

Advancements in Adaptive Noise Mitigation Using Smart Materials

Eva Kristiansen, Caleb W. Pearson

National Institute of Sound Research, Cambridge, United States

Abstract—This paper presents an experimental study on structural performance of an innovative noise barrier consisting of poly-block, light polyurethane foam (LPF) and polyurea. This wall system (flexi-wall) is intended to be employed as a vertical extension to existing sound barriers in an accelerated construction method. To aid in the wall design, several mechanical tests were conducted on LPF specimens and two full-scale walls were then fabricated employing the same LPF material. The full-scale walls were subjected to lateral loading in order to establish their lateral resistance. A cyclic fatigue test was also performed on a full-scale flexi-wall in order to evaluate the performance of the wall under a repetitive loading condition. The result of the experiments indicated the suitability of flexi-wall in accelerated construction and confirmed that the structural performance of the wall system under lateral loading is satisfactory for the sound barrier application. The experimental results were discussed and a preliminary design procedure for application of flexi-wall in sound barrier applications was also developed.

Keywords—Noise barrier, Polyurethane Foam, Accelerated construction, Full-scale experiment.

I. INTRODUCTION

NOISE barriers or sound walls are usually constructed along the roadways to mitigate the airborne noise emanating from vehicles. Most of the provinces across Canada have established a “noise barrier retrofit program”, which mainly involves the extension and renewal of the existing sound walls in urban environments, to mitigate noise pollution and minimize its impacts on public health. According to the published policy of ministries of transportation of several provinces (e.g. Ontario, Alberta and British Columbia), accelerated and cost-efficient construction techniques, which do not alter the structural system and foundation of the existing walls are desired. The program also focuses on the sound walls built in the last few decades which are not high enough and are required to be vertically extended 1-2 m to influentially absorb and reflect the vehicles noise.

An innovative sound wall system was developed in the University of Western Ontario, and was examined to serve as a vertical extension to the existing sound walls. The wall system (denoted as flexi-wall) consists of stay-in-place polyblocks as formwork, light polyurethane foam (LPF) reinforced with steel rebars as structural cores and polyurea as a coating of the wall surfaces (Fig. 1). Poly-blocks are interlocking light-weight blocks which are stacked up layer by layer and

act as formwork for the LPF cores. The poly-block is 20×20×80 cm and includes four cylindrical voids with 14 cm diameter. It is made of molded low-density polyurethane and weighs approximately 1 kg. The poly-blocks are fire-resistant blocks and have an excellent capability to absorb, mitigate and reflect a wide range of noises with unmatched frequency of reflective noise. Polyurea coating is an abrasion-resistant finishing layer, which is sprayed on the surfaces of the wall and sets within 2-3 minutes. This layer also enhances the surface resistance of poly-blocks against stone impact, weathering, fire development, chemicals and penetration. LPF is an expanding liquid mixture which is injected into the polyblock voids and cures within 10 minutes. Steel rebars are epoxied into holes drilled in the existing sound wall and connect the wall extension to its base.

In comparison with conventional masonry walls, a flexiwall is more noise-absorbing and can be built significantly faster. The construction of flexi-wall along roadways is also less obstructive since there is no need for construction vehicles and mobile cranes, which usually block or constrict the roads during roadside construction. This accelerated technique also reduces traffic congestion, construction noise and risk of road accidents during the construction period which results in lower cost of the project.

To investigate the structural performance of flexi-wall, several mechanical experiments on specimens and full-scale walls were conducted. Five compression tests were carried out on cylindrical samples of sLPF and its stress-strain behavior was established. The bond strength of LPF to steel rebars was also obtained through four pull-out tests. Two full-scale flexiwalls were constructed and their lateral resistance was experimentally determined. Finally, a full-scale flexi-wall was subjected to 15000 cycles of lateral loading in order to investigate its mechanical degradation during cyclic loading events (e.g. wind loading).

II. LIGHT POLYURETHANE FOAM

Light polyurethanes foams (LPF) are composed of a chain of diisocyanates and polyols and their mechanical strength completely correlates with their density, which ranges from 3 to 50 lb/ft³ (48-800 kg/m³) [1]. By changing manufacturing techniques, chemical formulation or production process, different polyurethane with different characteristics can be produced. Polyurethanes are currently being used in different industries such as, aerospace, automotive, furniture and medical equipment due their light-weight, formability and durability.

The application of LPF in buildings constructions is mainly limited to thermal insulation in sandwich panels and prefabricated walls. Some attempts have been recently made in order to incorporate light foams in load-bearing structural elements. For instance, the application of LPF in lightweight mortar has been examined and results indicated that LPF

improves workability and consistency of mortar while its flexural and compression strength remain unaffected [2]. There is also a growing interest in the use of expanding polyurethane foam to remediate expansive soil and differential settlement of concrete slabs and foundations [3].

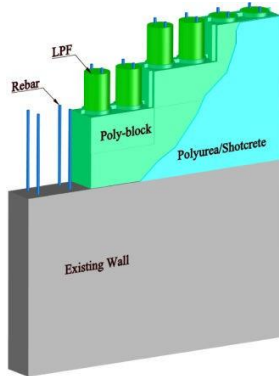


Fig. 1 Extending an existing sound wall using flexi-wall

Deformation of light foams under a uniform pressure is typically linear before the yield point, which is followed by a plateau with small stress variation (Fig. 2). The plateau region is irrecoverable and continues up to large strains at which point densification initiates. Locking stage takes place as the cell walls of the foam buckle and collapse and air escaping and stiffness hardening continue until the ultimate failure occurs [4].

In this research, a specific mixture of closed-cell light polyurethane foam with 140 kg/m^3 density was employed. The components of this LPF were mixed in liquid form below 60°C and then were injected into poly-blocks voids. This foam usually cures within 6-10 minutes and gradually reaches its maximum strength in less than an hour.

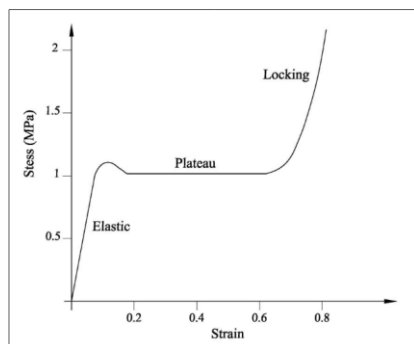


Fig. 2 Typical compressive behavior of LPF

III. FLEXI-WALL STRUCTURAL SYSTEM

The flexi-wall structural system comprises poly-blocks, LPF and reinforcements. Poly-blocks can distribute lateral loads almost equally to the LPF cores. As displayed in Fig. 1, the LPF cores inside poly-blocks are reinforced with steel rebars and form the structural cores of flexi-wall. Rebars connect and anchor the wall to its base and since the stiffness of rebars is considerably greater than LPF, they also provide lateral stiffness for the entire walls system. A layer of shotcrete may be also applied on the

surfaces of the wall to provide more structural integrity and consistency with the existing wall.

IV. COMPRESSION TEST OF LPF SPECIMENS

To determine the compressive behavior and particularly the yield strength of LPF, compression tests were carried out on five cylindrical specimens with 100 mm diameter and 150 mm height. To make the specimens, LPF liquid mixture was injected to the plastic cylindrical molds and after some minutes they were taken out to completely set. The bottom and top surfaces of the sample were then cut to provide a flat surface for loading.

Fig. 3 illustrates the compression test set-up of the LPF specimens. Two steel plates and a revolving joint were used to ensure that the load is uniformly distributed on the top surface of specimen. The load was applied at the rate of 0.2 kN/s through the loading cell of the testing machine. The compressive load and the total deflection of samples were recorded using the load cell. Since the specimens underwent very large deflections during the tests, true strain was calculated rather than less accurate engineering strain.

The tests were stopped once samples started to distort between 25% and 35% of strain since it is beyond the engineering strain range. Two LPF specimens before and after compression test are exhibited in Figs. 3 (a) and (b) and results of the test are illustrated in Fig. 4.

The solid lines in Fig. 4 display the compressive stress versus true strain of LPF specimens acquired from the experiments. In all cases, a peak was observed at the yield point, and the average strength within the plastic region was about 1.3 MPa . The dashed line in Fig. 4 is a bilinear representation of the average compressive behavior of LPF specimens, which is consistent with the typical compressive behavior of low-density foams.



Fig. 3 Compression test on LPF samples, (a) before loading, (b) after loading

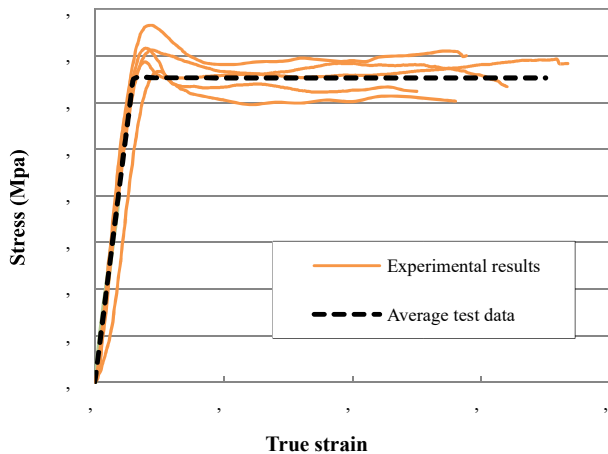


Fig. 4 Compressive Stress-strain relation of LPF samples

V. PULL-OUT TEST

The main objective of the pull-out test was to quantify the bond strength of steel rebar to LPF by measuring the required force to pull the embedded rebar out of the LPF core. The rebar dowels in the proposed structural system transfer the load to the wall footing and their length influences the wall lateral stiffness.

For this test, two wood formworks were made as shown in Fig. 5 (a) to hold the rebars at the center of the poly-block voids. The LPF was injected into the voids and allowed to harden, the formwork was then demolished and the samples were removed.

Rebar sizes of 10M and 15M with $f_y=400$ MPa (Grade 400R of CSA standard [5]) were selected and the net rebars' embedded length was 380 mm. The samples were assembled in the testing machine as displayed in Fig. 5 (b). The rebars were pulled at the rate of 0.2 kN/s while LPF cores were held by the fixed cross-head of the test machine. The test was performed for 2 samples of each rebar size. The peak tensile force (P) was recorded to calculate the bonding strength (f_b) assuming that stress is uniformly distributed along the embedment length of rebar, i.e.:

$$f_b = \frac{P}{\pi D_b L_b} \quad (1)$$

where D_b and L_b are diameter and embedment length of rebar, respectively. The bond strength of each test and the average results for 10M and 15M rebars are shown in Table I. These values are used for design of the wall and determination of development length of rebars inside the LPF cores.

VI. FULL-SCALE STATIC TEST OF FLEXI-WALL

Two full-scale wall tests were carried out to investigate the performance of flexi-wall as an extension to existing noise barriers. The first aim was to monitor the construction approach for the first time and verify the applicability of the wall system in accelerated constructions. As wind load is the predominant load used in design of noise barriers, the second aim of the full-scale wall tests was to determine the lateral resistance of flexi-wall.

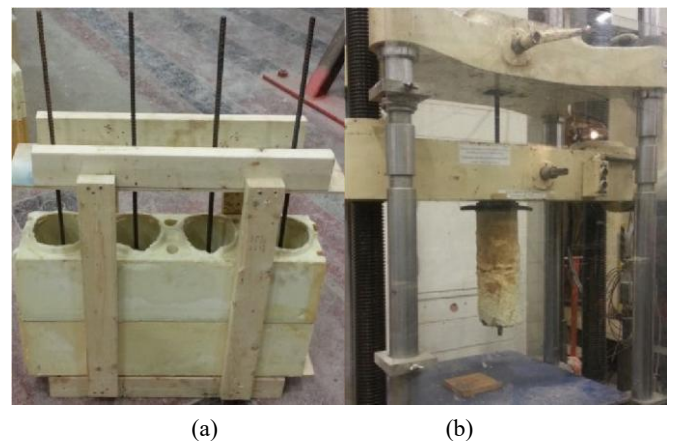


Fig. 5 Pull-out test arrangements (a) Pull-out test formwork, (b) Pullout test set-up

TABLE I
BOND STRENGTH OF LPF TO STEEL REBAR

| Test No. | Rebars size | |
|-----------------------------|-------------|------|
| | 10M | 15M |
| Test-1 (MPa) | 0.74 | 0.83 |
| Test-2 (MPa) | 0.76 | 0.87 |
| Average bond strength (MPa) | 0.75 | 0.85 |

Initially, wood formworks were made for the wall footings and concrete with $f'_c=30$ MPa was cast in place. The formworks were then disassembled, top surface of footings was leveled and the positions of rebars were marked. The dowels were inserted and epoxied into the drilled holes after curing the concrete using Hilty epoxy of HIT-HY150MAXSD which provides a high-strength bond.

The first course of poly-blocks was positioned on the footings and epoxied in order to prevent dislocation of polyblocks and leakage of LPF during the injection into the voids. The rest of the blocks were stacked on the first course and epoxied together. To ensure that LPF liquid does not leak out of the block joints, a layer of polyurea was sprayed to seal up all the seams and joints.

Fig. 6 demonstrates the structural configuration of full scale walls. They consisted of five poly-blocks whose voids were filled up with LPF. The walls were reinforced with 2×15 M and with 90 mm spacing in each core.

The whole test set-up was designed before the walls construction such that the wall footing properly places between existing anchor holes of the strong floor of the Structural Laboratory at Western University while the actuator loading plate meets the wall surface (Fig. 7).

A 2 mm layer of Polyurea was sprayed on the wall surfaces as a finishing layer. Although Polyurea does not influence on structural performance of flexi-wall, it brings higher surface resistance for the poly-blocks as well as integrity for the entire wall system.

Fig. 7 Full-scale test arrangements

VII. CYCLIC TEST OF THE FLEXI-WALL

Utilization of new composites in construction has been always a concern for designers. Despite the advantages of new materials, they have not been widely examined in practice and therefore their long-term performance is relatively unknown once employed in a load-bearing system. Since noise barriers are exposed to the repetitive wind load over its life span, a load-control fatigue test was conducted on a full scale flexiwall to determine its mechanical degradation under a highcyclic loading.

To reproduce the dynamic effects of wind load, a sinusoidal cyclic loading at 0.2 Hz frequency between a minimum moment

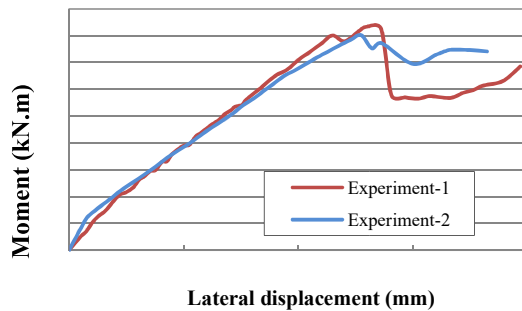


Fig. 8 Full-scale test results

A flexi-wall reinforced with $2 \times 15M$ rebar in each core was built similar to the walls that were tested under a push-over static loading. The wall was assembled as shown in Fig. 7, however, to push and pull the wall two steel plates were bolted to both sides of the wall and then connected to the hydraulic actuator.

The lateral load ramped up to the average value of cyclic load at the rate of 0.2 kN/s and the sinusoidal load was then initiated. The wall was subjected to 15000 cycles of loading and the test took 21 hours. The lateral load as well as the displacement of the wall top was recorded at synchronized intervals of 0.5 Hz using the load cell and two LVDTs, respectively.

The response of the flexi-wall for 16 cycles is depicted in Fig. 9, which shows the displacement of the top of the wall versus the base bending moment. Fig. 9 displays the hysteresis loops for the cycle of 1 to 15000 for every 1000 cycle. The maximum displacement in the first and last cycles is equal to 26.5 mm and 29.4 mm respectively, while moment peaks (4 kN.m and 10 kN.m) were maintained during the experiment with the tolerance of 0.15 kN.m. Since the response of the wall is in the linear domain, cyclic loss percentage can be calculated using the stiffness degradation of the wall which is equal to 5.71%. This value indicates that the repeatability of the wall behavior is quite sustainable over 15000 cycles of loading. It can also be concluded that the cyclic response of flexi-wall is mainly controlled by the steel rebars since the residual deformation of the wall is only 2.9 mm at most, after a high-cyclic loading.

of 4 kN.m and maximum moment of 10 kN.m was applied on the wall. The frequency of 0.2 Hz was chosen since the predominant frequency of a typical spectrum of wind energy is between 0.15 and 0.3 Hz and its maximum occurs at 0.2 Hz [6]. The maximum magnitude of cyclic load corresponds to factored flexural resistance of flexi-wall which is 65% of the ultimate flexural resistance obtained from the static tests. The minimum magnitude corresponds to the maximum magnitude divided by gust factor which is equal to 2.5 according to Canadian Highway Bridge Design Code [7]. These peaks basically represent the mean and maximum moment induced by wind load which can be applied on the wall in practice based on the maximum flexural resistance.

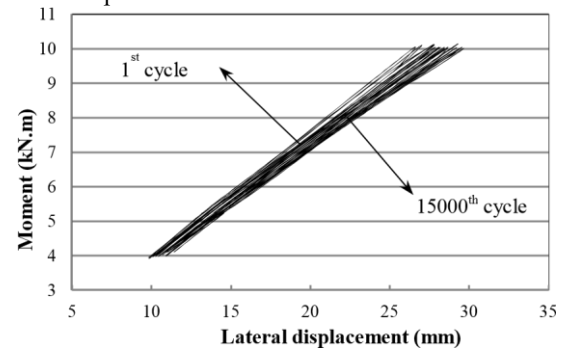


Fig. 9 Cyclic response of flexi-wall from 1 to 15000 cycles

VIII. DESIGN OF FLEXI-WALL

A preliminary design was conducted to evaluate the lateral resistance of a flexi-wall in practice based on Canadian standards [7], [8]. The factored flexural resistance for design of flexi-wall is selected equal to 65% of the yield strength of the wall achieved from the full-scale static experiments. As a result, the ultimate moment capacity of a unit length of flexiwalls reinforced with $2 \times 15M$ steel rebars with the proposed arrangement is equal to 13 kN.m. This value is equal to the maximum factored moment induced by a uniform wind pressure on a 2.5m high sound wall in Toronto area. The height suffices the required height of extension to an existing noise barrier.

IX. CONCLUSION

This study investigates the first known application of light polyurethane foam (LPF) in construction of an extension to existing noise barriers. An experimental program was carried out to determine the LPF mechanical properties as well as the lateral resistance of the entire wall system. A fatigue test was also performed on a flexi-wall in order to evaluate its longterm performance under a repetitive loading. According to the results of this study, the following conclusion can be drawn:

- 1) The construction of flexi-wall is significantly faster and more economic than conventional method for the investigated application. The outcomes of the experiments showed that the structural performance of the wall for accelerated construction is completely acceptable.
- 2) Under a static loading, flexi-wall exhibited a linear behavior up to yield point and its lateral resistance was satisfactory as a short extension to existing noise barriers.
- 3) The results of cyclic loading test confirmed the reliability of flexi-wall behavior in the range of design loading. The

cyclic loading yielded only 5.1% stiffness loss after 15000 cycles which is quite comparable to fatigue characteristics of other types of construction material.

- 4) The mechanical performance of flexi-wall is mainly governed by the steel rebars and as LPF is lighter and less expensive than cementitious material, flexi-wall can be a good alternative to other types of extension for the investigated application.

Even though not examined in the current study, but it is expected that applying a layer of shotcrete on the wall surfaces could enhance the flexural resistance, surface resistance and fatigue characteristics of the wall.

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