DESIGN, DEVELOPMENT AND TESTING OF A HARDENED UNDERGROUND TRANSPORTABLE COMPOSITE HYPERBOLIC PARABOLOID (HUTCH) SHELTER

T. F. Moriarty and P. von Buelow

The University of Tennessee
Knoxville, Tennessee

ABSTRACT

Two blast shelter modules, each providing approximately 500 sq ft (46 sq m), were prefabricated, transported, erected, bermed and tested. Each module was designed using modular structural panels based on hyperbolic paraboloids. The hyperbolic paraboloid shape is an efficient structural form for carrying impulsive type loadings due to its inherent ability to provide tensile as well as compressive load paths. This dual structural nature also lends itself well to composite designs. The precast panels were built up as composites, utilizing layers of polyester, reinforced concrete, fiberglass and asphalt. Three different levels of steel fiber reinforcement were examined. Each module contained three sets of panels with 0%, 1.25% and 5.5% fiber reinforcement, respectively. In addition, one module was designed with a pinned panel to panel connection, and the other module employed a bolted connection. The two methods of connection were assessed with regards to fabrication, field erection, inspection, and blast load resistance. A total of six blast tests were conducted using Mk 83 1000 lb bombs. The bombs were buried in the berm at distances producing either moderate or severe blast loads. Two tests were conducted on the pinned module and four on the bolted module, with one being a double shot on the same panel. Fabrication, erection, testing, cost estimates and applications are discussed.

DESIGN CONCEPT

The USAF has a need for a strong, versatile, economical structural shelter system that can protect equipment and personnel from near miss detonations of conventional weapons. In response to this need the Hardened Underground Transportable Composite Hyperbolic Paraboloid (HUTCH) shelter has been developed and tested (References 1 and 2). The major criteria considered in this design are:

- HIGH STRENGTH – controlled, factory fabrication
- HIGH MODULARITY – only two panel types per module – modules can be connected in a variety of configurations.
- TRANSPORTABILITY – lightweight, nesting panels
- EASE OF FIELD ERECTION – prefabricated to minimize field construction – strength not dependent on field conditions
- LOW COST – common construction materials

The HUTCH shelter, because it is based on geometries using hyperbolic paraboloids, is more effective at meeting these criteria than either a conventional flat walled box or a barrel vault shelter.

A single HUTCH shelter, shown in Figures 1, provides 500 usable square feet (46 sq m). It is octagonal in plan and completely assembled with just two panel types. To erect one module, eight apex (upper) panels and from four to seven base (lower) panels are required. The number of base panels used depends on the number of access points desired (from one to four.) Individual modules are designed to fit together to form larger building configurations as show in Figure 2.

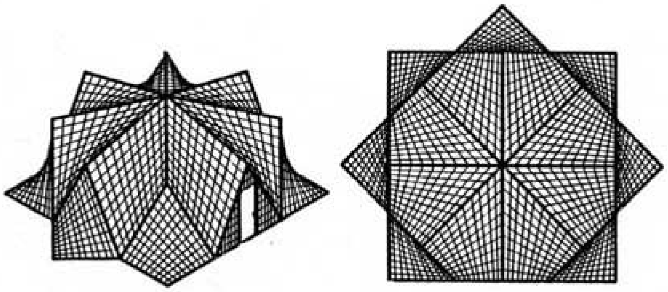

Figure 1. Isometric and plan views of a HUTCH module

Three panel material composites and two panel connection methods were tested. The three composite material systems were essentially: 1) high strength concrete with steel rebar reinforcement, 2) high strength concrete with steel rebar reinforcement plus 1.25% steel fiber reinforcement, and 3) a portland cement/fly ash slurry filled with 5.5% steel fiber and steel rebar reinforcement. The three material composite systems were evaluated on their ease of fabrication and quality control, strength under high impulse blast loadings, and cost. The two panel connection methods used were pinned connections and bolted connections. Both methods were evaluated on the same criteria as the material composites, plus a comparison was made on their ease of erection.

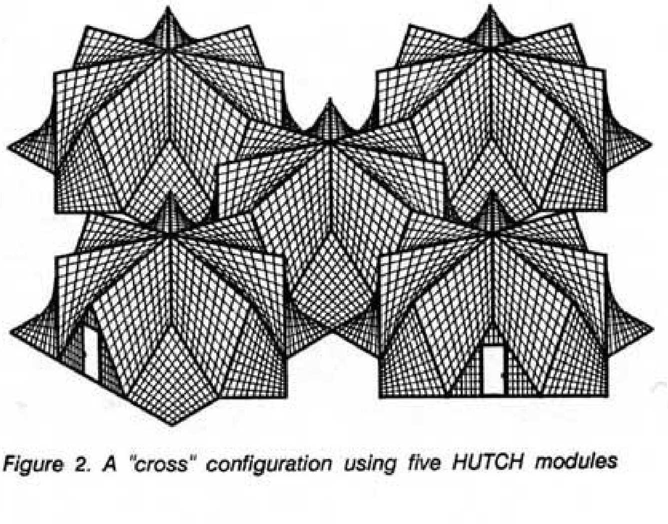

Figure 2. A "cross" configuration using five HUTCH modules

Strength

The HUTCH shelter panels are hyperbolic paraboloids which have double opposing curvature. This means that any point on the surface is simultaneously part of a concave curve and part of a convex curve. Both tension and compression load paths are provided at every point on the panel. Having both tensile and compressive load paths makes possible the use of composite material systems that would be structurally ineffective in any flat wall, arch or dome geometry. For example, the double opposing curvature of the HUTCH panels makes possible the structural application of high strength, lightweight fabrics.

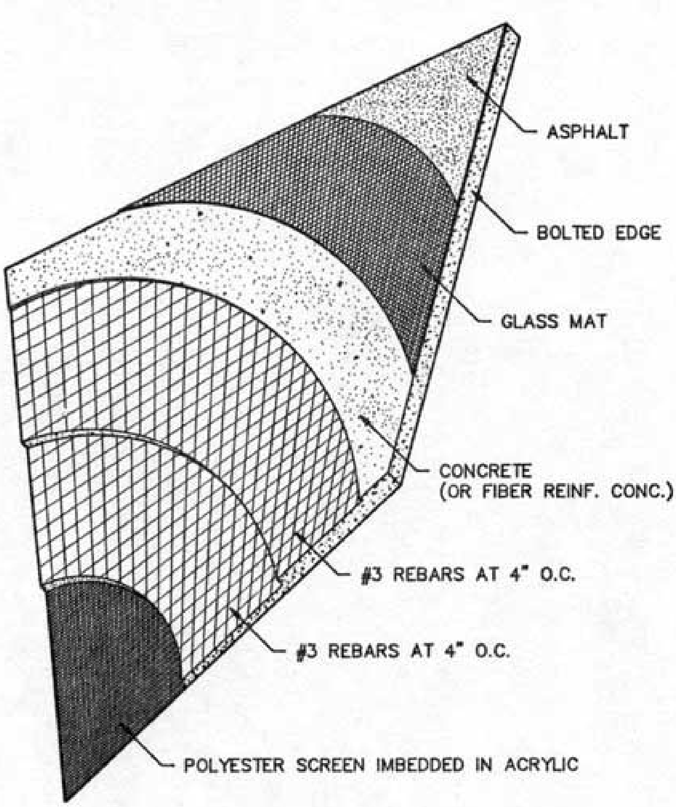

Figure 3. Cut-away view of a HUTCH panel material composite

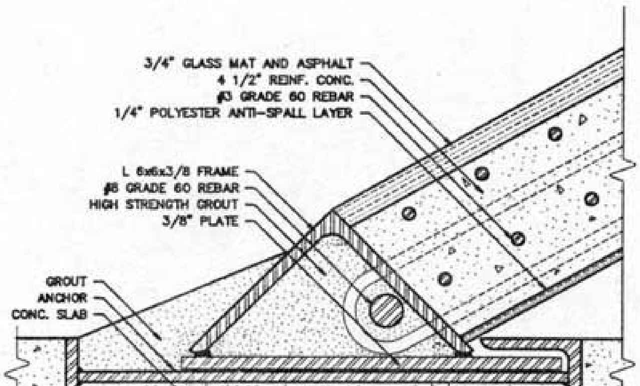

Figure 4. HUTCH slab to panel connection detail

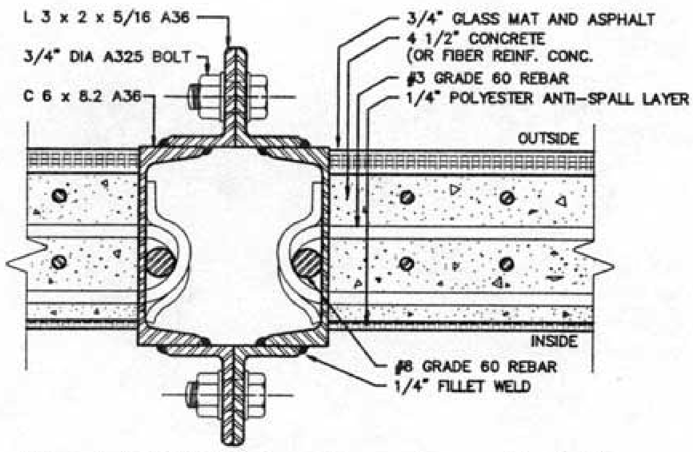

Figure 5. HUTCH bolted panel to panel connection detail

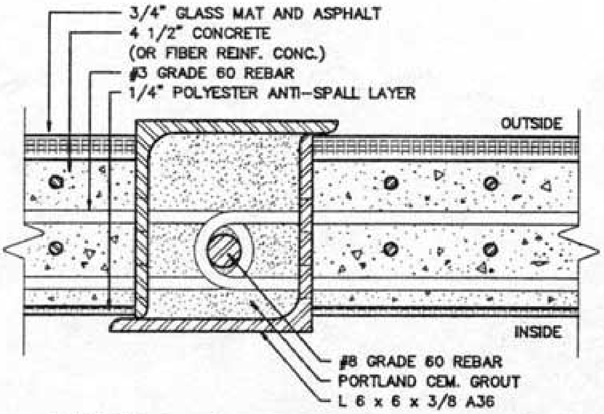

Figure 6. HUTCH pinned panel to panel connection detail

Modularity

Each HUTCH module is made up of just two types of panels: apex panels and base panels. To erect one module requires eight apex panels and from four to seven base panels depending on the number of access points. The fact that there are only two major building parts simplifies fabrication in that only two types of forms are needed to cast the panels. The fact that any base or apex panel is interchangeable with any other base or apex panel, simplifies the logistics of procurement, storage and deployment.

Because of the regular geometry of each HUTCH module, and the patterned way in which they connect to one another, a large variety of building configurations can be achieved. Each module contains 500 sq ft (46 sq m) and can be hermetically sealed from the adjacent modules. In case of damage to one module, that module can be sealed off to maintain a chemical/biological save condition in the rest of the surrounding modules. Building configurations can be developed to fit a variety of site conditions and functional requirements.

Transportability

The HUTCH shelter has been designed as a system which will be prefabricated at a remote facility, and shipped to the erection site. The maximum dimensions are small enough to allow transport by either truck or rail. In addition the geometry of the individual panels allows for nested packing. This reduces the number of loads required to transport the panels. Everything required to erect the two modules tested at Tyndall AFB was shipped form Knoxville, Tennessee on the two rail cars. Figure 7 shows the way in which the panels nest, reducing shipping cubage. The base and apex panels weighing 2 and 3 tons (1.8 and 2.7 metric tons) respectively, have built in lifting points, and are easily moved and loaded with a crane.

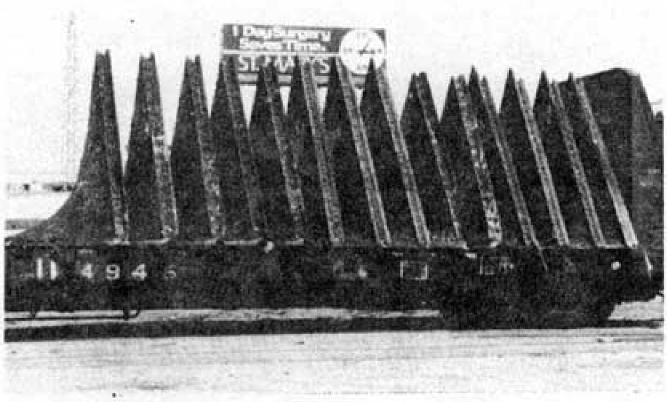

Figure 7. HUTCH panels loaded on rail car

FABRICATION PROCESS

The panels were built on open face forms. The steel frame, which is laid on top of the form, becomes the edge of the form, and an integral part of the completed panel. The different layers of each panel are laid up individually on the wooden forms starting with the inner layer and working out. The entire process takes on the average about 80 man hours per panel to complete once the materials are prepared.

Polyester Antispall Membrane

The first layer applied to the form is the polyester fabric which forms the interior surface of the shelter. Because of the tensile curve present in the panel, polyester fabric provides the same spall protection as heavier, more expensive steel plate. For this test prototype four layers of uncoated fabric were laid on the form and impregnated with acrylic. For production panels the same polyester fabric will be used, but with a commercially available, heat sealed, vinyl coating that offers a much more maintainable, fire resistant finish in the final product.

Steel Reinforcement

The major reinforcement is in four layers forming a double grid of grade 60 #3, deformed steel rebars. The rebars are placed through holes pre-punched in the steel frame. The pre-punched holes in the frame set the position and spacing for the rebars. The layers are separated and held in place during casting by 5/8" (1.6 cm) spacer rebars (see Figure 8).

Concrete

The concrete was batched at the fabrication site, placed with a small front end loader, and leveled in the form with shovels and hoes. A 1¼ hp (1000 watt) electric vibrator with a 1½" (3.8 cm) diameter head was used to compact the concrete as shown in Figure 9.

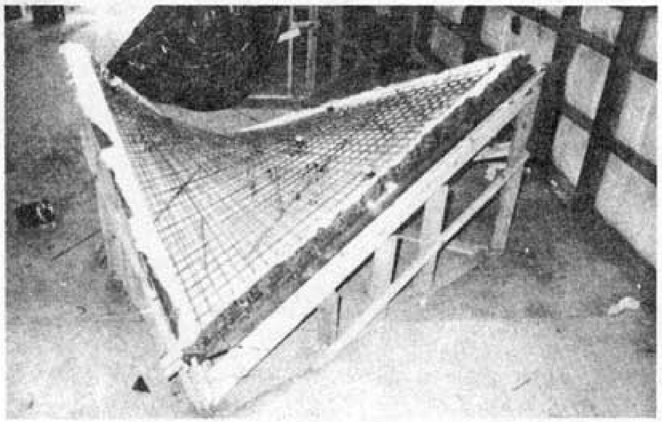

Figure 8. Base panel on form with steel reinforcement in place

Three batch designs were used containing different levels of steel fiber reinforcement. The three levels were 0.0%, 1.25% and 5.5% with average 28 day compressive strengths of 8,526 psi (58.78 MPa), 7,498 psi (51.70 MPa) and 8,955 psi (61.74 MPa), respectively. The addition of the steel fiber was intended to increase the plastic range of the concrete.

The casting process is virtually the same for plain concrete and the 1.25% steel fiber reinforced concrete. The 5.5% steel fiber reinforced concrete is more labor intensive to cast because the densely matted fiber must be rodded into place one handful at a time to achieve penetration through the four rebar layers.

Fiberglass and Asphalt Layer

The fiberglass and asphalt layer is applied after the panels are removed from the forms and placed outdoors. 24 oz/sq yd (0.81 kg/sq m) woven roving fiberglass is applied in 50 in. (1.27 m) widths and mopped with hot roofing asphalt. A total of four layers are built up. This layer provides a sealed outer skin strong enough to prevent soil from entering the protected space in the event of a local failure in the concrete.

Figure 9. Placing and compacting concrete in base panel form

ERECTION PROCESS

With the slab set, the first step is to place all of the base panels for a module into their anchor mountings on the slab. Next, every other apex panel is put in place and attached to the adjacent base panels. Two methods of connection were used. One module was designed with pinned connections, and the other with bolted connections. A center support aids in the placing of the apex panels. Finally, the remaining apex panels are secured in place and a center cap is bolted on. In the pinned module the cavity between the panels formed by the connected edges is filled with a portland cement grout, bonding the pin to the rebar loops of both panels. The grout is not used in the bolted module. The bolted module uses 3/4" ASTM A-325 structural bolts in the panel to panel connection. This was found to make the erection much easier than the pinned method. All of the bolts were in plain sight and easy reach which made inspection much easier and more reliable.

After the erection of both modules was complete, a soil berm was placed.

COMPUTER ANALYSIS

The responses of the HUTCH shelters to blast loads were predicted with the computer program DYNA3D (Reference 3) which is an explicit, three dimensional, finite element code for calculating the dynamic response of bodies: that are comprised of solids with nonlinear, elastic/inelastic, stress/strain relations, that can undergo large deformation, and that are subjected to high time rates of loading.

The computer models for determining the blast loading response of the modules, used the quadrant of the base panel nearest the weapon. The edges of the quadrant which coincided with the panel edge were modelled as fixed; the edges of the quadrant which bisected the base panel were modelled as attached to roller planes which allowed motion perpendicular to the panel surface. A panel was modelled in five layers corresponding to the material thicknesses and properties used in the actual panels. The total thickness of a panel was 5.5 in. (13.97 cm).

The Drake/Little model (Reference 4) was used to generate the blast loadings in the computer analyses.

There was general agreement between the blast resistance predicted by the computer analyses and those observed in the tests.

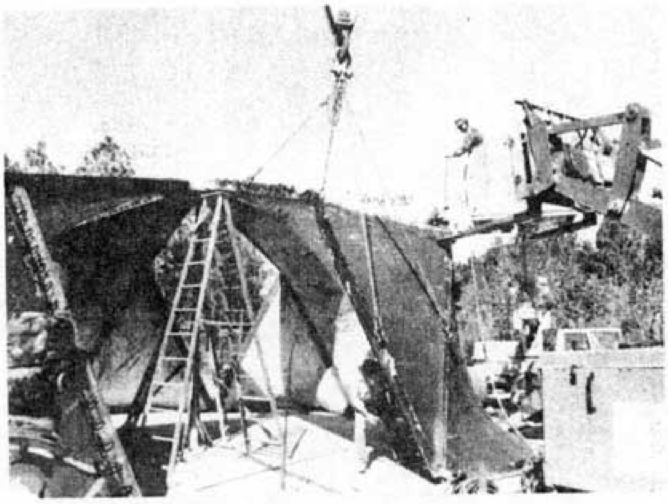

Figure 10. Erection of the pinned HUTCH module

Figure 11. Both modules in place before berming

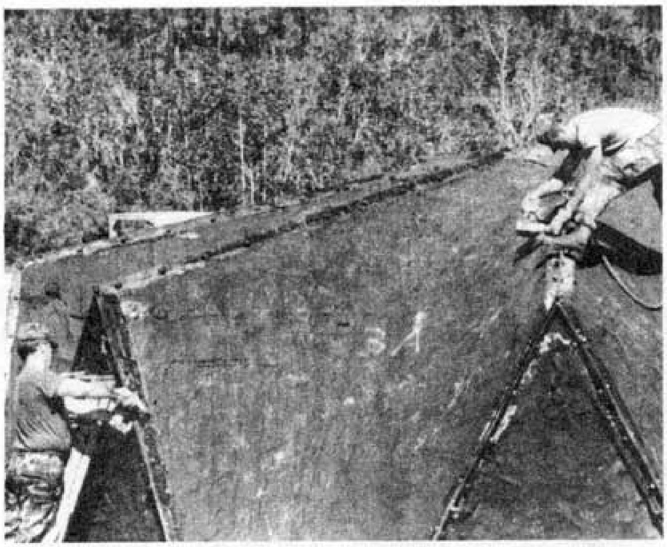

Figure 12. Tightening the bolts of the bolted HUTCH module

The permanent displacements for tests one, three and six (moderate blast loads) differ from the computer predictions (permanent displacement equals zero) because of the rigid body motion of base hypars relative to their anchor plates. The computer models modelled these anchor connections as rigid.

The permanent displacements for tests two, four and five (severe blast loads) differ from the computer predictions (permanent displacement equals: 3.8 in. (9.7cm), test two; 3.9 in. (9.9cm), test four; and 4.0 in. (10.2cm), test five) because of the rigid body motion of base hypars relative to their anchor plates just mentioned as well as the twisting inward and local buckling of the base panel to apex panel edge connections. The computer models modelled all of these connections as rigid. In test two, the actual inward displacement was further increased by the failure of a flawed panel to panel edge connection.

Figure 13. Test 4 of bolted 1.25% fiber module – exterior berm before the shot

TEST PROGRAM

Instrumentation

For each of the six blast tests the following data was recorded:

- Free Field Pressure
- Soil – Structure Interface Pressure
- Panel Acceleration
- Slab Acceleration
- Final Deformation
- Acoustic Pressure

The data was recorded on three, 14 channel recorders.

Free field pressures were recorded at distances of 12, 16 and 20 ft (3.7, 4.9 and 6.1 m) from the center of the charge. They were buried unmounted in the soil at the same depth as the center of gravity of the charge.

The soil/structure interface pressure gages were used at regular locations on the base and apex panels. The gages were mounted in steel receptacles which had been cast into the panels during fabrication. The active diaphragm was placed flush with the outside surface of the panel with all wiring routed out the back of the mount to the inside of the module.

Three directional accelerometers were mounted at the top and middle of each frame member and single directional accelerometers were mounted at the center of each panel tested. The slab accelerations were also recorded by three directional gages.

Selected geometric measurements were made of the modules before and after each test by hand with a tape measure. These measurements include the eight interior diameters of the module, and the midpoint of the base panel being tested. These measurements were made in order to have a spot check on the displacement data generated by integrating the accelerometer data.

Acoustic pressure data was recorded with gages mounted in a 1 in. (2.5 cm) diameter acrylic disk which in turn was attached by rubber bands to a 14 in. (35.6 cm) steel inertia ring. The inertia rings were hung at a height of 5.5 ft (1.68 m) above the slab by elastic cord tied to the midpoints of the upper edges of the apex frames.

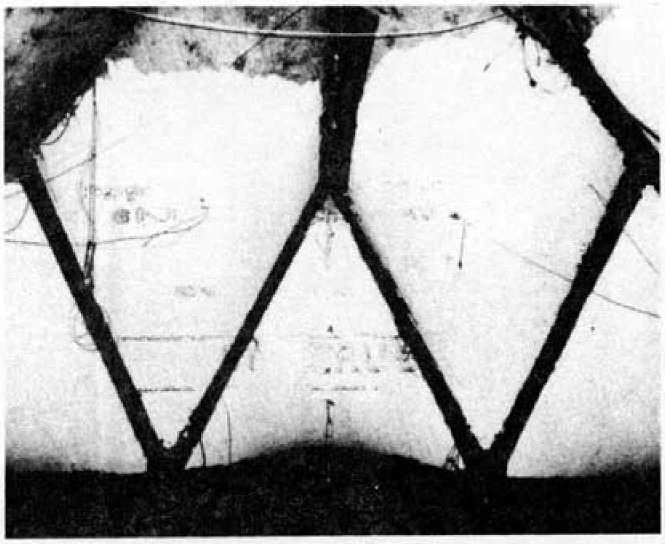

Figure 14. Test 4 of bolted 1.25% fiber module – interior before the shot

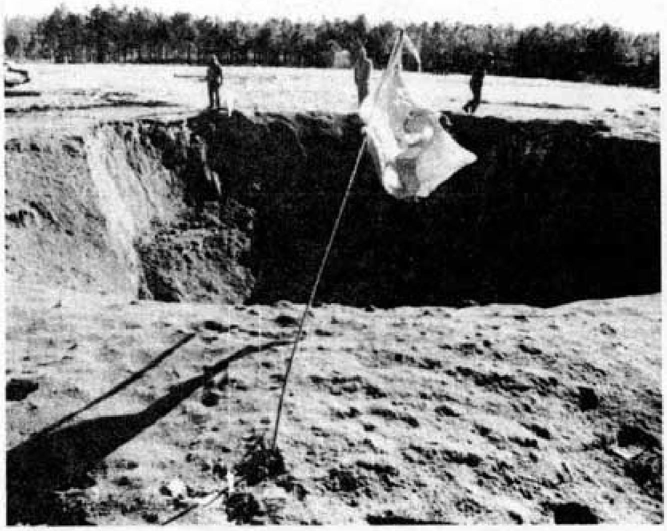

Figure 15. Test 4 of bolted 1.25% fiber module – crater

TEST RESULTS

The six blast tests were preformed using two different stand off distances. On the pinned module one moderate shot and one severe shot were made on the panels with plain concrete and 5.5% fiber concrete, respectively. The four tests made on the bolted module were two moderate shots repeated on the same plain concrete panel, and two severe shots, one each on panels with 1.25% and 5.5% fiber concrete.

The moderate shot on the plain concrete panel of the pinned module caused some ridged body shifting of the panel, but no plastic deformation. The severe shot on the 5.5% fiber concrete panel of the pinned module resulted in the failure of the pinned connection, allowing the panel to tilt inward 14°.

In the two successive tests made on the plain concrete panel of the bolted module, some shifting of the panel in the foundation anchor took place (about 2 in. (5 cm)), but again there was no plastic deformation in the panel.

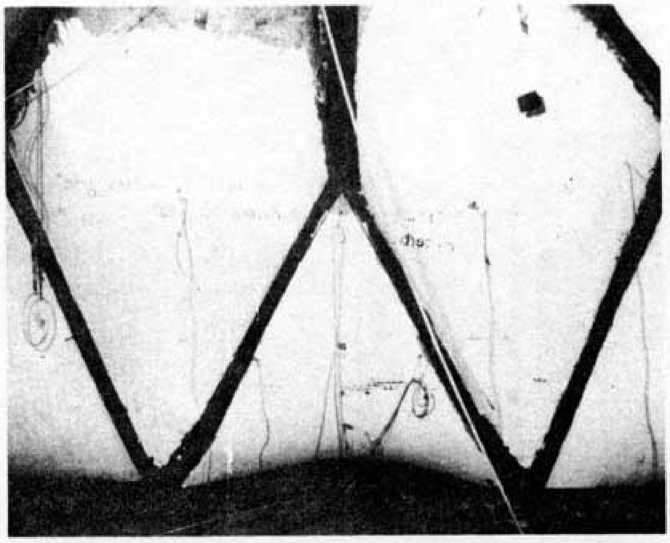

Figure 16. Test 4 of bolted 1.25% fiber module – interior after the shot

The two remaining shots on the bolted module tested the 1.25% fiber concrete panel and the 5.5% fiber concrete at close range. In both cases, no breaching or spalling was observed. More movement was present in the foundation anchor connection, and some of the foundation slab surrounding the anchor plates broke up. Plastic deformation of the shells did occur and the steel edge members were bowed inward on the tested panels. The concrete layer showed cracks but remained intact. Figures 15 and 16 show views of the interior of the bolted module before and after a severe blast test on the 1.25% fiber concrete panel.

COST ESTIMATE

Since this effort included the actual construction of two full scale modules, each with three different material composites, it was possible to collect sufficient data from actual purchases and work done to assemble accurate cost comparisons. The cost estimate shown in Table 1 is for the 1.25% fiber concrete with bolted connections. Data on labor expenditures was also collected. The figures presented indicate that the HUTCH system is more cost effective at providing blast protection by a factor of 3 over conventional, flat wall systems. The modular, prefabricated, HUTCH shelters are more labor efficient, and provide better quality control than field built systems.

CONCLUSIONS

Method of Joining Panels

During fabrication, additional effort was needed to place and orient the rebar loops used for the pinned connection above that needed for the bolted connection. During erection, the proper placement of the pins through adjoining panel rebar loops proved to be more difficult than anticipated, verification of proper placement of the pins was difficult and grouting the pinned connection cavities containing the pins and rebar loops was an erection step that was unnecessary for the bolted connection. Further, the bolted connection had the significant erection advantage of being able to align and pull together adjacent panels using the connection bolts. The bolted connections experienced only minor crippling due to blast loading. On the other hand, a pinned connection, that was flawed because a pin could not be properly inserted through all the required rebar loops, failed during a severe blast test. The bolted connection is superior to the pinned connection from the standpoint of fabrication, erection and blast response.

Panel Composite System

The three composite systems tested (with 0%, 1.25% and 5.5% steel fiber reinforcement) exhibited excellent blast resistance. The 0% steel fiber composite was subjected to moderate blast loads, while the 1.25% and 5.5% steel fiber composites were subjected to severe blast loads. The 1.25% and 5.5% steel fiber composites showed comparable blast resistance; however, for the bolted connection panels made with these composites, the 5.5% steel fiber composite was 22.7%, 5.4% and 10.1% more expensive than the 1.25% steel fiber composite in material, unskilled labor, and skilled labor, respectively. The 0% steel fiber composite was not blast tested to as high a load as the 1.25% steel fiber composite so that there is no direct test data to show how close the 0% steel fiber composite blast resistance is to the 1.25% steel fiber composite blast resistance. However, the material cost of the 0% steel fiber composite (for the bolted connection panels) was only 6.1% less than that for the 1.25% steel fiber composite while the unskilled and skilled labor costs for both composites were the same. Of the three composites tested, the 1.25% steel fiber composite was the most cost effective.

Slab/Anchor System

The HUTCH modules were erected on a cast in place slab/anchor system for a series of blast tests that was primarily concerned with the blast response of the composite panels and the panel to panel joining systems. For future deployments of HUTCH modules, to further reduce field work and erection time and to maximize the panel to anchor connection strength and rigidity, it is recommended that a prefabricated slab/anchor system be designed.

BOLTED SYSTEM – 1.25% FIBER CONCRETE

MATERIAL COSTS

ELEMENT	MATERIAL	QUANTITY	UNIT COST	TOTAL COST
EDGE	steel channel base plate	1,3620 # 1,400 #	$0.55/# $0.40/#	$7,491.00 $560.00
CONNECTION	3/4 in. bolts	528 pcs.	$55.55/100	$293.30
CAP PLATE	steel 3/4 in. bolts	340 # 48 pcs.	$0.59/# $55.55/100	$200.60 $26.66
CONCRETE	cement sand 3/8 in. agg. addmix	9.3 tons 12.4 tons 10.9 tons 25.75 gal.	$85.11/ton $15.00/ton $10.00/ton $2.49/gal.	$791.52 $186.00 $109.00 $61.63
REINFORCEMENT	#3 reinf. steel fiber	8,983 # 2,772 #	$0.23/# $0.50/#	$2,066.09 $1,386.00
TENSILE MEMB.	24 oz. glass asphalt	1,320 # 3,400 #	$0.89/# $0.10/#	$1,174.80 $340.00
SPALL COAT	polyester acrylic	605 sq.yd. 475 #	$2.50/sq.yd. $0.50/#	$1,512.50 $237.50
ANCHOR	steel shear connect.	3,114 # 217 pcs.	$0.40/# $1.20/each	$1,245.60 $260.40
FOUNDATION	concrete #3 reinf.	49 cu.yd. 7,280 #	$60./cu.yd. $0.23/#	$2,940.00 $1,674.40

TOTAL FOR MODULE $22,557.00
COST PER SQUARE FOOT $51.27

Table 1. Material cost estimate for the bolted HUTCH module with 1.25% steel fiber concrete

REFERENCES

1. Moriarty, T.F., von Buelow, P., Development and Testing of an Underground Protective Shelter Constructed of Hyperbolic Paraboloid Shell Elements, ESL–TR–86–37, Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403, September 1986.

2. Moriarty, T.F., von Buelow, P., final report for Development of Prefabricated Hyperbolic Paraboloid Shell Structural System, for Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403, 1989. (to be submitted)

3. Hallquist, John O., DYNA3D User's Manual (Nonlinear Dynamic Analysis of Solids in Three Dimensions), UCID–19592, Lawrence Livermore Laboratory, Nov 1982.

4. Drake, James L., Little, Charles D., Jr., "Ground Shock from Penetrating Conventional Weapons," Symposium on the Interaction of Non–Nuclear Munitions with Structures, USAF Academy, Colorado Springs, CO, May 9–13, 1983.