DEVELOPMENT OF A RESILIENT POLYURETHANE REINFORCED
MASONRY WALL SYSTEM

Forsythe, Carly¹, El-Dakhakhni, Wael²

¹ M.A.Sc., Graduate Student, McMaster University, Civil Engineering Department, forsytc@mcmaster.ca
² PhD, Martini, Mazarin and George Chair in Masonry Design, McMaster Univ., Canada, eldak@mcmaster.ca

Unreinforced masonry (URM) is one of the most common types of building construction used
across the world. Due to poor construction and lack of adherence to proper engineering design in
some developing countries, there is a strong need for a new type of masonry reinforcement
that is both easy to use and cost effective. In this preliminary study, masonry reinforced with
polyurethane foam was tested to examine how such reinforcement technique could improve
URM performance under compression and out-of-plane bending. Compression assemblages
reinforced with polyurethane foams of different densities were tested so as to develop an
understanding of how density relates to compressive strength. Those assemblages reinforced
with polyurethane foam showed an increase in compressive strength of 42% on average with
higher-density polyurethane foam assemblages exhibiting higher compressive strengths than
their lower-density counterparts. Of potentially more importance was the ability of the foam
to stabilize the face shells of the assemblages after web splitting, which essentially enables the
prism to carry more load. This binding effect enables the polyurethane to act as structural
integrity reinforcement, thereby preventing catastrophic collapse. In the out-of-plane
direction, the masonry walls reinforced with polyurethane foam were able to dissipate large
amounts of energy and demonstrate a significantly enhanced strength before the cracking
capacity was reached. The reported testing showed great promise and merits further testing
and investigation.

Keywords: Unreinforced masonry, polyurethane foam, compression, out-of-plane

INTRODUCTION

Unreinforced masonry (URM) construction is one of the most common types of building
construction used throughout the world. URM is especially prevalent in developing countries
due to its low cost and simplicity of construction. However, as homes constructed URM in
these developing countries are most often built without adherence to modern code
requirements or common engineering standards, these homes are left highly vulnerable to
collapse in an earthquake as they lack the specific design details necessary to keep them
standing.

Recent earthquakes have demonstrated the need to retrofit non-engineered URM housing
infrastructure in order to minimize future damage. However, as the January 12, 2010
earthquake in Haiti demonstrated, it is also necessary to come up with a solution to the lack of
adherence to proper building standards in developing countries in order to ensure their
housing is properly built to withstand future earthquakes. This can be done by developing a reinforcement/retrofit technique to be used in URM construction that is both inexpensive, easy to use, and does not require a high level of skill to be implemented.

This preliminary study focuses on the testing of various polyurethane foams to be used as reinforcement in URM. The main objective of this preliminary study is to look at the properties of polyurethane foam and investigate its suitability as a reinforcing material, as well as to determine the effectiveness of the different types of polyurethane foams at increasing the compressive and out-of-pane capacity of URM when it is used as reinforcement.

POLYURETHANE FOAMS
The properties of these rigid polyurethane foams can be altered by using various techniques, such as changing the foaming composition, using different techniques for mixing, and by providing different levels of confinement to the foam while it expands. However, changes that do not affect the density of the foam typically do not affect the overall properties of the foam. In order to obtain any noticeable change in strength properties, a change in density is required, which can be obtained by varying the amount of blowing agent used to make the foam (Dupont, 1998).

The strength of each particular rigid urethane foam may also be altered by using different catalysts, foaming agents, types of mixing, types of foaming systems, as well as different base polyols and isocyanates, which all can alter the cell structure of the foam. By changing these various ingredients, the foam can be made to be brittle with a high modulus and low elongation, or to be more flexible with a low modulus (Dupont, 1998).

Polyurethane foams can be affected by extreme temperatures. The foam can soften at high temperatures, leading to a loss in strength and a change in the foams dimensions. Low temperatures have less effect on the foam, making them only slightly harder and more brittle. However, between the general temperature range of -73°C to 121°C, the product is stable, with the yield point in compression remaining unaffected. Considering this stable temperature range is within the temperature limits that most countries experience, this product is clearly suitable for both northern and tropical climates (Dupont, 1998).

A benefit of using this material is its very fast cure time. High density polyurethane foams are able to reach 90% of their full compressive strength within 15 minutes of injection, with lower density foams reaching this state even quicker. Studies have shown that properties of the foam such as compressive, tensile, flexural and shear strength as well as elastic properties are greatly controlled by the density of the specimen, with higher densities of foam resulting in higher strength properties (Dupont, 1998).

The stress-strain curve for rigid polyurethane foams contains an elastic region in which stress is nearly proportional to strain. This elastic region can vary from 5-10% of total strain, and is only limited by the yield point of the material. This stress-strain relationship can be found in Figure 1 for a low-density polyurethane. Beyond this yield point, the foam has little elastic recovery, as the cell structure of the foam is crushed and permanently deformed. At this point on the curve, a plateau forms and deflection continues to increase with little to no increase in
stress. For low-density foams, this plateau can extend up to 70% strain in compression. As foam density increases, the extent of this plateau decreases proportional to the increase in density. The stress-strain curve is also sensitive to the loading rate, with a higher loading rate resulting in a decreased plateau length. Beyond this plateau region, the polymer increased in both strength and stiffness and it becomes denser (Dupont, 1998).

![Stress-Strain Curve for a Low-Density Polyurethane Foam](image)

**Figure 1: Stress-Strain Curve for a Low-Density Polyurethane Foam (Dupont, 1998)**

The majority of low density rigid polyurethane foams have an oblong cell structure which results in anisotropic behaviour. Most rigid polyurethane foams are typically up to twice as strong in the direction of foam expansion, with this behaviour being even more pronounced where the foam is allowed to expand through a long vertical distance. The amount of anisotropy in the foam can be reduced by injecting it into a confined space, thereby making the product denser. When injecting polyurethane foam into confined spaces, the outer perimeter layers of the injection surface start to cure while the centre is still very fluid and continuing to expand. This continuing expansion further densifies the outer layers and increases the products overall strength (Dupont, 1998).

In order to understand the complete effect that polyurethane foam density would have on foam properties and to provide a comparison of different commercially available products, foams were tested from two different companies. Company A foams are normally used as a subterranean filler material, one of a lower density (Polyurethane foam A-1) and one of a medium density (Polyurethane foam A-2). Company B polyurethane foams are normally used as insulation in masonry. These foams were of a very low density (Polyurethane foam B-1), a mid-range density (Polyurethane foam B-2), and a very high density (Polyurethane foam B-3).
EXPERIMENTAL COMPRESSION OF MASONRY ASSEMBLAGES REINFORCED WITH EXPANDING POLYURETHANE FOAM

In order to evaluate the enhancement to the compressive properties of masonry enabled by the polyurethane foam, masonry assemblages (prisms) were built that were four courses high by one course wide, with some assemblages built in a stack pattern and others in a running bond. As the masonry assemblages were relatively short in height, the polyurethane foam was able to be injected by inserting a rod down the length of the masonry core, and raising the rod accordingly as the foam rose. This process, which can be seen below in Fig. 2 was repeated for each core. The mortar in the masonry assemblages was allowed to cure for at least 28 days before the polyurethane foam injection process.

Figure 2: Polyurethane Foam Injection into Compression Assemblages

Polyurethane foams have great expansive capabilities, which allow the liquid material to expand at a significantly high rate as the chemicals react and the foam is formed. This high rate of expansion can put a great deal of pressure on the blocks, and if the expanding foam becomes confined in some way, the force of the expanding foam can force a separation between the mortar joint and the blocks, causing the assemblage to fail and come apart during the injection process. In the case of the A-2 compression assemblage, the outward pressure of the foam as it expanded was too much for the central mortar joint to take and the top and bottom half of the assemblage broke apart. Thus, only a two block high assemblage was tested using the A-2 polyurethane foam.

The masonry assemblages built in a stack pattern were built with openings on the ends of the cells, where the blocks did not line up perfectly, leaving an end area not filled in with mortar. When the polyurethane foam is injected into the cells of these assemblages, the foam is then allowed to seep out of these openings as it rises. As polyurethane foam becomes denser and hence stronger under confinement, as compared to when it is allowed to freely expand in all directions, measures were taken to close these openings on the masonry assemblages. A
mixture of foam tubing and duct tape was used on the stack pattern assemblages. On all assemblages built with the running bond, these holes were filled with mortar while they were being built.

The compression test set-up is shown in Fig. 3 and illustrates the configuration of the masonry assemblage within a compression test machine. The load applied was monitored by a load cell within the floor of the machine, and was connected to a data acquisition system which recorded the readings. LVDT’s were affixed to the masonry on each side of the assemblage to monitor deflections over the whole height of the specimen. The LVDT’s were located so as to span every mortar joint where most of the assemblage’s deflection was likely to occur.

In general, failure of all compression assemblages initiated in a similar manner. As the loading on the prims increased, a small crack would form in the web of the masonry block, in the direction parallel to the loading of the specimen, and would continue to grow and widen along the length of the specimen until failure occurred. In both the unreinforced assemblage and those assemblages filled with foam, the first visible crack in the specimen occurred at approximately the same load level, as can be inferred from Table 1. However, although the specimens failure initiated in a similar manner, the unreinforced assemblage, and those assemblages filled with foam behaved very differently following initial web-splitting.
Table 1: Summary of Compression Results

<table>
<thead>
<tr>
<th>Compression Assemblage</th>
<th>First Visible Crack (kN)</th>
<th>Ultimate Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>URM</td>
<td>460</td>
<td>574</td>
</tr>
<tr>
<td>Polyurethane Foam A-1</td>
<td>635</td>
<td>754</td>
</tr>
<tr>
<td>Polyurethane Foam A-2</td>
<td>450</td>
<td>911</td>
</tr>
<tr>
<td>Polyurethane Foam B-1</td>
<td>450</td>
<td>783</td>
</tr>
<tr>
<td>Polyurethane Foam B-2</td>
<td>460</td>
<td>800</td>
</tr>
<tr>
<td>Polyurethane Foam B-3</td>
<td>N/A</td>
<td>819</td>
</tr>
<tr>
<td>Average for Polyurethane Foams</td>
<td></td>
<td>813</td>
</tr>
</tbody>
</table>

When the vertical crack developed and expanded in the URM assemblage, the failure mode was very brittle and immediate, and the failure resulted in the complete disintegration of the sample and many pieces of flying debris. In contrast, those assemblages filled with foam were able to significantly increase their load capacity after these initial side cracks developed, and far surpass the load carrying capacity of the URM assemblage, increasing their load carrying capacity on average by 42%. This significant increase in failure load may be attributed to the increased cross-sectional area of the specimens and the strong tensile strength of the polyurethane foam. The benefit of the polyurethane foam reinforcement is that it is able to stabilize the face shell after web splitting, thus enabling the prism to carry more load as the face shell is still standing as one assemblage with no collapse. Even at ultimate failure, none of the foam-reinforced specimen suffered disintegration and were all capable of supporting their own self-weight as can be seen in Figure 4. Essentially, the bond strength between the polyurethane foam and the inner masonry block surface held all of the failed pieces of the assemblage together, preventing them from collapsing. This is particularly important as such bonding effect (acting as a structural integrity reinforcement) can significantly prevent catastrophic URM collapse.

Figure 4: A-1 Compression Prism Standing Post Failure
Of another significance is that each of the foam-reinforced specimens demonstrated residual strength after peak loading. This behaviour could be beneficial during an earthquake, when a building could be subjected to peak loading conditions only for a brief period of time. In this situation, the walls would still remain standing and be able to carry some gravity load.

The ability of a foam-filled masonry wall to stay intact while experiencing extreme failure has huge implications for performance-based engineering. As these assemblages were able to carry a significant amount of compression post-failure, this may suggest that masonry walls of a single story dwelling reinforced with these polyurethane foams would potentially be able to support the loading from the roof, even when the walls are completely damaged. Reinforcing URM buildings with this material may prevent them from total collapse and the loss of lives, and possibly resulting in placing affected buildings into the Life Safety instead of the Collapse Prevention seismic performance category.

Also of note, is that as the density of the specimen provided by each company increased from low- to high-density, the ultimate load that the masonry assemblage was able to carry increased likewise. The increase in compressive capacity as polyurethane foam density increased can be seen more clearly in Figure 5. As the medium-density foam provided by Company A was the highest performing foam overall, this testing also shows that although an increase in density does increase polyurethane foam’s compressive strength, there are other factors within the make-up of the foam that contribute to the making of a stronger foam.

PRELIMINARY TESTING OF MASONRY WALLS REINFORCED WITH EXPANDING POLYURETHANE FOAM SUBJECT TO OUT-OF-PLANE LOADING

The out-of-plane strength of URM walls depends on the tensile strength of masonry blocks, mortar, and the bond between them. Given that the tensile strength of mortar is generally very weak, URM performs poorly in the out-of-plane direction. In order to investigate how the polyurethane reinforcement could improve the performance of URM walls in the out-of-plane direction, preliminary testing was conducted using the A-1 and A-2 polyurethane foams. An eleven course high wall was selected to represent a 1m strip of wall in a single-storey
dwellings. The walls consist of full size 390mmx190mmx190mm block and standard construction 10mm mortar joints resulting in overall wall dimensions of 2.2mx1m.

In the construction of walls A-1 and A-2, a top-down approach was used to inject the walls with polyurethane foam. Copper pipe that is connected to a hose was inserted down a masonry core, and then with the application of air pressure, the liquid polymer flows from the suppliers truck, through the hose and down into the masonry during injection. As the polyurethane foam begins to expand and rise, the rod is gradually retracted until the entire core is filled. This process is repeated for each masonry core.

The testing apparatus consisted of two 4.0 m high columns connected to the laboratory strong floor, with two angle irons spanning between them at the top and bottom to create a pin-pin connection. The loading beam, made to resemble a roller and pin connection, spanned one third of the wall height so as to ensure a constant moment region in the middle third of the wall. The loading beam was attached to a load cell and a hydraulic actuator, all supported by a 3.0 m column, forming a triangle with the other two support columns. Linear variable displacement transducers (LVDT’s) were secured to the test wall at mid-height to provide the necessary out-of-plane deflection information about each specimen.

As loading was applied to each wall specimen, an extensive crack pattern developed, leaving at least two layers of mortar in the center region of the wall completely cracked. Once the full crack pattern had developed, each wall experienced a significant stepped drop in load capacity. As loading of the wall specimen continued, each wall continued to deflect while exhibiting a somewhat linear decline in load capacity. When the masonry was fully cracked and no longer capable of carrying any loading, the polyurethane foam then carried the remaining load until ultimate failure was reached. Shortly before reaching ultimate failure, both specimens exhibited unexpected behaviour. The load capacity of each wall increased by approximately 1kN while it experienced its last 50mm-100mm of deflection. The cracking capacity and ultimate capacity of each specimen is shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Cracking Capacity (kN)</th>
<th>Deflection at Cracking (mm)</th>
<th>Ultimate Capacity (kN)</th>
<th>Deflection at Ultimate (kN)</th>
<th>Energy Absorption (Nmm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall A-1</td>
<td>3.63</td>
<td>12.37</td>
<td>1.48</td>
<td>195.80</td>
<td>184,224</td>
</tr>
<tr>
<td>Wall A-2</td>
<td>5.83</td>
<td>27.23</td>
<td>1.30</td>
<td>354.14</td>
<td>300,727</td>
</tr>
</tbody>
</table>

From the load versus deflection diagram below in Figure 6, it can be seen that the A-2 polyurethane foam achieved a significantly higher performance than that of A-1. When the wall with the A-1 reinforcement began to fail during testing, the masonry and the foam cores acted as separate systems, with the masonry failing first, followed by the failure of the foam. As the foam cores were in fact not sufficiently bonded to the masonry, they were not able to act together as a system to take on the high loads being applied to the wall. In contrast, when the wall containing the A-2 foam was tested, the foam was fully bonded to the masonry and together they worked as a system to resist the applied loading. The A-2 foam which was of a medium density was able to withstand 60% more lateral force than the lower density A-1.
foam, and was able to absorb 63% more energy. Compared to the case of an unreinforced specimen, that when cracked exhibits sudden and complete failure, these specimens reinforced with polyurethane foam exhibit a much more ductile failure, and provide some residual strength in the specimen after the full crack-pattern has developed. This positive preliminary study requires further analysis into the potential out-of-pane load capacity that this type of reinforcement could offer.

Figure 6: Comparison of Lateral Force vs. Average Lateral Mid-Height Displacement of A-1 and A-2 Walls

CONCLUSIONS
Based on this preliminary study, examining the effects of polyurethane reinforcement on the compressive and out-of-plane strength of masonry, it is clear that this type of reinforcement technique can greatly increase the performance of a URM wall reinforced with polyurethane foam. The average ultimate compressive strength of the reinforced assemblages showed an increase of 42% over the URM specimen. With the specimens showing an increase from in compressive strength from 31% to 59% it is clear that even the lower density polyurethane foam specimens can contribute to a higher compressive strength and significant increases in compression strength can be reached.
Beyond the increases in compressive strength, the ability of each of the compression assemblages reinforced with polyurethane foam to remain completely intact upon failure shows great promise for this type of new reinforcement. Given that URM buildings experience such drastic brittle failure during earthquakes, which can lead to catastrophic collapse, the ability of the polyurethane foam to keep all of the broken debris together while still maintaining some residual compressive strength is extremely promising. If polyurethane foam is able to keep entire sections of wall together and support a light roof post-disaster, then such new reinforcement material could be of great use in how we design buildings in seismic regions in the future.

With out-of-plane failure being the most hazardous failure mode during an earthquake, the positive performance of masonry walls reinforced with polyurethane foam shows great potential applications. With wall A-2 being able to carry up to 5.8kN of loading while also being able to exhibit over 350mm of deflection before reaching ultimate failure, this shows that this type of reinforcement system may be able to dissipate a large amount of energy in an earthquake. Along with the reinforcements gluing effect, which bonds the masonry together post-failure, this preliminary testing shows the proof-of-concept and gives a great starting point for future proof-of-performance testing as we further investigate the out-of-plane behaviour of polyurethane foam products.

ACKNOWLEDGEMENTS

Financial support has been provided by the McMaster University Centre for Effective Design of Structures (CEDS) funded through the Ontario Research and Development Challenge Fund (ORDCF) as well as the Natural Sciences and Engineering Research Council (NSERC) of Canada. Provision of mason time by Ontario Masonry Contractors Association (OMCA), Canada Masonry Design Centre and Kappeler Masonry is appreciated. The continuous financial support of the Canadian Concrete Masonry Producers Association (CCMPA) is also gratefully acknowledged.

REFERENCES


