Modeling Blast-Resistant Protection Systems
Composed of Polymers and Fabric
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Abstract

Modeling techniques in support of retrofit designs for strengthening the blast resistance of conventional stud and masonry walls are discussed. These analytic models are intended to support the designing of retrofits to prevent damage to the walls caused by a moderate size terrorist bomb. These particular retrofits are designed for a relatively close in blast loads (i.e., within 20 to 30 feet) with impulses of 100 to 250 psi-ms. Retrofit models were generated for several metal stud and concrete block walls with inherently weak lateral resistance. The retrofit techniques modeled use polymers and synthetic or metal fibers in various ways to realize the needed blast resistance. The calculated responses and selections of design parameters are based on high-fidelity physics based finite models that are able to approximate the actual behaviors of wall systems.
Introduction

This paper describes several innovative concepts for retrofitting walls of conventional buildings to improve their resistance to airblast and ballistic fragments. Two conventional in-fill wall types (i.e., metal stud and CMU) are considered for retrofitting, as shown in Figure 1. None of these walls are load bearing and the metal stud wall, in particular, is often used as a partition wall. Both walls fail catastrophically under the applied blast load.

The work reported focuses on the modeling of these concepts so as to determine their resistant to a moderate blast load in the 100 to 250 psi-ms range, and to aid in selection of the design parameters. The capability of each retrofit is evaluated based on predictions made by high-fidelity physics based (HFPB) finite element models. DYNA3D is used to provide the HFPB results. The material characterization and parameters are based on previous Karagozian & Case (K&C) studies [1,2,3]. These studies provide validation of both the material characterization and the finite element models used to approximate the wall responses.

Laboratory Tests

Simple laboratory tests have been conducted to provide validation data for the computer models as well as to demonstrate the capability of some of the retrofits. Figure 2 shows specimens for one of these tests; in this case, a stack of bricks mortared together and covered on one side with a polyurethane spray. Different strengths and thicknesses of polyurethane are used. These brick stacks are used to represent, albeit in a simplistic form, the behavior of a brick wall so as to gather basic response data.

The brick walls are tested in bending using two different boundary conditions, as shown in Figure 3: pinned (Figure 3a) and fixed rotation with an applied axial load (Figure 3b). The responses shown in Figure 4 demonstrate the benefits of using a polymer in this application because of its ability to span the large cracks that occur in the mortar between bricks that occur in walls like this under flexure loads.

Wall Retrofit Concepts

The wall retrofit concepts to be evaluated and the materials used for them are depicted in Figures 5 to 8. The four retrofit concepts are described in Table I. They consist of a rigid polyurethane foam panel with a sheet of gauge metal attached to one side (WR1), gypsum wallboard with a sheet of gauge metal attached to one side (WR2), multiple ply Kevlar laminate (WR3), and a polyurethane spray (WR4), which are typically applied to the backside of the wall to strengthen it against blast. Each retrofit concept (i.e., WR1, WR2, WR3, WR4) uses a different detail at the wall’s top/bottom supports to attach the wall to the diaphragms. Two of these anchorage devices are shown in Figures 5d/e for the rigid polyurethane foam panel.

Response Predictions for Retrofit Concepts

WR1. Some of the basic features related to the performance of retrofit concept WR1 are shown in Figure 9. These include the occurrence of an overall flexure mode for the panel that is accompanied with a significant upward motion of the shoe anchoring the panel to the floor. The shoe rotation is a key feature of the design that enables it to function without tearing the sheet metal of the panel at its attachment to the floor. As can be observed in Figure 9c, the panel for the most part is in tension with forces well below its capacity.
**WR2.** For concept WR2, a somewhat smaller blast load was used since the stud wall inherently lacks robustness—vis-à-vis, blast loading—because of its primarily discrete nature, lack of mass, and use of relatively weak fasteners to attach the studs to the track and the track to the floor. This tends to yield wall retrofits that are less robust than those for masonry walls.

The response for a 6-inch 16-gauge metal stud that is wall retrofitted on both sides with a 20-gauge plate Sure-Board™ is shown in Figures 10 and 11. In this case, the height of the wall is 15 feet and the charge is 100 pounds of TNT at 30 feet. The response is primarily governed by the performance of the metal skins and the behavior and capacity of their anchorage to the floors. As shown in the figures, the track is bent upward by the front face skin. Were a more robust track and anchorage used, these retrofits could be strengthened nearly on a par with the masonry walls. A shorter height would also increase the capacity of this retrofit.

The WR2 retrofit has the added advantage of fitting well with standard construction practices and requiring no special wall preparation. This retrofit concept comes in a variety of strengths and can be constructed without altering the footprint of the wall or its basic appearance.

**WR3/WR4.** For concepts WR3 and WR4, which were applied to the CMU wall, the effect of various plies of Kevlar laminate and thicknesses of polyurethane spray are depicted in the response plots given in Figure 12. Both the Kevlar and polyurethane produce an acceptable result, limiting deflection to around 2% of span. The responses are grouped together because compression failure of the CMU at midspan (see Figure 12d) is controlling, making the response somewhat insensitive to the strength of the retrofit. The responses indicate that all the retrofits have significant elastic components to their response, as witnessed by the magnitude of the rebound.

The added strength of the stronger retrofits provides little benefit in reducing deflection, presumably because masonry failure is controlling, as shown in Figure 12d. However, the stronger retrofits may still be valuable by allowing the use of a less complex/ductile anchorage device.

**Conclusions and Summary**

The results from the retrofit analyses are presented in Table II. The calculations indicate that all four retrofit concepts can provide a valuable capability in adding blast protection to an existing building. The results indicate that the desired protection can be achieved in a number of ways. This study also demonstrates the need for using HFPB models in designing these type of systems because of the difficult nature of characterizing the behavior of retrofit systems like these, which are composed of disparate types of materials. The predictions indicate that retrofit concepts based on employing materials that have not previously been used or are not widely employed have substantial merit as candidate materials for use in improving the resilience of structural members.

**Acknowledgement**

This study was performed as an adjunct to the many studies Karagozian & Case (K&C) has conducted over the last several years related to increasing blast resistance of conventional buildings. The study was funded by K&C as part of our on-going program to develop new concepts for enhancing the blast resistance of structures.
References


Table I. Retrofit Concepts

<table>
<thead>
<tr>
<th>Retrofit Concept</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>WR1</td>
<td>A 4 × 10-foot panel constructed with a core of rigid polyurethane foam with a sheet metal skin attached to one face of the core. The other face of the core is glued to the wall to be retrofitted. A ductile shoe is used at the panel’s edge to transfer panel loads into the diaphragms and minimize the in-plane forces in the panel skin.</td>
</tr>
<tr>
<td>WR2</td>
<td>A 4 × 15-foot panel of Sure-Board™ (i.e., gyp board plus sheet metal) is added to the inner surface of a metal or wood stud wall (i.e., either over or in replacement of the existing gyp board). As shown in Figure 7a, Sure-Board™ and Kevlar laminate may be added to the exterior face to provide added wall stiffness and capacity as well as fragment protection (i.e., by using the Kevlar).</td>
</tr>
<tr>
<td>WR3</td>
<td>A Kevlar laminate is glued to the wall with polyurethane and tied to the diaphragms without an anchorage device.</td>
</tr>
<tr>
<td>WR4</td>
<td>Polyurethane spray is placed on one or both sides of a wall.</td>
</tr>
</tbody>
</table>
Table II. Summary of results from FEM models for the prediction of wall responses.

<table>
<thead>
<tr>
<th>Wall Designation</th>
<th>Wall Type</th>
<th>Height, ft</th>
<th>Retrofit Concept</th>
<th>Retrofit Specification</th>
<th>Maximum Deflection to Span Ratio, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Type 1</td>
<td>Metal stud wall</td>
<td>10</td>
<td>WR1: Rigid Polyurethane foam panel</td>
<td>1” thick foam, 20 GA skin</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2” thick foam 12 GA plate tied to shoes</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>WR2: Sure-Board™</td>
<td>20 gauge skin</td>
<td>8.3</td>
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<tr>
<td>Wall Type 2</td>
<td>Reinforced CMU wall</td>
<td>10</td>
<td>WR3: Kevlar laminate</td>
<td>2-ply</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4-ply</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6-ply</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>WR4: Polyurethane spray</td>
<td>¼ inch</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>¾ inch</td>
<td>2.0</td>
</tr>
</tbody>
</table>

(a) Wall Type 1: metal stud wall; other studs are also considered in the study (e.g., 6-inch and 16 gauge).
(b) Wall Type 2: CMU wall.

Figure 1: Wall sections defining the two wall types considered in retrofit study.
Figure 2: Three test specimens shown, bottom face up.

(a) Pinned support. (b) Fixed rotation with applied axial load.

Figure 3: Test setup.

(a) Midspan showing large crack spanned by polyurethane. (b) At support.

Figure 4: Typical results.
Figure 5: Wall Retrofit Concept WR1: rigid polyurethane foam panel [3].
(a) Photos.

(b) Laminate properties, two-ply; capacity 1,700 lb/in per ply.

Figure 6. Wall Retrofit Concept WR2: Kevlar laminate.
(a) Material test for Type I polyurethane spray.

(b) Material model of Type I polyurethane.

Figure 7. Wall Retrofit Concept WR 3: polyurethane properties.

- Initial plastic modulus
- Elastic modulus
- Specimen breaks

Initial plastic modulus: $E = 7,403$ psi
Elastic modulus: $E_t = 254$ psi
Specimen breaks: $f = 878$ psi
Density: $\gamma = 70$ pcf
(a) Section of Sure-Board™ stud wall (Kevlar on blast side provides optional ballistic protection).

(b) Photo of sample of hardened gyp board, trade name: Sure-Board™.

Figure 8: Sure-Board™ stud wall. This retrofit requires removal of the existing inner drywall panel of the stud wall and its replacement with Sure-Board™; alternatively, the Sure-Board™ could be attached directly to the existing wall, overlaying inner drywall panel. Sure-Board™ may be used for one or both sides of wall.
(a) Deformed shape at peak displacement.  
(b) Detail showing anchorage block.  

Figure 9: Response of retrofit stud wall (studs not shown) strengthened with retrofit WR1.

(c) Forces in steel skin, capacity = 36 ksi (12 gage; $t = 0.106\)”).
(a) Deformed shapes at various times, gyp board shows up as intermittent blue line, which represents side view of board as it bends inward.

(b) Displacement time history at wall’s centerline.

Figure 10: Response of Wall Type 1 strengthened with Retrofit Concept WR2.
Figure 11: Response and mesh details at wall anchorage for WR2.
Figure 12: Responses of Wall Type 2 strengthened with Retrofit Concepts WR3 and WR4.
(c) Effective stress history for ¾-inch thick polyurethane.

(d) Typical of residual damage states computed for wall
Figure 12: Responses of Wall Type 2 (strengthened) with Retrofit Concepts WR3 and WR4 (Continued).