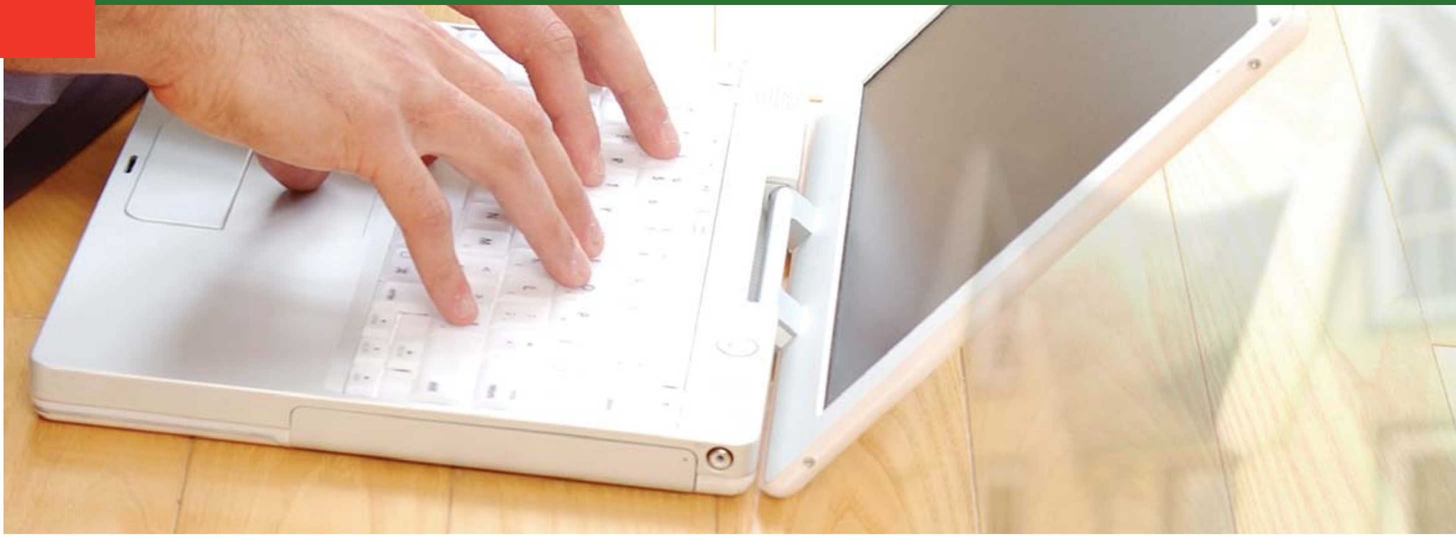
RESEARCH REPORT

External Research Program



Cement Skin EPS Core Building System: Proof of Concept Testing: Preliminary Structural Evaluation

Canada

CMHC SCHL

HOME TO CANADIANS

CMHC—HOME TO CANADIANS

Canada Mortgage and Housing Corporation (CMHC) has been Canada's national housing agency for more than 60 years.

Together with other housing stakeholders, we help ensure that Canada maintains one of the best housing systems in the world. We are committed to helping Canadians access a wide choice of quality, affordable homes, while making vibrant, healthy communities and cities a reality across the country.

For more information, visit our website at **www.cmhc.ca**

You can also reach us by phone at 1-800-668-2642
or by fax at 1-800-245-9274.

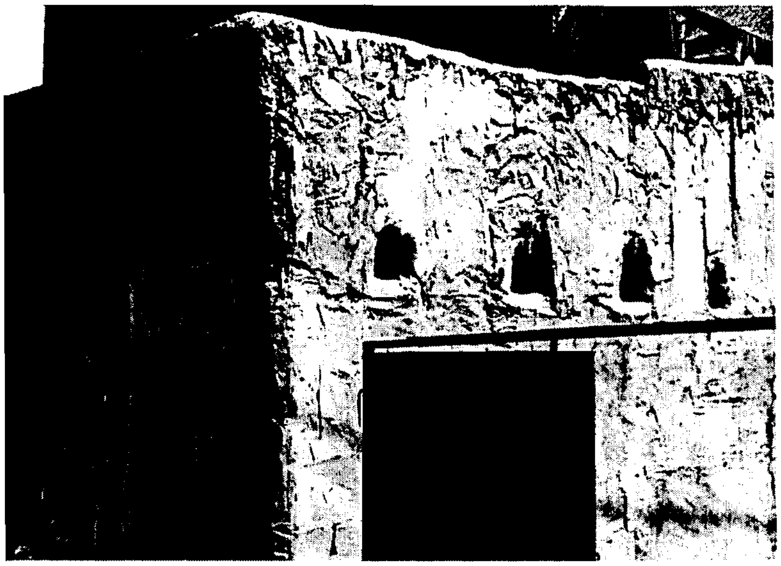
Outside Canada call 613-748-2003 or fax to 613-748-2016.

Canada Mortgage and Housing Corporation supports the Government of Canada policy on access to information for people with disabilities. If you wish to obtain this publication in alternative formats, call 1-800-668-2642.

Proof of Concept Testing

Cement Skin- EPS Core Building System

- Preliminary Structural Evaluation



Final Report

Presented to the External Research Program of the
Canada Mortgage and Housing Corporation

by Emmanuel Blain-Cosgrove
Ecohabitation

November 2001

Abstract

The balance between sustainability and affordability is hard to reach when considering choices of building envelopes. After working with different sustainable self-build techniques, Brad Robinson and Emmanuel Blain-Cosgrove developed a simple and fast stressed skin structural sandwich that is both cheap and sustainable. It is composed of an expanded polystyrene (EPS) panel core, wrapped in polymer mesh and covered with stucco on both sides. The result is a highly resource and energy efficient building envelope system. In order to verify its structural capacity, research was conducted by Prof. Yixin Shao from the Civil Engineering Dept at McGill University with funding from the CMHC's External Research Program. Among the proof-of-concept tests were compressive, shear and flexural performances of samples and a full-scale wall. Freeze-thaw (durability) and a blow-torch tests were also carried out, the latter being strictly for curiosity's sake. From the results, it could be concluded that the EPS sandwich is strong enough to serve as load bearing exterior wall for one-story residential housing, even by minimizing materials. Further work on the system could look at methods to improve fire safety and the effect of water saturation, as proposed by R. E. Platts, P. Eng, in his appended independent review of the research.

Executive Summary

This research was carried out on a cementitious-skin structural sandwich wall having a core of expanded polystyrene (EPS). It was conducted by Prof. Yixin Shao from the Civil Engineering Dept at McGill University with funding from the CMHC's External Research Program. As a simple site-built assembly, the method was initially intended for low cost owner-build applications. It can be used to construct high performance building envelopes that can be built quickly, with low-skilled labour, at low cost and with materials that are readily available.The proponents, Brad Robinson and Emmanuel Blain-Cosgrove developed the system with the challenges of sustainable building in mind; affordability, energy efficiency, minimal environmental impact materials, and occupant health. For this reason, vapour blown recycled EPS was used for the project.

The composite wall that was tested consisted of rounded expanded polystyrene panels wrapped with a 1 cm. grid polymer mesh, and coated with cementitious stucco on both the interior and exterior. Two more layers of mesh were applied under the proceeding coats of stucco, covering over the indented joints that were formed because of the rounded panels. In the context of building, the wrapped panels are placed into a wet footing or tied to a pre-set footing with metal anchors. A wooden top-plate is meshed to the top of the wall to allow the attachment of a roof or more stories.

The proof-of-concept work covered the critical issues with respect to use of the system including structural capacity, durability, thermal performance and fire resistance. The bulk of the study focused on the structural capacity of the 'frameless' structure. Following tests on samples, a full-scale 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, when compared to National Building Code requirements, were very promising:

- the wall could carry a gravity load 4 times higher than the NBC design load (38 kN/m). At buckling failure, the capacity reached to at least 10 times the design load (410 kN/m).
- the wall could carry at least a wind pressure of 5 kPa (100 psf) which was about 4 times the design load (1.2 kPa).
- The seismic load applied to the wall was 4 times the design load (2.9 kN).

It could be concluded that the EPS sandwich is strong enough to serve as load bearing exterior wall for one-story residential housing.

No testing was done for thermal performance; since the stucco is negligible, all the R-value lies in the well documented EPS. The severe freeze-thaw test to examine the effects of weathering revealed significant mass loss because of the high moisture content in the cement skins but no de-bonding of the cement to the core was observed. Finally, an inconclusive blow-torch experiment on a beam examined the effect of a flame on one cement plate and the heat's gradual melting of the EPS core.

The following are the recommendations based on the results, with the input from R. E. Platts, P. Eng:

- To improve frost resistance, an air entraining agent could added to the mix to provide the mechanisms for pressure to release during freezing
- Considering the strengths observed, the wall could be kept to 7 to 9 inches in thickness to improve environmental and cost implications. The stucco just ¾ in. thick; and just one or two layers of mesh in each face rather than three.
- Ensure the stucco wall is well protected with roof overhangs
- A better-fused material – ideally still from recycled EPS – giving more R per inch and better moisture resistance.
- Grooved and corrugated panels to enhance bond and to hold off the mesh to embed itself in the stucco, as well as to carry dead loads and maintain essential support for floor and roof above in a fire situation.
- using a fibrated gypsum plaster as the sole interior skin, load bearing, with its base protected against accidental wetting.

The knowledge about the EPS sandwich gained from the research is invaluable. The direction is set for further research, which will most likely surround fire safety. Although regulatory approval is far from being achieved, the proponents have been encouraged by the performance of the system. The technique, with all its positive attributes seems too good to be true and is well worth further work.

For any questions or comments, please feel free to contact us:

Emmanuel Blain-Cosgrove
10 ave de Pins O, #414
Montreal, Quebec
H2W 1P9
(514) 985-0004
admin@ecohabitation.com

Résumé

La présente recherche, portant sur un mur sandwich structural à âme constituée d'isolant de polystyrène expansé revêtue d'enduit cimentaire, a été menée au département de génie civil de l'université McGill grâce à du financement accordé dans le cadre du Programme de subventions de recherche de la SCHL. Devant simplifier la construction sur le chantier, la technique visait à l'origine à réduire les coûts pour les propriétaires-constructeurs. Elle permet, en effet, de réaliser rapidement une enveloppe de bâtiment assortie d'une performance élevée, avec de la main-d'oeuvre peu spécialisée, moyennant un faible coût et des matériaux facilement accessibles. Les promoteurs, en l'occurrence Brad Robinson et Emmanuel Blain-Cosgrove, ont mis au point le système en misant sur la création de bâtiments durables, exerçant peu de répercussions sur l'environnement, mais axés sur l'abordabilité, l'efficacité énergétique, le choix des matériaux et la santé des occupants. C'est pourquoi l'emploi d'isolant de polystyrène expansé recyclé a été retenu pour les besoins de la recherche.

Le mur composite mis à l'essai était composé de panneaux de polystyrène expansé arrondis aux rives et enveloppés d'un treillis polymère à grilles de un centimètre, les faces intérieures et extérieures revêtues de stucco cimentaire. Deux autres couches de treillis ont été posées, puis revêtues d'épaisseurs supplémentaires de stucco couvrant les joints en retrait formés en raison des rives arrondies des panneaux. Lors des travaux de construction, les panneaux enveloppés s'encastrent dans une semelle encore fraîche, sinon ils sont assujettis à la semelle en place par des dispositifs d'ancrage métalliques. Une sablière en bois enveloppe le dessus du mur pour permettre de fixer l'ossature du plancher ou du toit.

Le travail de validation de principe portait sur les questions primordiales de capacité structurale, de durabilité, de performance thermique et de résistance incendie du système. La majeure partie de l'étude a été consacrée à la capacité structurale du système « sans cadre ». À la suite d'essais menés sur des échantillons modèles, un mur sandwich de pleines dimensions a été réalisé et mis à l'essai en vue d'étudier la possibilité de l'utiliser comme mur porteur d'une maison de un étage. Les résultats des essais, confrontés aux exigences du Code national du bâtiment (1995), se sont révélés très prometteurs :

- Le mur pourrait soutenir une charge due à la pesanteur de 4 fois supérieure à la charge de calcul du CNB (38 kN/m). Lors de la défaillance (flambage du mur), la capacité avait dépassé d'au moins 10 fois la charge de calcul (410 kN/m).
- Le mur pourrait résister au moins à une pression du vent de 5 kPa (100 lb/pi^2), soit environ 4 fois la charge de calcul (1,2 kPa).
- La résistance aux charges sismiques appliquées au mur était de 4 fois supérieure à la charge de calcul (2,9 kN).

Le mur sandwich à âme en polystyrène expansé est suffisamment résistant pour constituer le mur extérieur porteur d'une maison de un étage.

La performance thermique du système a également été étudiée. Dans le système proposé, c'est l'isolant de polystyrène expansé qui offre la plus forte résistance au transfert de la chaleur, puisque celle du stucco est négligeable. Le cycle de gel et de dégel a occasionné une perte de masse de l'enduit cimentaire en raison de la teneur élevée en eau du revêtement cimentaire, mais aucune perte d'adhérence du ciment par rapport à l'âme n'a été observée. Une expérience qualitative tentée à l'aide d'un chalumeau a permis d'étudier l'effet de la flamme sur des poteaux sandwiches et le transfert progressif de la chaleur à travers la masse.

Voici les recommandations fondées sur les résultats des expériences :

- Pour améliorer la résistance au gel, il conviendrait d'ajouter un entraîneur d'air au mélange dans le but d'autoriser un dégagement de pression au cours des cycles de gel et de dégel.
- Pour les maisons de un étage, l'épaisseur totale du mur pourrait passer de 228 à 178 mm (de 9 à 7 pouces) et ainsi accroître sa performance en matière d'environnement et atténuer l'incidence financière. Il suffirait de mettre en oeuvre une couche de stucco de 19 mm (¾ po) avec une épaisseur ou deux de treillis pour chaque face, contrairement à trois.
- Le mur de stucco gagnerait à être bien protégé par un débord de toit.
- Un matériau mieux fusionné, provenant idéalement toujours de polystyrène expansé recyclé, offrirait une meilleure résistance thermique et une meilleure résistance à l'humidité.
- L'emploi de panneaux rainurés et ondulés devrait être envisagé dans le dessein d'accroitre l'adhérence et tenir le treillis en retrait pour mieux l'enrober dans le stucco et assurer le soutien essentiel du plancher et du toit en cas d'incendie.
- Le recours à un enduit au plâtre fibreux comme seul revêtement intérieur porteur, dont la base serait protégée contre tout mouillage accidentel, pourrait être envisagé comme solution de remplacement.

La direction d'autres recherches en matière de sécurité incendie et de raccordement structural est établie. Même si l'approbation des organismes de réglementation est loin d'être accordée, les promoteurs ont été encouragés par la performance du système. La technique, avec tous ses aspects favorables, mérite d'être davantage approfondie.

CMHC SCHL

National Office
700 Montreal Road
Ottawa ON K1A 0P7
Telephone: (613) 748-2000

Bureau national
700 chemin de Montréal
Ottawa ON K1A 0P7
Téléphone : (613) 748-2000

Puisqu'on prévoit une demande restreinte pour ce document de recherche, seul le résumé a été traduit.

La SCHL fera traduire le document si la demande le justifie.

Pour nous aider à déterminer si la demande justifie que ce rapport soit traduit en français, veuillez remplir la partie ci-dessous et la retourner à l'adresse suivante :

Centre canadien de documentation sur l'habitation
Société canadienne d'hypothèques et de logement
700, chemin Montréal, bureau C1-200
Ottawa (Ontario)
K1A 0P7

Titre du rapport: ____

____

Je préférerais que ce rapport soit disponible en français.

NOM ____

ADRESSE____
rue App.

____
ville province Code postal

No de téléphone ( ) ____________

Project Background

The following technical report presents the research conducted on a cement stressed skin building technique that uses polymer mesh covered expanded polystyrene (EPS) as a core. The research was done at McGill University under the direction of Prof. Yixin Shao with funding from the Canada Mortgage and Housing Corporation's External Research Program. The composite system was developed as a simple technique that can be used to build affordable, high performance building envelopes for cold climates.

The proponents of the system, Brad Robinson and Emmanuel Blain-Cosgrove have backgrounds in straw bale and related sustainable building techniques, from which the composite presented here was initially inspired. There is general consensus on the compressive strength, limited environmental impact and affordability as positive properties of load-bearing straw bale construction. However, the process of building homes with straw is often painstakingly long and labour intensive, requiring a great deal of parging and work to compress the material. Our solution to these problems was to use expanded polystyrene panels ("bead board" not to be confused with rigid extruded polystyrene), allowing us to prepare a 2 to 4 foot section of wall in minutes. Wrapped on-site, the panels are then placed upright onto a footing and parged with a minimal amount of stucco due to the consistent surface of the panels.

The resulting sandwich wall is intended to deal with many of the challenges of sustainable building; affordability, energy efficiency, minimal environmental impact materials, and occupant health. The cost of building is perhaps the most attractive aspect of this system. By limiting labour input to wrapping and parging, and by limiting material costs of envelope walls down to four basic components, EPS, mesh, cement/concrete and wood for the top plate, considerable savings are incurred when comparing the system to conventional wood frame construction. The sandwich is economical on the long term as well by reducing heating and cooling costs by providing a tight and uniform insulation as well as thermal storage on the interior skin. As for the core, the use of virgin styrofoam blown with HCFCs is strongly discouraged. Opposed to extruded polystyrene blown with HCFCs, "bead board" EPS foam panels are made with water vapour-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 the construction and on the long term, making it a good choice for a "healthy" building envelope.

A frequent reaction to this wall assembly is 'but where's the frame?'. After having used the system for a few demonstration projects that exceeded our expectations, we concluded that it would be worth proof-of concept testing to verify our assumptions on its structural strength. The concept of stressed skins is gradually becoming known to consumers, mostly due to Structural Insulated Panels. The system examined here offers all the benefits of SIPs while being affordable and not requiring any special manufacturing process. We find that this building system could prove to be a timely and useful tool for the challenges facing housing, with this research being the first step towards making the technique available.

Finally, the following people should be thanked for their crucial roles in this research: Brad Robinson for his genius in creating the system and for his brutally hard work for the preparation of the samples, Prof. Yixin Shao for his perseverance and impeccable work, Hani Khawaja our McGill student for his consistency and patience, Bob Platts for his valuable time and wealth of knowledge on stressed skins and buildings in general, Prof. Redwood and Mark Redwood for their help and support, and finally our sponsor the CMHC and the team at the External Research Programme who made the project possible.

Structural Evaluation of Cement Skin – EPS Core Building system

Test 1: Selection of cement skin and other materials

Cement-skin:

Tests were conducted to select a mixture proportion for cement skin. Table 1 shows 11 mix designs for cement-skin experimented for composite systems. The criteria used to select the proportion were high workability for manual application, high compressive strength and availability on job site. Additives of methyl cellulose (Mix 1) and latex (Mix 4) were tried to improve the adhesive bond of cement skin with EPS core. Cellulose fibers were added in Mix 3 for better toughness and workability. The commercial ready-mix cement products were also tested because they are readily available. The amount of water was adjusted in each try for a workable mix. The workability was decided by Mr. Brad Robinson, and kept consistent for all samples and full-scale wall.

The results of compressive strength are summarized in Table 2. They are the average of three cylinder tests. The dimension of the cylinder is 50 mm in diameter and 100 mm in height. The test set-up is shown in Photo 1. All batches with additives (Mix 1, Mix 3, Mix 4, Parging mix, and premixed mortar) showed low strength, and were therefore not under consideration. S-bond mix had reasonably good strength but was expensive. It was experimented as the first coat in a two-coat thin application to enhance the bond with EPS core. The sand mix 1 gave the best compressive strength. It was therefore decided the commercial sand mix be used in the project. The other reasons to use the commercial product are the availability for the site application and the better quality control.

However, it was found later that the quality of commercial sand mix was not consistent. The sand mix (listed as sand mix 2) from second order had only 54% strength as the first one. The manufacturer (Bomix) claimed that the strength of sand mix 2 (19 MPa) was normal. The high strength obtained in sand mix 1 was unusual. To avoid further inconsistency, decision was made to use lab mix for full scale wall construction. It was called wall mix 1 and wall mix 2 with slightly different water content (Table 1) for workability. The corresponding cylinder test results are shown in Table 2. Good repetition was achieved. Table 3 compares the 7-day strength with 28-day strength of sand mix 2. With normal air curing, there was no significant difference. A 7-day curing criterion was therefore set for all samples for different tests.

Core Materials

Two types of cores were examined for the composite system: soft EPS bead board (white color) and rigid polystyrene extruded SM board (pink color). The rigid SM product (Celfort) was used only for comparison of compressive tests on 305 mm (1ft) cubes. The test set-up is shown in Photo 2. The EPS board as received was 101 mm (4") thick. Three pieces were bonded together to make up the core of 305 mm (12"). In general, it was assumed that the direction of the bond line (horizontal or vertical) had no effect on the performance of the sandwich structure. Table 4 shows that the EPS is inferior in terms of the load carrying capacity and the thermal resistance. However, the researchers would still prefer the EPS core for environmental and cost concerns. The EPS used for this project was a low-grade product manufactured by Les Produits Isolofoam using water vapour as a blowing agent and over 80% recycled polystyrene. The EPS costs almost half the price of extruded foam, and so far, we have found that it performs just as well if not better for this application.

Reinforcing Mesh

Polypropylene-based plastic mesh (Quest Plastics LTD) was used as reinforcement for cement skin. The mesh size was 2.3 x 2.3 strands/in with a breaking load of 193 lb/ft.

Procedure for Sample Preparation

A 355 mm (14") thick wall was selected in this preliminary study with 305 mm (12") thick core coated by 25 mm (1") cement skin on two sides. The dimension of the wall thickness was kept constant for all tests. The core was wrapped completely by the mesh (Photo 2), and the cement applied directly onto the meshed core. Two additional layers of continuous meshes were added for cement reinforcement, one close to the core and the other close to the surface. Photo 3 demonstrates locations of three mesh layers in cement skin on a fracture surface. Samples were cured in the air to simulate the curing condition on construction site. Tests were carried out at the age 7 to 14 days.

Test 2: Compressive strength of the composite block

The cement-skin EPS/SM-core composite cubic blocks were assembled to test the load carrying capacity of the sandwich system. The load was applied parallel to the skin to simulate the 355 mm (14") thick wall in service condition (Photo 4). Sand mix was used for all samples except the single block 2 (SB2), where two cement coats were applied, the first with Spread'n Bond to enhance the bond between cement and core, and the second with sand mix to add up to the thickness of 25 mm (1"). A double block was constructed by connecting two single blocks together using continuous meshes to investigate the contributions by the joints. The use of top and bottom plywood plates (5/8" thick) was to distribute the load evenly to the skin. The typical shear failure of the sandwich block is shown in Photo 5. Table 5 summarizes the test results of all block samples. The conclusions were likely:

(1) Two-coat skin (SB2), one with polymer cement and one with sand mix, did not show better strength. Therefore, all the rest of the samples including the full-scale wall were prepared with only one coat of sand mix.

(2) With top and bottom plywood plates, the load could be distributed more uniformly and higher load-carrying capacity of the block was observed.

(3) Once two single blocks were joined together, the double block showed higher compressive strength than the single one, if the applied load could be distributed uniformly.

(4) The cement skin of blocks SB1 and DB1 had a 7-day compressive strength of 35 MPa. Using this strength, it is possible to calculate the theoretical load capacity of the sandwich system by assuming that all loads were carried by 305 mm x 50 mm (12" x 2") cement skin. The predicted load was 1777 kN/m. In comparison with the experimental average of about 1551 kN/m (Table 5), it was clear that the cement skin was loaded to compression failure. In block tests, the buckling of the thin skin was not observed.

(5) The comparison of SM core with EPS core was not conclusive, since SB3 with SM core was made by weaker cement skin (sand mix 2). However, the difference in failure modes shown in Photos 6 and 7 indicated that bond was much weaker in SM cored blocks. A complete debonding between SM core and meshed cement was observed at failure when the cement skin was still intact (Photo 7).

Test 3: Flexural strength tests of sandwich beams

Two sandwich composite beams of 305 mm (12") wide, 355 mm (14") high and 1219 mm (48") long with 25 mm (1") thick cement skin were tested in a 4-point bending set-up at one third span with a span of 1067 mm (42") (Photo 8). The cement skin was placed parallel to the base to measure the resistance of the wall to the lateral loads such as wind load. The typical load-midpoint deflection curves are shown in Fig. 1. The first tensile crack initiated at the bottom of the beam, followed by the two compressive cracks at top two loading points. The failure pattern is shown in Photo 9. The first crack load was 3.6 kN/m and the maximum load 12.1 kN/m. The corresponding moments were 0.66 kNm/m and 2 kNm/m, respectively.

Test 4: In-plane shear tests of sandwich beams

Two composite beams (305 mm x 355 mm x 1219 mm) were fabricated for in-plane shear tests to determine the shear resistance of the sandwich beam. They were tested in a 3-point bending set-up with a short span of 609 mm and a vertical cement skin (perpendicular to the base) to examine the shear capacity. The set-up is shown in Photo 10. The load-deflection curves are presented in Fig. 2, and the failure of the beam is shown in photo 11. Obviously, it was a typical flexural failure. The maximum load obtained was close to the theoretical failure load in flexion, indicating that the response of the sandwich beam was similar to that of the 50 mm (2") cement skin alone in bending. The contribution of the core was almost negligible. It was also found that the beam specimen, either 3-point simply supported beam or cantilever beam, is not a suitable specimen to test for the shear strength. Shear failure is not possible with beam specimens. Therefore, the initially proposed cyclic shear tests on the cantilever beams did not appear to be meaningful. Instead, cyclic shear tests on the full-scale wall up to seismic design load seemed more useful in house design. It was therefore decided the cyclic loading on full-scale wall test be added to investigate the seismic response.

Test 5: Full scale wall tests

An EPS sandwich wall of 2.75 m (9') high, 1.22 m (4') wide and 0.35 m (14") thick was constructed for full-scale wall test. The cement skin was 25 mm (1") on each side. The purpose was to test the resistance of the wall to 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. 3a) to simulate the end condition of a house and then with a cut open edge (Fig. 3b) to mimic a mid-unit of the wall.

For the closed edge section, tests were conducted in two steps:
(1) to examine the performance of the wall under gradually added design loads,
(2) to study the response of the wall to the doubled or tripled design loads.

For the open edge section, tests were conducted in four steps:
(1) to examine the performance of the wall under gradually added design loads,
(2) to study the response of the wall to the doubled or tripled design loads,
(3) to obtain the maximum wind load at first crack on the wall,
(6) to obtain the maximum gravity load and its corresponding failure mode.

For a single story residential house of 6.7 m x 13.4 m (22 ft x 44ft), the NBC design loads were calculated as follows:
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 22' wall = 48 kN
Gravity load on 44 ' wall = 24 kN
Wind load = 1.2 kPa (24 psf)
Seismic load = 2.9 kN (648 lb)

I. Construction of sandwich wall

Full scale sandwich wall was constructed on the strong floor directly under the 10^4 kN (2.2×10^6 lb) MTS machine in McGill University's Structural Lab. The overview of the machine and the site is shown in Photo 12. 25 MPa concrete footing (3m x 1m x 0.15m) was cast first with anchor bolts in position (Photo 13). Steel meshes were embedded in the concrete footing 0.3 m above the footing on two sides. The EPS core was then placed on the top of the footing after 4 days of casting, and guided by a wood frame to control the thickness of the cement skin. The core was wrapped by plastic mesh and joined at bottom by the 0.3 m tall steel mesh (Photo 14). The cement was applied manually (Photo 15) to simulate the site condition. Two layers of plastic meshes were added, one close to the core and the other to the surface (Photo 16). The finished wall is shown in Photo 17 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 was placed on the top end to evenly distribute the load and the load and displacement were recorded by Measurement Group System 5000 (Photo 17).

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 (Photo 18). The air pressure was measured by the differences of water height and converted to the unit of Pa (Photo 19). The schematic of the set-up for gravity load tests and wind load tests is shown in Fig. 4. 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.

The set-up for in-plane shear tests is shown in Fig. 5. 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. The detailed set-up is demonstrated in Photos 20 and 21. Two rollers were added on the top under the universal joint to provide a mechanism for movement while keeping the dead load on top. 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 test.

II. Tests on wall with closed edge

(1) Gravity load tests. Fig. 6 shows the first gravity load tests with load gradually added to 24 kN, 48 kN and 100 kN (at least twice the design load). LVDT 18 was used to record the midpoint displacement. The lateral displacement was nearly zero and no damage was observed anywhere.

(2) Wind load tests. Fig. 7 shows wind load tests at design load (1.5 kPa) and doubled design load (3 kPa) with various top loads (TL) as dead load while wind pressure was applied. Midpoint displacement was measured by LVDT 18. It seemed that the lateral displacement was slightly increased as the top load decreased. No damage was observed.

(3) Cyclic wind load tests. Figs. 8, 9 and 10 show the response of wall to the cyclically added wind pressure up to 3 kPa (twice design load), 5 kPa (4 times design load) and 6 kPa (5 times design load). A 48 kN dead load was kept on the top. Both LVDT 17 and 18 were used to detect displacement. The back side (LVDT 17) moved more than the front side (LVDT 18), suggesting that the two skins did not move by the same amount. No crack was noticed.

(4) Cyclic gravity load tests. Fig. 11 shows the response to the cyclically added gravity load up to 200 kN (4 times design load). Thick lines corresponded to loading while the thin lines to unloading. Very small displacement was detected, indicating a rigid wall. No wind pressure was applied in this case.

(5) Cyclic shear tests. Figs. 12 and 13 show the response to the cyclic shear load up to 2.9 kN (design load) and 11.6 kN (4 times design load), respectively. The tests were to simulate the seismic action on the house. The roof dead load of 5.1 kN was applied as constant top load. No damage was observed.

III. Tests on wall with open edge

After the above tests were done, the 6 mm cement skin on both sides was cut open as shown in Photo 22. Tests were repeated on the wall with open edge.

(1) Cyclic gravity load tests. Fig. 14 shows the test results. For three-times repeated tests up to 200 kN, there was still not much lateral displacement. The wall with the open edge was still stable and rigid. It was interesting to compare Fig. 14 with Fig. 11. The two skins in open edged wall tended to move away from each other (Fig. 14), while the two skins in closed edged wall moved in the same direction, although the displacements were very small.

(2) Cyclic wind load tests. Figs. 15, 16 and 17 show the wind load test results up to 1.5 kPa, 3 kPa and 5.5 kPa. At 5.5 kPa, the first transverse crack was initiated on the front surface with significant lateral displacement. The gap between the air bag and the wall was apparent (Photo 23). With open edge, the wall underwent much more lateral displacements. It was approximately 10 times more at wind pressure of 1.5 kPa, 10 times more of 3 kPa and 11 times more of 6 kPa. The differences between the two LVDTs were getting smaller when more displacements were measured. The crack pattern is displayed in Photo 24.

(3) Tests on cracked wall. Compressive tests were conducted to examine the vertical load carrying capacity of the cracked wall. The wall was loaded up to 300 kN, unloaded to zero (Fig. 18), and then loaded again to failure (Fig. 19). Significant lateral displacement was observed. For failure tests, the air bag was removed and LVDT 17 was placed on the back side. The two LVDTs exhibited almost identical values. Buckling was typical failure mode (Photo 25) and second transverse crack was observed (Photo 26). This multiple cracking was clearly attributed to the continuous mesh reinforcement. The test was stopped when the maximum displacement reached 38 mm.

Test 6: Freeze- thaw resistance tests

Since high water content was used in cement mix to keep workability, freeze-thaw tests seemed necessary to check the long term performance (ASTM C666). Three mortar prisms (280 mm x 77mm x 77mm) and four sandwich specimens of the same dimension were prepared for the tests (Photo 27). The sandwich specimens were composed of 25 mm (1") thick EPS core and two 25 mm (1") cement skins on both sides. Two sandwich specimens and three mortar prisms were immersed in containers filled with water and placed in an ASTM C 666 chamber with temperature cycled from +4 C to –17 C. The other two sandwich specimens were kept in the lab at room temperature as reference. The prisms were used to monitor the mass loss and section loss, and the sandwich specimens to test the strength of cement skin after 200 cycles. The freeze-thaw test started 14 days after the samples were cast and air cured. The mass loss and cross section loss were measured at 100 cycles and 200 cycles. The sandwich specimens were tested after 200 cycles in third-point bending set-up with cement skin perpendicular to the base at a span of 0.305 m. The test was similar to in-plane shear tests in Test 4 to investigate the strength of cement skin. The results are summarised in Tables 6 and 7.

The mass loss and section loss were observed. Photo 28 shows the lost mass collected in beaker for each prism after 100 cycles. The mass loss was then defined by the ratio of the lost mass to the initial mass. The lost mass was collected and weighed after being oven dried at 100 C. The average mass loss was 3.2% after 100 cycles and 6.3% after 200 cycles. The section loss was 3.4% at 100 cycles and 5.5% at 200 cycles. The loss mainly happened on the top and two side surfaces, like the scaling in salted concrete. The typical load deflection curves of sandwich specimens in third point bending tests are presented in Fig. 20. The average peak load was 2.31 kN for freeze-thaw cycled and 3.0 kN for control. The strength loss in cement skin after 200 cycles was about 9%. The average mass loss in sandwich specimens was 5.7% at 200 cycles.

It was noticed that the test condition under ASTM C666 Procedure A was severe: specimens were cycled inside water (saturated) between +4C and –17C at a rate about 4-6 cycles per day. It didn't represent the service condition of a typical wall in a residential house. However, the damage observed did raise a question on the mortar used in this project. If the water to cement ratio of 0.6 or even higher had to be used for workability, a proper air entraining agent should be considered to add to the mix for the protection. Although the sandwich specimens were used in strength tests, the results did not indicate a deteriorated bond after frost action.

Test 7: Blow torch tests for sandwich columns

The effect of high temperature on the integrity of the proposed system was examined by these blow torch tests. Instead of beams, three columns of 305mm x 335mm x 1219mm (12" x 14" x 48") were tested, since columns were closer to wall application than beams. The schematic of the test set-up and locations of thermal couples are shown in Figs. 21 and 22. A close view of the set-up is given in Photo 29 for test without top load, and in Photo 30 for test with top load. The torch was positioned about 100 mm away from the surface. The photos also show the pop-out of the cement layers by explosion. It usually happened at the outmost plastic mesh layer, where the plastic was melted into a gaseous form, causing the cement cover to explode. It was evident by the grid pattern left on popped-out cement pieces. The temperature distributions are presented in Figs. 23- 25. Five type T thermal couples were used to record the temperature at different locations.

For columns 1 and 2, the thermal couple positions are given in Fig. 21. TC2 was right after the front cement skin and detected the temperature directly from the touch. TC3 was also right behind the cement but 305 mm away from TC2. TC4 and TC5 were located in the middle of the core, and TC1 was at the back skin. The temperature distributions were pretty similar in the two tests (Figs. 23 and 24). It was hard to tell at what temperature the core started to melt. This was because once the damage became visible on the side, the core near the TC2 had already gone (Photo 31).

During the 1-hour blow torch test with 5.3 kN (1200 lb) weights on top, column 2 stood still even after the core was burnt, the cement skin popped out and a transverse crack initiated. Column 3 was tested with TC1 directly exposed to the fire (Fig. 22) through a small hole on the front skin. The temperature limit for the type T thermal couple was 400 C. When the temperature exceeded 400 C, the reading became zero (Fig. 25). Obviously, at the tip of the flame, the temperature was higher than 400 C. The temperature detected by TC2 right behind the skin and the TC1 was also higher than that measured in Columns 1 and 2, suggesting that the little hole generated a path for the heat.

Column 2 was also crushed to final failure after the blow torch test to examine the capacity of the fire damaged wall system. The load –displacement curve of the destructive test on the damaged column is shown in Fig. 26. The final crushing failure is displayed in Photo 32. The maximum load carried by the damaged column having a cross section of 305mm x 355mm (12" x 14") was 130 kN /ft = 426 kN/m. Compared to the NBC design load of 38 kN/m, the damaged column still exhibited a factor of safety by 11.

Conclusions and Recommendations

(1) 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 showed promise. 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 was 4 times higher than the NBC design load (38 kN/m). At buckling failure, the capacity reached to at least 410 kN/m. For wind pressure tests, the closed cross section had 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) which was 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 ± 1 mm in a wall of 2.7 m height. It is therefore conclusive that the proposed system is strong enough to serve as load bearing exterior wall in one-story residential housing.

(2) Bond between the core and the cement skin was studied qualitatively. The porous nature of EPS core provided spacing for cement to penetrate, leading to an interlocking bond and probably a better overall performance. It was evident by comparison of EPS with SM cores in sandwich blocks. However, the bond deterioration by frost action, if any, could not be quantified in beam tests. More tests with a different set-up would be necessary to understand the role of the interfacial bond in sandwich structures.

(3) 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 average maximum load was about 13 kN/m for EPS core and about 1550 kN/m for sandwich block with two 25 mm thick skins. It seemed that the contribution of the core to the structural capacity was negligible. Therefore, any materials that could hold the skins could be used as a core in the proposed system. This opens a wide range of possibilities for

designers to select core materials to build environmentally friendly, thermally efficient, structurally strong and economically feasible houses.

(4) Top wood plates were very useful in distributing the load evenly to the cement skin. It is recommended the top plates be always used and integrated into the wall system.

(5) The Freeze-thaw resistance of the cement skin was weak due to the high water to cement ratio. To have better frost resistance, it is recommended that air entraining agent be added to the mix to provide the mechanisms for pressure to release during the freeze-thaw cycling.

(6) Sandwich beams of 1.22 m long were tested with cement skins either parallel to the base or perpendicular to the base. It was found that the beam with skin parallel to the base exhibited very low strength that could not be predicted by the classical beam theory. It was possibly caused by the flexible core that made the assumption that plane remained plane in bending invalid. It is therefore necessary to carry out more research on the theory to incorporate the flexible core in a sandwich structure and to develop an analysis tool for wind load design. On the other hand, beam tested with skin perpendicular to the base performed just like cement beam without core. This was the strongest direction of the proposed wall. With the properties of lightweight and mesh reinforcement, the wall has demonstrated its potential to resist seismic action.

(7) Future work is recommended.

- Fire resistance needs more study. Full-scale fire test seems necessary to examine the sustainability of the sandwich structure on fire. Structurally, a possibility could be to replace the inner cement skin with a gypsum skin to provide more resistance to heat transfer and to delay the melting of the core. This concept requires support from further tests.
- Water permeability of the sandwich system is crucial to thermal efficiency. Saturated EPS will loss tremendously the thermal resistance and may deteriorate the bonding with the skin, leading finally to an unstable structure. Therefore, The permeability and thermal resistance of the saturated wall should be investigated.
- The load carrying capacities of the full-scale wall were tested to obtain the maximum gravity load and the maximum wind load. The maximum in-plane shear capacity was not fully explored due to the limit of the time. If the seismic applications are more of interest, the cyclic shear tests until failure are needed to determine the shear capacity.
- A theory is urgently needed to model the cross section of flexible core reinforced by rigid skin and to predict the resistance of the sandwich wall to lateral wind load.

Table 1: Mixture proportion of cement skin (by weight)

	Cement	**Sand**	**Water**	**Additive**	**Applications**
Mix 1	1	3	0.656	0.2% MC	
Mix 2	1	3	0.718	0	
Mix 3	1	3	1.085	5.2% cellulose fiber	
Mix 4	1	3	0.382	10% Latex	
Ready-mix products:					
Parging mix	**cement + sand** =1		0.158	0	
Premixed Mortar	**cement + sand** =1		0.146	0	
S-bond mix	**cement + sand** =1		0.191	0	1st coat in 2-coat skin in single block SB2
Sand mix 1	**cement + sand** =1		0.167	0	Single block & double block with EPS core
Sand mix 2	**cement + sand** =1		0.167	0	Single block with SM core Beams for 4-pt bending tests, Beams for 3-pt shear tests, Freeze & thaw samples, Columns for fire tests.
Mixture proportion for full scale wall:					
Wall mix 1	1	2.5	0.57	0	
Wall mix 2	1	2.5	0.6	0	Full-scale wall

Cement = Lafarge type 10 cement.
Sand = Oven dried sand, Bomix.
MC = Methyl cellulose, Dow Chemical.
Cellulose fiber = Recycled paper fibers.
Latex = Conchem XL-bond.
Parging mix = Cement + additives, Bomix.
Premixe mortar = masonry cement + sand, Bomix.
S-Bond mix = Spread'n Bond, cement + sand + polymer, Bomix.
Sand mix = cement:sand=1:3, Bomix.
Sand mix 2 = cement:sand=1:3, Bomix. (Sand mix 2 was ordered from the same company, but had much less strength (19 MPa) than the sand mix 1 (35 MPa), indicating that the commercial products were not consistent. Therefore in the full scale wall test, lab mix was used. It was called final wall mix.)
Wall mix = Final wall mix forcement skin on the full scale wall test.

Table 2: 7-day compressive strength of cement skin

	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Average (MPa)	Comment
Mix 1	8.36	5.8	9.1	7.75±1.7	Low strength
Mix 2	25.6	23.55	23.46	24.2±1.21	Good
Mix 3	6.75	7.11	7.16	7±0.22	Low strength
Mix 4	8.94	13.13	12.79	11.62±2.33	Low strength
Parging mix	8.39	8.24	8.56	8.4±0.16	Low strength
Premixed Mortar	6.2	6.04	6	6.08±0.11	Low strength
S-bond mix	22.44	23.06	20.72	22.07±1.21	Good, expensive
Sand mix 1	33.96	34.51	36.52	35±1.35	Very good
Sand mix 2	19.56	19.36	19.28	19.4±0.14	Good, 2nd order
Wall mix 1	29.77	28.90	29.08	29.34±0.62	Good
Wall mix 2	25.43	27.52	24.21	25.74±1.14	Good

Table 3: Comparison of compressive strengths of sand mix 2 at 7-day with 28-day

	Specimen 1 (MPa)	Specimen 2 (MPa)	Specimen 3 (MPa)	Average (MPa)
7-day Test	19.56	19.36	19.28	19.4±0.14
28-day test	19.87	19.75	21.59	20.40±1.03

Table 4: Compressive tests for load capacity of core material

Sample	Core	Top & bottom plates(5/8")	P_{max} (kN)	P_{max} (kN/m)	P_{max} (lb/ft)	R value (Thermal resistance)
RW-1	EPS	1	3.62	12	823	3.7/inch
RW-2	EPS	1	3.92	13	882	3.7/inch
SM-1	SM	1	15.23	50	3430	5/inch
SM-2	SM	1	17.5	57	3939	5/inch

Note: RW: recycled white EPS core wrapped with mesh (12"x12"x12"); SM: Cell Fort pink styrofoam core wrapped with mesh (12"x12"x12").

Table 5: Maximum load carried by single sandwich composite block

Sample	Core	Cement skin	Top & bottom plates (16mm thick for each)	P_{max} (kN)	P_{max} (kN/m)	P_{max} (lb/ft)
SB1-1	EPS	Sand mix 1	2	426	1398	95903
SB1-2	EPS	Sand mix 1	2	487	1598	109623
SB2-1	EPS	S-bond mix + sand mix	1	356	1168	80125
SB2-2	EPS	S-bond mix + sand mix	1	420	1378	94531
SB3-1	SM	Sand mix 2	1	248	814	55840
SB3-2	SM	Sand mix 2	1	192	630	43218
DB1-1	EPS	Sand mix 1	1	834	1368	93845
DB1-2	EPS	Sand mix 1	1	1124	1844	126498

Note: SB: single block (12"x12"x 14"); DB: double block (12"x24"x14").

Table 6: Mass loss and section loss of cycled mortar prisms

	Initial mass (g) (0 cycle)	Lost mass **after 100 cycles,** (g)	%Mass loss **after 100 cycles**, %	Initial cross section, mm^2	Section **after 100 cycles**, mm^2	Section loss, %
Specimen 1	3566	171	4.8	5929	5649	4.7
Specimen 2	3582	72	2.0	5929	5755	2.9
Specimen 3	3578	100	2.8	5929	5767	2.7
	Initial mass (g) (0 cycle)	Lost mass **after 200 cycles,** (g)	%Mass loss **after 200 cycles**, %	Initial cross section, mm^2	Section **after 200 cycles**, mm^2	Section loss, %
Specimen 1	3566	163	9.4	5929	5515	7.0
Specimen 2	3582	65	3.8	5929	5673	4.3
Specimen 3	3578	99	5.6	5929	5624	5.1

Table 7: Comparison of cycled and uncycled mini-sandwich specimens

	Freeze-thaw cycles	Mass before cycle (g)	Lost mass **after 200 cycles,** (g)	% Mass loss, %	Peak load in 4P bending tests at span = 305mm (kN)
Specimen 1	200 cycles	2505	170	6.8	2.36
Specimen 2	200 cycles	2516	118	4.7	2.26
Specimen 3	0 cycle	2494	0	0	3.2
Specimen 4	0 cycle	2501	0	0	2.7

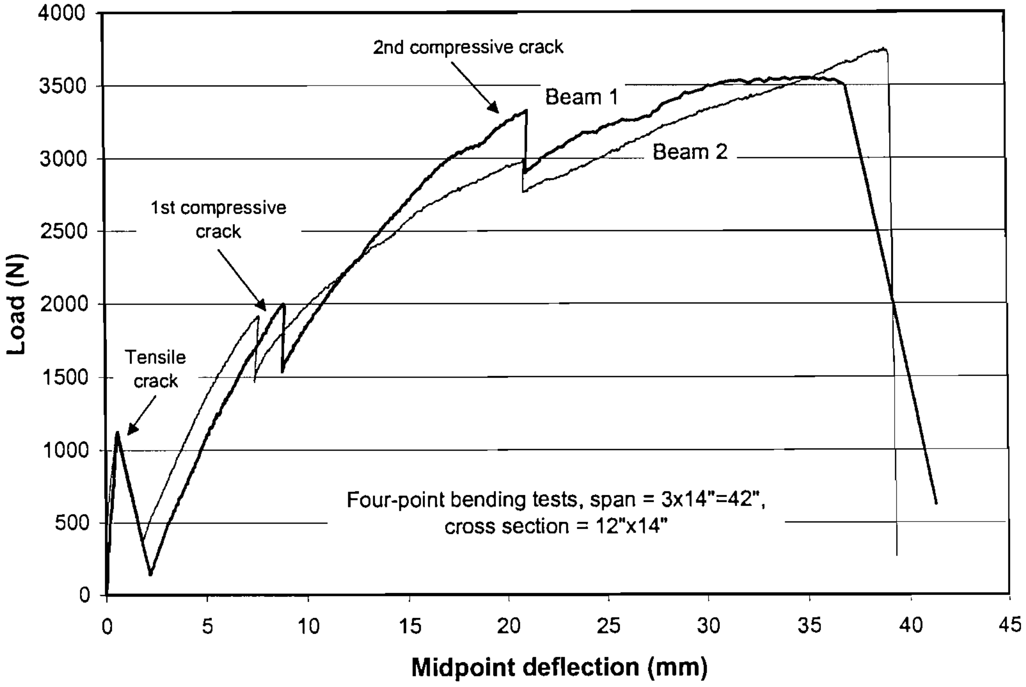


Fig. 1: Four-point bending tests of sandwich beams with skin parallel to base

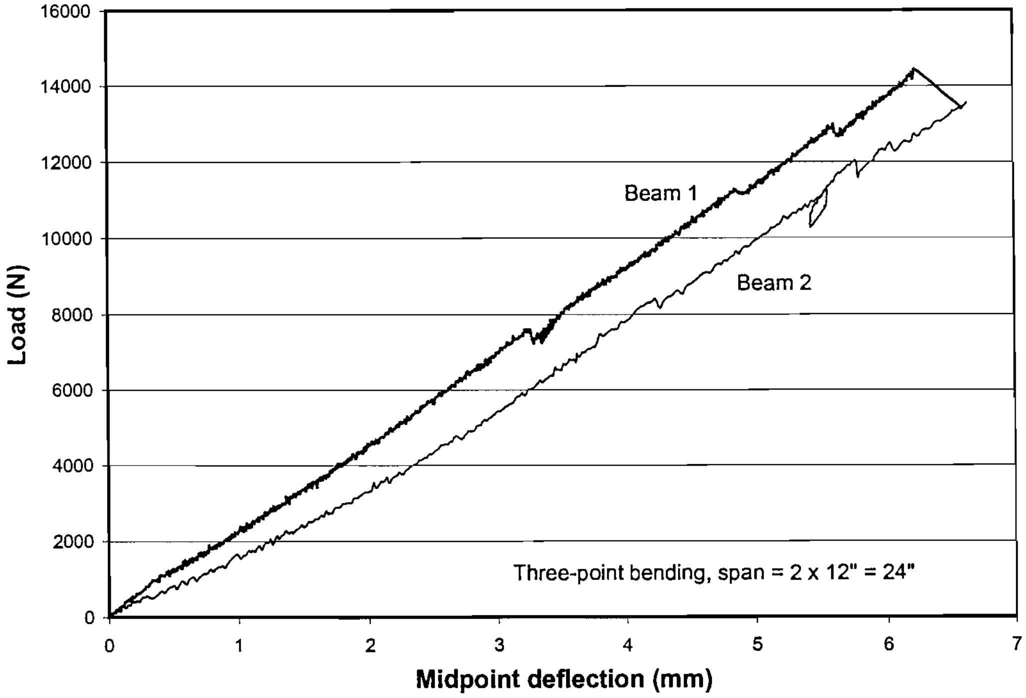
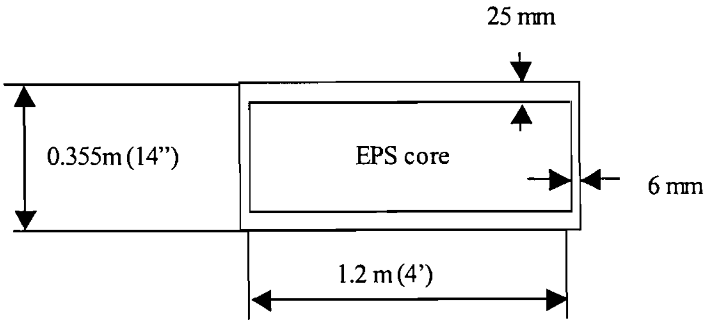
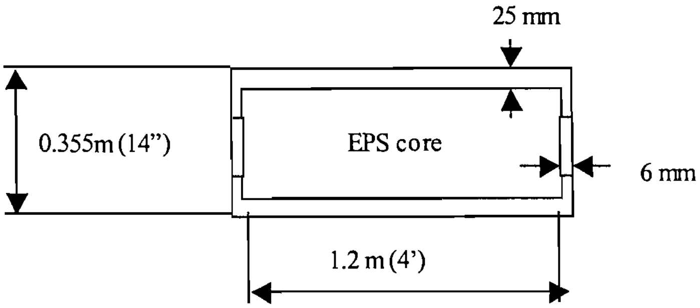


Fig. 2: Three-point bending tests of sandwich beams with skin perpendicular to base



(a): Cross section of EPS sandwich wall with closed edge



(b): Cross section of EPS sandwich wall with open edge

Fig. 3: Cross section of EPS sandwich wall

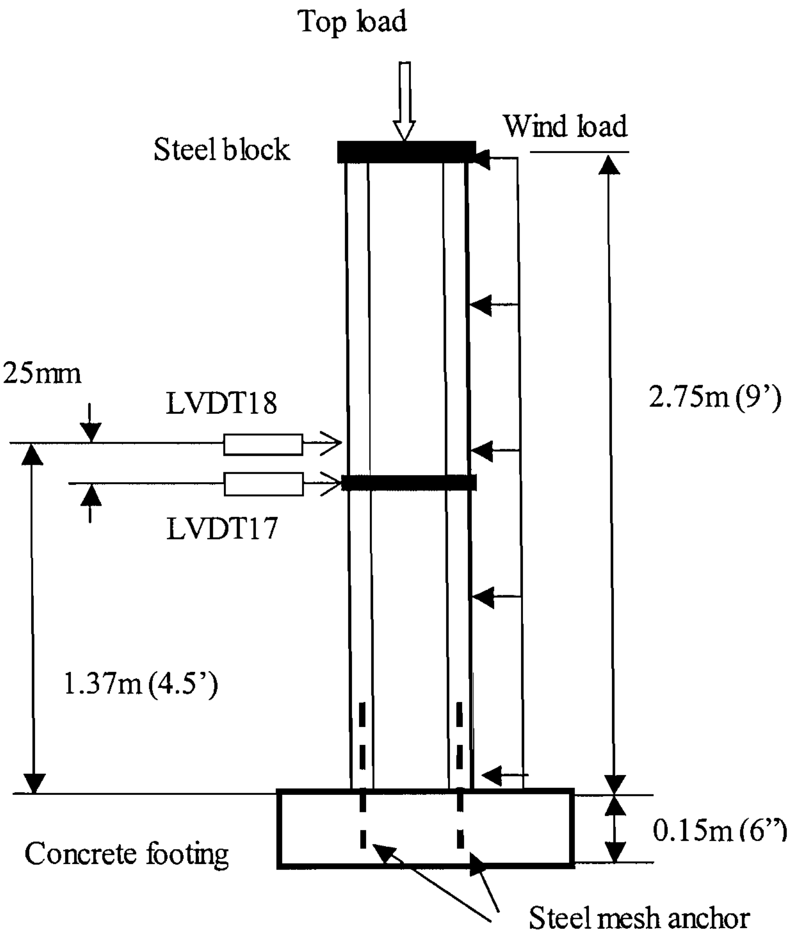


Fig. 4: Side view of sandwich wall (wall thickness = 0.355m (14"))

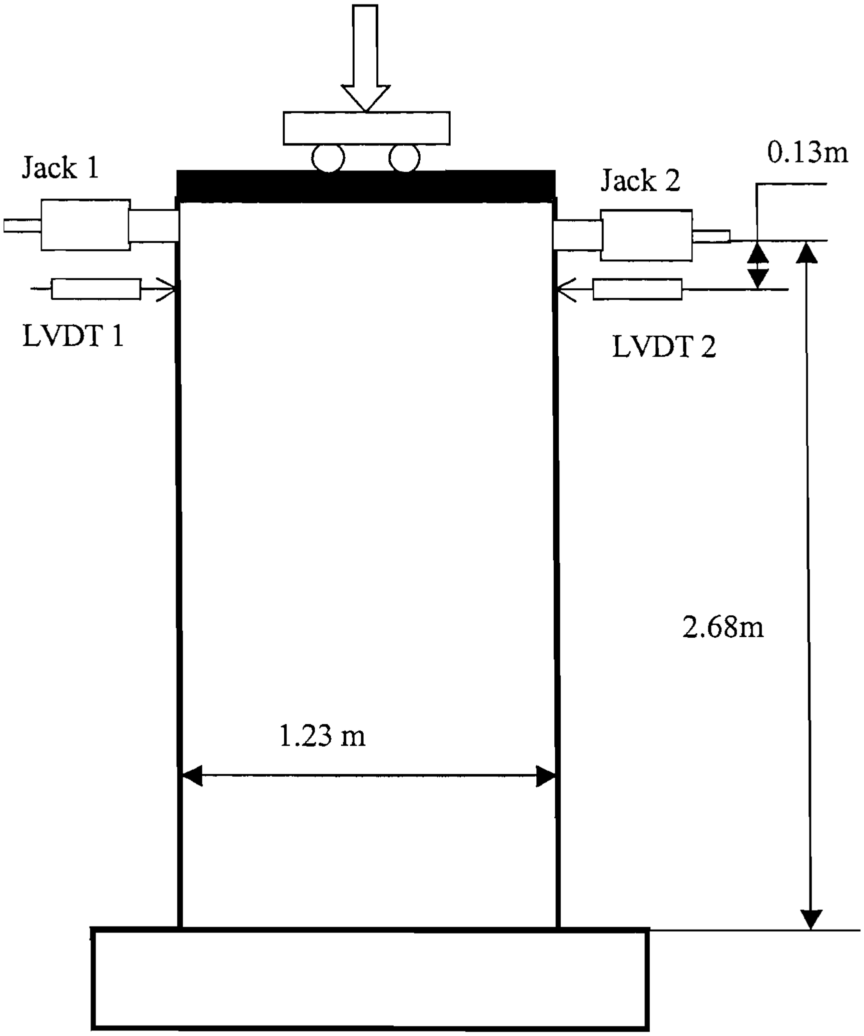


Fig. 5: Front view of sandwich wall

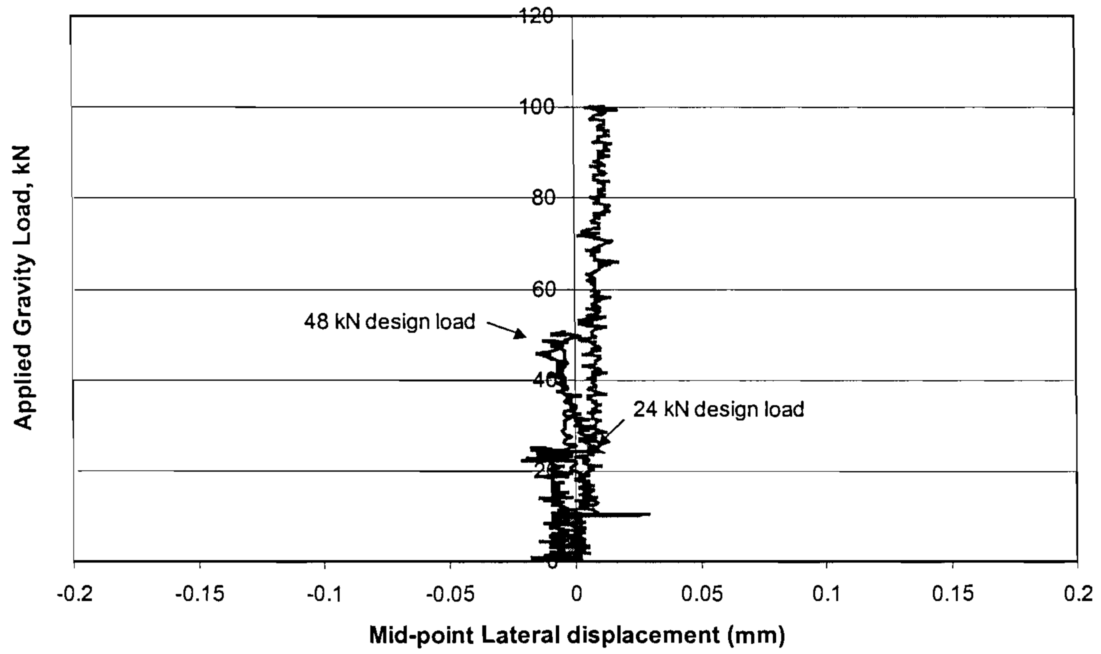


Fig. 6: Gravity load tests up to 100 kN

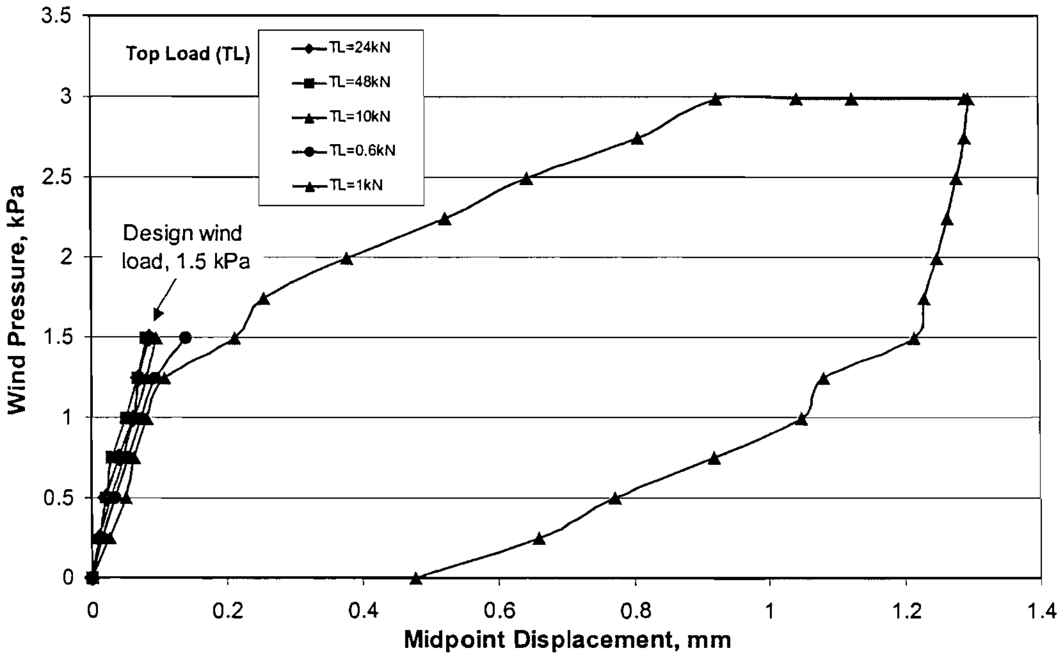


Fig. 7: Wind load tests up to 3 kPa (62 psf)

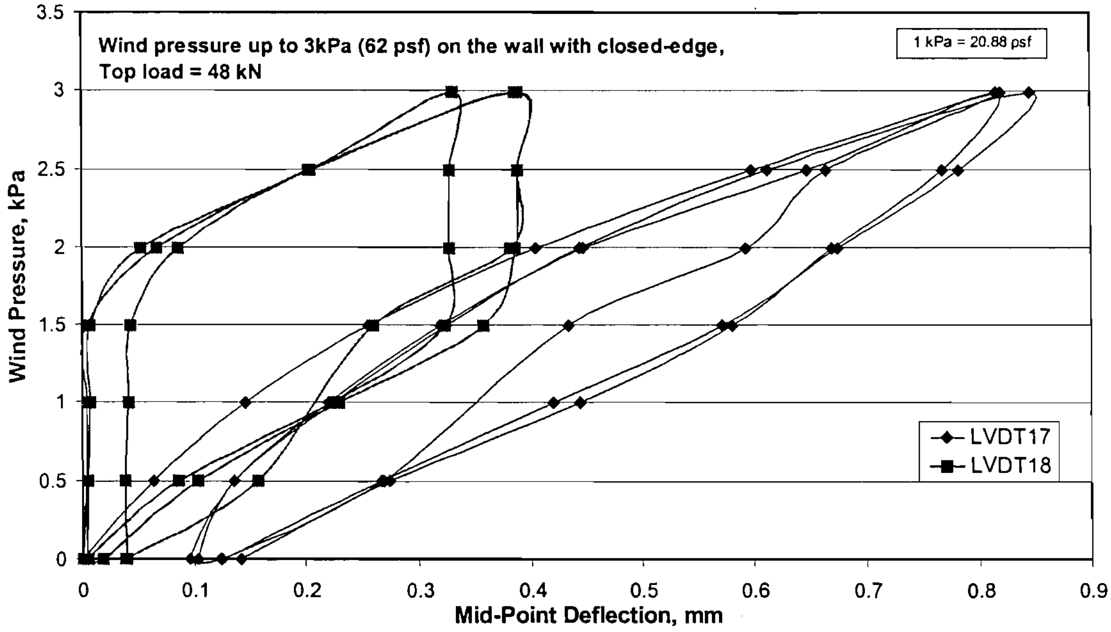


Fig. 8: Cyclic wind load tests up to 3 kPa (62 psf)

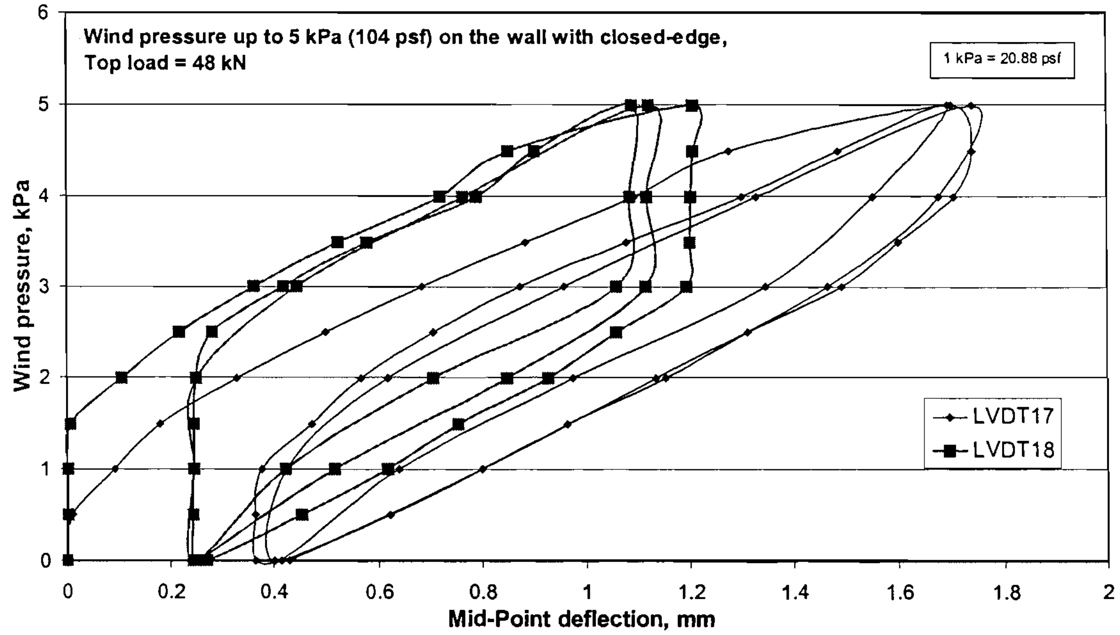


Fig. 9: Cyclic wind load tests up to 5 kPa (104 psf)

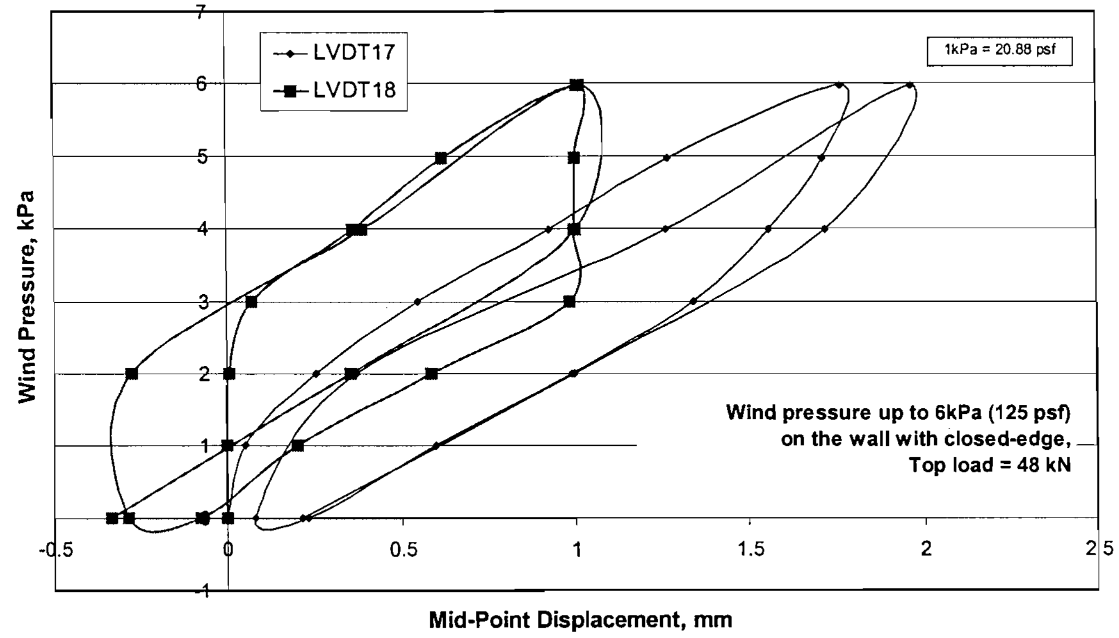


Fig. 10: Cyclic wind load tests up to 6 kPa (125 psf)

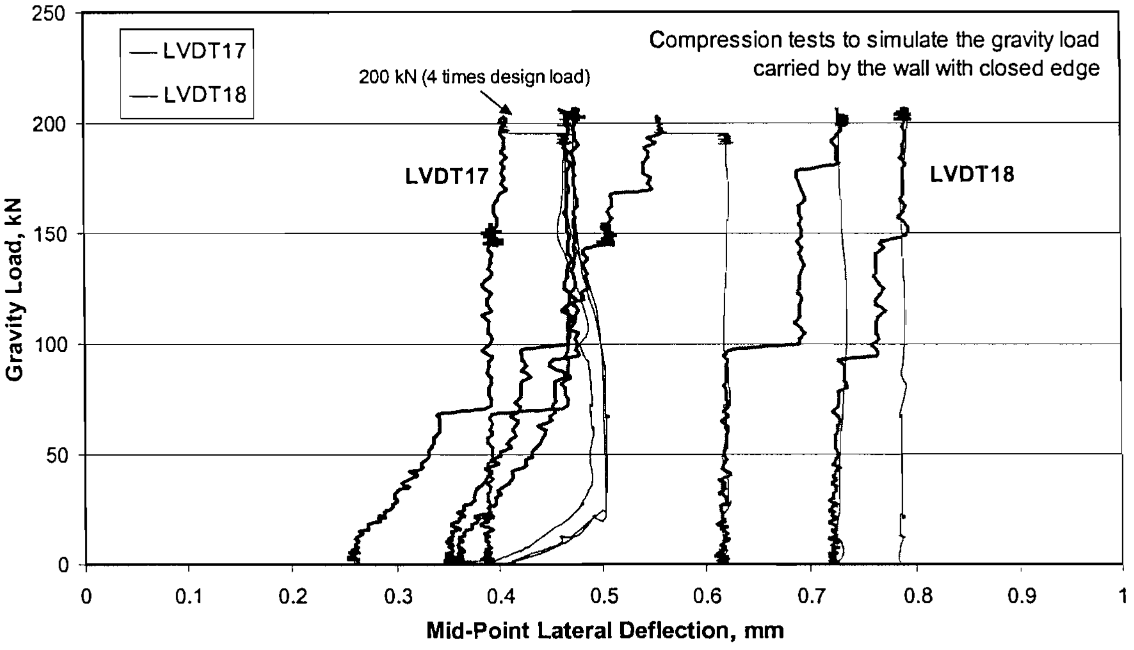
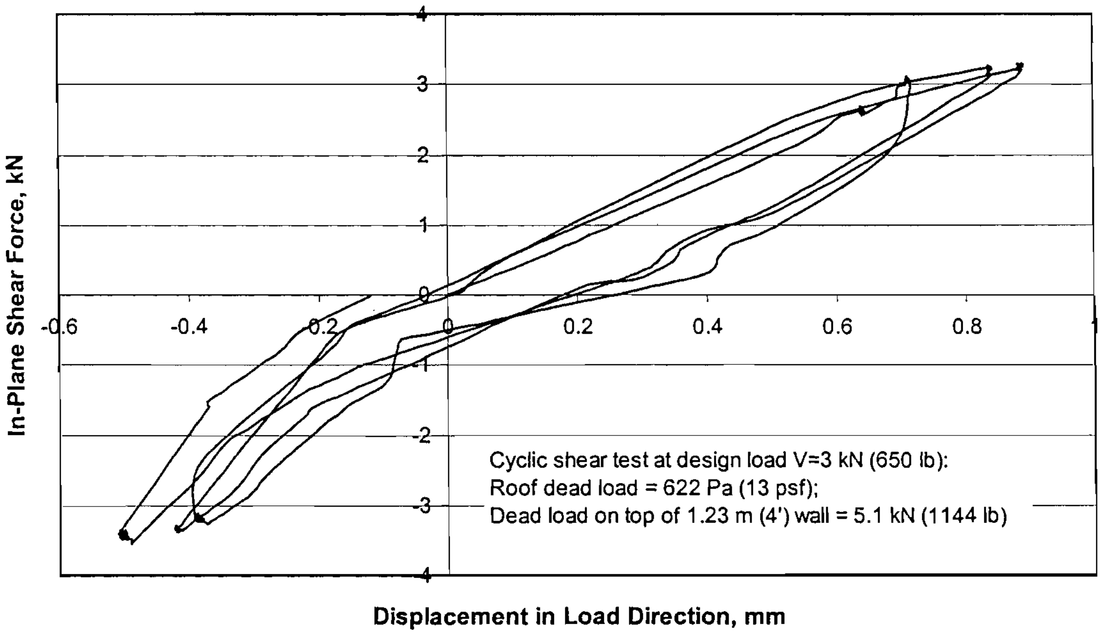
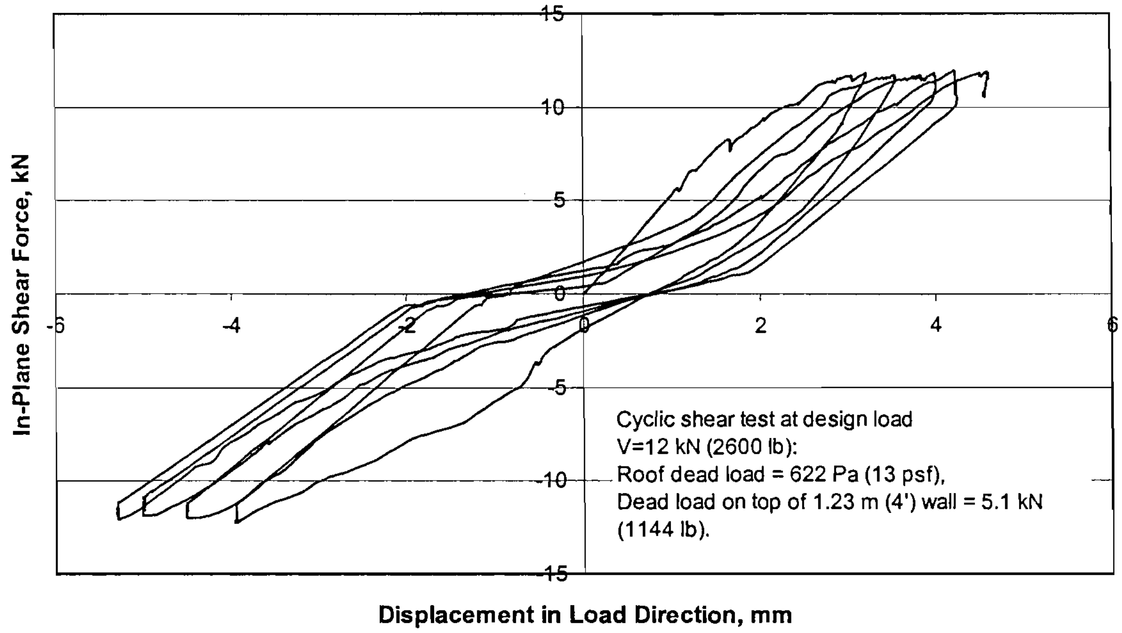


Fig. 11: Cyclic gravity load tests up to 200 kN (close edge)



Cyclic shear test at design load V=3 kN (650 lb):
Roof dead load = 622 Pa (13 psf);
Dead load on top of 1.23 m (4') wall = 5.1 kN (1144 lb)

Fig. 12: Cyclic in-plane shear tests up to 3 kN (650lb)



Cyclic shear test at design load
V=12 kN (2600 lb):
Roof dead load = 622 Pa (13 psf),
Dead load on top of 1.23 m (4') wall = 5.1 kN (1144 lb).

Fig. 13: Cyclic in-plane shear tests up to 12 kN (2600lb)

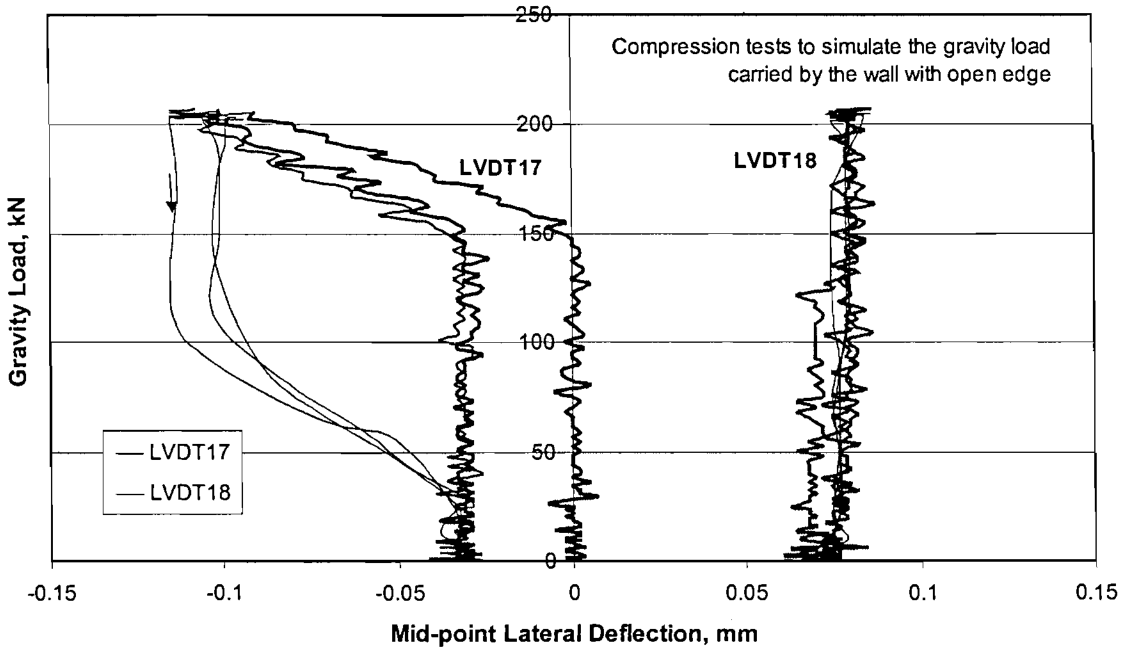


Fig. 14: Cyclic gravity load tests up to 200 kN (open edge)

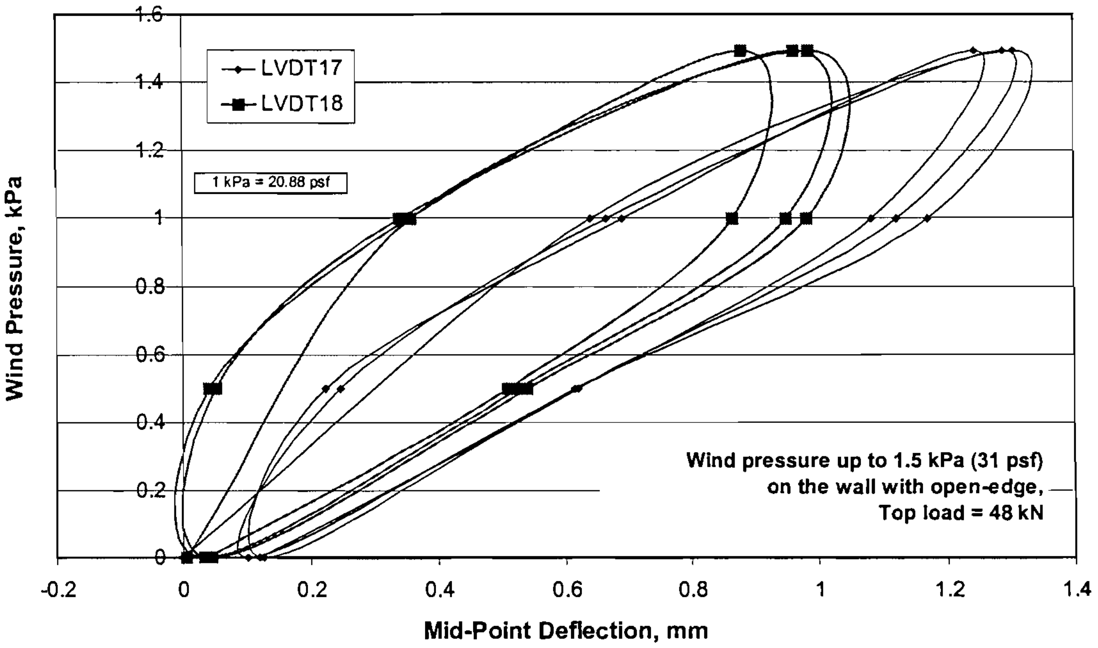


Fig. 15: Cyclic wind load tests up to 1.5 kPa (31 psf) – open edge

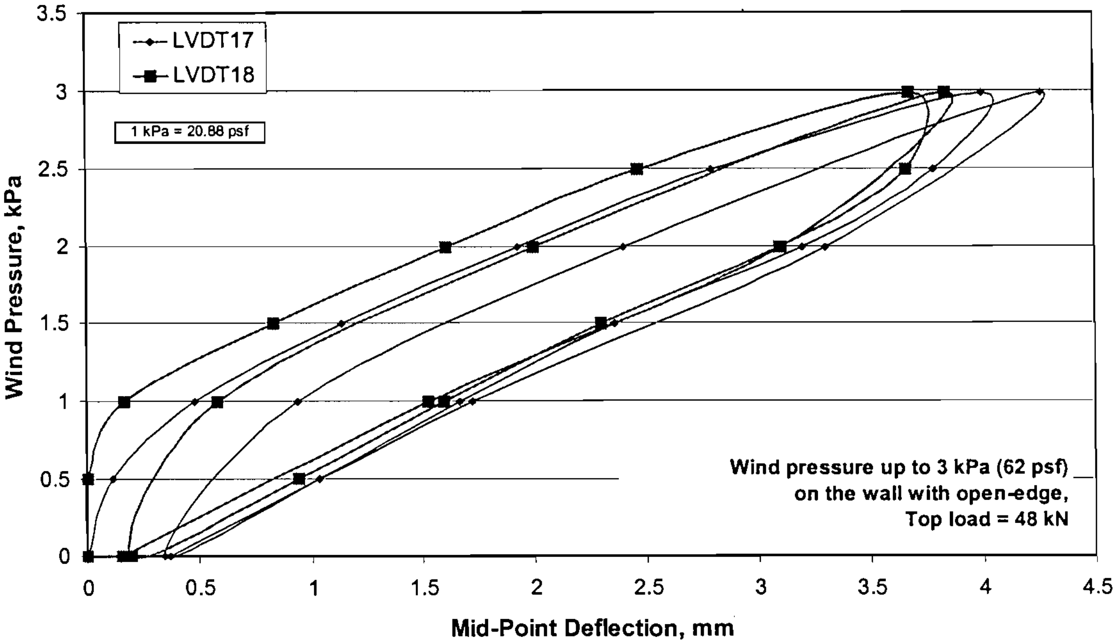


Fig. 16: Cyclic wind load tests up to 3 kPa (62 psf) – open edge

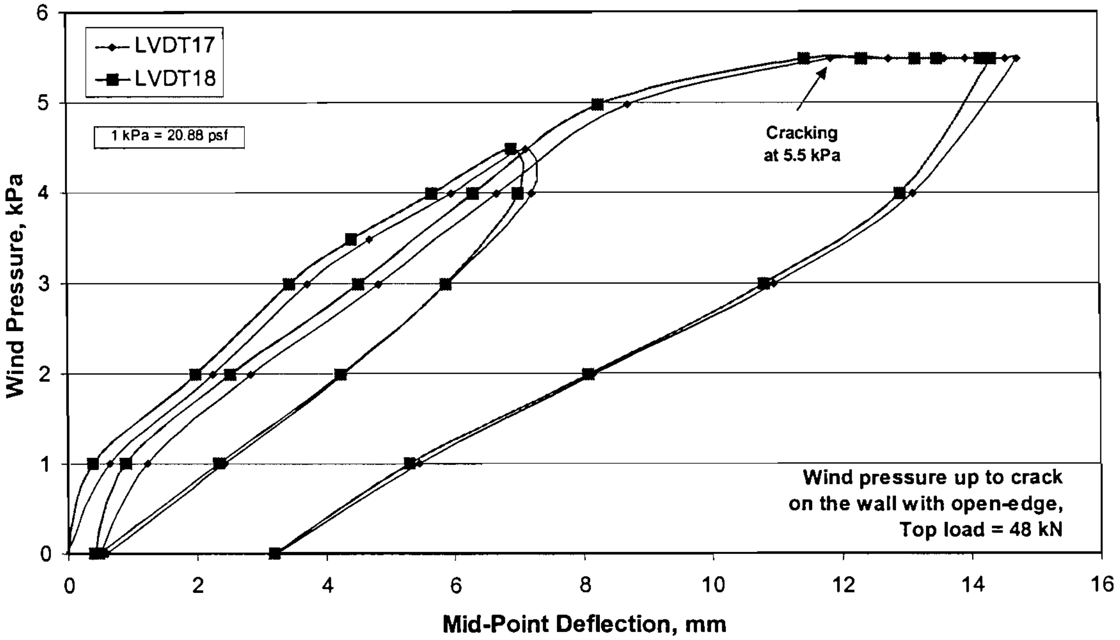


Fig. 17: Cyclic wind load tests up to cracking – open edge

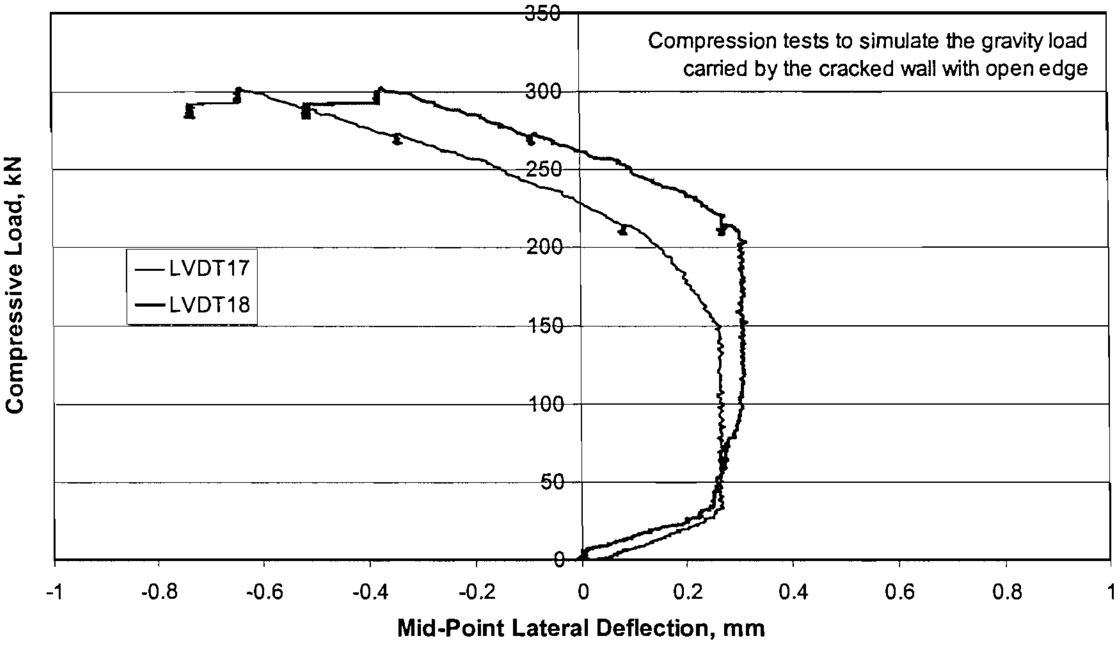


Fig. 18: Compression tests on the cracked wall up to 300 kN – open edge

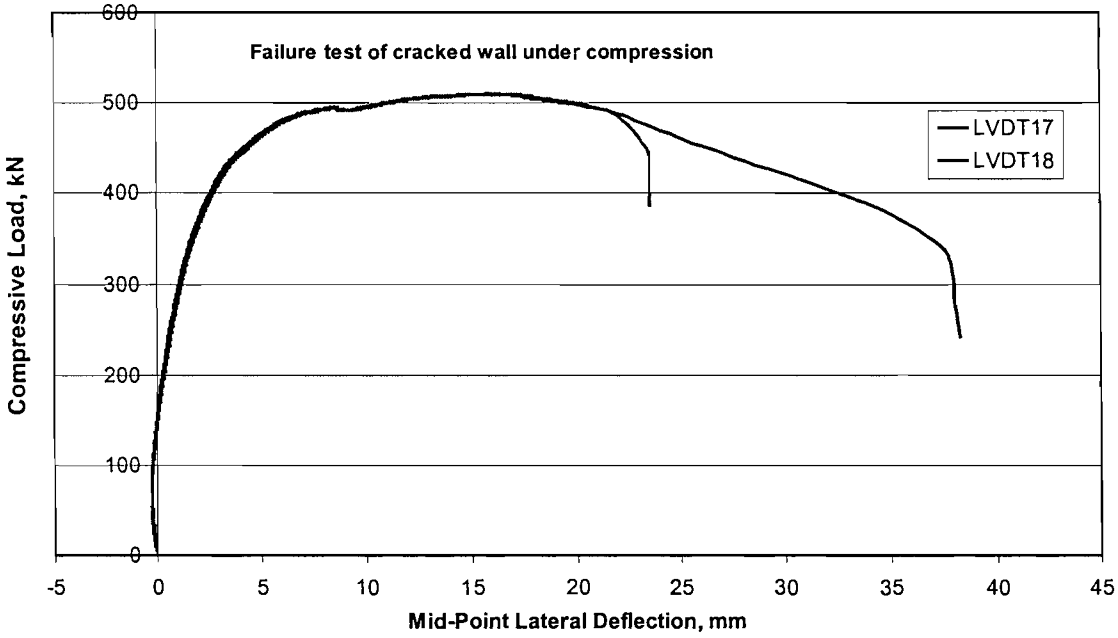


Fig. 19: Failure test of the cracked wall up to buckling –open edge

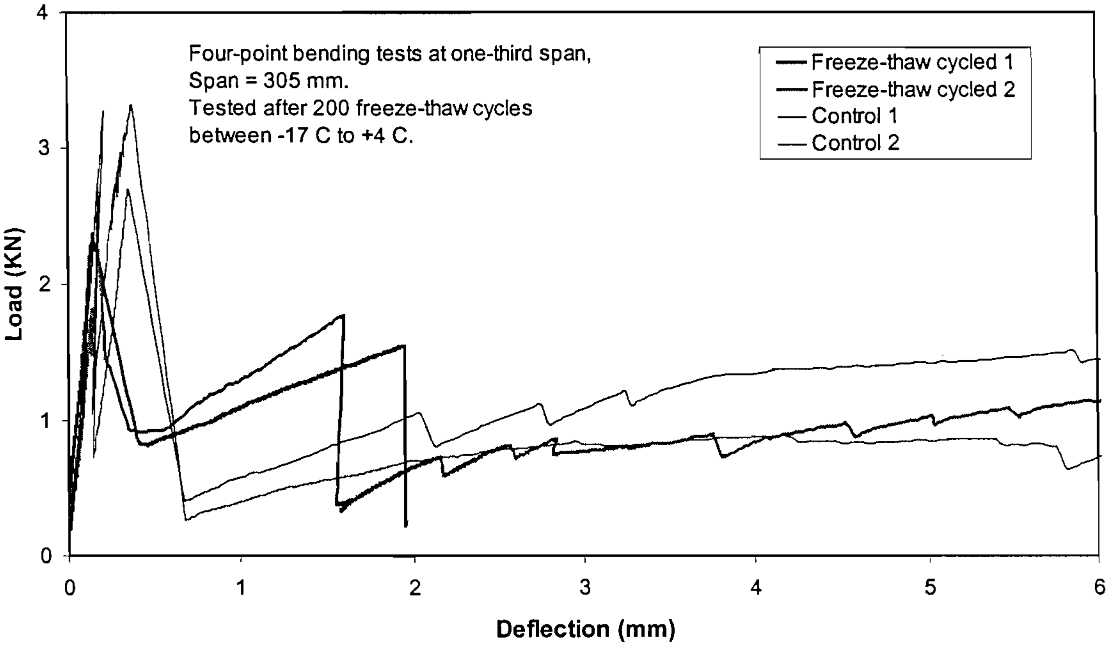


Fig. 20: Comparison of load-deflection curves of freeze-thaw cycled sandwich specimens with control

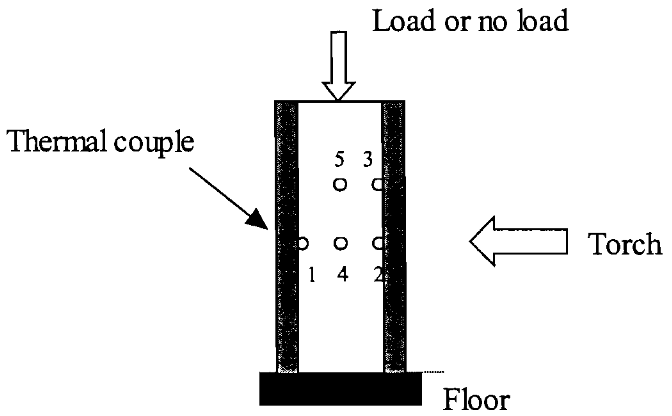


Fig. 21: Schematic of blow torch tests for sandwich column 1 (no top load) and column 2 (with 1200 lb weights on top)

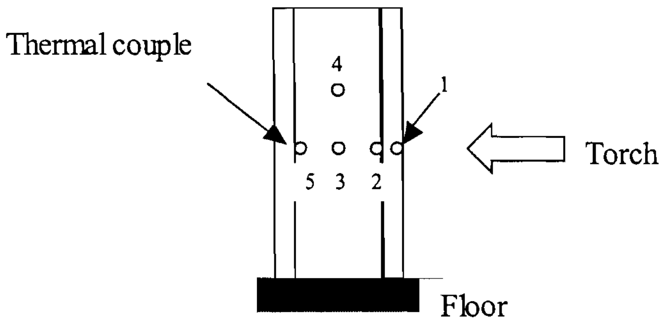


Fig. 22: Schematic of blow torch test for sandwich column 3 (no top load) with a thermal couple inside cement skin

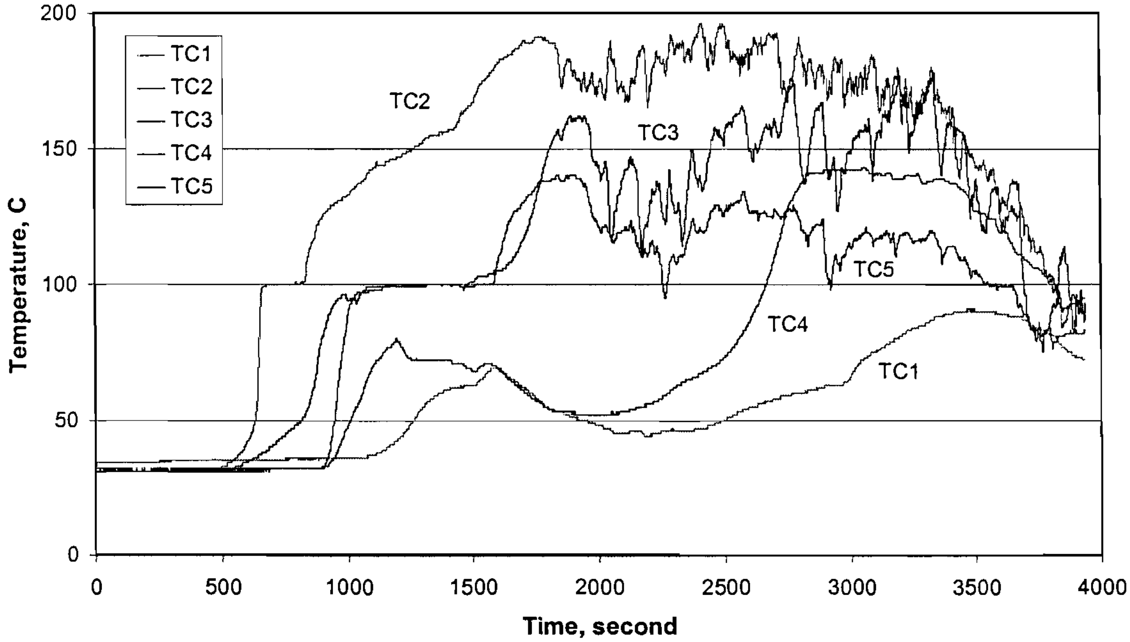


Fig. 23: Temperature distributions in column 1 during blow torch test

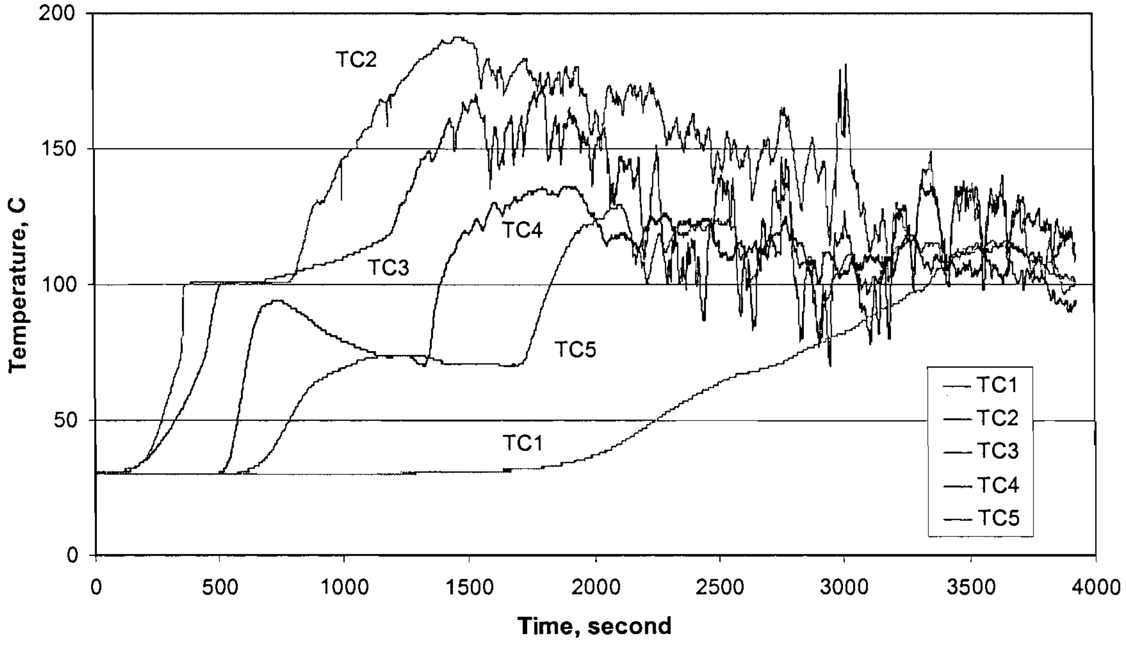


Fig. 24: Temperature distributions in column 2 during blow torch test (Dead load on top = 5.3 kN (1200 lb))

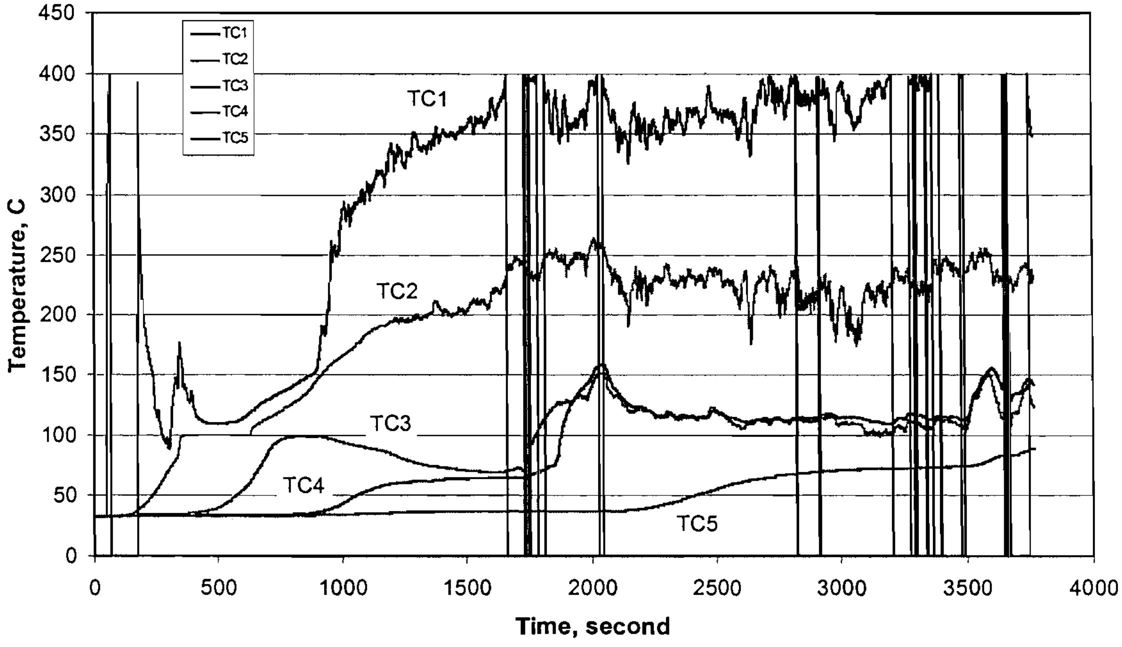


Fig. 25: Temperature distributions in Column 3 with TC 1 inside cement skin

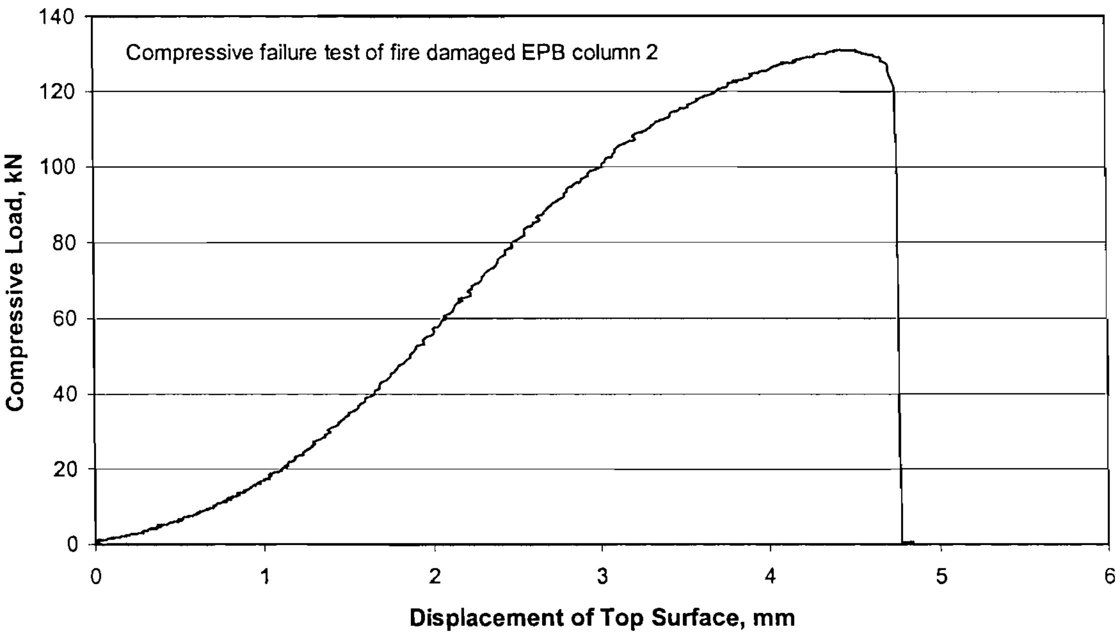


Fig. 26: Compressive strength of fire damaged sandwich column 2

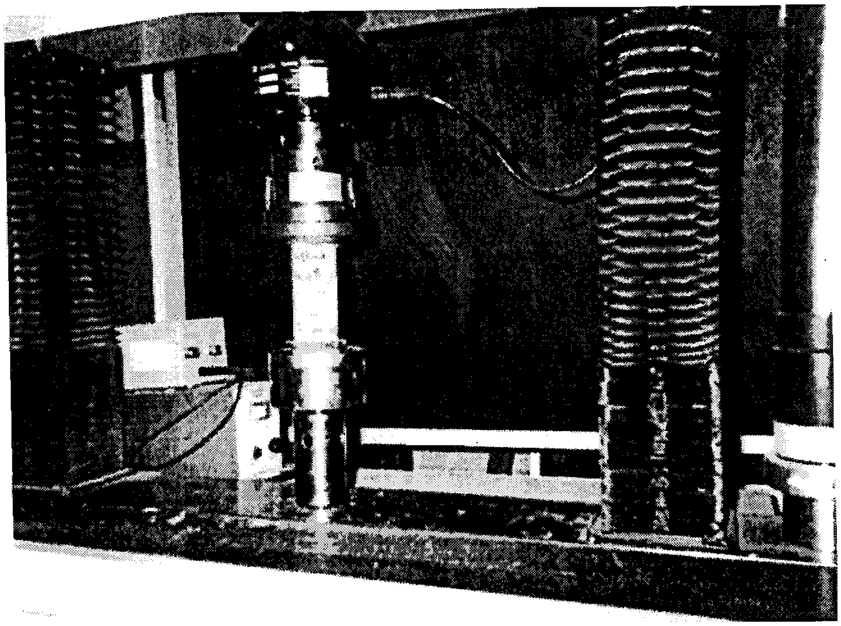


Photo 1: Cylinder tests for compressive strength of cement skin

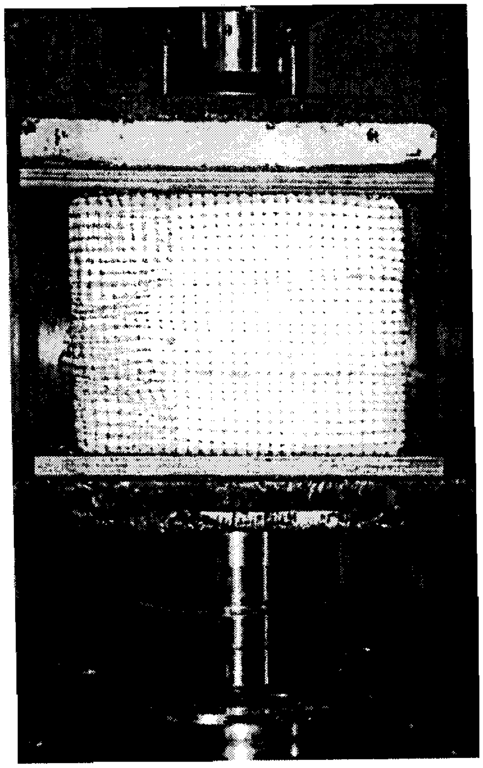


Photo 2: Test setup for compressive strength of core materials

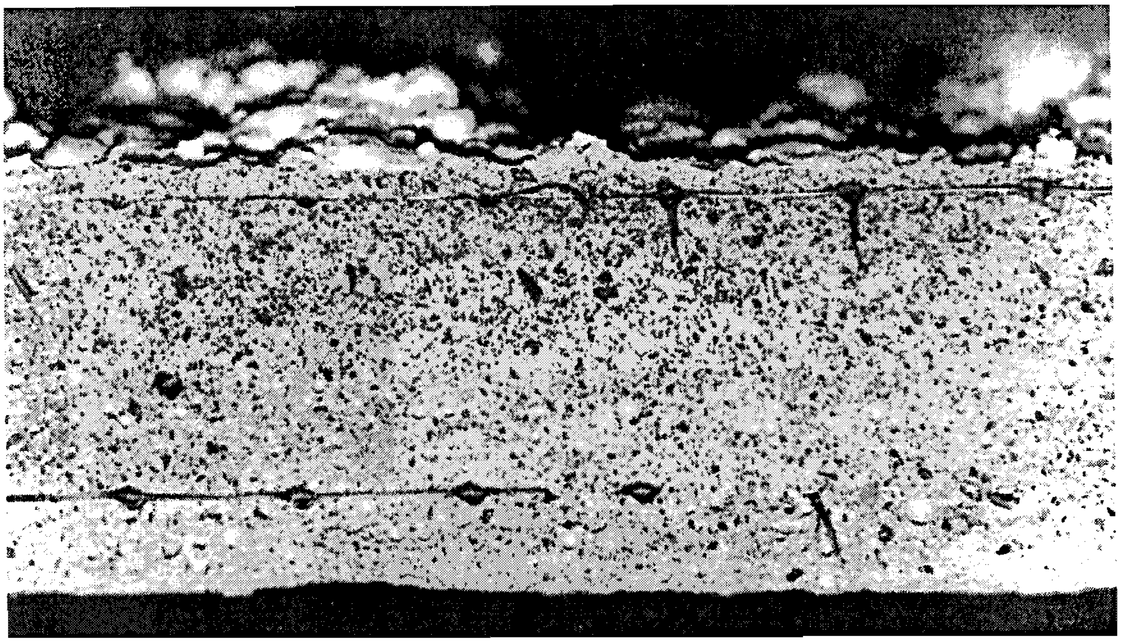


Photo 3: Three mesh layers in 25-mm thick cement skin

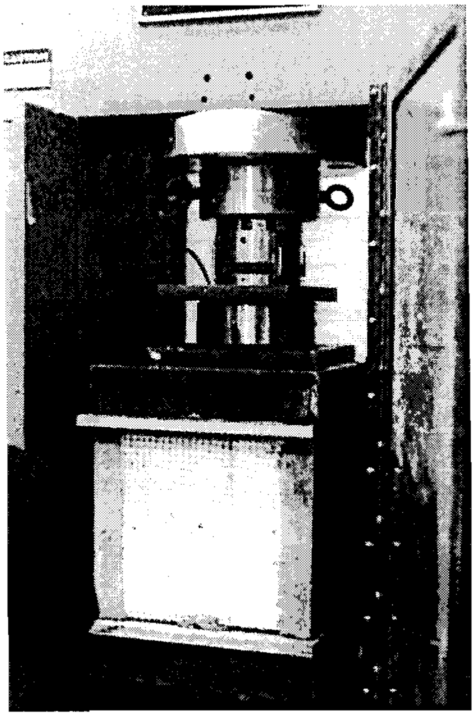


Photo 4: Setup for compressive tests of sandwich blocks

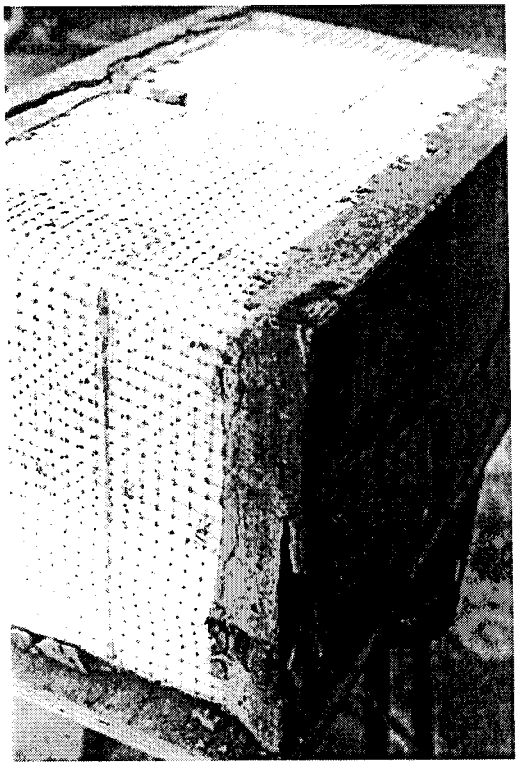


Photo 5: Compression failure of sandwich block

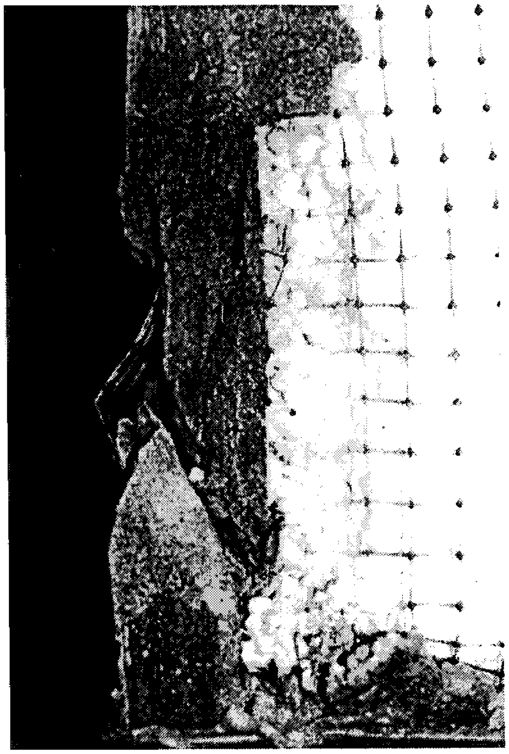


Photo 6: Strong bond between EPS core and cement skin

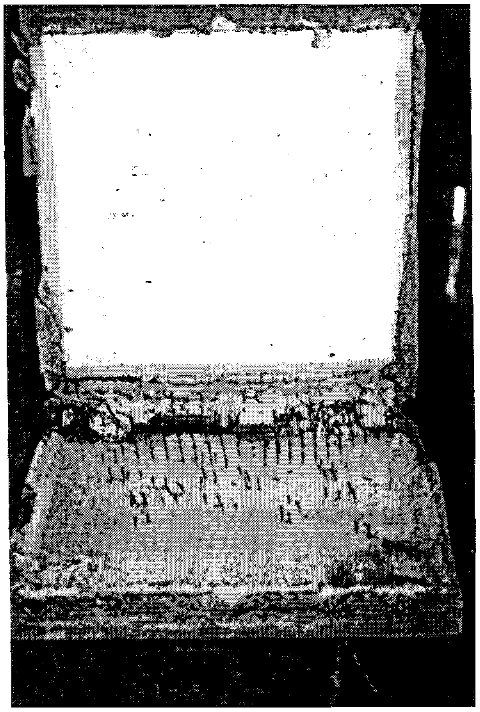


Photo 7: Weak bond between SM core and cement skin

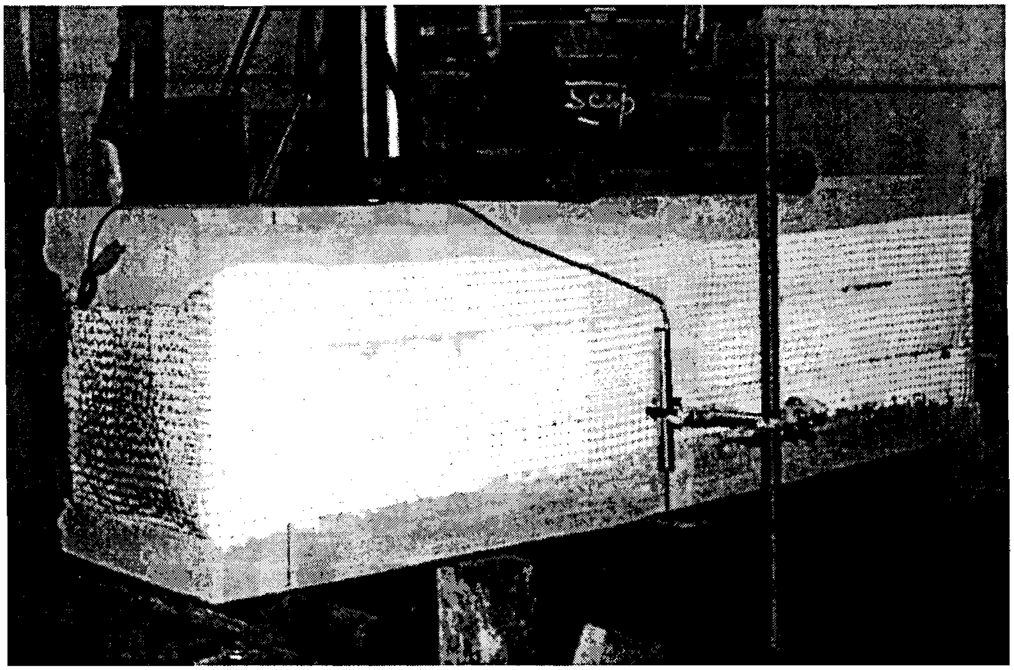


Photo 8: Setup for 4-point bending tests with cement skins parallel to base

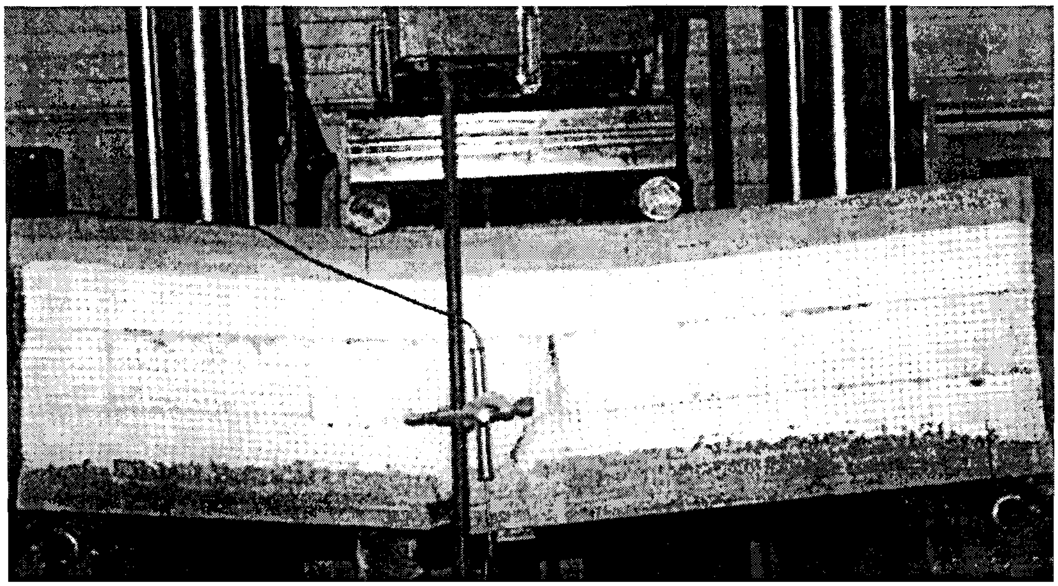


Photo 9: Failure of sandwich beam subject to 4-point bending

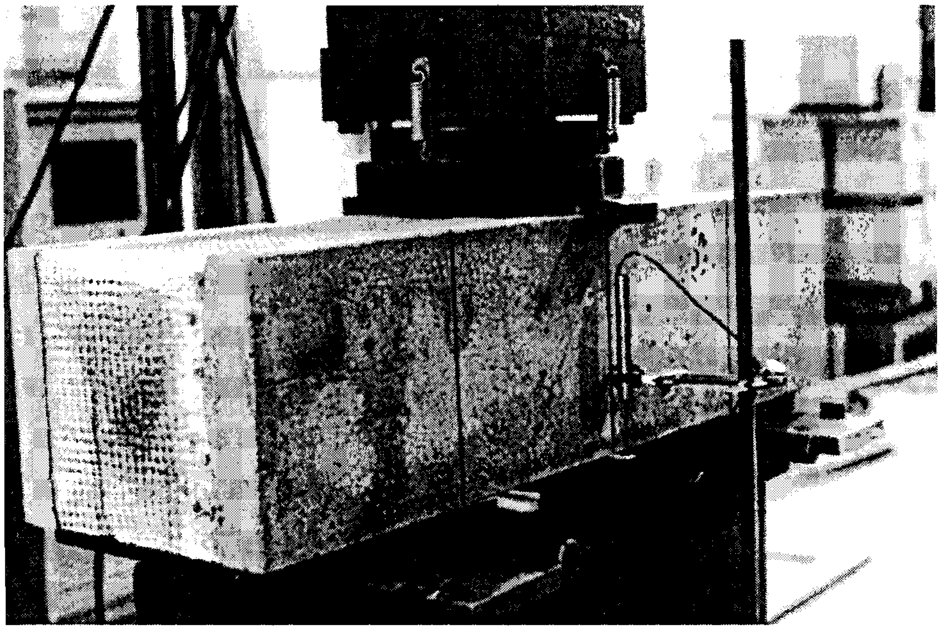


Photo 10: Setup for 3-point bending tests with skins perpendicular to base

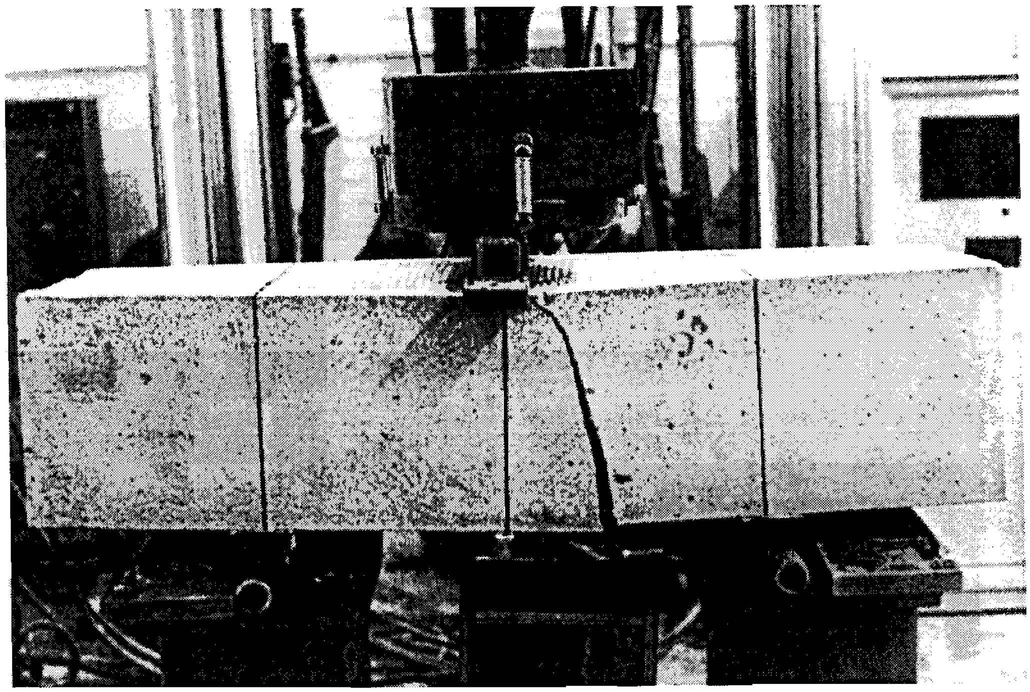


Photo 11: Failure of sandwich beam subject to 3-point bending

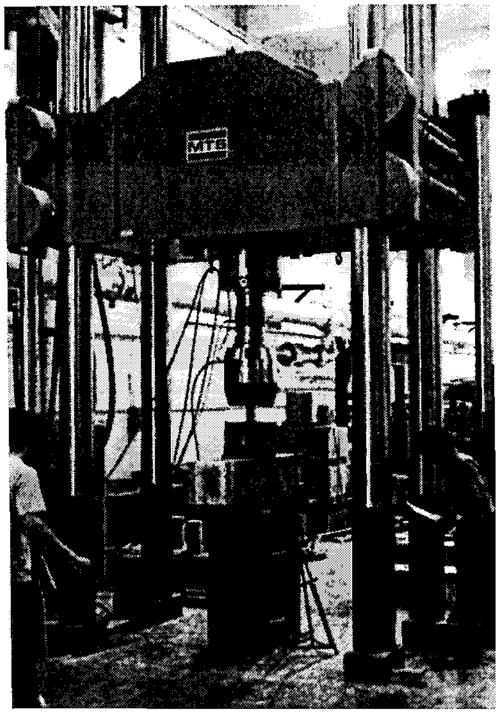


Photo 12: Overview of MTS machine and full-scale wall test site

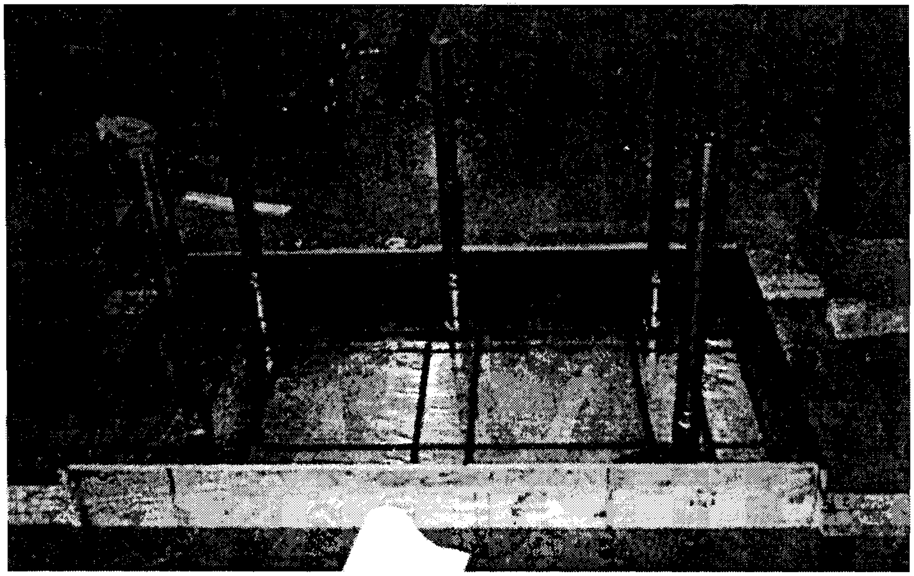


Photo 13: Formwork for concrete footing on strong floor

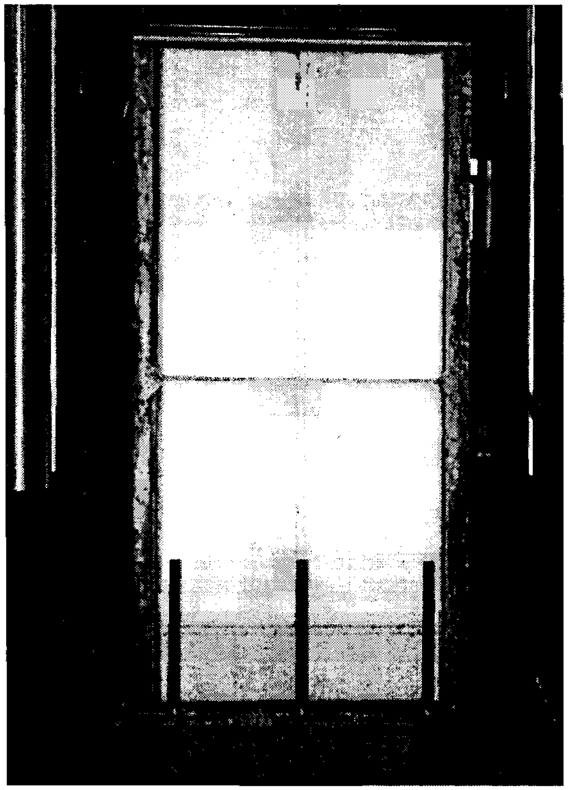


Photo 14: EPS core positioned on concrete footing

Photo 15: Application of first coat of cement on EPS core

Photo 16: Application of first layer of plastic mesh

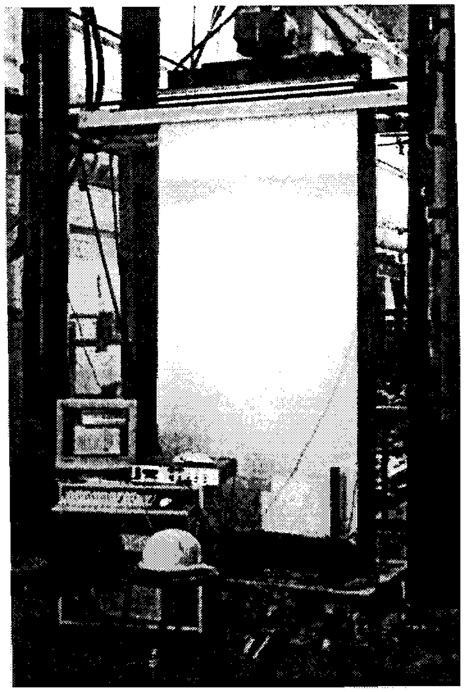


Photo 17: Finished wall with data acquisition system

Photo 18: Installed air bag to apply the wind pressure on closed edge wall

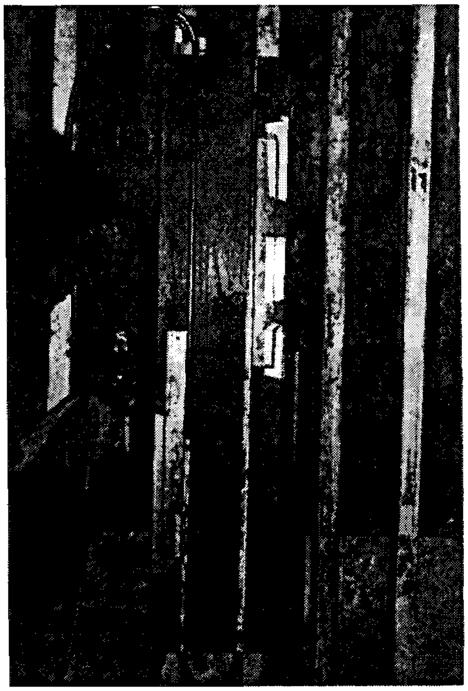


Photo 19: Installed water-filled manometer for wind pressure measurement

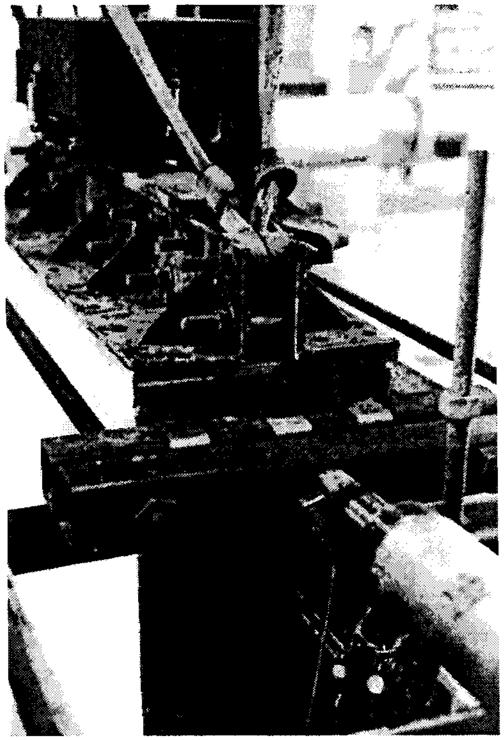


Photo 20: Setup for cyclic shear tests (right side view)

Photo 21: Setup for cyclic shear tests (left side view)

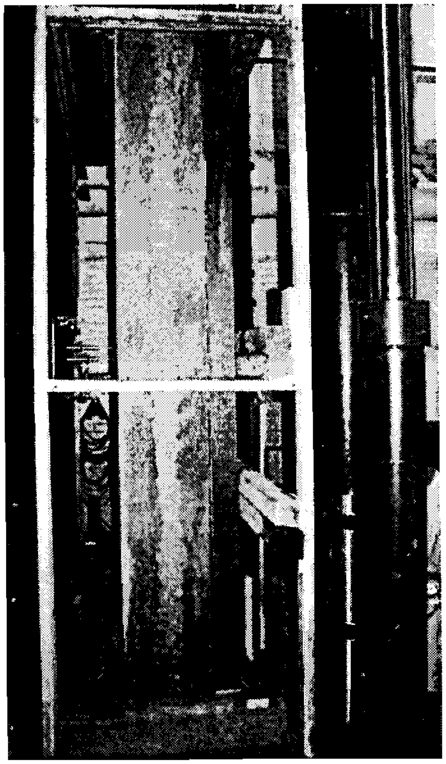


Photo 22: Open edged wall

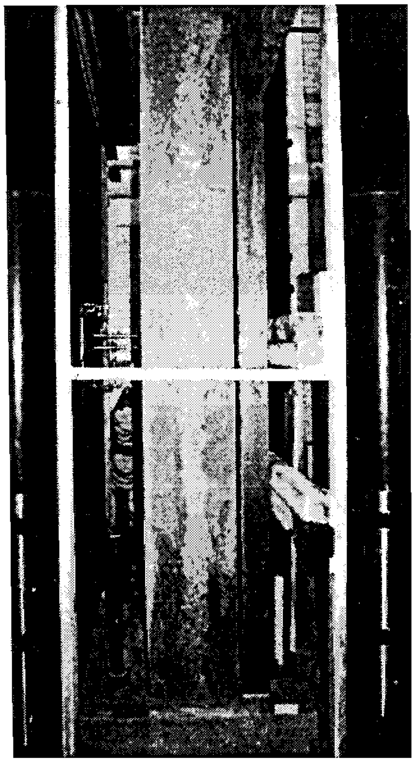


Photo 23: Opening of the gap between the wall and the inflated air bag

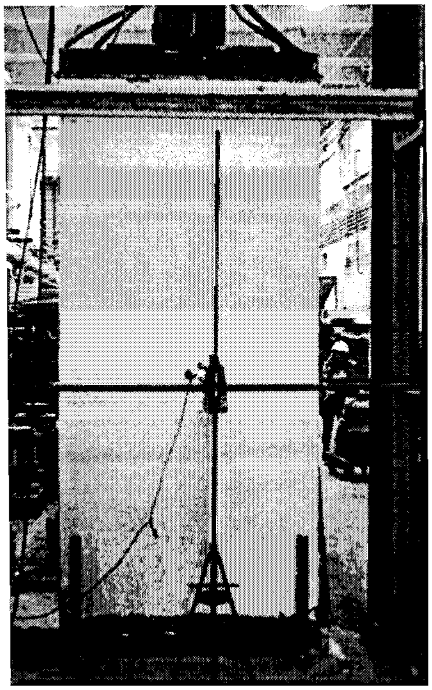


Photo 24: First transverse crack in cement skin at 5.5 kPa wind pressure

Photo 25: Buckling of the wall at a compressive load of 500 kN

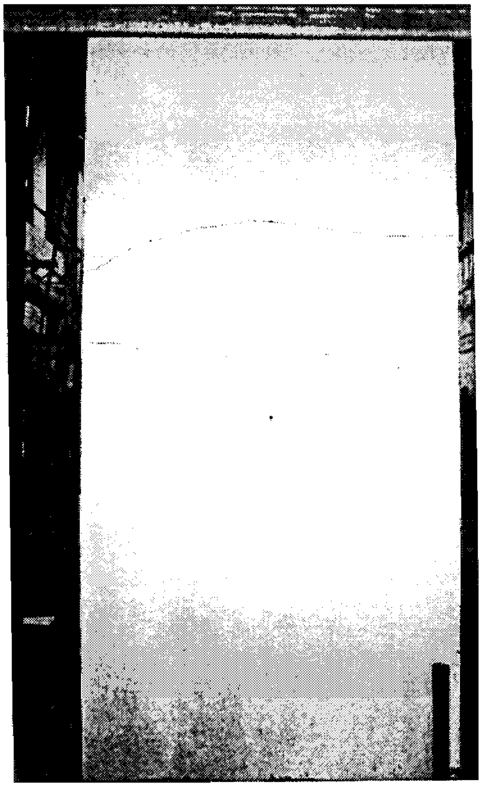


Photo 26: Second transverse crack at buckling failure

Photo 27: Samples for freeze-thaw tests

Photo 28: Mass loss in mortar prisms after 100 freeze-thaw cycles

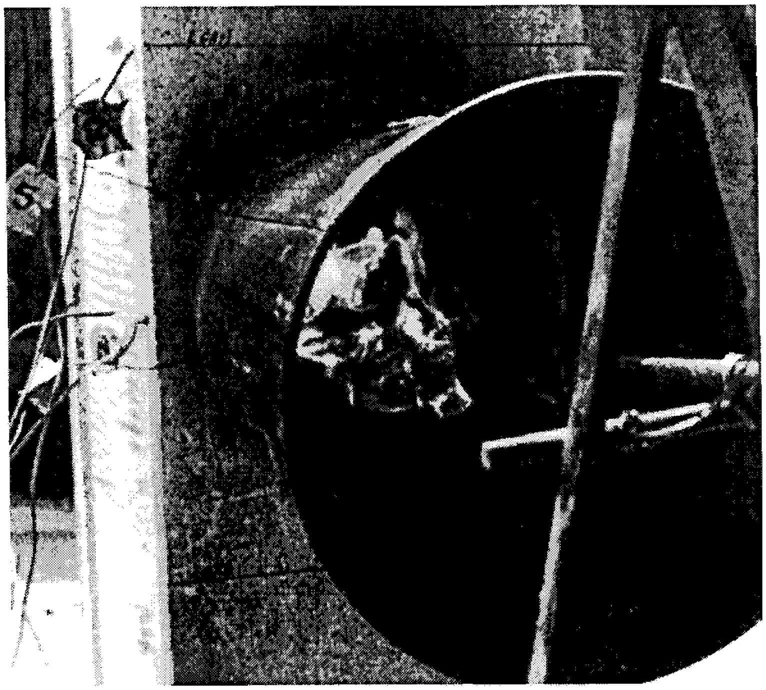


Photo 29: Blow torch test of column without top load

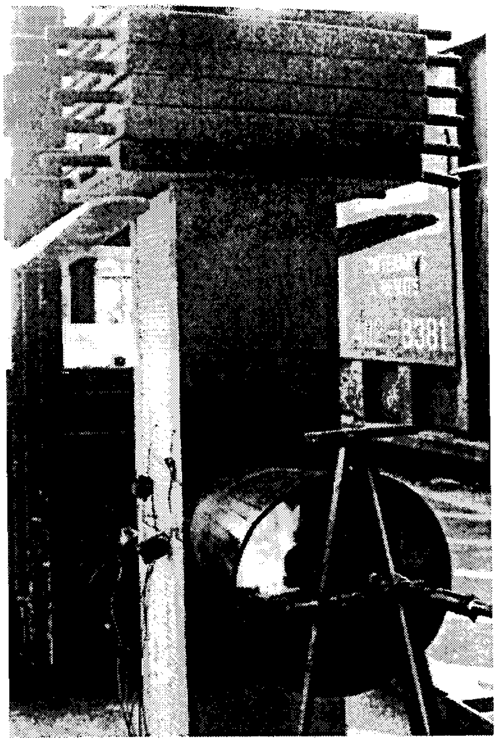


Photo 30: Blow torch test of column with top load (11.6 kN)

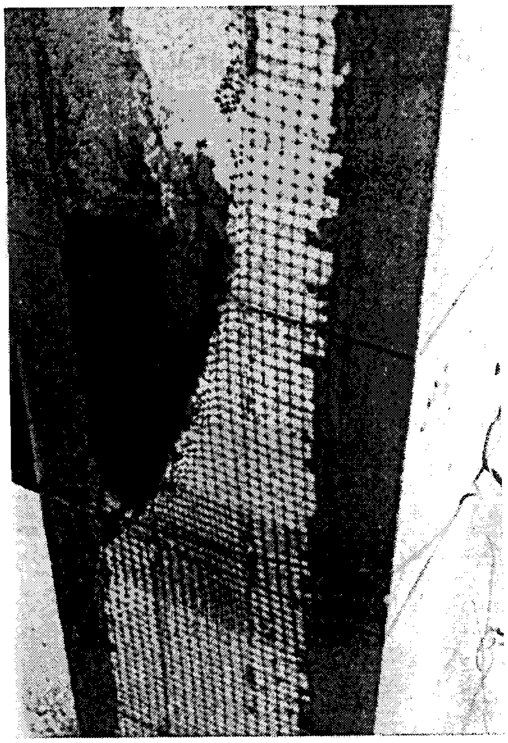


Photo 31: Burnt EPS-core in sandwich column

Photo 32: Crushing failure of fire damaged column

R. E. Platts, *P.Eng*

12 Bedford Crescent
Ottawa, Ontario, K1K 0E4
Tel/fax 613 746 3184
bobplatts@yahoo.com

PROOF-OF-CONCEPT TESTS OF STUCCO / EPS SANDWICH WALL STRUCTURE

Final Review for E. Blain-Cosgrove 06 Nov 2001; (Rev. 13 Nov)

Intent and Scope

The intent of this engineering review is to assess the McGill test findings recorded by E. Blain-Cosgrove under the title: 'Progress Report: Preliminary Evaluation of a Cement-Faced EPS Core Sandwich Building System', dated August 16th 2001. The broader intent and scope is to assess the findings in terms of potentials and limitations of the particular sandwich composite to form site-built exterior loadbearing walls for houses up to two storeys high. (An earlier review, 5th May 2001, had helped E.B-C decide on relevant proof-of-concept test procedures for the McGill test program.) The scope includes consideration of detailing that might best overcome limitations and avoid undue costs. The test findings have been updated since the August progress report by communications from E.B-C, so this review is intended as the final engineering assessment he requested.

General

The test program at McGill was exemplary in execution and reporting, with excellent presentation of results. The full-height wall tests and probably the freeze-thaw tests were particularly relevant in displaying the potential performance of a 12-in thick stucco/EPS (expanded polystyrene) sandwich as a loadbearing exterior wall, and are focused on here. The blowtorch fire test, done on a short specimen, does not relate reliably to a wall but does help explore the fire safety issue, so its results are considered too. The other small-specimen tests were tests of the stucco compositions only, not of the composite in any structural way, and were mostly useful in providing further test histories of sand-cement stuccoes; they are not addressed here.

In general, the results show that the composite did behave as theory and history would suggest: the sandwich structure, in stabilizing the skins against buckling and enabling them to work right up to maximum material strength, can provide remarkable strength and stiffness from a minimum of material. And that leads to the main criticism: the wastefulness of the present design. The wall thickness, stucco thickness and layers of mesh have all been increased greatly since the draft plan reviewed in May, and apparently for no defensible reason. The stucco/EPS wall structure is much stronger than a wood frame house wall is or needs to be, and it would still be so if only half as thick, with just half the EPS, three-quarters the stucco, and a fraction of the mesh as now. Further, the thick wall will tend to require more lumber in ancillary detailing than otherwise necessary. None of the materials is cheap, and only the particular EPS is substantially a recycled "waste" at present. The remarkable material efficiency opportunity offered by sandwich design must be much better seized if the proponents are to pursue their goals.

Structure

The test cycles reveal no surprises, as mentioned above. The small amounts of apparent creep are probably occurring in the EPS core, mainly, although some of the hysteresis could be a slippage or working of the panel on its test supports. Shear creep in the expanded polystyrenes has been well tested over the decades; while problematic and seriously limiting any use in panels in bending (roof or floor), especially in hot climates, it is not an issue in walls as used here – even if the wall thickness were halved and transverse shear stresses thereby doubled.

The crucial bond between skin and core seems very good, apparently a product of the penetration of the stucco into the structure of the recycled EPS – which itself confirms that the beads are rather loosely fused together, discussed above below.

Embedding the mesh in the stucco assures good reinforcing, but at least two and likely four of the six layers of relatively costly material are redundant for such a lightly stressed structure; just one layer per face, positioned into the stucco by a profile moulded into the core, should suffice (more on the core, below). However, in seismic zones the second and perhaps third layers of mesh might be desirable to help prevent catastrophic collapse; but just wrapping the one layer well around wall corners, and assuring wall plate continuity, may well be enough even there.

Thermal Performance and Core Design

The thick EPS offers high insulation value overall, extending well into the very flat area of diminishing returns. Calculations would show poor economics at such thickness. That, and the use of such loosely bonded recycled EPS, poses questions.

Field experience and tests have shown that such EPS will take up a lot of water between the beads when significantly exposed. (Testing history has related to uses as lifebuoys, rafts and roadway insulations, and foundation insulation.) Anything behind stucco can be considered substantially exposed to moisture unless protected by ample overhangs, which add cost. Water absorption drops the EPS thermal value substantially, and also poses durability questions as noted below. A much thinner core of better fused, higher-R EPS could cost less and offer economically ample and permanent insulation value (more per inch, and impervious to water) and probably better durability. Surface grooves can readily be moulded into such EPS core blocks – still formed from recycled material, ideally - to assure good bond while holding the mesh off the surface to let the stucco penetrate and surround it, gaining enough reinforcement.

Durability

In the absence of final results on freeze-thaw testing, it is said that this predictor of durability is giving encouraging results even with the loosely fused, permeable core as used. However, the relevance to actual usage conditions in Canada might be questionable: if the sand-cement stucco is of high quality, and/or the soaking period is short, then it may be that the lab freeze-thaw cycling is just testing stucco spalling within itself, and not saturating and testing the crucial interface zone. Denser, better fused EPS would assure better durability and better maintenance of high R value as mentioned, but the present EPS might be adequate and (given much reduced thickness) represent optimum material usage. The water penetration and freeze-thaw phenomena may have to be explored further for that to be confirmed.

Fire Safety

The exploratory test sample was small, with its thick skins behaving as fairly short columns needing little if any stabilization from the core to allow them to take load: not a wall composite test. The point-applied fire also bears little resemblance to the imposition of the ASTM time-temperature condition on a wall. And the stucco was fairly fresh, presenting excess moisture to help dissipate the heat and slow its flow to the EPS core. (Although it wouldn't take much to weaken this particular EPS; it would not be suitable to make coffee cups.) One might infer that a full height wall with fully dry inner skin (the main loadbearing one, and the one normally exposed to a fire), common discontinuities in skin quality such as thickness, and asymmetrically loaded as in service, would fail in a fire in 1/16th the load or time-to-failure shown; but the relationships are tenuous and even that performance should not be inferred. Where heat can penetrate quickly through the exposed skin, the EPF-core sandwich would fail structurally in minutes in a serious room fire. And such failure in just one room could quickly result in a house full of blinding, toxic black smoke.

(The exploratory test did show the powerful effect of moisture in dissipating heat as it is boiled out of a material. The time-temperature curve just under the exposed skin rose quickly to 100 deg. C and plateau'd perfectly for several minutes before resuming its climb. (This also serves to verify the calibration of the temperature sensors; no doubts there.) Such an effect is the key to the "gypsum solution" for thermoplastic-core sandwich structure, next. Incidentally, the temperature climb rate that resumed after boil-off was slower than before, probably suggesting that the insulating EPS had already shrunk away from the skin and an air space was already present and allowing convective transfer of heat away from the blowtorch zone.

Design Considerations and Detail Concepts

If the composite wall is kept to 7-8 inches overall thickness, as suggested above, then much of the ancillary detailing can well be the same or similar to wood frame construction: top and bottom plates, window and door bucks, lintels and headers, and the main junctions - foundation-floor-wall detailing, wall-floor-wall "platform frame" detailing for the second floor, and wall-ceiling-roof junction. Lumber or wood composite products can frame the details as in housing construction now or as evolving. Transfer of loads from plates or bucks into the structural skins of the sandwich can be assured in design and construction using simple design guidelines. Water shedding must be assured at all points, much as in wood frame or masonry construction but with particular care because stucco is such a notorious blotter.

<u>Concerning the matter of fire safety</u>, it's best to start with a minimum requirement, independent of codes: The structure should be able to retain its shape in a fully developed fire for at least 10 minutes to allow occupants to escape (within that time, toxic gases from the usual combustibles would become lethal, and further structural integrity would not mean further fire safety for the occupants); ideally, it should continue to retain its shape for a further 10 or 20 minutes minimum to protect fire fighters. So a 20 to 30 minute structural adequacy should be assured. Design solutions for this EPS core sandwich have been considered:

- Deeply "corrugate" the outer skin: With sandwich structural stability destroyed by heat through the fire-exposed inner skin, the vertically corrugated outer skin can be designed to stabilize itself sufficiently to carry dead loads, maintaining shape and essential support for floor and roof above. The EPS core blocks could be formed in two thicknesses to shape a profiled wall (in plan section), with the outer skin applied over the EPS to form say three inch deep by foot wide vertical "planks" superimposed on the wall plane. The floor and roof framing would be readily detailed to shift loads to the outer skin as the inner one buckled away.

- Incorporate auxiliary framing or the equivalent, in light post-and-beam fashion: This can be hidden within the wall planes, placing studs in the core at wide intervals – say 8-12 feet - and designing wall plates to span between them <u>under dead loads only, and free of usual stiffness requirements</u>. Such framing can be light, <u>and much of it can be there anyhow:</u> window and door bucks can extend full height of the wall, and the sandwich wall itself will act as fire-stable posts at all house corners or jogs, needing no framing there. (Alternatively, the framing may be exposed on interior or exterior as revealed post and beam, for architectural effect, but at significant further cost and wastefulness.)
- Protect the inner skin: The proven way to keep the interface temperature down much longer is to cover it with gypsum. This abundant material is loaded with water in its molecular makeup and is uniquely proficient in dissipating heat by virtue of boiling off. A further ¾ inch layer of common gypsum drywall or plaster over the sand-cement stucco would likely meet the performance criterion. "Fire code" drywall would not likely be needed.

  More ideally, fibrated gypsum plaster could be applied alone as the structural interior skin, replacing the sand cement stucco altogether. There are cellar files somewhere on such use of gypsum in structure, including loadbearing sandwich house walls: Bellrock in the UK, from the 1940s or thereabouts, and On-Site Structures in Saskatchewan and FRP(?) in California, all decades ago. Domtar had considerable research data on the subject, and probably has that and more now. The only caution is a serious one: gypsum loses most of its strength rather quickly if soaked. The base of the wall, or at least the gypsum interior skin, would have to be on a concrete upstand or equivalent curb to keep it protected from floor washing or plumbing or laundry leaks or spills. An impervious foot need not be an expensive solution.

The first and last of these solutions rank high, the last probably the highest for a further reason: the gypsum protection would not only retain structural adequacy but would delay the EPS from being exposed and creating black smoke and toxic gases that threaten occupants and firefighters. The structural gypsum interior skin merits strong consideration.

Summary and Conclusions

McGill University's engineering test program was well executed and reported, the full-height wall tests and probably the freeze-thaw tests being particularly relevant and the small-specimen blowtorch fire test at least being instructive. The results show that the composite did behave as theory and history would suggest: the sandwich structure, in stabilizing the skins against buckling and enabling them to work right up to maximum material strength, can provide remarkable strength and stiffness from a minimum of material. Bond of stucco skin to porous core seems very good, but moisture absorption and reduction in R would be a problem with such a porous EPS as the particular recycled material used, and durability would have to be explored more fully. More crucially, however, the wastefulness of the presently overly-strong design (surprisingly doubled in thickness and material usage since its ample introductory version, which would itself have been stronger than and thermally superior to a wood frame wall) belies the proponent's intent to achieve environmentally friendly and sustainable house construction. And the fire safety weakness, wherein heat entry at an exposed skin weakens and melts back the thermoplastic EPS core, destroying the sandwich loadbearing quality in minutes, was not addressed in the beefed-up design itself.

The wall should be kept to 7 to 9 inches in thickness for economical use of materials and money, reducing wastefulness in itself and in requirements for lumber ancillaries; stucco just ¾ in. thick; and just one or two layers of mesh in each face rather than three. The EPS core material might be suitable in its porous form as now – if the stucco is well protected with overhangs – but perhaps should be a better-fused material – ideally still from recycled EPS – giving more R per inch and better moisture resistance. It would be grooved to enhance bond and to hold off the mesh to embed itself in the stucco.

Concerning fire safety, a 20 to 30 minute structural adequacy should be assured. Favoured design solutions for this are: a) deeply "corrugate" the outer skin so that it can stabilize itself sufficiently to carry dead loads, maintaining shape and essential support for floor and roof above; b) protect the inner interface with gypsum drywall or gypsum plaster, which dissipates heat remarkably well in boiling off moisture from its molecular makeup. The best solution may well be b), using a fibrated gypsum plaster as the sole interior skin, loadbearing, with its base protected against accidental wetting.

The proponent's concept of a site-built stucco/EPS sandwich wall, given more efficient design for better material efficiency as noted, and perhaps becoming, from the outside in, a stucco/ EPS/ gypsum plaster wall for reasons of fire safety, appears to offer considerable potential for producing good house walls economically and sustainably.

R. E. Platts, P. Eng.