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FOAM WALL SYSTEM FOR EXPEDIENT FACILITIES

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JULY 1982

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This research has investigated the development of material systems, construction specifications, and construction criteria for using foam wall systems to improve the military's readiness and return it to full functional capability following war or other catastrophic damage. The foam wall systems would be used to construct expedient facilities where there are no facilities or where the facilities are inadequate. They would also be used to repair or replace damaged base facilities.

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It was found that wood-faced, polyurethane form-core sandwich panels provide the best and most economical system for expedient facilities. The foam-core sandwich panel systems are best for construction in remote locations, because they can be constructed on-site with available labor. The construction criteria and specifications developed as a result of this research are appropriate for efficient construction of expedient facilities.

PREFACE

This report documents work performed during the period March 1980 through March 1982 by the Materials Division (EM) of the U.S. Army Construction Engineering Research Laboratory (CERL). The work was performed under a series of single-year MIPR's which included MIPR S-80-22, MIPR N-81-16, and MIPR N-82-4 from the Air Force Engineering and Services Center (AFESC). Mr. Walter C. Buchholtz was the AFESC Project Officer, and Mr. Alvin Smith was the CERL Principal Investigator. The assistance of Messrs. Robert Muncy, Rob Eubanks, and Steve Sweeney of CERL is gratefully acknowledged.

Dr. Robert Quattrone is Chief of CERL-EM. COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

1. BACKGROUND

Efforts have been made in the past to develop add-on kits for upgrading military buildings that have been damaged or destroyed during an attack or catastrophic disaster; however, due to inherent design and material deficiencies, these efforts have been unsatisfactory in meeting time frame, weight, and mobility constraints. Similar attempts to provide new facilities for mobilization or relocation to very remote areas have suffered the same shortcomings; the designs considered have not provided optimum required performance and flexibility.

2. OBJECTIVE

The objective of this study was to develop material systems, construction specifications, and construction criteria for using foam wall systems to improve the military's readiness and return it to full functional capability following war or other catastrophic damage. Foam wall systems would be used to construct expedient facilities to house rapidly deployable air base support forces, supplies, and equipment where no facilities now exist (e.g., the Bare Base concept) or where sufficient facilities are not available (e.g., augmentation of existing forces). This foam wall system would also be used to repair or replace air base facilities damaged by war or disaster mitigation. Such repair or replacement is essential for recovering operational capabilities.

3. APPROACH

This two-year study encompassed: 1) identification of foam wall panel systems, 2) evaluation of the panel systems to meet building functional requirements and design of alternative foam wall systems, 3) preparation and testing of the most promising wall design, including an economic analysis, and 4) preparation of draft specifications and construction criteria.

Panel fabrication alternatives were extensively considered. It was necessary to provide some guidance that would allow both in-plant manufacture of panels with shipment to the use site or on-site production of panels.

4. SCOPE

This study was limited to wall elements; foundation and roof systems were considered only to the extent needed to account for wall-roof and wall-foundation interactions.

SECTION II

PRELIMINARY STUDIES

1. REVIEW OF PREVIOUS STUDIES

The use of foamed materials in wall systems was studied. Previous research done by the U.S. Army Construction Engineering Research Laboratory (CERL) had investigated the use of foam both as a single structural element (References 1,2,3) and combined with other materials to increase stiffness a provide insulation (References 4,5). Other research which dealt primarily with sandwich panel construction was also reviewed. In these studies, dense strong materials such as steel, aluminum, plywood, or plastic sheets were u as the face materials. Low-density materials, such as paper honeycomb, meta honeycomb, and various cellular (foamed) plastics were used as core materials. References 6 through 14 are representative of these studies.

2. MANUFACTURERS CONTACTED

Foam core sandwich panel manufacturers were contacted for information on their respective products. This investigation identified many different types of panel designs, which displayed a variety of core materials, facing materials, and combinations of the two. This directly provides prefabricated panel systems that will satisfy most building requirements. Most manufacturers have standard design structures and assembly methods that can meet the requirements of this study. Appendix A provides a representative list of panel/system suppliers. Users should seek detailed information directly from the manufacturers.

In contrast to commercially available panels, field fabrication of foam core wall panels permits more compact components to be shipped to the use site; panel fabrication and erection are then relatively fast and simple.

Research for the field-fabrication portion of this study considered standard, commercially available components and materials. These materials are identified by generic or trade name in this report.*

* Use of a trade name does not indicate approval or exclusive recommendation of the product cited, but rather is intended to be representative of products or materials of that general nature.

SECTION III

MATERIALS STUDIES

1. FOAMABLE RESINS

Most plastic (polymer) materials can be foamed by one or more methods. Some thermoplastics (which can be softened by adding heat) and most thermosets (converse of thermoplastics) are stable, foamed materials that can be produced conveniently. Both are appropriate for sandwich panel core materials. Only a few materials that are commercially available warranted consideration. The following sections discuss each type's advantages and disadvantages as they relate to this study.

a. Polyurethane

Polyurethane is available commercially as two-component liquid formulations in a variety of densities and characteristics. Preparing the foamed material requires mixing the two liquids in the proper proportions. The liquids react to form the polymer and at the same time generate heat; the heat typically volatilizes a "blowing agent" which is included in the proper amount in one or both of the liquids. The polymer is aggressively adhesive to most nonoily or nongreasy surfaces, and its bonds are strong and stable. Flame retardants may be included in the mixture to regulate the polymer's ease of ignition and/or restrict the rate of flame spread along the surface of the foam during a fire. Rigid polyurethane foams are thermoset materials. They are very appropriate for sandwich panel cores since they are self-adhesive, self-foaming, and self-curing when foamed in place between the panel faces. Slab stock polyurethane foam core panels can also be made by bonding facing materials to the foam core with an adhesive. This material has high strength per unit of weight and excellent thermal insulation properties.

b. Polystyrene

This plastic is available in two types of foam. The first is an extruded sheet foam made by forcing the molten polymer, which contains a blowing agent, through a die. The drop in pressure on the outlet side of the die causes the foaming agent to expand; the boards produced are cooled to below the softening temperature, while the dimensions of the board are regulated by long cooling dies. The second type is bead board, in which beads of the polystyrene are expanded individually and fused under pressure. Boards are then cut to size. To make foam panels, the boards are adhered to facing materials during a secondary operation.

A principal disadvantage of polystyrene is that it must be foamed by the manufacturer and must therefore be shipped as a high-volume, low-density material. However, it has many advantages. It is stable up to typical exposure temperatures (150°F [65°C]) and can be made flame-retardant by including additives. It has high strength per unit of weight. In addition, its thermal insulation properties are slightly more than half those of an equal density/thickness polyurethane foam.

c. Epoxy

Liquid epoxy resins are available that can produce foams comparable to polyurethanes on-site. They can also be made flame-retardant. Epoxies bond well to face materials, and their insulation properties are comparable to polyurethane foams. However, they are more than twice as expensive as polyurethane foam systems.

d. Phenolic

Phenolic foams, which are available as liquid systems, generally cost less than polyurethane foam systems. The foams produced are dimensionally stable; they may be foamed in place between facing materials or produced as slab stock to which facing materials may be bonded. The thermal insulation properties of phenolic foams are lower than those of polyurethane or polystyrene due to the open-cell nature of the phenolic foam. The phenolic foam also tends to be very brittle, especially at low densities. Preparation of the foam generally requires a post-cure at an elevated temperature. (The initial reactions are exothermic to reduce friability to a manageable level.) The phenolics are naturally fire-retardant, but, unless specifically formulated, tend to continue to burn by after-glow or punking. Unlike most other polymer foams, the phenolics produce very little smoke when they burn.

e. Urea-formaldehyde

This recently popular retrofit insulation foam is generated much like shaving lather; it has been used rather extensively within wall cavity spaces to insulate existing structures. This technique has caused numerous problems due to release of moisture and formaldehyde from the foam. This material is not appropriate for sandwich panels due to its very low mechanical properties and long-term shrinkage.

f. Summary

Of the commonly available foamable polymers, polyurethane foams give the best combination of needed physical properties, cost, and versatility of application. Only rigid polyurethane foam was considered further in this study.

2. FACING MATERIALS

Facing materials for sandwich panels used in structural applications are usually dense, strong materials, such as aluminum, steel, plywood, or reinforced plastic. The facing material bears most of the outer fiber burden during beam loading. The facings of a foam core sandwich panel may be considered analogous to the flanges of an I-beam.

a. Metal

Either flat or formed sheet metal (steel or aluminum) may be used as facing material. Thorough cleaning and/or a primer is required to achieve optimum bonding to a core material. The thickness of the facing material depends on specific design considerations, such as required load bearing, span, allowable deformation, etc. Metal facing materials are generally convenient, since they can be shipped in very compact stacks. They can also be prefinished with paints or other coatings. Metal facing materials are typically fire-resistant.

b. Wood

Plywood, particleboard, and structural flakeboard are excellent facing materials for polyurethane foam core sandwich panels. The grade selected should be exterior quality (including exterior glue or binder) and must be uniformly square and of acceptable dimensional tolerance to fit into molds. An appropriate paint finish is normally required to enhance moisture resistance. Polyurethane foam formed in place bonds to these materials with a bond strength that exceeds the tensile strength of the foam. Use of pressure-treated and flame-retardant wood sheet may be desirable for the applications of this study.

c. Reinforced plastic

Glass-reinforced plastic sheet materials are excellent, high-strength, lightweight skins for sandwich panels. They may be used in sheetform, like metal or wood, either for forming the foam in place or for bonding to foam slab stock. Another option is to fabricate a skin on slab stack foam by saturating a glass cloth or mat with resin on the slab stock surface. Weather-resistant and flame-retardant grades of glass-reinforced sheet material are available and should be used.

d. Miscellaneous

Gypsum wallboard, corrugated paper, foil, roofing felt, and many other facing materials are available for use in sandwich panel fabrication. Their use or non-use must consider the strength and stiffness required of the panel, handling weight, abuse resistance, and similar considerations. For example, gypsum wallboard is an excellent facing material for interior applications. However, it is very susceptible to handling damage and moisture exposure.

SECTION IV

SANDWICH PANEL DESIGN STUDIES

The performance of a sandwich panel depends mostly on the design and composite function of the constituent materials. It is essential that the various parts of the composite structure act in unison. The important structural considerations which affect design are: flexural performance, buckling resistance, impact resistance, and creep under load.

The first two can be precalculated easily, but conservative design factors should be used to protect against non-theoretical behavior. Impact resistance is qualitative, and both the need for impact resistance and the degree of resistance are subjective. Creep performance is a complex problem with sandwich composites, so design should be extra-conservative.

The following sections present the general design procedures used in this study. Much of this information is from Reference 15.

1. FLEXURAL PERFORMANCE

Table 1 lists the various modes of flexural failure.

The major factors governing the flexural performance of a composite panel are the maximum permissible facing stress (both compressive and tensile), core shear stress, and deflection (bending). Each factor will be discussed separately.

The introduction of plastics into the design of new structural systems for facilities requires development of a design logic rationale which is sensitive to the properties of plastics. Generally, plastic materials exhibit properties quite different from those of conventional structural materials such as steel and reinforced concrete. Fortunately, much of the conventional design rationale can be used directly for low-performance structural applications. This is not necessarily true for high-performance structures, however,

TABLE 1. TROUBLESHOOTING FLEXURAL FAILURE OF SANDWICH COMPOSITES.

(From W. E. Becker, U.S. Sandwich Panel Manufacturing/Marketing Guide, Technomic Publishing Co., 1968.)

Type of Failure	Description	Cause	Cure
Facing Failure	Facing fails in either tension (bottom facing or compression (top facing)	Facing is too weak to accept maximum fiber stress	Use stronger facing material or increase thickness
Core Compression	Facings bend locally causing skin depressions usually at load or reaction points	Local compresive failure in core	Use core with higher compresive modulus to reduce strains in core
Adhesion	Facings stripped clean of core material	1. Poor adhesion of core (foam-in-place) 2. Adhesive too weak in shear 3. Adhesive too brittle	1. Specify a primer coat 2. Check pouring procedure (foam-in-place) 3. Select more flexible adhesive
Core Shear 1. Cohesive	Usually in layers but not at facing/core interface	Non-homogeneous core, poor cell structure (pour-in-place)	Reinforce core near the facings. Reduce extent of foam shear during rise (foam-in-place)
2. Core Fissure	Vertical or horizontal	Core shear strength too low	Increase core strength or modify design to distribute the shear load
Excessive Deflection Under Load	Deflection exceeds design maximum (i.e., L/360)	1. The flexural stiffness of the facings is inadequate 2. The shear stiffness of the core is inadequate	1. Increase the facing thickness or use a material with a higher flexural modulus 2. Increase the core thickness or use a core material with a higher shear modulus

and more sophisticated techniques are required for incorporating variant material properties into the design rationale. The design of facilities such as foam wall structures is based on the assumption that all structural components can be designed using low-performance structural materials.

For purposes of design, a definition of design loads must be obtained. Unfortunately, information is not available to define the loads used for design of the foam wall facilities. With this in mind, a step-by-step example is presented to show the method of design. This method is an example for general use and is not specific for the present study.

A uniform pressure of 50 pounds/square foot is assumed on the exterior walls. This correlates with a 99 mph wind. That is,

$$P_w = C_p q \tag{1}$$

where P_w = wind pressure

C_p = pressure coefficient

q = dynamic pressure

Also,

$$q = 1/2 \, \rho \, V^2 \tag{2}$$

where ρ = mass density of air at given conditions

V = wind speed in feet/second.

Hence,

$$P_w = 1/2 C_p \quad V^2 \tag{3}$$

for a flat plate normal to the flow C_p = 2.0.

Also $\rho = 2.37 \times 10^{-3}$ slugs/cubic foot at 60°F and standard atmospheric conditions.

Thus,

$$50 \text{ pounds/square foot} = 1/2(2.0)\ (2.37 \times 10^{-3})V^2$$

where $V = 145.2$ feet/second

$= 99$ mph.

For roof corner uplift, a conservative value for the drag coefficient, C_p, of 5.0 was assumed. Subsequently,

$$P_w = 1/2(5.0)\ (2.37 \times 10^{-3})\ (145.2)^2$$

$$= 124.9 \text{ pounds/square foot}$$

This is the load assumed to be applied to the bottom side of the roof overhang.

The roof load is based on an assumed uniform pressure of 50 pounds/square foot, a moderately high snow load based upon a 50-year recurrence interval for the United States.

A safety factor of 2.0 has been used throughout. For convenience, combinations of the above loadings have not been considered in the design, since the likelihood of a high wind with a heavily snow-laden roof is assumed small. It has also been assumed that the environmental temperature lies in the range -50° to 150°F. The functional requirements for the facility will remain the same as those of the foam wall facility.

Behavior of the foam wall building will be similar to that of the current frame construction. The facility is composed of a roof, a foundation, and four exterior and two interior wall panels. The four exterior wall panels contain several window and door openings. Following are the design calculations for the walls.

A structural sandwich panel wall construction has been selected for the wall design. Its design requires consideration of three components: facings, cores, and core-to-facing bonding. Each component serves as a specific function: the facings carry all inplane loading, and the core-to-facing bond transfers load from the facings to the core. From a reliability standpoint, sandwich panel design forms a three-link chain; total sandwich panel integrity depends on preserving the integrity of each link.

The configuration of each component is important to the overall structural characteristics of the panel. Proper configuring of the components leads to the high stiffness-to-weight ratio desirable in structural systems for which structural component weight is a concern. In general, sandwich panels are configured as in Figure 1. The facings are usually of thin-sectioned, high-strength material. The core is generally a low-density material having a moderately high shear modulus. The core-to-facing bond is generally an adhesive capable of transferring shear between facing and core. The sandwich panel configurations considered below are based on this configuration.

Sandwich panel structures may include one or more panels of given dimension and may exhibit several modes of failure under load. The basic modes of

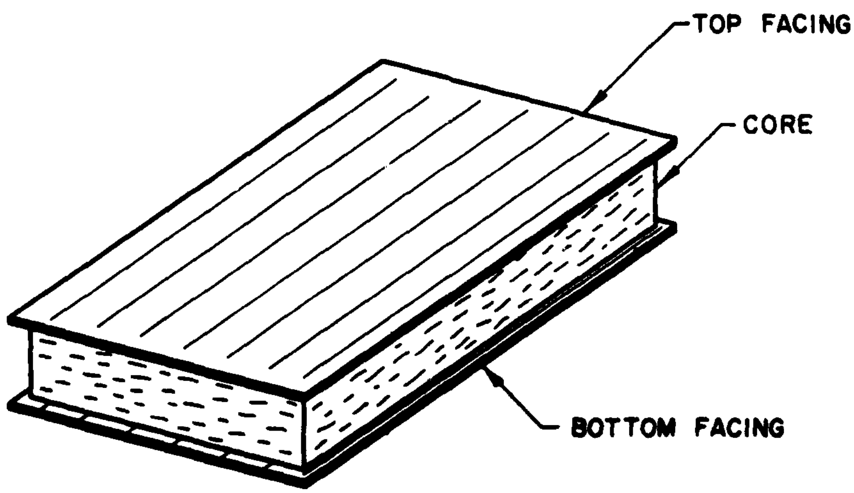


Figure 1. Sandwich Panel Configurations.

failure shown in Figure 2 will be considered in this design. General buckling of a sandwich panel results from compressive inplane force. This mode of failure is analogous to buckling of a wide flange section under an end compressive load. Shear crimping, which results from inplane load instability, occurs in sandwich panels with a low core shear strength. Dimpling of faces is a common mode of failure for sandwich panels in which the core is porous, as in the case of a honeycomb core. Wrinkling of faces, due to inadequate bond between core and facing or crushing of the core resulting from inplane load of the panel, must also be considered as a mode of failure for sandwich panel design.

Other modes of failure, not considered here, include yielding of the facing material due to a load normal to the sandwich panel (analogous to yielding of the flange of a wide-flange beam under load), and additional failure modes for the core in shear and flatwise compression resulting from loads normal to the sandwich panel. There are also several local modes of failure of facings, core, and core-to-facing bond.

Structural sandwich panel design requires satisfaction of four basic conditions:

a. The facings shall be designed to withstand the computed compressive stresses.

b. The core shall be designed to have shear rigidity and strength sufficient to prevent overall sandwich buckling, excessive deflection, and/or shear failure under computed design loads.

c. The sandwich panel shall have the large inplane tensile and compressive strength to prevent wrinkling of facings under computed design loads.

d. Since the core is cellular, the cell size shall prevent dimpling of either facing into the core spaces under computed design loads.

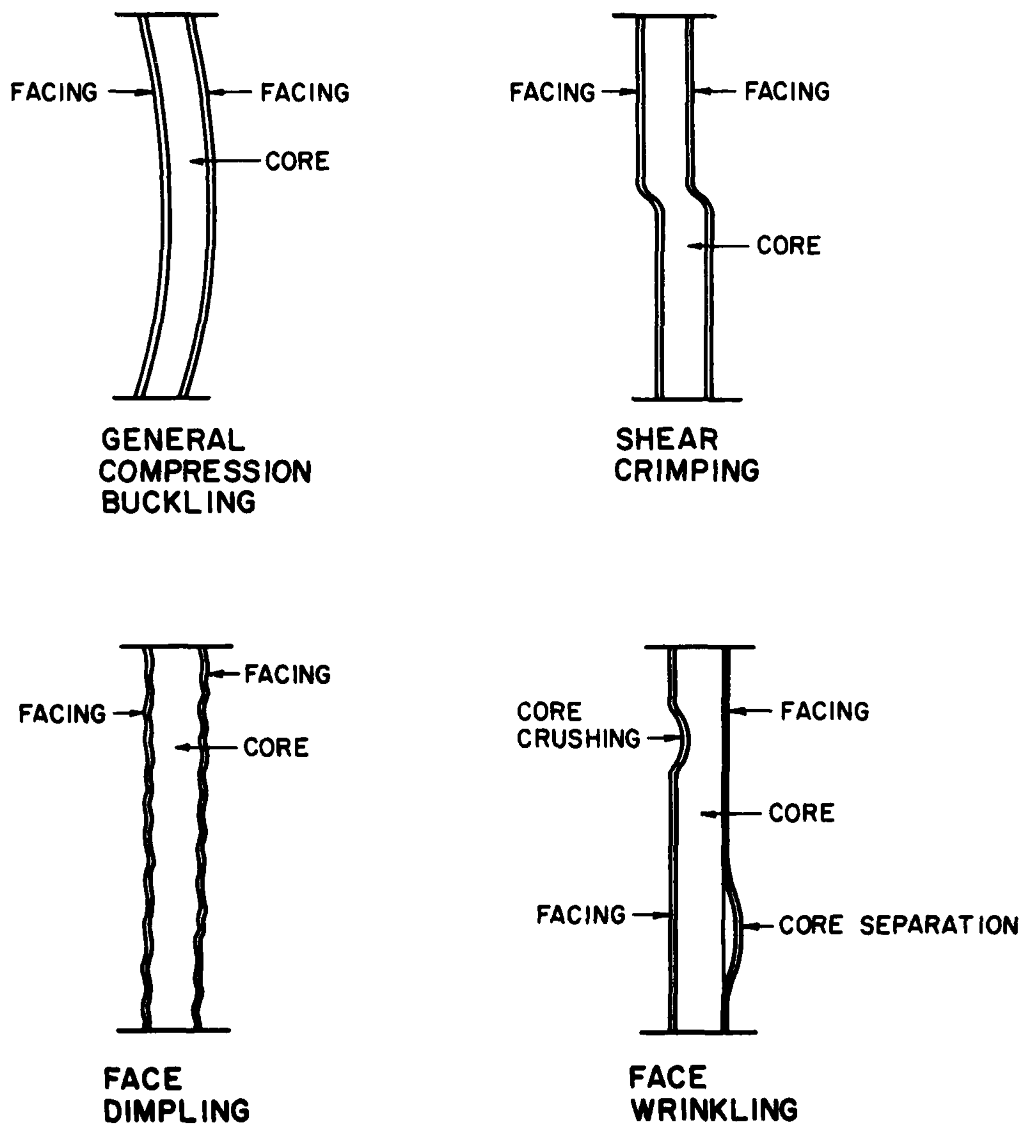


Figure 2. Basic Modes of Sandwich Panel Failure.

A number of panel configuration and load parameters must be determined:

1) Two facing thicknesses, t_{f1}, t_{f2}

2) Core depth, c

3) Cell thickness, $t_{c/s}$

4) Cell size, s

5) Panel length, b

6) Panel aspect ratio, a/b

7) Inplane load components, P_x, P_y

8) Inplane shear force component, Q

9) Transverse shear component, V

10) Moment parameters, M_x, M_y.

Given the material characteristics, optimization of sandwich panel design in terms of these 13 variables is a major task. Fortunately, certain simplified procedures that do not require this optimization are available for completing the design. These procedures will now be considered in detail for the wall design.

The first step in the design procedure is to determine the load parameters (P_x, P_y, Q, V, M_x, M_y) on the sandwich panel from the given design loads above. Assume that the x direction is the horizontal wall direction and the y direction is the vertical wall direction.

P_x (Figure 3a):

P_x = Wall area x pressure

P_x = 10 feet x 8 feet x 50 pounds/square foot = 4000 pounds

Factor of Safety = 2.0

P_x = 2.0 x 4000 pounds = 8000 pounds

$P_x = \frac{8000 \text{ pounds}}{8 \text{ feet}}$ = 1000 pounds/foot = 83.3 pounds/inch

P_y (Figure 3b):

P_y = Roof area x snow load

P_y = 20 feet x 20 feet x 50 pounds/square foot = 20,000 pounds

Factor of Safety = 2.0

P_y = 2.0 x 20,000 pounds = 40,000 pounds

Assume the perimeter of the facility minus door and window openings is

L = 4 x 20 feet-5 x 4 feet-10 feet = 50 feet

$P_y = \frac{40{,}000 \text{ pounds}}{50 \text{ feet}}$ = 800 pounds/foot = 66.7 pounds/inch

Q (Figure 3c):

Q = Inplane shear force component

Q = 10 x 8 feet x 50 pounds/square foot = 4000 pounds

Factor of Safety = 2.0

Q = 2.0 x 4000 pounds = 8000 pounds

Assume the contact surface of the facility wall is

l = 20 feet - 10 feet

$q = \frac{8000 \text{ pounds}}{10 \text{ feet}}$ = 800 pounds/foot = 66.7 pounds/inch

V (Figure 3d):

V_{max} = Transverse shear force component

V_{max} = 50 pounds/square foot x 8 feet = 400 pounds/foot

Factor of Safety = 2.0

V_{max} = 2.0 x 400 pounds/foot = 800 pounds/foot = 66.7 pounds/inch

M_x (Figure 3e):

M_{xmax} = Maximum wall cantilever moment

M_{xmax} = 1/2 x 50 pounds/square foot x 8 square feet = $\frac{1600 \text{ foot pounds}}{\text{foot}}$

Factor of Safety = 2.0

$M_{xmax} = 2.0 \times 1600 \frac{\text{foot-pounds}}{\text{foot}} = \frac{3200 \text{ foot/pounds}}{\text{foot}} = \frac{3200 \text{ inch-pounds}}{\text{inch}}$

M_y (Figure 3f):

M_{ymax} = Maximum wall bending moment

M_{ymax} = 1/8 x 50 pounds/square foot x 20 square feet = $2500 \frac{\text{foot-pounds}}{\text{foot}}$

Factor of Safety = 2.0

$Mymax = 2.0 \times 2500 \frac{\text{foot-pounds}}{\text{foot}} = 5000 \frac{\text{foot-pounds}}{\text{foot}} = 5000 \frac{\text{inch-pounds}}{\text{inch}}$

Note that the worst case-loading conditions are assumed except for the computation of M_y, where inadequate bond of one wall to another wall is not considered (the wall is considered simply supported instead of cantilevered).

Assume the sandwich panel to be designed has facings of equal thickness, a relatively thick cellular core, and perfect facing-to-core bonding. Also assume standard atmospheric conditions for the design. To design the wall panels, the following ten conditions must be met.

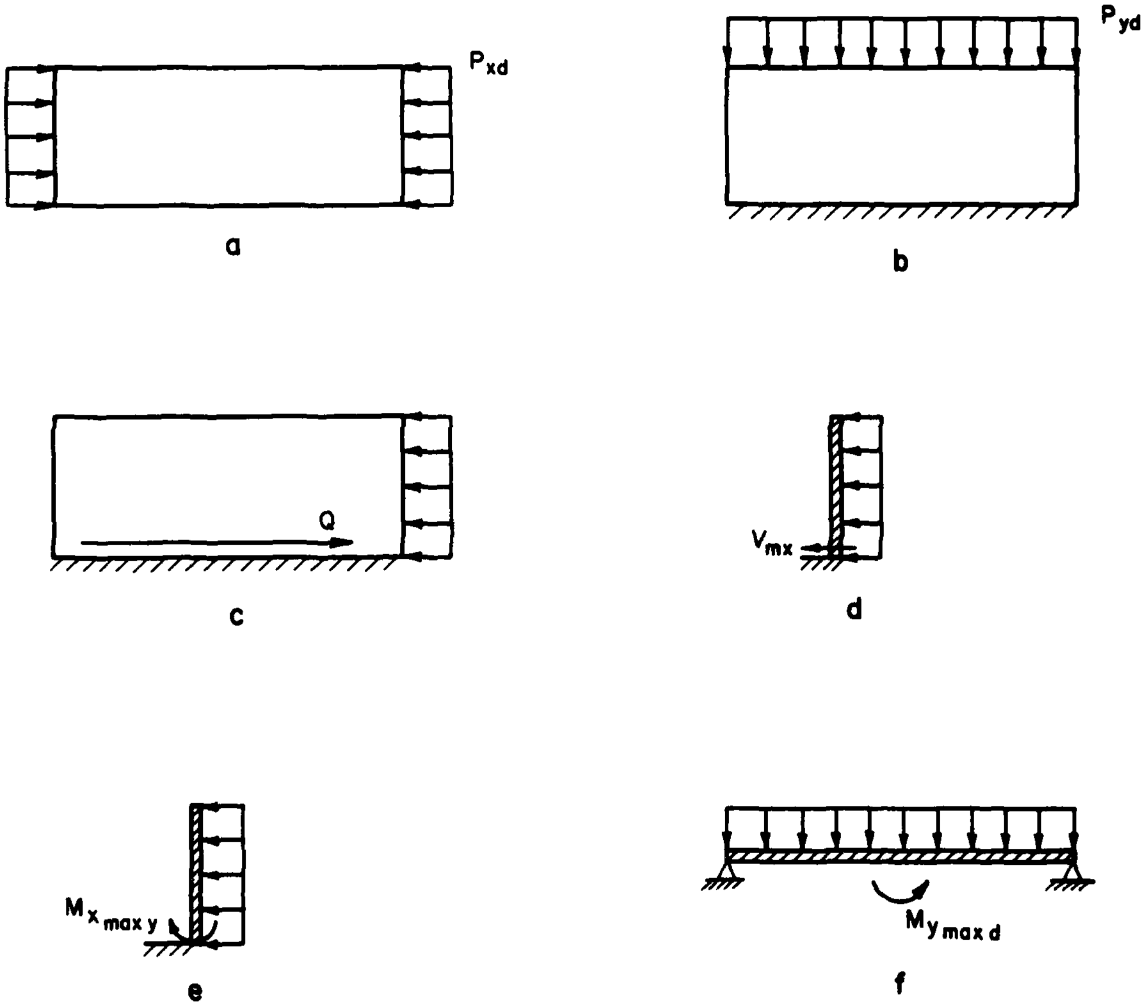


Figure 3. Facility Wall Loadings.

e. The minimum core cell size for which face dimpling will occur under compressive load is given by

$$s = 0.825\ t_f\ (F_c/E_f^{'})^{-2/3}$$

where s = core cell size (diameter of inscribed circle in inches)

t_f = facing thickness (inches)

F_c = compressive facing stress (pounds/square inch)

$E_f^{'}$ = effective compressive modulus of elasticity of the facing at F_c (pounds/square inch)

The minimum core cell size for which face dimpling will occur under shear load is given by

$$s = .71\ t_f\ (F_s\ E_f^{'})^{-2/3}$$

s, t_f and $E_f^{'}$ are as above

F_s = shear facing stress (pounds/square inch)

f. The minimum facing stress at which face wrinkling will occur is given by

$$F_c = .43\sqrt[3]{E_f^{'}\ E_c^{'}\ G_c^{'}}$$

where F_c and $E_f^{'}$ are as above

$E_c^{'}$ = effective core compressive modulus of elasticity (pounds/square inch)

$G_c^{'}$ = effective core sheer module (pounds/square/inch)

The minimum core cell wall thickness-to-cell size ratio for which face wrinkling will occur is given by

$$\frac{t_c}{s} = C\left[\frac{1.35F_c}{(E_f\ n_2^3\ E_c\ G_c)^{1/3}}\right]^{1.015}$$

where s and F_c are as above

t_c = the core cell wall thickness (inches)

E_f = the facing compressive modulus of elasticity (pounds/square inch)

G_c = the core shear modulus (pounds/square inch)

n_2 = plasticity coefficient (= 1.0)

C = a constant (= .5 square cell, = .33 hexagonal cell)

g. The minimum facing stress at which shear crimping will occur is given by

$$F_c = G_c' (c + 2t_f) / 2t_F$$

where t_f, F_c, and G_c' are as above

c = the core thickness (inches)

Also, the minimum ratio of core cell thickness to cell size is given by

$$\frac{t_c}{s} = C\left[\frac{F_c\ t_f}{1.21\ G_c\ (c + 2t_f)}\right]^{.65}$$

h. The minimum value of the ratio of core cell thickness to core cell size for compressive load is given by

$$\frac{t_c}{s} = .5\left[\frac{1.35F_c}{(E_f\ n_2^3\ E_c\ G_c)^{1/3}}\right]^{1.015}$$

with all parameters as above.

i. The minimum core depth at which general buckling of the sandwich panel will occur is given by

$$c = \left[\frac{4\ F_c b^2\ (1-\mu^2)^{1/2}}{\pi^2\ K_c\ \eta\ E_f}\right] - t_f$$

where t_f, F_c, E_f, and c are as above

K_c = instability parameter

η = plasticity coefficient (=1.0)

b = panel length perpendicular to the load

μ = Poisson's ratio for the facing

j. The minimum facing thickness for compression load on the facing is given by

$$t_f = \frac{N}{2F_c}$$

where t_f and F_c are as above

N = compressive load (pounds/inch)

k. The minimum facing thickness for shear load on the facing is given by

$$t_F = \frac{N_{xy}}{2F_s}$$

where t_F and F_s are as above

N_{xy} = shear load (pounds/inch)

l. The minimum value of the ratio of core cell thickness to core cell size for shear load is given by

$$\frac{t_c}{s} = C\left[\frac{1.35F_s}{(E_F\ \eta_2^3\ E_c\ G_c)^{1/3}}\right]^{1.015}$$

where all parameters are as above

m. The minimum value of core depth for shear load is given by

$$c = \frac{4\ F_s b^2\ (1-\mu^2)^{1/2}}{\pi^2\ K_s\ \eta_{EF}} - t_f$$

where t_f, F_s, E_f, c, η, b, and μ are as above

K_s = instability parameter

n. The minimum thickness facing plus core for which yielding first occurs at the facing surface is given by

$$(c + 2t_f) = \sqrt{\frac{6M}{\sigma}}$$

where t_f and c are as above

σ = yield stress of facing (pounds/square inch)

M = applied moment

The preceding set of conditions is not necessarily complete (e.g., creep is not explicitly accounted for). Some of these conditions are more important than others. For example, due to the stiffness of the facings as compared to the stiffness of the core, face dimpling will not be an important consideration for even very thin design wall facings; general sandwich panel stability, however, will be an important consideration.

At this point two other important considerations should be presented. First, the above formulas relating core cell size to overall panel parameters apply to very regular core cell configurations such as the square- or hexagonal-cell honeycomb. Although the core materials considered below have no such regular core cell configurations, core cell size and wall thickness are meaningful and defined variables in the foam core materials presented in the summary. This results in an extension of the use of the formula. It is quite possible that even though dimpling of the sandwich panel facings may not occur because of the facing transverse stiffness, the design equation for dimpling may provide information on core-to-facing bonding or debonding.

Second, several tacit assumptions about the values of various parameters involved in the design have been based on the analogy assumed to exist between sandwich panels with regular core cell structure and sandwich panels with random core cell structure. A rather conservative approach to the overall design based on yield strength of the sandwich panel facings has been assumed. The plasticity factors introduced into the above design relations allow for possible nonlinear material behavior of the sandwich panel facings. Due to the lack of information on inelastic behavior of the plastic sheeting, the plasticity factor was assumed to be unity (elastic behavior) in all instances.

Reference 16 provides excellent examples that will supplement information provided in this discussion.

2. MINIMUM DESIGN FEATURES

The methodology described above was used to design wall panels for a model structure. An analysis of the minimum face material properties required showed that 26-gage steel or aluminum, 1/16-inch (1.6-mm) glass-reinforced plastic, or 1/4-inch (6.4-mm) plywood or flakeboard interior and exterior skins would be adequate for 8-foot (2.44-m)-high wall panels. The polyurethane foam core minimum thickness was determined to be 2.6 inches (66 mm), based on typical properties of a 2.1 to 3.0 pounds/cubic foot (336 to 481 kg/m^3) foam.

An overall panel thickness of 4 inches (101.6 mm) was selected to be compatible with standard door and window hardware and framing lumber. This thickness provides a reasonably conservative design and increases both flexural and buckling resistance and creep resistance.

This panel design adequately resists wind loads of 80 mph (128.7 km/hr) with steady-state gusts to 120 mph (193 km/hr) and snow loads of 40 pounds/square foot (195 kg/m^2); these loads are resisted when the snow and wind forces act alone or together.

The panel designs selected for the model structure could be connected to any adjacent panels, corner junctions, interior partitions, door and window openings, and wall/foundation and wall/roof connections capable of withstanding interactive forces from dead and live loads.

SECTION V

PANEL FABRICATION STUDIES

The techniques for fabricating the foam core sandwich panels on-site that are described in this section also apply to preparing panels at another location. Other methods of forming panels (i.e., bonding faces onto foam cores) are acceptable if the finished panels meet design criteria. However, prefrabricated panels will require more space during shipping than unassembled materials.

1. MOLD DESIGN

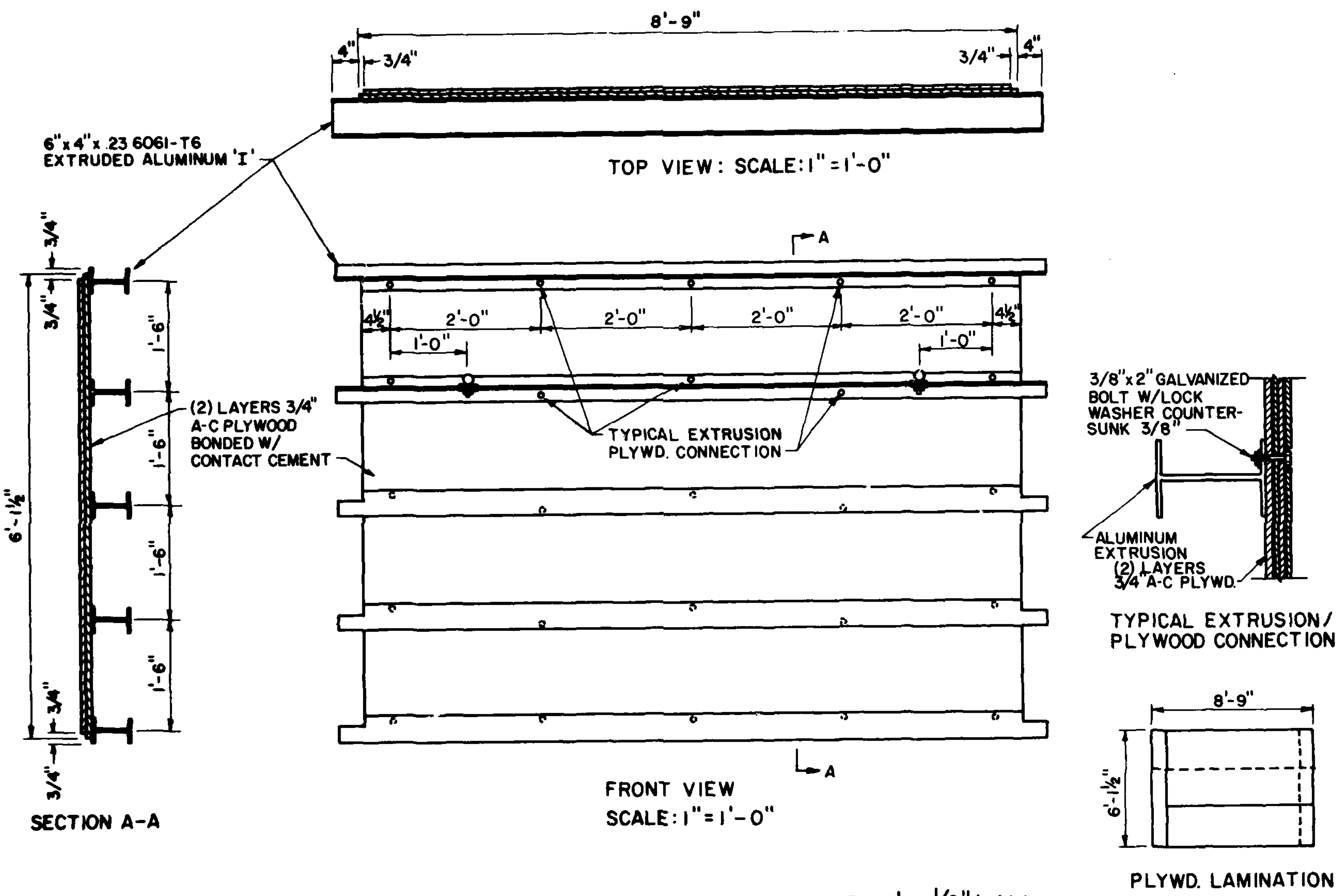
The mold used to make foam core sandwich panels must be able to tolerate the stresses exerted by the finished panels; i.e., the mold must resist the foam expansion pressure, incorporate blockout features, be easy to open and close, and be reusable.

The mold may be constructed either of wood or metal, but the joints must be liquid-tight. Two levels of internal pressure must be considered, based on the foaming techniques used. The lower-level pressure of about 5 psi (34.5 KPa) is adequate for "open top" foaming. A high-level pressure of about 5 psi (34.5 KPa) or greater can be anticipated if closed mold techniques are used. (In this method, an overcharge of foam material mixture is introduced into the mold, and the mold is closed except for small air vent holes.)

The open-mold technique was used in this study and produced adequate panels consistently. Figure 4 shows details of an aluminum/plywood mold for 6- x 8-foot (1.83- x 2.44-m) panels. A second mold made of plywood and wood framing was also constructed and used successfully.

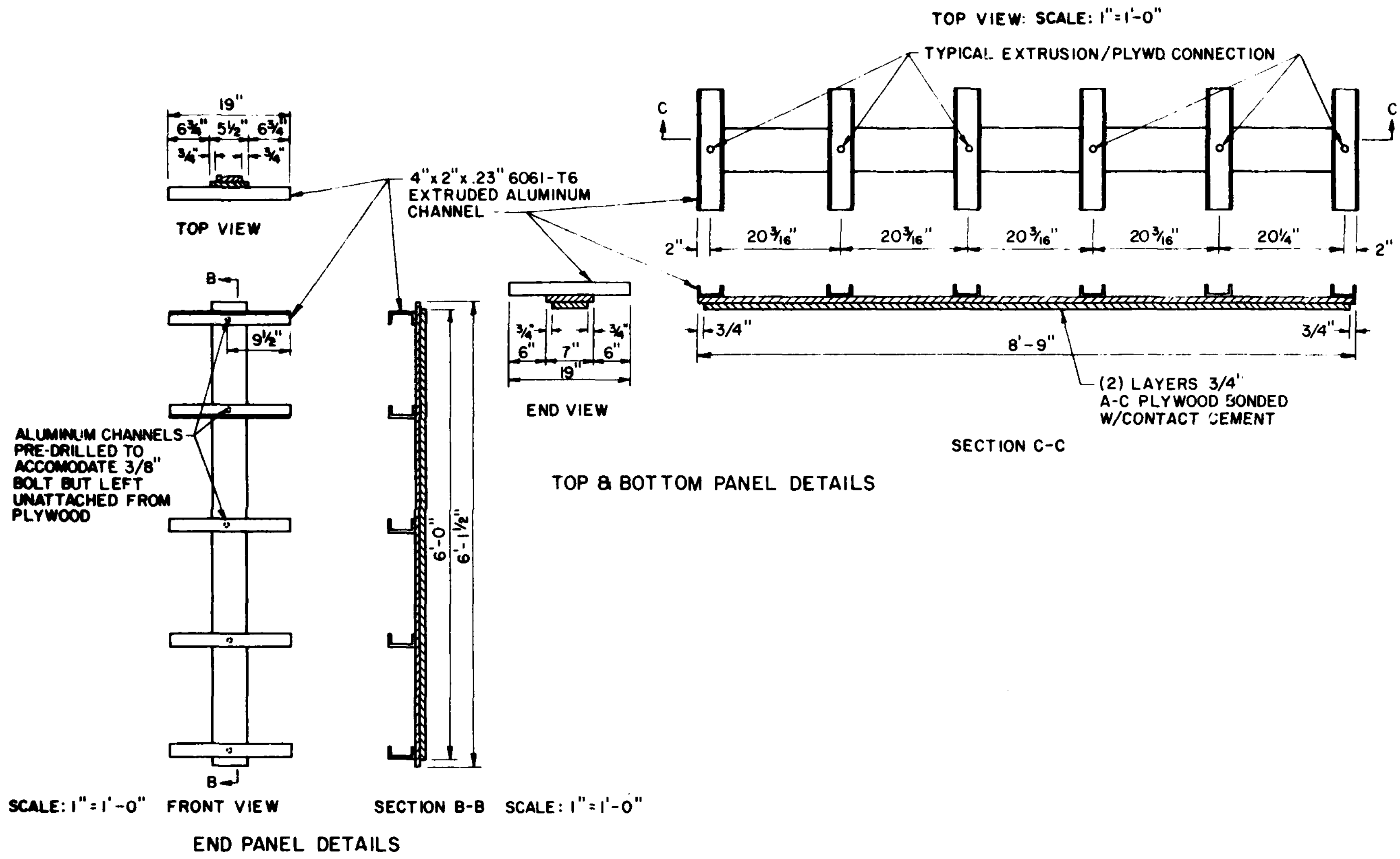
2. FOAM APPLICATION ALTERNATIVES

The foamable material may be introduced into the mold in several ways. In the batch method, the required quantity of foam materials is weighed, added



NOTE: SIX FOOT DIMENSIONS ON SECTION A-A WILL BE 4'-1 1/2"; ALL OTHER DIMENSIONS AND SPACINGS ARE UNAFFECTED.

Figure 4. Foam Panel Mold.



NOTE: SIX FOOT DIMENSIONS ON SECTION B-B WILL BE 4'-1 1/2"; ALL OTHER DIMENSIONS AND SPACINGS ARE UNAFFECTED.

Figure 4. Foam Panel Mold (Concluded).

together, thoroughly mixed, and poured into the mold. This method is acceptable, but is a tedious process for making a large number of panels. This process works best if the mold is tilted until its top is only a few inches higher than the bottom. This low angle allows the foam to expand more easily than if it had to expand the full width or length of the panel.

The method used to make the panels for this study used a proportioning pump and spray gun to measure, deliver, and mix the material. In addition, the material was frothed (partially foamed) as it was placed in the mold. The mold was set upright, and the froth spray directed down into the mold until the panel core was filled. This method was fast, easy, and reliable.

Factory production of foam core panels is a continuous, assembly-line method, with the face materials fed into position as foam material is deposited on a conveyor. A traveling press controls the foam expansion and panel dimensions. It may be possible for the military to adapt this technique to a mobile "panel mill," if a large number of panels is required at a site.

3. FACING COMPONENTS PREASSEMBLY

The plywood-faced panels for this study required only the minimal preassemble of nailing on edge spline along one long direction to both plywood facing sheets. Half of the spline thickness was nailed to the face sheets, and the other half was exposed. The opposite edge of the panel was blocked out by the mold to form a recess in the foam; this allowed the remaining half of the spline to be inserted into the edge of the succeeding panel when the building was assembled. Such provisions were not required for the fiber-reinforced plastic sheet-faced panels.

Door and window openings were made before the panels were foamed. The desired open area was blocked out by nailing the face materials to a rough opening frame of the appropriate size. This method was used for all types of face materials. The face material was left over the openings, particularly those for doors, until the building was erected in order to keep them as rigid as possible. The openings can be placed anywhere within the panel area, provided there is enough room away from the panel edge for the rough opening frame and/or the spline piece (if required).

4. MOLDING OF PANELS

The panels for this study were prepared by preassembling the facing materials, placing the assemblies into the mold, closing the sides/ends of the mold, and then securing them. Usually, the panel facing materials were not stiff enough to resist bending within the mold. The low-pressure molding method used would not reliably force the facing materials back to the mold. Therefore, blocks of foam were squeezed between the facing materials to hold them against the mold during the foaming.

The foam material was then froth-sprayed into the mold. The foaming material completely enveloped the foam space blocks. The mold was filled to within a few inches of the top before replacing its top. The remaining volume of the core was then filled with foam by injecting froth spray through three small ports in the top of the mold. Excess foam material escaped through these ports after the mold was full.

The panel was then left undisturbed in the mold until the initial cure was complete (generally not less than 20 minutes). The initial cure time is essential to give the panel dimensional stability. The production rate can be based on the in-mold time, and the number of molds can be established for a given output.

Following the initial cure time, the mold was opened and the panel was removed. It was set aside for post-curing to obtain its full strength. Usually one to two hours at moderate temperature is sufficient. The panels should not be stacked against one another during post-curing, since heat from the foam must escape during this phase.

Any trimming or post-molding operations, including painting, can be done after post-curing. The panels are then ready for storage or immediate use.

SECTION VI

TEST AND EVALUATION PLAN

The wall panels and model structure were tested to insure that they met certain required material, panel, and structural properties and characteristics. Standard tests, such as those prescribed by the American Society for Testing and Materials (ASTM), were used if available. If no standard tests existed, other tests were designed to provide the required conditions. A few tests were not conducted because testing capabilities were inadequate; however, implied results were obtained from other test data.

Table 2 shows the properties or characteristics required in foam wall systems; the remarks column gives comments on tests used, inferred results, and other pertinent information.

Tests and evaluations were performed whenever possible. When tests could not be conducted, researchers noted the ambient conditions that would most closely resemble required test conditions. For example, it was not possible to test the model under conditions of 80 mph (128.7 km/hr) winds; however, winds in excess of 60 mph (96.6 km/hr) did occur on several occasions, and gusts of more than 80 mph (128.7 km/hr) may have occurred during some storms. This information was then used to project possible results for tests that could not be conducted.

Tests of the materials, panels, and structure demonstrate only that the particular set of materials and assembly used in the model met the requirements. This data does not imply that any other set of materials, panel assembly, or structure will meet the requirements. The specifications resulting from this study will designate acceptable materials, design, and assembly. However, conformance to specified requirements must be certified by each supplier, designer, and fabricator.

TABLE 2. TEST/EVALUATIONS REQUIRED.

(Metric Conversions: $^{o}C = (^{o}F-32)(5/9)$; Btu/square foot = .0272 watts/m^2; 1 foot = .3 m; 1 inch = 25.4 mm; mph = .6 km/hr; pounds/square foot = 4.882 kg/m^2)

Title	Property/Characteristics or Performance	Remarks
Temperature	The panel wall systems shall be capable of withstanding exposure to temperatures ranging from $-25^{o}F$ to $125^{o}F$ (plus a solar load of 360 Btu/square foot/1 hour).	Test in temperature chambers and observe in structure.
Blowing Sand	The wall panels shall incorporate design features that preclude entrance of blowing sand and its adverse effects on external moving components and connecting points in the erection of a facility. The panels located near operating surface vehicles shall be designed for particle concentrations of 6.62×10^{5} pounds/cubic foot with wind speeds up to 59 feet/second at a height of 10 feet. Particle sizes shall range from less than 2.91×10^{-3} inches to 39.3×10^{-3} inches in diameter, with the bulk of the particles ranging in size between 2.91×10^{-3} inches and 13.8×10^{-3} inches. Temperatures shall be considered to be above $70^{o}F$ with accompanying relative humidities less than 30 percent.	Infer from air leakage tests. No ASTM standard test available.
Fungus	The panel wall system design shall include measures to assure that fungus growth will not degrade the shelter or any of its components.	ASTM D 2017
Marine Atmosphere	The panel wall system shall not suffer corrosion damage when exposed to 25 pounds/acre/year of seasalt fallout.	ASTM B 117
Rainfall	The panel wall system shall be capable of withstanding 2 inches/hour of rainfall, accompanied by a 40 mph wind, without leaking. (The normal length of the test for this requirement is 1 hour.)	ASTM E 331
Wind Load	The panel wall system shall not suffer any damage when exposed to winds up to 80 mph with steady-state gusts to 120 mph. (A steady-state gust is defined as 3 seconds.)	Calculated values; flexural and buckling tests (ASTM E72).
Snow Load	The facilities shall be capable of supporting a minimum snow load of 40 pounds/square foot.	Inferred from buckling tests.
Anchoring/Tiedown	The panel wall system shall contain external anchoring/tiedown points.	Design; observe structure.
Physical Security	The design shall include methods for securing all openings and removable components to prevent unauthorized entry.	Specify window/door locks as required.

TABLE 2. TEST/EVALUATIONS REQUIRED (CONCLUDED).

Title	Property/Characteristics or Performance	Remarks
Door Load	One of the foam wall panels shall have one personnel door measuring 80 inches x 36 inches respectively, in height and width. The door, frame, and hardware shall be capable of supporting a vertical load of 200 pounds applied to the door 36 inches from the hinge pivot line for 30 minutes with the door open to 90° with no permanent deformation to the door, hardware, or shelter. Additionally, the door shall be capable of withstanding a wind gust equivalent to 15 pounds/square foot in each direction when the door is open to its maximum angle of 100°.	Test as described by saddlebag load on door (no standard test).
Fire Resistance	The foam wall panel system burn rate shall not exceed a maximum of 2 inches/minute.	Specify materials to meet ASTM E119; 15-minute burn-through minimum.
Weather Seals	If weather seals are used, they shall be an integral part of the wall panel and fully operational over the service life of the wall panel or shall be designed for ready replacement in the field by the user.	Design/specify.
Airtightness	The facilities, after the wall panels are erected, shall be airtight to the extent that it shall take a minimum of 4 minutes for an air pressure differential (inside versus outside) of .5 inches of water of fall to .25 inch of water.	ASTM E 283 modified.
Corrosion	All wall panel components shall be adequately protected against corrosion per MIL-F-14072B. The use of dissimilar metal combinations shall be avoided. Selection of permissible couples shall be in accordance with Table II of MIL-STD-889B.	Use corrosion-resistant hardware, nails, etc., in design and specifications.
Weight	The design goal weight for the wall panel shall be capable of being lifted by two people.	Design to maximum of 140 pounds (56 kg); weigh panels.
Service Life	The shelter shall have a minimum service life of 10 years with two relocations (or deployments).	Cannot evaluate over service life required.
Heat Transfer	The value for heat conductance for an erected facility shall be 0.35 Btu/hour/°F/foot.	Calculate whole panel and structure; also infer from air leakage rates.

SECTION VII

PANEL TESTING

Pertinent tests applicable to foam core sandwich panels were conducted on Kemlite,® plywood, and Aspenite.® Tests were done for temperature, buckling resistance, weight, and heat transfer. Tests not discussed in this section and in Section VIII were deleted as being irrelevant in accordance with the rationale discussed in Section VI.

1. TEMPERATURE

High- and low-temperature tests were conducted on representative samples of foam core panels (see Figure 5).

Test samples measuring 1 foot, 0 inches x 1 foot, 0 inches x 4 inches (305 x 305 x 102 mm) were cut from the three wall panel types. The samples were placed in an oven heated to a temperature of 125°F (51°C) and left for three hours. Samples were removed and inspected for damage. After the specimens were heated for three hours and returned to room temperature, they showed no evidence of physical damage.

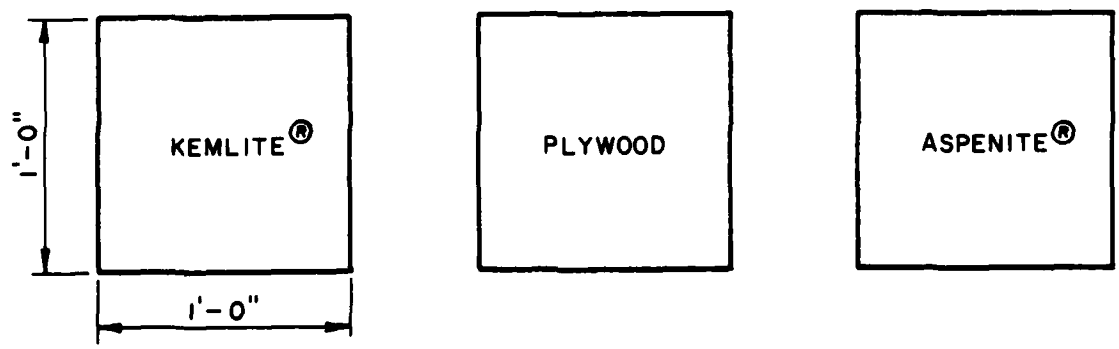


Figure 5. Temperature Test Setup.

Samples were then placed in a freezer cooled to a temperature of $-25^{o}F$ ($-31^{o}C$) and left for three hours. Samples were removed and inspected for damage. There was no physical damage evident in the specimens after three hours of cooling and a return to room temperature.

2. BUCKLING RESISTANCE (SNOW LOAD, WIND LOAD)

The required buckling resistance of the various configurations of foam core sandwich panels included in the model structure was calculated based on the following conditions:

Distributed structure dead load - negligible
Distributed snow load at 40 pounds/square foot - 320 pounds/1 foot
Double snow load to include wind load - 640 pounds/1 foot
Include safety factor of 2.0 to 1280 pounds/1 foot
Allowable deflection L/360 (conservative)
Consider as end-supported panel (conservative)

Thus, each running foot of wall must be able to support at least 1280 pounds (512 kg) within the allowable deflection limit.

Panel sections were randomly selected for the test and were cut 12 inches (304.8 mm) wide and 5.5 feet (1.65 m) long -- the maximum length capacity of the test machine. The allowable deflection for this length was 0.183 inch (3.85 mm). Dial indicators were installed along each panel face so that both the direction and amount of movement could be measured. The panel sections were loaded in increments, and the deflection response was recorded for each step.

Included in the test series were specimens of core foam material, glass-reinforced, plastic-faced panel (Kemlite®), flakeboard-faced panel (Aspenite®) and plywood-faced panel. Figures 6 through 13 show the test conditions, loads, and deflections.

The test results showed that the foam core alone was inadequate (as expected), but that each of the other material combinations of foam and face

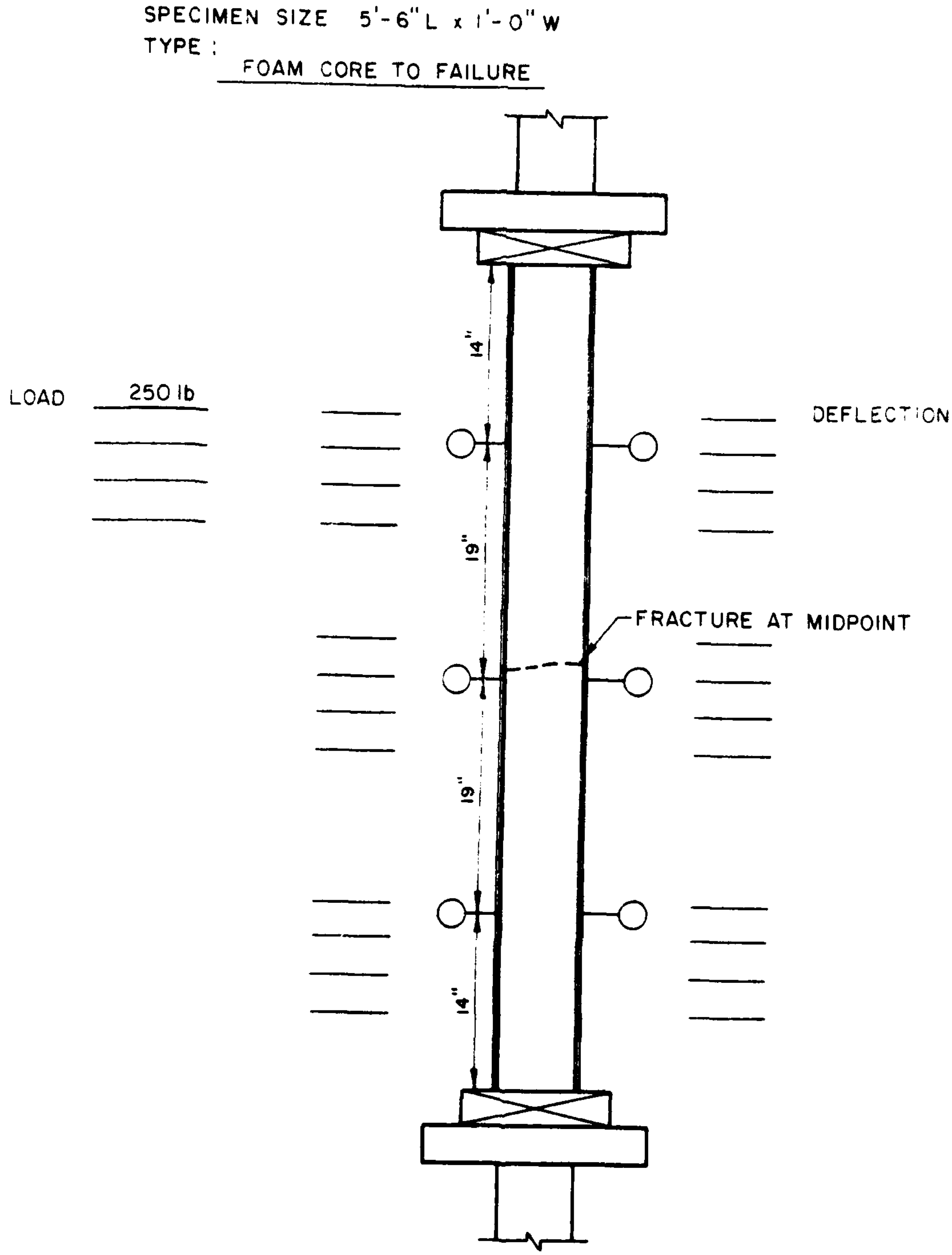


Figure 6. Buckling Resistance: Foam Core.

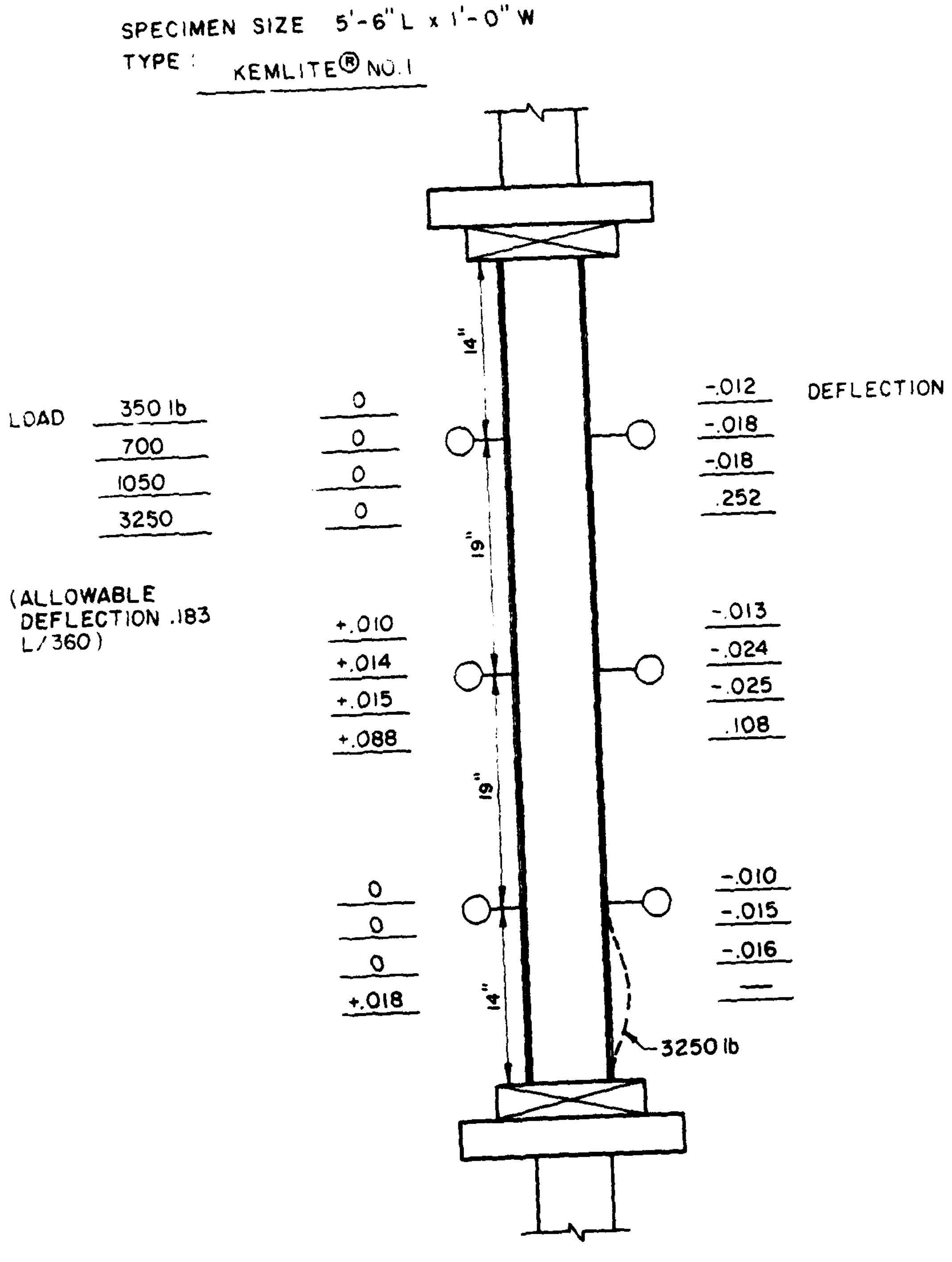


Figure 7. Buckling Resistance: Kemlite®.

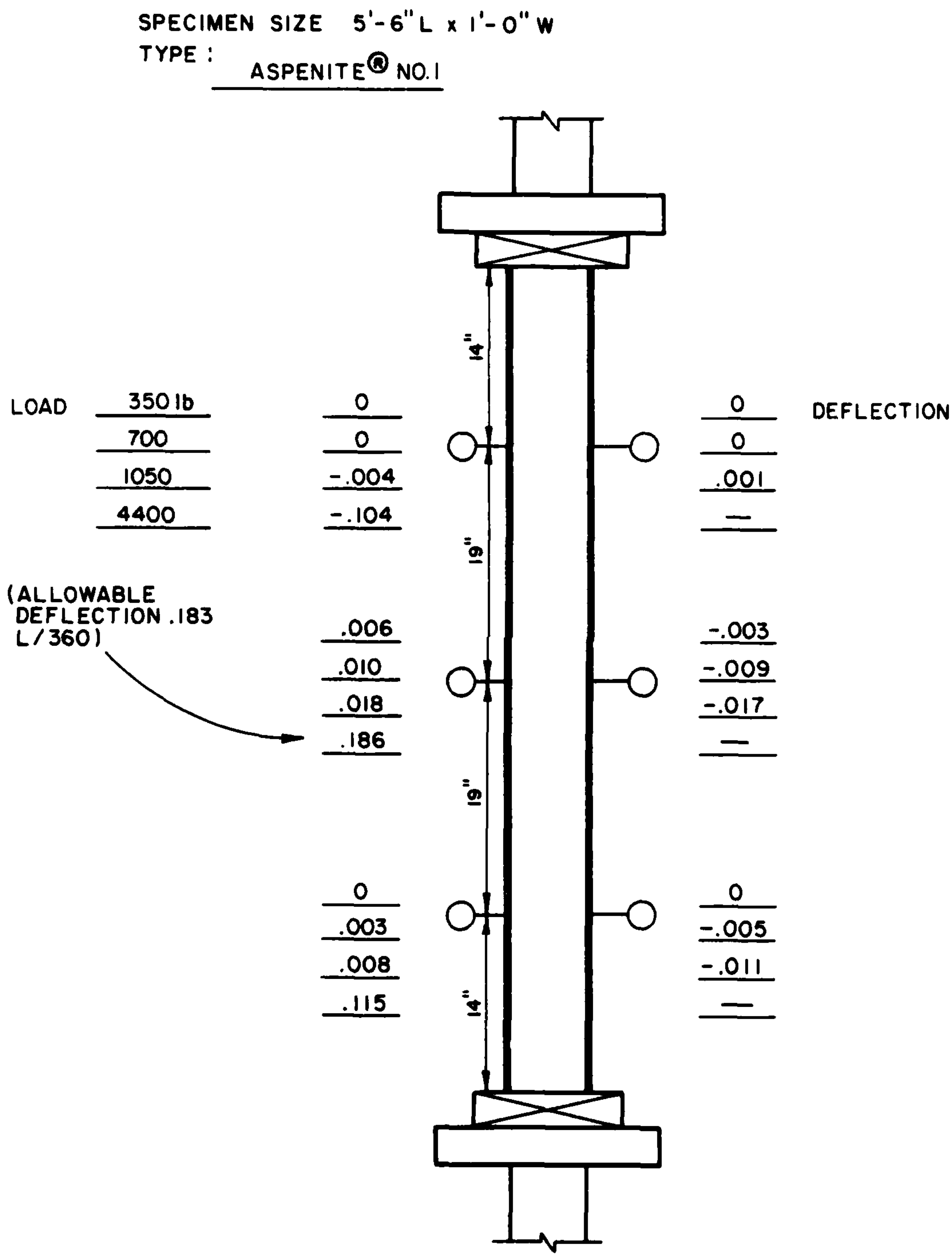


Figure 8. Buckling Resistance: Aspenite® 1.

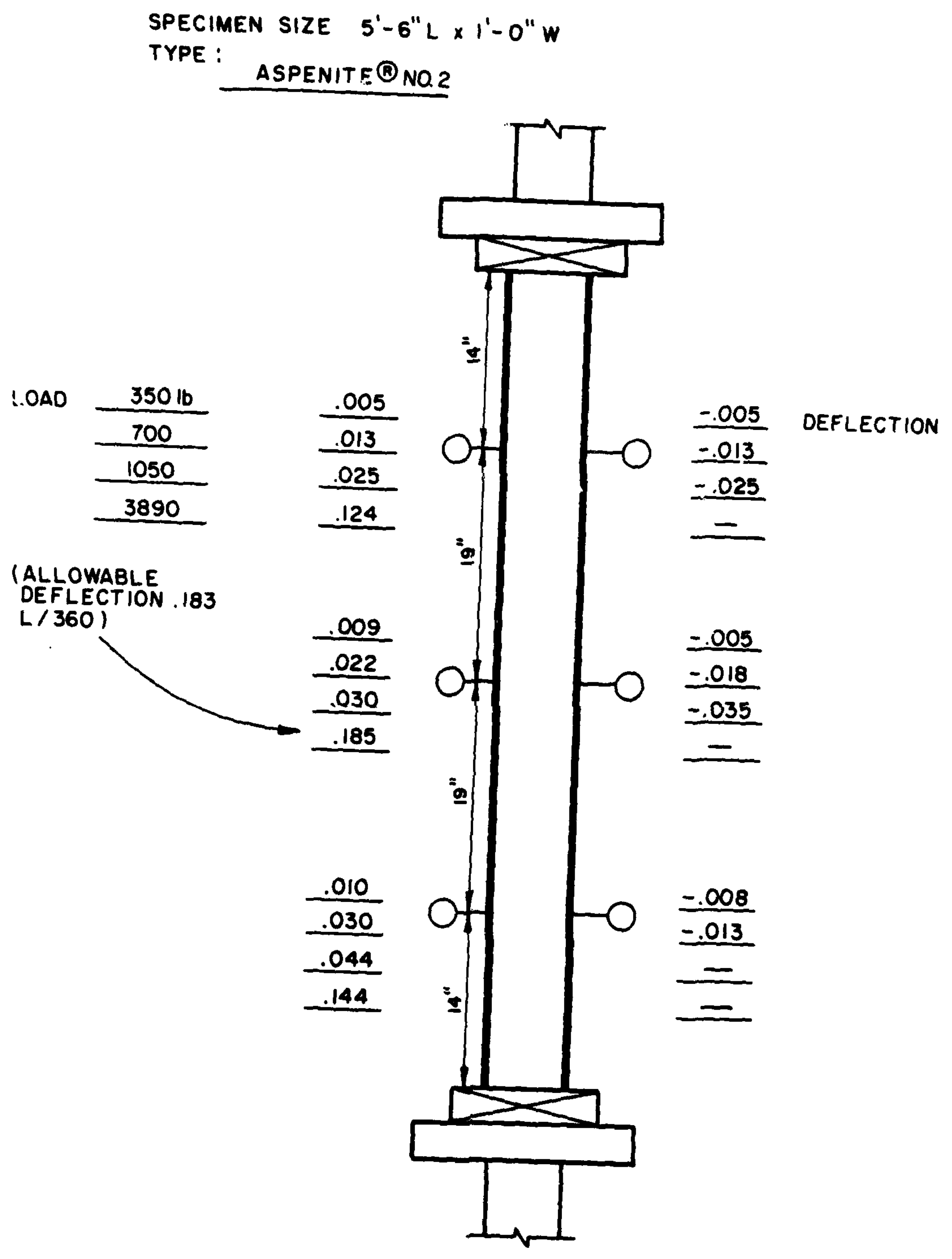


Figure 9. Buckling Resistance: Aspenite® 2.

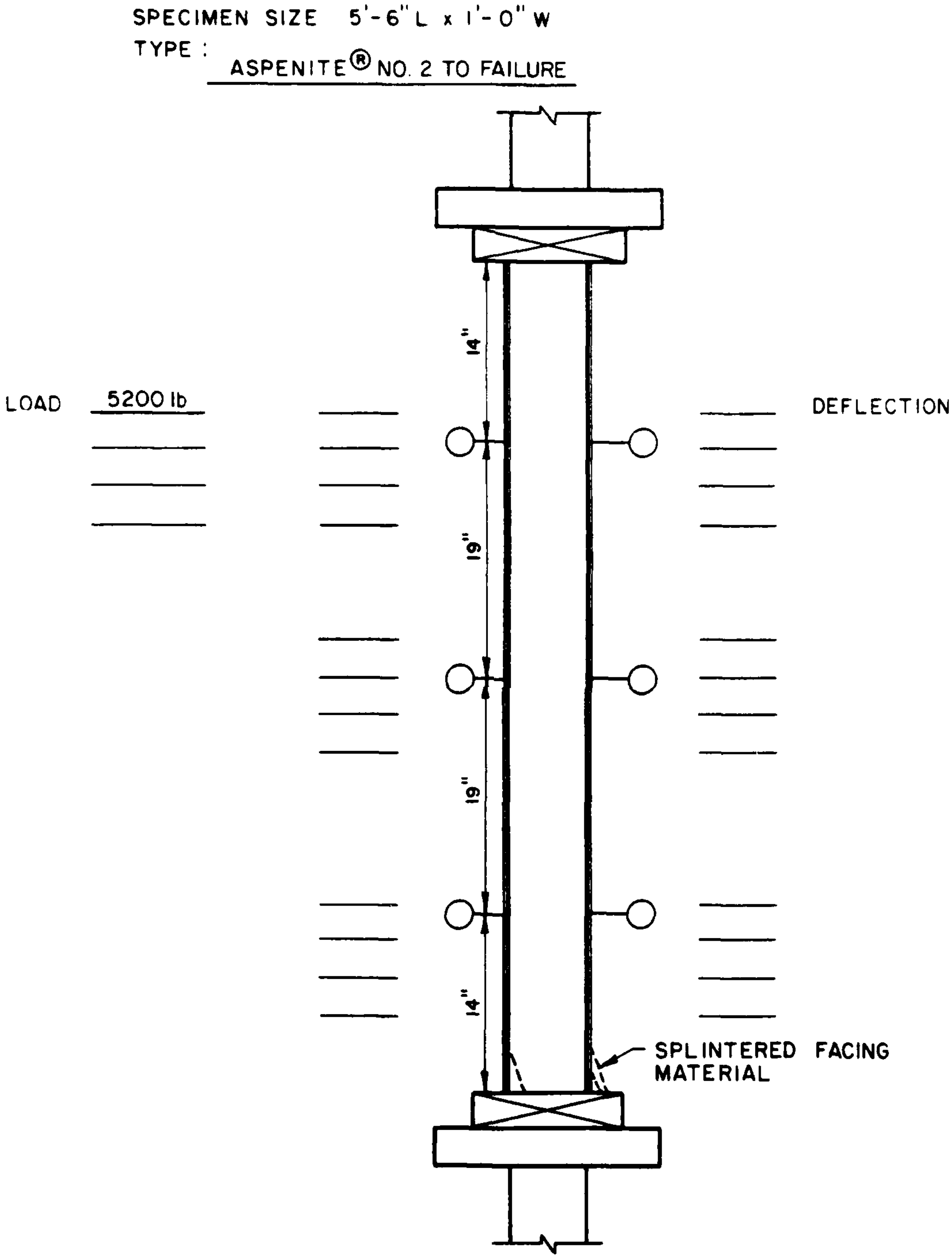


Figure 10. Buckling Resistance: Aspenite® to Failure.

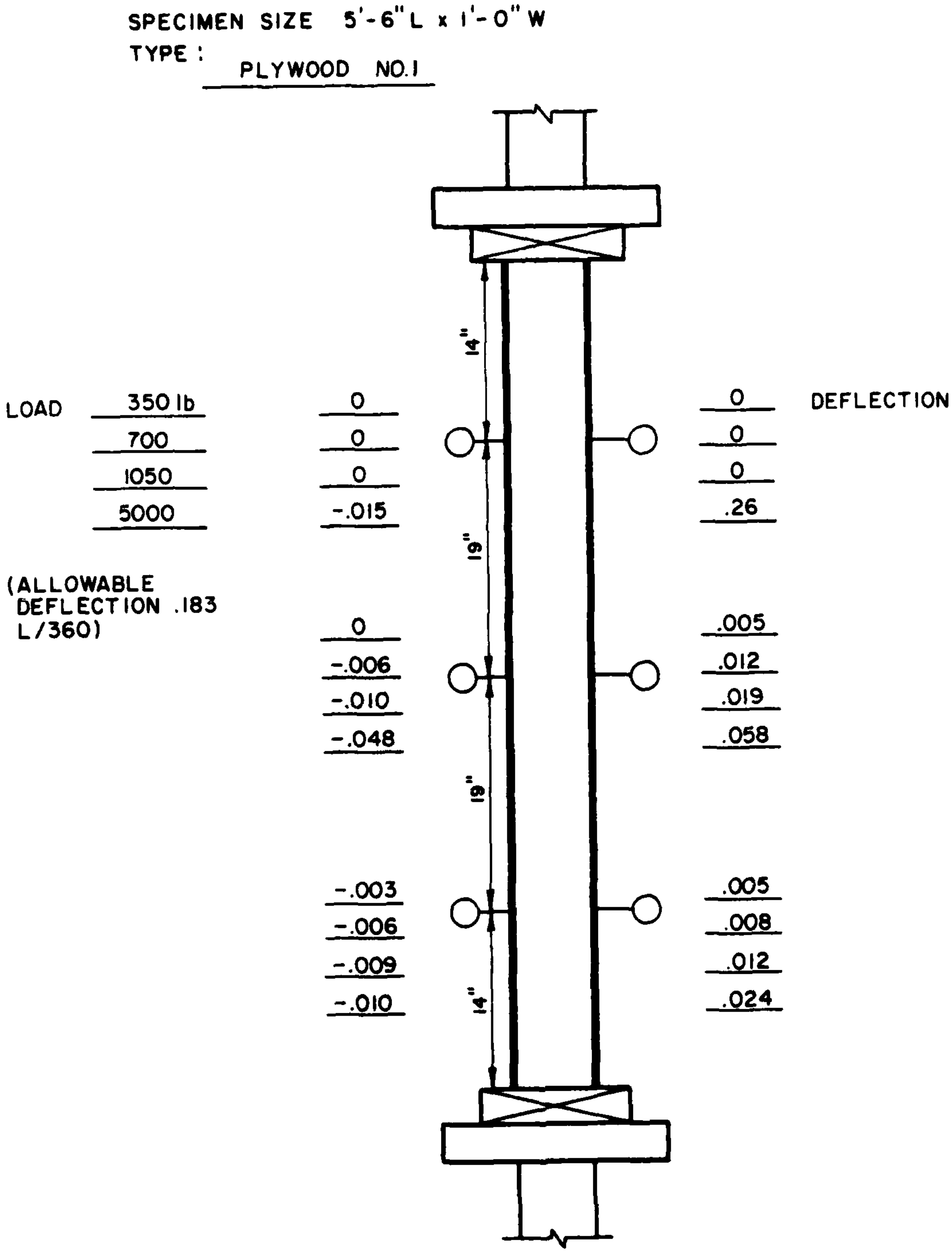


Figure 11. Buckling Resistance: Plywood 1.

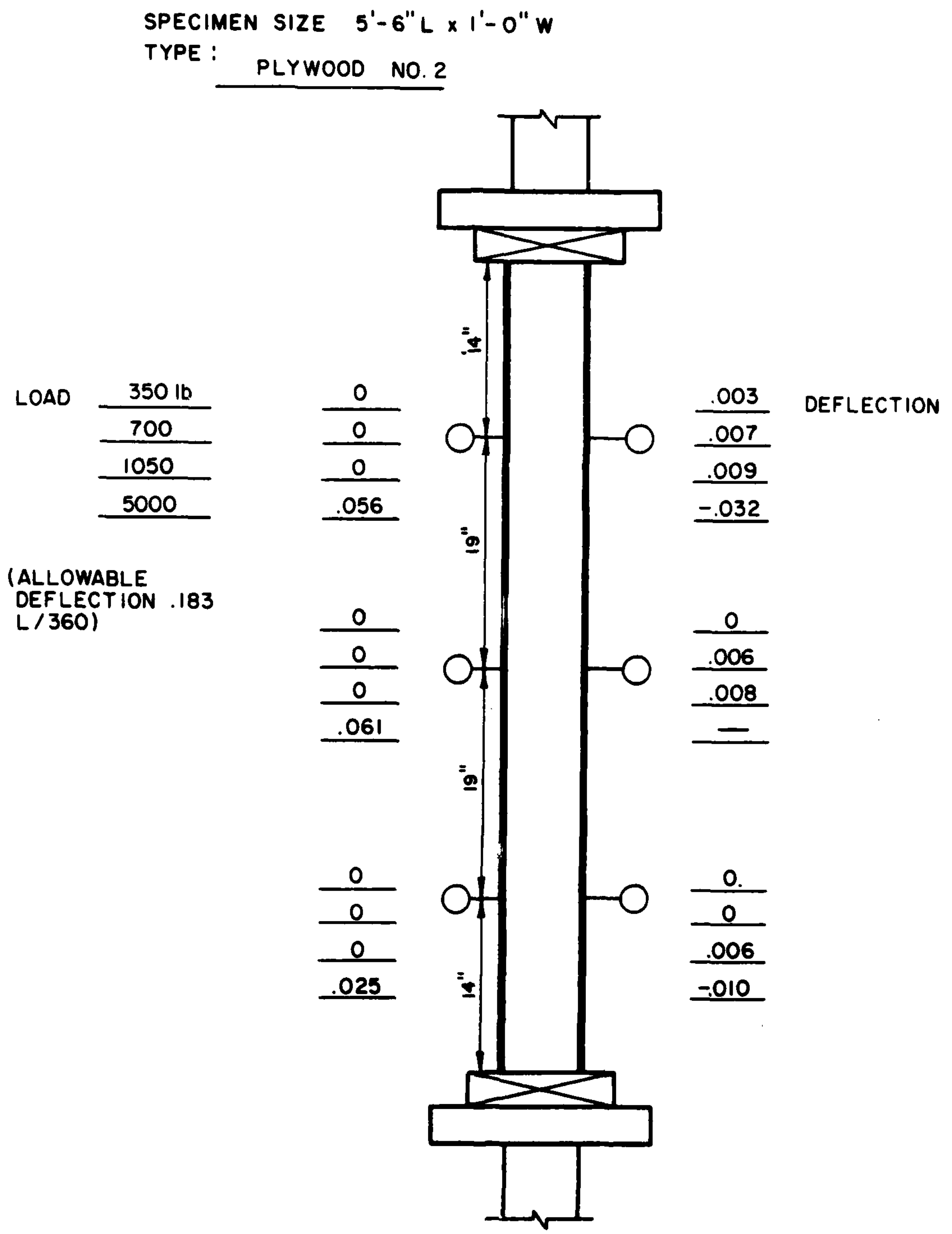


Figure 12. Buckling Resistance: Plywood 2.

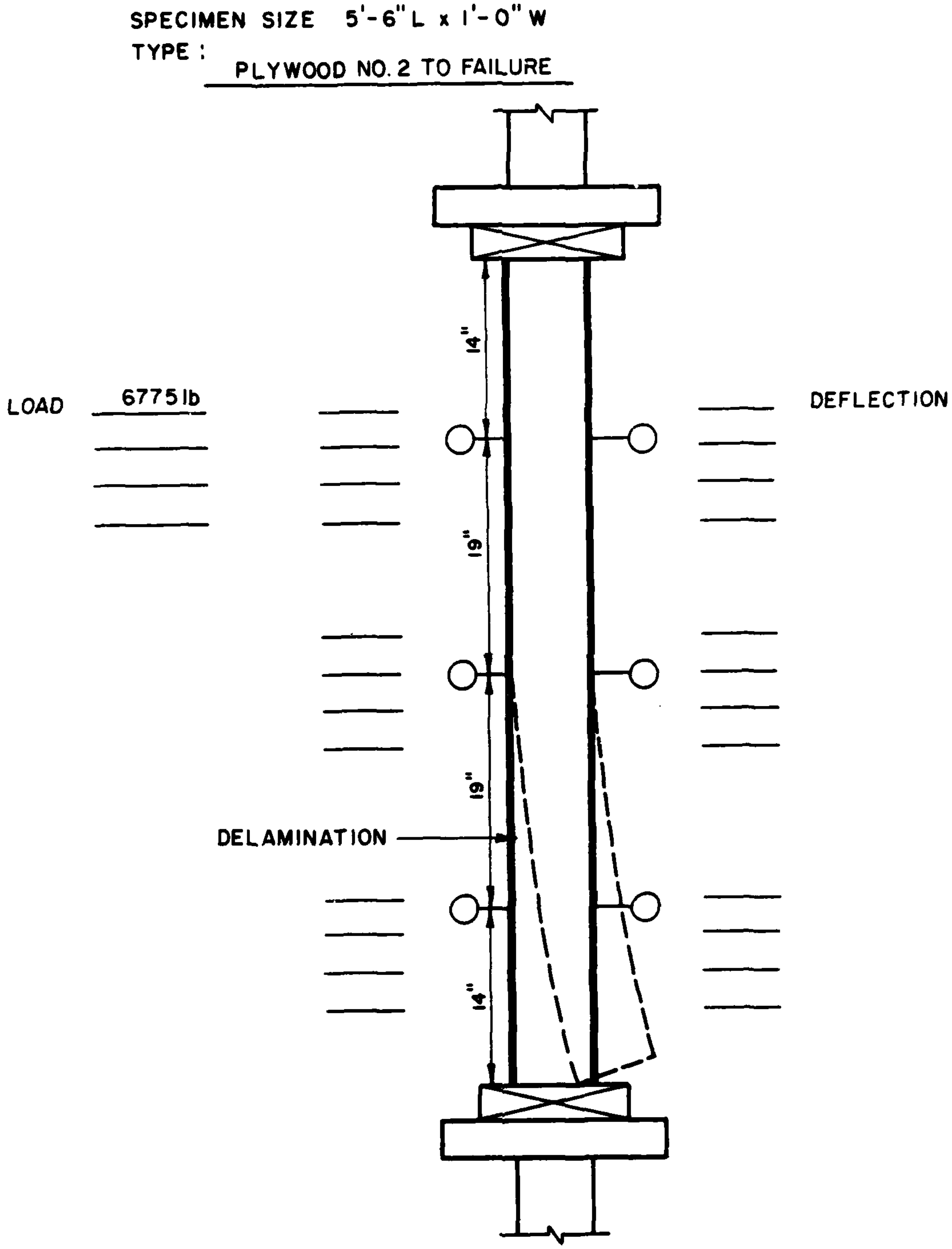


Figure 13. Bucking Resistance: Plywood to Failure.

materials were acceptable. Since the panels would be both end- and edge-supported in actual applications, the load resistance values may be considered ultra-conservative.

A snow load resistance of 40 pounds/square foot was inferred from the buckling resistance tests.

3. WEIGHT

The finished panels were weighed. Even the oversized 6- x 8-foot (1.8- x 2.4-m) panels were below the maximum weight of 140 pounds (56 kg) (two-man load).

Aspenite® (6- x 8-foot)	85 $\pm$ 4 pounds
Plywood (6- x 8-foot)	105 $\pm$ 9 pounds
Aspenite® (6- x 8-foot)	125 $\pm$ 10 pounds

All the foam core panels tested met the weight requirements.

4. HEAT TRANSFER

The heat transfer value of a completed panel was calculated based on the foam alone in order to provide a conservative estimate. The foam's conductance is 0.14 Btu/inches/hour/^{o}F/square foot. Since the minimum foam thickness of any panel was 3.5 inches (88.9 mm), the calculated conductance was 0.04 Btu/hour/^{o}F/square foot. This is far below the design goal of 0.35 Btu/hour/^{o}F/square foot (Table 2). The overall area of non-foam components (splines and other edge connections) is slight; thus, even if highly thermal conductive materials were used for these parts, the overall design goal would easily be met.

5. OTHER TESTS

Tests for fungus resistance, resistance to marine atmosphere exposure, fire resistance, corrosion, and service life were not conducted, since each of these is a function of the materials used in the construction. There are standard requirements to test construction materials for all of these requirements except service life, and they will be made a part of the specifications.

SECTION VIII

MODEL BUILDING ERECTION AND TESTING

1. SPECIFICATION DEVELOPMENT

Preliminary specifications and drawings for a model building were prepared. U.S. Army Corps of Engineers Guide Specifications for Emergency Construction provisions were used where possible. The preliminary specifications are included in Appendix B. The specifications include foundation and roof systems selected for the model structure, drawings, and construction details. The following paragraphs explain the incorporation of the specifications into the model.

a. Foundation/Floor Selection: The foundation and floor system selected for the model structure was a monolithic reinforced concrete foundation and slab. The sizing of the foundation and the floor thickness were based on soil conditions and anticipated loading conditions.

b. Panel Designs: Two panel designs and methods of erection were selected for use in the model. The first type was glass-reinforced plastic faces about 1/16 inch (1.6 mm) thick, preformed in 6- x 8-foot (1.8- x 2.4-m) sheets. The foam core was molded in place as described in Section V. The core material extended completely to all edges of the panel. The second type of panel consisted of either plywood or flakeboard faces with a foam core molded in place. One long edge of the 6- x 8-foot (1.8- x 2.4-m) panel had a 2- x 4-inch (50.8- x 101.6-mm) spline attached to the facings; half of the thickness was attached to the panel faces, and the other half extended beyond the face edges to act as a spline for an adjacent panel. The edge of the panel opposite the spline had a recessed groove molded in place for the spline joint. One end of each panel had a groove molded in the foam to allow the panel to be placed over a sole plate.

c. Erection/Fastening: The glass-reinforced, plastic-faced panels were erected by supporting the bottom edge of the panel in a 4-inch- (101.6-mm)-wide pultruded channel bolted to the foundation. At the width intervals of the panels, a vertical 4- x 4-inch (101.6- x 101.6-m)-wide flange pultruded I-beam had been bolted to the bottom channel and the foam sandwich panel inserted into the space between the beam flanges until it was against the web. The joints were bolted as indicated in the preliminary specifications (Appendix B). The specifications also describe sealing of the panel edges/columns. The wood-faced panels were erected and fastened by a spline and plate method and sealed as described in Appendix B.

d. Roof System: The roof system selected was based on the glass-reinforced, plastic-faced panel and I-beam pultrusion erection system described for the wall section. The ends of the panels extending over the edges of the building were capped with 4-inch (101.6-mm) pultruded channels. The peak of the roof was secured by a 6-inch (152.4-mm) pultruded channel (outside) and a 4-inch (101.6-mm) pultruded channel inside bolted together through the roof panels. The roof panels/beams/channels were sealed along the edges with silicone sealant.

e. Finish Work: Finish work included caulking all potential water or air leakage points and then painting. Window and door openings were cut out to remove the face materials from over the rough opening frames. Standard door and window units were installed and trimmed.

f. Observations and Comments on the Model Construction: The large panels were awkward to handle, especially when it was windy.

Close tolerances must be held with the glass-faced panel/pultrusion erection system. The edges of some panels had to be slightly crushed before insertion into the I-beams.

The wood-faced panel/spline erection system was implemented very smoothly; the wind problem associated with large surface areas of the panels was reduced by the use of smaller panels.

g. Specification Revisions: The specification sections for wall panel size, spline joint, and fastening were revised, based on what appeared to be the best system. The revisions are included in Appendix B.

2. ECONOMIC ANALYSIS OF WALL SYSTEMS

The economics associated with the three wall panel systems used in this study (Kemlite,® plywood, and Aspenite®) were examined. The costs of individual panels can be and were compared; however, the costs of the whole wall system must also be considered, since attachment materials can add substantially to the overall structure's expenses. For this analysis, the cost of windows and doors was not considered, since it was assumed that equal numbers of each would be used in all systems.

The wall panels were analyzed first. Table 3 presents the data for the three panel systems used. As shown, the flakeboard-faced panel system is the least expensive per unit of area.

The total wall system was then analyzed in the same manner. Results are presented in Table 4. In the overall analysis, the flakeboard-faced, foam-core sandwich panel was the least expensive. As shown by the data in the tables, the cost of the panel joining system can be a significant factor in the overall wall system.

3. TESTS OF THE MODEL STRUCTURE

Tests and observations were made of the completed model structure. Some of the desired tests could not be performed due to a lack of facilities.

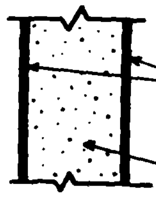
a. Wind Loading: The model structure was subjected to winds of 60 mph (36 km/hr) or greater on several occasions. During storms, the wind velocity may have exceeded this rate. After each wind loading, the structure was examined for any leakage or distress at joints. No problems were observed.

b. Rainfall: The structure experienced rainfall rates of 2 inches (50.8 mm) per hour at least three times during the test period (summer of 1981). At

TABLE 3. COST COMPARISON OF PANELS.

FOAM CORE SANDWICH PANEL COST COMPARISON

6' x 8' FOAM CORE PANEL . KEMLITE® FACING (2) SIDES



KEMLITE® ACRYLIC MODIFIED
BES 283 - EXTR GLASBORD FRP FLAT PANEL

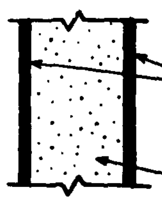
3-1/2" POLYURETHANE FOAM 2.5 PCF

6' x 8' PANEL

FACING				CORE	
FACING	$/EACH	$/SF	$TOTAL	$/SF	$TOTAL
(1) KEMLITE®	$33.74	.70			
				.75	36.00
(1) KEMLITE®	33.74	.70			
		1.40	67.48	.75	36.00

KEMLITE® PANEL	$/Ea.	103.48
	$/SF	2.15

6' x 8' FOAM CORE PANEL, AC EXT. PLYWOOD (2) SIDES



1/4" AC EXT GLUED
PLYWOOD

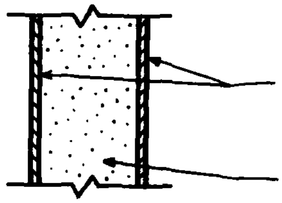
3-1/2" POLYURETHANE
FOAM 2.5 PCF

FACING	$/EACH	$/SF	$TOTAL	$/SF	$TOTAL
(1) 1/4" PLYWOOD SPLICE					
4' x 8'	9.75				
2' x 8'	4.88	.30	14.63		
				.75	36.00
(1) 1/4" PLYWOOD					
4' x 8'	9.75				
2' x 8'	4.88	.30	14.63		
		.60	29.26	.75	36.00

TABLE 3. COST COMPARISON OF PANELS (CONCLUDED).

PLYWOOD PANEL	$/EA	65.26
	$/SF	1.35

6' x 8' FOAM CORE PANEL, ASPENITE® (2 SIDES)



FACING	$/EACH	$/SF	$TOTAL	CORE $/SF	CORE $TOTAL
(1) 1/4" ASPENITE® SPLICE					
4' x 8'	6.68				
2' x 8'	3.34	.21	10.02		
				.75	36.00
(1) 1/4" ASPENITE®					
4' x 8'	6.68				
2' x 8'	3.34	.21	10.02		
		.42	20.04	.75	36.00

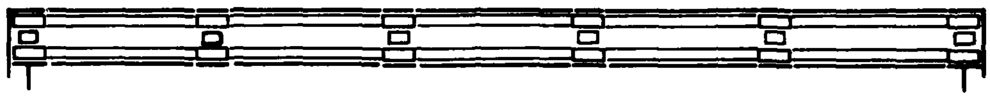
ASPENITE® PANEL	$/EA	56.04
	$/SF	1.17

SUMMARY

	$/SF	$ TOTAL
6'x8' (2) SIDES W/3-1/2" FOAM CORE	2.15	103.40
6'x8' PLYWOOD (2) SIDES W/3-1/2" FOAM CORE	1.35	65.26
6'x8' ASPENITE® (2) SIDES W/3-1/2" FOAM CORE	1.17	56.04

TABLE 4. WHOLE WALL SYSTEM COST ANALYSIS.

<u>FOAM PANEL WALL SYSTEM COST COMPARISON</u>

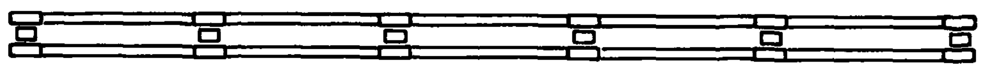


KEMLITE® /PULTRUSION WALL SYSTEM

WALL DIMENSION - 30' x 8'

MATERIALS:	$TOTAL
30' - 4 x 1 1/8 x 1/4 PULTRUDED CHANNEL	83.10
5 - 6' x 8' x 3 1/2' FOAM CORE PANELS W/KEMLITE® FACES	517.40
32' - (4) 4 x 4 x 1/4 x 8' PULTRUDED WIDE FLANGE BEAMS	208.00
16' - (2) 6 x 6 x 1/2 x 8' PULTRUDED ANGLE	168.00
16' - (2) 4 x 4 x 1/2 x 8' PULTRUDED ANGLE	51.04
40 - 3/8" x 5" Zinc Plated Hex Bolts	24.00
	$1051.54

1051.54 ÷ 240 = $4.38/SF



PLYWOOD/WOOD SPLINE WALL SYSTEM

WALL DIMENSION - 30' x 8'

MATERIALS	$TOTAL
30' - 2 x 4 TREATED (SILL PLATE)	12.00
5 - 6 x 8 x 4" FOAM CORE PANELS W 1/4" PLYWOOD FACES	326.30
6 - 8' - 2 x 4's (PANEL SPLINES)	8.10
216' - 1 x 3 (TRIM)	25.00
PAINT	21.00
	$392.40

392.40 ÷ 240 = $1.64/SF

TABLE 4. WHOLE WALL SYSTEM COST ANALYSIS (CONCLUDED).

ASPENITE®/WOOD SPLINE SYSTEM

WALL DIMENSION - 30' x 8'

MATERIALS:	%TOTAL
30' - 2 x 4 TREATED (SILL PLATE)	12.00
5 - 6' x 8' x 4" FOAM CORE PANELS W/1/4 ASPENITE® FACES	280.20
6 - 8' - 2 x 4's (PANEL SPLINES)	25.00
216' - 1 x 3 (TRIM)	21.00
PAINT	
	338.20

$338.20 ÷ 240 = $1.41/SF

<u>SUMMARY</u>

	$/SF	$TOTAL
KEMLITE® WALL SYSTEM	4.38	1051.54
PLYWOOD/WOOD SPLINE	1.64	392.40
ASPENITE®/WOOD SPLINE	1.41	338.20

times, the rainfall and high winds (greater than 40 mph [24 km/hr]) occurred simultaneously. The structure was examined for signs of leaking after each episode, but none were found.

c. Anchoring: The anchorage to the sole plate and to the channel was examined carefully after each wind loading and/or heavy rainfall to observe any problems with the holddown of the structure. No evidence of motion or joint loosening was found.

d. Physical Security: Standard door and window lock hardware was used to secure the structure's openings. The remainder of the building (i.e., the wall panel system), appeared to be at least as resistant to entry as a normal frame-constructed building.

4. DOOR LOADING AND SLAMMING

One of the two exterior doors was subjected to loading as described in Table 2. Figure 14 shows the test setup.

Two hundred and ten pounds pounds (84 kg) of sandbags were slung over the door in a saddlebag fashion. The door (opened to 90°) was checked for plumb using a 4-foot (1.2-m) spirit level prior to loading. The door was left in loaded fashion for 1 hour and rechecked with a spirit level.

No deformation of the door, hardware or wall system was evident.

The other door was subjected to vigorous slamming with no ill effects. The windows had to be opened during this test to prevent air cushioning from affecting the closing door.

5. WEATHER SEALS

Door seals and caulking were satisfactory, as indicated in the discussion of wind loading and rainfall.

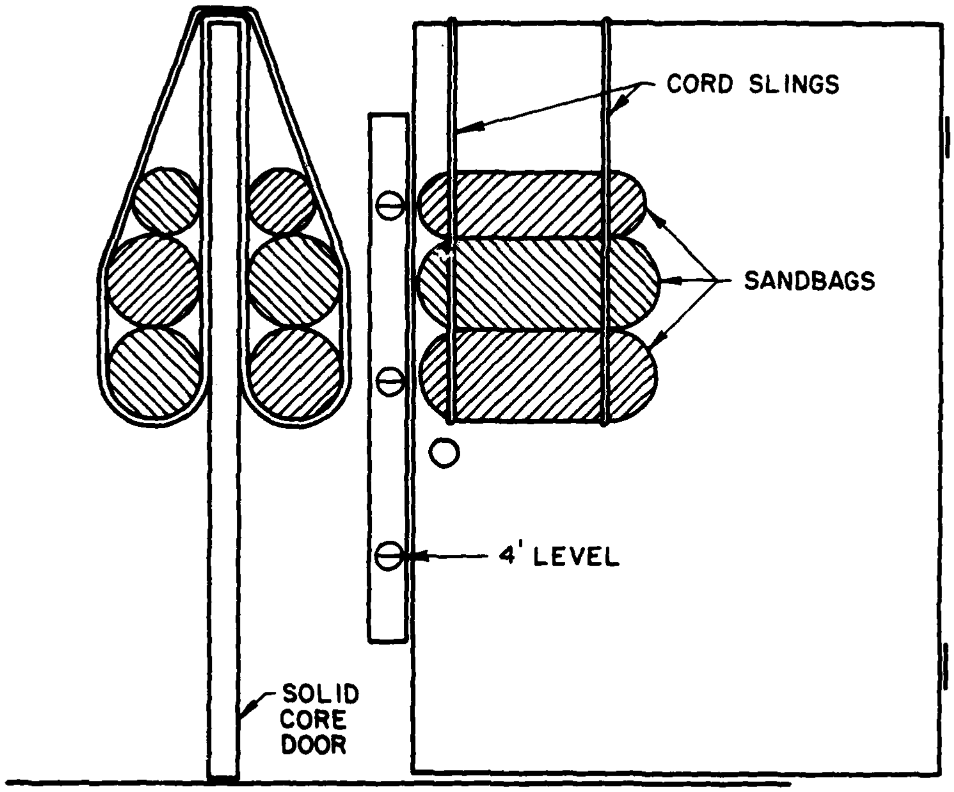


Figure 14. Door Load Test Setup

6. AIRTIGHTNESS

The model structure was tested for airtightness based on the requirements given in Table 2 (see Figure 15).

The test was set up by removing a storm window from the lower portion of a double-hung window, and sealing in its place a 1/4-inch (6.3-mm) piece of plywood with two openings to accommodate a piece of 3-inch (76.2-mm) PVC plastic pipe and a 1/2-inch (6.3-mm) piece of clear plastic hose.

A blower fan was connected to the 3-inch (76.2-mm) PVC pipe, and a monometer was constructed from the plastic hose. ΔP was measured in tenths of an inch.

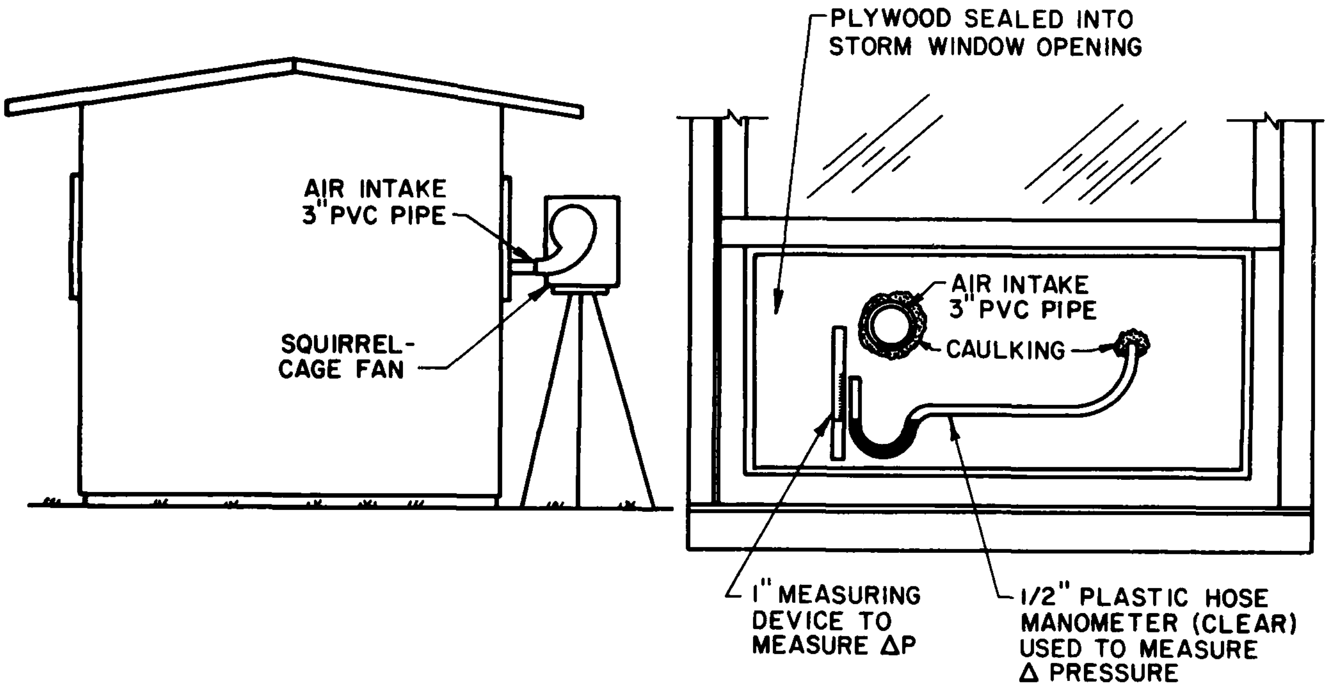


Figure 15. Airtightness Test Setup.

A wind speed measuring device was placed in the suction opening of the fan to measure air speed into the building in feet/minute. The blower was turned on, and the building was pressurized. This test revealed that it was not possible to achieve the required differential pressure of 0.5 inch (12.75 mm).

The air leakage rate observed in the test was compared to ASHRAE Standard Reference 90-75 (Reference 17) and to provisions in an ASTM monograph (Reference 18); it was found that the model was more airtight than most typical residential structures.

The maximum differential pressure developed in the structure was 0.375 inch (9.5 mm) of water. This pressure was retained for at least 20 seconds after the airpumps were turned off. The air flow at this differential pressure was 332 cubic feet per minute (9.4 m^3/min). Since the air flow at nearly equal internal and external pressures would be very low, the air infiltration rate is almost negligible.

7. RELOCATION

The structure was dismantled after 8 months, having experienced few problems. The bolted connections of the vertical columnar wide flange beams to the foundation were somewhat hard to reach, and in most cases, the pultruded angles used to make the connection broke. To prevent this problem, aluminum angles should be used at this joint.

The wood-faced panel and spline system was disassembled easily. Only about 100 feet (3.5 m) of the batten strips must be replaced when the structure is reassembled. Nails and caulking material must also be replaced. The building parts were transported to Tyndall AFB, FL, and were erected in January 1982 in the same layout as the one previously used. The parts were reassembled without difficulty.

SECTION IX

CONCLUSIONS

The following conclusions were derived from this research:

1. Polyurethane foam of the proper formulation is the most appropriate core material for foam wall system panels, especially if panel fabrication will be done on-site.

2. Wood-faced, foam-core sandwich panels having a spline interconnection, a fixed sole plate, and a preassembled top plate is the best wall system for expedient facilities. Other types of wall panel and connections are acceptable, but their costs will generally be higher.

3. The structural systems used in the model developed for this research appear to be satisfactory for relocation and re-erection.

4. The foam-core sandwich panel system is especially appropriate for remote locations because the panels can be constructed on-site by available labor. Panels manufactured in a plant may be competitive for less remote areas if transportation costs are not excessive.

5. The construction criteria and specifications developed for this project are adequate for efficiently constructing expedient facilities.

SECTION X

RECOMMENDATIONS

The wood-faced foam core sandwich panel and spline interconnection system is recommended for rapidly providing housing during disaster recovery mobilization and/or for remote area construction.

It is recommended that standard plans for required structures be prepared so that materials lists can be assembled and any necessary plans made to respond to needs for such structures.

REFERENCES

1. Smith, Alvin. Dome Shelter Construction with Polyurethane Foam. Technical Report (TR) M-225/ADA044992, U.S. Army Construction Engineering Research Laboratory (CERL), August 1977.

2. Williamson, G. R., et al. Inflation/Foam/Shotcrete System for Rapid Shelter Construction. TR M-215/ADA040789, CERL, May 1979.

3. Smith, Alvin. Construction with Field Moldable Polyurethane Foam Blocks. TR M-233, CERL, April 1978.

4. Kao, A. M., et al. Prefabricated Expandable Foam/Wood Structures for Theater of Operations. Interim Report C-45/ADA044991, CERL, September 1979.

5. Smith, Alvin. Feasibility of Structural Foam/Concrete Building for Theater of Operations Use. TR M-231, CERL, March 1978.

6. Styrofoam Sandwich Construction. Dow Chemical Bulletin 171-144, available from Dow Chemical Company, Plastics Department, Midland, Michigan.

7. The Design and Production of Structural Sandwich Panels with Polycell Foam System Cores. Polytron Corporation, Technical Data Bulletin 59-4, 21 May, 1959.

8. Building With Plastic Structural Sandwich Panels. Prepared by Massachusetts Institute of Technology, Department of Architecture, under a grant in aid from the Plastics Division of The Monsanto Co.

9. National Academy of Sciences, National Research Council. Sandwich Panel Design Criteria. Publication 708, Summmary of a Research Correlation Conference Conducted by the Building Research Institute, November 1959.

10. Darvas, R. Design Considerations for Sandwich Panel Construction. Wayne State University Polymer Conference Series, Cellular Plastics, 24-28 May, 1965.

11. Kuenzi, E. W. Minimum Weight Structural Sandwich. Research Note FPL-986, Forest Products Laboratory, U.S. Department of Agriculture, January 1965.

12. Hughes, B., and Wajda, R. L. Plastic Sandwich Panels with Various Foamed Core Materials and Their Behavior Under Load. Paper 29, Conference on Plastics in Building Structures, The Plastics Institute, London, June 1965.

13. Doherty, D. J., Ball, G. W., and Walker, G. B. The Physical Properties of Rigid Urethane Foam Sandwich Panels. Paper 33, Conference on Plastics in Building Structures, Plastics Institute, London, June 1965.

14. Fisher, B. N. The Design and Structural Applications of Urethane-Cored Sandwich Panels. Paper 34, Conference on Plastics in Building Structures, Plastics Institute, London, 1965.

15. Merritt, R. The Design of a Plastic Structural System. Technical Report M-121/ADA011224, CERL, 1975.

16. Becker, W. E. U.S. Sandwich Panel Manufacturing/Marketing Guide. Technomic Publishing Co., 1968.

17. ASHRAE Handbook of Fundamentals. American Society of Heating, Ventilating, and Air Conditioning Engineers. Chapter 21, 1977.

18. Building Air Change Rate and Infiltration Measurements. ASTM Special Technical Publication 719, American Society for Testing and Materials, pp. 12-16, 1980.

APPENDIX A

REPRESENTATIVE MANUFACTURERS

Materials manufacturers and suppliers contacted included the following list. It is representative and is not to be considered as complete. Inclusion does not represent an indorsement of the materials/products.

CS&M Incorporated
Rt 1, Chino Airport
Chino, CA 91710
714-597-1815

GREFCO, INC.
Building Products Division
2905 Butterfield Road
Oak Brook, IL 60521
312-654-4500

Cyclops Corporation
Elwin G. Smith Division
100 Walls Street
Pittsburgh, PA 15202
412-761-7474

Multiloc Corp.
222 W. Adams St.
Chicago, IL 60606
312-641-5180

National Steel Products Company
P.O. Box 40490
Houston, TX 77040
713-466-2211

Elliott Company of Indianapolis, Inc.
9200 Zionsville Road
Indianapolis, IN 46268
317-291-1213

Advanced Structures Corporation
235 West Industry Court
Deer Park, NY 11729
516-667-5000

Kornylak Corporation
400 Heaton St.
Hamilton, OH 45011
513-863-1277

U.S. Systems Corporation
496 Railroad Ave.
P.O. Box 955
Logan, OH 43138
614-385-5885

APPENDIX B

PRELIMINARY FOAM WALL BUILDING GUIDE SPECIFICATIONS

1. BUILDING SITE

- The proposed building site shall be cleared of all vegetation that would interfere with slab location and building construction.

- The site shall be free of standing water, and finish grading shall provide for drainage away from the building.

- All fill material shall be soil or soil-rock mixture which is free from organic matter and shall contain no rocks or lumps over 3 inches in greatest dimension.
  Fill shall be compacted to provide adequate bearing strength.

2. SLAB PREPARATION

- A 4-inch granular cushion under all interior concrete slabs-on-grade shall be clean mineral aggregate with particle size grading within the following limits:

  100% Passing through 1-inch mesh
  $\leq$ 5% Passing through No. 4 sieve
  $\leq$ 1% Passing through No. 20 sieve

3. FORMWORK

- All form material shall be No. 2 grade, seasoned, surfaced four sides.

- Construction of all forms shall be sufficiently tight to prevent leakage of concrete, and able to withstand excessive deflection when filled with wet concrete.

- Form for all cast-in-place concrete to the shapes, sizes, lines, and dimensions indicated on the drawings. Provisions for all openings, offsets, recesses, and other features of work shall be made as required by drawings.

- Care will be taken in the layout of forms to avoid unnecessary cutting of concrete after it is in place.

- 1/2-inch x 6-inch steel anchor bolts to be cast into the concrete shall be located prior to pouring the concrete by using templates specified in the drawings.

- Forms shall be braced and tied together to maintain position and shape and ensure safety to workers. All bracing and supporting members shall be constructed of ample size and strength to safely carry, without excessive deflection, all dead and live loads to which they will be subjected.

- Side forms for footings may be of earth, provided the soil will stand without caving and the sides are cut to the minimum dimensions indicated on the drawings.

4. ELECTRICAL

- All electrical outlets will be 120 V, surface-mounted receptacles as specified in drawings.

- Electrical wall switches shall be surface mounted with all wiring encased in conduit, as specified in drawings.

- All rough-in and finish electrical work shall be in accordance with CE-E-52 — U.S. Army Corps of Engineers <u>Guide Specification for Emergency Construction Electrical Work - Interior</u>.

5. PLUMBING

- All plumbing will be in accordance with CE-E-44-1 -- U.S. Army Corps of Engineers Guide Specifiction for Emergency Construction - Plumbing.

6. REINFORCEMENT

- All concrete reinforcement materials shall be new and free from rust. Fabrication and placement shall be as specified in drawings and in accordance with CE-E-5 -- U.S. Army Corps of Engineers Guide Specification for Emergency Construction - Concrete.

7. CONCRETE PLACEMENT

- Prior to placement of the concrete, all other work performed by the other trades shall be checked to verify completeness.

- A 4-inch concrete slab with 6-inch x 6-inch - 4/4 welded wire fabric (WWF) shall be poured in accordance with CE-E-5 -- U.S. Army Corps of Engineers Guide Specifications for Emergency Construction - Concrete.

8. BUILDING SHELL CONSTRUCTION PANEL CONSTRUCTION

- A building shell consisting of four walls and a roof shall be constructed from 2 pounds/cubic foot (minimum density) polyurethane foam core sandwich panels with a weather- and wear-resistant facing material on the exterior and a wear- and flame-resistant material on the interior.

- Panel construction may coincide with slab preparation and curing.

- Panel construction shall be by pouring, spraying or spray frothing polyurethane foam into panel molds which will contain an interior and exterior facing material. The foam shall expand to fill the mold and adhere to the facing material. Foam shall be introduced into the mold so that vertical rise shall be along the short dimension of the panel.

- Panels shall be constructed to a standard four-foot-wide dimension. Height and length dimensions shall be in accordance with the drawings and shall be achieved by blocking out appropriate portions of the forms. The same procedure will be exercised in locating door and window openings, i.e., inclusion of frames attached at the proper location and secured to the facing materials to prevent displacement during foam expansion.

- Interior partitions will be of similar construction, with the exception that a weather-resistant facing material is not required but may be used.

9. WALL CONSTRUCTION

- Wood-faced panels will be molded in four-foot widths with a spline attachment provision. (The spline joint will consist of one 2- x 4-inch nominal board nailed within and flush with the edges of the face material before foaming the core. After removal of the panel from the mold, a bead of acrylic latex will be placed along the exposed surface of this 2 x 4 and another 2 x 4 will be nailed to it so that the edges are aligned and straight. The panel mold will be equipped with an insert that will block out a groove in the foam core on the side opposite the spline and along one end. The blockout will provide a clear depth of 2-1/4 inches at each specific edge (Figure B-1)).

- Wood-faced panels will be erected by inserting the recessed groove at the bottom of the panel over a sole plate which has been secured to the foundation/floor system (Figure B-3). The panel will be oriented such that the edge recessed groove coincides with the spline extending from the adjacent panel. The panel being erected will then be moved into contact with the adjacent panel in such a manner that the spline and groove properly align and engage.

- A completed wall of wood-faced panels will be secured with a top plate assembly which is prefabricated for the purpose in accordance with details on the applicable drawing (Figure B-2).

- A batten strip and necessary flashing will be nailed through the bottom edge of the panel and into the sole plate in accordance with the applicable drawing detail (Figure B-3).

- Corner joints will be by spline joint (Figure B-4).

- Vertical batten strips will be nailed to the spline joints through the wood panel faces on both the exterior and interior walls in accordance with applicable drawing details (Figure B-1).

- Exterior batten edges will be caulked with acrylic latex caulking to make the vertical and horizontal joints watertight.

- Wood components will be painted with a minimum of two coats of water-resistant paint.

10. ROOF CONSTRUCTION

- Roof construction shall consist of a wood truss, wood decking system selected by the designer. Roof pitch and overhang shall provide for adequate drainage of the heaviest anticipated rainfall.

- Connection to the wall system shall be by nailing to the top plate of the wall after it is secured and aligned.

- Roof finish shall be as specified on applicable drawings.

11. INTERIOR PARTITIONS

- Interior partition wall panels shall be of the same materials as exterior panels with interior facing materials on both surfaces. Attachment to exterior walls will be by spline joint (Figure B-5).

- Wall construction shall be the same as for exterior walls.

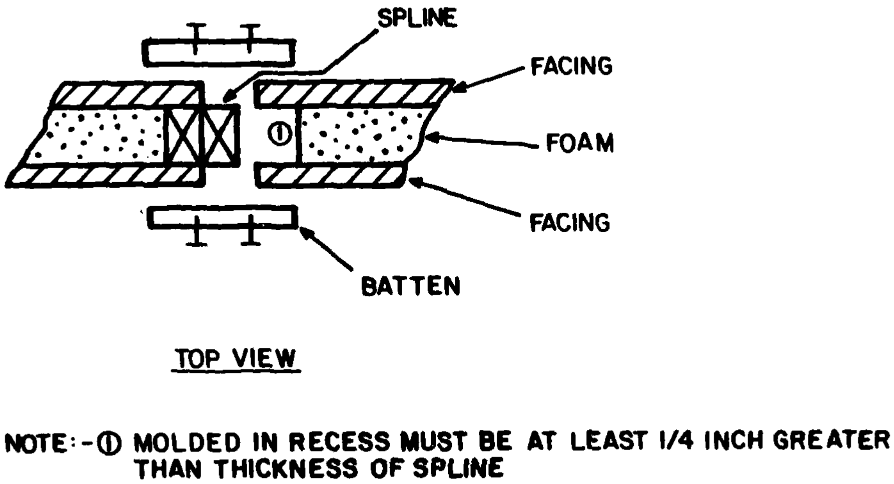


Figure B-1. Panel-to-Panel Joint With Interior and Exterior Battens.

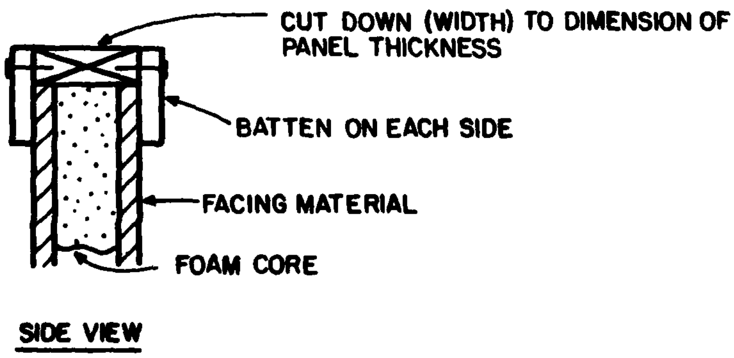


Figure B-2. Top Plate To Be Prefabricated. Installation Includes Nailing At Each Wall Panel Spline.

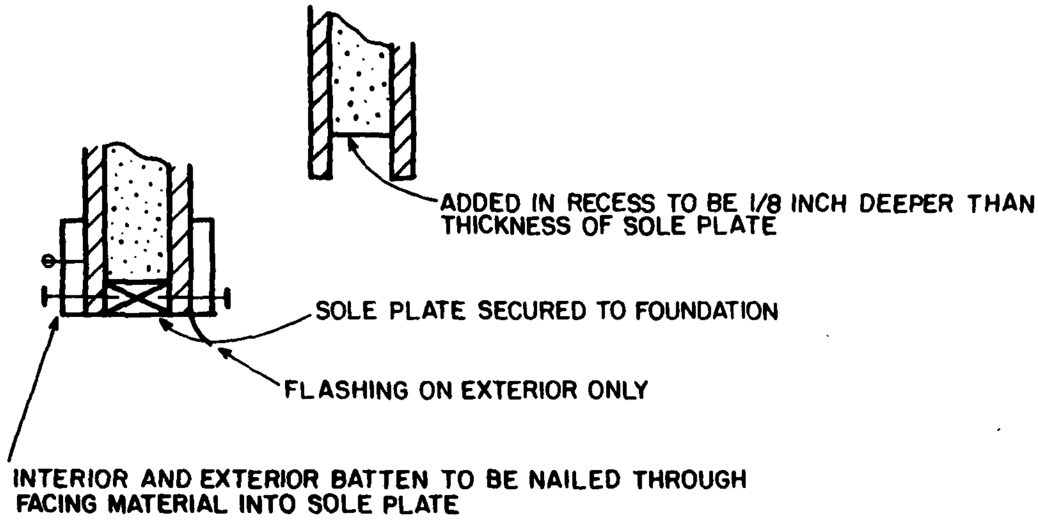


Figure B-3. Foundation Attachment Detail.

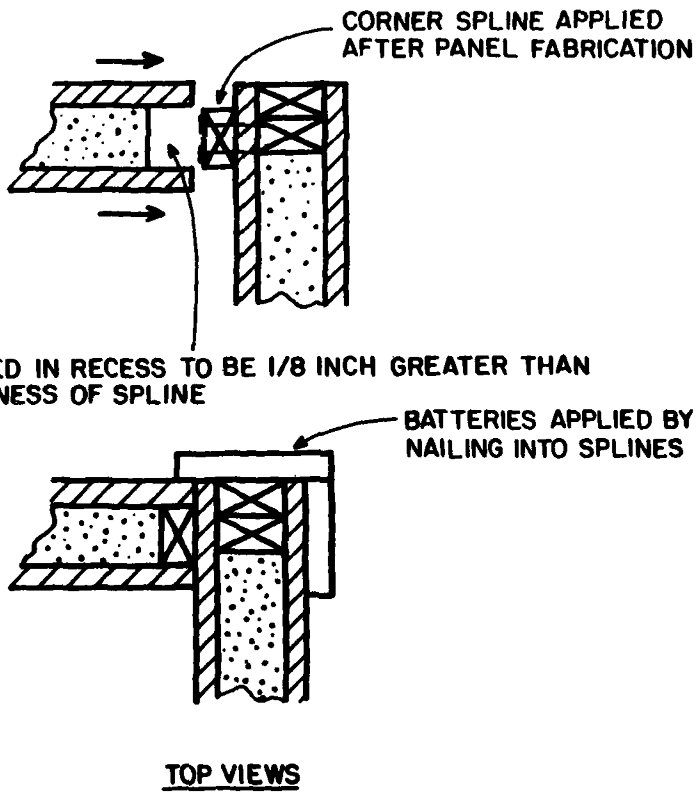


Figure B-4. Corner Detail.

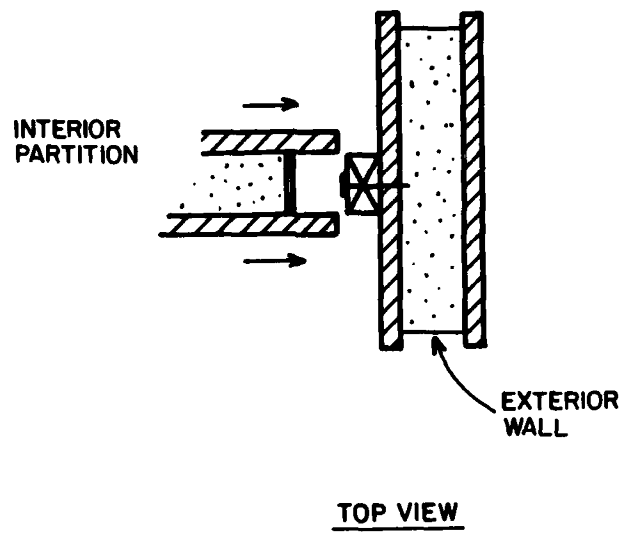


Figure B-5. Interior Partition To Exterior Wall Joint.

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