

FAILURE MECHANISMS IN UNREINFORCED CONCRETE MASONRY WALLS RETROFITTED WITH POLYMER COATINGS

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ABSTRACT

When a blast wave interacts with building walls composed of brittle materials like unreinforced masonry, fragments of wall can be violently thrown into the building. This threat is so severe that the United States Department of Defense has banned unreinforced masonry, one of the most common construction types in the United States, for most new construction. But what do we do about existing buildings? One strategy for protecting occupants is to insure that exterior walls can survive the blast by adding strength and mass to the wall, usually with concrete and steel. The Air Force Research Laboratory (AFRL) is pioneering a simpler and much lighter retrofit solution to introduce ductility and resilience into walls using elastomeric polymer coatings. The polymer bonds to the wall forming a tough elastic skin. Although fracture of the masonry may occur (restricting this technology to *non-load bearing* walls), the polymer material remains intact and contains the debris. The polymer retrofit technique can reduce the standoffs required to limit damage and casualties by as much as 80%.

Analysis of unreinforced concrete masonry unit (CMU) walls for out-of-plane loads is a complex engineering problem. Traditional beam theory and yield line solutions give conservative results for walls subjected to pressures below the threshold at which the mortar joints fracture. The assumptions inherent in these methods are violated as the components of the wall fail and the overall geometry of the wall system breaks down under blast loading. Large variability in mortar joint flexural bond strength or shear strength as well as inconsistencies in polymer thickness compound the difficulties in performing exact analyses. Failure modes can be idealized as purely flexural, purely membrane, or a combination flexural and membrane with local shear failures thrown into the mix. Each of these idealized response modes is discussed and analyzed in this paper. The influence of the failure mode on limit states and blast performance is also discussed.

INTRODUCTION AND BACKGROUND

The greatest threat from a bomb blast close to an unreinforced concrete masonry unit (CMU) wall is secondary fragmentation – pieces of the wall flying at high speeds inside the building. Secondary fragments can result in extensive injury and death. A key tactic to defeating this threat is to ensure the exterior wall of a building can survive the bomb blast without generating secondary fragments.

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To address this need, researchers at the Air Force Research Laboratory (AFRL) at Tyndall Air Force Base, Florida, began seeking alternative solutions in 1996. They initially investigated the use of fiber-reinforced composites to retrofit unreinforced masonry walls. The approach was to reinforce and to increase ductility in the walls with the composites and prevent fragments from penetrating into interior rooms. Numerous candidate fabric materials were investigated and significant success achieved using glass and Aramid (Kevlar) fabrics in an epoxy matrix.

In the fall of 1999 AFRL began a series of tests that took the ductility concept even further, spraying an elastomeric polymer – actually a commercial spray-on truck bed liner product – onto concrete block walls. The walls were successfully tested against large explosive blasts. Although the walls experienced large deflections and the concrete block was severely fractured, no wall fragments entered the room behind the wall. The polymer, which was less expensive and easier to apply than the fabric composites, effectively contained the shattered wall fragments and would have prevented serious injury to persons inside the building.

Based on this successful proof-of-concept testing, additional research and testing was undertaken at AFRL. The goal is to understand the failure mechanisms involved with polymer reinforced CMU walls and develop analytical models that can predict maximum wall deflection or collapse for a polymer reinforced CMU wall exposed to a specified threat.

TESTING

Explosive testing was conducted on full-scale walls and single CMU blocks. The boundary conditions for all wall tests were designed to impose one-way action. Polymer samples and CMU prisms were tested in the AFRL materials testing laboratory to observe and measure specific material properties. Table 1 is a summary of these tests. The data, videos and observations resulting from these tests form the basis for the remaining sections of this paper.

POLYMER – MASONRY INTERACTION

Applying polymer to the interior wall face significantly increases flexural capacity. More importantly, it also provides much needed ductility during flexural failure of the CMU wall subjected to transient dynamic loads such as blast. A mortar joint cross section for a typical CMU wall reinforced with polymer is shown below in figure 1.

Failure Mechanisms in Unreinforced Concrete Masonry Walls Retrofitted with Polymer Coatings

Table 1. Summary of Testing

Item	Description	Objective	Method
Wall	3.7 m by 2.3 m wall of 200 mm CMU block with 3 mm thick polymer reinforcement on the interior face, 150 mm overlap on to supports.	Measure reflective pressures, wall acceleration, wall deflection and capture video of wall response. Side by side comparison to identical wall without polymer.	Full-scale Explosive
Wall	3.7 m by 2.3 m wall of 200 mm CMU block with 3 mm thick polymer reinforcement on the interior face, 150 mm overlap on to supports.	Measure reflective pressures, wall acceleration, wall deflection and capture video of wall response. Looking to find polymer reinforcement limitations.	Full-scale Explosive
Wall	3.7 m by 2.3 m wall of 200 mm CMU block with 6-mm thick polymer reinforcement on the interior face, 300 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response.	Full-scale Explosive
Wall	3.7 m by 2.3 m wall of 200 mm with 3-mm thick polymer reinforcement on interior and exterior faces, 300 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response.	Full-scale Explosive
Wall	2.4 m by 2.4 m wall of 200 mm CMU block with 3-mm thick polymer reinforcement on the interior face, 150 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response. Side by side comparison with identical wall and more overlap.	Full-scale Explosive
Wall	2.4 m by 2.4 m wall of 200 mm CMU block with 3-mm thick polymer reinforcement on the interior face, 150 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response.	Full-scale Explosive
Wall	3.0 m by 2.3 m wall of 300 mm CMU block, typical window opening at center, 3-mm thick polymer reinforcement on the interior face, 300 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response. Targeting impact of window opening on wall response.	Full-scale Explosive
Wall	3.0 m by 2.3 m wall of 300 mm CMU block, typical window opening at center, 3-mm thick polymer reinforcement on the interior face, 300 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response. Targeting impact of door opening on wall response.	Full-scale Explosive
Wall	3.7 m by 4.9 m wall of 200 mm CMU block, door opening at center, 3-mm thick polymer reinforcement on the interior face, 300 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response. Targeting impact of door opening with stiffened door on wall response.	Full-scale Explosive
Wall	3.7 m by 4.9 m wall of 200 mm CMU block, door opening at center, 3-mm thick polymer reinforcement on the interior face and anchoring window frame, 300 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response. Targeting impact of large window tied to the polymer on wall response.	Full-scale Explosive
Wall	3.7 m by 2.3 m wall of 200 cm CMU block WITHOUT mortar, 3-mm thick polymer reinforcement bonded to the interior face, 300 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response. Looking to validate minimal influence of mortar strength on response. Side by side comparison to identical wall without polymer bonded to block.	Full-scale Explosive
Wall	3.7 m by 2.3 m wall of 200 cm CMU block WITHOUT mortar, 3-mm thick polymer reinforcement isolated from block (i.e. no bond) with plastic on the interior face, 300 mm overlap on to supports.	Measure reflective pressures, wall deflection and capture video of wall response. Create pure membrane response. Side by side comparison to identical wall with polymer bonded to block.	Full-scale Explosive
Block	Several single blocks spaced at various distances from the blast.	Observe post-explosion damage and/or movement.	Full-scale Explosive
Polymer	Adhesion tests using various substrate priming/preparation processes on steel, dry concrete and wet concrete.	Determine which priming process resulted in the best polymer to substrate (support structure) adhesion.	Laboratory
Polymer	Polymer bond shearing tests on dry concrete varying the tension load on samples.	Construct a tension-shear interaction diagram for polymer overlap on supporting concrete.	Laboratory
CMU Prisms	ASTM C1072 flexural bond strength tests on CMU prisms (2 blocks stacked) and no polymer reinforcement.	Plot load to failure versus displacement to calculate mortar to block flexural bond strength.	Laboratory
CMU Prisms	ASTM C1072 flexural bond strength tests on CMU prisms (2 blocks stacked) with polymer reinforcement.	Plot load to failure versus displacement to calculate static flexural capacity of polymer reinforced section and observe polymer strain behavior.	Laboratory

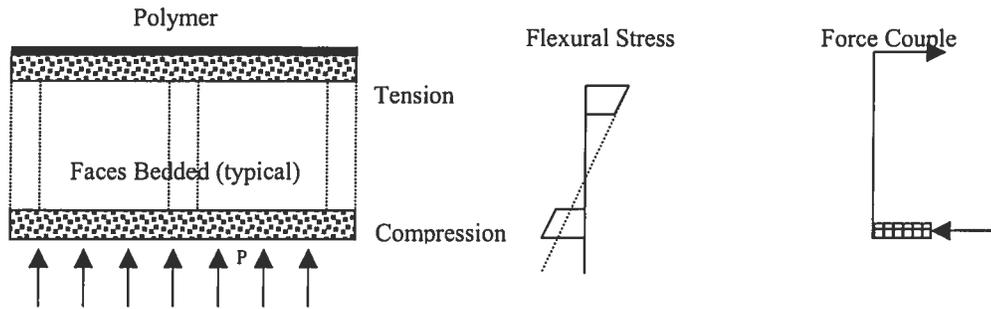


Figure 1. Typical Mortar Joint in Polymer-Reinforced CMU Wall

Adding 3-mm thick polymer more than doubles the flexural capacity of CMU without polymer. Rather than the flexural resistance falling off once flexural bond failure of the mortar occurs, the flexural resistance increases until the moment capacity of the reinforced section is reached and then stays relatively constant as the wall deflects.

The impact of polymer reinforcement on stiffness is not as easy to quantify. The increase in wall stiffness can be thought of as a combination of increased flexural stiffness and the resistance provided by membrane action. Figure 2 illustrates the wall configurations for each of these idealized responses. In a purely flexural configuration, the increased stiffness is due to an increase in the moment of inertia for the cross section.

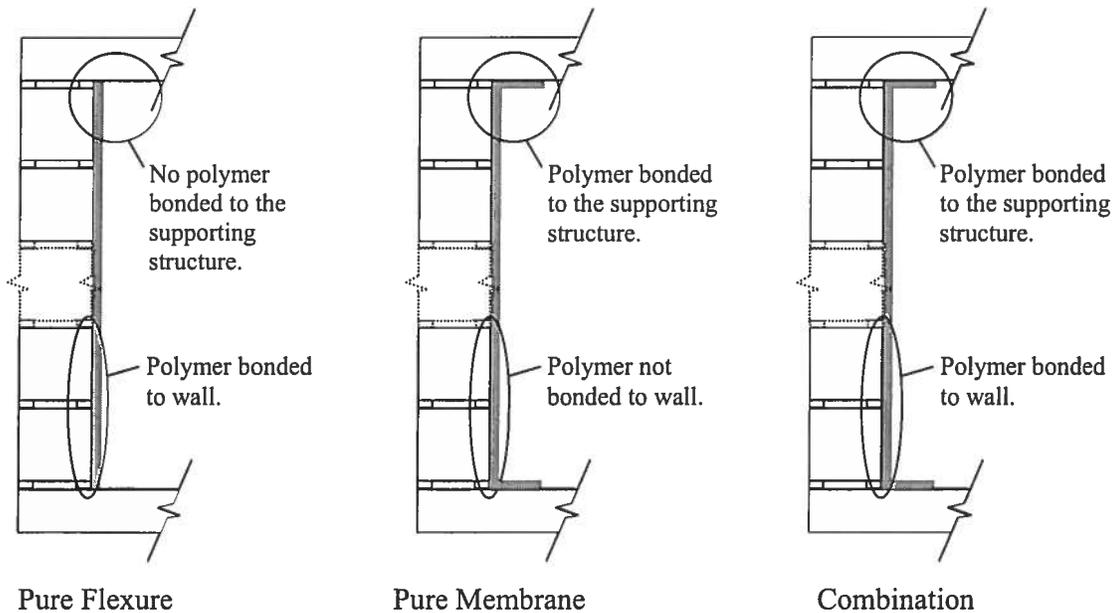


Figure 2. Idealized Polymer-Reinforced CMU Wall Responses

Figure 3 shows the progressive failure of a polymer-reinforced mortar joint in flexure, as observed during static testing. The length of polymer showing strain gradually increases as the blocks separate.

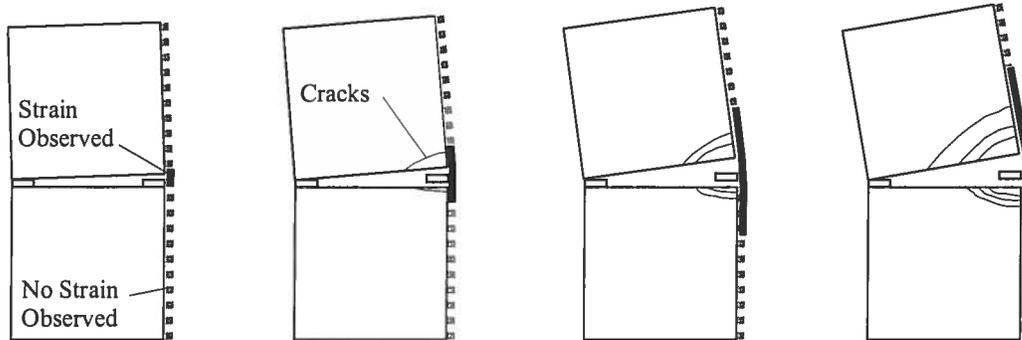


Figure 3. Progressive Failure of Polymer-Reinforced Mortar Joint in Flexure

Once polymer begins to tear, the length of polymer being strained extends across the mortar joint for slightly more than half a block in each direction. The bond between block and polymer is stronger in shear than the block tensile strength. Consequently, as the polymer strains it cracks the block. A shear failure in the mortar joint does little to affect this response to joint widening. Similar resistance to polymer straining is also present even in the areas where the block front face has fractured. This resistance simulates a higher modulus of elasticity but only intermittently and not in a way that is easily quantifiable.

WALL FAILURE MECHANISMS

Analysis of unreinforced CMU walls for out-of-plane loads is a complex engineering problem. Traditional beam and yield line methods give conservative results for walls subjected to low pressures. The engineering basis for these methods disappears as components of the wall fail and overall geometry breaks down. Walls failing in flexure can develop additional resistance through arching⁽¹⁾ mechanics if the right boundary conditions exist and the shear capacity is not exceeded. Another level of complexity is added to the analysis when the out-of-plane loading is the result of blast reflective pressure and impulse.

When subjected to blast loading the structural integrity of the individual CMU block plays a critical role in overall wall behavior and the ultimate failure mechanism. Consider the configuration illustrated in figure 4.

The CMU block geometry and material properties determine the P_F , P_L and K_L values for a plot similar to figure 4b. P_F is the pressure required to break a block with no resistance to movement. P_L is the pressure required to break a block that cannot move. K_L is the lowest stiffness where

pressure P_L will fail the block. Block integrity is maintained for pressure P and stiffness K combinations that fall below the line.

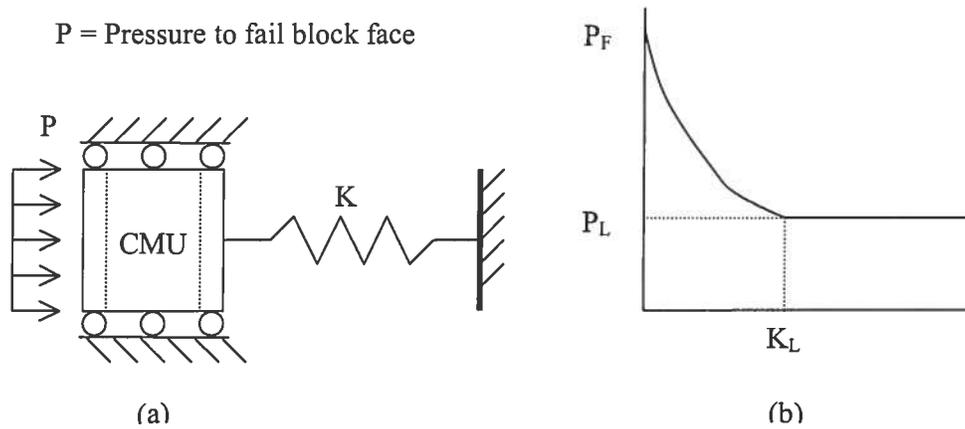


Figure 4. CMU Block Model

For a wall resisting out-of-plane pressure P the resistance to lateral movement K is predominantly provided by flexural stiffness. As illustrated in figure 5 flexural stiffness varies over the wall height and is inversely proportional to the wall deflection.

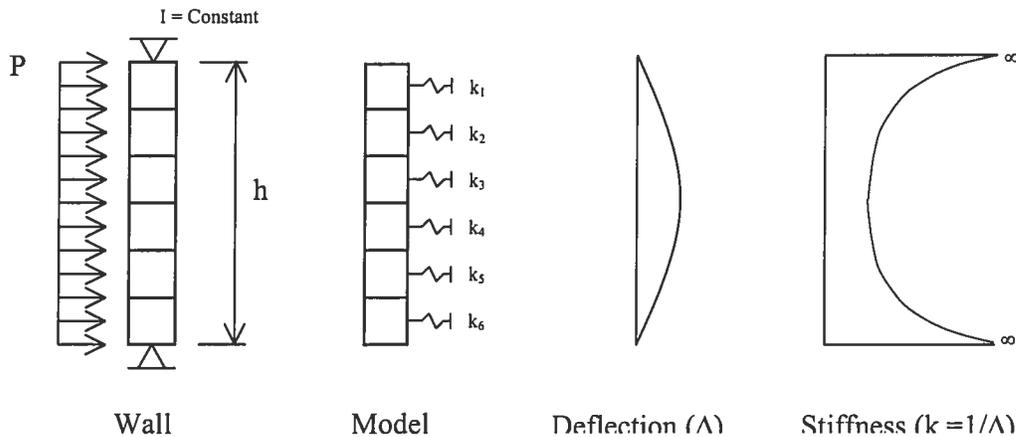


Figure 5. CMU Wall Subjected to Out of Plane Uniform Pressure

Combining single block dynamic behavior with the flexural stiffness analogy provides a reasonable explanation why blocks nearest to the support edges experience a higher rate of block face failures. Shock wave propagation in the front face is also creating tension and possibly spalling on the interior free surface. Any spalling will in turn weaken the front face.

It is reasonable to assume that the initial wall response is flexural for a large portion of the wall. Flexural wall response dissipates, as cross sectional structural integrity is lost. The following are the two primary causes for the loss of structural integrity under blast loads:

- Mortar joint separation due to bond, flexure or shear failure.
- Failure in the leading face of individual blocks.

Unfortunately a mortar joint failure occurs often in an unreinforced CMU wall subjected to blast loads. During blast testing, evidence of front face block failure is difficult to observe. It is only revealed if the wall remains standing. Consequently, block face failures have only been verified on reinforced walls. Wall reinforcing increases flexural stiffness, which in turn decreases the pressure necessary for front face block failure.

An engineer searching for solutions to strengthen an unreinforced CMU wall is in a tough spot. Reinforcing a wall to strengthen flexural resistance will likely decrease the duration of flexural response due to front face block failure. Front face block failure also limits the formation of an arching mechanism for flexural resistance.

The following critical factors make predicting a wall failure point difficult:

- Large variability in mortar joint flexural bond or shear strength.
- Inconsistencies in polymer thickness or continuity over surface irregularities.
- Front face block failure.

Some of the more probable and observed failure mechanisms are shown in figure 6. Observations during testing reveal that actual wall behavior involves each of these mechanisms at different stages or times in the wall response. The order for these failure mechanisms can vary due to the uncertainty inflicted by the same factors listed above.

If slope change at the critical stress area is severe enough (figure 6a,b and c) then shear may develop in the membrane at a rough block edge. The polymer will tear sooner in these situations than in those where the polymer is seeing predominantly tension.

The areas indicated by heavy, dark lines in figure 6 illustrate hypothetical, primary polymer strain areas for the different failure points. These areas represent a certain fraction of the overall height.

PREDICTIVE ANALYSIS METHODS

Overlapping polymer on to the supporting structure sets up membrane behavior. Although 3- to 6-mm thick polymer does have flexural strength of its own, the flexural resistance provided is negligible compared to its membrane resistance. In a pure membrane configuration like that

shown in figure 7, tension in the polymer is developed as the wall deflects. Figure 7 reflects the geometry of a parabolic membrane deflection.

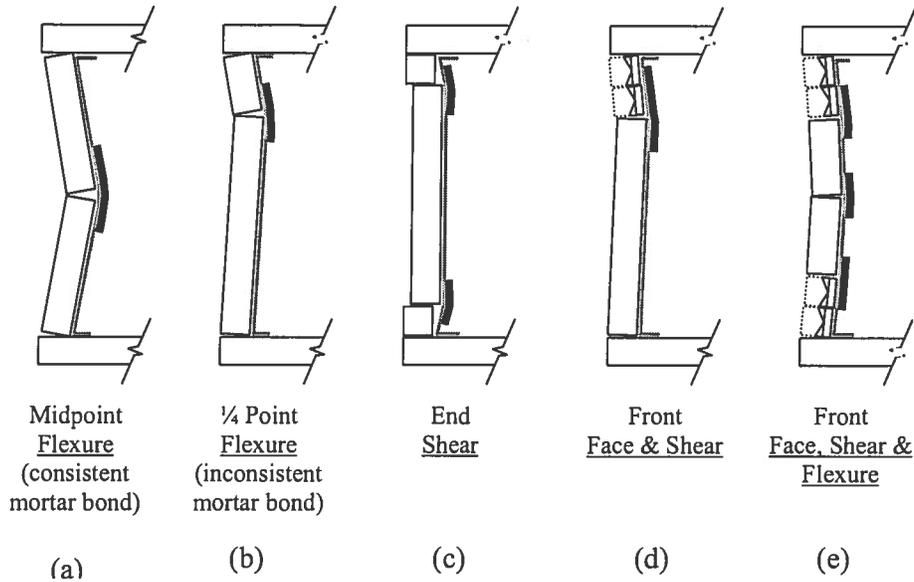


Figure 6. Observed Failure Mechanisms in Full-Scale Blast Experiments

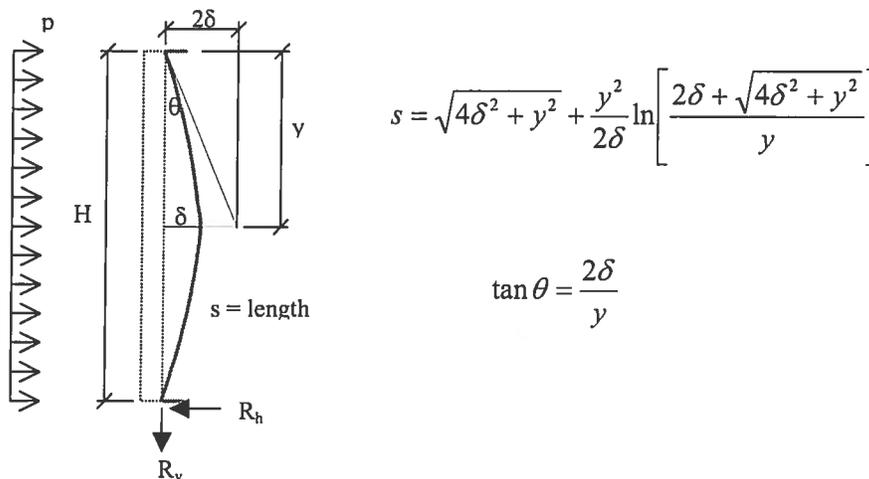


Figure 7. Parabolic Membrane Deflection

The absence of a bond between polymer and block in a pure membrane response theoretically allows the strain to be spread out over the whole wall height. Using this assumption with Hooke's law yields an equation for the membrane tension stress in the elastic region when subjected to a static pressure.

$$\text{Strain } (\varepsilon) = \frac{\text{Stress } (\sigma)}{E} = \frac{s - H}{H}$$

$$\sigma = \frac{E(s - H)}{H}$$

Letting T equal the tension in a polymer strip and

$$R_v = T \cos \theta$$

$$R_h = T \sin \theta = \frac{pH}{2}$$

Table 2 shows stress, tension and pressure values assuming deflections for a 3.7 m wall (one-way action) with 3-mm thick polymer.

Table 2. Pure Membrane Response (No Bond) Calculations

3.7 m One Way Wall with 3-mm Thick Polymer

Defl(δ) mm	Elongation mm	Over Full Height Stress(σ)		Membrane Action			
		Strain(ε)	kPa	Angle(θ)	T, N/m	R _v , N/m	p, kPa
2.5	0.5	0.01%	29	1.6	87	87	0.00
5.0	1.8	0.05%	117	3.1	350	349	0.01
7.5	4.1	0.11%	262	4.7	786	784	0.04
10.0	7.3	0.20%	466	6.2	1,397	1,389	0.08
12.5	11.4	0.31%	727	7.8	2,180	2,160	0.16
15.0	16.3	0.45%	1,045	9.3	3,136	3,094	0.28
17.5	22.2	0.61%	1,421	10.8	4,262	4,186	0.44
20.0	29.0	0.79%	1,853	12.3	5,558	5,429	0.65
22.5	36.6	1.00%	2,340	13.8	7,021	6,818	0.92
25.0	45.1	1.23%	2,883	15.3	8,650	8,344	1.25
27.5	54.4	1.49%	3,481	16.7	10,443	10,001	1.64
30.0	64.6	1.77%	4,133	18.2	12,398	11,780	2.11
32.5	75.6	2.07%	4,837	19.6	14,512	13,674	2.66
35.0	87.4	2.39%	5,594	20.9	16,783	15,674	3.28
50.0	174.9	4.78%	10,219	28.7	30,656	26,898	8.04
75.0	376.3	10.29%	14,873	39.4	44,619	34,499	15.47

$$\varepsilon \leq 4\% \quad E = 234,000 \text{ kPa}$$

$$4\% \leq \varepsilon \leq 9\% \quad E = 110,000 \text{ kPa}$$

$$\varepsilon > 9\% \quad E = 1,000 \text{ kPa}$$

The calculation summarized in table 2 illustrates that a membrane by itself offers very little resistance to wall movement. However, the advantage of the polymer is that offers a great deal of elastic deflection. The tension stress values are low enough to conclude that the critical factor governing overall membrane strength in this idealistic configuration is the polymer adhesion or bond to the supporting structure. A polymer membrane isolated from the wall is likely to pull off the supporting structure prior to tension failure.

For the actual case where polymer is bonded to the wall and supporting structure, test results indicate that polymer failure will most likely occur somewhere along the wall prior to pulling away from the structure. The primary explanation for this behavior is the bond strength between polymer and block as described in the previous section and illustrated in figure 3. These localized polymer strain areas are also illustrated in figure 6 at the high stress locations for the different failure mechanisms. When viewed in this manner, the polymer strain is occurring in a fraction of the overall wall height. Table 3 shows critical membrane stresses assuming the full parabolic elongation takes place in an effective length equal to 10% or 20% of the wall height.

Table 3. Localized Polymer Strain Calculations

3.7 m Wall (3-mm Polymer) - Strain Occuring in 10%-20% Wall Height

Defl(δ) mm	Elongation mm	Over 10% Height		Over 20% Height	
		Strain(ϵ)	Stress(σ) kPa	Strain(ϵ)	Stress(σ) kPa
25	0.5	0.12%	285	0.061%	142
50	1.8	0.49%	1,139	0.243%	570
75	4.1	1.09%	2,561	0.547%	1,281
100	7.2	1.94%	4,550	0.972%	2,275
125	11.2	3.04%	7,103	1.518%	3,551
150	16.2	4.37%	9,762	2.183%	5,108
175	22.0	5.93%	11,487	2.967%	6,943
200	28.6	7.74%	13,472	3.869%	9,053
225	36.2	9.78%	14,868	4.888%	10,337
250	44.6	12.04%	14,890	6.022%	11,584
275	53.8	14.54%	14,915	7.271%	12,958
300	63.9	17.26%	14,943	8.632%	14,455
600	245.1	66.25%	15,433	33.127%	15,101
1000	628.8	169.95%	16,470	84.977%	15,620

$\epsilon \leq 4\%$, $E = 234,000$ kPa
 $4\% \leq \epsilon \leq 9\%$, $E = 110,000$ kPa
 $\epsilon > 9\%$, $E = 1,000$ kPa

This simplified analysis yields polymer stresses that are consistent with the deflections/tears seen during full scale testing. It can be used as a practical method to predict polymer stresses when a deflection is known or assumed.

The same factors that make it difficult to predict a wall failure mechanism also make it nearly impossible for precise deflection predictions. An accepted practice for predicting maximum deflections is using a single-degree-of-freedom (SDOF) dynamic model based on flexural resistance. The flexural resistance provided by a polymer-reinforced wall neglecting arching is represented in figure 8.

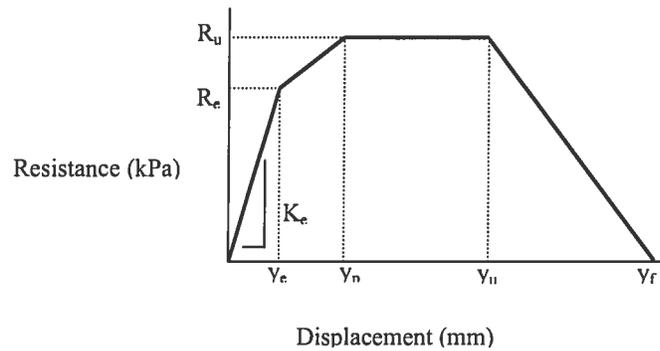


Figure 8. Resistance Function for Polymer Reinforced CMU Wall (No Arching)

These values are calculated as follows for a one-way simply supported wall.

$$R_e = \frac{8M_e}{L^2} \quad M_e \text{ is the uncracked Moment Capacity}$$

$$R_u = \frac{8M_u}{L^2} \quad M_u \text{ is the ultimate Moment Capacity}$$

$$K_e = \frac{384E(I_{\text{uncracked}})}{5L^4}$$

$$K_u = \frac{384E(I_{\text{transformed}})}{5L^4}$$

$$y_e = \frac{R_e}{K_e}$$

$$y_p = \frac{R_u}{K_u}$$

$$y_u = \text{Set at wall thickness.}$$

$$y_f = \text{Limit based on polymer overlap strength.}$$

An unreinforced wall collapses due to gravity at a deflection equal to the wall thickness. Beyond this point the polymer overlap on the supporting structure must hold half the wall weight in addition to membrane tension. Based on the polymer adhesion tests and table 3, this deflection is approximately 330 mm for a 3.7-m high wall with 3-mm thick polymer.

The resistance function defined by these values can be used in a SDOF dynamic model, but it will yield very conservative results and conclusions since it ignores arching resistance.

Maximum arching resistance (R_{a-max}) is based on the stress analysis similar to the one shown in figure 9.

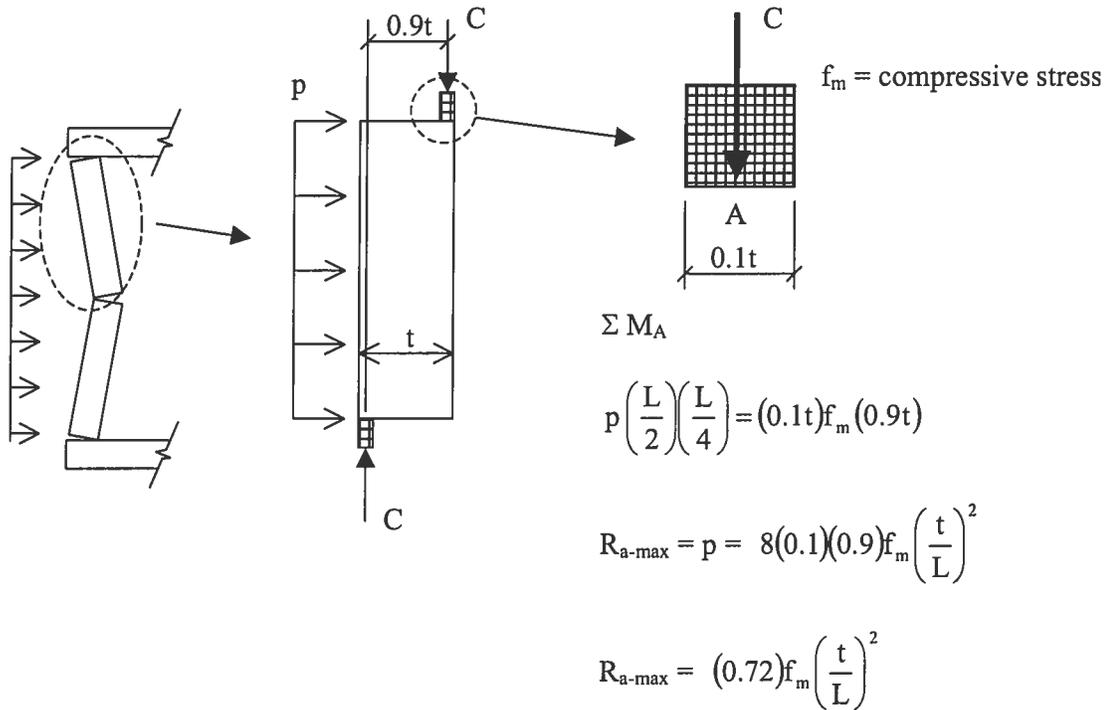


Figure 9. Calculation of Maximum Arching Resistance

Using the same analysis model, a lower bound for the deflection corresponding to R_{a-max} is $0.1t$. An upper bound can be calculated if the arching mechanism in each half of the wall is thought of as a masonry column (see figure 10 for illustration).

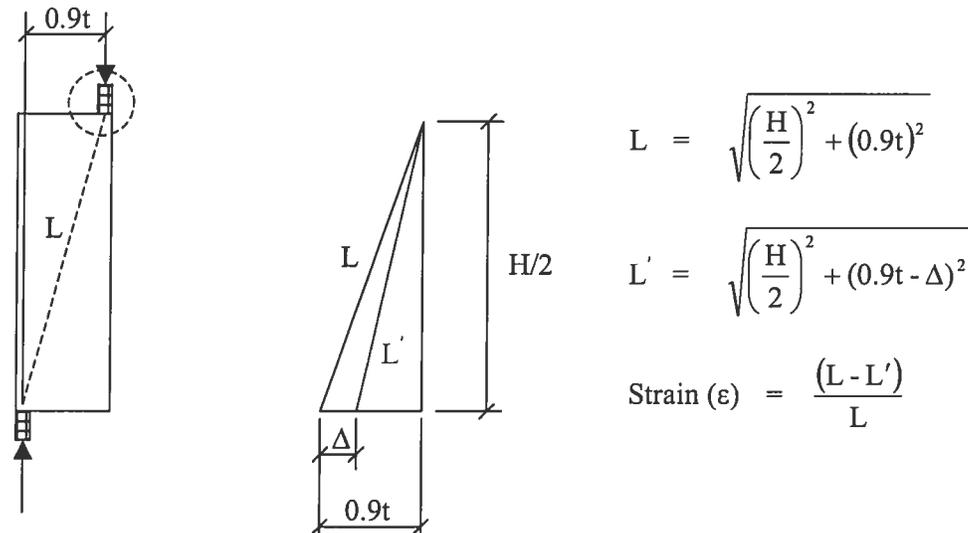


Figure 10. Upper Bound Arching Analysis

The column must compress for the wall to deflect. The typical compressive strain value used for concrete at yield is 0.003. The deflection corresponding to this strain value (Δ_y) is a reasonable upper bound for the deflection at R_{a-max} . The actual deflection (Δ_{a-max}) for R_{a-max} is somewhere between the lower and upper bound values. This deflection can be represented by the following equation:

$$\Delta_{a-max} = k \Delta_y \geq 0.1t \quad k < 1.0$$

The actual value for k is a function of L and block geometry (equivalent radius of gyration) similar to the slenderness ratio (KL/r) used in typical column analyses. Wall Analysis Code (WAC) version 3 developed by the US Army's Waterways Experiment Station⁽²⁾ calculates R_{a-max} and Δ_{a-max} ($k = 0.47$ for 3.7-m high wall) values which match well with the analysis method illustrated here. WAC was used to calculate R_{a-max} and Δ_{a-max} .

Given the right support conditions, like those in the full-scale test, it is reasonable to assume an arching mechanism is present during the initial flexural response. Unlike a CMU wall without polymer, this arching mechanism is not eliminated if a shear failure occurs in a mortar joint close to a support. Normal block displacement during shear failure is severely restrained by the bond between polymer and block. The development of arching resistance is dependent on wall geometry. Small block displacement due to a mortar joint shear failure limits the arching but does not eliminate it. Choosing how much of the full arching resistance develops before front face block failure and/or shear failure break down the mechanism is difficult to approximate. Arching resistance is dependent on the ratio of wall thickness to height. For blast loads assume no arching for walls with a thickness-to-height ratio of 0.02 or less. For thickness-to-height

ratios above 0.02, use the following equations to determine the percentage (75% max) of arching resistance above R_u that develops.

$$\alpha = \frac{\left(\frac{\text{thickness}}{\text{height}}\right) - 0.02}{0.05} \leq 1.0$$

$$\beta = \frac{(0.75)^2}{\alpha} \leq 0.75$$

The arching resistance plot is then capped at the following value:

$$R_a = R_u + \beta(R_{a-\text{max}} - R_u)$$

Figure 11 illustrates the limited arching resistance functions for a 3.7-m high wall using this analysis method.

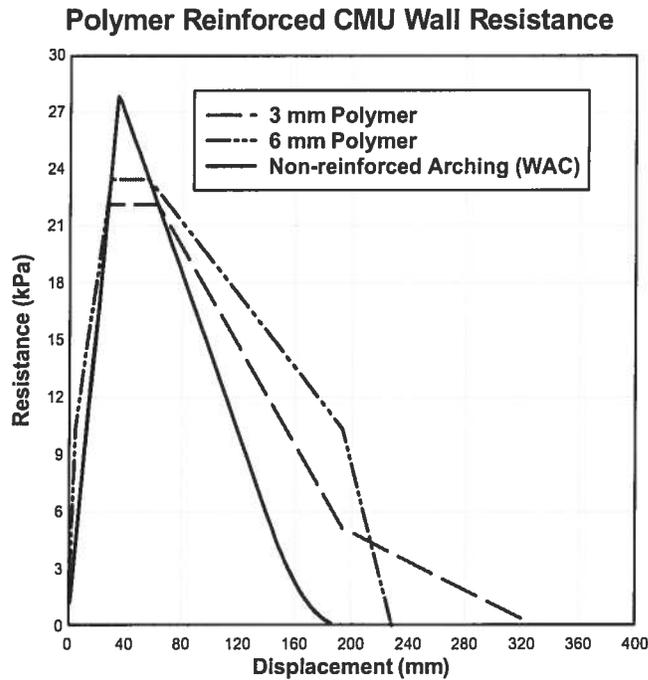


Figure 11. Resistance Functions for 3.7 m Walls with and without Arching

SDOF analyses using these resistance functions in WAC yield maximum deflections that match well with full-scale test data.

The most costly but best prediction method is to develop a high fidelity finite element model of the polymer reinforced CMU wall. Such a model was developed in this effort in cooperation with the University of Alabama at Birmingham. The model was used to validate SDOF deflection predictions, single block/wall failure mechanisms and conduct parametric studies on key engineering properties to determine influence on wall response. The model is also being used in developing a material specification for products acceptable as CMU wall retrofit coatings.

CONCLUSIONS

The inherent variability in CMU wall materials, construction methods and placement conditions make predicting a failure mechanism under blast loads very difficult. Actual response to blast loads will involve a combination of several failure mechanisms. That is the bad news. The good news is that the combination or order of failure mechanisms for a polymer reinforced wall does not need to be known to predict success or failure. The flexible nature of a polymer coating allows it to react as needed, locally and overall to prevent fractured CMU from becoming secondary fragment hazards.

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