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Monitoring and modelling of a prefabricated exterior envelope retrofit

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ABSTRACT
As part of a larger project to develop prefabricated technologies for retrofitting building envelopes of Canadian homes, a small building was retrofitted and instrumented. This prefabricated retrofit method is intended to be applied directly over existing cladding. Two prototype retrofit wall systems were installed on the building; a nailbase panel, and a wood frame panel. The existing wall had an RSI value of 1.80 m^2K/W (including film coefficients) and the resulting retrofitted walls reached values of 6.40 m^2K/W and 5.72 m^2K/W. With the addition of a new air barrier, blower door tests have shown a large reduction in infiltration from 7.62 ACH to 0.82 ACH at 50 Pa. This paper discusses the approach taken, the construction of the prefabricated panels, preliminary in-situ RSI measurements, and modelling of thermal bridging and energy savings for the pilot project.

KEYWORDS
Exterior wall retrofit, building energy simulation, prefabricated retrofit.

INTRODUCTION
Canada's housing stock consists of more than 11 million low-rise detached, semi and row-attached dwellings (Natural Resources Canada, 2018). More than two-thirds of these dwellings were built before the existence of residential energy efficiency standards. Although close to one million homes took advantage of retrofit program incentives to date, exterior wall insulation improvements have been uncommon, despite exterior walls often accounting for 25 to 35 percent of heat loss in residential buildings. Anecdotal barriers to exterior wall retrofits include: unpredictable costs; occupant and neighbour disruption; long completion times; and, perceived and real risk related to moisture issues.

This paper discusses Natural Resources Canada's Prefabricated Exterior Energy Retrofit (PEER) project (Natural Resources Canada, 2017a). This project seeks to develop technologies and processes for applying prefabricated components to retrofit existing homes and buildings from the exterior. Guided by a working group to provide technical guidance and market intelligence, the project team is collaborating with industry partners to develop technology specifications and build and test prefabricated panels. There are three main components: field dimensioning using 3D imaging and scanning; development of panel prototypes; and evaluation of their performance through field trial installations.

The PEER project team recently completed a proof-of-concept, pilot-scale field installation in Ottawa, Canada. The project involved surveying the existing building (using hand measurements, 3D laser scanning, and tacheometry), and fabricating and installing two prototype wall assemblies.

Many European projects have been addressing deep energy retrofits of the housing stock. (Ochs et al., 2016; Garay Martinez et al., 2017; Sandberg et al., 2016). The Energiesprong initiative that started in the Netherlands has retrofit thousands of social housing units to achieve net-zero performance and is now being adopted in other countries. These projects often focus on prefabricated approaches to envelope retrofit to minimize on-site work. Prefabrication has a longer history and higher prevalence in Europe than in North America.

In Canada, off-site fabrication for low-rise residential construction is uncommon, and virtually non-existent for retrofit. However, prefabrication promises a host of benefits, including: minimized demolition and time on site; reduced waste and landfilling; improved quality control; and cost-savings if achieved at scale. The PEER project seeks to explore whether prefabrication may help realize these benefits and overcome technical barriers to traditional, piecemeal approaches - ultimately to enable a leap to industrialized deep retrofit.

Other North American organizations are actively working to overcome barriers to deep and net-zero energy retrofits and to adopt or adapt Energiesprong-type programs in their regions (PEMBINA Institute, 2018; Clean Foundation, 2018; Sustainable Buildings Canada, 2018; Rocky Mountain Institute, 2018; NYSERDA, 2018).

EXISTING WALL ASSEMBLY AND RETROFIT PANELS

The pilot field installation was performed on a construction trailer used for storage of material on the CanmetENERGY campus in Ottawa, Canada. The exterior wall assembly of this building is representative of typical Canadian home construction from 1961-1983. A pitched truss roof was assembled on top of the existing roof with a raised heel to achieve the target ceiling R-value. The existing wall assembly consists of the following layers from interior to exterior:

- 3 mm fibreboard interior finish surface
- 0.2 mm polyethylene
- 38 x 89 mm studs @ 405 mm O.C. (on-center) c/w RSI 2.29 (estimated) fibreglass batts
- 8 mm OSB (Oriented Strand Board) sheathing
- Building paper, lapped not taped
- Prefinished profiled galvanized sheet steel cladding

Based on the isothermal planes method, this provides a total RSI value of 1.80 m^2K/W if a 23% framing fraction is assumed (Natural Resources Canada, 2016).

A narrow strip of the existing cladding was removed at the top and bottom of the existing walls, in order to tie-in the new air-barrier to the existing top plate and floor sheathing. Two different retrofit wall panels were installed directly over the remaining cladding. New windows and doors were preinstalled in the panels.

PEER Prototype 1: Nailbase

The nailbase panel consists of a high-density Expanded Polystyrene (EPS) core bonded to structural sheathing on the exterior and low-density batt adhered to the interior ("squishy layer"). The squishy layer is compliant and helps to plumb the panel and absorb surface irregularities. It also provides dimensional tolerance at panel corners and is vapour-open. This may aid upward drying by diffusion. The EPS core is factory cut to receive continuous structural members at the top and bottom of the panel. These members serve to connect several sub-panels together and provide strength and stiffness for transportation and hoisting. New windows and doors are installed in the EPS layer and supported by a wood perimeter buck. Vertical strapping is installed over a self-adhered, vapour permeable air and weather resistive barrier membrane to support cladding that is installed in the shop. A thicker EPS core layer could be specified to achieve higher R-values. The nailbase panel is described from interior layer to exterior layer in Table 1.

Table 1. Retrofit panel descriptions

	Nailbase	Woodframe
Layer 1	50 mm low-density (24 kg/m^3) fiberglass or mineral wool batt	90mm continuous cellulose insulation (56 kg/m^3)
Layer 2	150 mm Type-II expanded polystyrene (EPS) core with continuous let-in structure	38 mm x 89 mm studs @ 405mm O.C. c/w cellulose insulation (56 kg/m^3)
Layer 3	11 mm OSB sheathing	11 mm (OSB) sheathing
Layer 4	Self-adhered vapour permeable air and weather resistive barrier	Self-adhered vapour permeable air and weather resistive barrier
Layer 5	19x89 mm strapping @ 405 mm O.C.	19 x 89 mm strapping @ 405 mm O.C.
Layer 6	Prefinished engineered wood siding	Prefinished engineered wood siding

PEER Prototype 2: Woodframe

The woodframe panel consists of a 38 x 89 mm stud wall, sheathed with OSB with a self-adhered vapour permeable air and water resistive barrier membrane, strapping and cladding installed prior to arrival to site. The prefabricated stud wall is stood-off from the existing cladding and supported on brackets anchored into the foundation. The stand-off gap is specified to achieve the target thermal resistance. Dense pack fibrous insulation is blown-in on-site through designated access zones at the top and bottom of the panel. In the case of the pilot, a 90 mm stand-off gap was selected. The woodframe panel is described from interior layer to exterior layer in Table 1.

Support

Steel brackets were anchored to the existing rim joist. Both panel systems sit on a continuous bearing plate placed atop the brackets. The wall panels were attached at the top with steel straps fastened to the existing and new top plates.

Air barrier details

Both prototypes utilize an exterior air barrier consisting of self-adhering vapour permeable air/weather resistive barrier applied outboard of the sheathing. This membrane wraps the top and bottom of both panels and connects to the existing building with transition membranes.

Fig. 1 shows the construction trailer before, during, and after the retrofit. The installation of all the wall panels was done in less than a day.

MONITORING RESULTS

In order to verify the thermal performance of the retrofitted walls, measurements of clear wall RSI values were taken in-situ. This was accomplished with Hukseflux HFP01 heat flux sensors on the existing sheathing, and 100 kΩ NTC thermistors on the indoor wall surface and in the ventilated cavity, in line with the heat flux sensors. A total of 7 days was used for the initial measurement, but the RSI value converged in approximately one day. The results for both panels, and a comparison with a calculated value can be seen in the first two rows of Table 2. In addition to increased wall RSI, blower door tests have shown a large increase in airtightness from approximately 7.62 to 0.82 air changes per hour at 50 Pa pressure difference.

a) b) c)

Figure 1. Construction trailer before (a), during (b), and after (c) retrofit.

EFFECTIVE RSI-VALUE AND SIMULATION

The effective RSI-value, considering the effect of thermal bridging through framing at the top and bottom of the panel was assessed using THERM (Lawrence Berkeley National Laboratory, 2018). THERM is a 2D steady-state finite element heat transfer software. A vertical section of each panel was modelled with the existing wall construction, roof and floor. To account for additional bridging in the layers with insulation in the stud cavities, an effective conductivity was imposed on those layers. A framing fraction of 23% was assumed for stud cavities, but the top and bottom plate were removed from this fraction as they are explicitly modelled in the 2D vertical section. The overall effective thermal resistance was then determined for two scenarios:

a) The as-built case of the construction trailer without a foundation; and
b) A more typical scenario with an insulated foundation. The two panels are depicted on a foundation in Fig. 2.

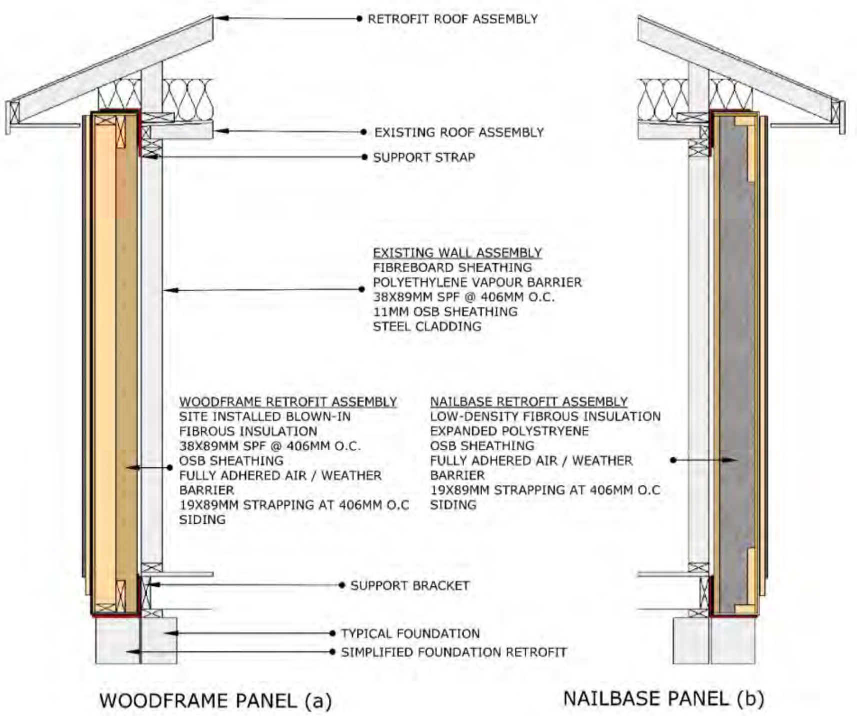


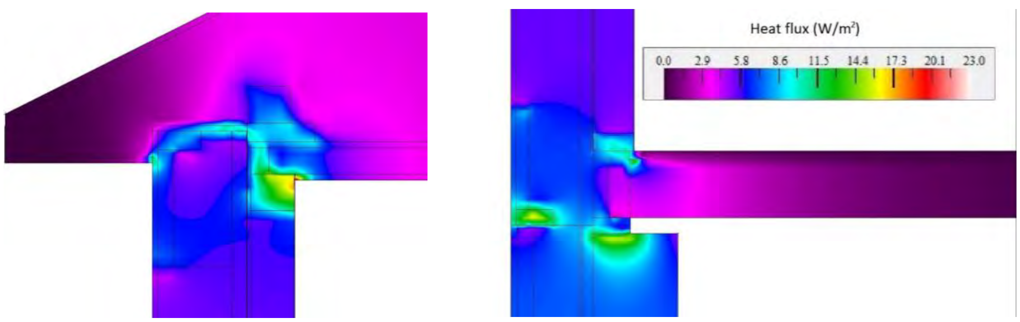
Figure 2. Section of Woodframe (a) and Nailbase (b) panels on existing hypothetical building.

The last three rows of Table 2 show the simulation results. The last row shows the results at the mid-point of the wall, where thermal bridging effects from the top and bottom of the wall are insignificant. There is a significant difference between the RSI values and the mid-point RSI values for both panels. This is due to thermal bridging through the wood portions at the top and bottom of the assembly, as seen in Fig. 3 for the nailbase panel on insulated foundation. Additionally, the woodframe panel performs worse than the nailbase panel because of additional thermal bridging caused by studs.

Table 2. RSI values for retrofit assembly, including existing wall

	RSI (m^2K/W) Nailbase	RSI (m^2K/W) Woodframe	Notes
Measured Clear Wall	7.80	7.80	a
Calculated Clear Wall	7.69	7.64	
Simulated Effective (insulated foundation)	6.77	6.03	
Simulated Effective (as-built)	6.40	5.72	
Simulated Mid-Point	7.07	6.24	

a Uncertainty: ±0.47 m^2K/W, method by Moffat (1988)



a) b)

Figure 3. Plot of heat flux at top (a) and bottom (b) of Nailbase assembly.

WHOLE BUILDING ENERGY IMPACTS

The effective thermal resistance values of the retrofit building envelope components and the measured air leakage rates were used to estimate the annual energy use of the existing building and the improvements. In addition to the two prototype wall panels, other retrofit measures included blown-in insulation in the attic, floor batts replaced with spray applied polyurethane, windows replaced with triple glazed units and doors replaced with urethane insulated units. Simulation was performed using HOT2000 v 11.3 (Natural Resources Canada, 2017b). The results in Table 2 show significant improvements in many performance metrics, including a 71.9% improvement in the Thermal Energy Demand Intensity.

Table 2. Whole Building Energy Impacts

Performance Metric	Unit	Pre Retrofit	Post Retrofit	% improvement
Air leakage at 50Pa	ACH	7.6	0.82	89.2%
Annual Gross Heat Loss	MJ	39627.0	14290.0	63.9%
Annual Heat Loss via Walls	MJ	15242.8	4695.8	69.2%
Annual Heat Loss via Air Leakage	MJ	3677.2	393.7	89.3%
Design Heat Loss	W	5760.0	2540.0	55.9%
Design Cooling Load	W	2902.0	2324.0	19.9%
Thermal Energy Demand Intensity	kWh/m2	230.3	64.7	71.9%

CONCLUSIONS

This paper presented preliminary results of a pilot project for prefabricated deep energy retrofit of building envelope for low-rise residential buildings. It was shown that thermal bridging can be an important source of heat loss, and that the bottom and top of the panels must be carefully designed while considering the existing building to minimize bridging. Additionally, annual simulations have shown significant improvements in thermal energy performance metrics. Field monitoring is continuing, and future work will include assessment of the hygrothermal performance of the envelope over an extended period.

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