cut to conform to the edges of the foundation. Using the LIDAR scan, we traced the foundation's irregular edges and translated them into the 3D model so that the CNC could make these angular cuts.

Once 3D modeling of the MPP was complete, the file format needed to be compatible with the CNC machine software. With the help of Phil Mann, the Lab Technical Manager at Oregon State's Emmerson Lab, we navigated the process of file format compatibility. Initial efforts involved exporting a Revit file to a SolidWorks file; however, this was not able to be achieved. The next step was to export the Revit file to Rhino as Rhino offers a greater variety of file export formats. After a series of trial and error, the .stl file export was able to be opened in SolidWorks. Unfortunately, there were still difficulties with the .stl file once it was opened in SolidWorks and Phil ultimately had to remodel the panels.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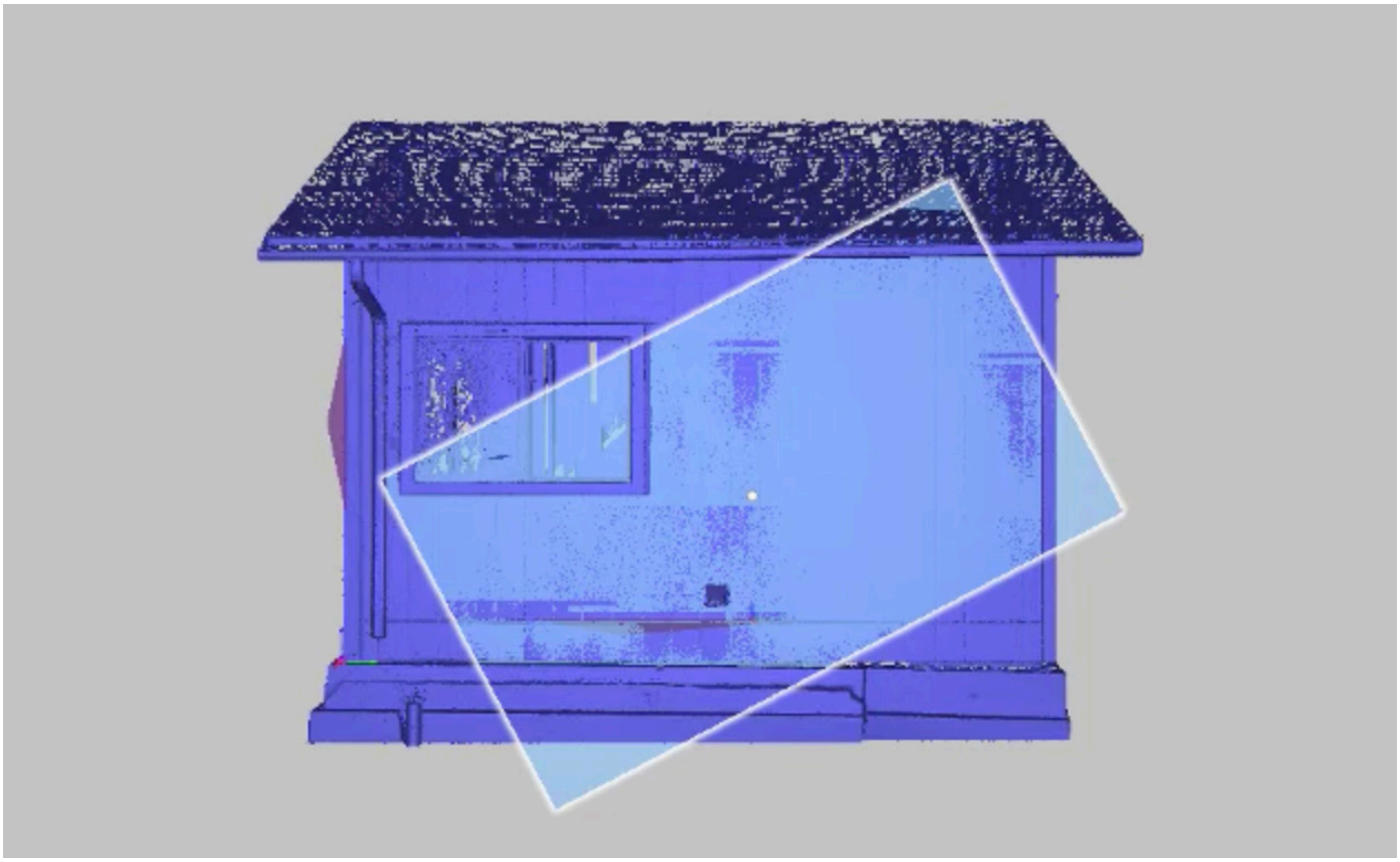

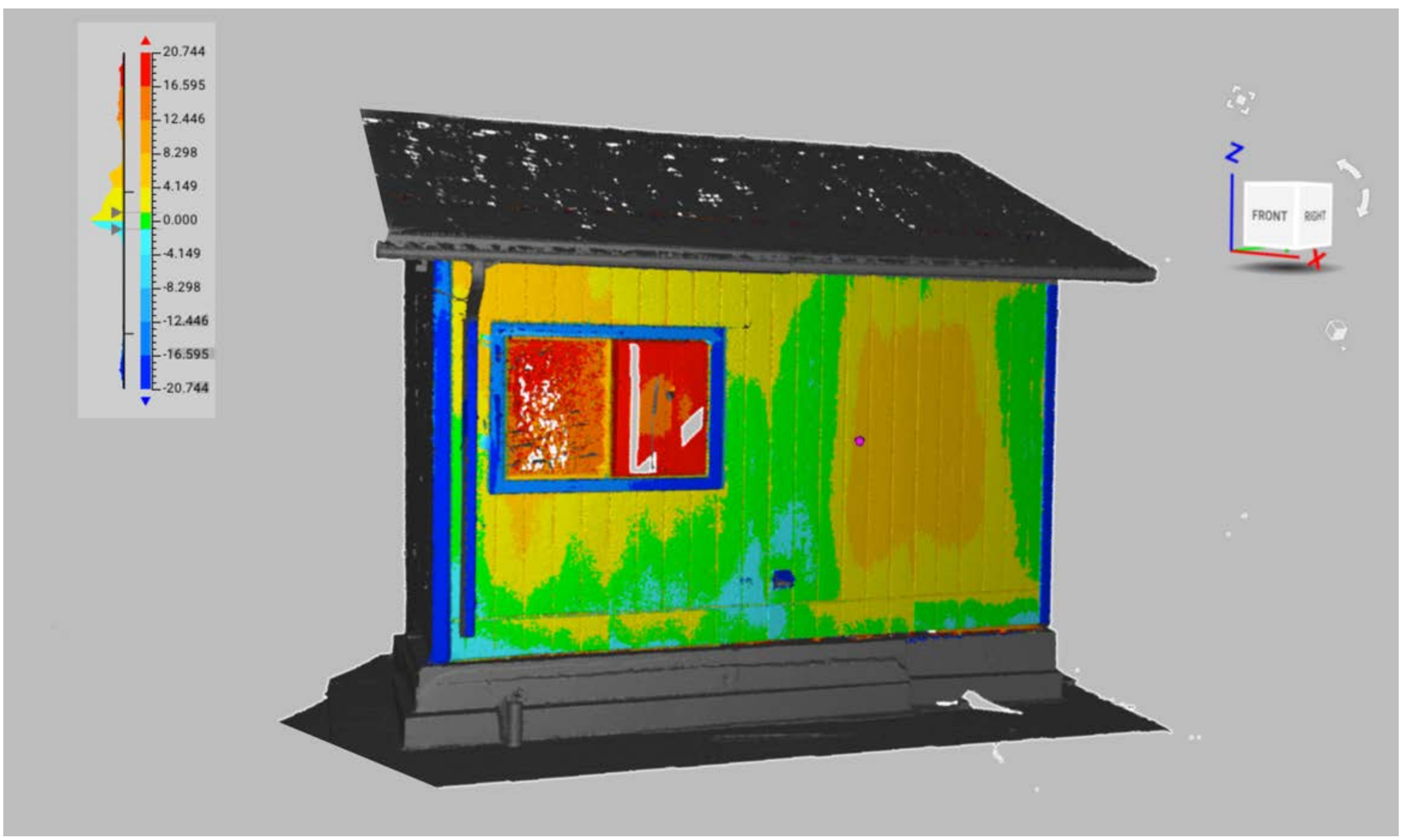
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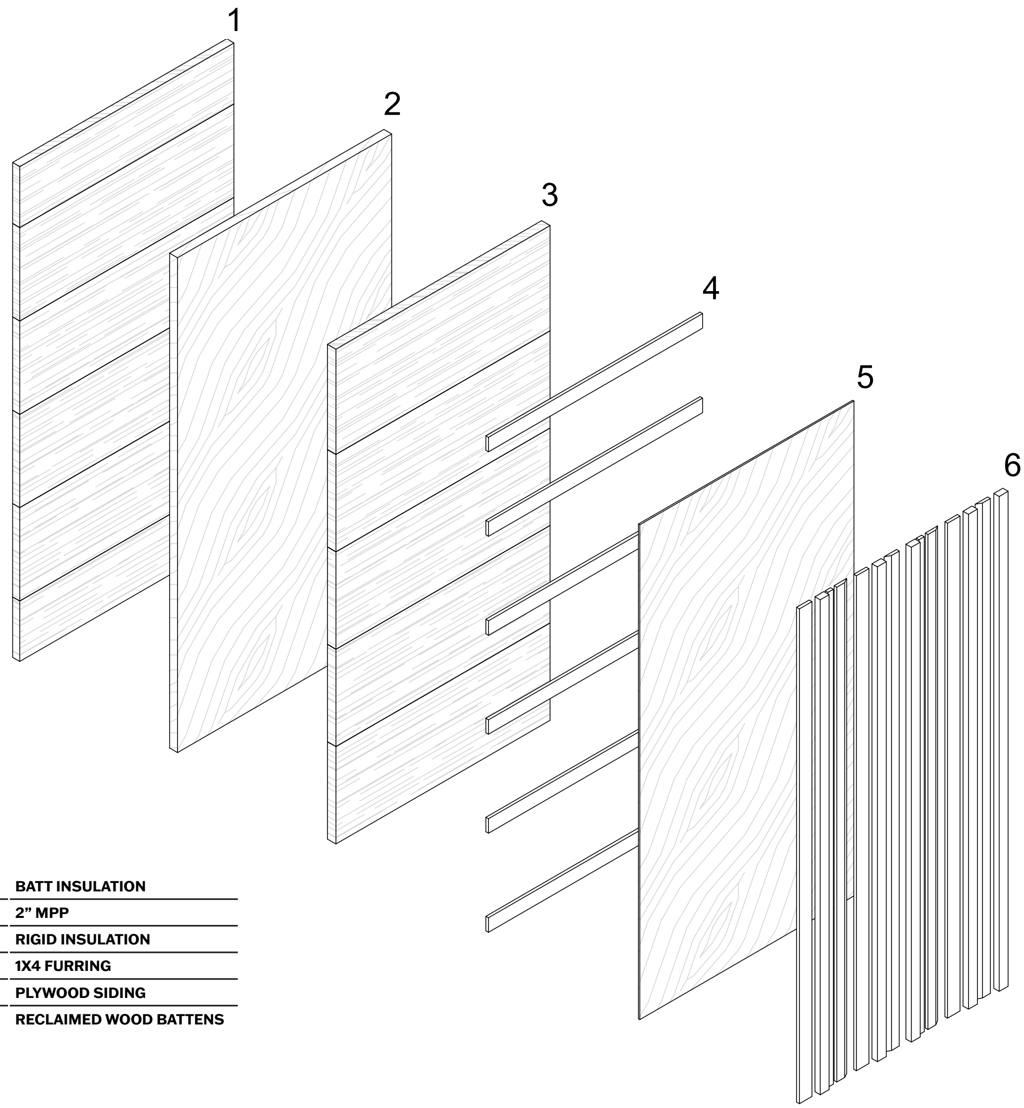
Step 3: Fabricate Panels Off-Site

Once cut files were ultimately 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 along with the subsequent addition of weather barrier, window, flashing, insulation, and cladding.

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

Some elements of facade panel assemblies are best accomplished with panels oriented flat. For example, bonding wood fiber insulation to

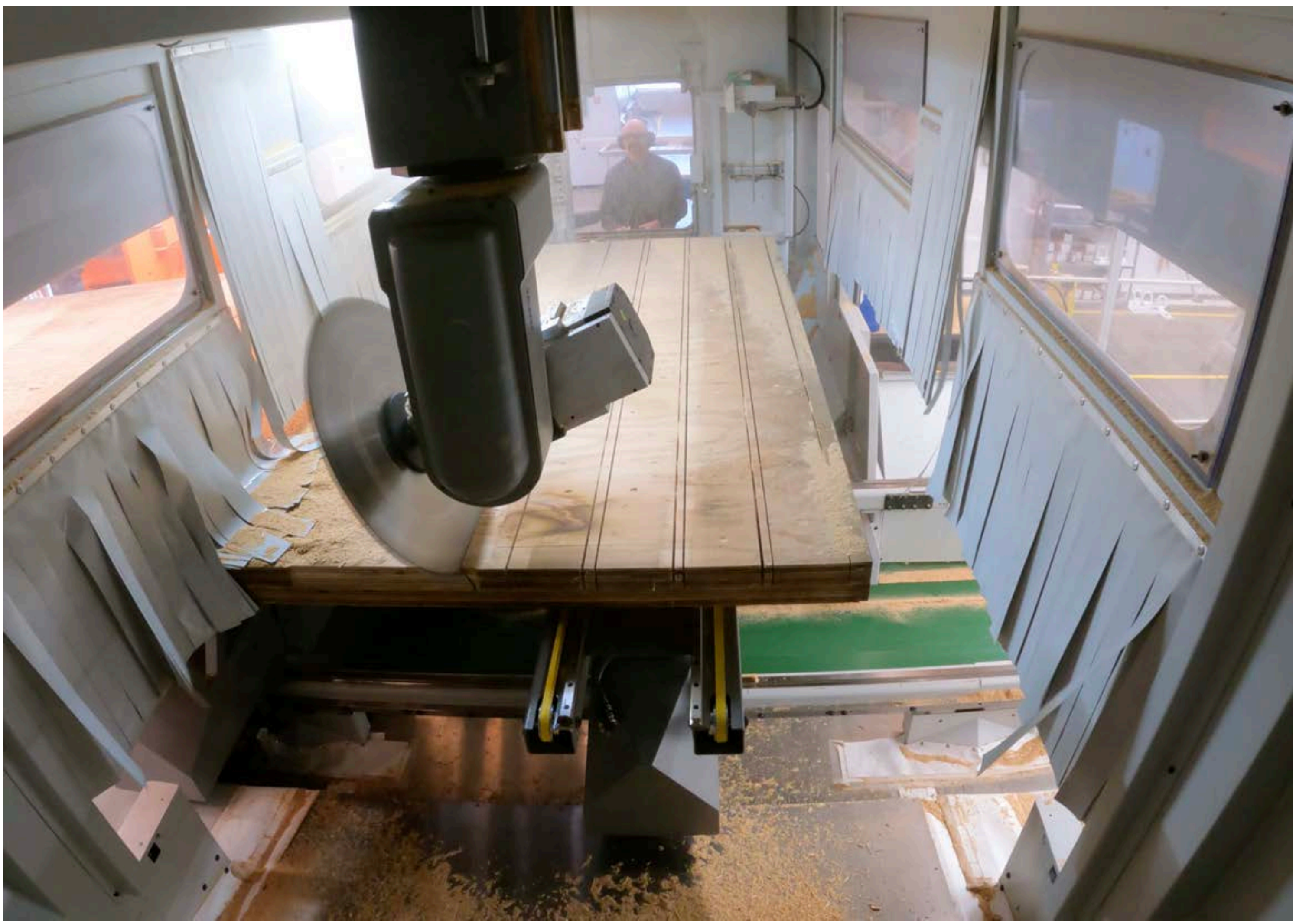


1	BATT INSULATION
2	2" MPP
3	RIGID INSULATION
4	1X4 FURRING
5	PLYWOOD SIDING
6	RECLAIMED WOOD BATTENS

the MPP prior to CNC milling of the composite panel was piloted and proved a successful means of reducing the overall fabrication labor. 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 facade 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 adds 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 facade aesthetic. Seismic connectors were intended to be limited to exposed vertical edges of each panel, with field-installed vertical siding elements used to conceal panel-to-panel joints on the completed facade. 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. This area, if left exposed for installation, needs future consideration for how it will be detailed to be incorporated into the overall facade design.



Step 4: Prepare Existing Building

On-site work includes the addition of the retrofit concrete foundation and associated ground work, which ideally occurs prior to scanning the existing building and initiating the panel fabrication process as was done with this mockup.

Once the fabricated panels are ready to be delivered and installed on-site, the building must undergo a few operations in preparation for efficient panel installation, a high priority when a crane would be required for a full building facade retrofit. Included in these preparations is the installation of a 52 mm MPP transfer joist at the roof diaphragm, removing the existing eave for ease of installation, plus removing gutter, downspout, trim, dryer vent, and existing window. If this were a multistory building, additional transfer joists would be installed at each floor level to tie back into those diaphragms as well. If carefully staged and sequenced with an interest to limit tenant disruption to at minimum a single day, window removal could occur just prior to panel installation, and once panels are in place a finish carpenter could follow behind to trim the interior connection between existing rough opening and new pre-installed window in the retrofit panel.

Step 5: Fly and Mount Retrofit Panels

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, then continued with the seismic shear panels at the corner and in-plane panel-to-panel location with approximately 6 mm tolerance between panels. For the purpose of positioning panels for this one-story mock-up, a forklift with an appropriate attachment for two-point lifting was used.

In rigging the panels for lifting and installation two Dragon lifting belts (Rothoblaas, Cortaccia, Italy) were used suspended from the forklift 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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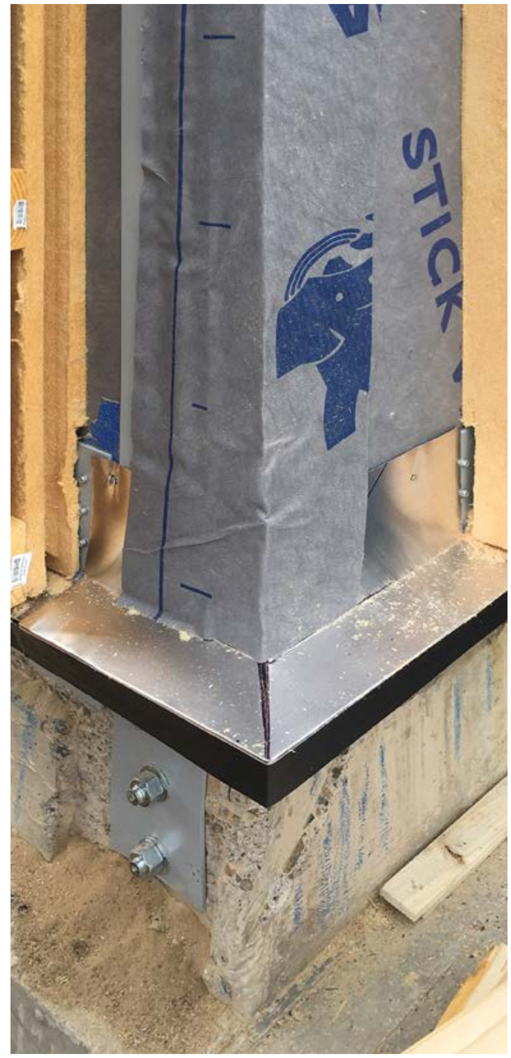
SSAN



Step 6: Close Remaining Envelope

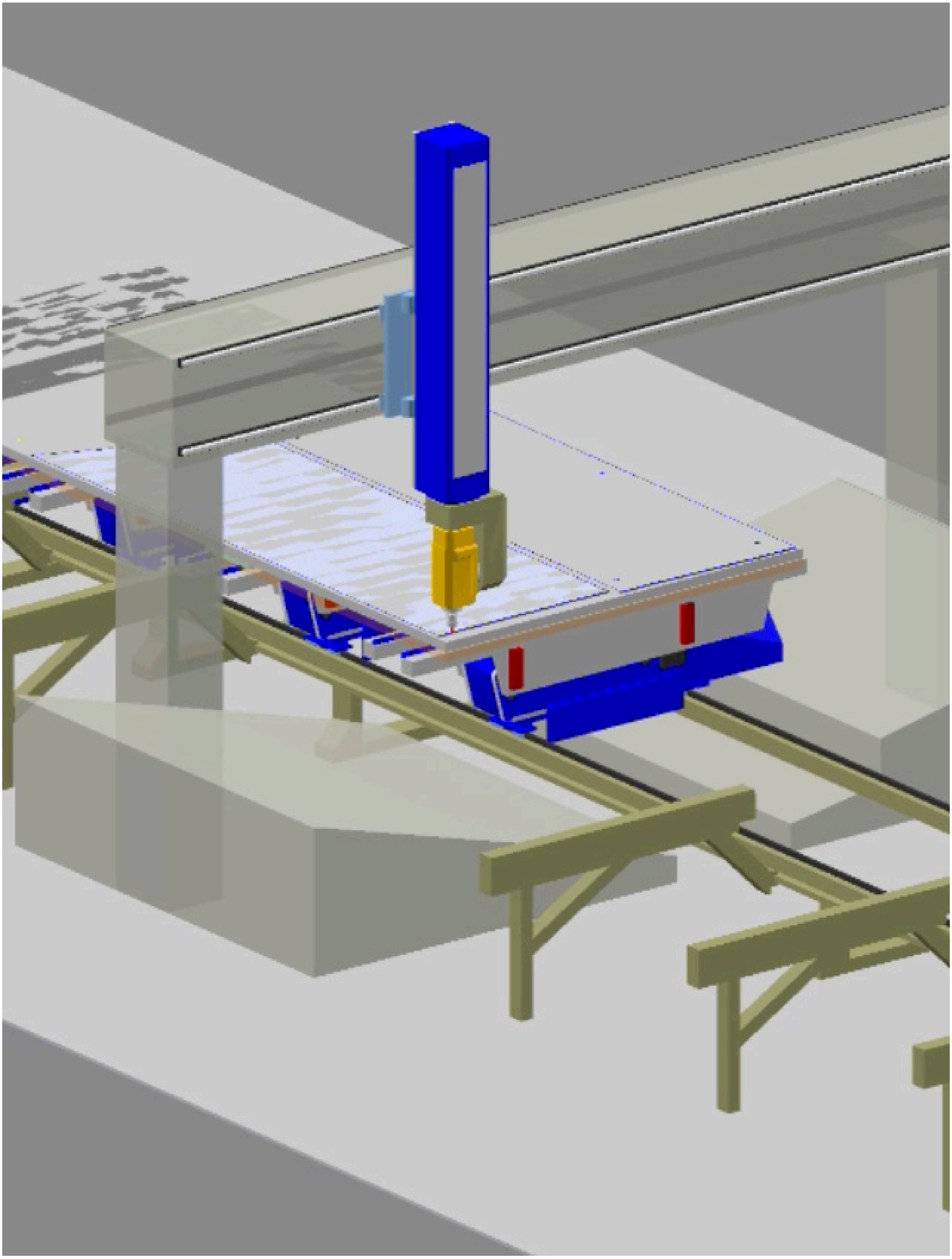
After completing all structural connections, we closed the joints with sealant, weather barrier, in-plane panel-to-panel plates, insulation, and cladding. Lastly, we installed the roof blocking, sheathing, shingles, and the foundation rigid insulation with cementitious board over the newly installed seismic connections.

Where deep overhangs from existing eaves impede retrofit facade 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. Though the scope of the current project is limited to facade 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 facade 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. If desired, that retrofit roof addition could replace or even extend the eave overhang.

05. COST ANALYSIS

Cost analysis (Goal 1, Obj. 1.4)

Use the data from Task #4 to estimate manufacturing and installation costs, both in materials and labor.



Cost Considerations

Cost is a primary consideration of whether a building owner may undertake a deep energy retrofit of an existing building enclosure. In the European *Energiesprong* model, the entire building enclosure (roof was not included in this research scope) is upgraded along with renewable energy upgrades and HVAC upgrades. This complete retrofit package allows the installer to provide a warrantied package of energy performance for a specific performance period, which, provides the owner with a known rate of return from energy savings and renewable energy generation to offset the additional cost of performing the retrofit. Thus, the owner or tenant does not have an increase in their monthly expenses.

The Netherlands has realized the majority of *Energiesprong* projects, largely due to Dutch expertise with construction prefabrication and substantial affordable housing building stock that is owned by the government, which provided an initial economy of scale to induce the capital investment required for high-tech digital fabrication.

In the United States, and in particular the U.S. West Coast, the housing and construction market conditions are dissimilar to those of the Netherlands and make the initial adoption of this system more challenging. First, the manufacturing base for building prefabrication is still emerging and is not as mature as in Europe. Second, multifamily housing (primarily 1-3 stories) is typically privately owned by private individuals, investment groups or real estate investment trusts (REITs) with tax subsidies for affordable housing. Thus, owners must derive economic value from retrofit investments. One could make the case that improved thermal performance will improve thermal comfort and acoustics for tenants, thus, tenants will have higher satisfaction resulting in lower vacancy rates. Furthermore, facade upgrades can improve aging building aesthetics and contribute to a positive carbon emissions story, thereby attracting additional tenant demographics. On the West Coast, adding additional building insulation can increase the weight of the existing LWF structure, thereby triggering mandatory seismic retrofits. By combining energy upgrades and seismic upgrades in one facade system, the project team hopes to reduce financial barriers to each of these individual retrofits that are necessary for long-term resilience, thus providing additional incentive to private owners.

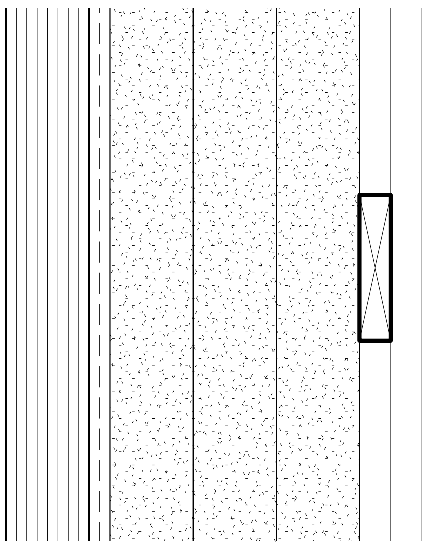
When considering costs for the facade retrofit there are hard costs, including material costs, digital fabrication costs, and installation costs and soft costs, including professional design services and permitting. The research team assumed that the structural and facade conditions of the existing case study building were sound; however, if this were not the case, costs could be widely variable and possibly tilt the proforma in the direction of new construction versus retrofit.

Material costs can vary based on number and size of windows and doors, market conditions, and the level of upgrade desired. At the outset of this project (2020) during the pre-design phase, the project team found that estimated costs for solid wall area could range from $7.88-$13.52 per square foot. However, shortly thereafter, wood fiber and other building materials experienced supply chain disruptions and volatile pricing due to the Covid-19 pandemic.

Since the U.S. market for prefabricated modular panels fabricated using digital tooling is still in its infancy, it was difficult to obtain reliable information on CNC costs. At the time of this writing, the panel manufacturer charged $20 per minute for CNC time. All three panels used on the mock-up required 11 minutes, 16 seconds (6 minutes 47 seconds for the multi-panel billet and 4 minutes 31 seconds for the panel that included a window cutout) of lab CNC run time. At the market rate of $20 per minute, this would be $225.33, or approximately $1.48 per square foot.

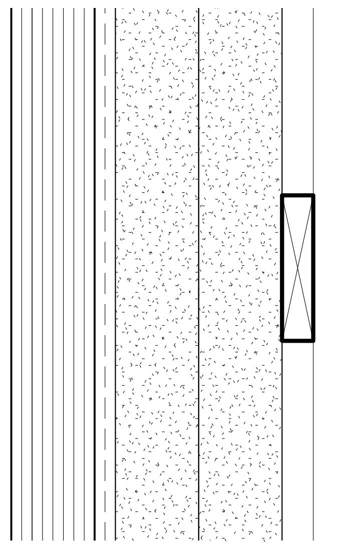
Labor costs can vary based on regional market conditions. For this project, we did not estimate regional labor costs but rather labor time. Of course, since the mock-up was an initial prototype and useful for developing

Panel Sections - Inboard MPP



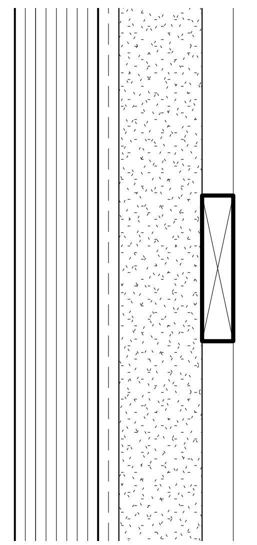
Option 1

PANEL R-VALUE: R-34.5
ESTIMATED COST: $13.52/sf
ESTIMATED WEIGHT: 9.04 lb/sf
OVERALL THICKNESS: 12”



Option 2

PANEL R-VALUE: R-18.5
ESTIMATED COST: $9.76/sf
ESTIMATED WEIGHT: 6.38 lb/sf
OVERALL THICKNESS: 8”



Option 3

PANEL R-VALUE: R-10.5
ESTIMATED COST: $7.88/sf
ESTIMATED WEIGHT: 5.05 lb/sf
OVERALL THICKNESS: 6”

the design itself, future versions would be fabricated more efficiently. Furthermore, the Emmerson Lab used to fabricate assemblies was not configured for standardized high-volume production. Thus, each panel required approximately 16 hours of labor (2 laborers at 8 hours each) to lay up with peel and stick weather barrier, steel seismic connections, window, rigid wood fiber insulation, battens, flashings, blocking, wood T1-11 cladding and wood trim.

Mounting the panels on the existing structure required 1 hour to remove the eave, 1 hour to place transfer joists and 1 hour x 3 laborers (one operating the boom, one guiding the panel into place and one drilling anchor bolt holes into concrete, securing expansion bolts and making wood fastener connections to transfer joist) to place all three panels and make structural connections. Remaining work included closing panel-to-panel joints that required 2 hours, adding roof blocking, plywood, roofing membrane and asphalt shingles that required 2 hours and adding rigid EPS insulation, cement board and mortar skim coat to foundation required 1.5 hours.

In all, the project team noted that increasing pre-fabrication of parts such as blocking, battens, insulation and closure panels to the standard 16″ wide dimension would significantly reduce time on site assiduously cutting pieces to size. Furthermore, the team tested options where wood fiber insulation could be adhered to the MPP substrate and cut with CNC tools during the cutting of the MPP panels. This would save significant labor in the fabrication of these panels and should be considered in future iterations. In addition, it was beyond the scope of this project but the roof could also be potentially upgraded with retrofit panels, incorporating the time spent re-roofing into the upgrade of this important building component.

06. DISSEMINATION ACTIVITIES

Industry outreach and dissemination (Goal 2, Obj. 2.1)

We will disseminate the technical findings by several means. Most importantly, key industry stakeholders will be invited to visit the mockup before testing. These include our collaborators at REALIZE and a limited number of our other contacts throughout the wood products and multifamily housing industries. We will develop promotional materials based on the technical report and distribute these strategically. We will publish an open-access journal article in Energy and Buildings or similar and present the system at the ACEEE Summer Study conference or similar. Outreach efforts will begin in advance of Task 4.

Publications

Completed

Fretz, M., Stenson, J., O. Orozco, G.F., Narancic, P., Casey, F., Northcutt, D., Van Den Wymelenberg, K., Sheine, J., and Barbosa, A.R. (2023). Developing an Application for Mass Plywood Panels in Seismic and Energy Wall Retrofits, *Proceedings of the 2023 World Conference on Timber Engineering*, Oslo, Norway, pp 1034-1043. https://doi.org/10.52202/069179-0141.

Orozco O., G.F., Barbosa, A.R., Fretz, M., Sheine, J., Stenson, J., Van Den Wymelenberg, K., Narancic, P., and Casey, F. (2023). Seismic and Energy Retrofit of Multifamily Light-Frame Timber Residential Buildings Using Mass Ply Panel (MPP) Wall Facade System, *Proceedings of the 2023 World Conference on Timber Engineering*, Oslo, Norway, pp 2669-2677. https://doi.org/10.52202/069179-0350.

Publications

Submitted

O. Orozco, G., Fretz, M., Barbosa, A., Stenson, J., Narancic, P., Casey, F., Northcutt, D., and Sheine, J. (2024). Developing an Application for Mass Plywood Panels in Seismic and Energy Wall Retrofits, *Proceedings of the 2024 World Conference on Earthquake Engineering*, Milan, Italy, June 30 - July 5, 2024. Review Pending.

Presentations

Completed

"Seismic and Energy Retrofit of Multifamily Light-Frame Timber Residential Buildings Using Mass Ply Panel (MPP) Wall Facade System." Presented by Gustavo Fernando Orozco Orozco at the 2023 World Conference on Timber Engineering, Oslo, Norway, June 2023.

"Developing an Application for Mass Plywood Panels in Seismic and Energy Wall Retrofits." Presented by Mark Fretz at the 2023 World Conference on Timber Engineering, Oslo, Norway, June 2023.

"Panelized MPP facade retrofits and panelized affordable housing." Presented by Mark Fretz and Judith Sheine to the Oregon Board of Forestry, which included visit to the mockup at Oregon State University, March 9, 2023.

"Panelized facade retrofits and panelized affordable housing." Presented by Mark Fretz for "Timber Talk" event at Waechter Architects, March 9, 2023.

"Forest to Facade." Presented by Mark Fretz to the Northwest Energy Efficiency Alliance Product Council, January 31, 2023.

"Forest to Facade." Presented by Mark Fretz at the TallWood Design Institute Research Symposium, October 13, 2022.

"Forest to Facade: Seismic + Energy Multifamily Retrofits." Presented by Mark Fretz at Portland's Sustainable Building Monthly, May 2022.

"Forest to Facade" Seismic + Energy Multifamily Retrofits." Presented by Mark Fretz, Payton Narancic and Jason Stenson at the Mass Timber Conference Technical Academy, which included visit to the mockup at Oregon State University, April, 2022.

"Forest to Facade: Developing an Application for Mass Plywood Panels in Seismic and Energy Wall Retrofits." Presented by Mark Fretz, Payton Narancic, Judith Sheine and Jason Stenson to the Build Health industry research consortium of the Institute for Health in the Built Environment, April 29, 2022.

Other

Completed

Institute for Health in the Built Environment maintains a project page on its website: https://buildhealth.uoregon.edu/wood-innovations-mpp-retrofits/

The Building Performance Workshop, a syndicated show on PBS, covered the mockup in a segment on their show called, "An Exoskeleton for Old Homes." https://www.youtube.com/watch?v=67CfagBmXY0&t=26s

07.
CONCLUSION

Findings and Next Steps

This project produced a physical demonstration mock-up of a seismic/energy panelized retrofit, utilizing MPP as the structural core, with performance upgrades to meet U.S. Department of Energy Zero Energy Ready Home (ZERH) Standard 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.

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 or compression and a shear plate that transfers the horizontal base shear 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. 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. Infill wall panels are connected to the MPP transfer joist via slotted steel plate connections.

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. Furthermore, the accuracy of the workflow, physical object to scan to digital model to physical object, is quite high and had an accurate fit without adjustments required on site. The team even used irregularities in the concrete foundation to test the accuracy of using the scan to create a panel edge that adapts to the concrete and maintains a plumb panel. This resulted in a good fit with quick installation. Possibly combining wood fiber insulation as a composite with MPP could save labor and tests conducted during this study demonstrated a high-degree of machinability with CNC operations.

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. 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 facade 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.

Images (clockwise from upper left): panel system over existing T1-11 wall, reflected to show inboard insulation and HVAC space, outboard insulation and ventilated cavity, flashings; panel foundation structural connections for seismic panel; rigid wood fiber insulation adhered to MPP and milled using CNC as a test case; fit of MPP panel window milled opening to existing LWF rough opening before application of interior finish.

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