Protective Roof Materials for Small Shaped Charge Munitions

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INTRODUCTION

The United States Air Force (USAF) must often protect assets from submunition threats. Submunitions are typically air delivered via a cluster bomb which contains a multitude of submunitions that are spread over a large area. The submunition is stabilized during its descent with a ribbon on the case rear and upon impact the submunition is initiated with a simple mechanical inertial fuse and detonates causing a shaped charge jet to form. A fragment field is also produced and disperses radially from the submunition. While the shaped charge is a significant threat for most armored and unarmored equipment, the fragment field only has sufficient mass and velocity to penetrate thin skinned objects such as fuel tanks. Hence, a protective structure must be able to defeat the overhead threat as well as near misses at ground level. A prototype structure to protect high value assets against damage from such a threat was developed, including requirements for erection time, wind and earthquake loads, and overall interior dimensions.

METHODOLOGY

Approach

The goal of this effort was to develop a structure that protects against shaped charge submunitions and can be erected in an expedient manner, in terms of manpower and clock time. The development of a novel armor system was based primarily on extensive live-fire testing, in which candidate solutions were identified, built, tested, refined and tested again; numerical simulations were limited but used as appropriate. To develop the structure that supports the armor, an aluminum truss concept and a steel frame concept were created; engineering design and analysis was used to develop final fabrication-level drawings and to determine cost and erection time/manpower for both approaches. A portion of the aluminum truss structure including armor was built and its performance was verified with a live fire test using the specified shaped charge threat.

Armor Design Concepts

Armor designs for shaped charge defeat typically include a strike surface or pre-detonation layer to initiate the shaped charge, allowing sufficient distance for the shape charge jet to particulate before hitting the primary protective layer. The use of standoff and a pre-detonation layer is a well-established concept. In this program, a variety of pre-detonation layer configurations and primary protective layers were devised, constructed and tested. The goal was to develop lighter and cheaper armor design packages than currently exist, using commercial off-the-shelf (COTS) and non-exotic materials; the hope was that much of the system could be obtained from a standard building supply company.

Field testing was used extensively to develop, evaluate, and refine armor concepts. In addition to providing the highest quality data, the advantage to this approach was the low cost for each test, due to the relatively simple specimen designs, readily available threat munitions, limited instrumentation requirements, and minimal effort to mount the specimens. The lessons learned from each cycle were combined with intuitive changes and new ideas for the specimens and designs that were evaluated in the next cycle. The pre-detonation layer concepts were evaluated first and the best approaches were combined with different primary protective layers to determine the overall performance of the system.

Testing

A total of 93 tests occurred during the course of this program at both government and independent labs. These included the Air Force Research Laboratory (AFRL)/Tyndall AFB, the Engineer Research and Development Center (ERDC)/Fort Polk, and Southwest Research Institute (SwRI). All testing occurred with a defused submunition, held statically on the armor and detonated with an RP 87 EBW detonator placed on the top center of the round pointing downward.

The pre-detonation layer concepts were placed directly under the shaped charge. The base armor for evaluation of residual penetration was a stack of 8-in × 8-in × 0.25-in (20-cm × 20-cm × 0.64-cm) AR500 plates at a fixed distance from the back of the target. Following each test, the plates that were penetrated by the threat were documented and replaced. The results from these tests were then compared to the penetration of the residual jet with no pre-detonation layer.

After the strongest pre-detonation layer concepts were determined, the protective layer designs were developed and tested. For the evaluation of the protective layer concepts, the depth of penetration (DOP) into the semi-infinite stack of rolled homogenous armor (RHA) was used as a rough baseline. A series of material combinations were investigated to determine which provided the best performance gains with the pre-detonation layer. A combination of aluminum witness plates (0.02 2024-T3) and steel witness packs (RHA) were placed under the target to assist in determining if the concept was close to passing.

Side targets were tested using a variety of methods. In each case, the targets were attached loosely to a perimeter support and positioned 12 to 36-in (30 to 91-cm) from the threat, oriented normal to fragment trajectory of the main beam spray.

Each of the labs used large steel welded stands to gain the desired standoffs between the targets and the shaped charge. In general, the stands may be considered rigid. An example of a test stand is shown in Figure 1. The testing at SwRI used a 0.5-in (1.3-cm) thick mild steel plate with a 5-in × 5-in (13-cm × 13-cm) square hole in the center to hold the targets. This allowed the target to deflect and the jet to pass through the holder. For the last test series, which used the 24-in (61-cm) square pre-detonation layers, the target was spanned across the top of the fixture with an 18-in × 18-in (46-cm × 46-cm) plate with a square opening. In no case was the pre-detonation or target layer clamped to the fixture. Most of the initial testing was performed with 6-in × 6-in (15-cm × 15-cm) targets. As solutions were further developed, 12-in × 12-in (30-cm × 30-cm) targets were used to help investigate larger panel performance.

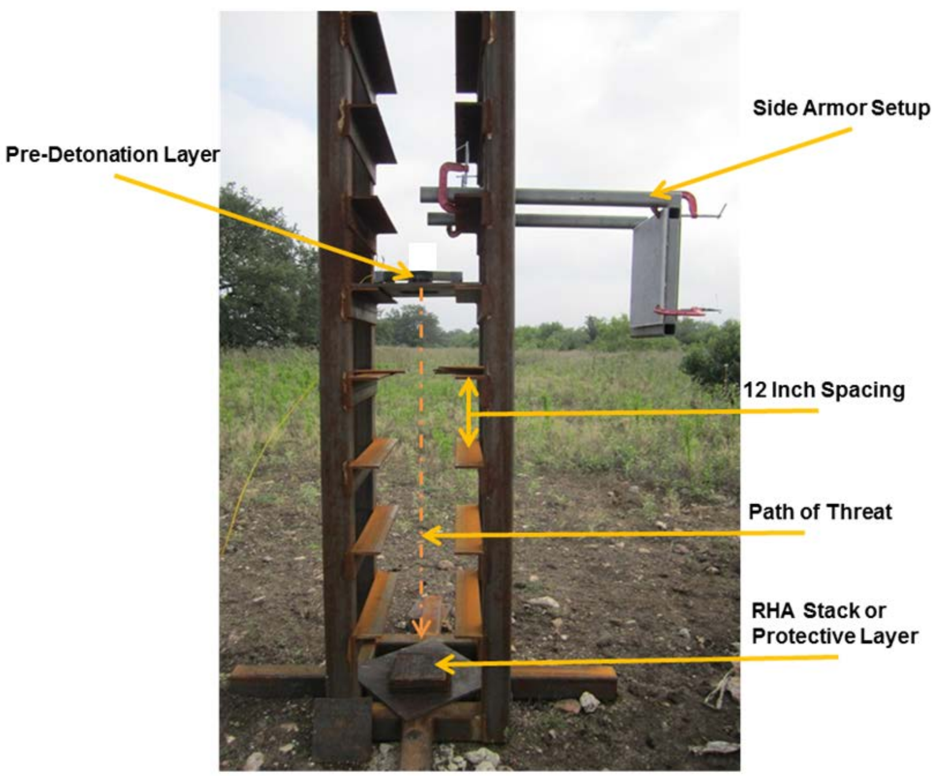

Figure 1. SwRI Welded Test Structure

A total of 35 tests were conducted to find the optimal pre-detonation layer. These layups consisted of two baseline tests (with no pre-detonation layer) and several tests with a wide variety of materials. In the two experimental baseline tests conducted at a 53-in (135-cm) standoff, the shaped charge penetrated between 1.06 to 1.31-in (2.7 to 3.3-cm) into the stack of AR500, or a penetration that would require approximately 43 to 53-psf (210 to 259-kg/m^2) of steel. Though many of the materials showed promise during testing, it was decided to concentrate on thin steel spaced by light foam, as it was considered one of the least expensive and lightest solutions that yielded some of the better results. The pre-detonation layer was found to be optimized with two layers of 22 gauge (0.8-mm) steel sandwiching 5.2-in (13.2-cm) of Foamular® extruded polystyrene, shown in Figure 2, having an areal density of approximately 3.1-psf (15-kg/m^2). Only one pre-detonation layer is shown due to its use in most testing, however, it is expected that the Foamular® extruded polystyrene could be replaced with expanded polystyrene based upon very limited testing of each. The current pre-detonation layer was chosen due to the availability and standardization of the Foamular® product. Pre-detonation layer materials are expected to cost roughly 4.00-\$/ft^2 (43.01-\$/m^2) and weigh 3.1-psf (15-kg/m^2).

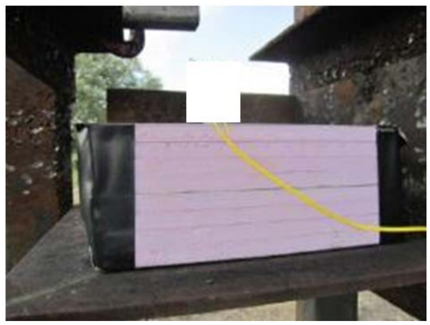

Figure 2. Optimized Pre-Detonation Layer

Although high speed video footage was taken from most of the tests, there did not appear to be a direct correlation between residual velocity and DOP into the witness pack, as evidenced by data from Test 2 (baseline test with cardboard to support the shaped charge) and Test 10 (0.125 in Al 6061/0.75 in Zodiaq® (quartz)/0.125 in Al 6061); see Figure 3. Both tests penetrated into five plates, despite there being an estimated velocity difference of 1.83-km/s between the two tests. Additionally, tip velocity did not prove to be a reliable parameter for investigation of jet spread as it appeared that target debris along a single axis view was not sufficient for a complete analysis as seen in Figure 4**.**

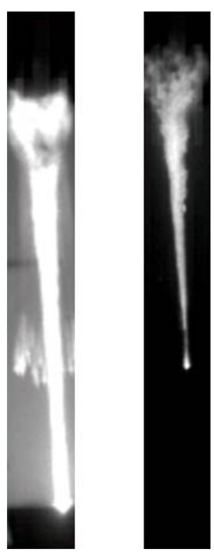

Figure 3. Frames at 200-ms After Detonation for Test 2 (left) and Test 10 (right)

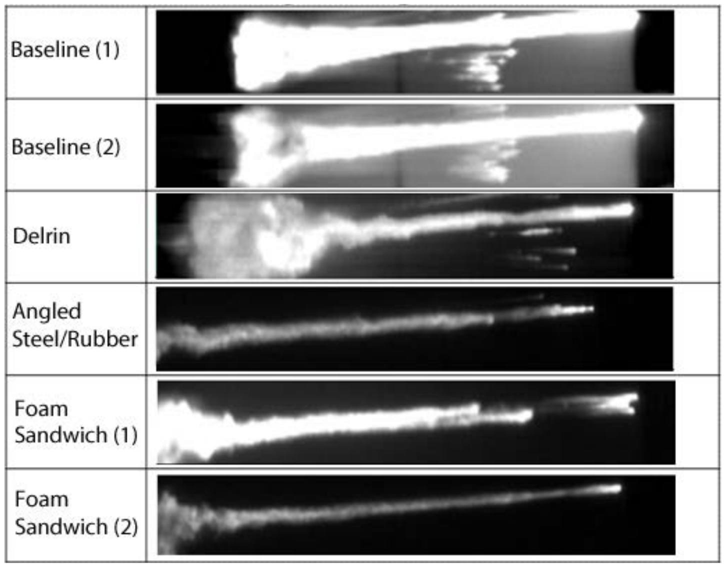

Figure 4. Video Frames from Various Tests

Numerical Simulations

CTH and EPIC were used to investigate and develop various armor solutions and to assess the DOP. To gain reasonable results, the simulations were performed with a model size of 313 × 8216 cells (2.6 million cells) in an axisymmetric mesh, which provided several zones through the liner thickness, as shown in Figure 5. This series of simulations provided results with approximately a 25% deviation from the average penetration depths of the two tests, which was considered acceptable for this effort. This high resolution mesh took multiple days on a large computer cluster to perform and hence limited the number of simulations that were performed. A secondary mesh using a lower resolution adaptive mesh refinement (AMR) methodology, shown in Figure 6, was also employed. In these simulations, the mesh was refined automatically during the simulation, in regions which needed the most refinement. While the results were not as accurate, it was hoped that relative performance variations could be discovered with this approach.

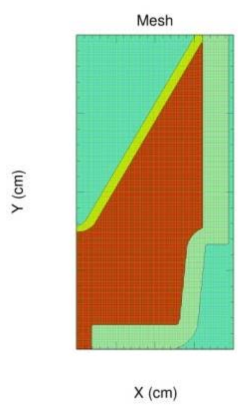

Figure 5. High Resolution CTH Mesh

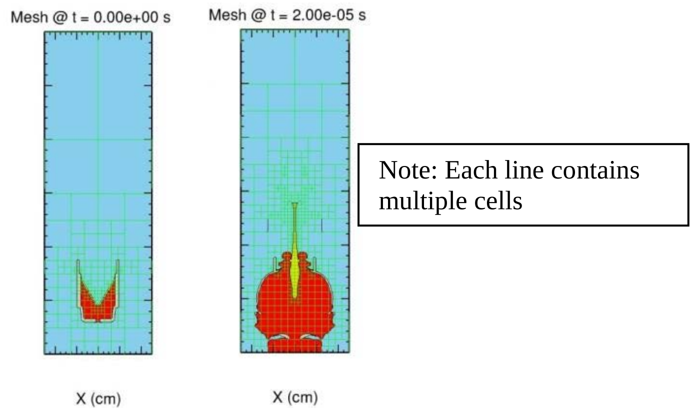

Figure 6. Lower Resolution AMR Mesh

ARMOR SOLUTIONS

Based upon limited testing and simulations, several armor solutions were identified. Table 1 presents the steel solutions; however, there were other armor solutions developed with a lower areal density. Armors A, B, and C are low cost systems which could be readily fabricated with available material and have some inherent structural capabilities. Armor A, 0.125-in (0.32-cm) 4130 steel over a hollow structural section (HSS) member, is the lightest of the steel solutions, with an average areal density (including the HSS sidewalls) of 39.9-psf (195-kg/m^2) and a rough cost of 49.50-\$/ft^2 (532.26-\$/m^2). Armor B is a solution comprised of a 0.188-in (0.48-cm) mild steel plate on top of the HSS. This allows for a more common steel to be used if the slightly more exotic 4130 cannot be procured. This solution adds an additional 2.5-psf (12.2-kg/m^2) of weight, but actually reduces cost. Armor C is based upon using 8x4x1/2 HSS members without a top plate versus the 0.375-inch (0.95-cm) thick HSS. This solution is both heavier and has more material costs. Additionally, its performance in limited testing appeared worse than Armors A and B. Also as noted in the comments column, some of these armors are considered “marginal” from testing, meaning that some residual spray was observed during some tests. This spray, however, did not penetrate into the witness pack but may have penetrated an aluminum witness plate. Finally, tests were performed to look at armor performance at large standoffs without the protective pre-detonation layer and led to the development of Armor D. The limited testing indicated that if the standoff was greater than 9-ft (2.7-m), 0.188-in (0.48-cm) mild steel on top of the HSS was able to defeat the threat.

Table 1. Steel Armor Solutions

Solution	Pre-Det Layer	Min Rec. Air Gap (in)	Protective Layer					Total Price (\$/ft^2)	Comments
	Layup		Layup	Layer AD (psf)	Layer Thick (in)	Areal Density (psf)	Thick (in)		
A	3.1 psf - 22 gauge mild steel/ 5.2in Foamular®/ 22 gauge mild steel	57.5	4130	5.0	0.125	39.9	4.1	49.5	Spray on witness in one test
			6-in × 4-in × 0.375-in HSS	34.9/30.6	4				
B	3.1 psf - 22 gauge mild steel/ 5.2in Foamular®/ 22 gauge mild steel	54	Mild Steel	7.5	0.188	42.4	4.2	46.9	Stop with spray on back of tube wall
			6-in × 4-in × 0.375-in HSS	34.9/30.6	4				
C	3.1 psf - 22 gauge mild steel/ 5.2in Foamular®/ 22 gauge mild steel	59.5	8-in × 4-in × 0.5-in HSS	45.8/40.8	4	45.8	4.0	55.8	Hole in witness plate
D	None	111.3	Mild Steel	5.0	0.188	42.4	4.2	42.8	Dimple on back of HSS
			6-in × 4-in × 0.375-in HSS	34.9/ 30.6	4				

Determining a set of recommended armors for the side fragments was difficult due to the variety of fragments created by this threat. Most of the fragments can be stopped by a very light armor. However, for the worst case fragment, the armor demands would increase dramatically. Recommended side armors for a “pseudo” worse case fragment based upon testing is shown in Table 2. The design of these recommended armors was also based upon normal impact. Armor E was the simplest, thinnest, and most likely cost effective solution available. Mild steel that is 0.25-in (0.64-cm) mild steel also appeared to work. For situations in which the armor needs to be easily removed, a 4-psf (19.5-kg/m^2) Kevlar curtain should work based upon limited testing with 3.5-psf (17-kg/m^2) of Kevlar for Armor G. Armor F and H were found to be alternative lightweight solutions that appeared to work fairly well, although Armor F typically did not contain all fragments.

Table 2. Side Armor Solutions

Solution	Side Target	Layup	Layer Areal Density (psf)	Layer Thickness (in)	Total Areal Density (psf)	Total Thickness (in)	Rough Price ($/ft^2)	Comments
E	High Hard	3/16 in High Hard	7.6	0.188	7.6	0.2	10.00	Simulations showed that this should stop fragments
F	16 gauge Foam	Mild Steel - A36	2.5	0.063	5.3	2.1	4.03	One test passed, one test failed
		3x FOAMULAR® Insulating Sheathing extruded polystyrene (XPS) - Pink	0.3	2				
		Mild Steel - A36	2.5	0.063				
G	Kevlar	4 psf Kevlar 29	4.0	-	4.0	-	92.80	3.5 psf Kevlar had one frag through, extra layers may stop all fragments
H	Tegris	Tegris 4600	3.0	0.625	6.0	1.3	64.00	Test 3 had no fragments penetrate
		Tegris 4600	3.0	0.625				

STRUCTURAL SOLUTIONS

Two structures were designed to support an armor solution: 1) a lighter arch structure comprised of prefabricated aluminum trusses shown in Figure 7; and, 2) a steel framed structure consisting of readily available materials shown in Figure 8. The client required that both structures be easily deployable via shipping containers and assembled in the field within 24-hrs. A parts list and assembly procedure were developed during the design process to ensure the client’s needs were met. These solutions provide the end user with options for protection based upon time, money, and weight constraints.

Certain assumptions were made with regard to the amplification factors applied to the wind and seismic loads. While the wind speed of 120-mph (193-km/hr) was specified by the client, no importance or exposure categories were provided. PEC chose an importance category of IV and Exposure Category of D with a K_{zt} of 1 as the structure was assumed to be an essential facility as defined in Table 1-1 of ASCE 7-05 and was assumed to be located in a flat unobstructed area. To be consistent with the wind loading, the same importance factor was used for calculating the seismic load. Per ASCE 7-05 section 11.4.2; “Where the soil properties are not known in sufficient detail to determine the site class, Site Class D shall be used unless the authority having jurisdiction or geotechnical data determines Site Class E or F soils are present at the site.” Assumptions from ASCE 7-05 coincide with UFC 3-310-04.

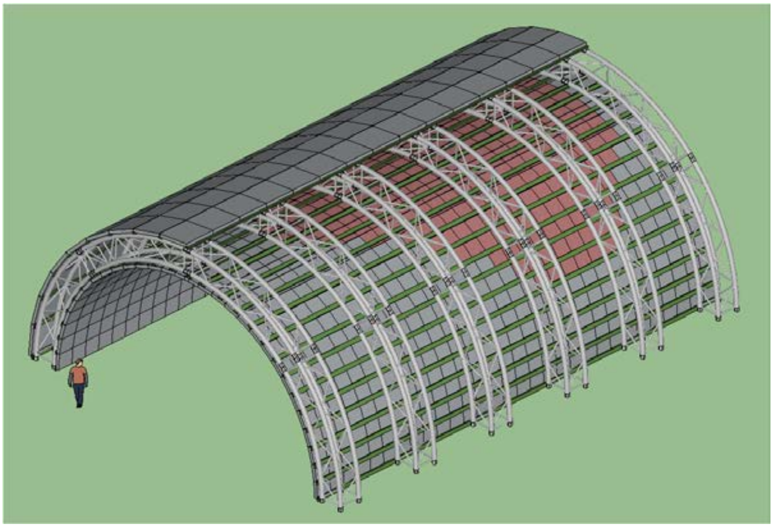

Figure 7. Prefabricated Aluminum Truss Arch Structure

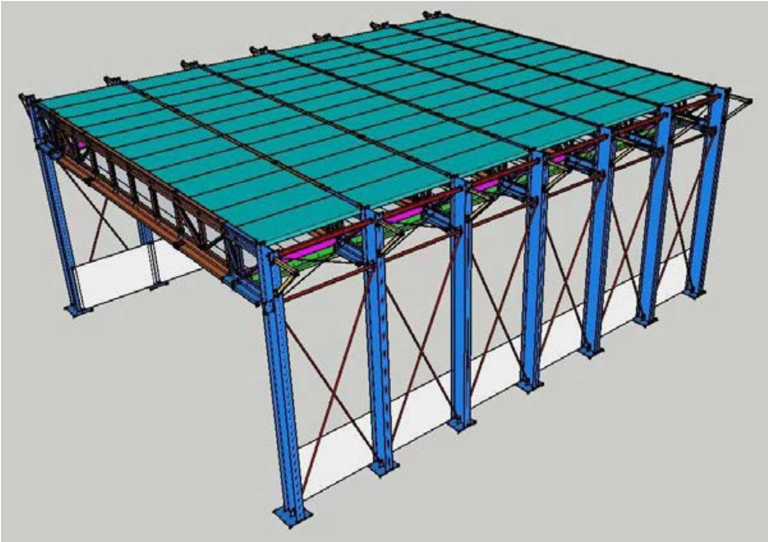

Figure 8. Steel Framed Structure

Arch Structure

The arch structure was designed by Total Structures (TS), an aluminum truss design company in California, with input from PEC. The seismic requirements controlled the design of the arch structure due to the large hanging mass of the armor system and the associated seismic assumptions. The arch structure incorporated 6 sets of arches with a rough size of 30-in (76.2-cm) wide by 50-in (127-cm) deep. The arches were comprised of 8 truss sections and are constructed from welded 6061-T6 aluminum.

Truss to truss connections were made via a zinc-plated carbon steel fork-end connection (male to female) using a stainless steel clevis pin (with a R-Clip for retention purposes) to lock the items together. The armor panels were attached to the interior and exterior of the truss with custom extrusions. The custom extrusions included two mating extrusions for the outer connection and one for the inner connection. The extrusions were in turn connected to the truss via an existing TS proprietary custom extrusion welded to each truss (D-Block). Only two different truss designs were required for the entire system, seven of one style and one of another per arch.

The bases of each arch were fabricated from 1-in (2.54-cm) thick mild steel plates and flat bar. The truss to base plate connection was made via the same aforementioned clevis pins, using female forks at the lower end of the truss mating with the steel plate, which in effect became the male connector. The base plate was also designed to accept the guy cable assembly connections, which run between the arches for stability. All bases were identical in design and all parts were identical and symmetrical between each bay.

The truss was designed for interior armor panels at 30-psf (146.5-kg/m^2), 3-in (7.6-cm) thick and external panels which were 5-psf (24.4-kg/m^2) and 5-in (12.7-cm) thick. However, based upon the recommended armor solutions, these panels may be altered to 21-psf (102.5-kg/m^2), 4.3-in (10.9-cm) thick and the exterior to 3-psf (14.6-kg/m^2) and still 5-in (12.7-cm) thick. The truss frame could be further optimized based on the lighter panels.

Box Structure

The box structure was designed by PEC using SAP2000. The seismic requirements provided by the client controlled the design of the structure due to the large suspended mass of the armor system. Thus, a special moment frame was designed. The box structure was comprised of 7 sets of columns and trusses. The columns are W24 × 68s. The truss section was comprised of 2C 9 × 13.4 members 3.75-ft (1.14-m) on center with 2L 2.5 × 2.5 × 3/8-in web members. The Main Lateral Force Resisting Systems (MLFRs) in the building were the special truss moment frames in the short direction and ordinary concentrically braced frames in the long direction. These systems were designed following the guidance set forth in AISC 341-05. All members were common steel alloys (A36, A992 Gr 50, and A500 Gr 46).

The parts were designed to be assembled in the field using bolted connections and following specific installation requirements when needed to meet seismic design requirements. All parts were identical and symmetrical between each bay.

The armor solution for the box structure consisted of the steel HSS armor with pre-detonation layer solutions. The pre-detonation layer covered the full foot print of the structure with 4-ft × 10-ft (1.22-m × 3.05-m) panels spreading between the trusses. The bottom armor layer consisted of HSS members pre-attached to the bottom cord of the truss with intermediate HSS panels placed in-between bays. The steel cover layer for the HSS members was pre-attached to the HSS panels. The bottom panels had a small 0.5-in (1.27-cm) gap between them to assure fit and the bottom protective layer spanned the center 39.5-feet (12.04-m) of the structure. This dimension was limited by the size of the shipping containers.

In addition to overhead protection, near miss protection was required for fragments from the side of the submunition. For the box structure, a 0.18-in (0.46-cm) thick high hard steel [or 0.25-in (0.64-cm) mild steel] wall was placed on the two side walls and extends up 6-ft (1.8-m) from the base.

At the open ends of both structures, a soft 4-psf (19.5-kg/m^2) Kevlar curtain was used which can be drawn into position or quickly removed. The curtain used a wire rope stretched between the two sides of the arch with a winch type system.

A comparison of the two structures is provided in Table 3. Note that in comparison to the arch structure, the box structure is a simpler design, is less expensive by almost 50%, employs easily-obtained commercial-off-the-shelf hardware and is more easily erected.

Table 3. Comparison of Two Structural Solutions

	Arch Structure	Box Structure
External Dimensions (W × L × H)	59.3 × 60 × 29.7 ft	50.5 × 60 × 26.9 ft
Internal Dimensions (W × L × H)	48.9 × 60 × 24.0 ft	46.5 × 60 × 20.8 ft
Primary Structural Material Used	Aluminum	Steel
Number of Bays / Bay Spacing	5 / 12 ft	6 / 10 ft
Recommended Primary Armor	High Strength Steel/High Performance Polymer Sandwich Panel	Common Steel Shapes
Approx. Structure Wt. for full unit	77 kips	51 kips
Approx. Armor Wt. for full unit	78 kips	120 kips
Total Wt	155 kips	171 kips
Rough Avg Areal Density	43.6 psf	56.4 psf
Estimated Structure Cost (Materials and Fabrication)	$320k	$155k
Estimated Armor Material Cost	$285k	$178k
Total Estimated Costs (Sum of Structure mat and fab + armor materials)	$605k (excludes “one-off” costs $38k)	$333k
Rough Avg Areal Cost (internal dimensions)	$206/sf	$119/sf
Number of Estimated Cargo Containers	6	7
Estimated Crew Size for 24 hr Erection	14	12
Rough Equipment Required	24 ton crane, telehandler, scissor lift (2)	24 ton crane, telehandler, scissor lift, hammer drill
Rough Foundation Requirements	New foundation with cast in place anchors for assumed panel weight	Post installed anchors into assumed slab

ARCH SUB-SECTION ASSEMBLY AND LIVE-FIRE DEMONSTRATION

The arch structure design was selected for evaluation in a live-fire demonstration. As a full scale assembly with all six arches would have been excessive for the desired demonstration, a test sample composed of two arches was fabricated, with each arch consisting of two truss sections joined together (shown in Figure 9). In an effort to reduce cost but retain operational characteristics, aluminum I-beams were chosen to constrain the pre-detonation and armor layers instead of the costly custom extrusions. The pre-detonation layer was the 3.1-psf (15-kg/m^2) solution mentioned earlier, while the armor layer was a 21-psf (103-kg/m^2) high strength steel/high performance polymer sandwich design. The panels were installed on half of the test sample trusses by sliding them into the I-beam pockets. With a team of six individuals and a front end loader, complete assembly of the truss sections and insertion of the pre-detonation and armor layers took just over one hour. The estimated total assembly time was 20 hours for six full arches with pre-detonation and armor layers, leaving four hours for crane manipulation and foundation adjustments, if necessary, thus meeting the 24 hour assembly/erection goal. Performance of the pre-detonation and armor solutions was as expected with moderate shaped charge jet particulation caused by the pre-detonation layer and no complete penetration of the armor layer.

Figure 9. Two Arch Sections with Pre-detonation and Armor Layers Covering Half of the Test Sample.

SUMMARY AND RECOMMENDATIONS

Using a test-based approach for iterative armor design improvements and evaluation, unique armor systems and the supporting structure were designed for the submunition shaped charge threat. The proposed armor systems have undergone limited testing and were shown to be successful.

Two structural solutions for implementing the armor design in field conditions were devised: a box structure and an arch structure. The box structure was composed of commonly available materials and was shown to be simpler, significantly cheaper, and easier to erect.

The proposed armors and structural systems could be further optimized, resulting in both reduced costs and lighter weight. There are three recommendations for system improvement: 1) further optimization of armor for weight and cost, 2) a more complete penetration test matrix, and 3) determination of better manufacturing methodologies. Each of these steps is necessary to gain the best end product. The structural designs that were developed used conservative design guidelines with nominal dimensions and were not fully optimized for weight or assembly. There are also final fabrication details to be developed.

ACKNOWLEDGEMENT

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