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ABSTRACT

One of the greatest threats from a terrorist bomb attack comes from fragmentation – pieces of walls, windows, fixtures, and equipment flying at high speeds 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 breaking apart and contributing to the fragment problem. To address this need, the Air Force Research Laboratory at Tyndall Air Force Base, Florida began a series of tests to investigate the use of an elastomeric polymer coating to prevent fragmentation from lightweight structural elements such as concrete block walls and temporary lightweight buildings. The elastomer material is a highly ductile polymer that can be sprayed onto building surfaces. Recent tests indicate the coating applied to the interior surfaces of a lightweight portable building can offer protection for occupants against an explosive charge at a relatively close distance. The polymer bonds to the wall forming a tough elastic skin. Although structural failure of the supporting walls does occur, the elastomer material remains intact and contains the debris. During full-scale explosive tests, the retrofitted building experienced significant deflections but no wall fragments were observed entering the room. Post-test observations indicate the ductile response of the polymer membrane can effectively contain the splintered wall components and can prevent serious injury to persons inside a room. The polymer retrofit technique can reduce the standoffs required to limit damage and casualties by approximately 50%, and is an effective tool in providing military commanders in the field with an expedient method to protect deployed forces from terrorist and enemy bomb attacks.

INTRODUCTION

The bomb has long been a favored weapon of terrorists, political dissidents, criminals, and others intent on killing people, destroying property, or disrupting operations. Since the Khobar Towers bombing in Dhahran, Saudi Arabia in June 1996 (Figure 1), the Department of Defense has focused on improving its ability to combat

Figure 1. Khobar Towers Bombing

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terrorism. As part of this effort, military laboratories are studying ways to improve a building's resistance to bomb blast effects. The Air Force Research Laboratory (AFRL) at Tyndall Air Force Base, Florida is currently investigating a unique and innovative concept using relatively low cost, highly ductile elastomeric polymers applied to building walls for rapid and cost-effective blast protection.

BACKGROUND

One of the greatest threats from a bomb attack comes from fragmentation – pieces of walls, windows, equipment, and vehicles flying at high speeds 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 breaking apart and contributing to the fragment problem. The usual approach is to add strength and mass to the wall – to "beef" it up, usually with concrete and steel. Such "fortress" approaches are difficult to implement, time-consuming, and prohibitively expensive. An easier, less expensive, and lighter weight solution was needed, so the Air Force Research Laboratory began looking for ways to introduce ductility and resilience into building walls.

Truck Bed Liner

In the fall of 1999 AFRL began evaluating an elastomeric polymer – actually a commercial spray-on truck bed liner product – with concrete block walls. The truck bed liner material is a proprietary elastomeric polymer that is flexible, ductile, and has modest strength. It can be sprayed using standard Occupational Safety and Health Administration (OSHA) safety practices for a hazardous material. The thickness of application is relatively easy to control, and the polymer bonds to a wide variety of surfaces.

Spraying Polymer *Post-Test*

Figure 2. Blast Test on Masonry Wall with Elastomeric Polymer Retrofit

We coated an 8-foot by 8-foot wall inside and out with the polymer, and successfully tested it against 80+ psi blast pressures. Unreinforced concrete block infill walls typically shatter and fail at 2-4 psi pressures. Although the wall experienced large deflections and the concrete block inside the polymer coating was severely fractured, the wall remained in place and no fragments entered the cubicle (Figure 2). The polymer effectively contained the shattered wall fragments and would have prevented serious injury to persons inside the building.

Lightweight Structure Retrofits

The success of our "truck bed liner" retrofit was so significant that the Air Force Research Laboratory decided to tackle an even tougher problem – improving the blast resistance of lightweight modular structures. Explosive tests at Tyndall (and countless incidents of hurricanes and tornadoes striking trailer parks) have demonstrated the relative fragility of these types of structures (Figure 3).

Figure 3. Damage from 12 psi Bomb Blast

In order to evaluate the potential for an elastomeric polymer to improve the blast resistance of a lightweight structure, we applied the polymer to both the outside and inside of a 10-foot by 20-foot construction trailer. 500 pounds of ammonium nitrate – fuel oil (ANFO) explosive were used to generate 12 psi pressures on the trailer. As can be seen in Figure 4, the trailer walls underwent large deflections and the polymer had some tears in the membrane, but virtually no wall fragments entered the occupied space.

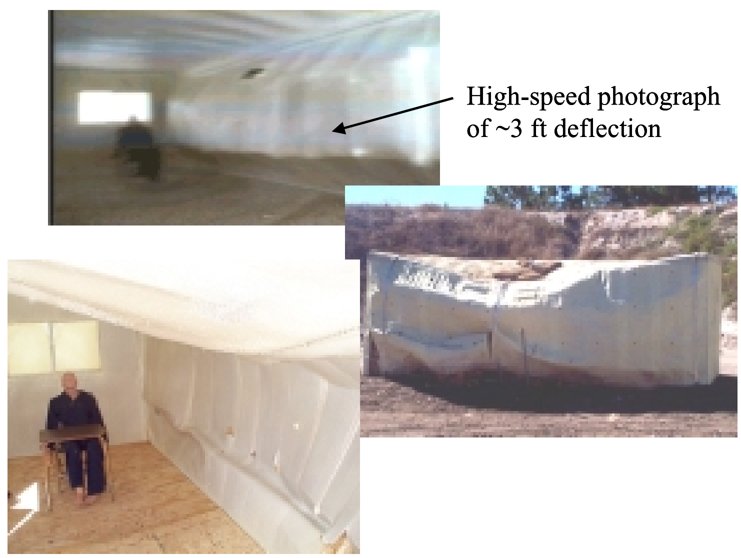


Figure 4. Results of 12 psi Blast Test on Trailer with Polymer Retrofit

LIGHTWEIGHT STRUCTURES PROGRAM

Based on our successful proof-of-concept testing, the Air Force Civil Engineer urged AFRL-Tyndall to aggressively pursue a polymer retrofit program with a goal of issuing field guidance on retrofitting lightweight structures by summer 2000. These types of structures, characterized by timber stud walls, exterior aluminum siding and interior veneer-plywood paneling, are widely used during extended deployments, such as our forward installations in Southwest Asia. In response to this need, AFRL focused existing protective construction programs to meet this goal. Before this guidance can be issued, however, several important issues need to be resolved, including:

- Selecting a polymer with acceptable strength and elongation characteristics that is cost effective, easy to apply, and has no environmental or flammability problems,
- Defining the failure criteria (e.g., how much wall deflection is acceptable?),
- Designing a frame retrofit to prevent the overall structure from crushing, and
- Quantifying the relationship between amount of explosive, required standoff distance, and the selected failure criteria.

POLYMER SELECTION

The initial step in the Lightweight Structure Program was investigating available polymer materials with enhanced structural properties (as compared with the original truck bed liner, or *baseline* polymer). While the baseline polymer had excellent elongation properties, its modulus of elasticity and rupture strength were relatively poor. A stiffer, stronger polymer could perhaps reduce the large wall deflections encountered in the proof-of-concept testing. We also wanted to ensure the selected material was safe from an environmental and fire standpoint and was affordable.

A total of 21 prospective polymers were evaluated. Seven of the materials were extruded thermoplastic sheet materials, 13 were spray-on materials, and one was a brush-on material. As a group, the prospective polymers possessed ultraviolet and temperature stability, flame resistance, and could be purchased at relatively low cost. While all were reportedly nontoxic once in place and cured, the spray-on and brush-on polymers were considered toxic during application, requiring special handling equipment such as protective clothing, gloves, masks and respirators.

Laboratory Tensile Testing

All polymers were tested for structural properties using AFRL's MTS load frame, operated at a relatively high loading rate of 0.33 inches/second. Table 1 shows averages for groupings of the polymers, with the baseline polymer included for comparison. The extruded thermoplastics were much stiffer and stronger than the other classes of polymer. However the envisioned retrofit approach, creating a continuous protective shell within the occupied space, made extruded panels a difficult choice to implement. As a result, this class of polymer was eliminated for the near-term Lightweight Structures Program. Extruded thermoplastics may be suitable for new construction applications in the future, however. The single brush-on polymer material (also a truck bed liner) proved weak, brittle, and had very long cure times (due to the need to evaporate the volatile solvents), which effectively eliminated it from further consideration.

The 13 spray-on polymers were made up of seven polyurethanes, one polyurea, and five polyurea/urethanes. These polymers have similar chemistry and are applied in the same way as the baseline polymer, which is also a polyurethane. They have fast gel and cure times, making application to vertical and overhead surfaces feasible. Because of their molecular morphology, the polyureas are typically stiffer than polyurethanes and can be elongated to a lesser extent. As a result, urethanes are often combined with ureas to increase ductility. Figure 5 shows the results of tensile testing on four of the 21 tested materials.

Table 1. Average Tensile Strength Values for Tested Polymers (ASTM D638)

Application (# Tested)	Secant Modulus of Elasticity (psi)	Elongation at Rupture (%)	Maximum Tensile Strength (psi)
Extrusion (7)	164,000	52	8100
Spray-on (13)	11,400	109	1400
Brush-on (1)	1,000	25	300
Baseline Polymer	1,000	94	800

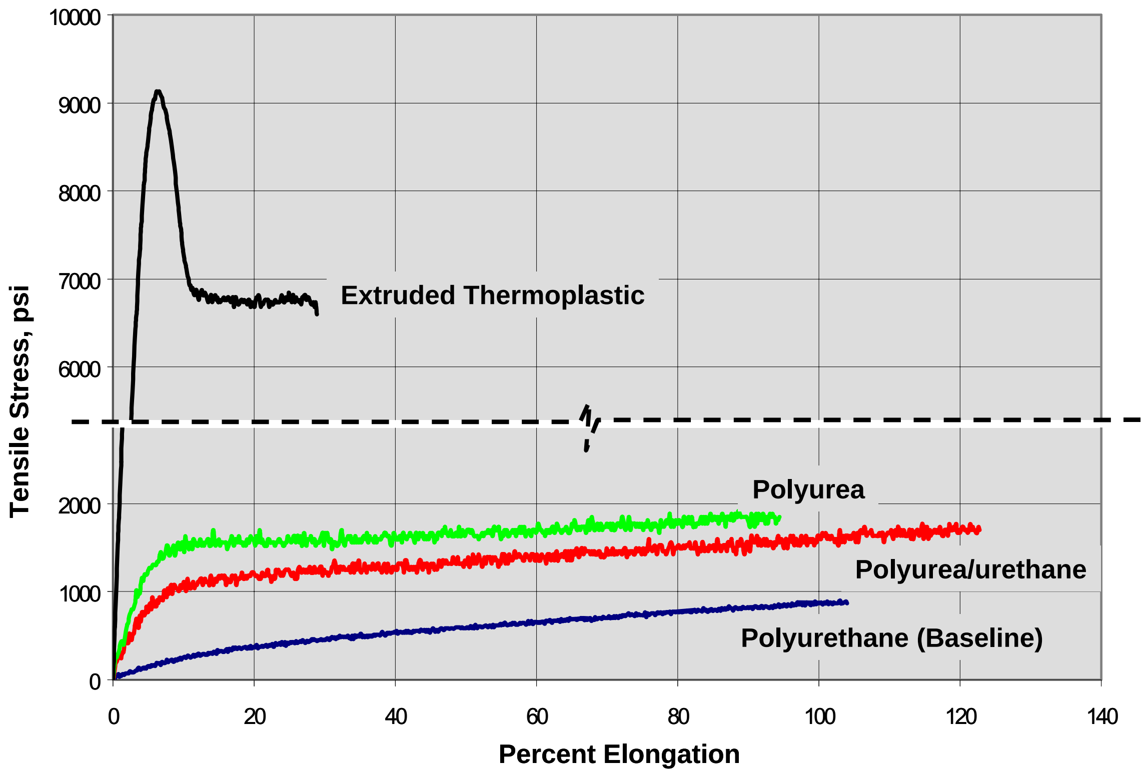


Figure 5. Typical Results from Polymer Tensile Testing

Flammability Testing

AFRL's Fire Research Laboratory at Tyndall AFB conducted the flammability testing on the 21 polymers. Tests were done using the cone calorimeter to determine the flammability of the materials at radiant heat fluxes of 25kW/m^2 and 50 kW/m^2. None of the coatings burned at 25kW/m^2, whereas all of the samples burned at 50 kW/m^2. The time to burn ranged from 10 to 167 seconds. The upper range (longer burn times) were typical of the thermoplastics and the lower typical of the spray-on liners. All of the thermoplastic samples produced a little smoke over the duration of the test. They melted under the intense heat but hardened when allowed to cool. Two of the spray-on liners initially buckled under the heat but regained adhesion after being removed from the heat source. Some liners melted under the radiant heat and there was liquid present within the ash. The rest of the spray-on polymers formed into char materials after producing a thick, black smoke.

Tests were also conducted using ASTM D635 to establish relative burning characteristics of the polymers. In this test, the end of a horizontal bar of material is exposed to a gas flame for 30 seconds, and the time and extent of burning (up to 100 mm) recorded. As a group, the thermoplastics tended to burn relatively slowly, with three of the seven burning the full 100 mm. Five of the spray-on liners burned aggressively, but the extent of burning for two of these was only 25 mm or less. Six of the thirteen liners burned the full 100 mm.

The coatings that displayed good tensile properties but did not fare well in the flammability tests were not discarded from being candidates. An alternative to reduce or eliminate the flammability of the spray coatings and thermoplastics was to use flame retardant additives. These additives could be combined with the chemicals during mixing, with only a slight reduction in strength properties.

The Selection

In order to best control deflection of the walls while retaining ductility, the spray-on polyurea-based liners were selected for further evaluation as a retrofit material. The selected polymer was the pure polyurea due to its strength, flammability, and cost. The key characteristics are shown in Table 2.

Table 2. Properties of Selected Polymer (Polyurea)

Property	Measured Value
Modulus of Elasticity	34,000 psi (initial); 24,000 psi (secant)
Elongation at Rupture	89%
Stress at Rupture	2011 psi
Maximum Tensile Strength	2039 psi
Toxicity (according to manufacturer)	Nontoxic once cured
Flame Test (ASTM D635)	ATB=infinite, AEB=19 mm
Estimated Material Cost @ 80 mil thick	$0.95/ft^2

MODELING

In order to predict wall deflections at various explosive yields and standoffs, we sought to develop a first-order engineering model that idealized the dynamic system. The temporary buildings considered in this study are three-dimensional structures, composed of exterior walls, roof, floor, interior partition walls, windows, and doors. The overall response of the building to an external explosion and the level of protection provided to occupants of the building are governed by the aggregate response of these components. For this initial effort, we focused on developing a direct solution to predict the maximum dynamic response of the wall facing the weapon. This response can then be compared with a criterion (e.g., maximum deflection) associated with an adequate level of protection for building occupants.

We required an expedient mathematical representation of the dynamic response of an exterior wall to external blast loading. The single-degree-freedom (SDOF) approach was selected for this purpose. The SDOF model idealizes the dynamic response of the wall by calculating the time history of the motion of a single point on the wall. The critical response point occurs at the center of the wall section. The SDOF approach involves developing a static resistance function (load versus deflection) for the component based upon the details of the wall construction, transforming the wall properties into an equivalent SDOF model, and solving the equation of motion to determine the response of the critical response point.

The first step in developing the SDOF model was to postulate a static resistance function for the exterior wall. The resistance function is made up of the load-deflection properties of each of the components present in the wall system. In order to derive a combined static resistance function for the wall system, we made several simplifying assumptions, including:

1. The lightweight wall system (before retrofitting) is composed of:
    a. Timber stud wall
    b. Sheathing (plywood, particle board, veneer paneling, drywall, etc.)
    c. Thin exterior metal skin
2. The wall system will be retrofitted as follows:
    a. One (or more) layers of high-elongation polymer
    b. Interior steel frame
3. The deflection, Δ, of each component in the wall system is constrained to be equal to the deflection of the wall as follows:

$$\Delta_{wall} = \Delta_{stud} = \Delta_{sheathing} = \Delta_{skin} = \Delta_{frame} = \Delta_{elastomer}$$

4. All wall components have a frictionless surface, i.e., no shear stress is transmitted from one component to another.
5. The static resistance of the stud walls, $R_{stud}\ (\Delta_{wall})$, and of the steel frame retrofit, $R_{frame}\ (\Delta_{wall})$, can be idealized as a simply supported beam using classical beam theory.
6. The static resistance of the sheathing, $R_{sheathing}\ (\Delta_{wall})$, can be idealized as a thin plate using classical thin plate theory.
7. The static resistance of the thin metal skin, $R_{skin}\ (\Delta_{wall})$, and of the elastomer retrofit, $R_{elastomer}\ (\Delta_{wall})$, can be idealized as a simply supported thin membrane using classical membrane theory.
8. The total static resistance of the wall, $R_{wall}\ (\Delta_{wall})$ can be represented by the sum of the resistances of each of the components that make up the wall:

$$R_{wall}(\Delta_{wall}) = R_{stud}(\Delta_{wall}) + R_{sheathing}(\Delta_{wall}) + R_{skin}(\Delta_{wall}) + R_{frame}(\Delta_{wall}) + R_{elastomer}(\Delta_{wall})$$

9. A uniform pressure, *p*, acting normal to the surface of the wall system, comprises the static loading.

Using these assumptions, we developed a composite static resistance function for the wall system. Figure 6 shows one such composite resistance function for a typical 7-foot high by 20-foot long wall. The stud wall provides a significant resistance to the first few inches of displacement until brittle failure of the timber stud occurs. The lightweight steel retrofit frame yields at a relatively small displacement and continues to deflect in a ductile manner. Once the studs fail, the elastomeric membrane provides the majority of the resistance of the wall to a uniformly applied pressure. The lightweight sheathing and metal skin contribute very little to the composite resistance.

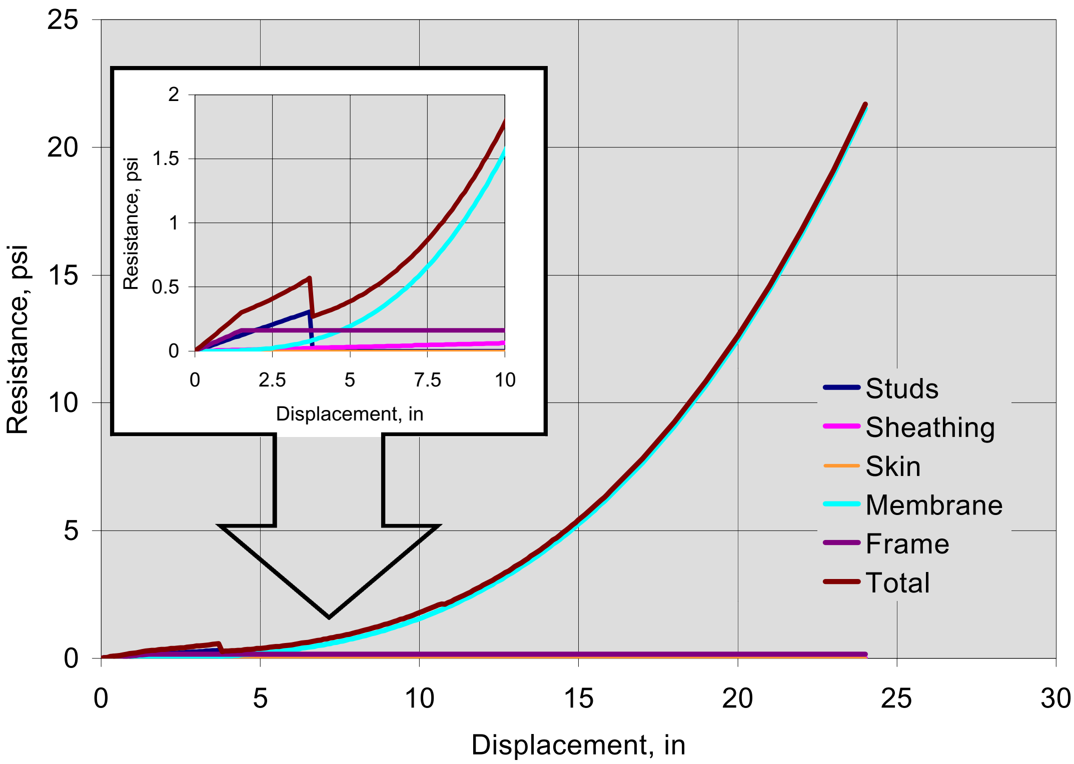


Figure 6. Typical Composite Resistance Function for Lightweight Shelter Wall.

We used the Wall Analysis Code (WAC), developed by The US Army Engineer Research and Development Center (ERDC) at the Waterways Experiment Station, to perform the SDOF analyses. The WAC provides the flexibility to allow a user-defined resistance function in a framework that transforms the model to an equivalent SDOF system, calculates the actual and SDOF equivalent loads, and solves the equation of motion to determine the response-time history (Slawson).

Inputs for the WAC include net explosive weight (NEW), bomb standoff, wall dimensions, wall mass, user-defined resistance function and load-mass factor. The pressure-time histories in the WAC are generated from the Ballistics Research Laboratories (BRL) fits for hemispherical airblasts (Kingery and Bulmash). The WAC allows the user to consider both positive and negative phases of the blast loading. Clearing effects from the sides or top of the building can also be considered. Output from the WAC includes pressure-time histories, wall motion histories (displacement, velocity and acceleration), wall resistance-time histories, and wall resistance as a function of dynamic displacement.

Our first order engineering model ignores the effects of window and door openings in the wall. It also cannot model the support provided by interior partition walls. However, we reason that the fidelity of our model is commensurate with the levels of confidence we have in the type and variability of construction found in lightweight structures, along with the many unknowns associated with an actual bomb attack (amount and type of explosive, configuration, initiation, location, surrounding topography and buildings, and so on).

TESTING

Overall Approach

Due to the limited time available for this effort, and based on the success of our proof-of-concept test shots in the fall of 1999, the overall testing approach was to simultaneously tune and validate the SDOF model using full scale explosive tests. The model would then be used to determine required standoff for bomb yields larger and smaller than actually tested.

The first test, termed the Component Wall Test, was comprised of two lightweight walls in concrete reaction structures. The primary purpose of this test was to ensure the newly-selected polyurea material would perform well at the high strain rates of an explosive test. Following the successful completion of this test, two tests on used single-wide construction and house trailers were conducted. This series of tests was used to evaluate various polymer and reinforcement schemes, and to attempt to improve on the large deflections observed during proof-of-concept testing.

Component Wall Test

The Component Wall Test was comprised of two 8-foot by 8-foot lightweight walls built within reinforced concrete reaction structures. One test wall was retrofitted with an 1/8-inch coating of the elastomeric polymer, while the other test wall received a 1/4-inch coating. The two walls were tested using 500 pounds of ammonium nitrate/fuel oil (ANFO) explosive, detonated 103 feet away. This charge produced a measured pressure of 11.7 psi on the face of the walls, with an impulse (area beneath the pressure-time curve) of 51.3 psi-msec.

As can be seen in the sequence of high-speed photographs of Figure 7, the aluminum siding initially wrapped around the 2x3 studs, then the siding and studs were pulled out during the negative phase of the pressure wave, leaving behind the interior paneling and polymer coating. The polymer effectively prevented wall fragments from entering the occupied space.

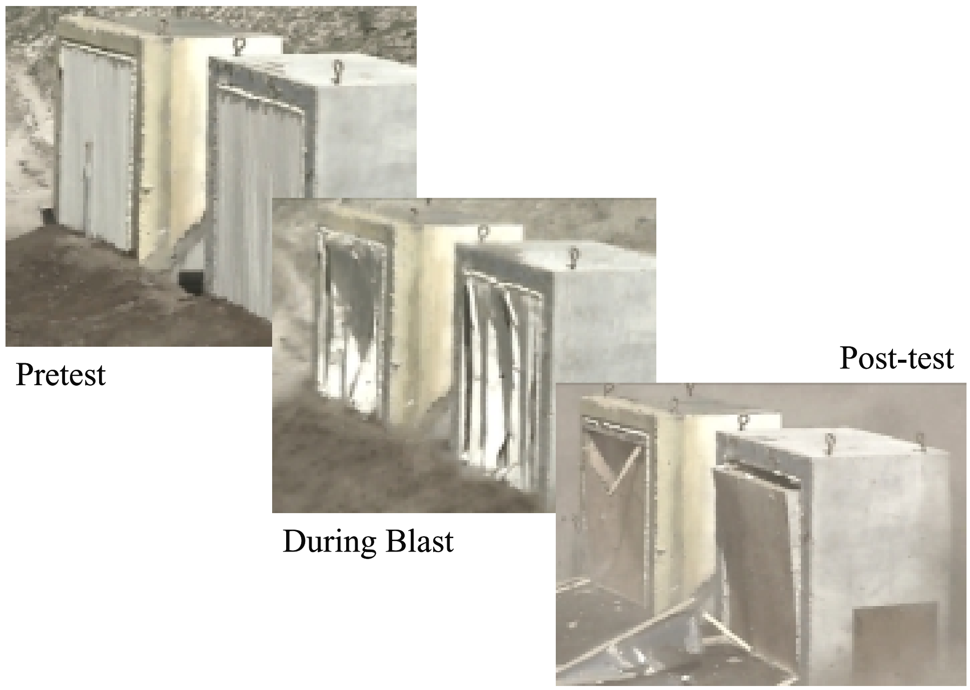


Figure 7. Component Wall Test

Overall, the polymer seemed to perform well. There were some adhesion failures of the polymer to the rigid concrete walls, but inadequate cleaning and preparation of the concrete may have contributed to these problems. Also, the rigid concrete walls provided a relatively unyielding attachment point, whereas in a lightweight building the entire structure will flex in response to a large dynamic load, resulting in lower stress concentrations along the edges.

Structure 1 Test

Following the Component Wall Test, AFRL proceeded to evaluate the polymer retrofit technique on a full-scale lightweight structure. The test article was a used 7-foot high by 8-foot wide by 20-foot long construction-style trailer (Figure 8). The structure had 2x3 timber stud walls spaced at 16-inch centers. The exterior was lightweight aluminum siding, and the interior was 1/8-inch veneer paneling. The structure was reinforced with an interior frame comprised of 1-inch by 1-inch by 1/8-inch thick steel tubing (F_y = 30 ksi) on nominal 4-foot centers (Figure 9). The interior of the building (including the frame) was sprayed with an 1/8-inch elastomeric polymer coating.

The retrofit technique was tested using 500 pounds of ANFO detonated 103 feet away. This charge produced a measured pressure of 11.2 psi on the face of the structure, with an impulse of 53.8 psi-msec. The front wall deflected inward approximately 11.6 inches, and the ceiling deflected downward 2.2 inches.

Figure 8. Structure 1 Test Article

The post-test evaluation of the Structure 1 Test showed that while the structure was severely damaged, the polymer retrofit generally worked well. Figure 10 is a frame from the high-speed camera showing the deflection inward of the front wall. This figure shows the side window pane tearing loose, and the door beginning to enter the building. The door ended up outside the structure due to the negative pressure pulling it out. The interior walls had a single tear along a stud (Figure 11), whereas two of the windows had tears along the edge of the glass, with the side window being completely pulled outside. As seen in Figure 11, the greatest danger to occupants likely comes from the fixtures and furniture flying about the room.

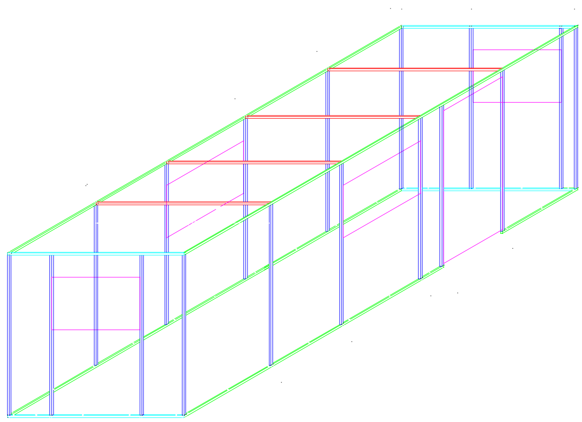


Figure 9. Steel Reinforcement Scheme for Structure 1 Test

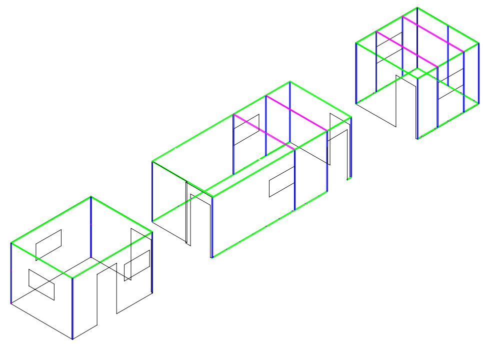
Figure 10. High-Speed Photo of Structure 1 Test

Figure 11. Post-Test Interior View of Structure 1

Structure 2 Test

For the second structure test, AFRL decided to test a larger lightweight structure with varying retrofit approaches against a larger explosive yield. The intent of this test was to "push the envelope" of the retrofit technique. The test article was a used 10-foot wide by 8-foot high by 44-foot long house trailer, divided into three rooms. This building had 2x4 timber stud walls on 16-inch centers, aluminum siding, and interior paneling. The structure was reinforced with an interior frame of 1x1 tubing, with the nominal spacing being either 4 or 10 feet (Figure 12). The end rooms were sprayed with a 3/16-inch polymer coating, whereas the center room received a 1/4-inch coating.

House Trailer



Reinforcement Scheme

Figure 12. Structure 2 Test Article

Structure 2 Test once again employed 500 pounds of ANFO to produce the structure loadings, this time detonated 83 feet away. The measured pressure on the face of the structure was 18.6 psi, with an impulse of 86.5 psi-msec. Deflection measurements were:

Table 3. Deflection Measurements for Structure Test 2

Polymer Coat (inches)	Reinforcement Spacing (inches)	Wall Deflection (inches)	Ceiling Deflection (inches)
1/4	120	20.0 (failed)	2.6
3/16	120	12.8	2.8
3/16	48	12.3	5.3

The post-test evaluation of this test proved illuminating, as the various retrofit approaches were all challenged at the large pressure and impulse loadings, and many failed. Polymer tears were observed on nearly all exterior walls, with the front wall tears significant enough to permit some debris fragments to enter the rooms. The 21-foot long center room went beyond simple deflection to failure (Figure 13). Both insulated metal doors were torn from their hinges and pushed past the doorjamb and into the building. Once again the unrestrained furniture and fixtures created a deadly environment inside the structure, which emphasizes the fact that preserving the exterior shell intact in a bomb blast only solves part of the problem for protecting occupants.

Figure 13. Results of Structure 2 Test

ANALYSIS OF RESULTS

The Tyndall AFB testing program was designed to evaluate several variables associated with the polymer retrofit technique, including coating thickness and spacing of reinforcement. The program was also designed to evaluate, tune and validate the single-degree-of-freedom model developed for lightweight structures. As discussed below, trends in the data proved relatively elusive, due in part to the limited number of test data points.

Polymer Thickness

Looking at the effect of polymer coating thickness, we were initially interested in the uniformity of the coating and how close the actual thickness was to the target thickness. As shown in Table 4, while the average thickness tended to be slightly less than the target thickness, considerable variability existed. The reasons for the variability include the inexperience of the technicians with the new application apparatus, plus the high level of difficulty associated with spraying vertical and overhead surfaces containing joints, angles, and so on. The impact of thickness variability was inconclusive although the tears in the polymer tended to occur in the thinner sections, as expected.

Reinforcement Spacing

The 1x1x1/8-inch tubing used in the polymer retrofit technique is designed to prevent the ceiling from crushing down into the occupied space. This crushing was a problem in early proof-of-concept testing, which employed either no reinforcement, or reinforcement spacing of approximately 20 feet. Two nominal spacing schemes were tested: 4-foot and 10-foot spacing. For both structure tests the reinforcement did an excellent job of preventing crushing, limiting ceiling deflections to between 2.2 and 5.3 inches. As for controlling wall deflections, the model predicts the contribution of the reinforcement spacing is minimal, and the very limited test data (both quantitative and qualitative) support this prediction.

Table 4. Polymer Coating Statistics

Target Thickness (inches)	Tear? (# samples)	Average Thickness (inches)	Standard Deviation (inches)	Minimum Thickness (inches)	Maximum Thickness (inches)
0.125	No (8)	0.136	0.043	0.095	0.216
0.125	Yes (3)	0.094	0.034	0.055	0.116
0.188	No (8)	0.181	0.060	0.075	0.230
0.188	Yes (6)	0.182	0.028	0.140	0.225
0.250	No (3)	0.237	0.025	0.210	0.260
0.250	Yes (1)	0.165	-	-	-

Impact on Standoff

Along with saving lives, one of the key benefits of improving the blast resistance of a structure is to permit reduced standoffs between a likely threat and a building. Reduced standoffs give a military commander and his security planners much greater flexibility in accomplishing their missions. Figure 14 shows the current recommended standoffs for lightweight structures based on data published by the USAF Force Protection Battlelab (FPB). Also shown on this figure are the improved standoffs associated with the polymer retrofit technique. The actual tests are plotted on the chart with qualitative interpretations of damage (slight, severe, or failure). The curves are extrapolated based on the SDOF model. Because of the fragmentation control provided by the ductile polymer, large wall deflections can be tolerated. The SDOF model used 8 inches of deflection for slight damage, 10 inches for severe damage, and 12 inches for failure.

Figure 14 demonstrates the impact the polymer retrofit technique can have on standoff. As an example, for a non-retrofitted structure the standoff from a small car bomb (220 pounds TNT) is approximately 140 feet at failure and 200 feet for severe damage, using the FPB curves. If the structure is retrofitted with a polymer coating, the standoffs are reduced to 80 feet at failure and 100 feet for severe damage, a 45 to 50% reduction. Reductions of this magnitude can greatly ease the challenges faced by land use planners to implement security measures.

Nonstructural Issues

One of the clearest results of the explosive tests (and of other testing and actual events) is the importance of nonstructural items. Even if the basic structure survives a terrorist bomb attack, many people can die or be injured by windows, doors, fixtures and furniture. The importance of a comprehensive solution to bomb blast protection cannot be overstated. Fortunately, great improvements in protection can be achieved at relatively modest cost and effort.

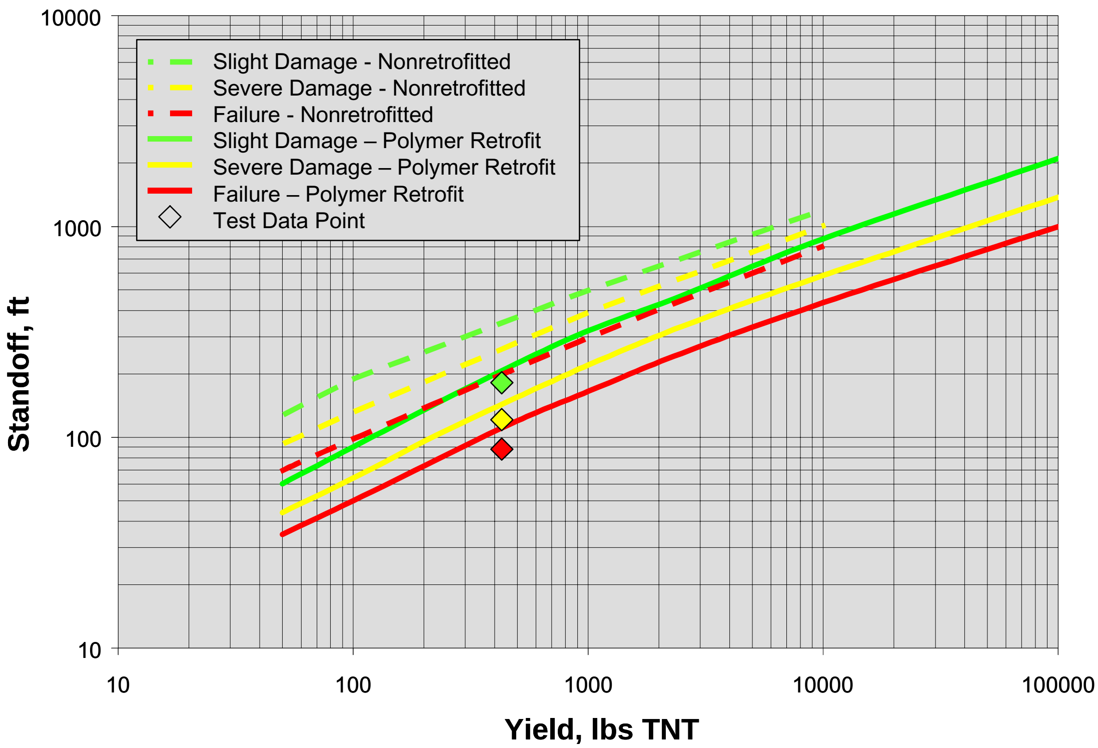


Figure 14. Standoff Curves for Retrofitted and Nonretrofitted Lightweight Structures

Glass is estimated to cause approximately 80% of the injuries in a terrorist bomb attack. Ordinary annealed glass breaks up into deadly shards and daggers traveling at hundreds of feet per second or more. Extensive research into glazing retrofits has been undertaken by others, notably the Army's Engineer Research and Development Center at the Waterways Experiment Station. One of the retrofits that proved very successful during the Tyndall AFB tests was 1/4-inch laminated glass that was glued into the aluminum frame using automotive urethane adhesive. The glass shattered but was retained in the frame, resulting in no threat to occupants. Alternatively the window can be sprayed over with the polymer, providing blast protection approaching that provided by the retrofitted walls. Of course, the window is no longer transparent and functional.

Lightweight structures typically use metal-skinned, insulated exterior doors that open outward. The Tyndall tests suggest such doors provide some protection for smaller bomb blasts, but will greatly contribute to deadly debris at higher blast loads. These doors tend to easily deform and enter the occupied space. Simply stiffening the door and reinforcing the jamb with angle iron can significantly improve blast performance at relatively modest cost and effort.

Even if the exterior shell of a lightweight structure remains intact, people inside are still vulnerable to falling light fixtures, flying furniture, and so on. These buildings are typically only lightly tied down, and the shock of a bomb blast can easily place unsecured items into motion. However, simple actions such as securing light fixtures to ceiling joists using seismic retrofit detailing and anchoring furniture to the floor or wall studs can greatly reduce the hazards associated with these items, and help make the protection afforded by the contents of a structure commensurate with the protection afforded by the building shell.

CONCLUSIONS

Although still a very new and immature technology, the polymer retrofit technique shows exceptional promise for affordably improving blast protection in existing buildings. Employing exceptional ductility and good strength, along with the ability to spray onto existing surfaces in a retrofit fashion, polymers have proven themselves capable of controlling much of the building fragmentation associated with terrorist bomb attacks. In planning protection against specific threats, this technique can reduce the standoffs required to limit damage and casualties by 50%. As part of a comprehensive security program, the polymer retrofit technique can greatly increase options available to military commanders in executing their force protection duties.

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