MATERIALS

Mortar mix with sand to cement ratio of 2.5 and water to cement ratio of 0.6 was selected as cement skin. The 7-day compressive strength was 19.4±0.14 and 28-day compressive strength 20.4±1.03. With normal air curing, there was no significant difference between 7-day and 28-day properties. Therefore the full-scale wall tests were carried out 14 days after thin cement applied and cured in the air.

EPS bead board was the insulation of choice for the project. In contrast to extruded polystyrene, where HCFCs are used as the blowing agent, "bead board" EPS foam panels are made with water vapor-blown polystyrene. Furthermore, the product used for this research was made from over 80% pre- and post-consumer recycled polystyrene, that is easily recyclable at the end of a building's life cycle. Finally, the materials used in the system are relatively benign with regard to off-gassing, during and post-construction, making it a good choice for a "healthy" building envelope. It costs almost half the price of extruded foam. The board as received was 101 mm (4") thick. Three pieces were bonded together to make up the core of 305 mm (12"). The compressive tests were performed to determine the maximum load capacity of the core. It was about 12.5 kN/m (852 lb/ft). The thermal resistance of the EPS bead board is about R = 3 h.ft2.F/Btu/in. For 305 mm (12") thick EPS core, the thermal resistance of the wall is R = 36. This is a high performance wall in a very cold climate. The building codes require that R = 20 be the standard in Canada.

Polypropylene-based plastic mesh was used as a wrapping reinforcement for EPS core, as a connection between core and skin, as well as an internal reinforcement for cement skin. The mesh size was 2.3 strands per 25.4 mm (1 in) and same in two mesh directions. The breaking load was 2816 N/m (193 lb/ft).

EXPERIMENTAL PROGRAM

An EPS sandwich wall of 2.75 m (9') tall, 1.22 m (4') wide and 0.35 m (14") thick, including the 25 mm (1") cement skin on each side of the wall, was constructed for full-scale wall test. The purpose was to determine the capacity of the wall to resist the vertical gravity load, the horizontal wind load and the cyclic shear load.

In order to obtain more information from the full-scale wall tests, the sandwich wall was constructed first with a closed edge box-section (Fig. 1a) to simulate the end condition of a house and then with a cut open edge (Fig. 1b) to represent a mid-unit of the wall.

For the closed edge section, tests were conducted to examine the performance of the wall when the applied load is first gradually increased to the design load level, and then continued to four times the design load. The gravity load tests were performed first, followed by wind load tests and in plane shear tests. Each test underwent three load-unload cycles and visual inspection was carried out to detect the possible cracks.

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For the open edge section, similar procedure was followed to repeat the tests with weaker cross section. The gravity load tests were performed again to the design load and then to four times design load as well with three cycles of load and unload for each. The wind pressure was applied afterwards to the design load and gradually increased until the first transverse cracking. The cracked wall was finally tested to buckling for maximum load bearing capacity at failure.

According to NBC (1995), a single story residential house of 6.7 m x 13.4 m (22 ft x 44ft) in Montreal area should be designed to carry the following loads:
Gravity load on 6.7 m (22 ft) wall = 38.5 kN/m (120 lb/ft^2 x 22ft = 2640 lb/ft)
Gravity load on 13.4 m (44 ft) wall = 19.3 kN/m (120 lb/ft^2 x 11ft = 1320 lb/ft)
Wind load = 1.2 kPa (24 psf)
Seismic load = 2.36 kN/m (162 lb/ft)

On a 1.22 m (4 ft) wide wall, the design loads are:
Gravity load on 6.7 m (22') wall = 48 kN
Gravity load on 13.4 m (44') wall = 24 kN
Wind load = 1.2 kPa (24 psf)
Seismic load = 2.9 kN (648 lb)

CONSTRUCTION OF SANDWICH WALL

Full-scale sandwich wall was constructed on the strong floor directly under the 10^4 kN ($2.2x10^6$ lb) MTS machine in McGill University's Structural Lab. concrete footing (3m x 1m x 0.15m) was cast first with anchor bolts in position. Steel meshes were embedded in the concrete footing, extending 0.3 m above the footing on two sides (Fig. 2). Four days after casting the concrete footing, the EPS core was placed on the top of the footing and guided by a wood frame to control the thickness of the cement skin. The core was wrapped by plastic mesh and connected to the footing by the 0.3 m tall steel mesh. The cement skin was applied manually to simulate the site condition in remote areas. Two additional layers of plastic mesh were added; one close to the EPS core and the other near the surface. The finished wall is shown in Fig. 3 with top end braced by timbers, the bottom end bolted to the strong floor and front surface painted white to monitor the cracking. A 25mm thick plywood plate was placed on the top of the wall to evenly distribute the gravity load.

An air bag was built using a polypropylene plastic sheet in a wooden frame braced by timbers and supported by steel columns of the MTS machine. The air pressure in the bag was measured by the differences of water height. The schematic of the set-up for gravity load tests and wind load tests is shown in Fig. 2. Two LVDTs were used to record the displacements of the mid-point of the wall. LVDT 18 measured the front surface displacement and LVDT 17 the back surface (air bag side) displacement. The latter was accomplished through a steel rod embedded inside the wall and glued to the back surface by epoxy.

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The set-up for in-plane shear tests is shown in Fig. 4. Two hydraulic jacks, two load cells and two LVDTs were installed to carry out the in-plane cyclic loading. The top end of the wall was clamped by a steel frame to allow the push from two sides by the jacks. Two rollers were added on the top under the universal joint to provide a mechanism for movement while the wall was simultaneously subjected to a gravity load. When jack 1 was pushing, LVDT 2 recorded the displacement. While jack 2 was pushing, LVDT 1 collected signals. The cycle was done at least three times for each design load.

RESULTS

Full scale tests of wall with closed edge

Fig. 5 shows the response of the wall to the cyclically added gravity load up to 200 kN (4 times design load); no wind pressure (lateral load) was applied. Thick lines corresponded to loading while the thin lines to unloading. Very small lateral displacement was detected, indicating the rigidity of the wall was maintained during the load–unload cycles to four times the design capacity.

The response of the wall to the cyclically added wind pressure up to 5 kPa (4 times design load) is demonstrated in Fig. 6. A 48 kN dead load was kept on the top. Both LVDT 17 and 18 were used to detect displacements. It seemed that the back side (wind side) displacement detected by LVDT 17 was larger than the front side (LVDT 18), suggesting that the two cement skins did not move by a same amount. The residual displacement after the first cycle was almost negligible. No crack was noticed.

Figs. 7 displays the wall response to the cyclic in-plane shear load up to three complete cycles and at a load of 11.6 kN (4 times design load). The tests represent the expected loads due to a seismic event on the house. The roof dead load of 5.1 kN was applied as constant gravity load. No damage to the wall was observed.

Full scale tests of wall with open edge

To examine the structural behavior of the wall only with two face skin layers, the 6 mm thick cement on two sides was cut open. Tests were repeated on the wall with open edge to simulate the mid-wall unit in a building envelope. Figs. 5 – 7 have showed that there is no significant degradation in strength and stiffness of the wall with closed edge after cyclically loaded to four times design loads.

Fig. 8 exhibits the results of cyclic gravity load tests after three cycles at 200 kN. The maximum lateral displacement monitored by two LVDTs was 0.1 mm, indicating the wall with open section was still stable and rigid, and could be used for failure analysis. It was interesting to compare Fig. 8 with Fig. 5. The two skins in open edged wall tended to move away from each other (Fig. 8), while the two skins in closed edged wall always moved in the same direction. The two lateral displacements (Figs. 5 and 8) were of the same order of magnitudes.

Fig. 9 demonstrates the cyclic wind load test results up to the wind pressure of 4.5 kPa and 5.5 kPa. At 4.5 kPa, the wall with open edge exhibited similar response as the wall

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with closed edge. The first transverse crack was initiated at 5.5 kPa on the front tensile surface with significantly irreversible lateral displacements. The gap between the air bag and the wall was apparent due to the deflection of the wall. With open edge, the wall underwent approximately 10 times more deflections than that observed with the closed end. The differences between the two LVDTs were observed to decrease when larger lateral displacements occurred, suggesting that the bond between the cement skins and the EPS core by the plastic mesh was maintained.

Compressive tests were conducted to examine the vertical load carrying capacity of a cracked wall. The wall was loaded up to 300 kN, unloaded to zero and then loaded again to failure (Fig. 10). Significant lateral displacement was observed. In failure tests, the air bag was removed and LVDT 17 was placed on the back side. The two LVDTs exhibited almost identical values. The typical failure mode is buckling. A second transverse crack was also observed during the buckling yielding. The test was stopped when the maximum mid-height displacement reached 38 mm. The load capacity of the cracked wall was 406 kN/m.

CONCLUSIONS AND RECOMMENDATIONS

A full-scale EPS core-cement skin sandwich wall was constructed and tested to examine the possibility of being used as load bearing wall in one story residential house. The test results were promising.

For both closed edge and open edge cross sections, the wall could carry a gravity load of 164 kN/m with barely any lateral displacement. This is 4 times higher than the required NBC design load (38 kN/m). At buckling failure, the capacity reached at least 406 kN/m.

In wind pressure tests, the closed cross section had shown resistance to lateral displacement almost 10 times higher than the open section. Both sections could carry at least a wind pressure of 5 kPa (100 psf); about 4 times the design load (1.2 kPa).

The seismic resistance of the wall was investigated by in-plane cyclic shear tests. The maximum load of 11.6 kN was applied to represent 4 times the design load (2.9 kN). The corresponding hysteretic permanent deformation was approximately 1 mm in a 2.7 m tall wall.

The cement skin EPS core wall system demonstrated sufficient strength to serve as load bearing exterior wall for one-story residential housing without traditional wood frames. For a frameless house using this sandwich system, the joint design and construction between the walls and the wall to roofing play a critical role and need to be investigated.

The high load carrying capacity of the wall system is attributed to the fully developed strength in thin cement skin stabilized by the core. The maximum average load was about 13 kN/m for EPS core and about 1550 kN/m for sandwich block with two 25 mm thick skins. The contribution of the EPS core to the structural capacity appears to be negligible. Therefore, any materials that can hold the skins may be used as a core in the proposed

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system. This represents a wide range of opportunities for designers to select core materials to construct environmentally friendly, thermally efficient, structurally strong and economically feasible residential houses and commercial buildings.

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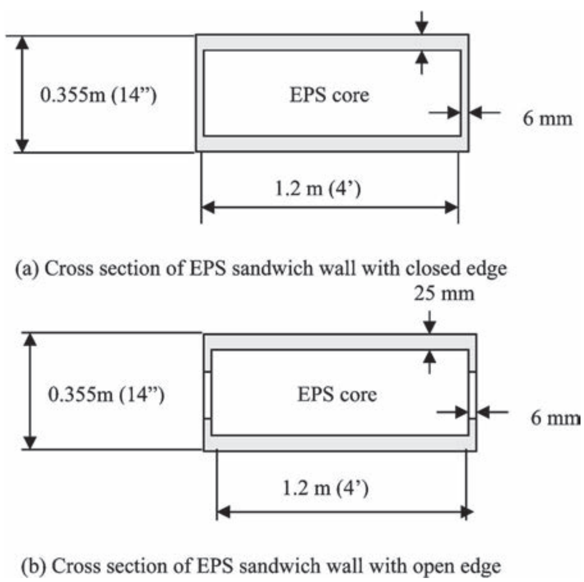

Fig. 1: Cross section of EPS sandwich wall

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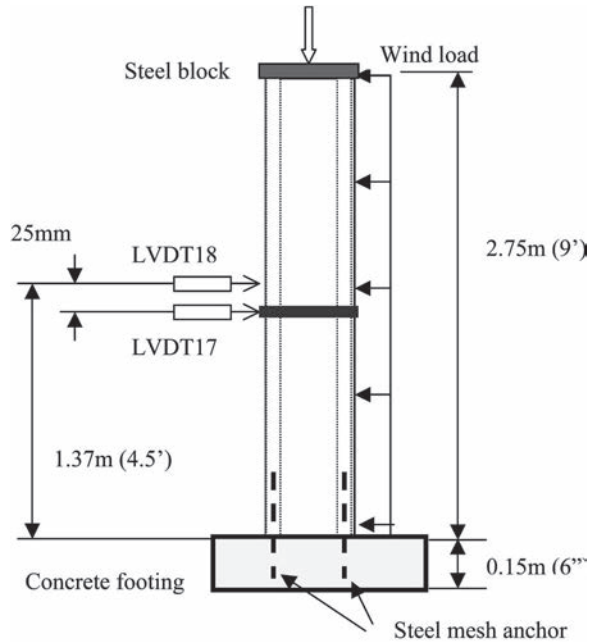

Fig. 2: Side view of sandwich wall (wall thickness = 0.355m)

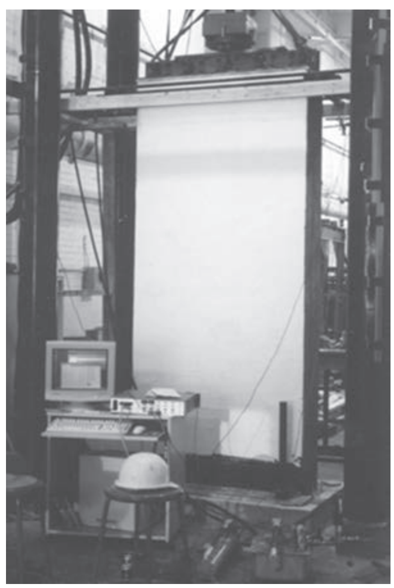

Fig. 3: Finished wall

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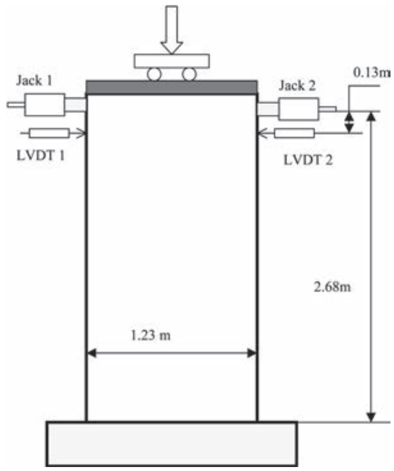

Fig. 4: Front view of sandwich wall

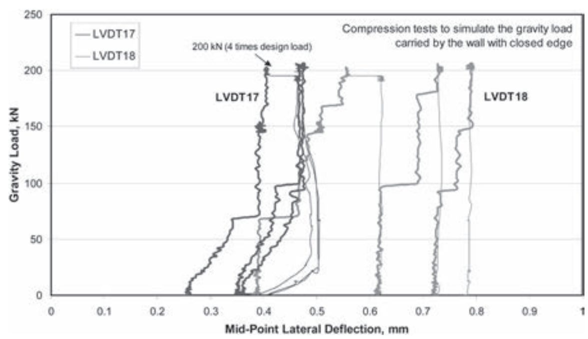

Fig. 5: Cyclic gravity load tests (closed edge)

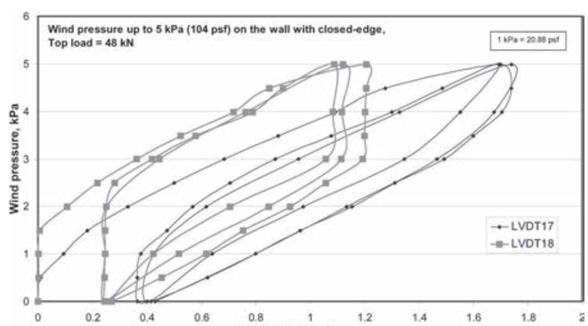

Fig. 6: Cyclic wind load tests (closed edge)

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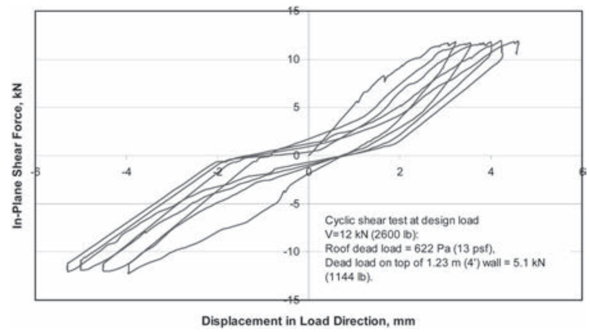

Fig. 7: Cyclic in-plane shear tests (Closed edge)

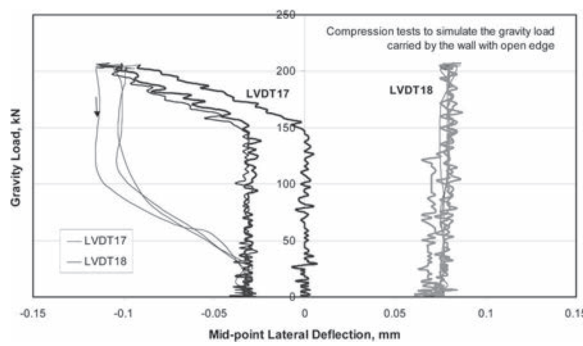

Fig. 8: Cyclic gravity load tests (open edge)

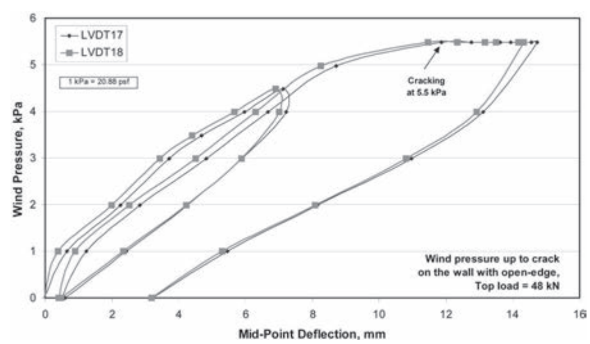

Fig. 9: Cyclic wind load tests up to failure (open edge)

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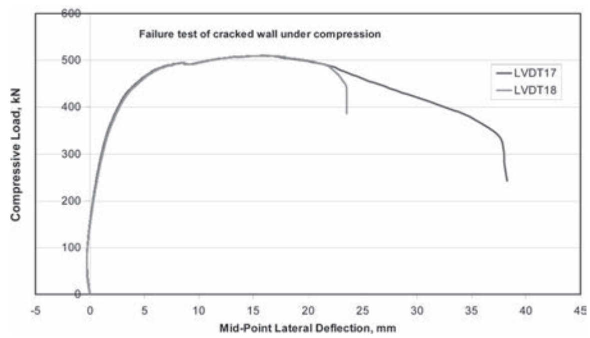

Fig. 10: Failure test of cracked wall up to buckling (open edge)

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