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BLAST AND PENETRATION RESISTANT TACTICAL SHELTERS

by

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July 31, 1979

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Introduction:

→ The objective of the research was to investigate the Air Force's tactical shelter designs and determine the extent to which blast and penetration resistance could be incorporated into the design. This was to be done within existing weight, cost and other constraints specified in the relevant Military Specifications.

~~We deal here with~~ → the standard 8x8x13 ft rectangular parallel piped, although the work here is applicable to the 8x8x20 ft shelter. This shelter must be capable of efficient transport by plane, ship, helicopter, rail, or truck without damage to the structure. → to p. 2

The shelter should be capable of withstanding a 7.25 psi overpressure (peak pressure). I have used this figure, which is independent of the structure itself, because the shelter will overturn, or be bounced about at higher pressures. Above 7.25 psi the shelter tends to be pulled loose from its anchoring cables and is consequently blown along the ground by the blast. Thus higher overpressures present a problem that is a limiting case since shelters are often deployed on trucks or in open country and airports. It is clear that 7.25 psi is a reasonable design objective.

We can begin by considering non-nuclear weapons and looking at weapons that supply overpressures in the neighborhood of 7 psi overpressures. These threats include G.P. bombs, artillery and rockets. However, this is misleading due to the tendency of these weapons to destroy the shelter by penetration of large amounts of shrapnel if the shelter is close enough to the weapon to see 7 psi overpressures. Therefore it makes more sense to define a shrapnel threat for non-nuclear weapons. To this end a 40 gram

fragment with a velocity of 600 meters/sec. can be used.

fr. p. 1 → An objective of this study was to design a material for the shelter that would be capable of withstanding small arms fire. It was determined that protection could not be guaranteed against 7.62 mm ball rounds with the weight constraints imposed. To accomplish this one would need a structure equivalent to an armored personnel carrier. The only solution possible here (it is not possible in many cases to move shelters out of areas where they are subjected to small arms fire since communications, radar, missile guidance, tank repair, helicopter repair, medical facilities, etc. tend to be compartmentalized in tactical shelters) is to erect revetments around the shelter or place the shelter in a depression. It should be pointed out that protection against 7.62 mm ball can be provided using kevlar composites, but the weight of the shelter must be substantially, but not excessively, increased.

The other major requirements for a tactical shelter are

1. A nine mile per hour railroad humping test
2. Static loading of 75 lb/ft².
3. No water entry on fording
4. No water entry due to rain
5. No dust entry
6. Thermal insulation from a -65°F low to a 120°F high plus a solar heating load
7. Corrosion resistance including salt fog
8. Blackout capability
9. Fungus resistance
10. RFI, EMI, and EMP protection (may be by add-ons in some cases)
11. Helicopter transport (drop test)
12. Shelter stacking test

Keywords:
Blast resistant
Shelters
(SDW) ↗

13. High altitude depressurization test.

and so on.

These items make it practically impossible to improve an existing design to accomplish an additional task or improve upon its design in a given area. For example, a material that may add substantially to blast resistance may not be as resistant to a particular form of fungus. Moreover, the directive for joint procurement of tactical shelters by the Air Force, Army and Navy restrict innovation even more. K. Underwood makes this point clear [1],

"During the past 10 years, there has been a movement within the military services to buy commercial construction equipment for non-combat use. Because of previous industry-wide abuses in furnishing substandard commodities to the military, a system of Military Specifications (MIL SPECS) was developed to ensure that some quality minimums would be maintained. Unfortunately, the massive paperwork mechanism of the MIL SPEC system is very difficult to alter, either to reflect the change in needs of the military user or any improvements in the manufacturing state-of-the-art." The problem, while not of great significance to the mission of the Air Force, is nonetheless important. The importance lies in the fact many thousands of these tactical shelters will be purchased over the next few years for many purposes: ILS systems, artillery control, antiaircraft systems, radar systems, telephone units, communications systems, helicopter transmission repair facilities, machine shops, photographic development facilities, latrines, CBW shelters, data reduction facilities, drone control, medical operating room, intensive care unit, power stations, weather station and, meeting room.

The strategic situation that is evolving at this time indicates that the type of conflict we will encounter in the near future will require an increasing level of dependence upon tactical shelters. We have lost many of our foreign bases and those that remain have been degraded, due to various controls by the host country, to the extent that they can not be counted on in a crisis. This means we are no longer close to many areas of potential military confrontation. Thus, military equipment, personnel, fuel, and entire systems will have to be transported over increasingly larger distances. This must be coupled with the need to respond to threats more quickly than in the past. The general proliferation of sophisticated aircraft, mobile artillery, mechanized divisions and air transport imply that even moderately sophisticated nations can move with great speed on the battle field if not confronted with a technically superior resistance. Our response time is now counted in days and not hours. However, these problems are somewhat counterbalanced by the Air Force's efficacious developments in area of cargo aircraft: greater speed, greater cargo capacity, lower cost per ton, shorter take-off and landing strips. Thus the capability for relatively rapid response to distant threats exists and this obviates the need for tactical shelters. The time and manpower necessary to transport equipment to a tactical site and then to erect it and render it operable, does not exist. The equipment must be preconfigured and in operating order instantaneously upon delivery.

Blast and Penetration Resistance:

At this point in the study the methods of [2] are sufficient for design purposes. At a later time it may be appropriate to become more sophisticated and study the details of the response of composites to blast and penetration from both macroscopic and microscopic viewpoints. The applications and extensions of existing computer codes to the problem may also be considered at a later time if there is any hope for a pay-off of significance.

In general the effects of a blast load on the tactical shelter will be determined by the magnitude (type) of explosion, its location relative to both the ground and the shelter and the orientation of the shelter with respect to explosion and ground. AFM 88-22 [2] can be used to predict the front wall loading p. 4-61, the rear wall loading p. 4-62, and the roof and side wall loadings p. 4-62 and 4-63. Multiple explosions are also considered p. 4-65. In general, the 7.25 psi overpressure standard allows one to make use of the tables in AFM 88-22 for design purposes.

To treat penetration problems one can make use of the Gurney method and use a hand calculator to make the computations, or use sophisticated computer codes. For our purposes the Gurney method is sufficient. Let v_0 be the initial velocity of a fragment and v_s the velocity at which the fragment strikes the shelter. Consider a charge evenly distributed in a uniform metal case. The weight of the explosive is W and the weight of the metal casing is W_c (lbs.).

$$v_0 = \left[\frac{2E'W}{W_c + W/2} \right]^{1/2}$$

Note that $(2E')^{1/2}$ is the Gurney energy constant that can be obtained from tables. The number of fragments produced is

$$\ln N_f = \ln\left(\frac{8W_c}{M_A^2}\right) - \frac{W_f^{1/2}}{MA}$$

where N_f is the number of fragments larger than W_f . M_A is dependent on the explosive and casing. Further

$$v_S = v_0 \exp(-0.0004 R_f/W_f^{1/3})$$

where R_f is the distance travelled by the fragment. Thus given our design criterion of a 40 gram fragment with a velocity of 600 meters/sec. we can work backwards and calculate the types of weapons that the shelter will offer some protection from.

Composites:

A survey of composites for tactical shelter applications was presented in [3]. This study uses [3] as a foundation. However, it should be pointed out that it is difficult to exceed the all around efficiency of the first modern composite which was developed around 1934 and eventually used in the W.W. II Mosquito. It had a core of balsa-wood with skins of birch plywood [4]. Given the most basic tactical shelter requirements it is evident that only sandwich construction yield both the light weight and stiffness that is desired. The basics of sandwich construction for tactical shelter use can best be gleaned from [5]. However, the appearance on the scene of Kevlar 49 with its

ballistic protection capabilities and very low weight to strength ratio induces us to recommend a Kevlar sandwich construction for the next generation of tactical shelters. Kevlar 49 was developed to replace steel in the belts of radial tires [6]. The advantage of Kevlar can easily be summarized [7]. Clearly, we are discussing a sandwich construction with Kevlar faces and Nomex, aluminum or paper core. We use marine applications data [7] for comparison, because of the corrosion, fungus, water and other requirements for tactical shelters.

There exists a wealth of data on Kevlar use in the aerospace industry. Kevlar composites used as a substitute for fiberglass yielded a 40% weight savings in the Space Shuttle ducting systems. In the Lockheed L-1011 similar parts yielded a 25% weight savings. Similar cases occurred in the UTTAS helicopter and Trident C-4 [8,9].

Relative to fiberglass, Kevlar is three times as stiff per unit weight and it has a higher damage tolerance due to its being able to deform more before failing. The ballistic protection afforded by Kevlar is well known [10]. In [10] Kevlar body armor worn by police stopped 0.38 caliber bullets fired point-blank and a 30.06 ball at 120 yards. These garments were made of seven plies of Kevlar 29 in a plain 31 by 31 weave. Kevlar 49 is used on the AH-64 as a shrapnel shield [11].

Kevlar 49 has a tensile strength of $400,000 \text{ lb/in}^2$ and a modulus of $18,000,000 \text{ lb/in}^2$ with a percent elongation to fracture of 2.5 and a density of 0.052 lb/in^3 . The fiber does not melt. A Kevlar sandwich composite that is almost off-the-shelf can be described with a view towards tactical shelter applications [12]. This was proposed for the floor of the DeHavilland Dash 7.

This is a sandwich of Kevlar 49/epoxy facings with a Nomex honeycomb core. The proposal was for a top face of 3 plies of 281 Style Kevlar 49; a bottom face of one ply of 281 Kevlar 49 and one ply of 220 Kevlar 49. The Nomex core has a 1/8" cell size of 6.0 lb density one-half inch thick. This yields a total panel thickness of 0.538" with a weight of 0.56 lb/ft². For our purposes (tactical shelters) a weight of a pound per square foot could be tolerated and the additional Kevlar would provide very substantial penetration resistance.

Kevlar/Epoxy Lamina: Mechanical Properties:

Now that a Kevlar sandwich has been recommended, let us look at properties of a typical Kevlar/epoxy face. We follow the work of Guess and Gerstle here [13]. They used Kevlar 49 with a DER-332 resin with T-403 hardener in a 100:36 mix ratio. The hardener is a Bisphenol-A epoxide and the hardener is a polyoxypropylene glyceride amine.

For an orthotropic lamina we denote the moduli parallel and transverse to the filaments by E_L and E_T and the corresponding Poisson's ratios by ν_{LT} and ν_{TL} . The shear modulus is denoted by G_{LT} . For a thin lamina we have a state of plane stress and the reduced stiffness matrix is:

$$Q_L = E_L / (1 - \nu_{LT} \nu_{TL})$$

$$Q_T = E_T / (1 - \nu_{LT} \nu_{TL})$$

$$Q_{LT} = Q_{TL} = \nu_{LT} Q_T = \nu_{TL} Q_L$$

$$Q_S = G_{LT}$$

Here the stresses and strains are defined in the principal material directions (L and T) for an orthotropic lamina. In this case (for a cylinder) we must transform to the Z-axis (height of cylinder) and the θ -axis (in the hoop direction). The result is:

$$Q_{ZZ}(\phi) = Q_L \cos^4 \phi + 2(Q_{LT} + 2Q_g) \sin^2 \phi \cos^2 \phi + Q_T \sin^4 \phi$$

$$Q_{\theta\theta}(\phi) = Q_L \sin^4 \phi + 2(Q_{LT} + 2Q_g) \sin^2 \phi \cos^2 \phi + Q_T \cos^4 \phi$$

$$Q_{Z\theta}(\phi) = (Q_L + Q_{LT} - 4Q_g) \sin^2 \phi \cos^2 \phi + Q_{LT}(\sin^4 \phi + \cos^4 \phi)$$

$$Q_{\theta Z}(\phi) = Q_{Z\theta}(\phi)$$

the angle of rotation from the Z-axis is ϕ . Now by averaging the contribution of each layer in the laminate we obtain the stiffness matrix (for n equal layers h)

$$\hat{Q}_{ij} = \frac{1}{h} \int_{-h/2}^{h/2} Q_{ij}(\phi) \, dn$$

or

$$\hat{Q}_{ij} = \frac{1}{h} \sum Q_{ij}(\phi), \quad i, j = Z, \theta.$$

To predict strength we look at the tension-torsion curve which has a radius of $1/3(F_L + F_T)$ [14] where the F's are the unidirectional strengths parallel and perpendicular to the filament direction. It turns out that $1/2(F_L + F_T)$ is a better estimate of the strength of a Kevlar/epoxy laminate. It is an upper bound of its strength in biaxial tension. The Norris-Ashkenazi [15] failure criterion can be taken to be a lower bound, viz.

$$\left(\frac{\sigma_\theta}{F_\theta}\right)^2 + \frac{\sigma_\theta}{F_\theta} \frac{\sigma_2}{F_2} + \left(\frac{\sigma_2}{F_2}\right)^2 \geq 1.0$$

Relation to Existing Standards:

We now look at the extent to which a blast and penetration resistant tactical shelter meets existing needs of the Air Force. We begin by looking at thermal insulation. The double-wall sandwich construction of a Kevlar-honeycomb-Kevlar material for ceiling, walls and floor provides for low thermal conductivity. This advantage results as a side benefit of the need for stiffness and is not due to specific design for thermal insulation. Thermal insulation is very important in shelter design since shelters may be deployed in the tropics or the arctic. Rapid response to threats requires that our equipment be capable of responding to a threat in any geographic location. The alternative of, say, hot weather shelters and cold weather shelters is not acceptable.

The standard windows, doors and vents can be used in a blast resistant shelter. Only minor thought need be given to adapt aluminum-foam or aluminum-honeycomb concepts to Kevlar-honeycomb design. Blackout provisions will remain the same, as will heating kits, air conditioning kits, lighting and power outlet kits.

It is understood that the shelter will meet ISO standards [16] , USAF system 463L with mobilizers and be compatible with the MH-5 helicopter lift.

EMI isolation can easily be designed in; within the Kevlar plies at the face-core interface or by way of an add-on kit. This takes care of the overall shelter shielding. The filtering of all wire penetrations must also be achieved.

With respect to repair Kevlar panels offer some advantages over aluminum. To quote from [8],

"The TWA aft engine fairings, which had required considerable rework prior to installation in Ship III [Stone, R. H., Flight Service Evaluation fo Kevlar-59/Epoxy Composite Panels in Wide-Bodied Commercial Transport Aircraft-Second Annual Flight Service Report, NASA CR-132733, Oct. 1975], provided an evaluation of repair procedures on Kevlar-49 parts. These panels were repaired using standard fiberglass field repair materials and techniques, and the satisfactory performance of these parts in service indicates that Kevlar-49 parts generally can be repaired in the same manner as fiberglass components, requiring no revision in airline maintenance procedures. The most significant rework on these parts was relocation of all fastener holes. The holes were filled with a glass filled epoxy...."

A blast and penetration resistant shelter will also meet load, shock and vibration standards. It is resistant to humidity, rainfall and salt fog. Thus the shelter will be electrically nonconductive, it will not corrode, it will not support combustion, will have a storage life greater than 10-years, it exhibits inherent Chemical/Biological protection, it is inert to solvents, has low moisture absorption characteristics and a low shrinkage coefficient.

Another idea of the efficacy of Kevlar sandwich construction for tactical shelters can be gleaned from the severe tests on a Kevlar-foam sandwich aircraft propellar [17]. A vibratory load many times normal was applied to the shank for 70×10^6 cycles while purposely damaging various shank parts, viz., holes were completely drilled through the Kevlar at the shank plug end and portions of the primary retention rovings were peeled away to weaken the member. No blade related failure occurred--failures were related to the hub. Further, the outboard portion of the blade was subjected to severe bending loads and subsequently damaged by drilling holes into the Kevlar, scratching the surface and drilling into the leading edge. No deterioration in blade strength or damage propagation was observed.

Lifetime and Degredation Predictions:

Here a phenomenological method for the prediction of the degradation of an element of sandwich material is developed. It is not practical to study fibers, fiber-fiber interactions, ply behavior, ply interaction, epoxy response, epoxy-fiber-laminate interactions, adhesive behavior, honeycomb behavior, humidity, stress, temperature, ultraviolet and etc. cycling. Thus we develop a method of prediction based on the response of the material itself [18].

The second Piola-Kirchhoff stress tensor S is determined by the past history of the strain E ,

$$S = Q[E^t(s)] \quad s \in [0, \infty)$$

and $E^t(s) = E(t-s)$ for time t and place x . To determine the damage using the functional Q it is first necessary to perform a gedanken-experiment. Subject a sample of the sandwich to a prescribed strain history so that it experiences some permanent deformation. Next, load the specimen in such a manner as to force it back into its original geometric shape. To determine the damage we compare the response of this specimen to a geometrically identical virgin specimen. Let E_1 be a reference strain history applied at $t=0$. The corresponding stress will be given by

$$S_1 = Q[E_1^t]$$

for the worked specimen. For the virgin specimen we have

$$S_2 = Q[E_2^t]$$

Now we can define the damage tensor D by

$$D = S_2 - S_1 .$$

This tensor is a measure of the relative change in the material properties of the sandwich due to the pre-working. Since both specimens have identical shape and are identical in composition, fabrication, and every other respect we must attribute the difference in response (if $D \neq 0$) to damage in our specimen of sandwich material. We do not know what this damage is attributable to in a microstructural sense and it is not important to know this in order to predict the important engineering consequences we are interested in. The damage tensor D is represented by a functional. This reflects the fact that different strain histories will, in general, induce different states of damage. The details of the damage tensor and its properties are described in [18].

Concomitantly, one may make use of the response probability technique to predict damage due to blast on the entire structure. Recall, that we have described the use of the Gurney method to predict penetration into the structure and for more precise predictions of penetration various computer codes may be called upon. The response probability density function technique was developed to predict sonic boom damage [19]. This technique works well if the blast waves and the strength of shelter are distributed lognormally. The advantage in this method lies in its simplicity. We express the response R that we seek as the quotient of a sensitivity s and an excitation e ,

$$R = \frac{s}{e} .$$

Both s and e can be expressed as products of statistically independent factors

$$e = \pi e_i$$

$$s = \pi S_j$$

yielding the result that the logarithms of e and s are the sums of the logarithms of their respective factors.

$$\log_{10} e = \sum \log_{10} e_i$$

$$\log_{10} s = \sum \log_{10} s_i .$$

Now we sample each of the factors and take the log of each reading to verify that the distribution of the logs is normal. Deterministic factors have delta functions as probability density functions and do not influence the shape of the combined probability density function.

A mean and variance for each distribution of the log of a factor is computed. The mean of the log of the response is computed as the difference of the sensitivity factor log means minus the excitation log means,

$$E(\log_{10}R) = E[\log_{10}(s/e)]$$

$$E(\log_{10}R) = \sum E(\log_{10}s_j) - \sum E(\log_{10}e_i)$$

$$\text{Now } \text{var}(\log_{10}R) = \sum \text{var}(\log_{10}e_i) + \sum \text{var}(\log_{10}s_j)$$

From a standard table we find the probability for the normal probability density function of $\log_{10}R$

$$Z = \frac{E(\log_{10}R)}{[\text{var}(\log_{10}R)]^{1/2}}$$

In the case of our shelter R is the strain (motion), s is characteristic of the material's mechanical properties and e is the imposed stress.

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APPENDIX I

"I do not know that I have anything to say on the subjects more specifically discussed in this report, but I hope I shall not do violence to the spirit of your kind invitation or too much presume on your patience if I shall say a few words on that general subject which you discussed with great clearness....."To be more readily understood I shall use your notation and terminology, and consider the most simple case possible."

Letter from J. Williard Gibbs to Oliver J. Lodge
January 8, 1887

A tactical shelter is a rectangular parallelepiped of dimensions 8x8x20 ft or 8x8x13 ft that is capable of efficient transport by helicopter, rail, ship or truck without incurring any structural degradation. The objective of this study is to take the basic shelter as defined above and design into it a significant amount of blast and penetration resistance. To accomplish this objective a number of different aspects of the shelter and its environments must be studied:

I. Typical Nuclear Threat: We should define the typical blast and projectile threat that a shelter deployed in a tactical situation is most likely to experience. For a nuclear blast, the maximum survivable overpressure (peak pressure) is generally assumed to be 7.25 psi. This is not due to any inherent structural limitations, but is a consequence of the fact that at pressures somewhat higher than 7.25 psi, the shelter will overturn, be pulled loose from its anchoring cables, be blown along the ground by the blast. Thus the higher overpressures present a problem that cannot be solved by a light-weight structure. The reasonability of the 7.25 psi figure as an upper bound is clear. Thus our design objective for blast is established.

II. Typical Non-Nuclear Threat: Let us begin by looking at weapons that can supply overpressures in the neighborhood of 7 psi overpressures. These threats include G.P. bombs, artillery, and rockets. However, even a cursory study of these weapons will show that if they explode close enough to a target (shelter) to deliver peak overpressure of 7 psi, they will easily destroy the shelter by penetration of large amounts of shrapnel. Thus the non-nuclear threat is a ballistic one and to meet it the shelter must be able to resist penetration. For tactical shelter purposes I can define the typical shrapnel threat as a 40 gram fragment impacting the shelter with a velocity of 600 meters/second.

III. Small Arms Threat: The weight of a shelter capable of withstanding small arms fire of, say, 7.62mm ball rounds would be too heavy to effectively be air-transportable. Thus a shelter designed to resist small arms fire would cease to be a tactical shelter, but would be a structure with walls of the same order of magnitude as an armored personnel carrier. Therefore, it is recommended that tactical shelters be moved out of areas where it is subjected to small arms fire, or that revetments be erected around the shelter, or that the shelter be placed in a depression.

Now a typical threat has been defined: 7.25 psi Peak Pressure of the Applied Pulse. A 40 gram Fragment with Impact Velocity of 600 Meters/Second.

It is proposed that these two criteria be added to the standard shelter design criteria, and that all future tactical shelters meet these criteria.

Moreover, taking typical threats into consideration it is recommended that all six faces of the shelter meet these criteria. Now is the proper time to bring up precisely what is meant by saying "the tactical shelter meets the 7.5 psi and 40gm at 600 m/sec criteria."

Let us begin with the latter. For a shelter (panel) to meet the 40gm 600 m/sec criterion, a projectile with those characteristics, if it penetrates the panel, must have zero velocity upon entering the shelter.

For a shelter to meet the 7.25 psi criterion it must be capable of meeting all the requirements for certification of a new shelter including:

- a. Nine mile per hour railroad humping test.
- b. Static loading (75 lb/ft²).
- c. Fording (no water entry).
- d. Rain (no water entry).
- e. DUST (no dust entry).
- f. Thermal insulation including low temperature (-65°F), high temperature (120°F) plus a solar heating (BTU) load.
- g. Corrosion resistance (salt fog).

- h. Blackout capability.
- i. Fungus resistance.
- j. RFI, EMI, and EMP protection.
- k. Helicopter transport.
- l. Stacking test (of shelters), etc.

The reason for this definition is that in experiencing the 7.25 psi blast the shelter will undoubtedly exhibit some permanent deformation. This can be tolerated if the shelter is able to perform its function. The reason all the tests should be performed is that there are hundreds of uses for tactical shelters and it is not practical to qualify each one at 7.25 psi. Thus we have assumed that if the shelter meets the design criteria before and after the blast, it can perform its function after the blast.

Among the uses of tactical shelters are: ILS systems, artillery control, antiaircraft systems, radar systems, telephone units, communications systems, helicopter transmission repair facilities, machine shops, photographic development facilities, latrines, CBW shelters, data reduction facility, drone control, operating room, intensive care unit, power station, weather station, and meeting room.

The demand for tactical shelters in the coming years will doubtless increase significantly due to the changing international conditions, which are now beginning to become clear and the type of conflict we are likely to encounter in the future. To begin with, the loss in the number of overseas bases and the degradation (by some foreign control) of the mission of others means that we are no longer as close as we once were to the scenes of prospective military confrontations. Thus, supplies, personnel and material will have to be brought over increasingly larger distances. In addition the required response time to threats has been steadily decreasing. Thus the modern scene is generally one in which there are a few well stocked bases far away from many areas of potential threat and the time required for an effective threat response is in the neighborhood of 24 hours. These problems have been somewhat counter balanced by some efficacious developments in cargo aircraft. They have become faster with greater cargo capacity and the cost of shipping a ton of cargo has concomitantly dropped to a relatively low level. At this point the capability for quick long range response to long distance threats exists. Thus the need for tactical shelter systems is obvious. There is not sufficient time or manpower to dump equipment

at a tactical site and have it set up and put into an operable configuration. The equipment must be preconfigured and in operating order immediately upon delivery. Moreover, the equipment and its operators must be protected from the environmental hazards it will encounter. In addition, the vagaries of warfare dictate that this equipment be mobile to the extent that it can be almost instantaneously moved by truck or helicopter to a new site.

It is clear that shelters of the electronic type, radars, missile control, artillery control, communications, etc. will be high priority targets on an aggressor's list. However, given the many uses of the tactical shelter, and the inability, in some cases, to distinguish their functions from their external appearance, all shelters in tactical areas should have the penetration protection specified above.

There are three basic types of shelter construction:

I. Aluminum faced rigid foam with aluminum reinforcing beams.

II. Aluminum faced honeycomb (resin impregnated paper or nomex)

III. Aluminum faced plywood with rigid foam core.

The aluminum faces are typically 0.8mm thick and the foam is approximately 5cm thick. Typically, the foam shelter is reinforced with 3in x 3in aluminum hat sections. The honeycomb shelters have either kraft paper or nomex cores with cell sizes from 0.25 in to 0.40 in with densities of 3.0 to 5.0 lb/ft².

It has been known for some time that the standard shelter would not survive the effects of a moderate blast environment. In the 500 ton TNT Dial Pack explosion in July 1970 with S-250, S-335 and S-390 shelters it was found that empty shelters did not survive, but shelters with equipment racks did. The next explosive event (1972) called Mixed Company used S-280 shelters hardened by the addition of aluminum sheet and showed that shelters without hardening or racks failed catastrophically while the aluminum sheet strengthened shelters survived.

The conclusion of the Mixed Company test was that the S-280 shelter must be structurally modified to survive a 7.25 psi blast. In the 1976 Dice Throw event two retrofitted S-280 shelters, a paper honeycomb S-280, a shelter in a revetment, a shelter on a truck in a ditch and an S-280 on a truck (for overturning data) were tested.

The retrofitted (hardened) shelters had bonded to them aluminum honeycomb kevlar faced panels as shown in Figure 3. The kevlar panels were formed of nine layers of fiber bonded with epoxy. The kevlar provided bending stiffness to resist the blast, thermal radiation protection and fragment protection. This retrofit has a weight of 363 kg [1].

Without going into detail it has been determined that the 7.25 psi peak overpressure is survivable by a tactical shelter with a retrofit, and it is possible to build this survivability into the next generation of tactical shelters.

It was determined that expandable shelters will not even survive blast at the 3.0 psi level. Therefore we do not consider expandables in this report, because its construction is inconsistent with blast protection.

The structural analysis of an S-280 shelter subjected to a 5 and 7.25 psi overpressure was performed by the Navy Civil Engineering Laboratory at Port Hueneme CA using the SAP IV code on a quarter panel (used because of symmetry considerations). The S-280 foam and beam standard shelter was analyzed and the standard S-280 shelter was analyzed and the standard S-280 retrofitted with aluminum honeycomb sandwich was similarly analyzed as shown in Figure 4. The bases for the calculations are presented below in the appendix [1].

Another important point relative to Air Force shelters [2] is that tie down cables have a negligible effect on the shelter response except locally at the attachment points. There is in existence a computer program [3] that will predict the overturning of a shelter. According to preliminary calculations; an 8x8x13 ft shelter with tie down cables will overturn at the 10 psi overpressure level.

APPENDIX II

a. It is possible to design a blast and penetration resistant tactical shelter with small penalties for weight and cost, but with the advantage of having a structure better able to meet many of the other requirements for a tactical shelter.

b. The use of a single sheet high strength panel must be carefully looked into. This panel of, say, boron-graphite fiber reinforced material would have all the necessary strength properties. Equipment could be mounted on the wall itself by means of aircraft adhesives. In fact, if a 32 ft single sheet of the material could be made it could be bent into shape, necessitating the use of three fewer joints. This design has clear advantages, the major one being simplicity: no delamination problems, none of the moisture, fungus or strength problems. However, there will be a thermal problem. The insulation abilities of a single sheet is not as effective as a composite. Therefore an add-on kit of insulation (to be placed on the outside) should be available for use when the situation warrants it.

c. The use of a single sheet of high strength material bonded to a kevlar fiber material should be looked into. Typically, the metal would be the inside layer and the kevlar the outside layer. The kevlar would provide thermal insulation and significant penetration resistance.

d. A single sheet kevlar panel is also a possibility for tactical shelter use. Typically, this panel would have a corrugated or a ribbed construction to increase its stiffness.

e. The use of kevlar in sandwich construction must be looked into with some intensity. The use of kevlar as one or both panels in a honeycomb construction is probably one of the most practical concepts for a tactical shelter panel. We could have two faces of kevlar with an aluminum honeycomb core. One face of aluminum and one face of kevlar with a paper or nomex core. One could also have aluminum sheet glued to kevlar sheet for each face of a sandwich construction. The use of kevlar in conjunction with polycarbonate foam instead of aluminum in the configurations described above should also be investigated, as should the same configurations for kevlar-fiberglass combinations.

f. The use of a foam filled sandwich should not be abandoned. One should look into kevlar reinforced rigid foams and the commercially available glass reinforced polyurethane foam.

In addition there are off-the-shelf syntactic foams with very desirable properties for shelter use. These foams should be configured with many (kevlar, aluminum, polycarbonate, fiber reinforced composites, fiberglass) facing materials for an appropriate evaluation.

g. Another concept that must be carefully studied is that of the add-on kit for blast and penetration resistance. Even though the use of an add-on kit is contrary to the principles of mobility, rapid deployment, and low cost, the concept is useful and the data gathered from it would be valuable in any trade-off analysis.

h. The frame and connections to it should be designed to dissipate as much energy as possible and maintain the structural integrity of the panels.

APPENDIX REFERENCES

1. CRAWFORD, J.E., et al, Summary of Results for the Stress Analysis of the S-280 Shelter and the Proposed Strengthened S-280 Shelter, TM No. M-51-76-03, Civil Engineering Laboratory, NCBC, Port Hueneme, CA, 1 Jun 1976.
2. CULLIGEROS, J.M., and J.P. WALSH, Finite Element Analysis of the Blast Response of a Complete Shelter System and Effects of Equipment Rack Modifications, BRL Contract Report No. 324, December 1976.
3. HOBBS, N.P., et al, TRUCK-A Digital Computer Program for Calculating the Response of Army Vehicles to Blast Waves, Kaman Avidyne Report No KA TR-136, Burlington, MA, March 1977.

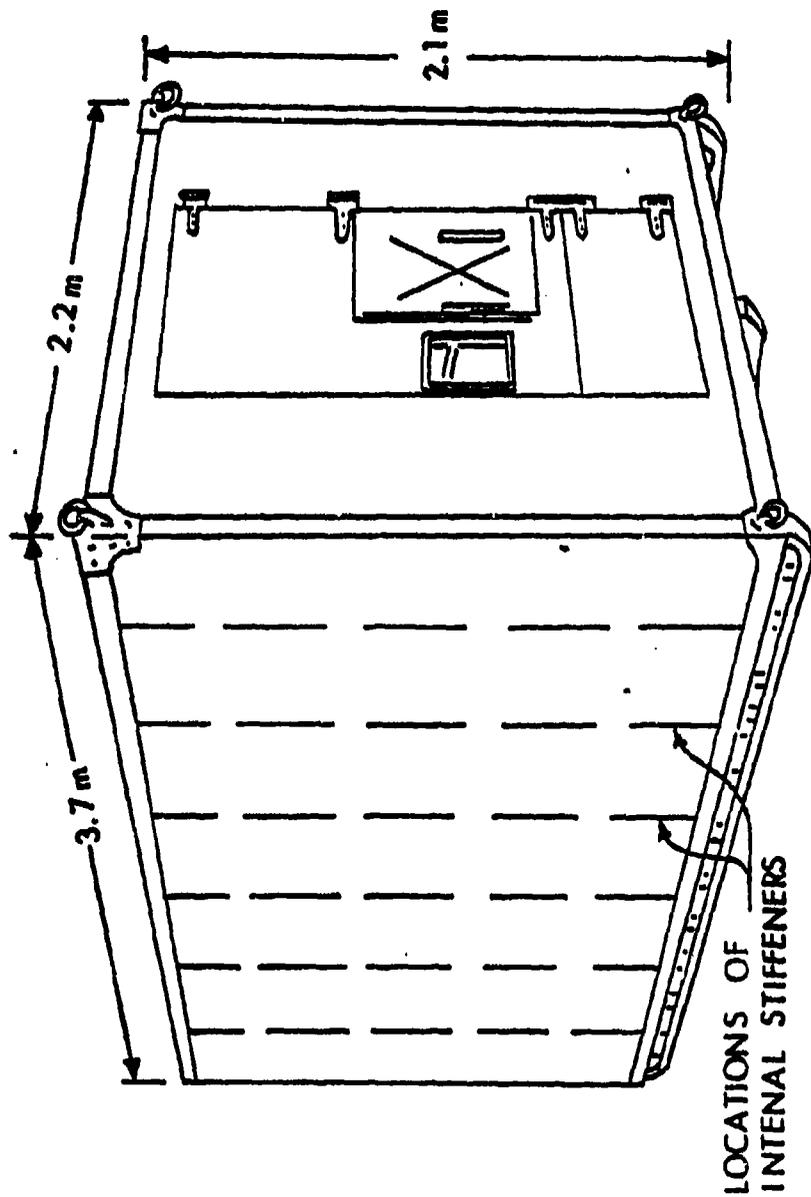


Figure 1. Schematic of S-280 Shelter

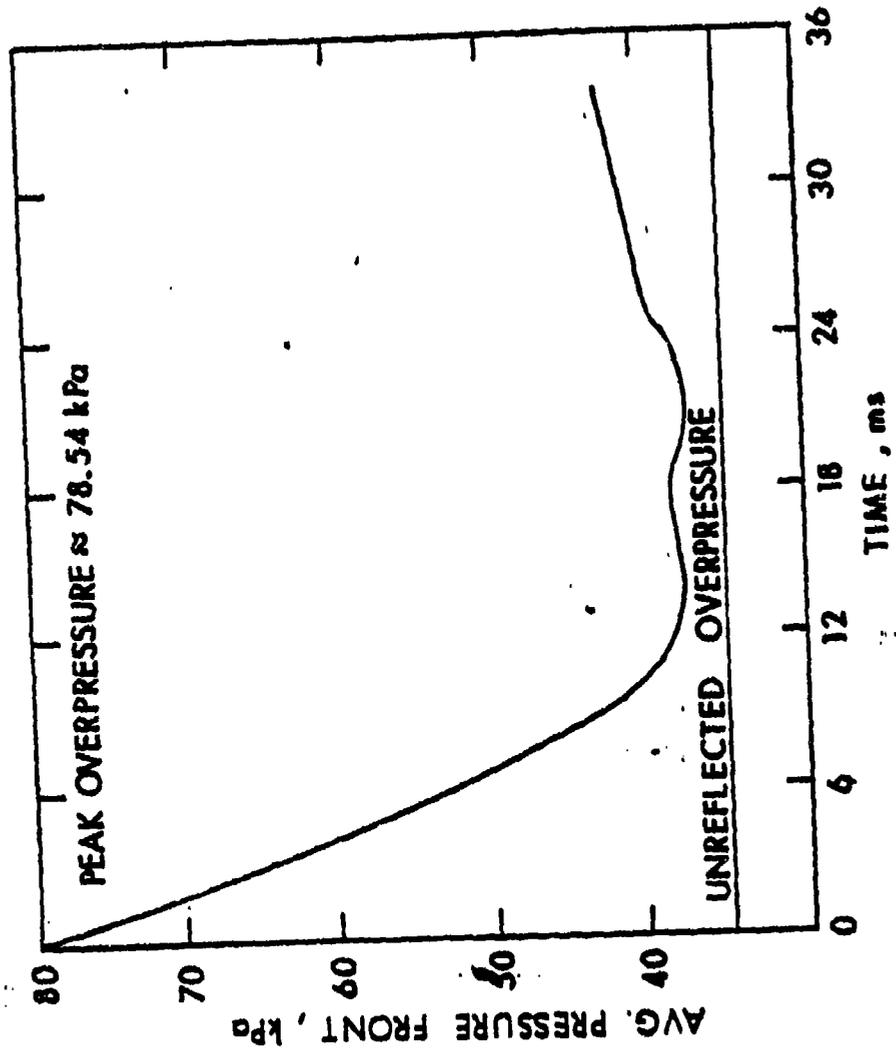


Figure 2. Typical Pressure - time history

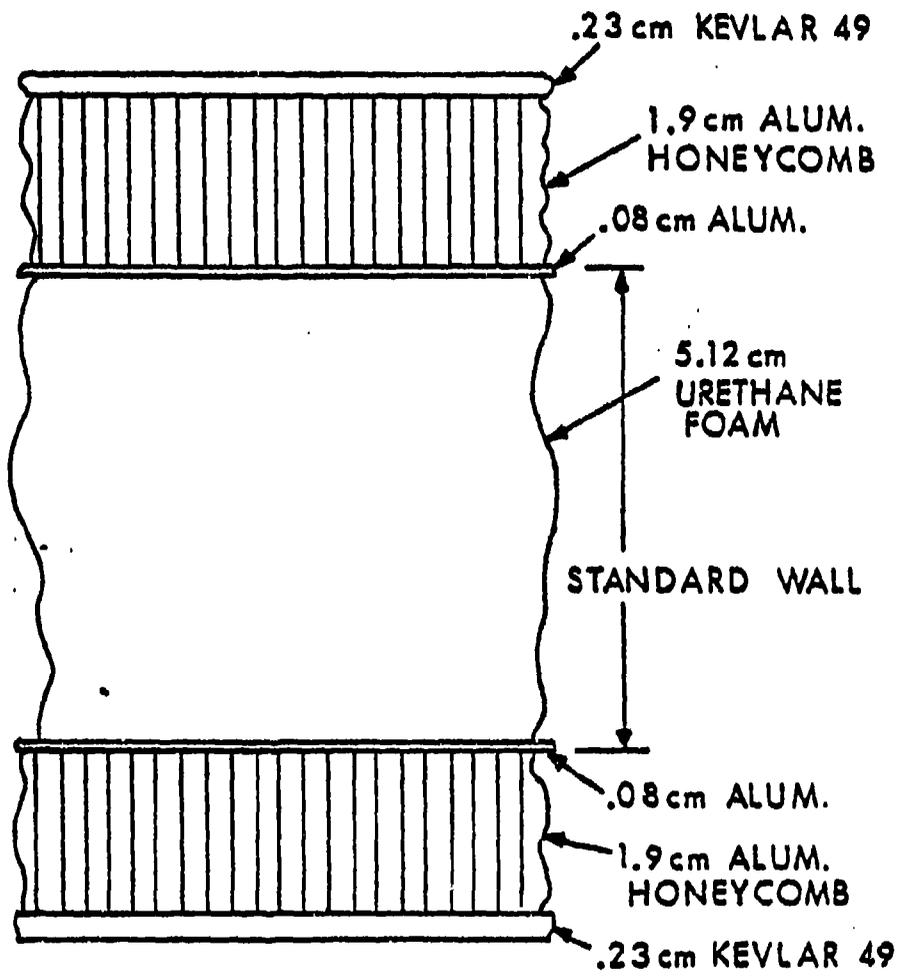
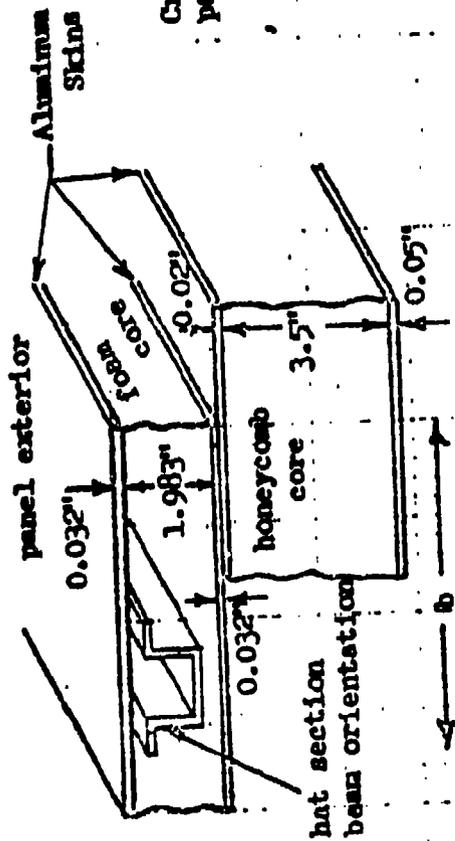
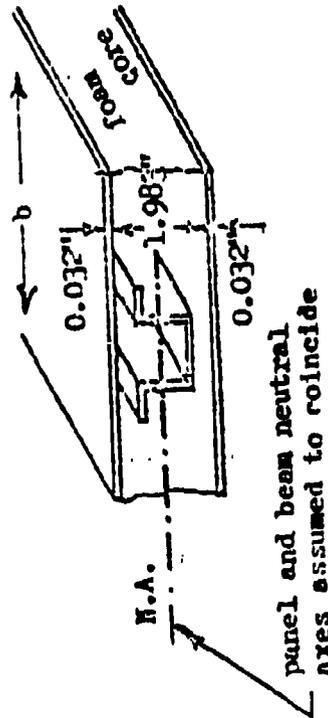


Figure 3. Hardened Wall

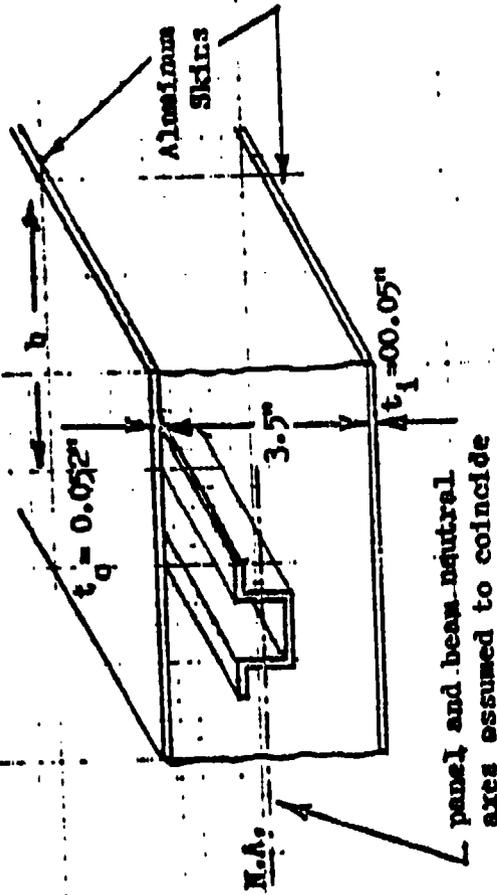


(a) Cross-section of Modified S-280 Shelter



(b) Cross-section of S-280 (Al/Foam) Shelter
as analyzed

Cross-section of Honeycomb panel to be added



(c) Cross-section of Modified S-280 (Al/Foam/Honeycomb)
as analyzed

Figure 4 - Cross-sectional Diagrams of S-280 Shelter Model Panels

Bending stress may be computed from the bending moment.

$$\sigma^b = \frac{M c}{I}$$

The in-plane (membrane) stress may be computed from the in-plane equivalent stress,

$$\sigma^m = \sigma^e \frac{t_e}{t_{Al}}$$

Aluminum/Foam Panel

$$c_{max} = 0.99 \text{ in.}$$

$$I = 0.065 b \text{ in.}^4$$

$$t_e = 3.49'' \quad t_{Al} = 0.064''$$

Therefore,

$$\sigma^b = 15.23 M \text{ nsi}$$

and,

$$\sigma^m = 54.53 \sigma^e \text{ nsi}$$

Aluminum/Foam/Honeycomb Panel

$$c_{max} = 1.8 \text{ in.}$$

$$I = 0.315 b$$

$$t_e = 6.09'' \quad t_{Al} = 0.101''$$

Therefore,

$$\sigma^b = 5.71 M \text{ nsi}$$

and,

$$\sigma^m = 60.27 \sigma^e \text{ nsi}$$

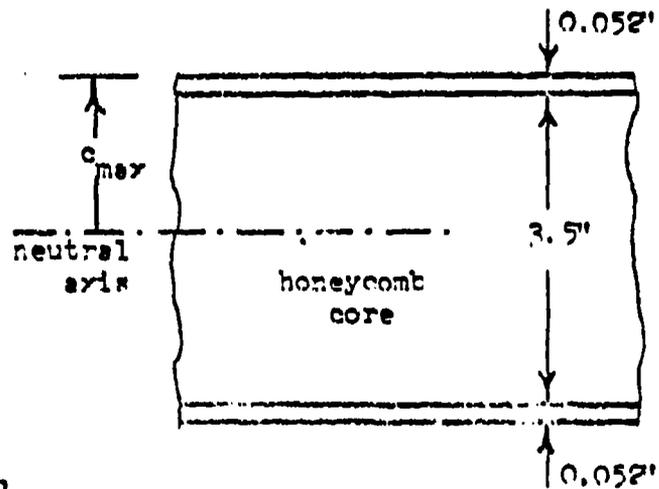
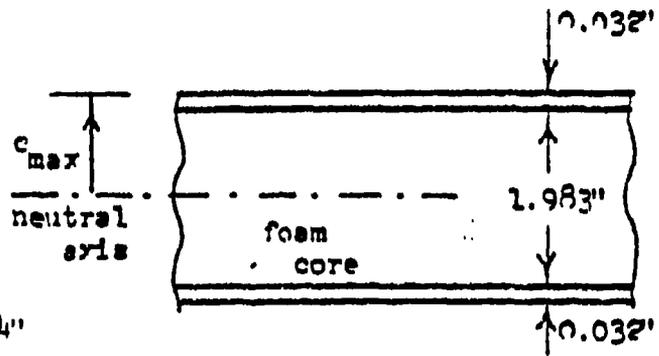


Figure 5 - Basis for Panel Stress Calculations

Table I. Dice Throw Design Requirements and Restraints

REQUIREMENTS

Yield - 36 kilo Metric Tons (40 KT)

Overpressure - 50.4 kPa

Thermal Radiation - 64 cal/cm²

Fragments - 0.3 to 3.9 g

RESTRAINTS

Additional Mass - 318 kg

Additional Wall Thickness, External - 5 cm

Decrease in Aisle Space - 30 cm

Table II: Hardened Wall Material Properties

<u>ALUMINUM FACES</u>	<u>URETHANE FOAM CORE</u>	<u>ALUMINUM HONEYCOMB</u>	<u>KEVLAR PANELS</u>
6061-T6 Alloy	Density = 32 & 64 kg/m ³	Density = 130 kg/m ³	KEVLAR 49 cloth
Modulus of Elasticity = 73 GPa	Shear Modulus = 1.4 & 2.8 MPa	Cell Size = 3.2 mm	Area Density = 0.23 kg/m ²
Yield Stress = 276 MPa		Foil = 0.051 mm	Style = Du Pont 328
		Thickness = 19 mm	Plain Weave
		Type: Hexcel 5056 CR III	Epoxy Resin: Hexcel F-185

BOND MATERIAL

Hexcel HP-302 - 28.5 MPa lap shear strength
 Hexcel HP-326 - 22.4 MPa lap shear strength
 Hexcel HP-347 (KEVLAR to Honeycomb)
 40 MPa lap shear strength

SHOCK ISOLATORS

Barry Cupmounts
 UC-2060-T6

TABLE III.S-280 Shelter Panel Properties

	Al/Foam Panel			Al/Foam/Honeycomb Panel		
	Al Skin	Foam	Equivalent	Al Skin	Honeycomb	Equivalent
t (thickness, in.)	0.032	1.983	3.49	$t_0 = 0.052$ $t_1 = 0.050$	3.5	6.09
E (Young's Modulus, psi.)	1.0×10^7	0	183000	1.0×10^7	0	168000
G (Shear Modulus, psi.)	3.76×10^6	200	69000	3.76×10^6	25600	77700
ν (Poisson's Ratio)	0.33	0	0.33	0.33	0	0.33
w (Weight Density, lb/in ³)	0.0972	0.00116	0.00244	0.0972	0.00301	0.00425
I (Moment of Inertia, in ⁴)	0.065 b	0	0.065 b	0.315 b	0	0.315 b

Table 4 Results for Dynamic Response of Complete S-280 Shelter

Peak pressure of applied pulse (psi)	Peak Displacement δ_{max} (in.)	Beam Element 4 Axial Stress		Plate Stresses due to Membrane Forces and Bending Moments (psi)										P O max	
		F	σ_F	M	σ_M	σ_z^c	σ_z^m	σ_x^c	σ_x^m	σ_{xz}^c	σ_{xz}^m	σ_x^c	σ_x^m		σ_{xz}^c
5	5.14	1486	2908	93000	35	2109	59	3556	2	121	69459	13556	1771	114000	
		21340	90586	4275	67350	7014	110000	105	1650	43825	926	44000			
5	1.17	1328	2599	22000	25	1507	47	2833	2	121	26231	43825	926	44000	
		4476	19000	4330	24724	7174	40992	141	805	4472	11005	21000			
7.25	1.74	2051	4013	32000	43	2592	24	1446	42	2531	13795	4472	21000		
		6668	28305	1962	11203	530	3026	1484	8474	65859	1409	66000			
5	1.55	1380	2700	24000	40	2411	72	4339	3	181	39903	65859	1409	66000	
		5082	21573	6566	37492	10774	61520	215	1228	20748	15962	31000			
5	1.55	1380	2700	24000	25	1507	46	2772	2	121	7468	44918	4900	46000	
		5082	21573	1044	5961	7381	42146	837	4779	13546	4066	10243	20000		
5	1.55	1380	2700	24000	40	2411	72	4339	3	181	39903	65859	1409	66000	
		5082	21573	1950	11135	522	2981	1340	7651	20748	15962	31000			

1. Al/foam S-280 Model with Imposed rotational symmetry
2. Al/foam/honeycomb S-280 Model with imposed rotational symmetry
3. Case 2 with 7.25 psi pressure pulse
4. Al/foam/honeycomb S-280 Model without rotational symmetry

Table 4. (cont.) Results for Dynamic Response of Complete S-280 Shelter

e	Peak pressure of applied pulse (psi)	Peak Displacement δ_{max} (in.)	Beam Elements 4 Axial Stress		Plate Stresses due to Membrane Forces and Bending Moments (psi)														
			F		Element No.	σ_z^m		σ_x^c		σ_x^m		σ_z^c		σ_z^m		σ_x	σ_z	σ_{xz}	P
			N	M		H_z	b_{σ_z}	H_x	b_{σ_x}	M_{xz}	$c_{\sigma_{xz}}$	b_{σ_z}	$c_{\sigma_{xz}}$	b_{σ_x}	$c_{\sigma_{xz}}$				
5	21000	1.33	939	1837	3	21	1266	39	2351	1	60	3860	39026	39000					
			4427	18792	126	31	1868	12	723	36	2170	36	6423	36675	676	3920	39000		
7.25	36000	2.31	2002	3917	3	40	2411	73	4400	3	181	7183	67330	68000					
			7550	32049	126	63	3797	31	1868	63	3797	63	11021	62930	1258	7364	68000		
7.25	31000	1.98	1377	2694	3	33	1989	63	3797	2	121	5773	58462	59000					
			6572	27897	126	45	2712	21	1266	53	3194	53	9570	54645	1011	5349	12267	25000	

δ_{max} - peak deflection (in), node 4, Y-direction
 F - Beam axial force (lb)
 M - out of plane beam bending moment (in-lb)
 $\sigma = \sigma^c + \sigma^m$
 σ_x^c - computed membrane equivalent stresses
 σ_x^m - computed bending moments
 σ_z^c - computed membrane equivalent stresses
 σ_z^m - computed bending moments
 σ_{xz}^c - computed membrane equivalent stresses
 σ_{xz}^m - computed bending moments
 σ_p - maximum principal stress

5. Case 4 with 10% of critical damping
6. Case 4 with 7.25 psi pressure pulse
7. Case 4 with 7.25 psi pressure pulse and 10% of critical damping

Appendix A CALCULATION OF EQUIVALENT PANEL PROPERTIES

1. For bending and membrane stiffness of Al/Foam

$$AE: \quad \underbrace{bt_e E_e}_{\text{equivalent}} = \underbrace{bt_f E_f}_{\text{foam}} + \underbrace{bt_a E_a}_{\text{aluminum}} \quad (1)$$

$$EI: \quad E_e \frac{bt_e^3}{12} = E_f I_f + E_a I_a \quad (2)$$

since $E_f = 0$, (1) and (2) for a unit thickness ($b=1$) become

$$t_e E_e = 0.064 (10^7) = 6.4 \times 10^5 \quad (3)$$

$$E_e t_e^3 = 12 (10^7) (0.065) = 7.8 \times 10^6 \quad (4)$$

$$\text{where } I_a = \frac{b}{12} ((2.047)^3 - (1.983)^3)$$

$$I_a = 0.065b$$

then from (3) and (4)

$$t_e = 3.49 \text{ inches}$$

$$E_e = 1.8 \times 10^5 \text{ psi}$$

2. For shear stiffness of Al/Foam

$$t_e G_e = t_f G_f + t_a G_a$$

$$G_e = \frac{1.983 (200) + 0.064 (3.76 \times 10^6)}{3.49} = 69,000 \text{ psi}$$

3. For mass density of Al/Foam

$$\rho_e = \frac{w_f t_f + w_a t_a}{t_e} \left[\frac{1}{386.4} \right]$$

$$= \frac{0.00116 (1.983) + 0.064 (.0972)}{3.49 (386.4)}$$

$$\rho_e = 6.32 \times 10^{-6} \text{ Slugs/in}^3$$

$$w_e = 0.00244 \text{ lbs/in}^3 \text{ (wt density)}$$

4. For bending and membrane stiffness of Al/Foam/Honeycomb

(Note: Figure 4C defines the cross section used for stiffness calculation)

$$AE: \underbrace{bt_e E_e}_{\text{equivalent}} = \underbrace{bt_h E_h}_{\text{honeycomb}} + \underbrace{bt_a E_a}_{\text{aluminum}} \quad (5)$$

$$IE: \frac{E_e bt_e^3}{12} = E_h I_h + E_a I_a \quad (6)$$

since $E_h = 0$, (5) and (6) become

$$t_e E_e = 0.102 (10^7) = 1.02 \times 10^6 \quad (7)$$

$$E_e t_e^3 = 12 (10^7) (0.315) = 3.78 \times 10^7 \quad (8)$$

$$\text{where } I_a = \frac{b}{12} ((3.6)^3 - (3.5)^3)$$

$$I_a = 0.315b$$

then from (7) and (8)

$$t_e = 6.09 \text{ inches}$$

$$E_e = 168,000 \text{ psi}$$

5. For shear stiffness of Al/Foam/Honeycomb

$$t_e G_e = t_h G_h + t_a G_a$$

$$G_e = \frac{3.5 (25,600) + 0.102 (3,760,000)}{6.09}$$

$$G_e = 77,700 \text{ psi}$$

6. For mass density of Al/Foam/Honeycomb

(Note: Figure 4a defines the cross section used for mass calculation)

$$\rho_e = \frac{w_h t_h + w_a t + w_f t_f}{t_e} \left(\frac{1}{386.4} \right) = \frac{0.00301(3.5) + 0.0972(0.134) + 0.00}{6.09 (386.4)}$$

$$\rho_e = 1.10 \times 10^{-5} \text{ Slugs/in}^3$$

$$w_a = 0.00425 \text{ lbs/in}^3 \text{ (wt. density)}$$

Appendix B CLASSICAL SOLUTIONS

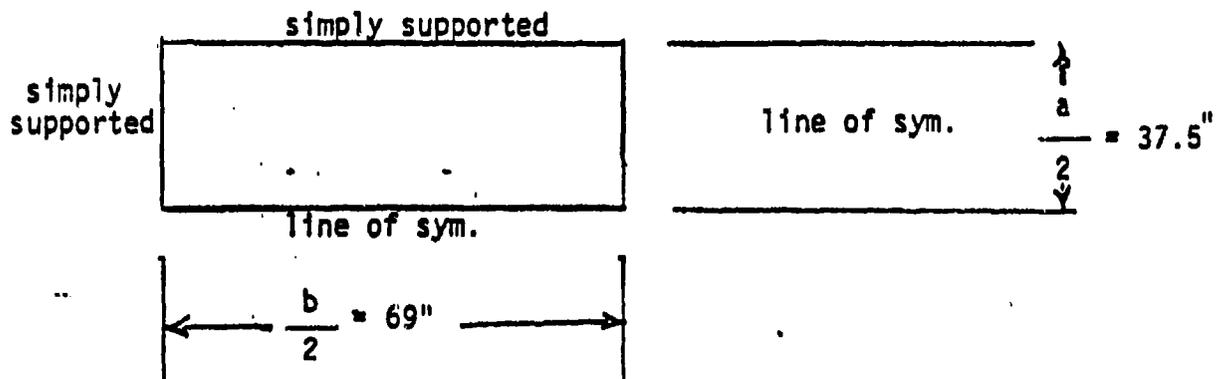
From Timoshenko, Theory of Plates and Shells, p. 129 and Table 5 on p. 133,

for a simply supported rectangular plate $\nu = 0.3$

$$w_{\max} = \frac{\alpha q a^4}{E h^3}$$

our finite element plate analysis uses a $\nu = 0.33$
from pg. 129

$$w_{\max} = \frac{\alpha q a^4}{E h^3} \left(\frac{1-\nu^2}{0.91} \right) \quad (1)$$



for the Al/foam and the Al/foam/honeycomb plate the aspect ratio is given by

$$\frac{b}{a} = \frac{69}{37.5} = 1.84$$

from Table 5

$$\left. \begin{array}{l} \alpha \\ \frac{b}{a} = 1.8 \end{array} \right\} = 0.1017$$

$$\left. \begin{array}{l} \alpha \\ \frac{b}{a} = 1.9 \end{array} \right\} = 0.1064$$

the curve for α is approximately linear in the range $1.8 < \frac{b}{a} < 1.9$

So to find a value of α at $\frac{b}{a} = 1.84$ we will linearly interpolate between the given points

Therefore,

$$\alpha = 0.1036$$

For,

$$q = 1 \text{ psi}$$

$$\nu = 0.33$$

$$a = 75 \text{ in.}$$

$$E_{\text{Al/foam}} = 1.8337 \times 10^5 \text{ psi}$$

$$E_{\text{Al/foam/honeycomb}} = 1.6755 \times 10^5 \text{ psi}$$

$$h_{\text{Al/foam}} = 3.49 \text{ in.}$$

$$h_{\text{Al/foam/honeycomb}} = 6.0876 \text{ in.}$$

we can substitute into equation 1,

$$w_{\text{max Al/foam}} = \frac{(0.1036)(1)(75)^4}{(1.83 \times 10^5)(3.49)^3} \cdot \left[\frac{1 - (0.33)^2}{0.91} \right]$$

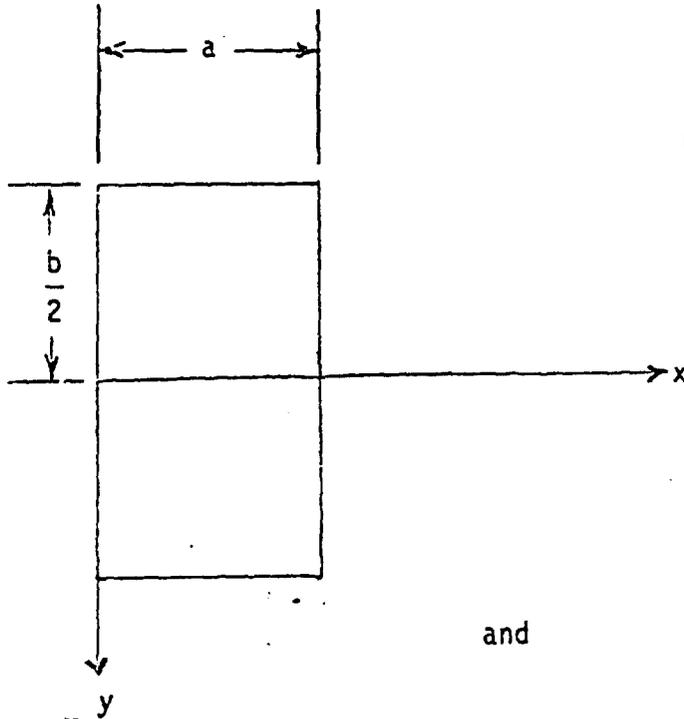
so, for the Al/foam plate,

$$w_{\text{max}} = 0.412 \text{ in.}$$

Likewise for the Al/foam/honeycomb plate,

$$w_{\text{max}} = 0.025 \text{ in.}$$

Also from Timoshenko; p. 133, we can calculate the maximum bending moments used to compute the in-plane stresses



$$\beta_1 = 0.0476$$

$$\beta = 0.0963$$

$$M_{x_{max}} = \beta q a^2$$

$$M_{y_{max}} = \beta_1 q a^2$$

and $q = 1 \text{ psi}$
 $a = 70''$

For both the
 Al/foam and
 Al/foam.honeycomb
 plate

$$M_{x_{max}} = (0.0963) (1) (70)^2$$

$$M_{x_{max}} = 472 \text{ in-lb}$$

$$M_{y_{max}} = (0.0476) (1) (70)^2$$

$$M_{y_{max}} = 233 \text{ in-lb}$$