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THE UNIVERSITY OF ALBERTA

THE DEVELOPMENT OF A MANUFACTURING PROCESS FOR THE PRODUCTION OF WALL PANELS FOR MULTIPLE-FAMILY DWELLINGS

by

(C) KRISHAN LAL SURI

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

DEPARTMENT OF MECHANICAL ENGINEERING

EDMONTON, ALBERTA

SPRING, 1974

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "THE DEVELOPMENT OF A MANUFACTURING PROCESS FOR THE PRODUCTION OF WALL PANELS FOR MULTIPLE-FAMILY DWELLINGS" submitted by KRISHAN LAL SURI in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

J. Sprague
Supervisor

A. Craggs

....

Date April 26/74

ABSTRACT

This study was undertaken to develop a manufacturing process for the production of wall panels for multiple-family dwellings, within the income of low-to-medium income family. Factory manufactured pre-finished sandwich panel construction was designed as an economic substitute for on-site construction using conventional building materials. An efficient and economic locking mechanism including load bearing studs was developed for the sandwich panel joints.

To determine the economic feasibility of the chosen system, design of a manufacturing facility for the sandwich panel was included in this study.

The manufacturing cost of the sandwich panel has been found lower than prevailing costs of the conventional material. Besides the material costs, significant savings towards erection costs of homes are anticipated by implementing the designed system.

ACKNOWLEDGEMENTS

The author is highly grateful to Dr. J.C. Sprague for his guidance and supervision of this study. Thanks to Mrs. Carol Reed for typing the thesis.

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INTRODUCTION

Purpose

The purpose of this study is, "To develop a manufacturing process for the production of wall panels for multiple-family dwelling system, that is appealing, structurally strong and within the income of the low-to-medium income family".

The average dwelling cost increased from $15,229 to $22,553 over the period 1963-1972 [1]. The index for the cost of building material (100 for the base year 1961) rose to 159.6 during the period 1961-1972. The index for the wage rate of construction workers increased to 233.3 and the composite index for the construction cost increased to 194.6 over the period 1961-1972.

In spite of increases in the cost of dwellings, in the year 1972 housing construction reached record high levels. Housing starts increased by 7 percent to approximately 250,000 units and completions rose to approximately 232,000 units. Market demand, for the 232,000 completed dwellings was considered high. Single family and duplex units were highest in demand. Completion in this category in metropolitan areas totalled 64,888 units and the number of unoccupied units at the end of the year was 4,644. Out of the unoccupied dwellings the majority were in the price range of $20,000 to $40,000. This indicates a strong need for more low cost dwellings. The demand for the newly completed row and apartment dwellings was also high. The high demand for the housing can be attributed to rising incomes and the increase in the population in the 25-34 age group.

To offset the effect of continuously rising costs of construction manpower, the trend in the housing industry is to develop factory built housing systems.

With the development of a wide range of light weight, foam plastics at comparatively low prices and low maintenance sheet materials, the application of prefabricated, light weight, structurally strong sandwich panels seems to be very promising for factory built housing systems to replace the high cost conventional building materials.

In this study an attempt has been made:

1. To develop a system that will provide factory built prefinished component packages for homes.

2. To build low cost houses by reducing the construction costs through mass production of homes as compared with the individual construction.

3. To substitute economical sandwich panels for the conventional building materials.

Methodology and Scope

To achieve the purpose this study expands on other studies in the department [2,3] into multiple-family dwelling units.

The feasibility of substitution of structural sandwich panels for the conventional building materials has been studied in this report.

The sandwich panels are manufactured in the factory to be directly erected on the construction site with a suitable locking mechanism. A wood and steel structure has been designed to support the loads.

A structural sandwich panel is basically a stressed skin structure. The sandwich construction panel is comprised of strong, comparatively thin sheet material bonded to a thick, light weight core material. The stressed skin action is achieved with the skins taking the direct tensile and compressive stresses and the core taking shear stresses and preventing local buckling of the thin skins. The major contribution of the light thick core material is to keep the skins away from the neutral axis providing a high section modulus with a comparatively light structure. This property of the sandwich structure offers the highest efficiency obtained from the thin skins in either beam or column loading.

The following parameters have been checked theoretically with respect to the skins, the core materials and the sandwich construction.

1. Structural stability
2. Thermal insulation
3. Fire resistance
4. Water and vapour absorption and transmission
5. Sound insulation
6. Adaptability with respect to appealing and acceptable finishes.
7. Span capabilities
8. Ease in transportation over long distances

9. Ease of warehousing and site erection

10. Overall economy in panel manufacturing.

Several thin sheet materials were studied for use as skin material for the sandwich construction. Some of these materials are plywood, glass-fibre-reinforced plastic, paper plastic, oil treated hardboard, particle board, rigid polyvinyl chloride (P.V.C.), steel and aluminum sheets.

Similarly several materials such as paper honeycomb, extruded particle board, hardboard, extruded foam polystyrene, bead foam polystyrene, foamed rigid polyvinyl chloride, rigid polyurethane foam were studied as prospective core materials for the sandwich construction.

The selection of optimum core and skin materials was made with respect to the housing requirements prevailing in Northern Canada.

A manufacturing facility has been designed for the manufacture of the sandwich panel, based on a yearly requirement for 500 homes of the chosen two storey quadruplex multiple dwelling model. The selling price of the sandwich panel is determined by the annual equivalent cost of the manufacturing facility.

CHAPTER I

THE MULTIPLE-FAMILY DWELLING SYSTEM

1.1 Problem Statement

The increasing need for urban housing has encouraged the trend to multiple family dwelling complexes. In the wake of the surge in multi-family housing in Canada, and interest of some large producers in full systems, the Division of Building Research arranged a field and factory study with leading system contractors in Northern Europe (September 1966 to September 1967, [4]). 10% to 25% direct savings gained through mass production, reduced manpower requirement and shortened construction financing has been reported.

The system reported in [4] uses large precast concrete panels for the major components of the building such as crosswalls and gables, floors, stairs, landings and, sometimes unit bathrooms, partial kitchens, precast foundations and basements.

The precast panels are finished at the site. The interior and services are included in advanced subsystems. Total factory and site work is reported to involve 500 to 800 man hours for a three bedroom dwelling unit. The traditional home construction in North America generally requires from 1100 to 1400 man hours of site labour.

To develop a system to provide factory manufactured major components for dwelling units for the low-to-medium income family requires study into the feasibility of using other construction materials than conventional materials.

In this study an attempt was made to build multiple-family dwellings, using light weight prefinished sandwich construction panels for the walls and the roof systems. As a part of the total system a suitable manufacturing facility for the sandwich panel has been designed in Chapter IV.

1.2 Models of the Multiple-Family Dwelling Units

The models of multiple-family dwelling systems studied include two, three and four bedroom units.

1.2.1 Two Bedroom Unit

The two bedroom unit shown in figures 1.1 and 1.2 has a floor area of 384 square feet per floor. The kitchen, living and dining rooms are located on the main floor and the bedrooms and bathroom on the second floor. The unit should meet the requirements of a married couple with no or one child. The dwelling has two bedrooms of 132 and 126 square feet in area. The living room and the dining room area are 132 and 126 square feet respectively. The kitchen area is about 54 square feet.

1.2.2 Three Bedroom Unit

Figures 1.3 and 1.4 show the floor plans for the main and the second floors of a three bedroom dwelling. The main floor area is 528 square feet and contains living and dining rooms, kitchen and a 1/2 bathroom. The second floor area including

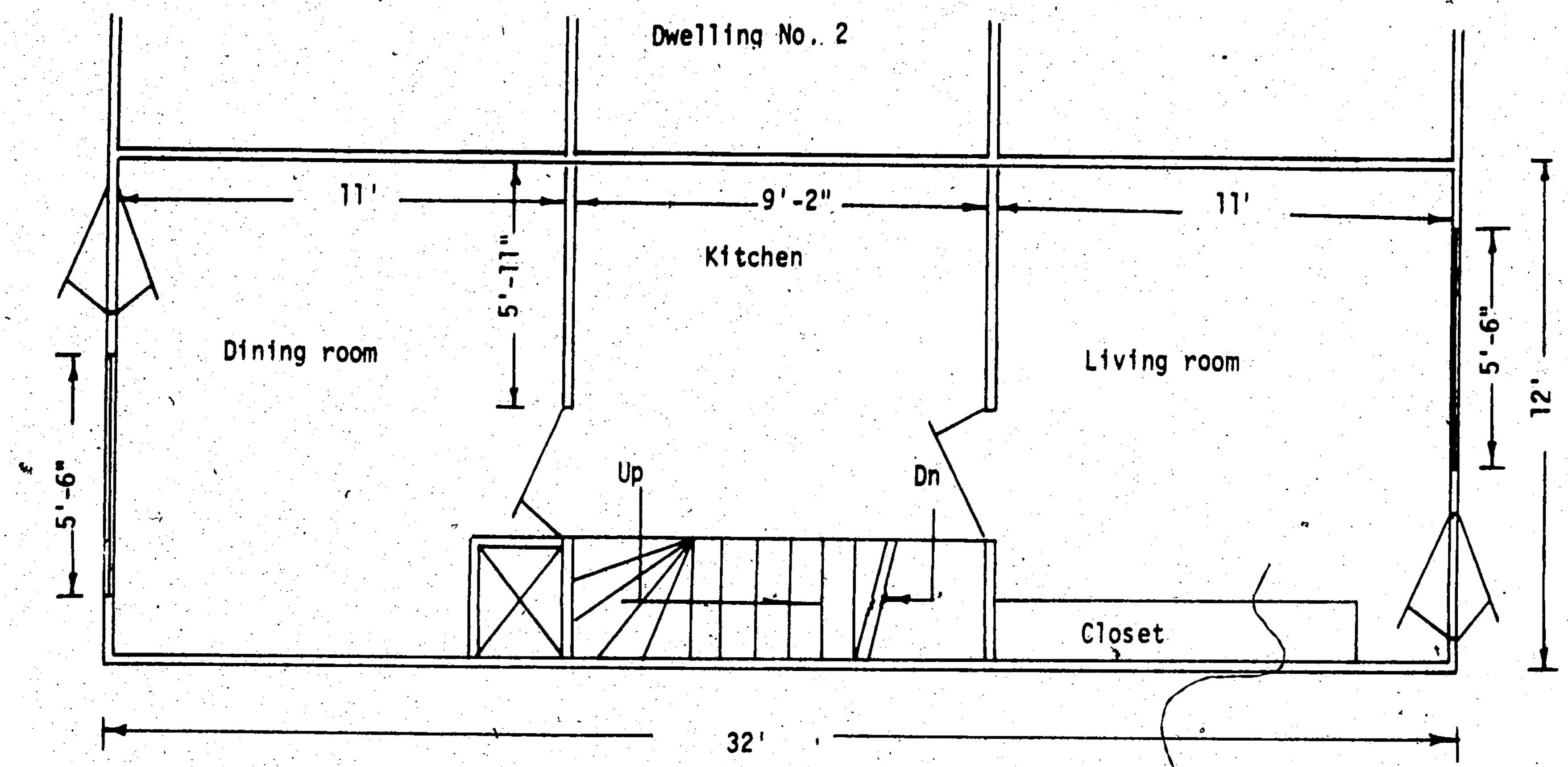

Figure 1.1 768 square feet two bedroom two storey dwelling unit floor plan (main floor)

Scale: 1/48 (J"=4')

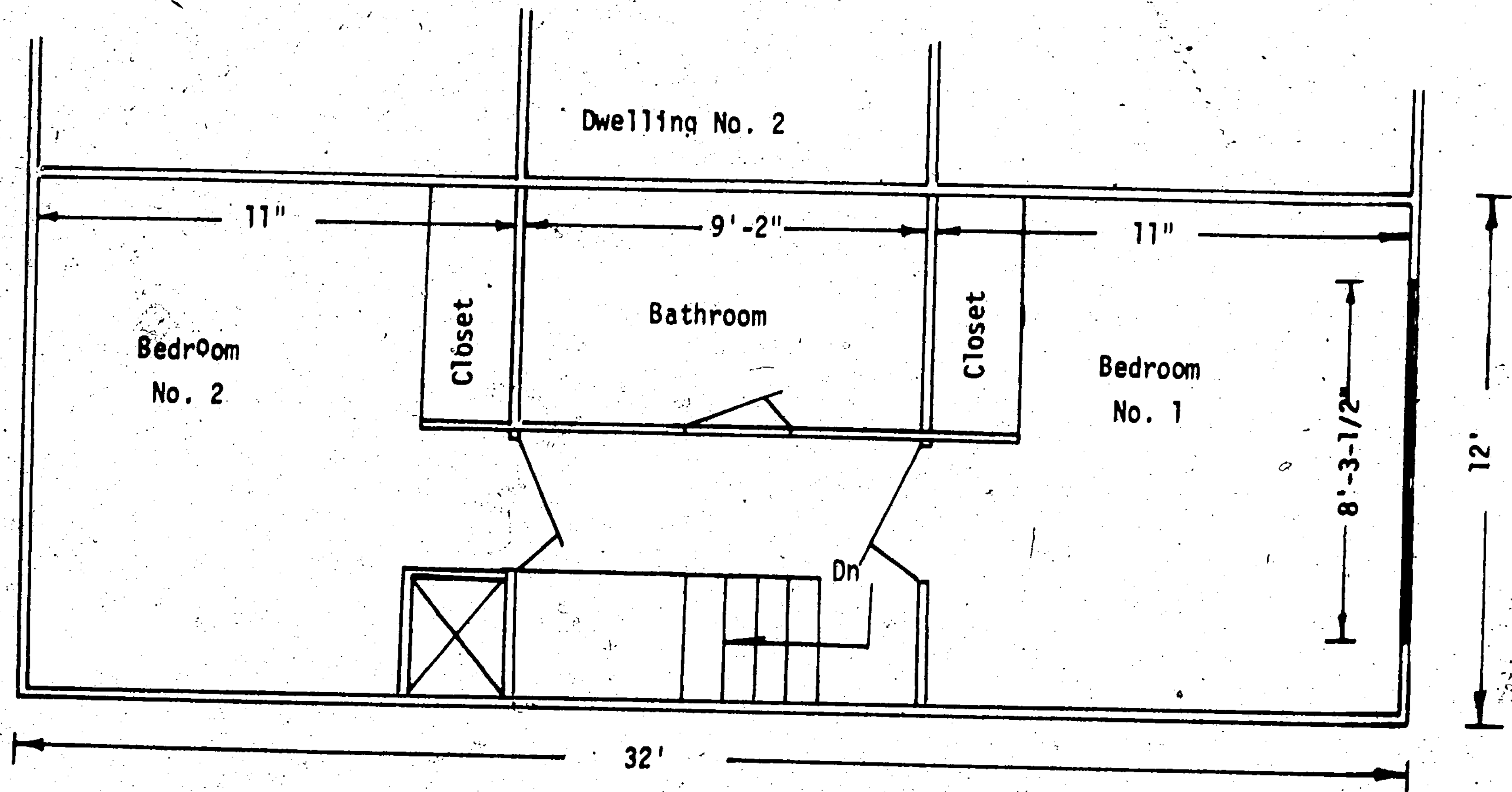

Figure 1.2. 768 square feet two bedroom two storey dwelling unit floor plan (second floor)

Scale:1/48 (1" = 4'

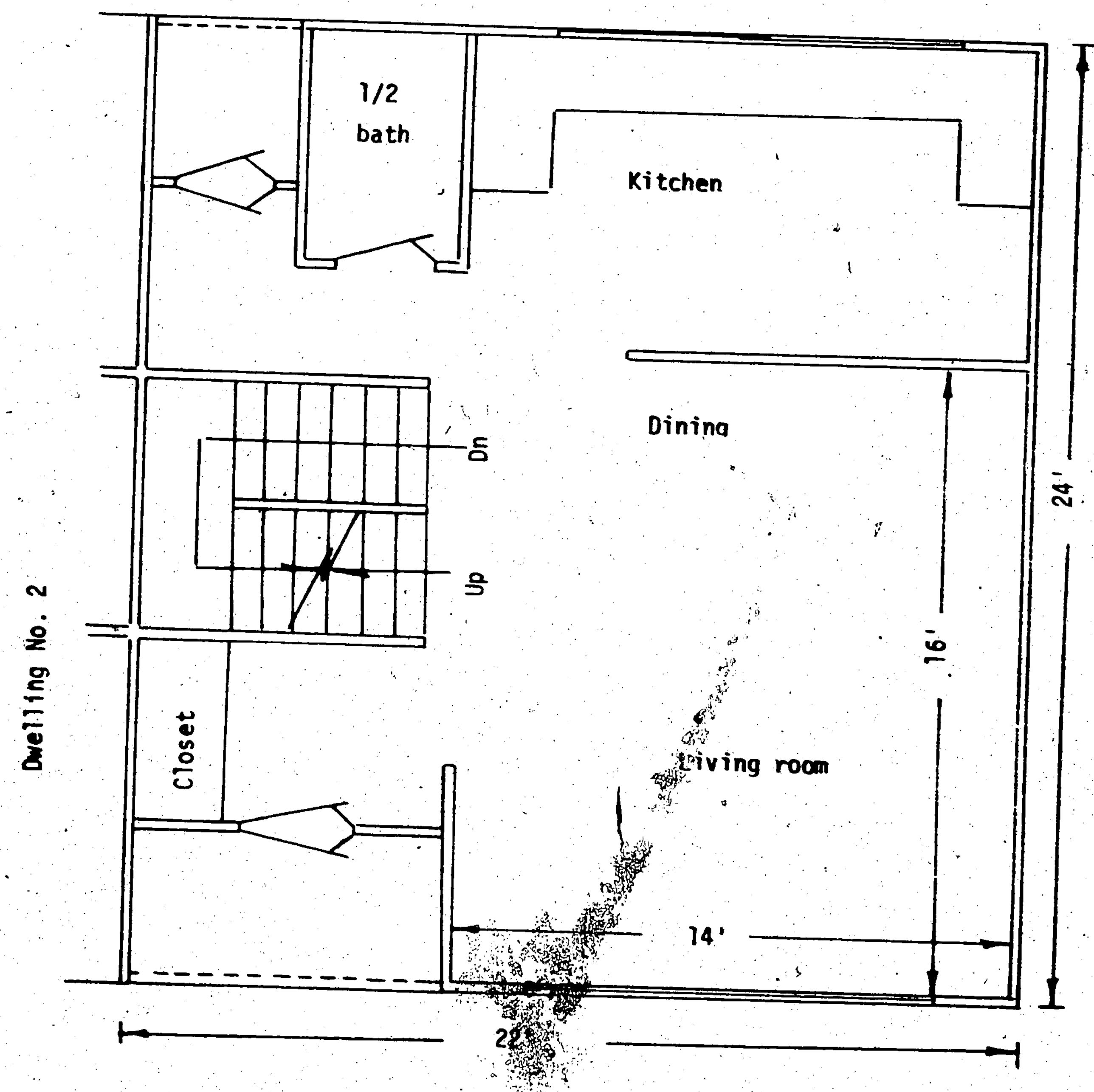

Figure 1.3 1056 square feet three bedroom two storey dwelling unit floor plan (main floor)

Scale: 1/48 (1"=4')

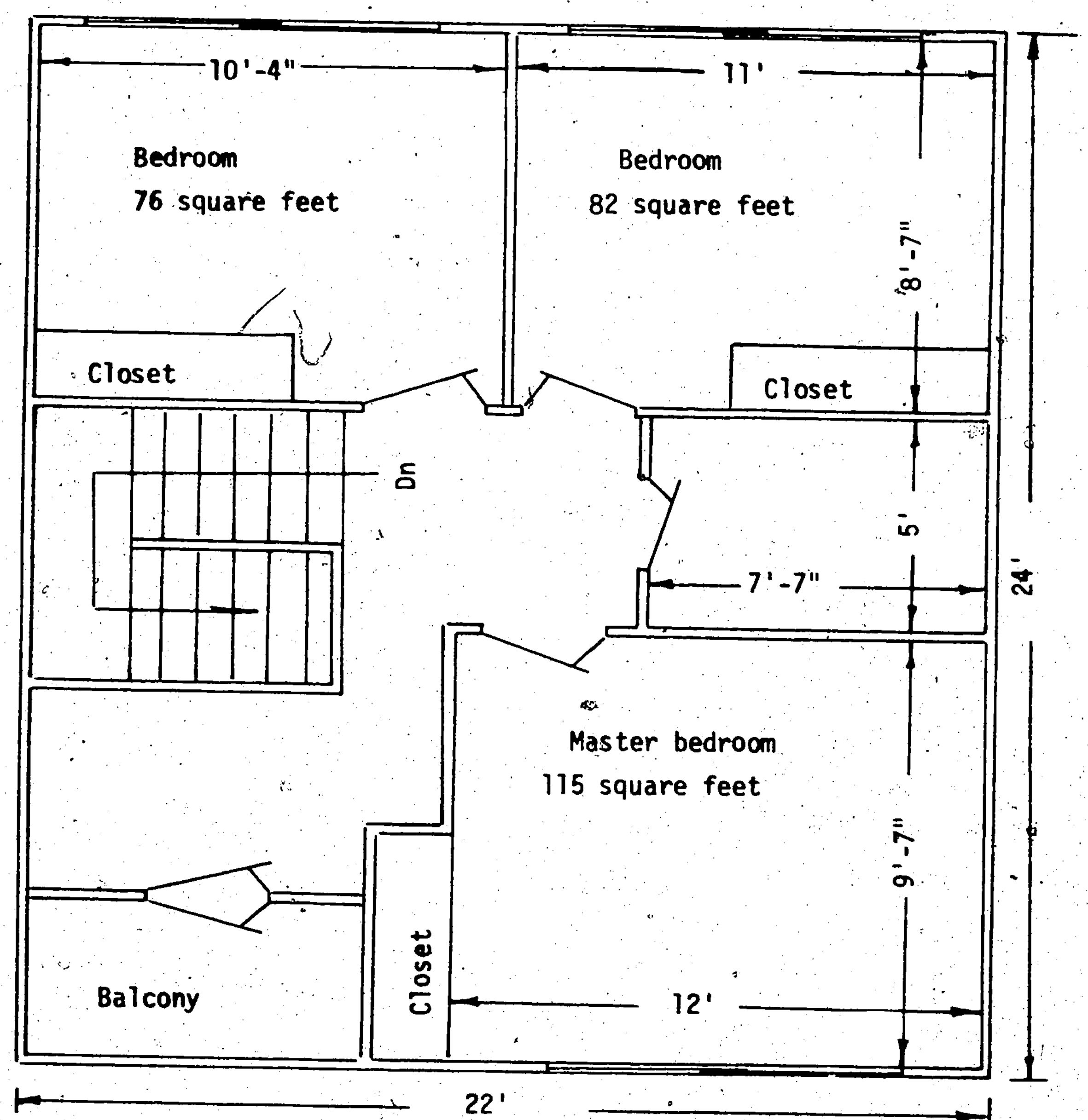

Figure 1.4 1056 square feet three bedroom two storey dwelling unit floor plan (second floor)

Scale: 1/48 (1"=4')

balcony is 528 square feet and contains three bedrooms and a main bathroom. Area of master bedroom is 115 square feet and other two bedroom areas are 82 and 76 square feet. The balcony area is 32 square feet. The dwelling unit should meet the requirements of a family with two to three children.

1.2.3 Four Bedroom Unit

Figures 1.5 and 1.6 show the floor plans for the main and second floors of a four bedroom dwelling. Each floor area is 576 square feet. The main floor contains a living or family room, 192 square feet in area, a kitchen, 64 square feet in area together with 80 square feet area for the dining room and a half bath 24 square feet in area. The second floor contains four bedrooms and a full bathroom. The area of the master bedroom is 123 square feet and the other three bedroom areas are 96, 80 and 102 square feet. The main bathroom has an area of 48 square foot. The dwelling unit should be of interest to a family with two to three children.

1.3 The Chosen Model for Detailed Design

The chosen model for detailed design is a two storey quadruplex unit. The unit is comprised of two bedroom dwellings. The floor area per floor for each dwelling is 384 square foot. Each dwelling has a living room, a dining room, a kitchen, a bathroom and two bedrooms. The living and dining rooms together with the kitchen are located on the main floor and bedrooms to-

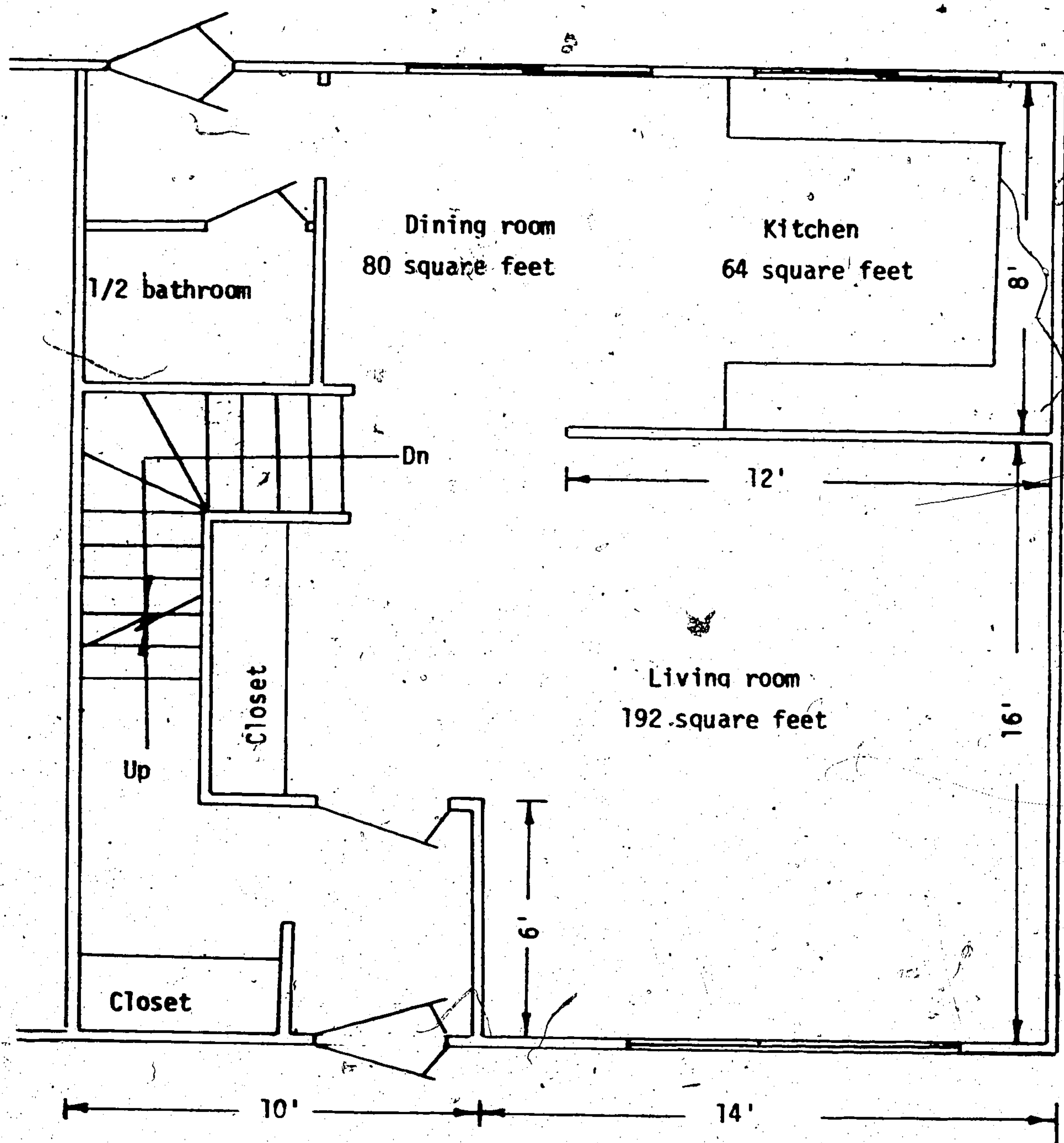

Figure 1.5 1152 square feet four bedroom two storey dwelling unit floor plan (main floor)

Scale: 1/48 (1"=4')

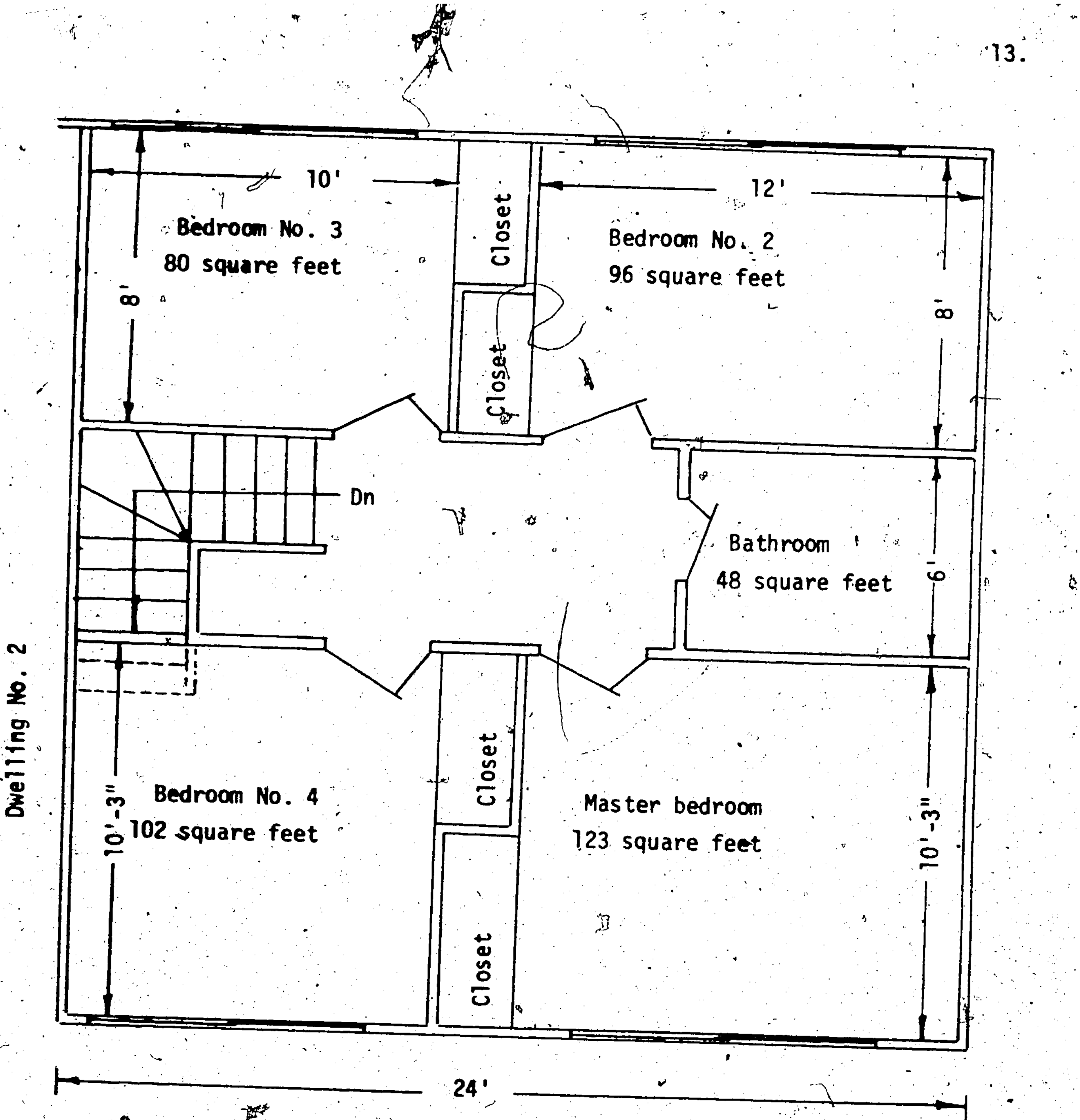

Figure 1.6 1152 square feet four bedroom two storey dwelling unit floor plan (second floor)

Scale: 1/48 (1"=4')

gether with the bathroom are located on the second floor. Each dwelling has separate main entrances located in the front and the rear. The floor plans of the dwellings of the chosen model are shown in figures 1.1 and 1.2.

1.3.1 Lot Areas

Lot areas (for each dwelling unit) shall not be less than 2,000 square feet [5].

1.3.2 Yard Sizes

The specified yard sizes are:

1.3.2.1 Rear Yard

The rear yard shall not be less than 25 feet from the nearest point of the main wall of the dwelling to the rear lot line. In addition where the required window of a living room faces the rear, distance from the window to the rear lot line shall be not less than 35 feet clear of any obstruction. On a corner lot, the rear yard may be measured on either of the two sides of the house furthest removed from the two intersecting streets.

1.3.2.2 Side Yards

Side yards, clear of all projections except a 2 feet eave projection and a one foot chimney projection, shall be not less than 4 feet for a one-storey building plus 2 feet for each additional storey or partial storey except as provided in the following:

1. where a building wall adjacent to a side lot line contains windows, the side yard shall be increased if necessary to meet the Fire Protection requirements of Residential Standards,

2. a side yard may be less than required above where the building wall complies with the Fire Protection requirements of Residential Standards, provided that a registered easement on the adjacent property permits maintenance access along the side of the building for a width of 4 feet for one storey buildings plus 2 feet for each additional storey or partial storey.

1.3.3 Width of Subdivision Lots

Lot widths will normally be calculated from the yard sizes of individual houses. In applications for subdivision acceptance, where the house type is not known, a minimum average interior lot width of 50 feet for detached and 35 feet for each half of a semi-detached house should be provided. On corner lots, where house types are not known, the minimum lot width for detached housing should be 55 feet and for each outside half of a semi-detached house, 40 feet.

In accordance with the above mentioned regulations the lot size chosen for the quadruplex unit is 112 feet x 72 feet (area 8,064 square feet). The layout of the chosen unit is shown in figure 1.7.

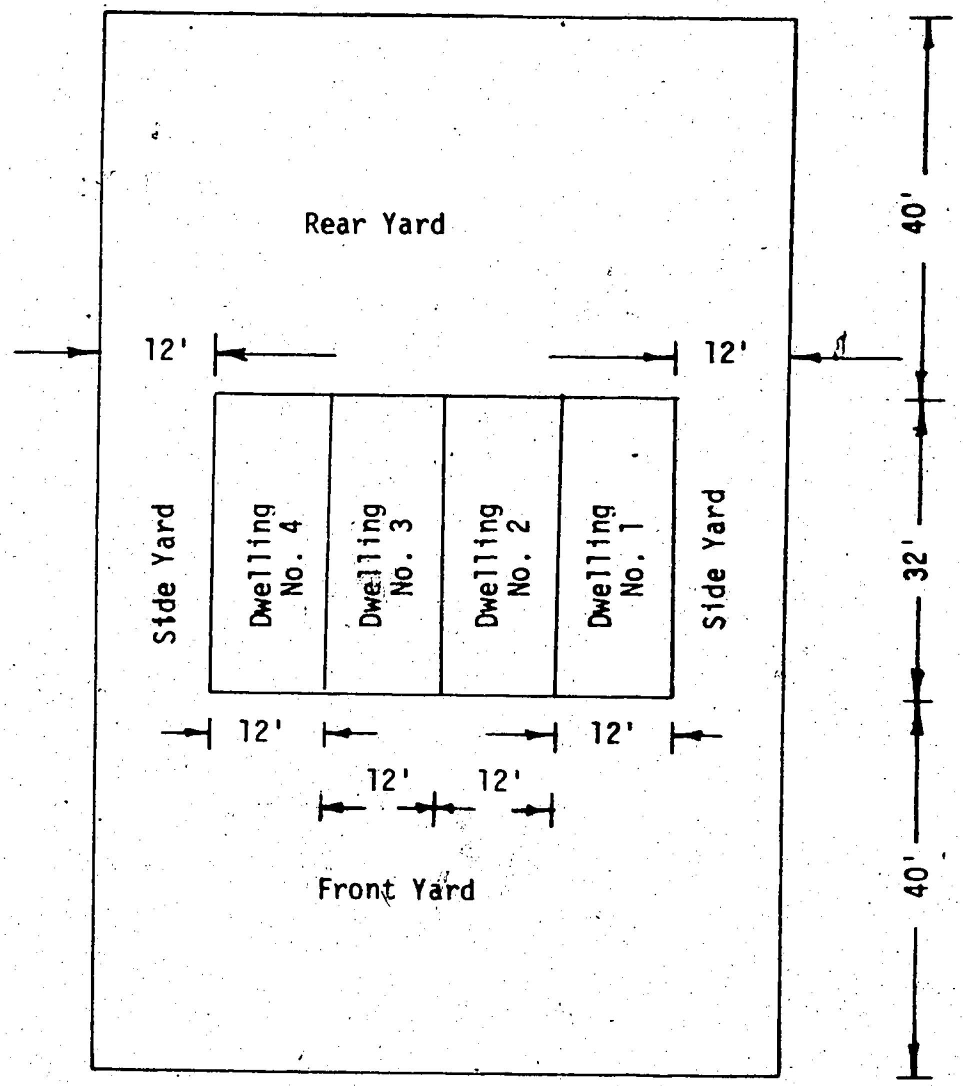

Figure 1:7 Layout for 768 square feet floor area two storey, quadruplex unit on 8064 square feet lot.

Scale: 1/240(1"=20')

CHAPTER II

THE SANDWICH PANEL DESIGN

2.1 Selection of the Panel Skins, Core and Bonding Materials

A sandwich panel essentially is a stressed skin structure. High structural strength is obtained from thin skin material by bonding to a relatively thick and soft core material.

The skins carry the direct stresses when the sandwich is loaded as a beam, column or diaphragm; whereas the core keeps the skins away from the neutral axis to provide higher section modulus, stabilizes the skins against local buckling and wrinkling and carries shear stress. The core material chosen for this study will also provide thermal insulation.

2.1.1 Skin Materials

Table 2.1 lists the tentative properties of some of the skin materials, for the purpose of a comparative study.

A brief study of some of the skin and core materials was completed in this chapter.

2.1.1.1 Steel

Steel is one of the most prospective materials for use as skins in sandwich panel construction. It offers the following advantages.

1. High stiffness factor (EI) permits use of longer spans for limited allowable deflections.
2. Good dimensional stability.

Table 2.1

Properties of Skin Materials for Sandwich Panel Construction

Sheet Material	S.G.	E, Axial	T_y,ULT.	T_W Working	Dimension response	Flame Spread	Other
Steel ASTM A 446	7.85	29 x 10^6	37000Y	22000	.065%(T)	0	
Aluminum HA.4.MC10-H16	2.7	10 x 10^6	21000Y*	12000*	.13%(T)	0	
Fibre Glass Plastic	1.4	1 x 10^6	8500	2100	.12%(T)	60	Wet degrades
Paper Plastic	1.4	1.1 x10^6	16000	4000	.13%(T)	100	Wet degrades
Plywood (3-ply)	.56	1.2 x10^6	4800Y	1600	.10%(R.H.)	115	

* TABLE I, page 516-519 Canadian Structural Design Manual 1970.

3. Adaptability towards a variety of plastic and organic coatings and decorating materials for internal as well as external uses.

Some of the disadvantages in using steel as a skin material are:

1. Accidental scratches may cause stains due to rusting of exposed portion.

2. Heavier panel as compared to those with aluminum skins may increase handling and construction costs.

2.1.1.2 Aluminum

Aluminum has an obvious advantage in weight over steel for use in sandwich panel construction. A durable wide range of plastic coatings can be applied and accidental scratches do not cause stains as in the case of steel.

Some of the disadvantages in using aluminum over steel are:

1. Low stiffness factor limits span requirements.

2. Low dent resistance requires comparatively stiff core.

3. Dimensional changes due to temperature variation are high.

4. Aluminum reacts with steel, thus needs the use of special plastic coated nails. Use of aluminum as an inside skin in sandwich panels for dwellings may cause difficulties in supporting common metallic fixtures.

2.1.1.3 Plywood

Use of plywood as a construction material is perhaps the most common. Some of the advantages of using plywood as a skin material in the sandwich construction are:

1. High dimensional stability.
2. High resistance against denting.
3. Use of a comparatively thick cross-section at moderate cost and weight can achieve same span capability as in the case of steel or aluminum.

Some of the disadvantages in using plywood as a skin material are:

1. Difficulty in applying paint base, but this can be overcome by applying Kraft phenolic overlays as a paint base.
2. High fire spread rating as compared to metallic skins, but use of common overlays can reduce it to 100 or less.

Other feasible skin materials are: Glass-fibre-reinforced plastic (FRP), Particle board Paper plastic, Hardboard, Asbestos cement and Rigid Polyvinyl chlorides but due to high cost and limited strength their use is very limited.

2.1.2 Core Material

Table 2.2 lists the approximate properties of the various core materials discussed below.

Table 2.2

Properties of Core Materials for Sandwich Panel Construction

Material	S.G.	G(psi)	τ Short Term psi	τ Long Term psi	E psi	σ Short Term psi	K BTU/°F/in/ hr/sq.ft.	Water Vapour Transfer	Others
	Along the span					Perpendicular to surface			
Paper Honeycomb	.027	9000	50	(Assumed) 12	21000	90	.40	Direct air	Poor dent resistance
Styrofoam FR (Dow product)	.0304 (1.9 lbs/ cu.ft)	1100	35	2-4	2200	30* (average)	.26	1.0 perms	Fair dent resistance
Styrofoam S.M. (Dow product)	.035 (2.2 lbs/ cu.ft)	1200	35	2-4	7500	30* (average)	.20	0.6 perms	Fair dent resistance
Foam Polyurethane	.032 (2 lbs/ cu.ft)	350	30	(Assumed) 3	700	30 at 10% yield	.12	3	Self bond to skin
Extruded Particle Board	.26	3800	80	15	12000	500 yield	Air or fill	High	Very good dent resistance

* Compressive Strength at 5% deflection or yield.

2.1.2.1 Paper Honeycomb

High strength phenolic resin impregnated kraft paper honeycomb is a promising core material for sandwich construction. This core offers sufficient strength and skins stability. Some of the disadvantages in using paper honeycomb as a core material are:

1. Low thermal insulation requiring additional layers of insulation material which can be successfully overcome by foaming in place polyurethane layers on both sides of the honeycomb.
2. Open cells provide comparatively low dent resistance.

2.1.2.2 Extruded Particle Board

In Europe, extruded particle board cores have been used as core material together with treated hardboard skins as exterior walls and door panels. Its lengthwise strength and dimensional stability are reported to be very poor. In addition the core needs additional insulation material which makes it expensive and unsuitable for Canadian housing construction.

2.1.2.3 Extruded Foam Polystyrene

Moderate strength, lightweight, good insulation and vapour barrier properties are the major advantages in using extruded foam polystyrene. Low modulus of rigidity limits the longer spanning requirements. Dent resistance is poor. Light weight and ease in panel fabrication offers additional advantages in factory built housing systems. The fire hazard are low as compared to other similar products. Lower thermal conductivity of styrofoam permits insulation savings. Metallic and plywood facings can easily be bonded to the core material.

2.1.2.4 Foamed Polyurethane

The major advantages in using polyurethane as a core material in sandwich panel construction are:

1. Polyurethane can be foamed in place.

2. It is self binding to most skin materials thus eliminates the need of adhesives.

3. Polyurethanes extremely low thermal coefficient offers additional advantage of savings in insulation.

Some of the disadvantages are:

1. Low strength specially creep values.

2. Emission of toxic gases when exposed to fire.

Other feasible core materials are deformed particle board and hardboard; Bead foam polystyrene; Foamed rigid polyvinyl chloride.

2.1.3 Bonding Materials

In sandwich construction panels skins are bonded to the core by a bonding material which is a commercially known adhesive. The selection of a suitable adhesive requires consideration of the following factors:

1. Materials to be bonded.
2. Type of bond desired.
3. Bond strength.
4. Surface preparation.
5. Method of application.
6. Overall cost based on per square foot of panel area.

2.1.3.1 Materials to be Bonded

Foamed Polystyrene (Dow Chemical Product Styrofoam SI) has been chosen as the core material and steel as outer and inner skins material for the sandwich panels under study. The adhesive chosen should be suitable to produce a durable bond between the skins and the core materials.

2.1.3.2 Type of Bond

The adhesive chosen for the sandwich panel construction should provide a structurally rigid bond between the skins and the core materials.

2.1.3.3 Bond Strength

Bond strength between the skins and the core materials of the sandwich construction panel depends on the characteristics of the adhesive, thickness of the adhesive layer, the mechanical and physical properties of the core and skin materials, surface preparation for the constituent materials and the method of bonding [6]. A structural adhesive should be resistant water and water vapours, temperature variations, biological influences and chemicals in the environment.

Tests conducted by the Forest Product Laboratory, Forest Service U.S. Department of Agriculture, Madison, Wisconsin [7] show that the panels using certain vinyl-phenolic and epoxy-phenolic adhesive gave satisfactory performance. The results were based on test specimen taken from the panels exposed over periods of 6, 12, 24 and 36 months, under stressed and non-stressed conditions.

2.1.3.4 Surface Preparation

Surface preparation with respect to the core and skin materials should be done in accordance with the adhesive manufacturer's recommendations.

2.1.3.5 Method of Application

Method of application primarily depends on the manufacturer's recommendations and the production volumes involved. For the purpose of this study the roller coating method has been chosen, based on the advantages mentioned below.

1. Roller coating is more suitable for continuous production as compared to spraying or manual applications.
2. Roller coating does not produce fumes, thus, no environmental hazards are involved as compared to spraying methods.

3. Roller coating results in more economical use of adhesive.

2.1.3.6 Chosen Adhesive

Adhesive No XLC-7175 manufactured by the 3M Company of Canada has been chosen for the sandwich construction panels in this study. The following factors are considered for the selection of the adhesive.

1. Suitability towards bonding steel skins to Styrofoam SI core material.
2. Suitability towards roller coating method of application enabling continuous production of the panels.
3. Water base, non-toxic and non-flammable.
4. Low drying time.
5. Higher bonding strength.
6. Coverage per gallon approximately 1100 square feet surface area with a glue line thickness of 5 to 6 mils.

2.2 Parameters to be Checked

The following parameters need to be checked in accordance with the "Canadian Building Code", with respect to the material selected for the sandwich construction.

1. Thermal insulation properties.
2. Fire resisting properties.
3. Moisture absorption properties.
4. Vapour transmission properties.
5. Sound loss and sound transmission class rating.
6. Dimensional response with respect to change in temperature and humidity.
7. Span capabilities.

2.2.1 Thermal Insulation

The Canadian Building Code [8] specifies minimum thermal resistance ("R" value) for other than electrical heating, 10.00 units for walls and floors, and 12.50 units for roofs, for the areas where mean annual total degree days exceed 11,000.

Assuming other than electric heating and minimum thermal resistance 12.50 units for the roof and walls:

$$R = 12.50 = \frac{\text{Insulation thickness in inches}}{\text{Coefficient of thermal conductivity in B.T.U./hr/sq.ft/°F/in.}}$$

$$= \frac{t}{k}$$

k = .20 for Styrofoam SI

t = .20 x 12.50 = 2.5 inches.

2.2.2 Fire Resisting Properties

As specified in [8] Part 3 subsection 3.1.4.5 (1)d thermal and sound insulation should not have flame spread rating more than 75 when the insulation is placed between two layers of noncombustible materials without an intervening air space. Flame spread rating for all walls and ceilings of assembly halls, institutional and residential buildings, or any exit or corridor leading to an exit should not exceed 150.

Surface fire spread rating for sandwich construction with steel and aluminum skins is zero and with plywood can be limited to 100.

Thus, a sandwich construction using Styrofoam SI and metallic or plywood facings will fall within the specified limits.

2.2.3 Moisture Absorption Properties

Water absorption (% by volume) for Styrofoam SI, self extinguishing type is limited to a maximum of .25%.

2.2.4 Vapour Transmission Properties

The Canadian Building Code specifies that lightweight cellular plastic-type insulation may be used without additional vapour barrier protection provided such insulation has a permeance rating of not more than 4 perm-inches and is installed in continuous contact with masonry or concrete.

Water vapour transmission rating for Styrofoam SI is 0.6 perm/in. thickness.

2.2.5 Sound Loss and Sound Transmission Class Rating

Lightweight, stiff and continuous sandwich panel construction is a poor sound barrier. As specified in Canadian Building Code.

1. A construction shall provide a sound transmission class rating of not less than 45 between dwelling units in the same building and between a dwelling unit and any space common to two or more dwelling units,
2. every service room or space such as storage rooms, laundry, workshop, building maintenance room or garage serving more than one dwelling unit, shall be separated from dwelling units by a construction providing a sound transmission class rating of not less than 45.

Noise in multiple dwelling systems consists of airborne and impact sounds. When a source radiates its sound energy into the surrounding air, it is termed airborne sound. Typical examples of airborne noises are human voice, radio or other instruments being played in adjacent dwellings [9] and street noise produced by traffic.

When a sound source, not only radiates sound energy into the air, but also causes vibrations in the solid bodies such as floors, walls etc., it is termed structural borne sound. Vibrating water pipes secured to the walls, steps and piano or other musical instruments are a few examples of structural borne sound.

To provide minimum STC 45 rating in a multiple dwelling system, for critical areas such as bedrooms and living rooms, the following areas need consideration.

1. Layout of Dwelling Units

Dwelling units should be located as far from external sources of noise as possible. Windows and doors should be located away from the noisy side.

Internal layout of the dwelling unit in a multiple dwelling building is also very important. Bedrooms and living rooms of one dwelling should not be placed adjacent to the kitchen or bathroom of other units. Service pipes should be padded at joints and placed in the walls adjacent to non-critical areas.

2. Sound Insulation of Walls

The sound insulation property of a single wall depends mainly on its superficial density (weight per square foot area). Other things being equal doubling the weight of the partition wall results in sound transmission loss of 5 db. To achieve a S.T.C. 50 or higher rating a single wall must weigh 80 lbs per square foot.

A heavy single sandwich partition wall of good mechanical properties and weighing 4 lbs. per square foot will roughly yield a STC 30 rating.

Experimently it is determined that [10] average sound reduction index, in the frequency range of 100-3150 cycles per second, is given by the expression:

$$14.5 \log_{10} m + 21 \text{ db}$$

where:

m is the superficial density in lbs. per square foot for the partition.

Thus for a partition weighing 4 lbs. per square foot

Sound insulation index

$= 14.5 \log_{10} (4) + 21$ db

$= 29.7$ db $\simeq 30$ db

Thinner and lighter panels when twinned to create a double leaf wall system, may yield a satisfactory S.T.C. rating. The air gap between the leaves must have a minimum value, depending upon the superficial density of the leaves. Roughly the air gap between leaves should be 4 inches for 3 lbs. per square foot superficial density panel and 3 inches for 4 lbs. per square foot panels.

Good sound insulation can be achieved [10] from a twin leaf wall if

$$md > 11.75$$

where m = superficial density of each leaf in lbs. per square foot

and d = air gap in inches between the leaves.

Therefore, higher sound insulation properties can be obtained by increasing the air gap between two leaves of comparable light weight per square foot.

The effectiveness of twin leaf wall construction against sound transmission may reduce, specially at high frequencies, due to the transmission of vibration through the supporting members, such as studs and rafters etc. This can be overcome by using a separate framework for each leaf, reducing the number of studs to the minimum possible, by providing resilient material between the stud and the leaves or by staggering the studs (Figure 2.1). Screw fasteners do not effect appreciably.

A studless twin leaf wall supported at the top and bottom edges only may provide a highly effective sound barrier.

2.2.6 Dimensional Response with Respect to Change in Temperature and Humidity

Steel:

Thermal coefficient of expansion of steel is comparatively low, as shown in Table I the percentage change over 100°F temperature variation is .065% of the linear dimension. A sandwich construction skin is continuously bonded over the core, thus differential expansion or contraction of the skins results in bowing of the panel. This limits the maximum allowable deflection under loads.

Maximum deflections from the plane due to differential expansion of skins tightly bonded over the core and restrained at the ends can be approximately evaluated from:*

$$\delta = \frac{k\ell^2}{800\ h}$$

where: δ = maximum deflection at the centre

k = percentage change of one skin compared to the other

h = thickness of the core

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* See page 19 [22].

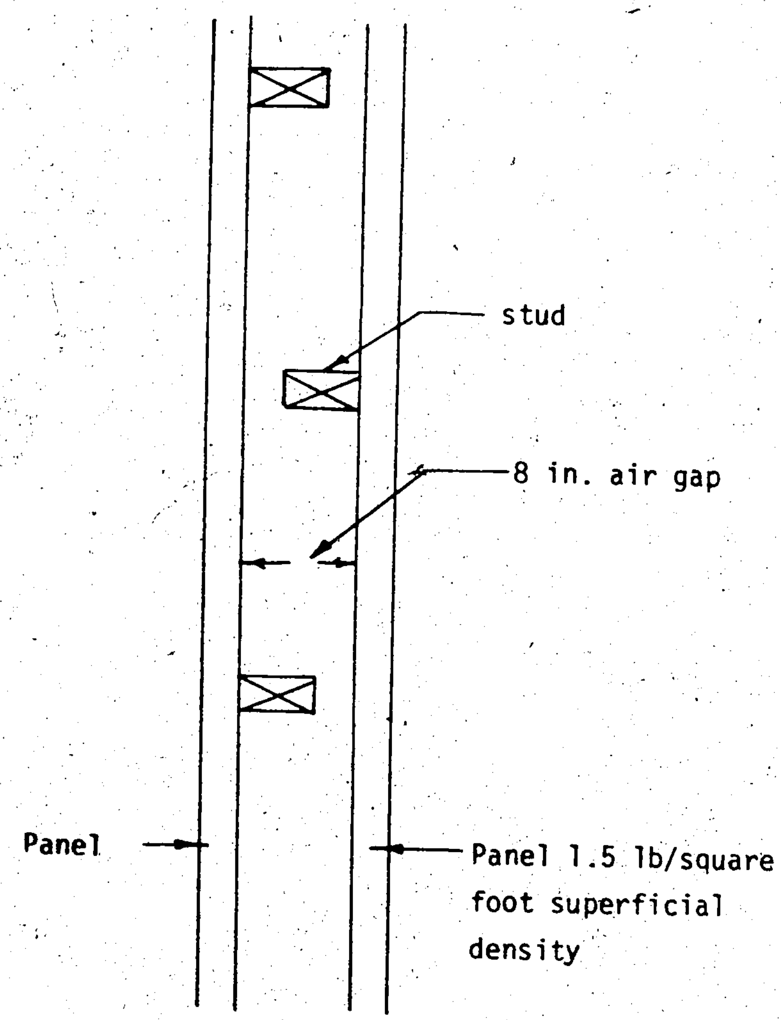


Figure 2.1 Party wall for S.T.C. 45

Sound Insulation Rating

For a sandwich panel with steel skins and a span of 10 feet.

$$\delta = \frac{.065 \times 100 \times 144 \text{ in}^2}{800 \times 2.5} = .468 \text{ in}$$

Aluminum:

For a sandwich panel with aluminum skins and span of 10 feet.

$$\delta = \frac{.13 \times 100 \times 144 \text{ in}^2}{800 \times 2.5} = .936 \text{ in.}$$

Plywood:

For plywood skins the problem of dimensional changes due to temperature differential is negligible but change due to the relative humidity need consideration.

In the winter due to heating, internal skin may be exposed to 20 percent relative humidity whereas the outer skin to 80 relative humidity. This differential in Relative Humidity causes a percentage dimensional change by about .1% and thus deflections due to bowing can be evaluated as in the case of metallic skins.

For a sandwich panel with plywood skins and a span of 10 feet.

$$\delta = \frac{.1 \times 100 \times 144 \text{ in}^2}{800 \times 2.5 \text{ in}} = .72 \text{ in.}$$

Bowing of the panels can be reduced considerably if the panel ends are not tightly secured to the supports.

2.2.7 Span Capabilities

Table 2.3 lists the possible spans under different loads and deflections, with respect to the sandwich panel.

Maximum deflection at the center of the span for the sandwich panel loaded as a beam is given by the following relation [22].

$$\delta = \frac{5W\ell^3}{384\ EI} + \frac{W\ell}{8bcG}$$

where:

δ = maximum deflection

W = total uniformly distributed load

ℓ = span in inches

EI = stiffness factor

b = width of the sandwich panel

c = core thickness

G = shear modulus of rigidity of core material relating to span direction.

The above relation is based on the following assumptions.

1. The sandwich panel is simply supported at the ends.
2. The sandwich panel is divided in strips to act as a beam.

Table 2.3

Span, Weight and Cost of Panel With Various

Skin Materials, Load and Deflection Requirements,

Using 2.5 in. Thick Styrofoam SI* as a Core Material

Skin Material		'ℓ' span in inches										
		Distributed Load 40 psf			Distributed Load 30 psf			Distributed Load 20 psf			Weight of Panel in Pounds per sq. ft.	Cost** of Panel in Dollars per sq. ft.
Outside	Inside	Maximum Allowable Deflection			Maximum Allowable Deflection			Maximum Allowable Deflection				
		ℓ/180	ℓ/240	ℓ/360	ℓ/180	ℓ/240	ℓ/360	ℓ/180	ℓ/240	ℓ/360		
1. 26 gauge steel	1/4 in. Plywood	120	102	90	126	114	96	144	132	120	1.9166	0.6875
2. 30 gauge steel	1/4 in. Plywood	108	96	84	120	108	93	141	126	108	1.6666	0.65
3. .0253 in. thick aluminum	1/4 in. Plywood	102	90	78	114	102	90	132	120	108	1.53	1.06
4. 26 gauge steel	26 gauge steel	126	114	96	138	126	108	162	144	126	1.9583	0.60
5. 30 gauge steel	30 gauge steel	108	96	84	120	108	93	144	126	108	1.4583	0.525
6. .0253 in. thick aluminum	.0253 in. thick aluminum	96	90	75	108	99	84	126	114	99	1.1925	1.341

* Dow Chemical Product

** Cost includes only the direct material costs of skin and core materials.

Stiffness factor EI for a normal sandwich with identical thin skins can be obtained from

$$EI = \frac{Ebtd^2}{2}$$

where:

E = modulus of elasticity of skin material in the direction of the span.

t = thickness of the skin

d = distance between centroides of the skins

For sandwich panels with skins of different materials and different thicknesses, the stiffness factor can be obtained from

$$EI = \frac{b(E_1t_1 \times E_2t_2)d^2}{E_1t_1 + E_2t_2}$$

where:

E_1 and E_2 are modulus of elasticities of the skin materials and

t_1 and t_2 are their thicknesses respectively.

The core stiffness does not contribute significantly, therefore above formulas do not include the core stiffness factor.

If the skin thicknesses are considerable, the above stiffness factor can be modified as shown below.

EI for thick skins

$$= \frac{b(E_1t_1 \times E_2t_2)d^2}{E_1t_1 + E_2t_2} + \frac{b(E_1t_1^3 + E_2t_2^3)}{12}$$

2.3 The Chosen Materials for the Sandwich Panel

Table 2.3 lists span capabilities of the sandwich panel, using 2.5 inch thick styrofoam SI as a core material with various skin materials. Span calculations are based on 40, 30 and 20 psf uniformly distributed loads and ℓ/180, ℓ/240 and ℓ/360 maximum allowable deflection. Weight and cost of the panel per square foot is based on costs of the skins and the core materials only.

The sandwich panel using 26 gauge steel sheet for inner and outer skins represents the highest span capabilities, heaviest panel and low cost per square foot of the panel area, whereas the sandwich panel using 0.0253 in. thick aluminum skins represents lowest span capabilities, with lowest weight and highest cost per square foot panel area. Other combinations of outer and inner skin materials fall in between with respect to the span capabilities, weight and the cost.

The following materials are chosen for the sandwich panel construction.

Skin Material: Both skins 30 gauge galvanized steel sheet.

Core Material: 2.5 inches thick Styrofoam SI 2.2 lb/cu. ft. density.

The chosen material is selected as optimal with regard to:

1. Structural soundness.
2. Aesthetic attractiveness

3. Ease in production and handling
4. Adaptability of the skin materials toward a wide range of finishes
5. Low cost and weight per square foot of panel area.

CHAPTER III

THE STRUCTURAL DESIGN FOR THE MULTIPLE-FAMILY DWELLING SYSTEM

3.1 The Wall System

The wall system is designed to satisfy the requirements of the multiple-family dwelling system.

The chosen wall system uses factory manufactured pre-finished sandwich construction panels, to be directly erected at the construction site with the locking mechanism provided. The wall panels are non-load bearing. The structural and live loads will be supported by load bearing studs placed in the locking mechanism.

The wall system provides:

1. Easy installation on the site with a minimum number of joints and site finishing.
2. Trouble free tolerance and ruggedness to withstand shipment over long distances.
3. Panel interchangeability.
4. Low Panel inventory.

3.1.1 Thirty-two Feet Exterior and Party Walls

Term party wall applies to the walls separating dwelling units, irrespective of the ownership or tenancy. The 32 feet exterior and party walls are comprised of four trapazoidal panels. Load bearing studs will be placed at 8 feet on centre, inside the locking mechanism. The panel arrangement in the exterior and party walls is shown in figure 3.1.

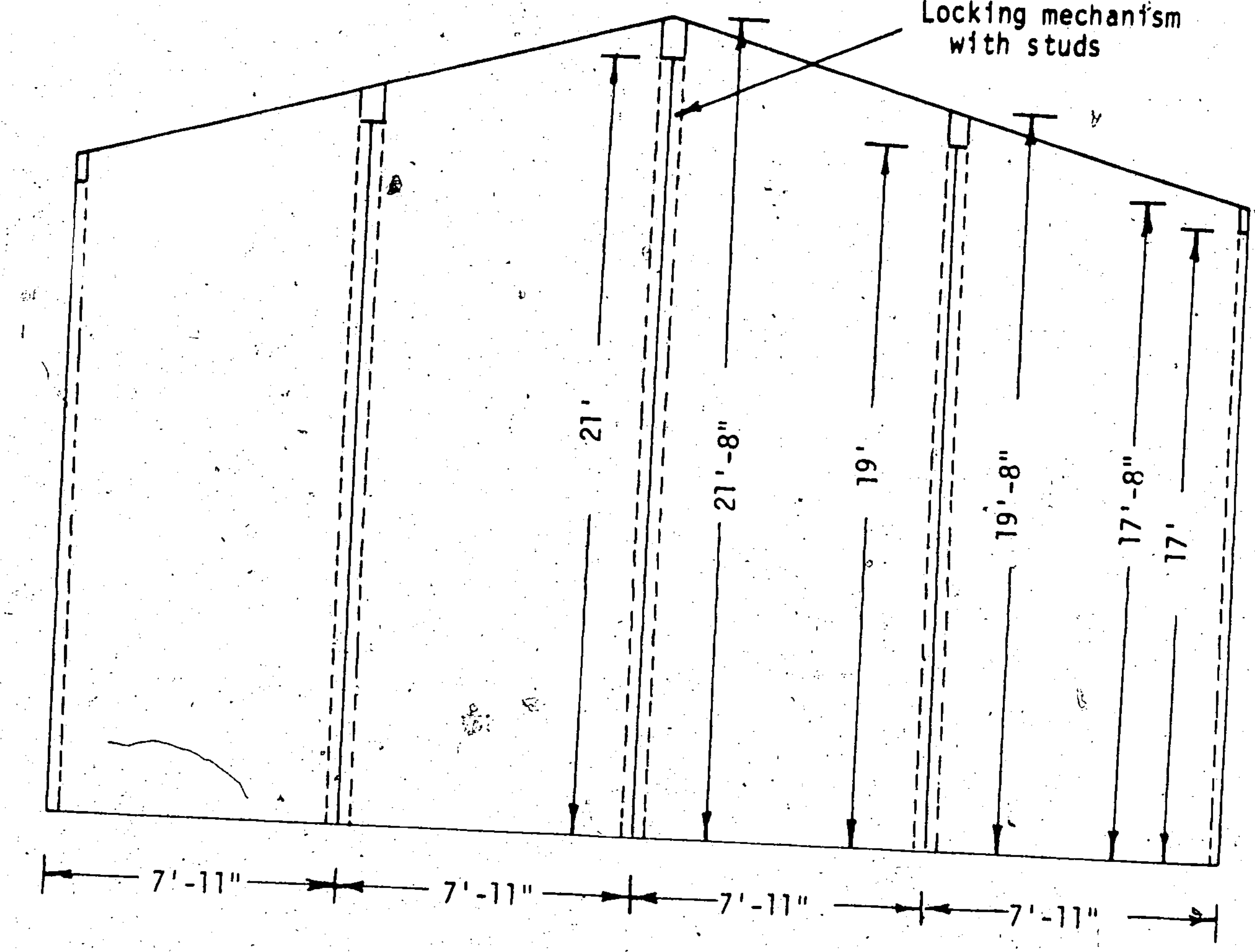


Figure 3.1 32 feet exterior and party wall panel layout.

Scale: 1/60(1"=5')

3.1.2 Twelve Feet Exterior Walls

The 12 feet exterior walls of the main floor will have a window and a door as shown in figures 3.2 to 3.5.

Each of the 12 feet exterior walls for the second floor will have a window as shown in figures 3.6 and 3.7.

3.1.3 Interior Walls

The main floor interior wall system of the basic two storey dwelling unit with 768 square feet of floor area is comprised of two 11 feet 9 inches by 7 feet 11 inches walls separating the kitchen and stairways from the living and dining rooms. Each wall contains 2 feet 8 inches by 6 feet 6 inches interior door.

The second floor interior wall system is comprised of two 11 feet 9 inches by 7 feet 11 inches walls separating the bathroom and stairways from the bedrooms. A 12 feet by 7 feet 11 inches wall containing a 2 feet x 6 feet 6 inches door is used for separating the bathroom from the main passageway.

The chosen interior wall system allows:

1. low panel inventory with respect to the types and sizes of panels,
2. flexibility towards the adaptability of the panels for various floor plans,
3. use of panels manufactured in the same plant and with the same material as exterior wall panels,
4. structurally sound, economical and aesthetically attractive construction.

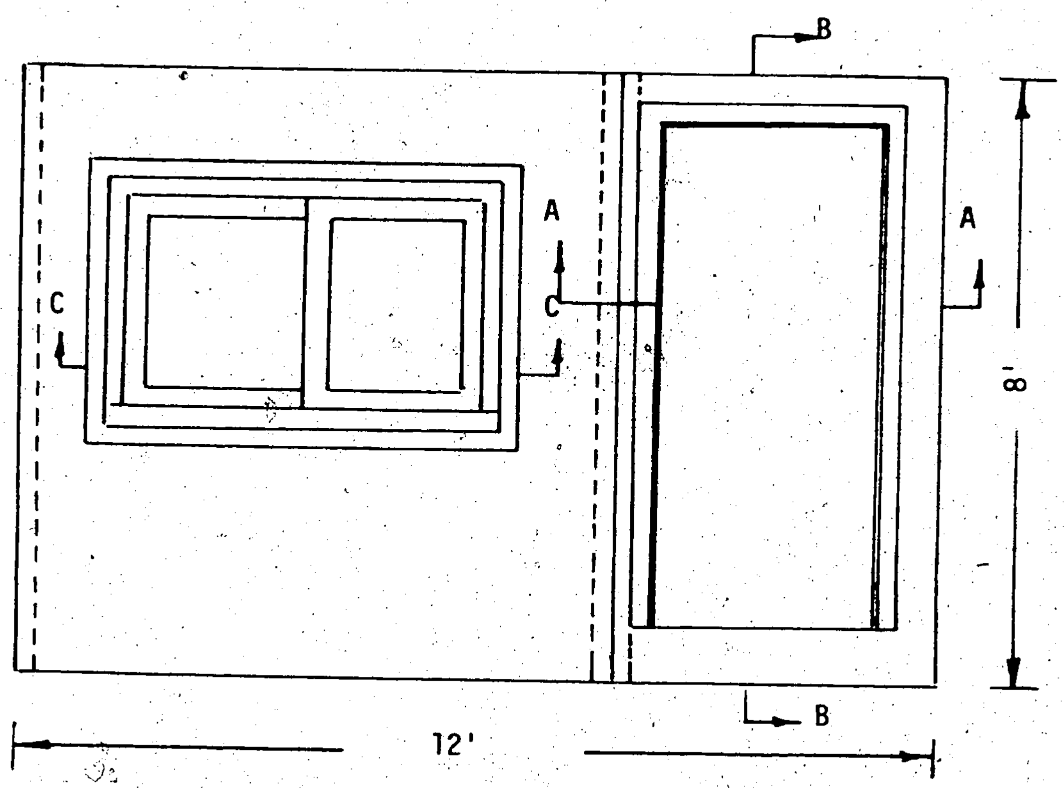


Figure 3.2 12 feet exterior wall (main floor) with window and door.

Scale: 1/30(1"=2'-6")

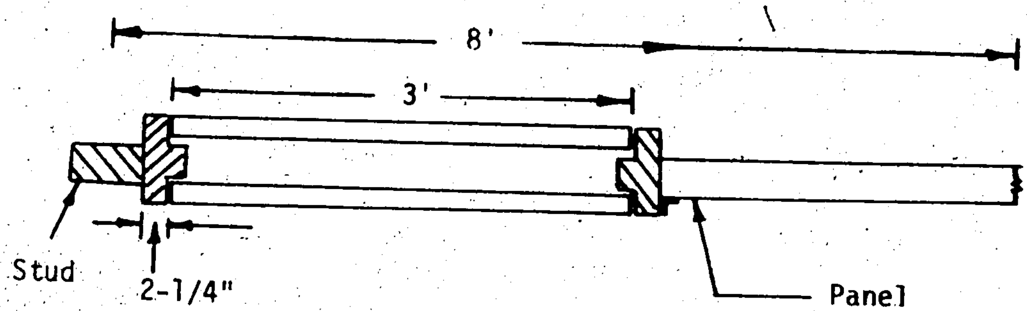


Figure 3.3 Exterior wall section "A-A" showing door cross-section

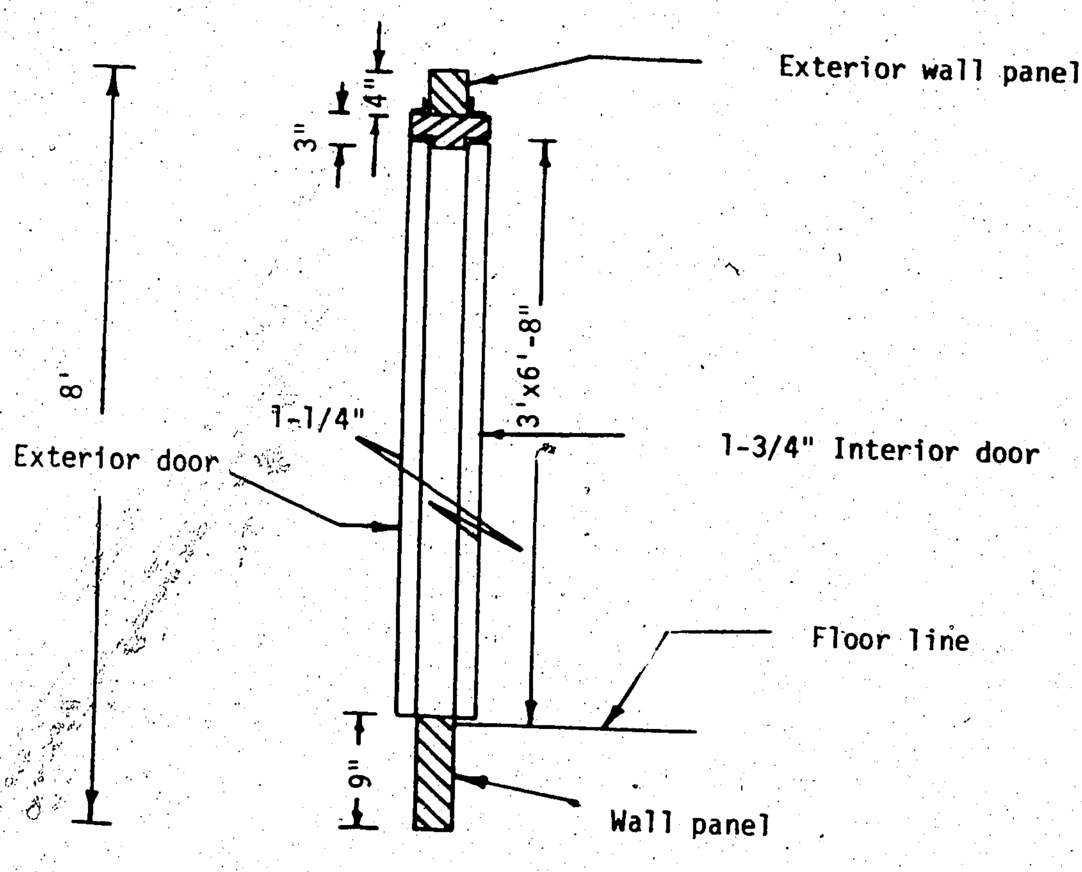


Figure 3.4 Exterior wall section "B-B" showing vertical section of door.

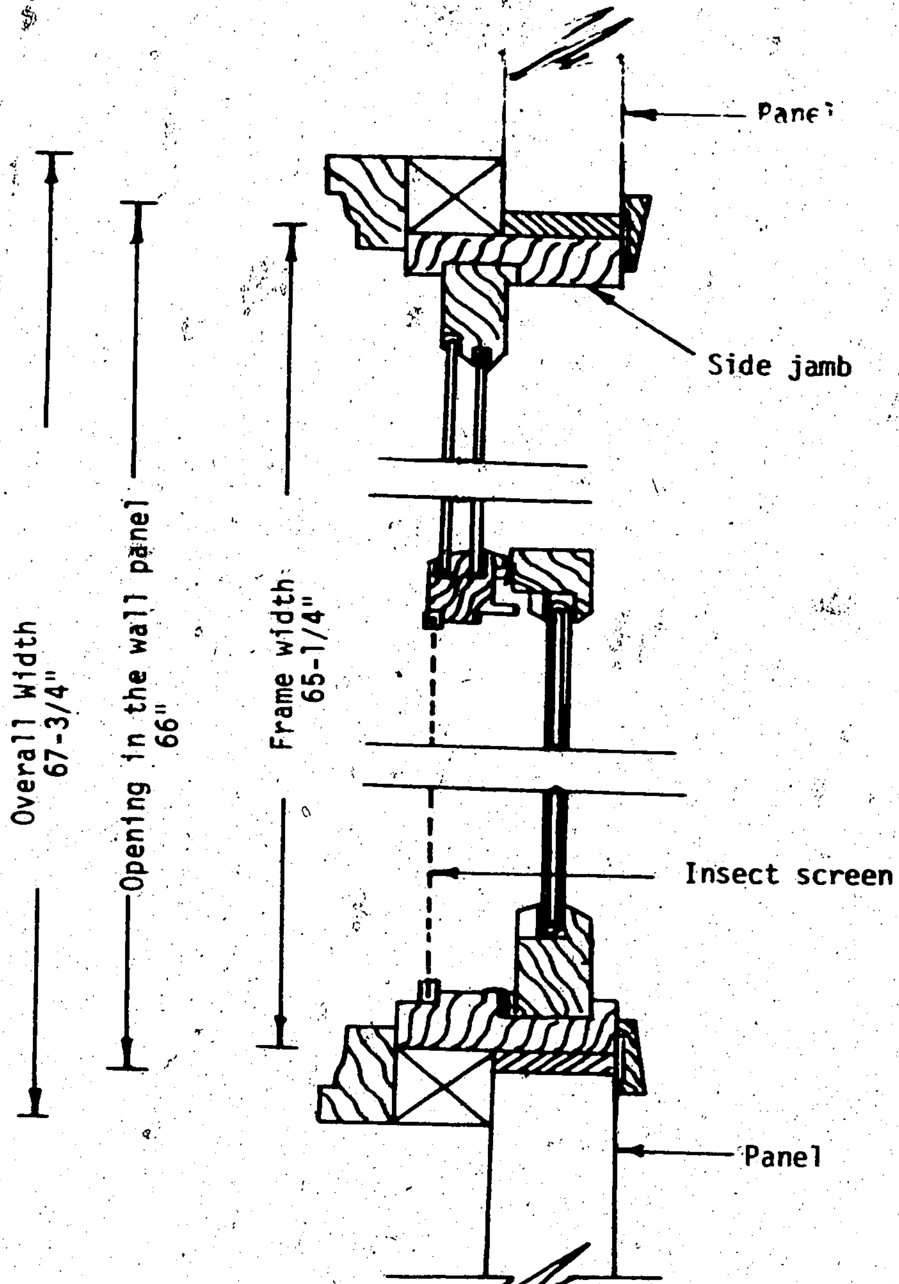


Figure 3.5 Exterior wall section "C-C" showing window cross-section

Scale: 1/4(1"=3")

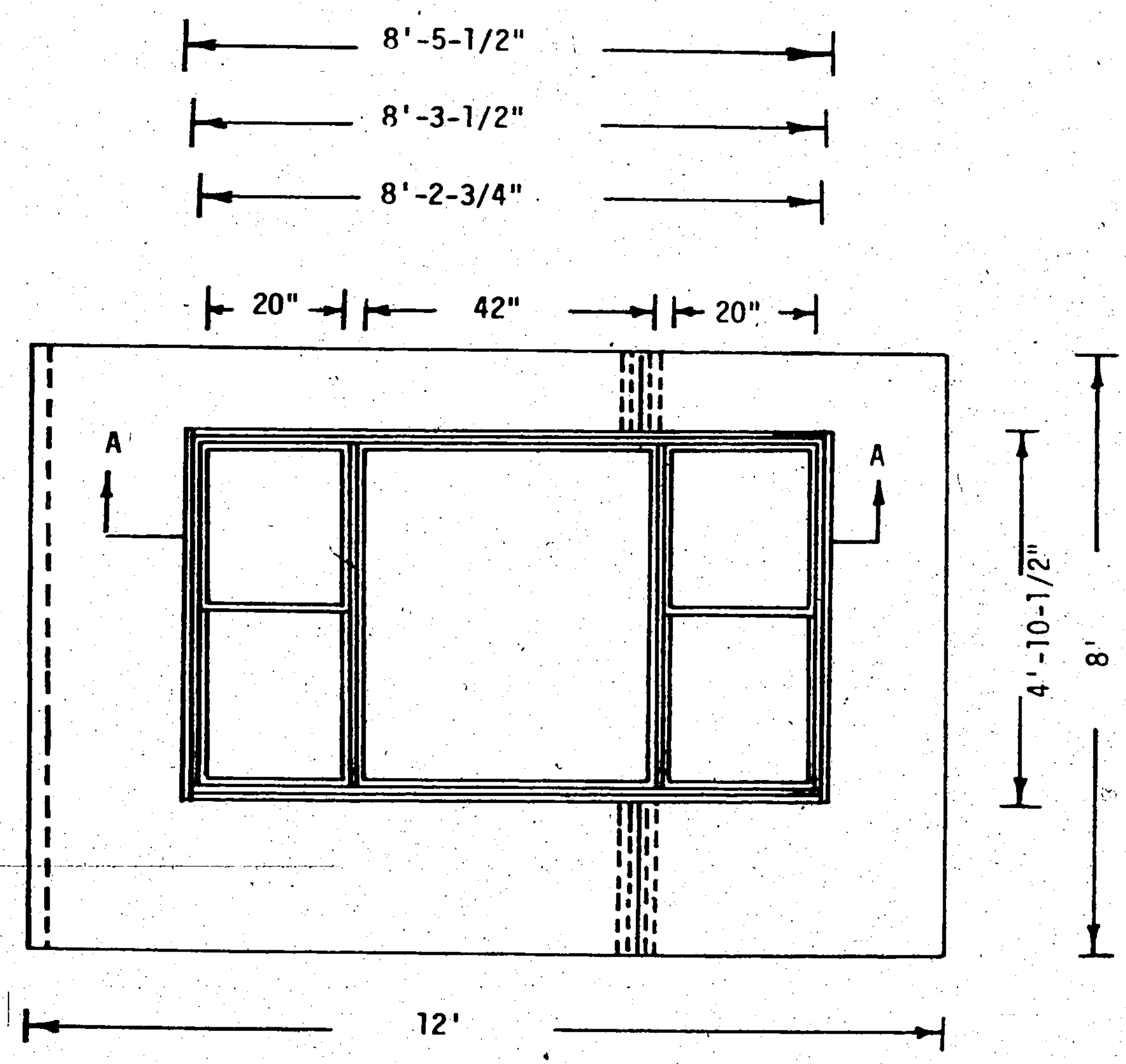


Figure 3.6 12 feet exterior wall (second floor) with window.

Scale: 1/30(1"=2'-6")

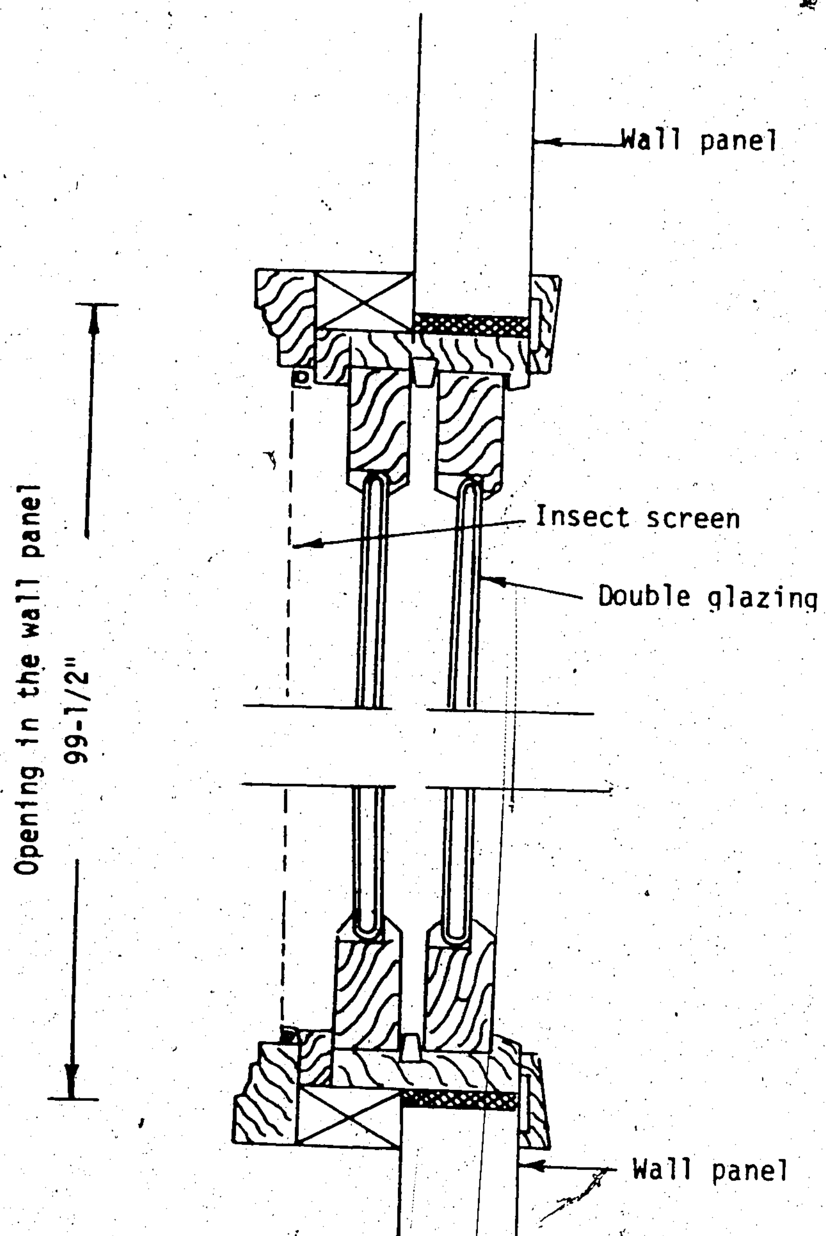


Figure 3.7 12 feet exterior wall (second floor)
Section "A-A" showing window cross-section.
Scale: 1/4(3"=1'0")

3.1.4 The Panel Locking Mechanism

A simple locking mechanism has been designed for the wall panels of the multiple-family dwelling system. It allows quick and efficient installation at the site and provides:

1. Structural stability,
2. sealing against air leakage, vapour and frost transmission,
3. thermal insulation at the joint,
4. accommodation for initial panel irregularities and dimensional change in the skin material due to temperature variation,
5. quick and simple assembly.

The locking mechanism is basically a spline joint. The spline will be manufactured by bonding 3/16 inch plywood skins to a 2 inches thick Styrofoam SI core. The spline contains a 3 inches by 2 inches box section steel stud with a wall thickness of 3/16 inch (designed in Appendix A). The overall thickness of the spline will be 2-3/8 inches.

Basically there are four connections involved in the dwelling construction. They are:

(1) Wall panel connection, (2) Corner connection,
(3) T-connection and (4) Roof panel connection.

The panels will be provided with skin material extending over the core by 3 inches along the edges to be joined. The extended portion of the skins will have elliptical holes to accommodate fasteners. Elliptical holes will allow expansion and contraction of the skins, thereby reducing the bowing of the panels under temperature variations. The panel edges and the spline surface will be coated with a semi-rigid structural adhesive, which will act as a sealant against air leakage and water and vapour transmission and at the same time will allow expansion and contraction of the skins due to temperature variation.

The connections will be manufactured from three basic pieces shown in figures 3.8 A, B and C (with or without studs). Piece A will constitute wall panel to panel connection, B and A when joined together will provide a T-connection and B and C will make a corner connection. Where simply an interior wall is required to be connected to the exterior or other interior wall, piece C will be used (containing no stud if wall is not supporting any structural load and panel span is less than the maximum allowable under the loads as shown in Table 2.3).

Figures 3.9, 3.10 and 3.11 show the wall panel connection, corner and T-connection respectively.

The panel joint can be readily covered with a plastic cap or wooden flashings at the site for an acceptable finish.

The chosen design has been selected with respect to the following advantages.

1. The locking mechanism offers ease in installation, light weight and structurally sound construction.
2. The locking mechanism can be manufactured in the same plant, using the same equipment, that is used for the panel manufacturing.
3. Studs are enclosed inside the locking mechanism.

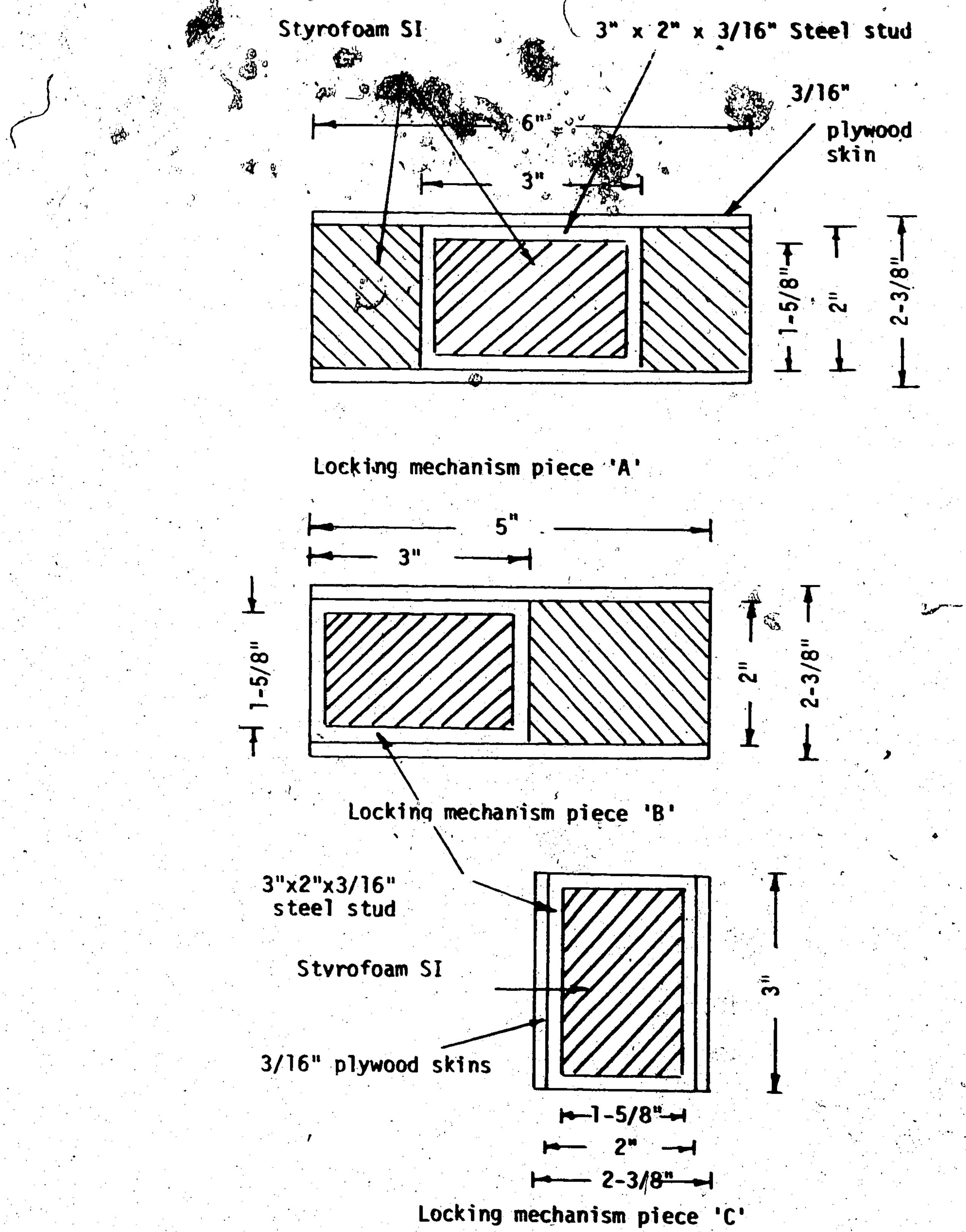


Figure 3.8 Details of locking mechanism pieces.

Scale: 1/2(1"=2")

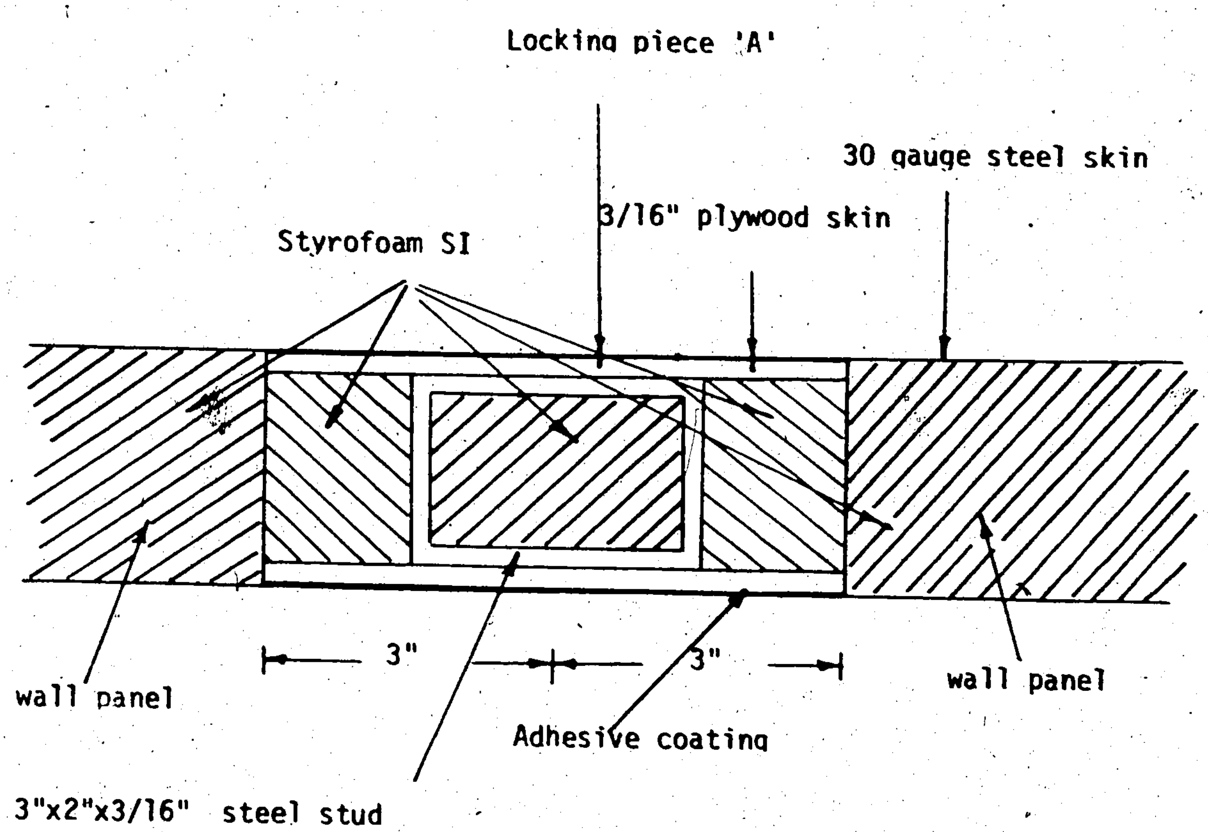


Figure 3.9 Wall panel connection top view

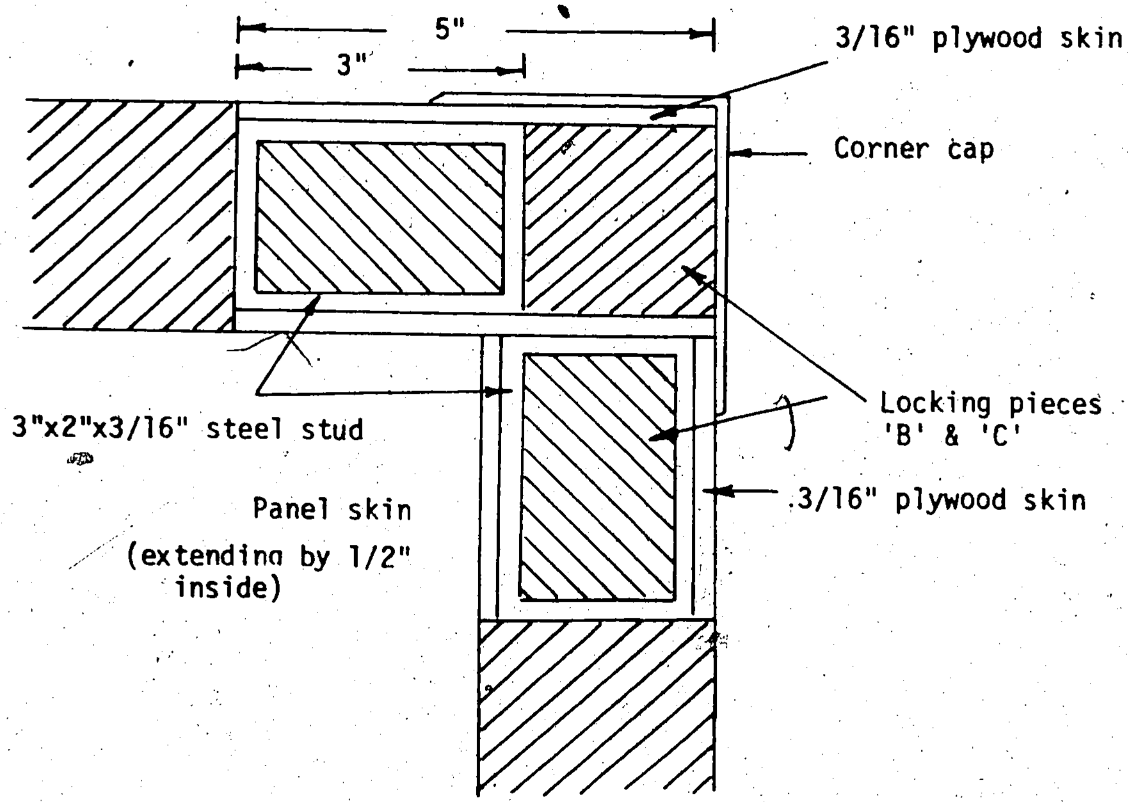


Figure 3.10 Corner Connection top view

Scale: 1/2 (1"=2")

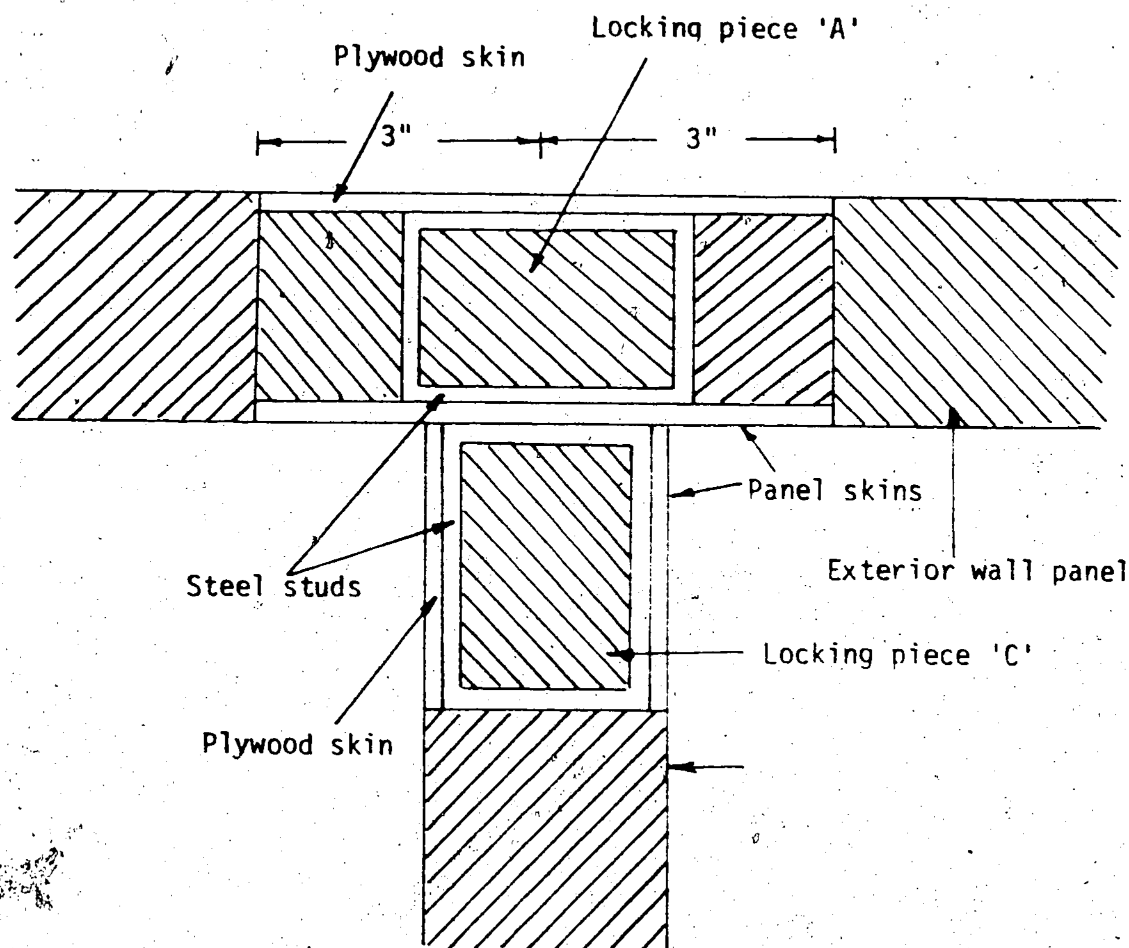


Figure 3.11 Cross wall connection top view

Scale: 1/2(1"=2")

4. The locking mechanism involves low inventory, as many combinations can be obtained from three basic pieces.

5. The locking mechanism offers almost the same insulation, water and vapour transmission resisting properties as the wall panels;

6. Any extension in the construction can be easily achieved.

7. Similar panel ends throughout the system allows panel interchangeability.

8. Hollow stud section can be used to contain electric wiring and filled with Styrofoam chips at the site to improve thermal efficiency of the joint.

3.1.5 The Wall Panels

A sandwich construction panel was designed for the wall system of the multiple-family dwelling system. The sandwich panel will be manufactured from 30 gauge steel sheets bonded to 2.5 inches thick Styrofoam SI (Dow Chemical's product) core.

2.5 inches thick Styrofoam provides the required insulation and vapour barrier. Continuous bond between the skins and the core materials will prevent any possibility of vapour condensation inside the panel. The structural and other properties of the sandwich panel are dealt with in Chapter II.

3.1.5.1 Thirty-two Feet Exterior and Party Wall Panels

Two trapezoidal panels 7 feet 11 inches in width and 21 feet 8 inches and 19 feet 8 inches in length along the two sides along with two panels 7 feet 11 inches in width and 19 feet 8 inches and 17 feet 8 inches in length along the two sides will constitute 32 feet exterior and party walls.

The vertical edges of the panels will have the skins extending over the core by 3 inches to lock the panel with the locking mechanism. The panel arrangement for the exterior and party walls is shown in figure 3.1.

3.1.5.2 Twelve Feet Exterior Wall Panels

3.1.5.2.1 The Window Panel

The panel will be provided with an opening 66 inches by 43-1/2 inches for the main floor window and 72 inches x 57-3/4 inches opening for the second floor window. The panel skins will extend over the core by 3 inches along the 17 feet edges for locking the panel with the locking mechanism.

A horizontal slider type window will be installed in the 66 inches x 43-1/2 inches opening in the dining room and a fixed window in the living room panel. The windows will provide a 15 square feet glass area for each of the dining and the living rooms. The windows will be of double glazing type with insect screen for the dining room window shown in figure 3.5. The window for the bedrooms will be a vertical slider type with a 27 square feet glass area for each bedroom. The details of the window panel are shown in figure 3.12.

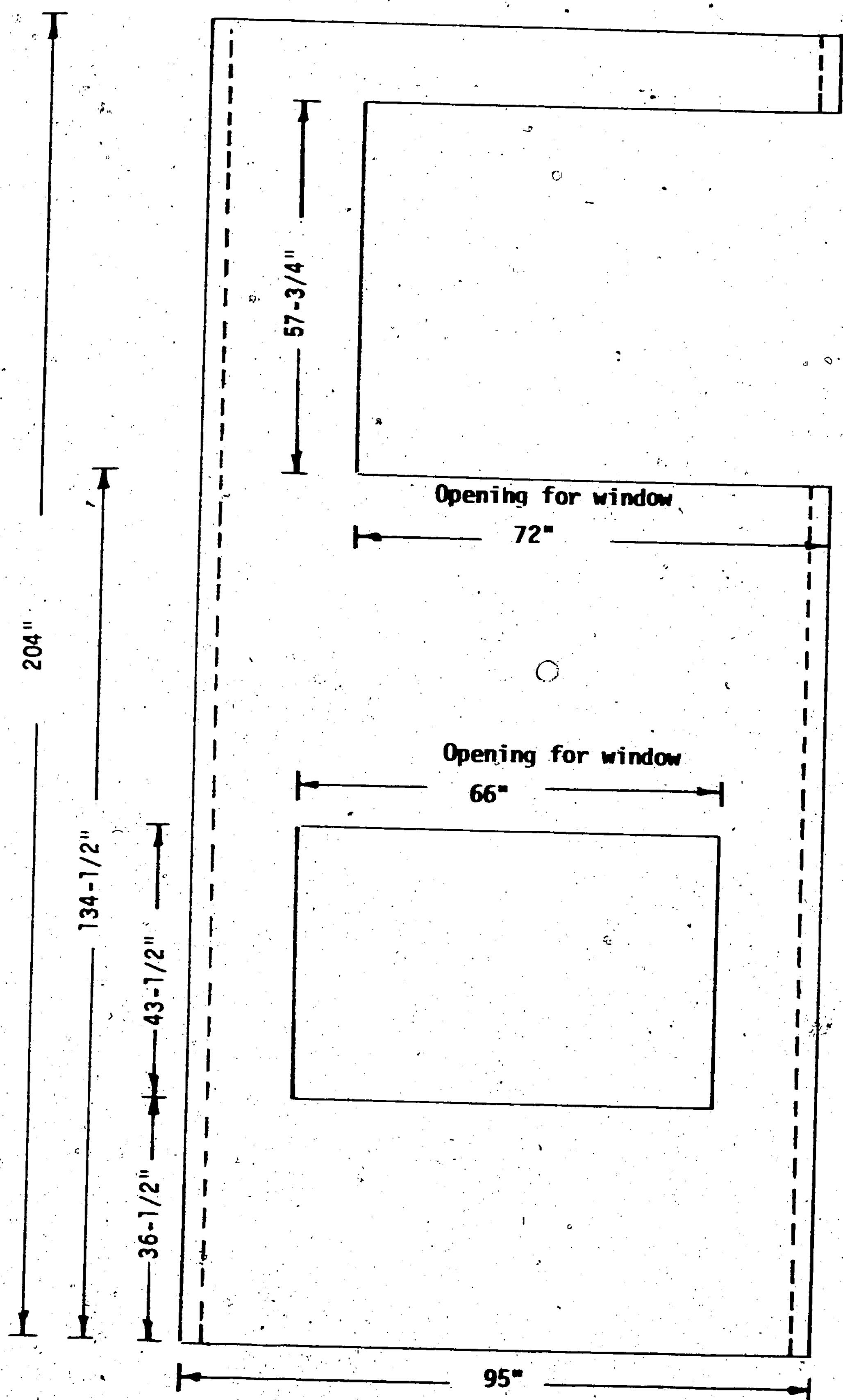


Figure 3.12 7'-11" x 17' window panel

Scale: 1/24(1"=2')

3.1.5.2.2 The Door Panel

The door panel will be provided with a 42 inches by 83 inches opening for the door and 27-1/2 inches by 57-3/4 inches opening for the second fllor window, as shown in figure 3.13.

3.1.5.3 The Interior Wall Panels

The interior wall panels chosen for the multiple dwelling system are identical to the exterior wall pane in construction. The prefinished interior wall panels will use the same locking mechanism as the exterior wall panels.

Two 11 feet 9 inches x 7 feet 11 inches panels will be used for the main floor to separate the kitchen and the stairways from the living and dining rooms. The panels will have a 38 inches by 83 inches opening for the interior door frame.

For the second floor interior walls, two 11 feet 9 inches x 7 feet 11 inches panels will be used to separate the bathroom and stairways from the bedrooms and one 8 feet by 7 feet 11 inches panel will be used to separate the bathroom from the main passageway. Bedroom closets wall will use two 2 feet by 7 feet 11 inches panels.

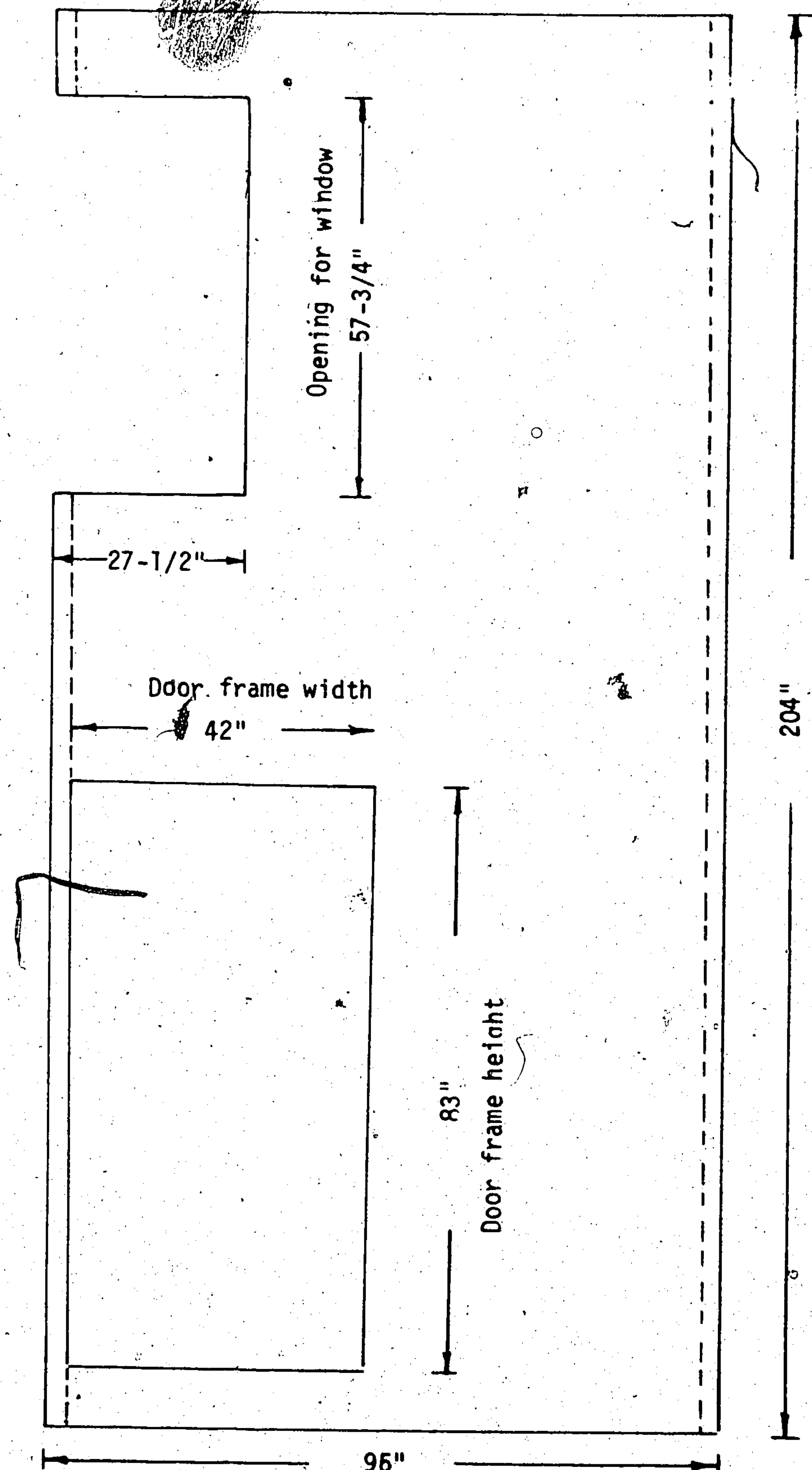


Figure 3.13 7'-11"x17' door panel

Scale: 1/24(1"=2')

3.2 The Roof System

The designed roof system for the multiple-family dwelling units will use similar panels as those used in the wall system. The basic quadruplex unit of the multiple-family dwelling system will have a common roof but individual ceilings for each dwelling. The roof will have a 3/12 slope. The panels will overhang by one foot over the exterior walls. The 50 feet long roof will use only two sizes of the panels. They are 17 feet in length and 7 feet 11 inches and 2 feet 6 inches in width.

The chosen roof system provides the following advantages.

1. The panels will be prefinished and manufactured in the same plant from the same skins and the core materials as the wall panels. This will result in low material inventory and eliminate roof insulation.
2. The same basic locking mechanism will be used for locking the roof panels together, as used for the wall panels.
3. The insulation, water and vapour transmission resisting properties of the panels will result in quick and economical construction.
4. The metallic skins of the panels will not need shingles, but the top skin will have a similar profile as the exterior wall panels to prevent slipping.
5. Only two sizes of panels required for the roof system will result in low panel inventory.
6. Use of wooden rafters will eliminate studding in the roof panels or locking mechanism.

7. The closed ceiling system will provide optimum aesthetic attractiveness to the buyer.

3.2.1 The Roof Panels

The roof panels are designed as I-beams, where the skins of the sandwich panel act as flanges and the core as the web of the beam. Under a 40 pound per square foot snow and wind load and maximum allowable deflection $\ell/240$ the span capability of the panel is 96 inches (refer to table 2.3).

The details of the panel are shown in figure 3.14.

Figures 3.15 and 3.16 show the panel layout for the roof system. In figure 3.17 the panel to panel locking is shown. The locking is basically a spline joint. The spline will be nailed to the rafters and the panels will be secured to the spline in the same way as in the wall system.

3.2.2 The Ceiling

Insulation is built into the roof system, hence the ceiling will not require any insulation, water or vapour barrier. No structural loads will be supported by the ceiling, hence a light weight ceiling can be used. The ceiling material can be selected from a variety of materials available. The chosen system provides an individual ceiling in each dwelling of the multiple-family dwelling unit. The ceiling boards will be attached to the joists which are secured to the roof beams. A similar ceiling will be used for the first floor ceiling where the ceiling boards will be directly nailed to the floor joists of the second floor,

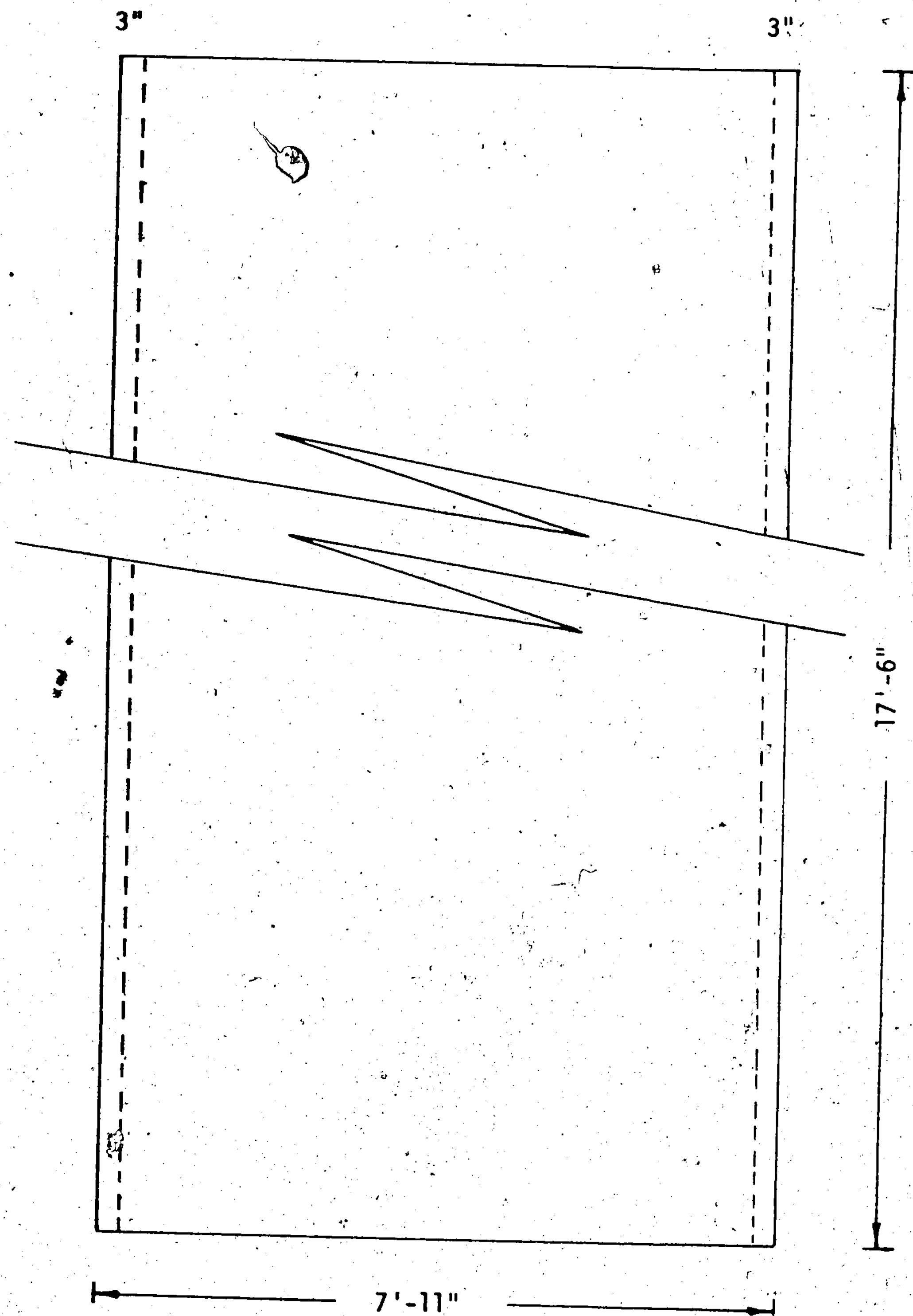


Figure 3.14 7'-11" x 17'-6" roof panel

Scale: 1/24(1"=2')

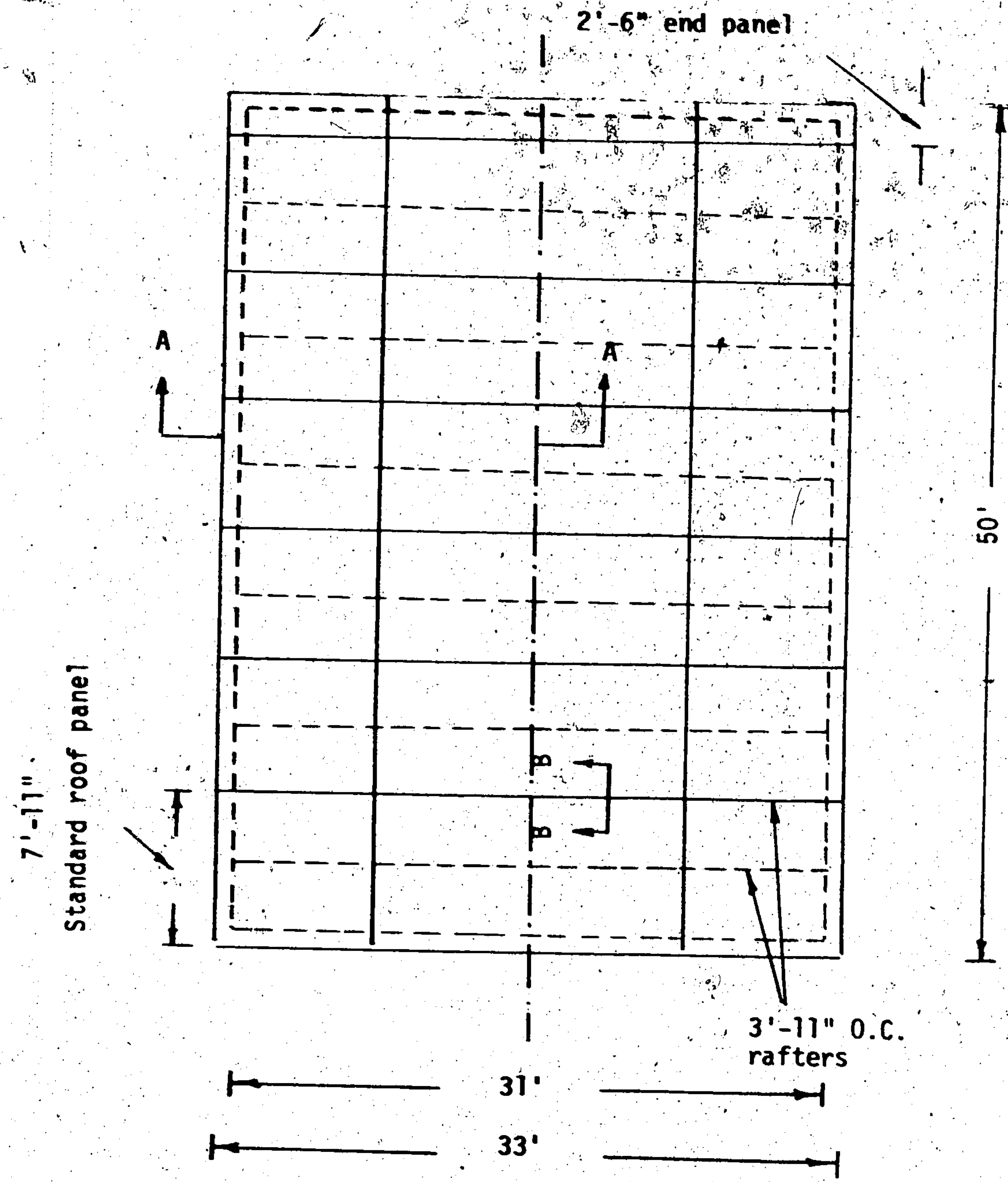


Figure 3.15 The roof panel layout

Scale: 1/120(1"=10')

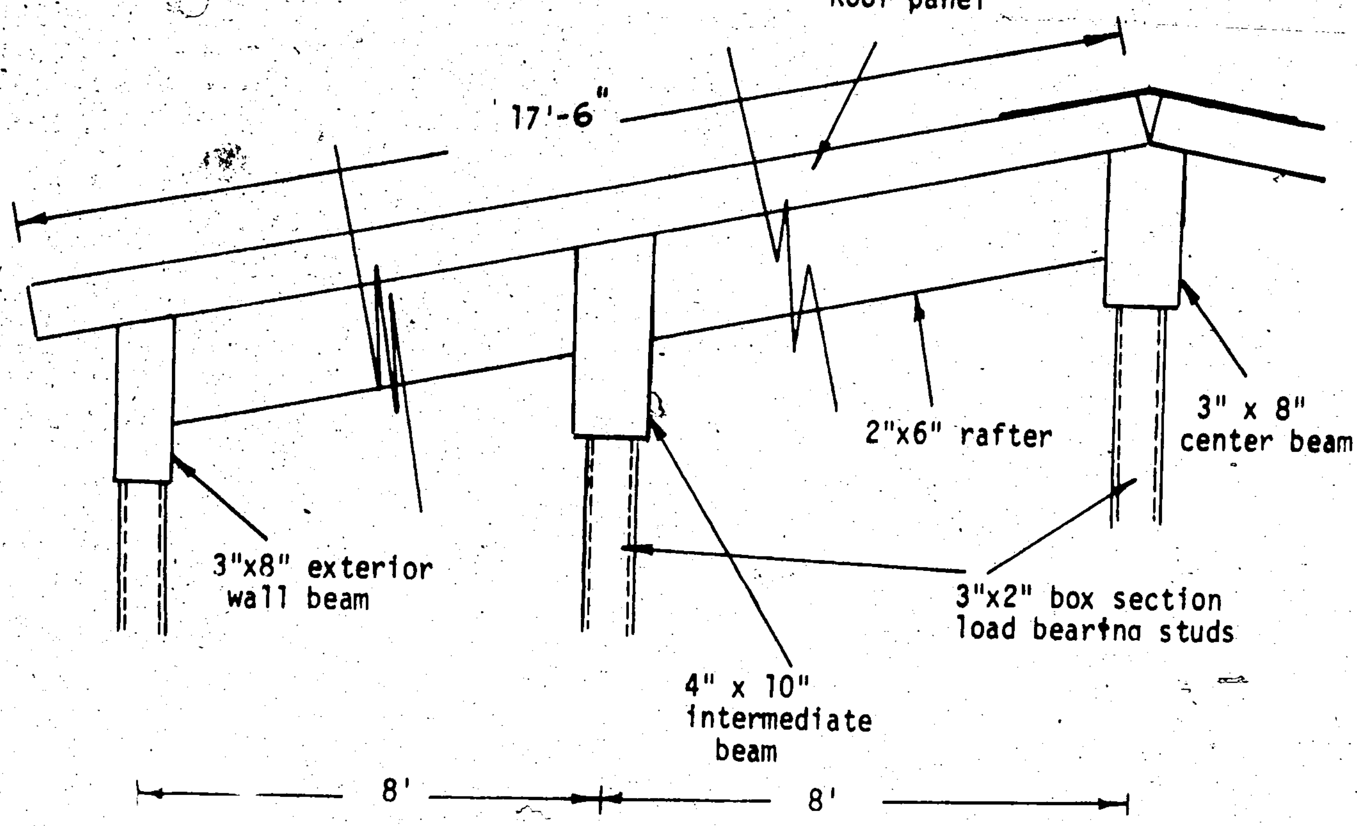


Figure 3.16 The roof section "A-A"

Scale: 1/10(1"=10")

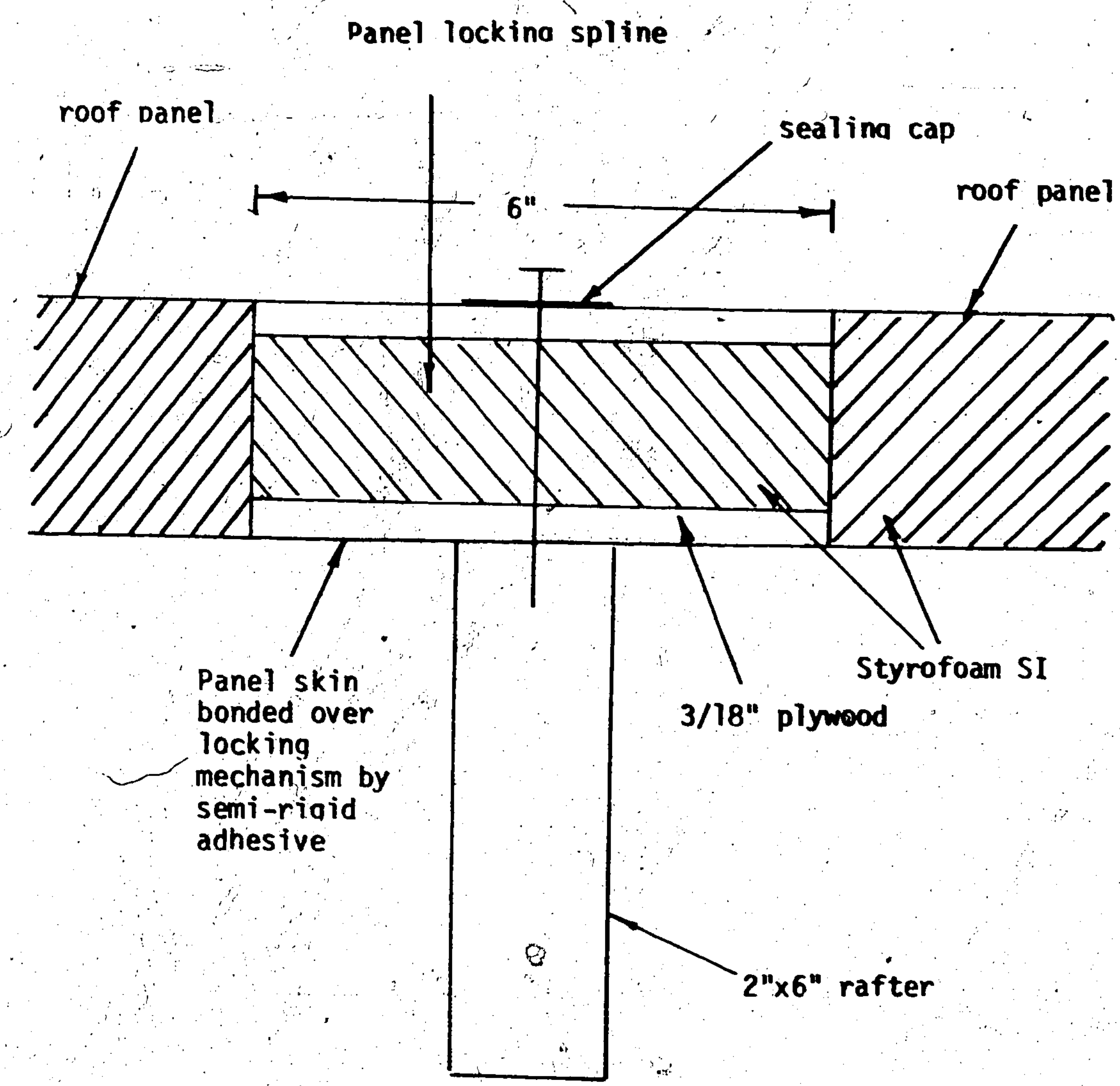


Figure 3.17 The roof section "B-B"

Scale: 1/2(1"=2")

this will eliminate the need for separate ceiling joists.

3.3 The Floor System

The floor design is basically a stressed skin structure, where 1/2 inch thick plywood sub floor will be directly nailed to the floor joists. The designed floor will support only dead and live floor loads, no structural load will be transmitted to the floors. The designed floor loads are 40 psf. The chosen joist section of 2 inches by 8 inches (nominal) is based on the following requirements and specifications [13].

1. Minimum span capability 12 feet.
2. Maximum allowable deflection $\ell/360$.
3. Modulus of elasticity of the lumber to be used 1,600,000 psi.
4. Live load of 60 psf with plastered ceiling, excluding the dead load due to the flooring material and weight of the joists.
5. Spacing of the joists on 12 inch centres.

The floor joists will be supported at the ends on wooden beams. The designed cross-section of the beams is 6 inches x 8 inches (see Appendix A). The chosen system has been selected with respect to the following advantages.

1. Simplicity in handling, transportation and erection.
2. Joists and beams can be cut to the required size and nailed together at the site.
3. Various floor finishes can be adapted economically to meet the aesthetic needs of the buyer.

4. Floors can be assembled on-site by semi-skilled personnel.
5. The chosen system will meet the economic as well as aesthetic requirement of the buyer.

3.3.1 The Floor Supporting Structure

3.3.1.1 Main Floor

The joists will be supported at the ends on the sill plates of the 32 feet exterior and party walls. Floor joist headers will be bolted to the exterior or party wall panels.

The details of the main floor supporting structure are shown in figure 3.18.

3.3.1.2 Second Floor

The second floor joists will be supported at the ends by the beams. The designed cross-section of the beams is 6 inches x 8 inches (Appendix A). The joists will be secured to the side of the beam.

The beams supporting the joists will be supported on 3 inch x 2 inch x 3/16 inch box section steel studs placed inside the locking mechanism at the interior and exterior or party wall connections. The details of the second floor are shown in figure 3.19.

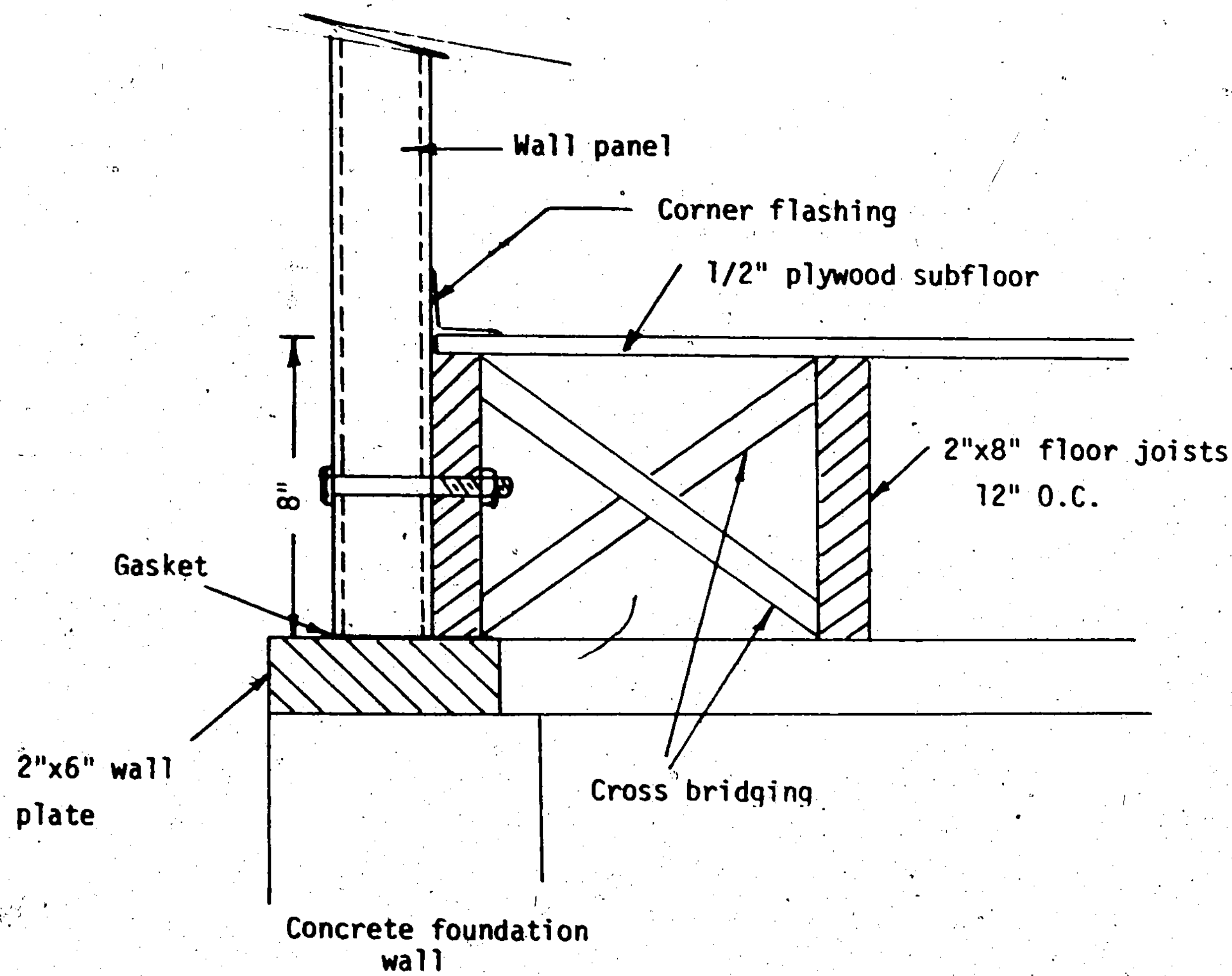


Figure 3.18 Main floor supporting structure.

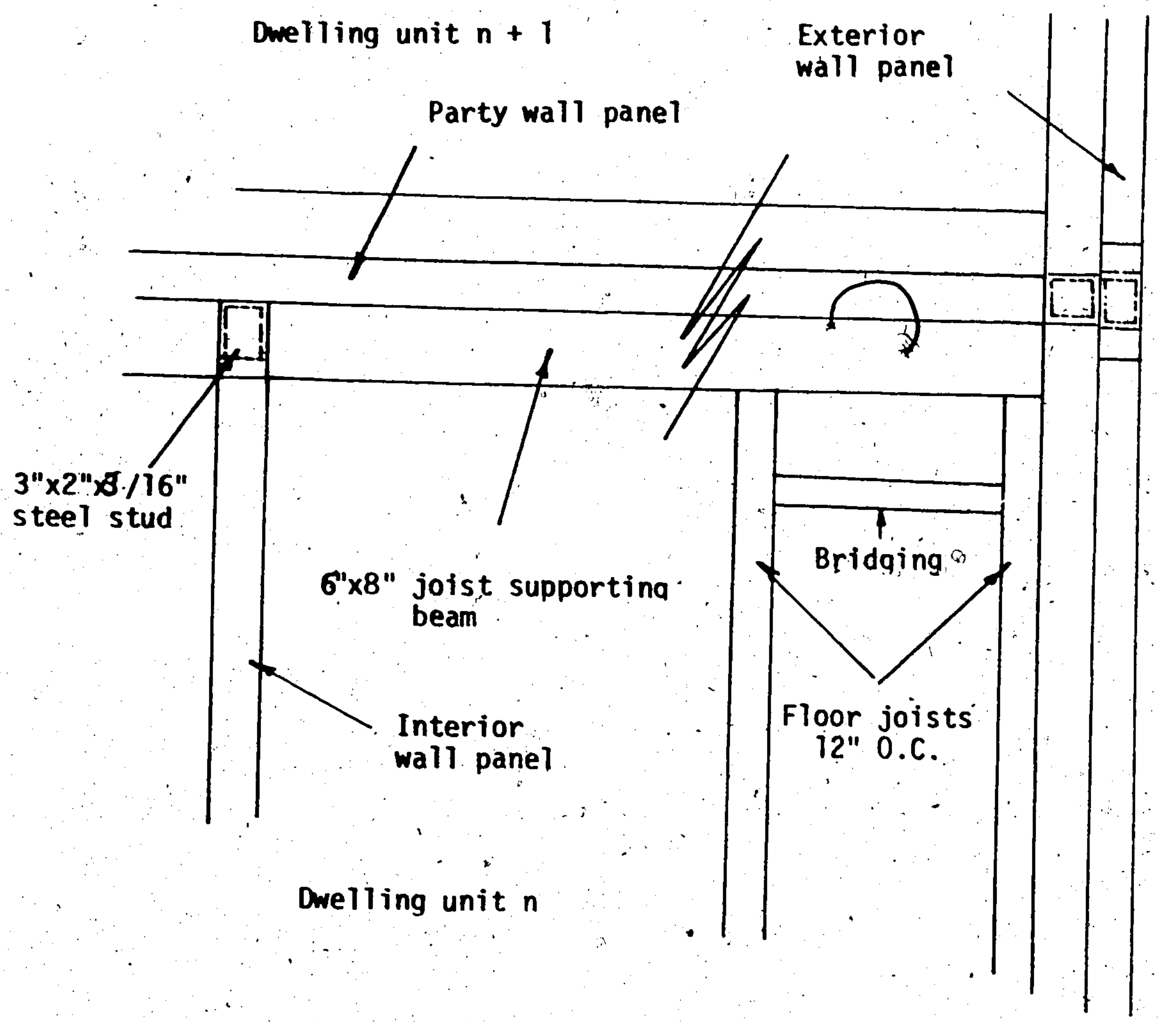


Figure 3.19 Top view of second floor supporting structure.

Scale 1/10(1"=10")

CHAPTER IV

THE DESIGN OF THE MANUFACTURING FACILITY FOR THE SANDWICH PANELS

4.1 The Manufacturing Facility

The design of the sandwich panel manufacturing facility should meet the following requirements.

1. Annual production of 1,070,000 square feet of the panel, to meet the annual requirements of 500 homes (see Appendix C).
2. Manufacture the prefinished sandwich panels for the wall and the roof systems designed in Chapter III.
3. Manufacture the sandwich panels up to 24 feet in length and 7 feet 11 inches in width.
4. Manufacture the sandwich panels from 30 gauge steel sheet coils and 2-1/2 inch thick 2 feet by 8 feet Styrofoam boards.
5. Manufacture locking mechanism from plywood skins and Styrofoam core materials with or without steel studs.

The designed manufacturing facility has initial installed capacity to manufacture 1,100,000 square feet of the panel area per year. The plant is assumed to work 8 hours per day and 250 days per year.

Table 4.1 lists the size, type and quantity of the panels required per day based on the 125 quadruplex units (500 homes) per year.

Table 4.1

Size, Type and Quantity of the Sandwich Panel Requirements per Day

S.No.	Description	Type	Panel Size		Quantity required per day	Approximate unfinished surface area in sq. ft.
			Unfinished	Finished		
1	Exterior wall panel	One skin profiled	21'-8"x7'-11"	(21'-8",19'-8") x 7'-11"	2	346
2	Exterior wall panel	Both skins plain	21'-8"x7'-11"	(21'-8",19'-8") x 7'-11"	3	520
3	Exterior wall panel	One skin profiled	19'-8"x7'-11"	(19'-8",17'-8") x 7'-11"	2	315
4	Exterior wall panel	One skin profiled	17'x7'-11"	17' x 7'-11"	6	816
5	Exterior wall panel	Both skins plain	19'-8"x7'-11"	(19'-8",17'-8") x 7'-11"	3	472
6	Roof panel	One skin profiled	17'-6"x7'-11"	17'-6" x 7'-11"	6-1/8	860
7	Interior wall panel	Both skins plain	11'-9"x7'-11"	11'-9"x7'-11"	8	768
8	Interior wall panel	Both skins plain	8'-7'-11"	8'x7'-11"	2	128
9	Interior wall panel	Both skins plain	2'-6"x7'-11"	2'-6"x7'-11"	4	80

Manufacturing of the several sizes can be grouped together. For example panels at S.No 8 and 9 can be cut from the panel at S. No. 7. Table 4.2 lists the basic panel sizes and quantities to be manufactured per day.

Table 4.2

Basic Panel Sizes and Quantities Manufactured Per Day

S.No.	Panel Size	Type	Quantity required per day	Approximate surface area
1	21'-8" x 7'-11"	One skin profiled	2	346
2	21'-8" x 7'-11"	Both skins plain	3	520
3	19'-8" x 7'-11"	One skin profiled	2	315
4	19'-8" x 7'-11"	Both skins plain	3	472
5	17' x 7'-11"	One skin profiled	6	816
6	17'-6" x 7'-11"	One skin profiled	6-1/8	860
7	11'-9" x 7'-11"	Both skins plain	11	1034

4.2 Production Planning

The sandwich panel manufacturing process consists of the following operations.

1. Uncoiling of the steel coils.
2. Lock-forming to join two 48 inch wide sheets into one 95 inch wide sheet.
3. Profile generating on the sheets required for the sandwich panels listed in table 4.2.
4. Shearing of steel sheet in accordance with the required panel sizes.
5. Surface cleaning for both the skins and the core materials.
6. Adhesive application to the two sides of the core material and one side of each of the skins.
7. Drying, to enable instant assembly of the skins to the core material.
8. Bonding the skins to the core material.
9. Pinch rolling the sandwich to secure a structural bond between the skins and the core materials.
10. Painting, to provide prefinished panels to be directly erected at the construction site.
11. Paint curing, to enable panel manufacturing on a continuous basis.
12. Cutting the panels in the required size.
13. Warehousing.

The detailed design of the manufacturing facility, and equipment selection primarily depends on operation No. 6, that is, the method of adhesive application. The following two methods were studied in detail and the roll coating method was chosen.

1. Spray Coating Method of Adhesive Application

The adhesive is applied to the skins and the core materials by dispensing the adhesive through spray guns. More than one spray gun can be used simultaneously depending upon the surface width of the stock to be coated and travelling speed of the stock. This method is most suited to the coverage of large surface areas of uneven contour. An even adhesive layer thickness can be produced through strict control of adhesive consistency. This method of adhesive application may cause health and fire hazards due to solvent spray mists, unless adequate ventilation is provided.

2. Roll Coating Method of Adhesive Application

The roll coating method of adhesive application uses the technique of adhesive spreading over the surface of the stock by a transfer roller, suitably grooved depending upon the desired adhesive layer thickness. Adhesive is transferred to the transfer roller by a pickup roller partly immersed in the adhesive or adhesive can be stored between the transfer roller and the doctor roller forming a crotch type reservoir.

This method is excellent for adhesive application to large surface areas of flat sheets on a continuous basis. The roll coating method provides the fastest production rate and most uniform adhesive coverage. It is more economical then spraying and both surfaces of the stock can be coated at the same time, which cuts the drying time needed. This method does not cause health or fire hazards and the adhesive layer thickness can be easily controlled by adjusting the pressure of the rolls.

4.2.1 Equipment Selection

The equipment selection is based on the operations described above in Section 4.2. For the sandwich panel manufacturing facility the basic equipment requirement is listed below.

1. Uncoiler
2. Lock-former
3. Profile generator
4. Shear
5. Suction cups with overhead conveyor
6. Surface cleaner
7. Roll coaters
8. Drying oven
9. Roller conveyors and work table (air table)
10. Pinch rolls
11. Panel hanger with overhead conveyor
12. Vertical type spray painting equipment
13. Paint curing oven
14. Sawing machines
15. Pallets
16. Forklift truck

4.2.2 Flow Process Charts

Having decided with respect to the manufacturing process and equipment needed, the flow process charts were developed. The relevent flow process charts are described below.

4.2.2.1 Operation Process Charts

With the information available with respect to the quantity required and the production processes involved, the operation process charts can be developed for the most economical processes and sequence of processes. Operation process charts are the summary of "how to make the product". Besides the operation sequence information with respect to the raw material and time required for the operations involved can be shown on the operation process charts [14]. Figure 4.1 shows the operation process chart for the manufacturing of the sandwich construction panel.

4.2.2.2 Product Flow Process Charts

The product flow process chart is basically similar to the operation flow process chart except it adds more information. The product flow process chart adds transportation and storage activities to the information recorded in the operation process chart. Thus product flow process chart also includes the nonproductive activities, such as transportation and storage, besides the productive activities. Figure 4.2 represents the product flow chart for the manufacture of the sandwich panels.

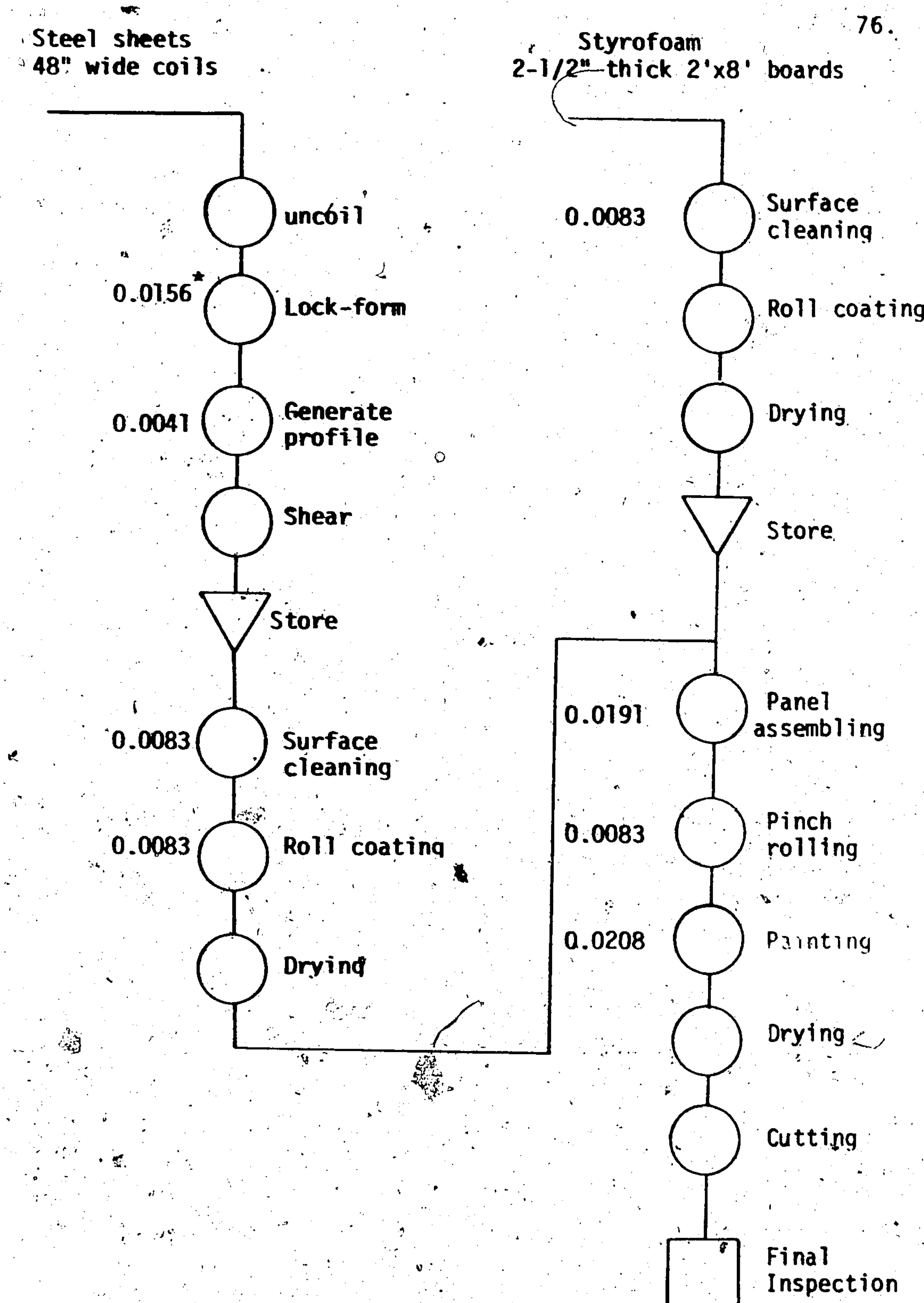


Figure 4.1 Operation process chart for the manufacture of the sandwich panel.

* Operation time in minutes per square foot of the panel.

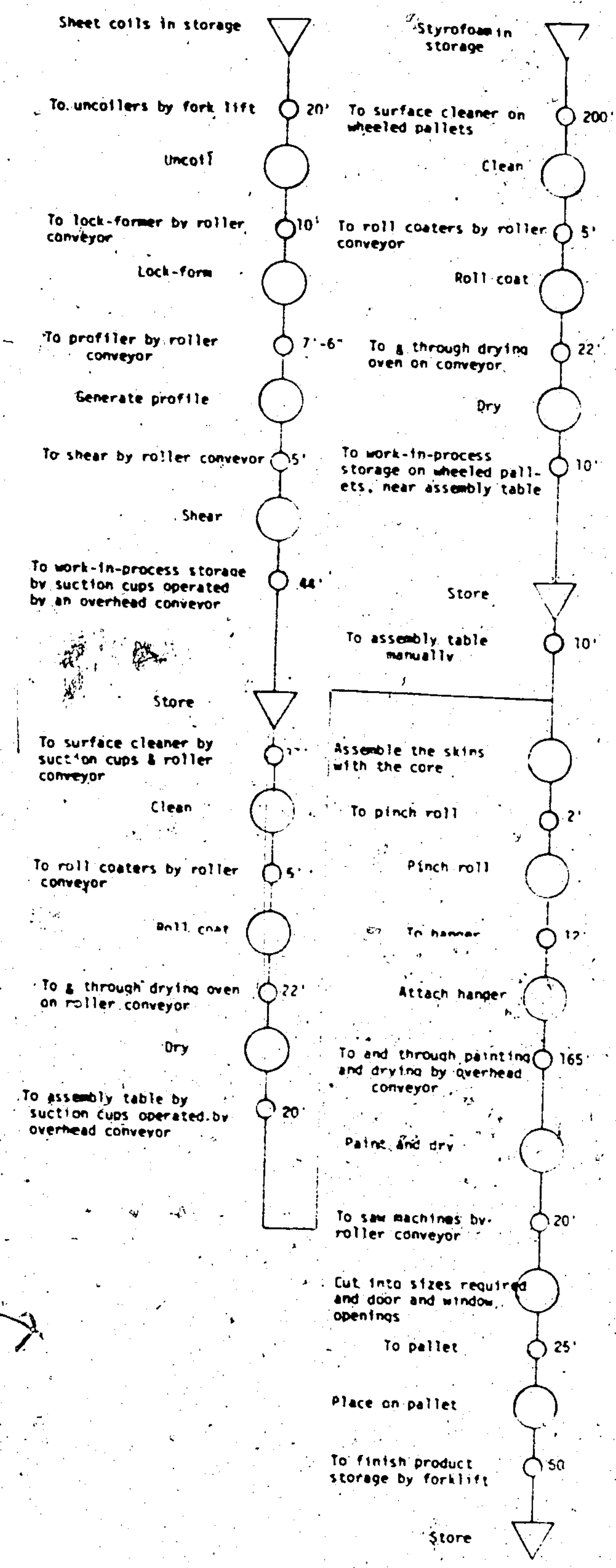


Figure 4.2 Product flow process chart for the manufacture of the sandwich panels.

4.3 Manufacturing Process

The sandwich panel manufacturing includes 16 basic operations (see figure 4.1 operation process chart), starting from the sheet uncoiling ending at finished panels to be transported to the home construction site.

The uncoiler uncoils two 48 inch wide sheets simultaneously. Sheets are fed by a roller conveyor to the lock-former. The lock-former joins the two sheets into one 95 inch wide sheet. The 95 inch wide sheet is fed to the profiler, which generates a profile on the required length of the sheet, otherwise sheet simply passes through the profiler. The sheet is cut in the required sizes by a shear placed next to the profiler. The sheets are stored in a work-in-process storage till such time as the roll coating operation is to be performed. The sheets are picked up by suction cups attached to a grid operated by an overhead conveyor. Two 95 inch wide sheets are fed together to the roll coaters through the surface cleaner. The gap between the coating rolls is automatically adjusted by a control switch in accordance with the thickness of the stock. Both the sheets are coated at the same time on the outer sides. The sheets are taken through the drying oven over a powered endless conveyor. The dried sheets come out of the oven onto a roller conveyor. The top adhesive coated sheet is picked up by a second suction cup type lifting mechanism and moved over the assembly or work table.

Previously adhesive coated Styrofoam boards are placed over the steel sheet in accordance with the panel size. The Styrofoam boards are stacked near the work table on wheeled pallets. Two semi-skilled personnel do the work of placing and positioning the Styrofoam over the steel sheet at the work table. After covering the steel sheet with sufficient Styrofoam a second sheet is picked up with the suction cups and placed over the Styrofoam. The sandwich thus formed is lightly tapped manually before running it through the pinch rolls for final bonding. The sandwich comes out of the pinch rolls onto a roller conveyor. A hanger is moved by an overhead conveyor and the sandwich in the hanger is moved through the painting booth. Both sides of the sandwich are painted at the same time by two spray guns moving up and down in a reciprocating motion. The spray pattern width is controlled in accordance with the paint thickness required and sandwich speed through the spray booth. The two gun system allows the use of different paints, if desired, for the two sides of the panel. After painting the sandwich is moved through the paint curing oven, and over a roller conveyor where the hanger is detached and returned back to its starting point. The sandwich is then cut in to the required panel sizes and door and window openings are cut. The prefinished panels are picked up by a forklift and placed over wheeled pallets. The pallets are moved to the finished product warehouse by the forklift truck.

The details of each process involved in the sandwich panel manufacturing, along with the equipment specifications and cost are described in the following sections.

4.3.1 Uncoiling

Two 48 inch wide 30 gauge, galvanised steel coils are uncoiled on a continuous basis by a variable speed uncoiler.

The specifications and the cost of the chosen uncoiler are given below.

1. Coil width	48 in.
2. Weight capacity	10,000 lbs.
3. Maximum outer diameter	24 inches
4. Maximum inner diameter	6.24 inches
5. Motor	3 HP
Number of units required	2
Cost	$3000 per unit
Total	$6000

Supplier: General Metal Machinery, Edmonton

4.3.2 Lock-forming

Modified "Reeves Type Snap Lock-forming" machine supplied by Brown Boggs Foundary and Machine Co. Ltd., Hamilton, Ontario has been chosen. Seven station machine to form both receiver lock and offset lock for Reeves type snap locks (figure 4.3), will be modified to meet the requirements of continuous production.

The specifications of the lock-forming machine are:

1. Capacity	24 to 30 gauge steel sheet
2. Forming speed	35 feet per minute

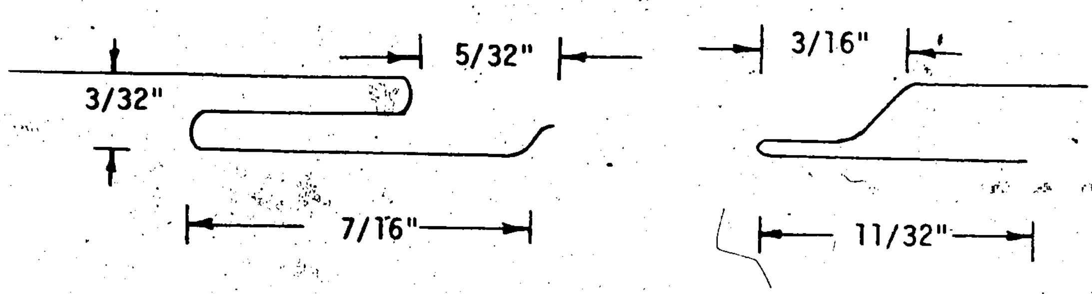


Figure 4.3 Modified Reeves type snap lock

3. Motor — 4 H.P., 3600 R.P.M.

4. Side roller Conveyers (two) — 4' x 4'

Estimated cost:

1.	Lock-forming machine	\$4000
2.	Roller conveyers	\$ 200
	Total	\$4200

4.3.3 Profiling

The 95 inch wide sheet is fed to the profile former as shown in the schematic diagram in figure 4.4. The chosen profile is shown in figure 4.5.

The profile is generated along the 95 inch width of the sheet, while the sheet is in motion. The periferal linear speed of the profile forming rollers will be kept the same as that of the sheet, so that no kinks are formed. The teeth on the profiling rollers are spaced in such a way that the desired profile is obtained on a continuous basis. Both the upper and lower roller move at the same speed.

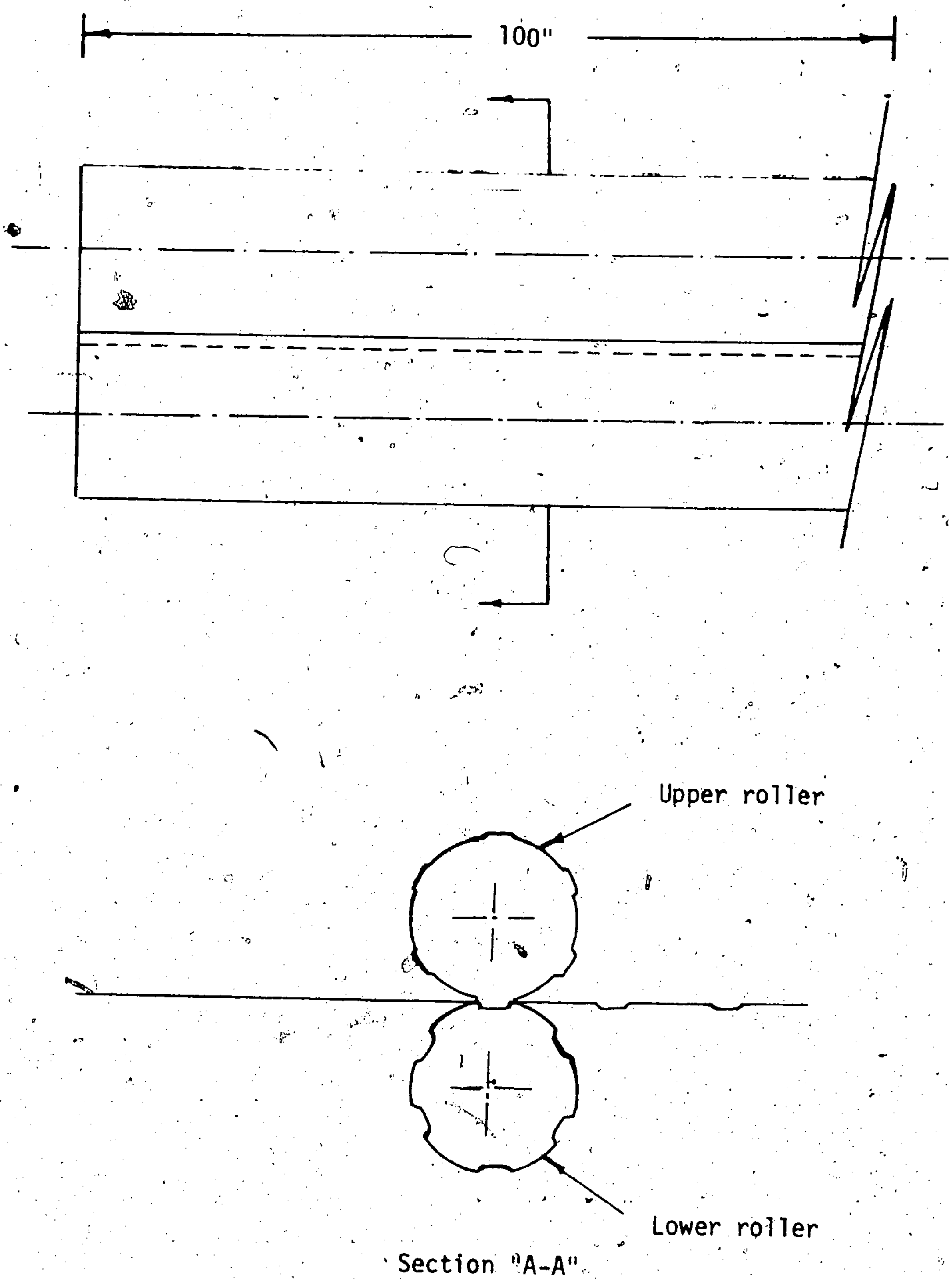


Figure 4.4 Schematic diagram of profiler.

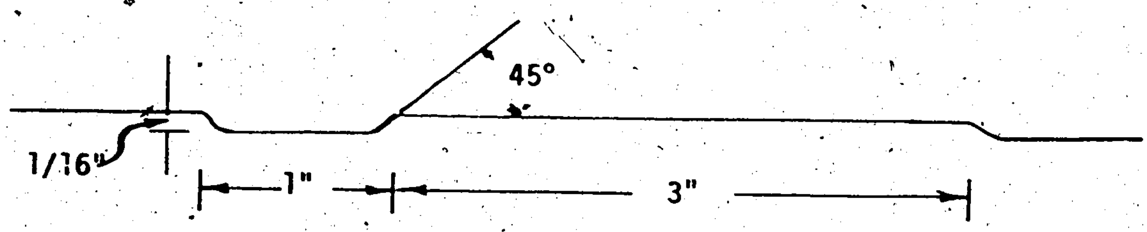


Figure 4.5 Profiled section of steel sheet

Capacity of the press required:

= width of the sheet in inches x thickness of the sheet in inches x yield strength of the sheet material

= 95 in. x .012 in. x 33000 psi.

$$= \frac{95 \times .012 \times 33000 \text{ lbs}}{2240 \text{ lbs/ton}} \simeq 20 \text{ tons.}$$

The specification and estimated cost of the chosen profiler:

1.	Width	100 inches
2.	Capacity	20 tons
3.	Roller speed	8 r.p.m.
4.	Roll diameter	7.63 inches
5.	Number of teeth required	6
6.	Motor	2 HP.
	Estimated cost:	$4000

4.3.4 Shearing

Capacity of the shearing press can be approximately calculated by multiplying thickness of the stock to be cut (in inches) by one third of its length (in inches) and then multiplying the resulting figure by 80. The result will give the press capacity in tons [15].

Capacity for the required press to shear 95 inch wide 30 gauge steel sheet

$= .012 \text{ in.} \times 95 \text{ in}/3 \times 80 \text{ ton/in}^2$

$\simeq 32$ tons

The specification of the shearing machine are:

1. Width of the blade — 100 inches
2. Capacity — 30 to 40 tons
3. Motor — 3 H.P.

Estimated cost: $18,000

4.3.5 Surface Cleaning

Minute foreign particles embedded in the surface of the core material or dust particles on the sheet metal should be removed before adhesive application.

Model No. 410 supplied by Black Brothers Company, Mendota, Illinois with the automatic two position brush roll will be modified to suit 100 inch wide stock cleaning. The cleaner is placed just before the coating rolls. Both sides of the stock is cleaned simultaneously by this equipment. Two tough Tampico fiber brushes, each 8-1/2 inches in diameter, rotating in the opposite direction of stock travel, sweep foreigh particles or dust into the exhaust ducts system. Schematic diagram of the cleaning system is shown in figure 4.6.

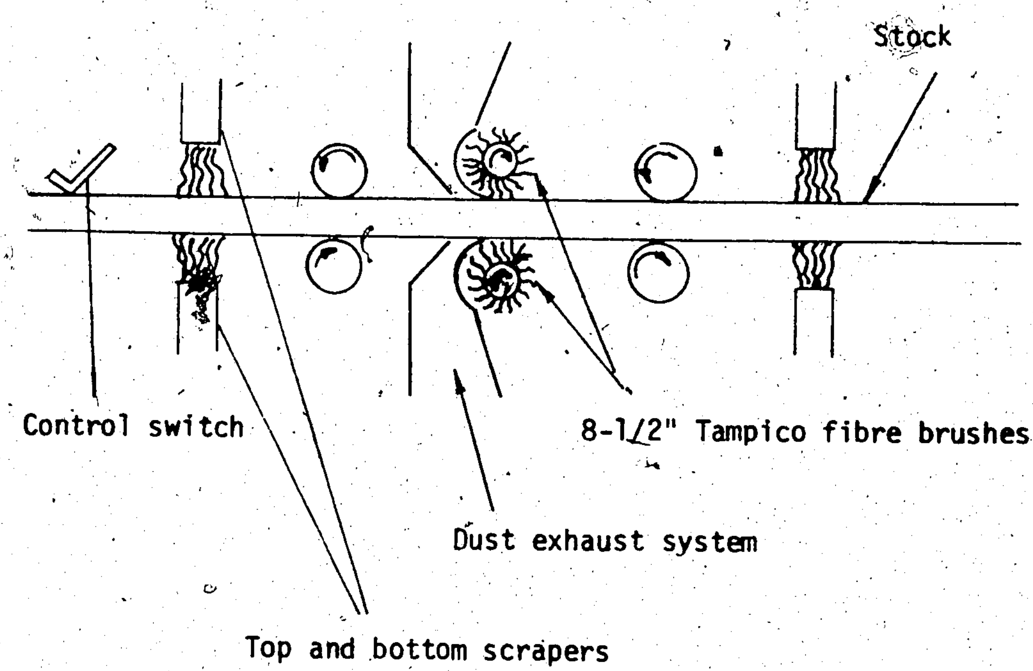


Figure 4.6 Two sides stock surface cleaning system.

Specifications of the chosen equipment are:

1. Width	110 inches
2. Tampico brush roll outer dia.	8-1/2 inches
3. Diameter of suction outlet	7 inches
4. Variable drive feed	25-125 FPM
5. Top and bottom stripper wires	
6. Top and bottom scraper	
7. Automatic stock feed	
8. Automatic two position brush	
9. Variable drive brush	
10. Motors	One 2 H.P., and one 1-1/2 H.P.

Estimated cost:

1. Base machine	$5,800
2. Variable drive feed	$ 590
3. Variable drive brush	$ 580
4. Top and bottom stripper wires	$1,200
5. Top and bottom scraper	$ 860
6. Automatic two position thickness adjustment	$1,000
Total	$10,130

4.3.6 . Roll Coating

The stock (core or skin material) is fed between the coating rolls by a power roller. A control switch automatically adjusts the position of the top coating roll in accordance with the thickness of the stock. The position of the bottom roll remains fixed. The automatic positioning of the top roll enables the coating of thick core material as well as thin skin material fed in any sequence without any manual adjustment for the stock thickness. A continuous supply of the adhesive to the coating rolls is maintained by doctor rolls. The adhesive layer thickness can be controlled by the consistancy of the adhesive or by the roll adjustment. According to the adhesive manufacturer's recommendations optimum bond results are achieved using a dry adhesive weight of 2.5 to 3 mgs. per square foot of bond area. Top and bottom coating rolls allow the coating of both sides of the thick core material or two sheets of the skin material at the same time.

The specification and the cost of the chosen model are as given below.

Model No. 22D Series 1175 supplied by Black Brothers Company, Mendota, Illinois.

Maximum stock width	110 inches
Coating roll diameter	11-3/4 inches
Doctor roll diameter	8-1/2 inches
Variable speed drive	30 to 150 f.p.m.
Daily workload capacity	1 to 2 shifts
Maximum stock thickness	4-1/2 inches
Motor H.P.	5

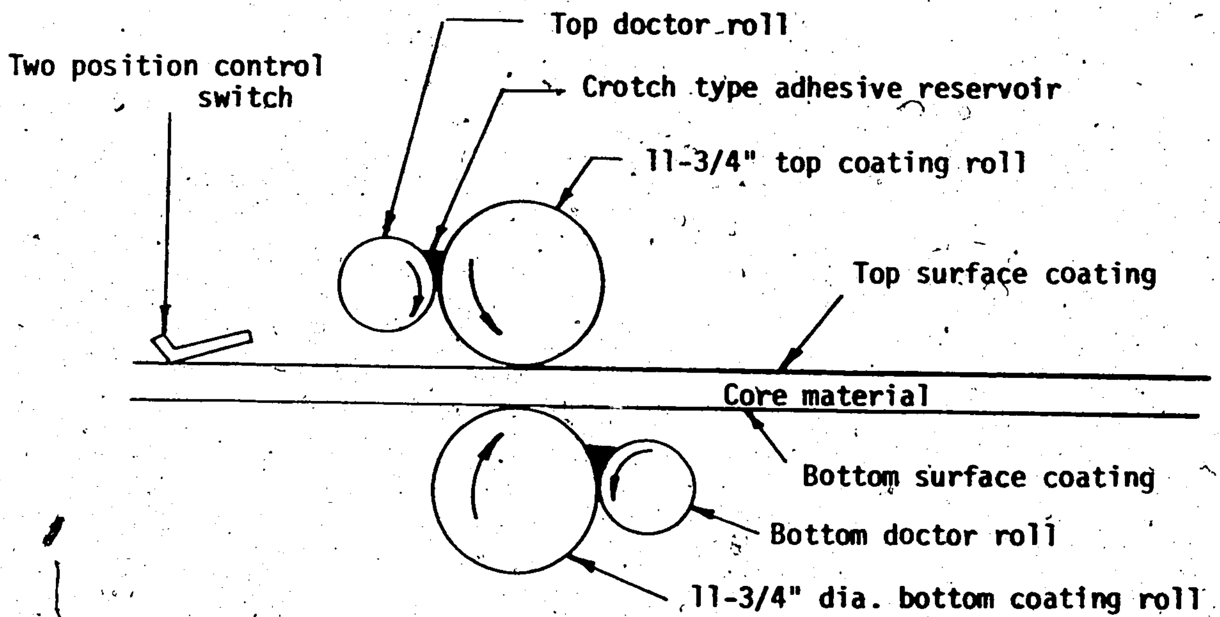
1. Features selected: two position upper roll for two different stock thicknesses, maximum stock thickness difference 4 inches.

2. Roller arrangement: top and bottom coating rolls to coat both sides of the stock at the same time.
3. Cadmium plated critical parts.
4. Electrical interlock on roll nip guard.
5. Roll opening indicator capable of reading in .001" increments.
6. Explosion proof motors and electrical equipment.
7. A stainless steel, air operated pump (Model BB-085) to move adhesive directly from 55 gallon drum to the roll reservoirs with automatic liquid level control device.
8. Power driven outfeed rolls.

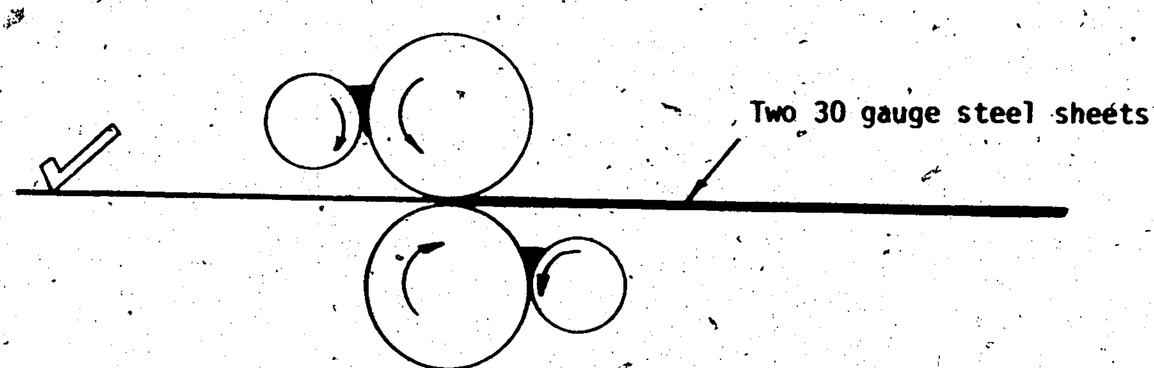
Cost of the equipment and accessories:

1.	Top and bottom spreader	$ 14,260
2.	Roll opening indicator	$ 152
3.	Cadmium plated critical parts	$ 270
4.	Single hand wheel doctor roll adjustment (two numbers)	$ 660
5.	Electrical interlock on roll nip guard	$ 309
6.	BB-085 pump (including elevator and S.S. agitator)	$ 1,499
7.	Automatic two position upper roll adjustment	$ 1,000
	Total	$ 18,150

Schematic arrangement of the roll coating system is shown in figure 4.7.



Thick core material coating arrangement.



Thin skin material (two sheets) coating arrangement.

Figure 4.7 Two position roll coating arrangement for Styrofoam and steel sheets.

4.3.7 Drying

Quick drying is an essential process in the continuous production of laminated products. Drying of adhesives is achieved by moving the stock through baking ovens.

Basically, two types of ovens are utilized. They are: (1) Convection ovens which are mostly gas heated and (2) Infra red ovens which can be electric or gas heated, depending on the choice of the user, but commonly electric infra red ovens are used. At low drying temperature required drying time is much lower in case of the infra red oven as compared to the convection type oven, as shown below.

Temperature	Drying time for infra red oven	Drying time for convection type oven
250°F	10-12 minutes	45 minutes
275°F	8 minutes	30 minutes
300°F	5 minutes	15 minutes

The limiting factor in case of the panel manufacturing is the core material. Styrofoam will lose its strength if exposed to a temperature above 175°F. Therefore for quick drying infra red ovens with quartz tubes was selected. The length of the oven depends on the speed of the stock going through the oven. According to the adhesive manufacturers recommendations a 20 feet long oven will permit stock speeds up to 30 feet per minute with the use of water base XLC 7175 adhesive (3M product). The drying time can be reduced by an efficient air exhaust system to remove vapours.

The chosen equipment will provide variable temperature control.

Specification of the chosen equipment are:

1. Quartz tube infra red drying system
2. Maximum width 10 feet
3. Length of the oven 20 feet
4. Variable temperature control
5. Variable speed exhaust fan

The estimated price of the equipment:

1.	Infra red quartz tube heating system including controls and installation	$8,000
2.	Exhaust fans	$2,000
3.	Shroud	$2,000
	Total	$12,000

4.3.8 Panel Assembly

The panel is assembled manually. The assembly is done on an air table. After a steel sheet is placed onto the air table by the suction cup mechanism, the Styrofoam boards are placed onto the steel sheet by two semi-skilled personnel. The styrofoam boards are placed in such a way that three inches of the steel sheet from the longitudinal edges is left uncovered. A jig as shown in figure 4.8 is used to position the Styrofoam boards on the steel sheet. The jig consists of two 26 feet long 2" diameter steel pipes and locks fixed to the air table. The pipes are rolled over the air table and are locked at a distance of 89 inches in between. The Styrofoam boards are placed in such a way that joints between two boards does not fall under the joint in the steel sheets

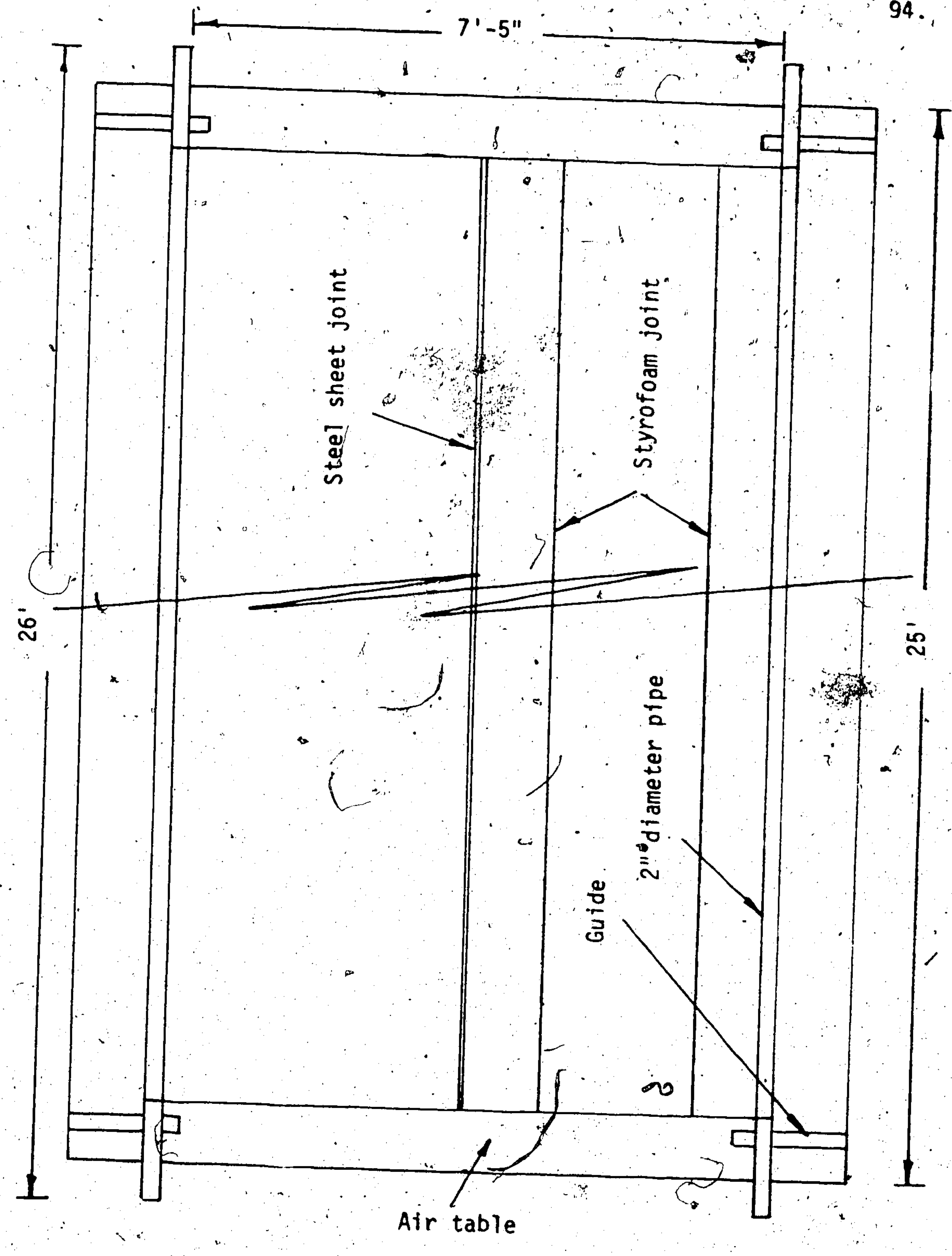


Figure 4.8 Sandwich panel assembly table and jig.

Scale: 1/24(1"=2')

and joints in the panel width are staggered. After placing sufficient Styrofoam boards, the Styrofoam is covered with the second steel sheet. The sandwich is lightly tapped before it is fed to the pinch rolls.

The specifications of the chosen equipment are given below:

Air table:	
1. Length	25 ft.
2. Width	10 ft.
Four wheeled pallets:	8 ft. x 8 ft.
Jig:	
Pipe length	26 ft.
Pipe diameter	2 in.

Estimated costs:

1. Air table	$4,000
2. Four wheeled pallets at $100 each	$ 400
3. Jig pipes and guides with	$ 200
Total	$4,600

4.3.9 Pinch Rolling

Fast tack adhesive dramatically reduces bonding time required and permits immediate panel fabrication. To secure proper bond high pressure is required to be applied on the bonding surfaces. This can be achieved in several ways, such as applying pressure through hydraulic or pneumatic presses or passing the laminated product through pressure roller. The latter method is most suited to continuous production. The chosen process uses a pneumatic pinch roll system. The chosen model is a heavy duty 110 inche rotary press pneumatic model RPP series 1175, supplied by Black Brothers Company, Mendota, Illinois. The specifications of the chosen equipment are:

1.	Maximum laminated product width	110 inches
2.	Variable speed drive	30 to 150 f.p.m.
3.	Diameter of combining rolls	11-3/4 inches
4.	Explosion proof electric system	
5.	Quick open-close roll action	
6.	Roll opening indicator (digital read out)	
7.	Idle study rolls	2 nos.
8.	Magnetic brake	
9.	Elevator opening	4-1/2 inches
10.	Maximum combining pressure (based on 80 p.s.i. air supply)	12,000 lbs.
11.	Motor	3 H.P.

The costs of the chosen pinch roll equipment and accessories are given below.

1.	Base price	$8,307
2.	Variable speed attachment	$1,436
3.	Explosion proof electric system	810
4.	Roll opening indicator	152
5.	Study rolls (2 numbers)	$1,192
6.	Magnetic brake	902
	Total	$12,799

4.3.10 Painting

The panel will come out of the pinch rolls over onto a roller conveyor. The hanger (described in detail under material handling system) will pick up the panel for painting. Painting will be done by a spray process. The chosen system uses two vertical type automatic spray machines. Each spray machine consists of a vertical mounted beam that supports the rails on which the spray gun carrier moves up and down. The vertical type of spray system allows spraying from both sides of the conveyor. The process provides high production speeds as only one drying period is required for both sides, thereby resulting in savings in time, handling, space and money. The chosen system is capable of handling various sizes of panels. The system provides variable gun speeds and spray widths. The chosen painting equipment has the following specifications.

1. Speed of painting guns	variable
2. Spray guns operating air pressure (minimum)	40 psi
3. Air consumption	12.9 cubic feet per minute at 60 psi
4. Spray pattern width with gun at 24 inches from the panel	54 inches
5. Painting capacity	7000 to 14,000 square feet per hour
6. Air compressor pressure	175 p.s.i.
7. Air compressor capacity	18 cubic feet per minute
8. Motor	5 H.P.

Estimated cost:

1.	Two guns	$ 400
2.	Air compressors and accessories	$ 2,000
3.	Hoses and accessories	$ 400
4.	Painting enclosure	$ 2,000
	Total	$ 4,800

4.3.11 Paint Curing

An infra red quartz tube oven similar to that described in 4.3.7 for adhesive drying is chosen for the paint curing. The estimated cost of the oven and accessories is as given below.

1.	Infra red quartz tube oven	$ 8,000
2.	Blower	$ 2,000
3.	Shroud	$ 2,000
	Total	$12,000

4.3.12 Panel Cutting

The panel is cut to the required size by a single circular saw. The doors and window openings are cut by four adjustable circular saws operating simultaneously to provide a square or rectangular cut. To shave the panel edges in true square cut, two grinders move along the panel edges over a guided path. The chosen system has the following equipment and accessories.

1. A vertical circular saw with a one H.P. motor.
2. Four vertical circular saws with the arrangement to adjust the height and distance between saws each operated by a one H.P. motor.

3. Two grinders with soft stones.

Estimated cost:

1. Five circular saws		$ 2,000
2. Grinder with guide rails		$ 1,000
	Total	$ 3,000

4.4 Material Handling

The material handling system is a non-productive system, but nevertheless very important. Material handling system may represent 15 to 25 percent of total production costs. An efficient material handling system can reduce the overall production time and labour involved, thereby, overall production costs.

The material handling system designed for the panel manufacturing facility starts at unloading of raw material and ends at loading of the finished panels on to the transport units.

4.4.1 Unloading of Raw Material

The designed system uses a forklift truck to unload steel coils and Styrofoam into storage. The same forklift will be used to load the steel coils onto the uncoiler and the Styrofoam on to the wheeled carts. The specifications and the cost of the chosen model is as listed below.

1. Capacity*	8,000 lbs at 24 inch load center
2. Turning radius	100 inches
3. Maximum height	120 inches

* The chosen high capacity forklift truck will be used to handle pallets with panels weighing up to 4000 lbs at a 54 inch load center.

4.	Mast elevated (maximum height)	144 inches
5.	Travel speed (maximum)	9.2 m.p.h.
6.	Lifting speed	95 f.p.m.
7.	Lowering speed	70 f.p.m.
8.	Fuel	Diesel
	Estimated cost:	$ 21,000

4.4.2 Material Handling System for the Skin Material

95 inch wide steel sheets come from the shear onto a roller conveyor. The length of the sheet varies from 11 feet to 22 feet. The designed system consists of suction cups to pick up the sheets from the roller conveyor, move them to the work-in-process storage or to another conveyor, which feeds the sheets to the roll coaters through the surface cleaner.

The suction cups are attached to a grid. The suction cups, which are not required are cut off by closing the valves as shown in figure 4.9. This arrangement allows the handling of sheets of various sizes. The grid is attached to the hook of an overhead electrically operated hoist. The hoist carrier moves over the guide rails along three alternate paths as shown in figure 4.10. A two way connecting arrangement (shown in figure 4.11) of the hoist guide rails allows the hoist carrier to travel along the three alternative routes. They are:

(1) Moving the sheets from the roller conveyor No. 1 to work-in-process storage .

(2) Moving the sheets directly from conveyor No. 1 to conveyor No. 2.

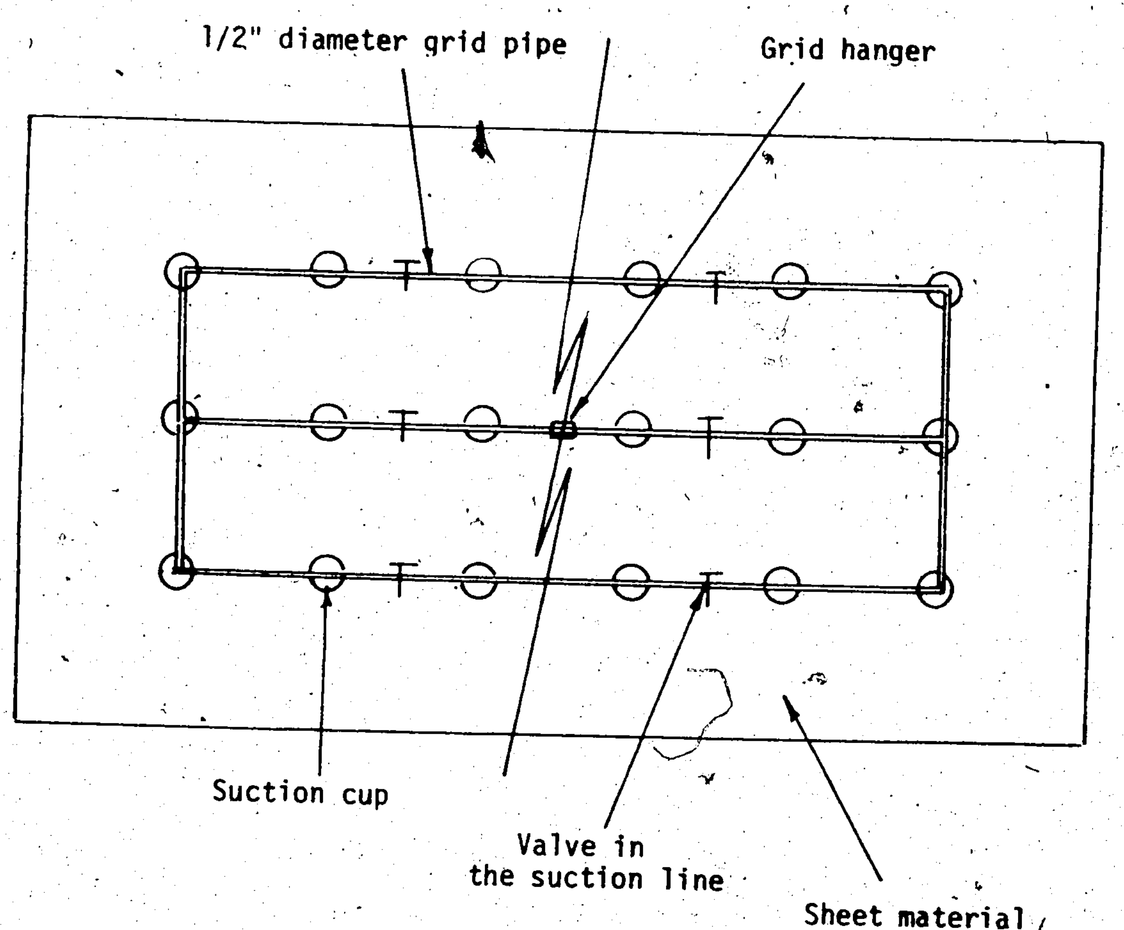


Figure 4.9 Skin material handling mechanism with suction cups.

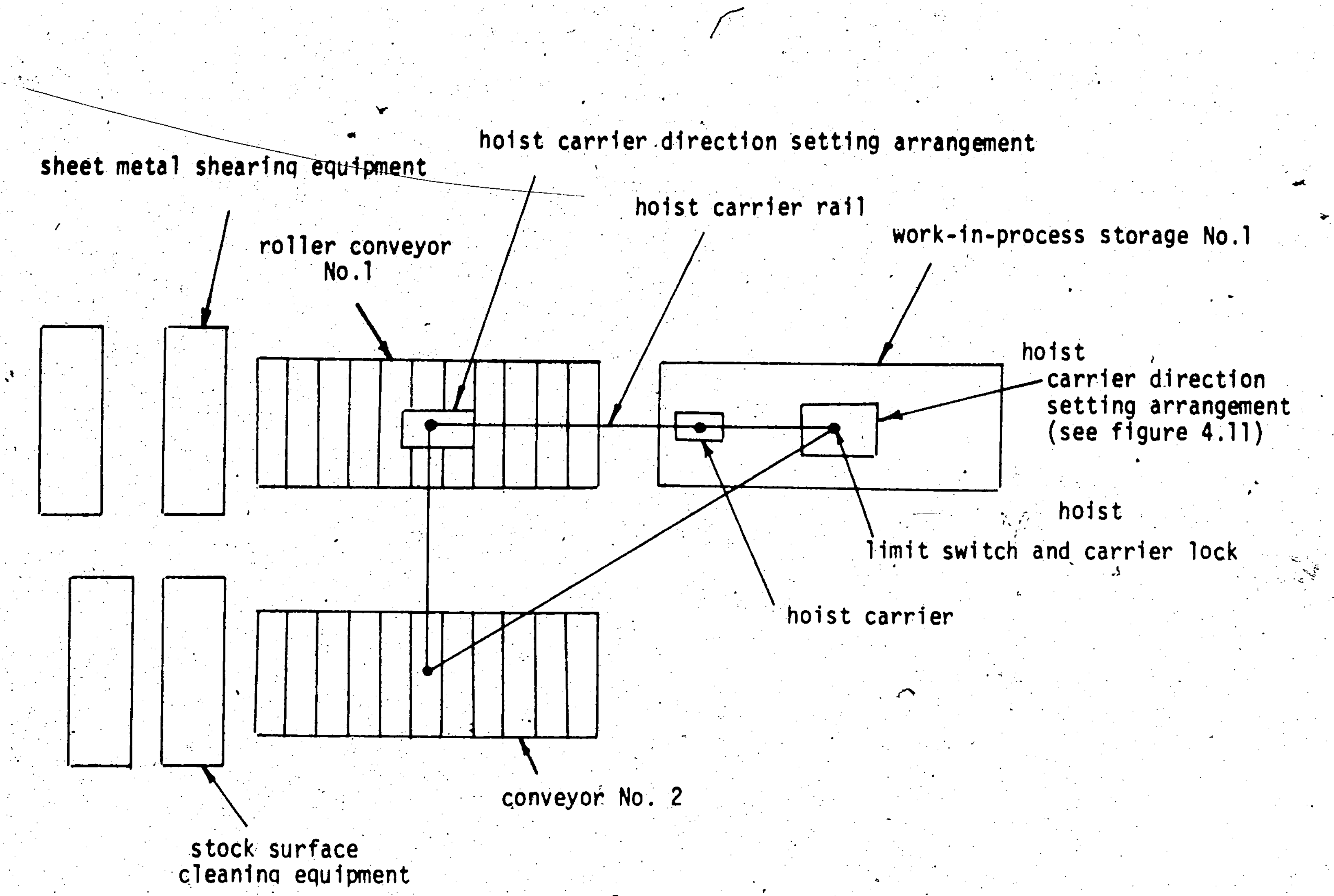


Figure 4.10 Alternate routes for the skin material handling mechanism.

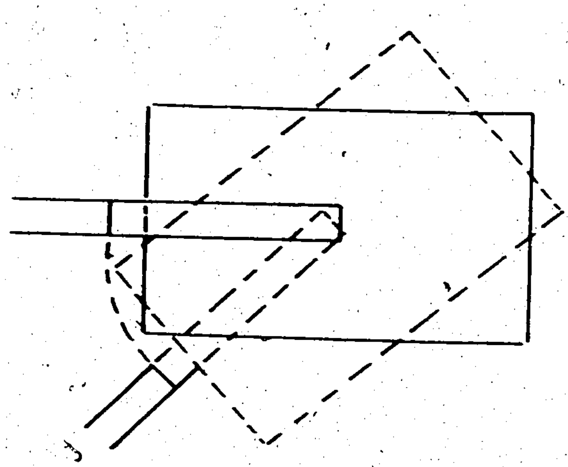


Figure 4.11 Details of carrier direction setting arrangement.

(3) Moving the sheets from the work-in-process storage to the conveyor No. 2.

The specifications and the estimated costs of the equipment and accessories are given below.

Specifications:

1.	Length of conveyors Nos. 1 and 2	22 feet
2.	Width of conveyors Nos. 1 and 2	8 feet
3.	Suction cup	30 numbers
4.	Suction cup diameter	5 inches
5.	Suction pressure (vacuum)	5 psi
6.	Hoist capacity	500 pounds
7.	Grid pipe	1/2 inch diameter steel pipe
8.	Length of grid pipe	62 feet
9.	Motor	1 H.P.

Estimated cost:

1.	Conveyors	$ 1,000
2.	Suction cups at the rate of $10 each	$ 600
3.	Grid pipes and valves	$ 400
4.	Hoist mechanism	$ 4,000
	Total	$ 6,000

The hoist carrier guide rails are provided with three limit switches. At each end of the hoist carrier travel a cam type lock is provided to prevent the bouncing of the carrier. The cam locks are opened by the limit switches. As the limit switch closes, the lock at starting, releases the grid carrier. At the end of travel, due to impact, another lock holds the carrier till the suction is released and the sheets are placed in a predetermined place. The second limit switch reverses the travel direction as well as opens the carrier lock. The chosen system works automatically except that the path of the carrier has to be set up manually.

The stock at conveyor No. 2 is positioned correctly and fed to the surface cleaner manually. The power rollers on the surface cleaner will feed the stock automatically to the coating rolls. As described earlier, the gap between the upper and the lower coating rolls is automatically adjusted in accordance with the thickness of the stock to be coated, by a two position arrangement of the upper roll.

The steel sheets come out of the drying oven onto a roller conveyor No. 3 similar to the roller conveyors No. 1 and 2. The sheets come out in pairs, each sheet coated with adhesive on the outer side. A similar suction cup mechanism as described above is used to pick up the steel sheets one by one. The first sheet picked up is moved to the work table (air table) and positioned manually. A team of two workers place Styrofoam (already coated and stored in work-in-process storage No. 2) onto the steel sheet on the work table. After placing sufficient Styrofoam boards onto the steel sheet, a second steel sheet is moved to the work table, (the bottom surface of second sheet is coated with the adhesive hence the sheet can be placed directly onto the Styrofoam) and positioned manually.

4.4.3 Material Handling System for the Styrofoam

The chosen system consists of three stages.

Stage 1: Styrofoam received in the receiving section is stored in the warehouse by the forklift truck.

Stage 2: Styrofoam boards are stacked onto the eight feet by eight feet wheeled pallets and moved to the conveyor No. 2. Each layer of Styrofoam consists of four 2 feet x 8 feet boards placed side by side.

A simple overhead frame grabs four boards at a time and places them on to the conveyor No. 2. Every time the hanger returns it is lowered automatically till the air cylinder touches the Styrofoam surface of the stack. Another control switch operates the hoist in such a manner that the height of the hanger over the conveyor is automatically adjusted. One semi-skilled person positions the Styrofoam boards on the conveyor and feeds them to the surface cleaner.

Schematic diagram of stage two of the Styrofoam is shown in figure 4.12.

The equipment required and the estimated cost of the equipment for the Styrofoam handling system is given below.

Overhead monorail hoist:

1. Capacity	250 lbs.
2. Motor	1 H.P.

3. Two air operated telescopic cylinders
with end thrust plates as shown in the figure 4.12.

Estimated costs:

1. Hoist and accessories		$ 750
2. Air cylinders and frame		$ 250
	Total	$1,000

Stage 3: The Styrofoam boards come out of the oven onto the roller conveyor No. 3 and are picked up manually and stored in the work-in-process storage No. 2. Two semi-skilled personnel perform the job. At a coating speed of 30 ft. per minute the total time required to coat one day's requirement of the Styrofoam is 18.33 minutes. Therefore, the remaining time of the above referred semi-skilled personnel is utilized in panel fabrication to place the Styrofoam boards onto the steel sheet and feed the sandwich assembly to the pinch rolls.

4.4.4 Material Handling System for the Panel

The panel comes out of the pinch rolls onto a roller conveyor No. 3, where a hanger is attached to it as shown in figure 4.13 and the panel is picked up vertically. The panel is moved through the painting booth, where two spray guns moving up and down on guide rails paint the panel while the panel is in motion. Both sides of the panel are painted at the same time. After painting the panel is moved through the paint curing oven and finally placed onto the roller conveyor No. 4. The hanger is

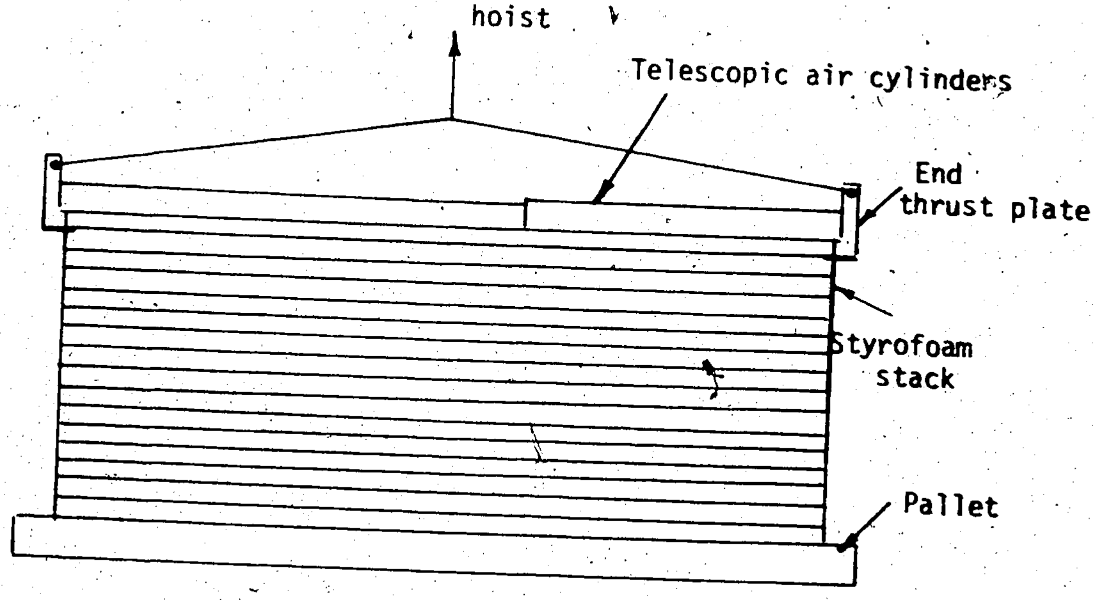


Figure 4.12 2' x 8' Styrofoam boards handling mechanism.

Scale: 1/24(1"=2')

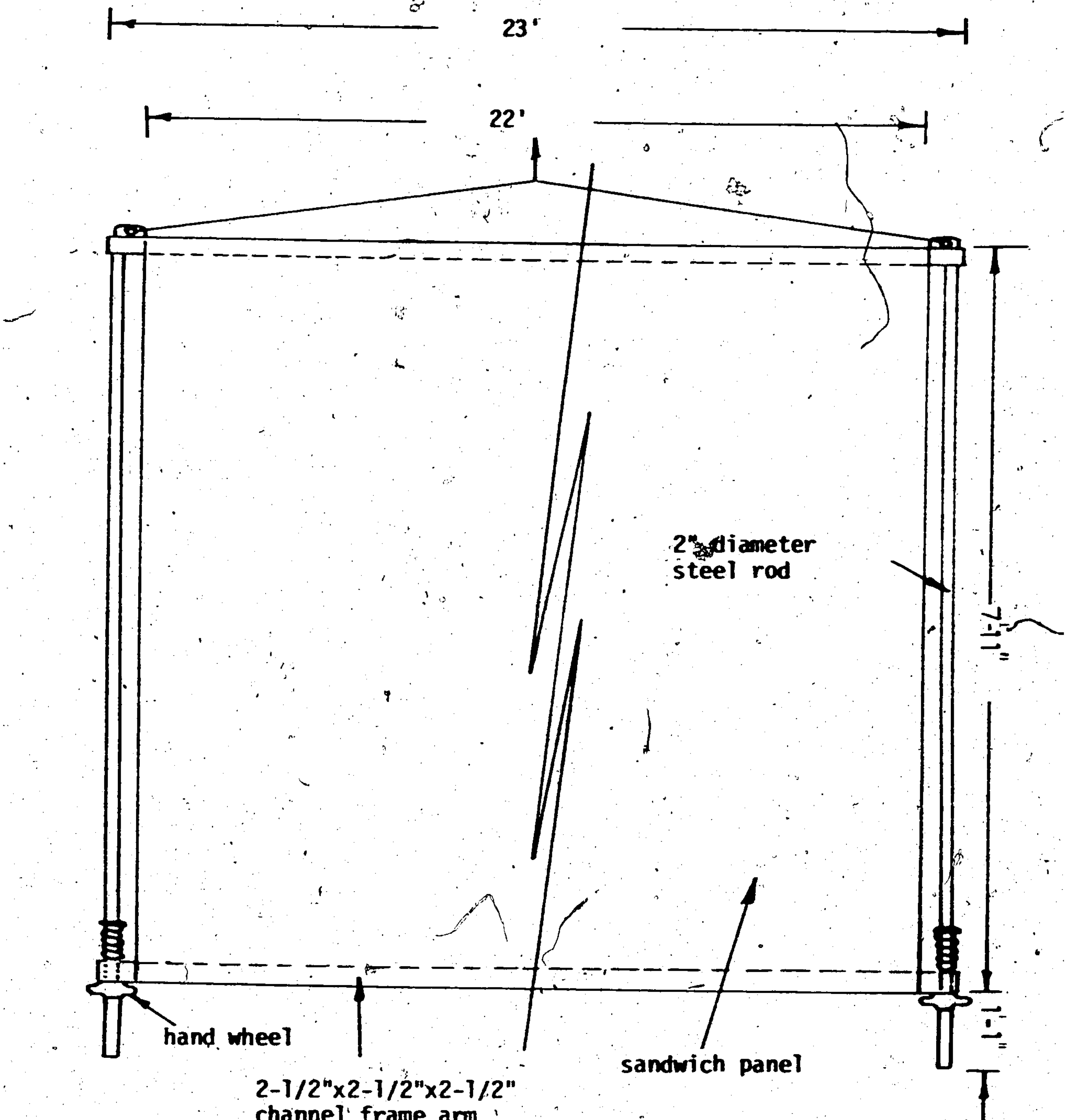


Figure 4.13 Hanger for handling the sandwich panels.

detached and returned back to roller conveyor No. 3.

After the panel is cut to the required size and the openings for door and window are cut and sides shaved the panel slides into the guide chanels and moved over the hydraulic table. When full length of the panel slides into the guide rails, the guide rails open and allow the panel to chop onto a wooden pallet placed on the hydraulic table. The dropping of the panel will not cause any damage since a very small space exists between panel and the pallet and also there is a small air emission between the panel and the pallet due to large cross section of the panel. The panel does not scratch with other panel or the pallet while sliding into the guide rails.

To move the panels through the guide channels smoothly, a ball and socket system is used. The panel slides over the balls smoothly without scratching (figure 4.14).

The hydraulic table is automatically lowered by the amount equal to the thickness of the panel so that it is level with the roller conveyor No. 5.

After collecting sufficient panels based on a unit load of approximately 4000 lbs the forklift truck removes the loaded pallet, places it on a fifth wheel cart and places an empty pallet on the hydraulic table. This system allows sufficient free time for the forklift to attend to other jobs, such as handling steel coils, Styrofoam boards and loading transport units for shipment.

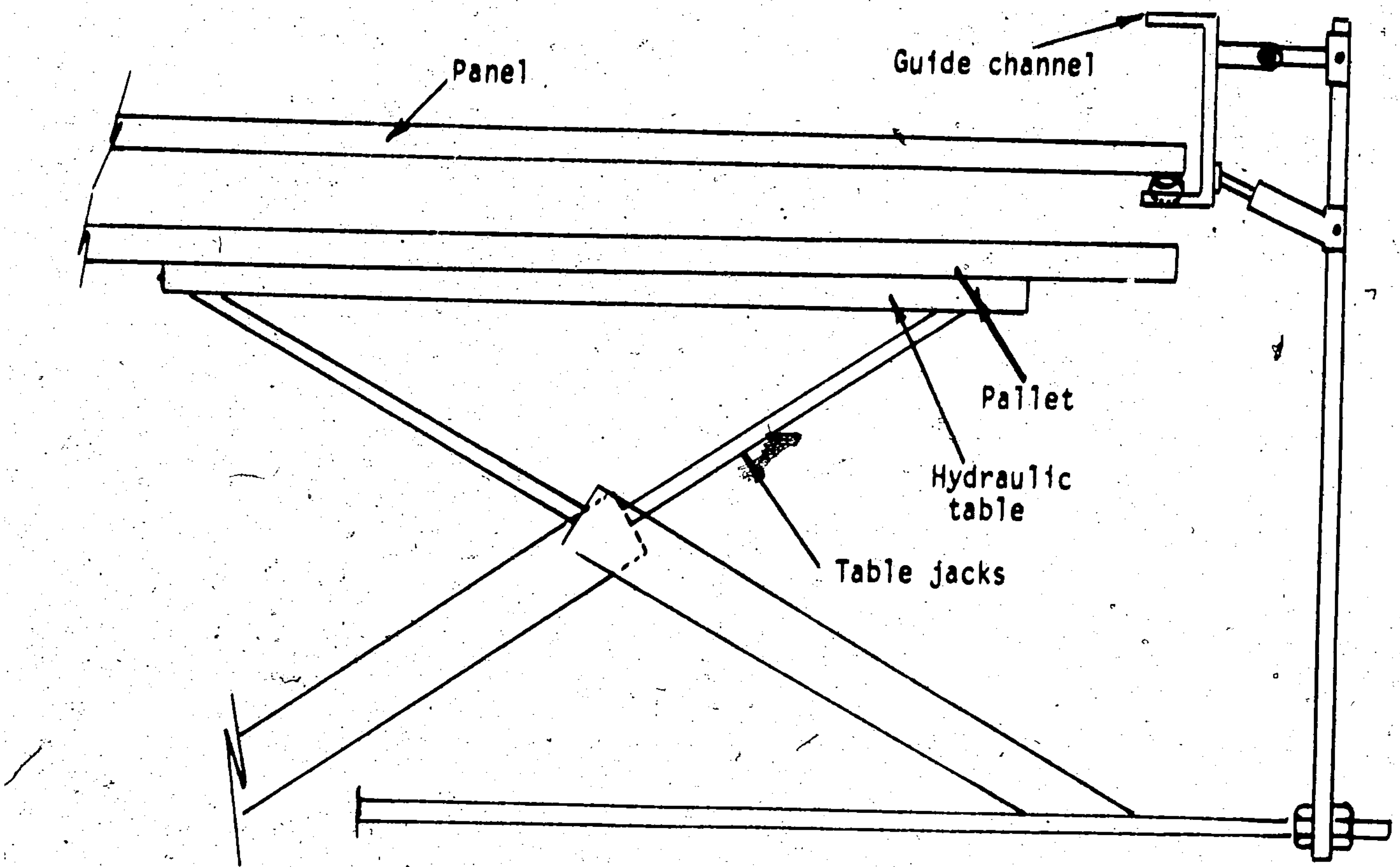


Figure 4.14 Panel guiding mechanism with hydraulic table.

The specifications of the equipment required and the estimated costs are given below:

Roller Conveyor Nos. 3, 4 and 5

1.	Length	24 feet
2.	Width	8 feet
3.	Overhead conveyor: monorail, variable speed	
4.	Load capacity	1000 lbs.
5.	Motor	2 H.P.

Hanger Frame:

1. 2-1/2 inch x 2-1/2 inch x 2-1/2 inch x 1/8 inch two channels each 23 feet long.
2. Two steel rods each 2 inches in diameter and 9 feet in length, threaded along a one foot length, 4 threads per inch
3. Two 6 inch diameter wheels, wheel boss with internal threads 4 threads per inch.

Hydraulic table:

1.	Capacity	6000 lbs.

Guide channels:

1. Two 3 inch x 6 inch x 1/8 inch channels each 25 feet long with ball and sockets 6 inches on centre.

Estimated cost:

1.	Roller conveyors at $500 each	$1,500
2.	Overhead conveyor system	$5,000
3.	Hanger	$ 200
4.	Hydraulic table	$8,000

5. Guide railes with accessories $5,000

Total $19,700

4.5 Packaging

4.5.1 The Pallet

The pallet used for the packaging will have a width of 8 feet and a standard length of 8 feet with increments of one foot. For smaller panels more than one panel will be accommodated on the pallet lengthwise. The panel sizes above 8 feet in length will be accommodated by joining more than one standard pallet. This method will allow low pallet inventory and ease in pallet storage and handling.

4.5.2 Packaging Process

After placing the panel onto the pallet it is covered with a polyethelene sheet or kraft paper. This provides protection against damage while placing the next panel. The panels are tied with plastic straps to avoid rubbing against each other during transportation.

4.6 Time Calculations to Determine Equipment Utilization

The time calculations are based on the daily production requirements of 4,400 square feet of the sandwich panel and the following assumptions.

1. Set up time = 30 minutes per 8 hours shift

2. Personal allowance = 30 minutes per 8 hours shift

3. Fatigue allowance = 10%
4. Rating factor = 100%
5. Number of channels = 1
6. Shop efficiency = 80%

Table 4.3 lists normal times available and required for various operations involved in the sandwich panel manufacturing.

The normal time is actual time required for an operation. The normal time required for various operations is calculated from the production rate of the equipment and the universal standard times obtained from MTM (Methods-Time-Measurement)* technique.

The normal time availabe is determined from the following relation.

$$\text{Normal time} \left(1 - \frac{\%\ \text{allowance}}{100}\right) = \text{Standard time}$$

By definition standard time is the sum of the normal time, allowance for personal time, fatigue and delays normal to the job [14] and is obtained from the shop planning time, using the following relationship.

$$\text{Standard time} = \text{Shop planning time} \times \text{shop efficiency}$$

The shop planning time is the total time available for a job based on the production volume. The shop planning time per square foot of panel manufacture is obtained from:

---

* See Section 4.6.5 for description of the Methods-Time-Measurement technique.

Shop planning time per square feet of panel $= \dfrac{8 \times 60 \text{ minutes} - \text{set up time}}{4400 \text{ ft}^2}$

$= \dfrac{480 \text{ minutes} - 30 \text{ minutes}}{4400 \text{ ft}^2}$

$= 0.1090$ minute

Standard time $= 0.1090 \times$ shop efficiency

$= 0.1090 \times 80/100$

$= 0.0872$ minute/ft^2

Normal time $= 0.0872 \times (1 - \dfrac{\% \text{ allowance}}{100})$

Personal allowance per 8 hours = 30 minutes

$= \dfrac{30 \times 100}{8 \times 60}\% = 6.25\%$

Fatigue allowance = 10%

Total allowance = 10% + 6.25%

= 16.25%

Normal time $= 0.0872 \times (1 - \dfrac{16.25}{100})$

$= 0.0730$ minute/square foot of panel.

4.6.1 Lock-forming Process Times

Speed = 16 ft/minute

Length of the sheet metal processed per shift

$= \dfrac{4400 \text{ ft}^2}{4 \text{ ft}}$

= 1100 ft

Normal time $= \frac{1100 \text{ ft}}{16 \text{ ft/minute}}$

$= 68.75$ minutes

Normal time per square foot of panel

$= \frac{68.75 \text{ minutes}}{4400 \text{ ft}^2}$

$\doteq 0.0156$ minute

4.6.2 Profiling Process Times

Speed $= 16$ ft/minute

Length of sheet metal processed per shift

$= \frac{2337 \text{ ft}^2}{8 \text{ ft}}$

$= 292$ ft.

Normal time $= \frac{292 \text{ ft}}{16 \text{ ft/minute}}$

$= 18.25$ minutes

Normal time per square foot of panel

$= \frac{18.25 \text{ minute}}{4400 \text{ft}^2}$

$= 0.0041$ minute/ft^2

4.6.3 Surface Cleaning Process Times

Speed $= 30$ ft/minute

Surface area to be cleaned per shift

= 4400 square feet of Styrofoam

+ 4400 square feet of steel sheet

= 8800 square feet

Length of stock $= \dfrac{8800\ ft^2}{8\ ft}$

$= 1100\ ft$

Normal time $= \dfrac{1100\ ft}{30\ ft/minute}$

$= 36.67$ minutes

Normal time per square foot of panel

$= \dfrac{36.67\ minutes}{4400\ ft^2} = .0083\ minute/ft^2$

4.6.4 Roll Coating Process Times

Speed $= 30$ ft/minute

Length of stock to be coated

$= \dfrac{8800\ ft^2}{8\ ft}$

$= 1100\ ft$

Normal time $= \dfrac{1100\ ft}{30\ ft/minute}$

$= 36.67$ minutes

Normal time per square foot of panel

$= \dfrac{36.67\ minutes}{4400\ ft^2}$

$= 0.0083\ minute/ft^2$

4.6.5 Panel Assembly Times

Time required for assembly of the skins and the core materials is critical, as the assembly work is performed manually.

To determine the standard time, MTM (Methods-Time-Measurement) technique has been used in this study and supplemented with estimated time for non-standard operations.

MTM is a system of predetermined time values which analyzes any manual operation into the basic motions required to perform the operation and assigns a time value to each motion which is determined by the nature of the motion and the conditions under which it is performed [21].

The standard time values, however, provide estimates for the work time only. To determine total cycle time for a job rest time, delay allowances, and allowance for personal time are added to the standard work time [14].

Breakdown of the time required for the panel assembly is given below.

1. Walk to the control switch to operate suction cup mechanism (average walking distance 10 feet) = .0568 min.
2. Reach the control switch = 14.2 TMU*
   = .0085 min.
3. Hoist lowering time at a speed of 6 feet per minute, through a distance of 6 inches, $= \frac{6}{12} \times \frac{1}{6} = .0833$ min.
4. Hoist raising time = .0833 min.
5. Hoist travelling time at a speed of 60 feet per minute, through a distance of 20 feet = .3333 min.
6. Hoist lowering time to release the sheet = .0833 min.
7. Hoist raising time after releasing the sheet = .0833 min.

---

* 1 TMU = .0006 minute

8. Reach the jig pipe = 9.5 TMU

= .0057 min.

9. Move jig pipe to preset position, through a distance of 12 inches = 10 TMU

= .0060 min.

10. Walk to Styrofoam stacked on pallets (average distance 10 feet) = .0568 min.

11. Reach to pick up Styrofoam board = 9.5 TMU

= .0057 min.

12. Grasp Styrofoam = 4 TMU

= .0024 min.

13. Walk to the work table with the boards of Styrofoam approximately weighing 12 lbs. = .0568 min.

14. Position Styrofoam boards onto the steel sheet = 2 x 48.5 TMU

= .0582 min.

15. Walk to open jig lock (average distance 25 feet) = .142 min.

16. Reach jig lock = 9.5 TMU

= .0057 min.

17. Disengage jig lock = 7.5 TMU

= .0045 min.

Sum of the Universal Standard times required for the operations 1 to 9 = .7435 min.

Number of times operations 1 to 9 performed

= 2

Total standard time required for the operations 1 to 9

= 2 x .7435 min.

= 1.4870 min.

Sum of the standard times required for operations 10 to 14

= .1799 min.

Number of Styrofoam boards required per 22 feet by 8 feet panel = 11

Number of channels = 2

Number of times operations 10 to 14 performed

= 6

Total Universal Standard time required for operations 10 to 14

= 6 x .1799

= 1.0794 min.

Sum of the Universal standard times required for the operations 15 to 17 = .1522 min.

Number of times the operations 15 to 17 performed

= 2

Total time for the operations 15 to 17

= 2 x .1522 min.

= .3044 min.

Estimated tapping time = .5 min.

Total panel assembly time = 1.4870 + 1.0794 + .3044 + .5

$= 3.3708$ minutes

Normal time per square foot of panel

$$= \frac{3.3708 \text{ minutes}}{22 \text{ ft} \times 8 \text{ ft}}$$

$$= 0.0191 \text{ minute/ft}^2$$

4.6.6 Pinch Rolling Times

Speed = 15 ft/minute

Length of panel to be processed per shift

$$= \frac{4400 \text{ ft}^2}{8 \text{ ft}} = 550 \text{ ft}$$

Normal time $= \frac{550 \text{ ft}}{15 \text{ ft/minute}}$

$$= 36.67 \text{ minutes}$$

Normal time per square foot of panel

$$= \frac{36.67 \text{ minutes}}{4400 \text{ ft}^2}$$

$$= 0.0083 \text{ minute/ft}^2$$

4.6.7 Painting Times

Conveyor speed 6 ft/minute

Painting guns speed 16 ft/minute

Length of panel to be painted

$$= \frac{8800 \text{ ft}^2}{16 \text{ ft}}$$

$$= 550 \text{ ft}$$

Normal time $= \frac{550 \text{ ft}}{6 \text{ ft/minute}} = 91.67$ minutes

Normal time per square foot of panel

$$= \frac{91.67 \text{ minutes}}{4400 \text{ ft}^2} = 0.0208 \text{ minute/ft}^2$$

Table 4.3

Summary of Time Available and

Time Required, Based on Per Square Foot

of the Sandwich Panel Manufacturing Operations

Operation	Time Available in Minutes	Time Required in Minutes	Percentage Idle Time
Lock-forming	0.0730	0.0156	78.63
Profiling	0.0730	0.0041	94.38
Surface cleaning	0.0730	0.0083	88.63
Roll coating	0.0730	0.0083	88.63
Panel assembly	0.0730	0.0191	73.83
Pinch rolling	0.0730	0.0083	88.63
Painting	0.0730	0.0208	71.50

4.7 The Plant Layout

The designed plant layout provides storage space for the following:

1. Styrofoam boards - one month's supply.
2. Steel coils - two month's supply.
3. Finished product - one week's production.
4. Office space - within the same building.

5. Two work-in-process storage areas for temporary storage of steel sheets and Styrofoam boards.

The plant layout has been designed with respect to the following:

1. Material flow in a straight line till inter-related processes end.
2. Automation where economically feasible.
3. Economical use of space for the equipment layout.
4. Personnel safety.

The manufacturing facility will be located on a one acre lot.

Total building area is 25,250 square feet, including 1175 square feet for the offices and 6075 square feet of area for the indoor storage of the finished product. An open area of 18,310 square feet, including 2400 square feet of paving is left for parking, shipping and future expansion.

The overall minimum length and width of the lot required is 225 feet by 150 feet respectively.

The equipment layout is designed in accordance with the flow process charts developed in section 4.2.2 (figures 4.1 and 4.2).

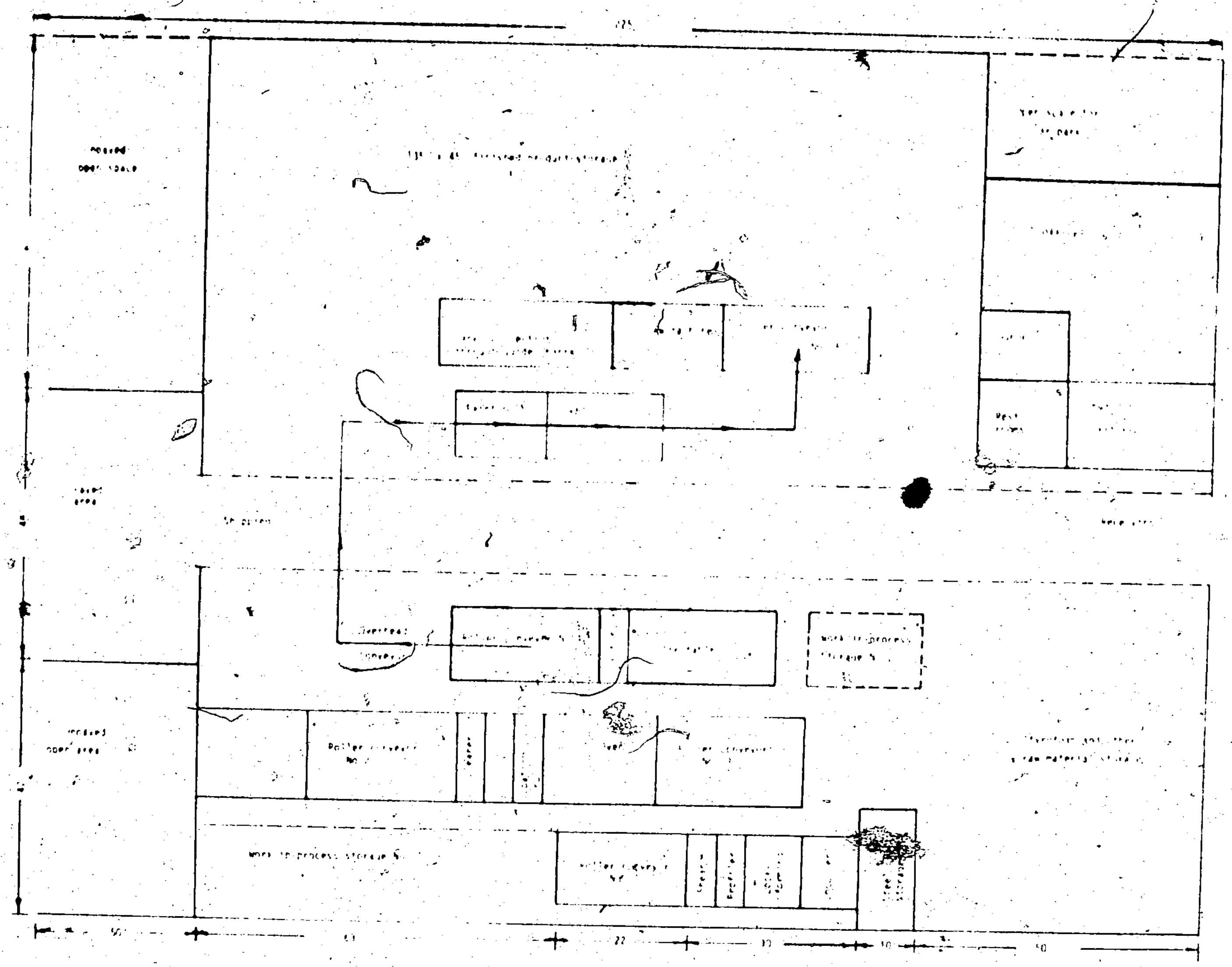


Figure 4.15 The plant layout for the sandwich panel manufacturing facility.
Scale: 1/360(1"=30')

CHAPTER V

ECONOMIC STUDY OF THE SANDWICH PANEL MANUFACTURING FACILITY

To determine the manufacturing cost of the designed sandwich panel the "Annual Equivalent Cost" method is applied in this study.

5.1 The Panel Manufacturing Cost

The manufacturing cost of the panel is determined on the basis of the following assumptions.

1. Annual production: 1,100,000 square feet of the panel area to meet requirements of 500 homes (125 quadruplex units) per year (reference Appendix C).
2. 250 working days per year.
3. Acceptable minimum rate of return on the investment after taxes (MARR) = 20%.
4. Estimated life of the investment 5 years.
5. Straight line method of depreciation for the building and equipment.
6. Capital structure: 100% equity capital.
7. Rate of income taxes: 50%.

The panel manufacturing cost consists of the capital costs, direct material costs, direct labour costs and factory overhead costs.

5.1.1 Capital Costs

The capital costs are the sum of the following costs.

1. Cost of the land.
2. Cost of the building.
3. Cost of the plant and equipment.
4. Startup costs.
5. Working capital costs.

5.1.1.1 The Land

The manufacturing facility needs a building area of 25,250 square feet (figure 4.15) and 8500 square feet of open area for parking, and pavement for shipping.

Land area taken	= 1 acre
	= 43,560 square feet
Cost of the land	= $10,000

5.1.1.2 The Building

Total building area	= 25,250 square feet
Cost of the building at $10 per square foot	= $252,500
Cost of paving at $2 per square feet (2400 ft^2)	= $4,800
Total	$257,300

5.1.1.3 The Plant and Equipment

Table 5.1 lists the equipment required for the sandwich panel manufacturing facility, including life, estimated salvage in year 5, the annual estimated cost of maintenance and annual depreciation (calculated on a straight line basis).

Total cost of plant and equipment = $174,780

Estimated salvage value in the year 5 = 79,085

5.1.1.4 Startup Costs

The startup costs include the transportation, installation and testing of the equipment prior to the regular production starts. The startup costs are estimated at 10% of the total plant and equipment cost and capitalized for the purpose of the economic study. The startup costs are depreciated over the life span of the investment, by the same method as the equipment.

Estimated startup costs = $16,500

Annual equivalent depreciation = 3,300

5.1.1.5 Working Capital

By definition working capital is the difference between the current assets and the current liabilities. The working capital turns over continually and the salvage value for the purpose of the economic study equals the initial value.

Table 5.1

Initial Cost, Life, Salvage Value in Year Five, Maintenance Costs and the Annual Depreciation with Respect to the Equipment Required for the Sandwich Panel Manufacturing Facility

Equipment	Quantity Required	Estimated Life in Years	Initial Cost $	Estimated Salvage in Year 5 in $	Cost of Maintenance in $/year	Depreciation in $/year	Remarks for the Cost of Maintenance
Uncoiler	1	15	6,000	4,000	100	400	General maintenance
Lock-former	1	10	4,200	2,100	100	420	General maintenance
Profiler	1	10	4,000	2,000	100	400	General maintenance
Shear	1	15	18,000	12,000	250	1,200	Blade changing and general maintenance
Surface Cleaner	1	15	10,130	6,755	500	675	Brush changing and general maintenance
Roll Coater	1	15	18,150	12,100	500	1,210	Cleaning and general maintenance
Oven	2	10	24,000	12,000	2,000	2,400	Tube replacement and general maintenance
Panel Assembly Equipment	1	5	4,600	0	50	920	

Table 5.1 (continued)

Equipment	Quantity Required	Estimated Life in Years	Initial Cost $	Estimated Salvage in Year 5 in $	Cost of Maintenance in $/year	Depreciation in $/year	Remarks for the Cost of Maintenance
Pinch Rollers	1	15	12,800	8,530	1,000	853	General maintenance
Painting Equipment	1 set	5	4,800	0	200	960	Parts replacement and general maintenance
Saw Machines	5	5	2,000	500	200	300	Blade changing and general maintenance
Grinder	1	5	1,000	0	100	200	Stone changing and general maintenance
Forklift	1	15	21,000	14,000	2,000	1,400	General maintenance and repairs
Roller Conveyors	5	5	2,500	0	100	500	General maintenance
Suction cups and hoist	2	5	5,000	0	200	1,000	Cups replacement and hoist maintenance
Hoist for Styrofoam handling	1	10	1,000	500	50	100	General maintenance

Table 5.1 (continued)

Equipment	Quantity Required	Estimated Life in Years	Initial Cost $	Estimated Salvage in Year 5 in $	Cost of Maintenance in $/year	Depreciation in $/year	Remarks for the Cost of Maintenance
Air Table	1	5	2,000	0	50	400	General maintenance
8' x 8' Pallets	4	5	400	0	40	80	General maintenance
Overhead conveyor and hanger	1	10	5,200	2,600	100	520	General Maintenance
Hydraulic Table	1	5	8,000	0	100	1,600	General Maintenance
Panel Guiding Mechanism	1	5	5,000	0	50	1,000	General maintenance
Office Equipment and Furniture		5	10,000	2,000	500	1,600	General maintenance and periodic replacement
Miscellaneous equipment and tools		5	5,000	0	500	1,000	Periodic replacement
Total			174,780	79,085	8,790	19,138	

Calculations for the working capital are based on a turn around period of two months. The two months period is chosen on the basis of the information received from the Central Mortgage and Housing Corporation. According to the information after submitting the report, of completion and inspection of homes, to the Central Mortgage and Housing Corporation normally in a couple of weeks time payment is received. To arrive at the current assets value a selling price of $1.20 per square foot of panel is assumed. The selling price includes the Minimum Attractive Rate of Return (MARR) on the investment in the panel manufacturing facility.

Current Assets

1. Accounts receivable (60 days outstanding), equivalent to two months (42 working days) sales or production volume, at $1.20 per square foot of panel (184,880 square foot)

= $ 221,760

2. Inventories

Finished product: one week's i.e. 5 working days production = (22,000 square feet of the panel) x ($1.00 per square foot manufacturing cost)

= $ 22,000

Raw Material:

Two months steel supply at \$.15 per pound (30 gauge steel weighing 0.5 lbs/square foot) (8800 square foot per day requirement) x (42 working days at 21 days per month)

$$= 8800\ ft^2 \times .5\ lbs\ (ft^2 \times \$.15/lb \times 42\ days)$$

$$= \$27,720$$

One month Styrofoam supply

(21 working days) x (2-1/2 inches thick, 4400 square foot per day requirement) x (\$.15 per board foot)

$= (21\ days) \times (2.5\ in \times 4400\ ft^2/day) \times (\$.15/in/ft^2)$

= \$34,650

One month paint supply

(21 days)x(8800 square feet surface to be painted) x $(\$.05/ft^2)$

$= 21\ days \times 8800\ ft^2/day \times \$.05/ft^2$

= \$9,240

One month packaging material

(21 days) x (4400 square feet panel area per day) x (\$.018 per square foot of panel area)*

$= 21\ days \times 4400\ ft^2/day \times \$.018/ft^2 = \$1,663$

Total raw material inventory

= \$27,720 + \$34,650 + \$9,240 + \$1,663 = \$73,273

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* From Sections 5.1.2.3

Total inventory	= \$73,273 + \$22,000
	= \$93,273
30 days sales tax at 12%	= \$26,611
Total current assets	= \$343,644

Current liabilities:

Accounts Payable Outstanding

One month's purchases (excluding steel)

	= \$34,650 + \$9,240 +\$1,663
	= \$45,553
Working capital	= 343,644 - 45,553
	= \$298,091
say	= \$300,000

Table 5.2 lists the summary of the capital costs, the salvage values of the assets and annual maintenance costs with respect to the land, building and equipment.

Table 5.2

Summary of the Capital Costs, the Salvage Values and the Annual Maintenance Costs

Assets	Capital Cost in $	Salvage Value in Year Five	Annual Maintenance Costs
Land	10,000	10,000	500
Building	257,300	205,840	2,000
Manufacturing Equipment	164,780	77,085	8,290
Office equipment and furniture	10,000	2,000	500
Working Capital	300,000	300,000	0
Startup Costs	16,500	0	0
Total	$758,580	$594,925	$11,290

5.1.2 Operating Costs

The operating costs include the following costs.

1. Direct material costs

2. Direct labour costs

3. Packaging costs

4. Factory overhead costs, including supervisor's salary, utilities, inspection, selling, administrative, insurance and property taxes.

5.1.2.1 Direct Material Cost

Direct material cost includes the cost of the material consumed in the sandwich panel manufacturing. For the designed panel direct materials are:

1. 30 gauge steel sheet skins;
2. 2-1/2 inches thick Styrofoam S.I.; and
3. XLC 7175 (3M product) water base adhesive.

Cost of steel sheet per square foot of panel area

= 2 x 1 ft^2 x .5 lb/ft^2 x \$0.15/lb.

= \$0.15

Cost of Styrofoam per square foot of panel area

= 2-1/2 in. x 1 ft^2 x \$.15 per board ft.

= 2.5 board ft.* x \$.15 per board ft.

= \$.375

Cost of the adhesive per square foot of panel area (based on a 2.5 to 3 mgs. per square foot of bond area)

= \$.04

Total direct material cost per square foot of the panel area

= \$0.15 + \$0.3750 + \$0.04

= \$0.565

Direct material cost per year = \$0.565/ft^2 x 1,100,000 ft^2

= \$621,500

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* 1 board feet = 1 in. x 1 ft. x 1 ft.

5.1.2.2 Direct Labour Costs

Table 5.3 lists the manpower requirement along with the respective hourly wage rate for the sandwich panel manufacturing facility.

The tradesmen work under the supervision of a supervisor, who assigns and inspects their work. The wage rates represent weighted average rates [16] prevailing in Alberta in the year 1973.

At hourly total wages of $33.14

Direct labour payroll per year

= $33.14 x 8 hours/day x 250 days/year

= $ 66,280

Fringe benefits (including pension plan and health insurance contributions)

= 30% of payroll

= $.30 x 66,280 = $19,884

Total direct labour costs per year = <u>$86,164</u>

5.1.2.3 Packaging Costs

Cost of an 8 feet x 8 feet wooden pallet = $30 each.

Quantity of pallets required (based on a unit load of 4,000 lbs per pallet) per year

$$= \frac{1,100,000 \text{ ft}^2 \times 1.5 \text{ lbs/ft}^2}{4000 \text{ lbs}}$$

= 412.5

say = 420

Table 5.3

Manpower Requirements and Wage Rates

for the Sandwich Panel Manufacturing Facility

Job Description	Number of Personnel Required	Wage Rates per Hour	Remarks
Fork lift operator	1	$4.64*	Heavy duty truck driver, weighted average rate for manufacturing firms
Uncoiler, lock-former, profiler, shear, steelsheet and styrofoam handling	1	$3.88	Semi-skilled trades helper
Panel assembly	2	$7.76	Semi-skilled trades helper
Painter	1	$4.30	Journeyman level
Electrician	1	$5.28	Journeyman certification
Packaging (labourer)	2	$7.28	Semi-skilled trades helper
	9	$33.14	

*Wage rate represents higher of weighted average of the prevailing rates [16] in Alberta and Edmonton, for the manufacturing firms.

Assuming returnable pallets and initial provision for one month requirement;

Pallet inventory = 420/12 = 35

Cost of the pallets at \$30 each = \$30 x 35 = \$1,050

Polyethelene Covering Material Cost:

Annual requirement = 125% x 1,100,000 ft^2

$= 1,375,000\ ft^2$

Cost of Polyethelene Sheet per Year

$= 1,375,000\ ft^2 \times \$.0125/ft^2$

$\simeq \$17,200$

Plastic Straps:

Annual requirement (approximately 50 feet per unit load)

$$= 100\ ft \times \frac{1,100,000\ ft^2 \times 1.5\ lbs/ft^2}{4000}$$

$= 52,500\ ft$

say $= 55,000\ ft$

Annual cost (approximately \$30/1000 ft)

$= \$30 \times 55,000/1000$

$= \$1,650$

Total annual cost of the packaging material

$= \$19,900$

Cost of packaging per square foot of the panel area

$$= \frac{\$19,900}{1,100,000} = \$0.018$$

5.1.2.4 Factory Overhead Costs

The overhead costs include salary of the supervisor, cost of equipment maintenance, power and utilities, administration, selling, fringe benefits to the staff, insurance and property taxes.

Supervisor's salary:

The supervisor is responsible for production planning, assigning and inspecting the work of the personnel listed in table 5.3.

Supervisor's salary = \$1450 per month	
Annual cost = \$1450 x 12 = \$17,400	
Fringe benefits = \$17,400 x 30% =	\$5,220
Total	\$22,620
Maintenance costs from table 5.2	= \$11,290

Power and Utilities Costs:

Total H.P. required for equipment operation

= 37.5 say 40

= 40 H.P. x .746 KW/H.P.

= 29.84 KW

Power required for the drying ovens

= 4[illegible]

Power requ[illegible] for the building lighting

= 25 KW

Power required for the building heating:

Total area required to be heated (based on 10,000 degree days below 65°F for Edmonton area).

Basic formula for the heat loss by transmission through any surface is given below.

$$H_t = AU(t_i - t_o) \quad \text{B.T.U./hr}$$

where H_t = Heat loss due to transmission

U = Heat loss coefficient BTU/hr/ft^2/°F temp difference = .1 for the insulated building

A = area of the walls, floor, roof and other exposed surfaces

= 2 x 16 ft x 150 ft + 2 x 16 ft x 175 ft + 150 ft x 175 ft (for the designed building for panel manufacturing facility)

= 36,650 square feet

t_i = inside temperature to be maintained

t_o = outside temperature

Yearly heat load = 36,650 ft^2 x .1 x 10,000 BTU

= 3,665 x 10^4 B.T.U.

Average hourly heating load

$$= \frac{3665 \times 10^4 \text{ B.T.U./year}}{250 \times 8 \text{ hour/year*}}$$

= 18,325 BTU/hr.

---

* Assuming building heating in working hours only.

Providing a 10% allowance for intermittent heating [17]

Total heating load per hour

= 18,325 + 1832

= 20,157 B.T.U/hour

$$= \frac{20,157 \times 778}{33000 \times 60} \times .746 \text{ KW}$$

$\simeq$ 6 KW

Total power required

= 29.84 + 48 + 25 + 6

= 108.84

say = 110 KW

Monthly power consumption = 110 x 8 x 21 KWH

= 18,480 KWH

Cost of electricity at $0.0125/KWH, per month

= 18,480 KWH x 0.0125/KWH

= $231

Annual cost of electricity = $231 x 12 = $2,772

Annual cost of water at $25 per month = $25 x 12 = $300

Total power and water costs = $3,072

Administration Costs:

General Manager's salary	$24,000 per year
Secretary (stenographer)	$ 6,000 per year
Receptionist salary	$ 5,000 per year
Accounting clerk or senior	
Bookkeeper salary	$ 6,684 per year

Janitors (two part time 4 hours a day) at \$2.42 per hour per janitor	\$ 4,840 per year
Total	\$46,524 per year
Fringe benefits at 30% of 46,524 =	\$13,957
Total =	\$60,481

Selling Costs:

Sales Manager salary and benefits	\$20,000 per year
Miscellaneous or unforseen costs at \$10 per day	\$ 2,500 per year

Insurance Costs:

Fire and accident at 1.5% of building and equipment costs	\$ 6,500

Property taxes:*

Property tax 54** mills ⊙ of assessed value of the property

Estimated property taxes

$$= \frac{\$54}{1000} \times 159{,}660$$

$$\simeq \$8{,}622$$

Business tax = 10% of the annual equivalent gross estimated rent

$$= \$.15/ft^2 \times 26{,}500\ ft^2$$

$$= \$3975$$

---

* Information obtained from City of Edmonton Finance Department

** Subject to changes

⊙ 1 mill = \$1 per \$1,000

Total taxes = \$12,597

say = \$12,600

Total factory overhead costs

= 22,620 + 11,290 + 3,072 + 60,481 + 20,000 + 2,500 + 6,500 + 12,600

= \$139,063

Total operating costs per year

= Direct material costs + Direct labour costs + Packaging material costs + Factory overhead costs

= \$621,500 + \$86,164 + \$19,900 + \$139,063

= \$866,627

say = \$870,000

5.2 Revenue Requirements

The Annual Equivalent Costs (A.E.C.) or Revenue Requirements is the sum of the After-Tax Cash Flow Requirements (ATCFR), Income Taxes and Annual Operating Costs.

Revenue Requirement (Annual Equivalent Costs)

= ATCFR + I.T. + Operating Costs

where:

I.T. = Income Taxes

ATCFR = First Cost + Return on investment - Salvage Value

$= \text{First Cost } (a/p)_5^{20\%} - \text{Salvage Value } (a/f)_5^{20\%}$

where:

Total First Costs = $758,580 (from Table 5.2)

Total Salvage Values = $594,925 (from Table 5.2)

$(a/p)_5^{20\%}$ = Annual equivalent of present sum (p) at 20% interest rate and 5 years life of investment = .33438*

$(a/f)_5^{20\%}$ = Annual equivalent of future sum (f) at interest rate of 20% and 5 years life of investment = .13438*

ATCFR = 758,580 x .33438 - 594,925 x .13438

= 253,654 - 79,946

= $173,708

Income Taxes:

IT = ϕ(ATCFR - AEDE)

where:

ϕ = Income Tax Factor

$$= \frac{t}{1 - t}\left(1 - \frac{r_d \, i_d}{i_c}\right)$$

t = Income Tax rate = 50% = 0.50

r_d = Debt Capital ratio = 0

i_d = Interest on debt capital

i_c = Interest on composite capital = 20%

$$\phi = \frac{0.50}{1 - 0.50}(1 - 0) = 1$$

AEDE = Annual Equivalent Depreciation Expenses

= $19,138 (from Table 5.1)

---

* See Interest Tables page 604 [20].

IT = 1(173,708 − 19,138)

= \$154,570/year

Operating Costs

= \$870,000/year (from 5.1.2)

Revenue Requirements or AEC

= 173,708 + 154,570 + 870,000

= \$1,198,278

5.3 The Selling Price of the Panel

Revenue Requirements = Revenue from sales

= Annual production (annual sales volume) in square feet of the panel area x selling price per square foot

= 1,100,000 ft^2 x selling price/ ft^2

or selling price/ft^2 = $\frac{\$1,198,278}{1,100,000\ ft^2}$

= \$1.09

Selling price \$1.09 per square foot of the sandwich panel includes the cost of manufacturing and selling the panel with an after-tax return of 20% on the investment. It does not include cost of transportation, erection and hardware.

CONCLUSION

The purpose of this study was to develop a system to provide low cost homes within the income of the low-to-medium family.

To achieve the purpose feasibility of substitution of pre-finished sandwich panels for conventional building material was studied. The feasibility study includes the properties of the chosen material for the sandwich panel and design of an economical manufacturing facility for the sandwich panel manufacturing.

The sandwich panel manufacturing facility can meet the annual demand of more than 500 homes. The sandwich panel production can be doubled without incurring any capital expenditure on one shift operation basis and can be raised to four times by operating the plant in two shifts with minor changes. Therefore, manufacturing cost of sandwich panel can be considerably reduced by increasing the production volume.

Besides the cost of the sandwich panel other costs such as transportation, erection, cost of hardware, wiring, plumbing and utilities need to be determined for arriving at the overall cost of homes under the designed system.

Figure 5.1 shows the price indexes variation for the period 1969-1973 with respect to lumber and lumber products, wall board and insulation, steel sheet, and polystyrene plastic foam (data taken from catalogue No. 62-002, prices and price indexes Statistics Canada,. The increases in the prices of lumber and wall board insulation material was higher as compared with the increases in the prices of steel sheet and polystyrene. Therefore, substitution of sandwich panels seems to be more prospective now as compared with the past.

The manufacturing cost of $1.09 per square foot of the sandwich panel designed in this study compares favourably with the manufacturing cost of $1.25 per square foot of prefinished sandwich panel using the same skins material and polyurathane foam as the core material [3].

Adding to the manufacturing cost, the costs of transportation and erection ($0.38 per square foot of the panel [3]), gives the installed cost of $1.47 per square foot of the sandwich panel construction. This compares favourably with the installed cost of $1.85 per square foot of on-site construction.

The above comparison shows that the rising costs of the conventional on-site construction with wood as a major construction material can be offset by factory manufactured sandwich panels, using steel sheet as the skins and Styrofoam as the core materials.

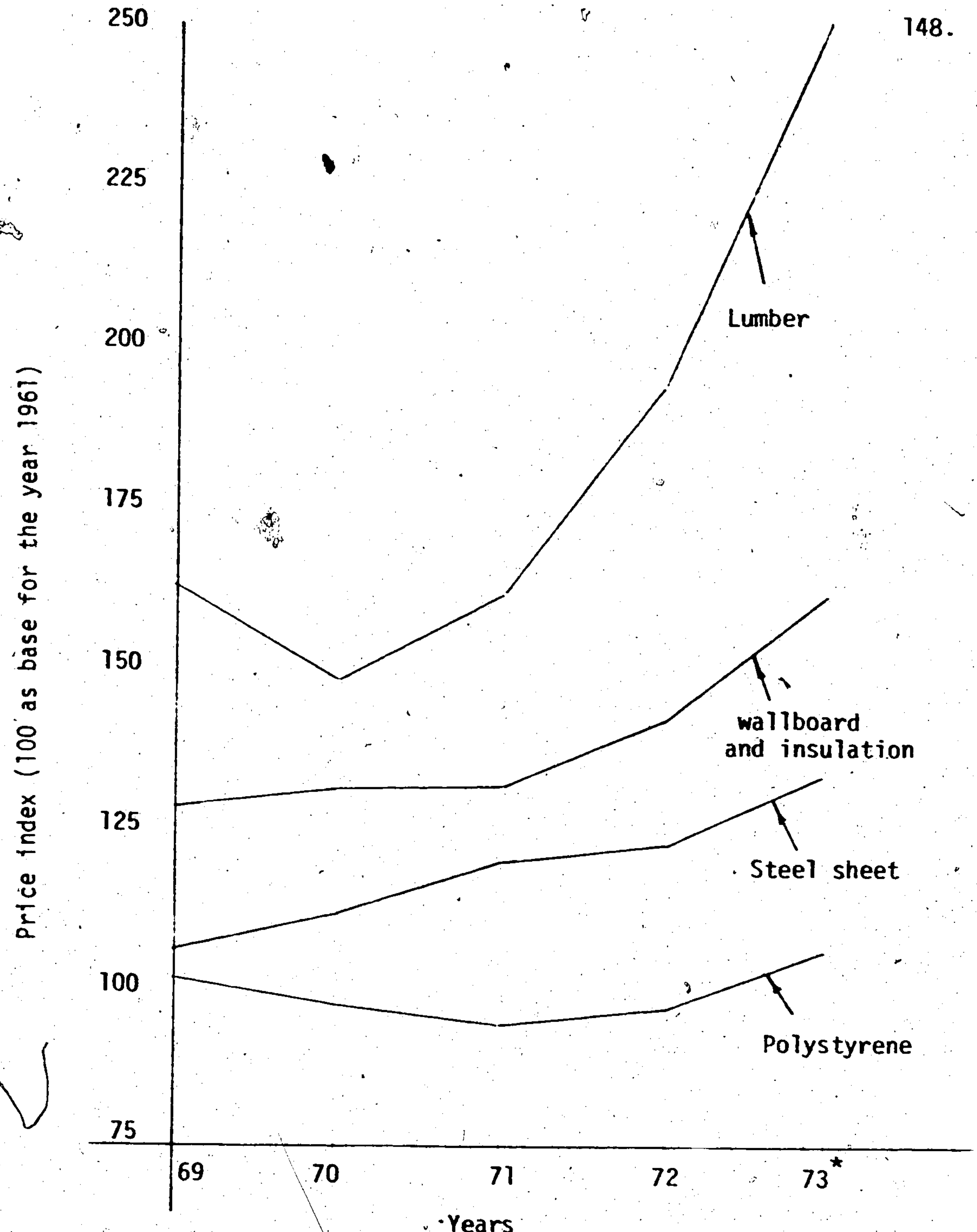


Fig. 5.1 Comparison of price indexes with respect to lumber, wallboard and insulation, steel sheet, and polystyrene.

* 1973 price index for the month of Dec.

BIBLIOGRAPHY

[1] Central Mortgage and Housing Corporation, Canadian Housing Statistics 1972, Central Mortgage and Housing Corporation, Ottawa, Ontario.

[2] Joon, D.C., The Design of the Flexi-grow Housing System, 1973.

[3] Saxena, S., The Design of a Manufacturing Facility, 1973.

[4] Platts, R.E., System Housing, The Shelter Industry in North Europe, Technical Paper No. 290, DBR, NRC of Canada.

[5] Central Mortgage and Housing Corporation, Site Planning Hand-book, Central Mortgage and Housing Corporation, Ottawa 7, Canada.

[6] Shields, J., Adhesive Handbook, Compiled by SIRA for the Ministry of Technology, London, Butterworths.

[7] Bodnar, M.J., Symposium on Adhesive for Structural Applications, Held at Picatinny Arsenal Dover, New Jersey, September 27-28, 1961.

[8] National Research Council of Canada, National Building Code of Canada 1970, National Research Council of Canada, Ottawa, Canada.

[9] Willi Furrer, Room and Building Acoustics and Noise Abate-ment. Translated by Robinson, E.R., and Lord, P., Washington, Butterworths, 1964.

[10] Berry, G., Design of Light Weight Partitions with High Sound Insulation, Conference on Plastic in Building Structures, 14-16 June, 1965, Paper 22, The Plastic Institute, London.

[11] Northwood, T.D., and Veale, A.C., Sound Insulation Between Apartments, National Research Council Canada, Division of Building Research, Ottawa, August 1964.

[12] Northwood, T.D., Dickens, H.B. and Hansen, A.T., Noise Control in Residential Buildings, Technical Paper No. 230 of the Division of Building Research, National Research Council, Ottawa, February 1967.

[13] Parker, H., Simplified Engineering for Architects and Builders, John Wiley & Sons, Inc., New York.

[14] Buffa, E.S., Operations Management Problems and Models, John Wiley and Sons, Inc., New York, London, Sydney, Toronto.

[15] Oberg, E., and Jones, F.D., Machinery's Handbook, Eighteenth Edition, Second Printing, 1969, Industrial Press Inc., New York, N.Y. 10016.

[16] Alberta Treasury Bureau of Statistics, Seventeenth Annual Report, Alberta Salary and Wage Rate Survey, August 1973.

[17] ASHRAE, Handbook of Fundamentals, Heating, Refrigerating, Ventilating and Airconditioning.

[18] National Research Council of Canada, Canadian Structural Design Manual 1970, National Research Council of Canada, Ottawa, Ontario.

[19] Baumeister, T., Standard Handbook for Mechanical Engineers, 7th edition, McGraw-Hill Book Company, New York, N.Y. 1967.

[20] Smith, G.W., Engineering Economy, Analysis of Capital Expenditure, The Iowa State University Press, Ames, Iowa, 1970.

[21] The Maytag Company, Methods Time Measurement Application, Industrial Engineering Department, Newton, Iowa.

[22] Platts, R.E., Structural Sandwich Components in Building, Technical Paper No. 267 of the Division of Building Research, National Research Council of Canada, Ottawa, July 1968.

APPENDIX A

CALCULATIONS FOR THE STRUCTURE OF THE MULTIPLE-DWELLING SYSTEM

The calculations are based on a four-plex unit with basic floor plan of 32 feet x 12 feet (384 square feet) per floor per dwelling unit of two stories.

1. Roof Loads

1.1 Dead load of roof

Weight of roof panels (50' x 35')	2625 lbs/unit
Weight of rafters (26 pcs., 2"x6" x 16.5 ft)	1146 lbs/unit
Total	3771 lbs/unit

1.2 Snow loads

$S = C_s \cdot g$ *

where s = design snow load in psf

g = ground snow load in psf

= 27 psf for Edmonton

C_s = snow load coefficient

$= (.8 - \frac{\alpha - 30}{50})$

$= (.8 - \frac{19 - 30}{50})$ ** $= 1.02$

* Page 57 [18]

** Page 616 [18]

$S = 1.02 \times 27$ psf = 27.54 psf

Total snow load = 27.54 psf x 50 feet x 35 feet

= 48,200 lbs.

If the roofs are exposed to the wind, the value of the snow load coefficient is reduced by 25%, that is the effective snow load

= .75 x 48,200 lbs

= 36,150 lbs.

1.3 Wind loads

$p = q\, C_e\, C_g\, C_p$

where p = designed wind pressure in psf

q = hourly wind pressure in psf

= 10.7 psf for Edmonton

C_e = exposure factor

= 1.0

C_g = gust effect factor

= 2.5

C_p = external pressure coefficient

= .7

$p = 10.7 \text{ psf} \times 1.0 \times 2.5 \times 0.7$

= 18.7 psf

$p' = 18.7 \times .45$

= 8.415 psf

Total wind load on the roof

= 8.415 psf x 50 ft x 17.5 feet

= 7363 lbs.

Total snow and wind load on the roof

= 36,150 lbs + 7363 lbs

= 43,513 lbs

Designed load on the roof is the maximum of the snow load without considering the effect of wind and considering wind effect, that is 48,200 lbs.

1.4 Total load on the roof

= Dead load + Maximum of the snow or snow plus wind load

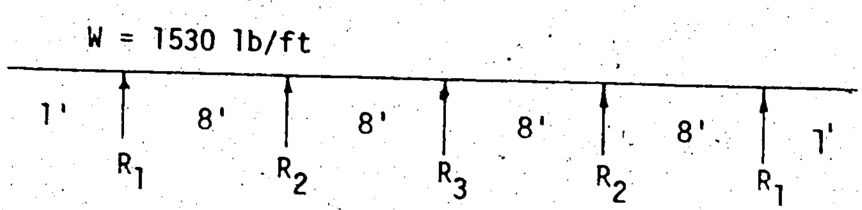
= 3,771 + 48,200

≈ 52,000 lbs

Roof load per running foot $= \frac{52,000 \text{ lbs}}{34 \text{ feet}} \approx 1530$ lb/ft.

1.5 Design of beam cross-section

Total roof load is supported by five beams. Reaction or load on each beam can be calculated from per linear foot load on the roof.



Reaction on a support depends on the total number of supports and the support number from left or right.

$$R_2 = \frac{17}{28} W\ell + \frac{15}{28} W\ell$$

where:

$\frac{17}{28}^*$ represents the load factor on the left side of the support R_2 (between two consecutive supports) and

$\frac{15}{28}^*$ represents the load factor on the right side of the support R_2 (between two consecutive supports)

Thus $R_2 = (\frac{17 + 15}{28}) \times 1530 \text{ lb/ft} \times 8 \text{ ft}$

$R_2 = \frac{32}{28} \times 8 \times 1530 \simeq 14,000$

$R_3 = (\frac{13 + 13}{28}) \times 8 \times 1530 = 11,365 \text{ lbs}$

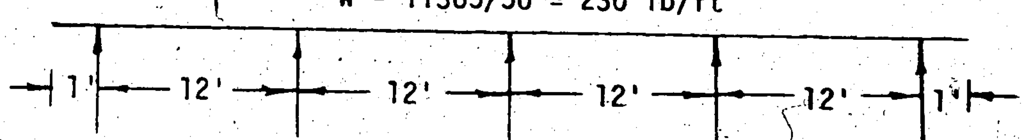
$R_1 = (1530 \times 34 - 2R_2 - R_3)/2$

$= (52,020 - 2 \times 14,000 - 11,365)/2$

$\simeq 6330 \text{ lbs.}$

1.5.1 Top centre beam (R_3)

$W = 11365/50 \simeq 230 \text{ lb/ft}$



Maximum Bending Moment

$M_{max} = .125\, w\ell^2$

$= .125 \times 230 \text{ lb/ft} \times (12 \text{ ft})^2$

$= 4,140 \text{ lb-ft}$

$= 49,680 \text{ lb-in}$

* See [19]

Required section modulus for the steel beam

$$= \frac{M_{max}}{\text{Allowable stress}} = \frac{49{,}680 \text{ lb-in}}{16000 \text{ lb/in}^2}$$

$$= 3.1 \text{ in}^3$$

Required section modulus for the wooden beam

$$= \frac{49{,}680 \text{ lb-in}}{1500 \text{ lb/in}^2} = 33.1 \text{ in}^3$$

Section of possible alternatives:

Steel beam; Light WF junior beams.*

S_x = 3.5, weight 5.5 lb/ft, depth 7 in, flange width 2.078 in. and flange thickness .180 in.

Douglas fir beam;** 4" x 8" S_x = 33.98 in^3, weight = 7.5 lbs per linear foot.

Maximum deflection (Allowable deflection = $\ell/240$)

Steel beam:

$$\delta = \frac{5\ W\ell^3}{384 \times E \times I_x}$$

$$\delta = \frac{5 \times 230\ \text{lb/ft} \times 12\ \text{ft} \times (144\ \text{in})^3}{384 \times 30 \times 10^6\ \text{lb/in}^2 \times 12.1\ \text{in}^4}$$

$\simeq$ .3 in.

Maximum allowable deflection

$$= \frac{\ell}{240} = \frac{144\ \text{in.}}{240} = .6\ \text{in}$$

Calculated value is within allowable limits

4" x 8" Douglas fir beam:

$$\delta = \frac{5 \times 230\ \text{lb/ft} \times 12\ \text{ft} \times (144\ \text{in})^3}{384 \times 1{,}760{,}000\ \text{lb/in}^2 \times 127.44\ \text{in}^4}$$

= .48 in.

which is less than .6 in allowable maximum deflection.

Steel beam:

Weight = 5.5 lb/ft x 50 ft = 275 lbs.

Cost = 275 lbs x $0.20/lb. = $55

---

* Page 73 [18]

** Page 82 [18]

Wooden beam:

Weight = 7.5 lb/ft x 50 ft = 375 lbs.

$$\text{Cost} = \frac{400}{3} \text{ FBM} \times \$.36/\text{FBM}$$

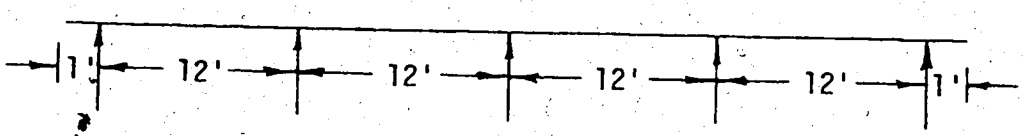
$$= \$48$$

Chosen material:

Douglas fir beam 4" x 8" Section 50 ft. long.

1.5.2 Intermediate Beams (R_2)

W = 14,000 lb/50 ft = 280 lb/ft



$$M_{max} = .125\, W\ell^2$$

$$= .125 \times 280 \text{ lb/ft} \times (12 \text{ ft})^2$$

$$= 5040 \text{ lb-ft}$$

$$= 60{,}480 \text{ lb-in}$$

Required section modulus for wooden beam

$$= \frac{M_{max}}{\text{Allowable stress}} = \frac{60{,}480 \text{ lb-in}}{1500 \text{ lb/in}^2} = 40.32 \text{ in}^3$$

Section modulus of 4" x 10" beam

$$S_x = 54.52 \text{ in}^3$$

Maximum deflection

$$\delta = \frac{5W\ell^3}{384 \times E \times I_x} = \frac{5 \times 280 \times 12 \times (144)^3}{384 \times 1{,}760{,}000 \times 258.99}$$

$$= .2865 \text{ in.}$$

Allowable maximum deflection $= \frac{\ell}{240} = \frac{144}{240} = .6$ in.

hence designed section is safe.

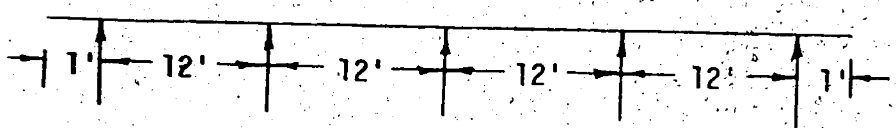
Weight = 9.6 lb/ft x 50 ft = 480 lbs

Cost $= \frac{4 \times 10 \times 50}{12}$ FBM x \$.36/FBM

= \$60

1.5.3. Exterior wall upper beams (R_1)

W = 6330 lb/50 ft ≃ 130 lb/ft



M_{max} = .125 x 130 lb/ft x (12 ft)^2

= 2,340 lb-ft

= 28,080 lb-in

Required section modulus for wooden beam

$$= \frac{M_{max}}{\text{Allowable stress}} = \frac{28080 \text{ lb-in}}{1500 \text{ lb/in}^2}$$

≃ 19 in^3.

Section modulus of 3" x 8" beam

S_x = 24.60 in^3

Maximum deflection

$$\delta = \frac{5 \times W \times \ell^3}{384 \times E \times I_x}$$

$$= \frac{5 \times 130 \times 12 \times (144)^3}{384 \times 1{,}760{,}000 \times 92.28}$$

= .3734 in.

Maximum allowable deflection $= \frac{\ell}{240} = \frac{144}{240}$ in $= .6$ in

Hence designed section is safe.

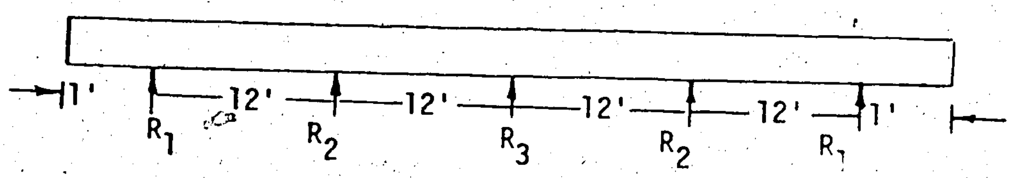
Weight = 5.7 lb/ft x 50 ft = 285 lbs.

Cost $= \frac{3 \times 8 \times 50}{12}$ FBM x \$.36 FBM = \$36.00

1.6 Design of Stud Cross-section

1.6.1 Centre load bearing studs

$W = (230 + 7.5)$ lb/ft $= 237.5$ lb/ft



Maximum reaction will be at the support R_2

$$R_2 = \left(\frac{17 + 15}{28}\right) \times 12 \times 237.5 \text{ lbs}$$

$$= \frac{32}{28} \times 12 \times 237.5 \text{ lbs}$$

$$\approx 3260 \text{ lbs}$$

Required area of cross-section for steel column

$$A = \frac{R_2}{\text{Allowable stress}} = \frac{3260 \text{ lbs}}{16{,}000 \text{ lb/in}^2}$$

$$= .2037 \text{ in}^2$$

Required moment of inertia

$$I = \frac{P_{cr} \cdot \ell^2 \cdot S}{n \times \pi^2 \times E}$$

where: $n = 4$ for both ends fixed

S = safety factor = 5

$$I = \frac{3260 \text{ lbs} \times (252 \text{ in})^2 \times 5}{4 \times (3.14)^2 \times 30 \times 10^6 \text{ lb/in}^2}$$

$= .875 \text{ in}^4$

For

3 in. x 2 in. rectangular hollow section with .1875 inch wall thickness (Wilkinson Company Ltd)

$I_x = 1.06 \text{ in}^4$

$A = 1.73 \text{ in}^2$

Weight = 5.59 lb/ft x 105 ft/unit

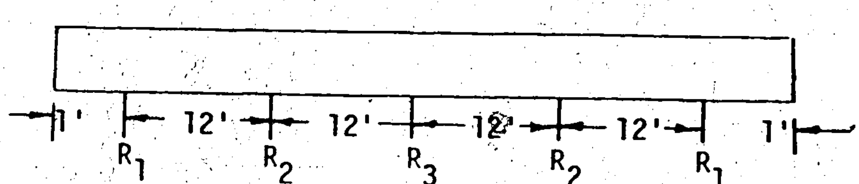
= 587 lbs/unit

Cost = 587 lbs x \$.20 /lb

= \$117/unit

1.6.2 Intermediate load bearing studs

$W = (280 + 9.6)\text{lb/ft} = 289.6 \text{ lbs/ft}$



Maximum reaction will occur at the support R_2

$R_2 = (\frac{17 + 15}{28}) \times 12 \times 289.6$

$= 3970 \text{ lbs}.$

Required area of cross-section for steel column

$$A = \frac{R_2}{\text{Allowable stress}} = \frac{3970 \text{ lbs}}{16{,}000 \text{ lb/in}^2} = .248 \text{ in}^2$$

Required moment of inertia

$$I = \frac{P_{cr} \cdot \ell^2 \cdot S}{n \times \pi^2 \times E}$$

$$= \frac{3970 \text{ lbs} \times (228 \text{ in})^2 \times 5}{4 \times (3.14)^2 \times 30 \times 10^6 \text{ lb/in}^2}$$

$$= .8721$$

Chosen section:

3 in x 2 in rectangular hollow section with .1875 inch wall thickness

$I_x = 1.06 \text{ in}^4$

$A = 1.73 \text{ in}^2$

Weight and cost:

Weight = 5.59 lb/ft x 190 ft/unit

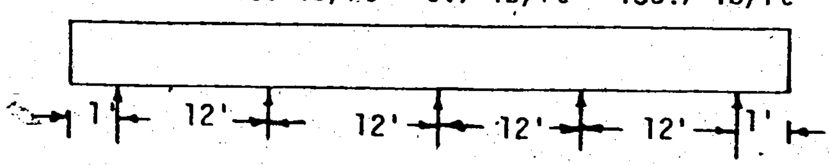
= 1062 lbs/unit

Cost = 1062 lbs x \$.20/lb

= \$212/unit

1.6.3 Exterior wall studs

W = 130 lb/ft + 5.7 lb/ft = 135.7 lb/ft



Chosen cross-section:

Load per feet run is less than that in 1.6.1 and 1.6.2 hence cross-section already designed in the above sub-sections will be safe for the exterior wall studs also.

Weight and cost:

Weight = 5.59 lb/ft x 170 ft/un

= 950 lbs/unit

Cost = 950 lbs/unit x $.20 /lb

= $190/unit.

2. Floor Loads

2.1 Second Floor

2.1.1 Dead loads

Weight of the floor panel = 1/2 x 1/12 ft x 32 ft x 12 ft x 34 lb/ft^3

= 544 lbs/dwelling.

Weight of floor joists

(2" x 8" x 11.75', 32 pcs.) = $\frac{2 \times 8 \times 11.75}{12 \times 12}$ x 32 lbs/ft^3

= 1336 lbs/dwelling

Weight of the interior walls

= 12 ft x 8 ft x 3 x 1.5 lb/ft^2

= 432 lbs/ft^2

Weight of carpet for two bedrooms

= 288 ft^2 x 4 lbs/sq. ft.

= 1150 lbs/dwelling

2.1.2 Live Loads

Live loads = floor area x 40 lbs/ft^2 *

= 384 ft^2 x 40 lbs/ft^2

= 15,360 lbs.

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* See page 145 [18]

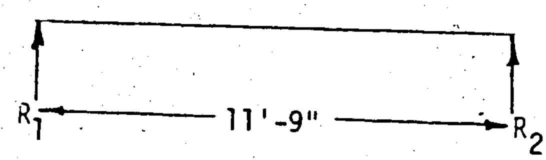
Total floor loads

= 544 + 1336 + 432 + 1150 + 15,360

≈ 18,830 lbs/dwelling.

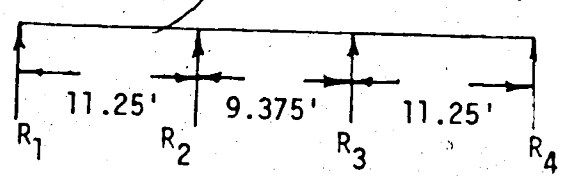
2.1.3 Required cross-section for second floor supporting beams

Total distributed load = 18,830 lbs.



$R_1 = R_2 = 18{,}830/2 = 9415$ lbs.

$W = 9415$ lbs/32 ft ≈ 295 lbs/ft



Maximum bending moment

$M_{max} = .125\ W\ell^2 = .125 \times 295 \times (11.25)^2$

= 4667 lb-ft

= 56,004 lb-in

Required section modulus for wooden beams

$$= \frac{M_{max}}{\text{Allowable stress}} = \frac{56{,}004}{1500} = 37.33\ \text{in}^3$$

Douglas fir beam 6" x 8"

$S_x = 51.56\ \text{in}^3$

Maximum deflection (Allowable deflection

$= \ell/240 = \frac{11.25}{240} \times 12 = .56$ in.)

$$\delta = \frac{5 \cdot W\ell^3}{384 \times E_x I_x}$$

$$= \frac{5 \times 295 \text{ lb/ft} \times 11.25 \text{ ft} \times (11.25 \times 12 \text{ in.})^3}{384 \times 1{,}760{,}000 \text{ lb/in}^2 \times 193.35}$$

$$= .3124 \text{ in.}$$

which is less than allowable limit hence section is acceptable.

Weight and Cost:

Weight = 11.4 lb/ft x 32 ft x 2 pcs.

= 730 lbs/dwelling

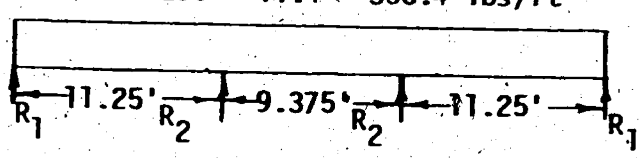
$$\text{Cost} = \frac{6 \times 8 \times 32 \times 2}{12} \text{ FBM} \times \$.36/\text{FBM}$$

= \$92/dwelling

= \$368/unit.

2.1.4 Second floor load bearing studs:

$W = 295 + 11.4 = 306.4$ lbs/ft



$$R_1 = \frac{4}{10} W\ell = \frac{4}{10} \times 306.4 \text{ lbs/ft} \times 11.25 \text{ ft.}$$

= 1380 lbs.

$$R_2 = \frac{6}{10} \times 306.4 \text{ lbs/ft} \times 11.25 \text{ ft} + \frac{5}{10} \times 306.4 \text{ lbs/ft} \times 9.375 \text{ ft.}$$

= 2068 lbs + 1436 lbs = 3504 lbs.

Maximum reaction is at the support R_2

Required area of cross-section for steel column

$$= \frac{3504}{\text{Allowable stress}} = \frac{3504 \text{ lbs}}{16{,}000 \text{ lbs/in}^2}$$

= .22 square inch.

Required moment of inertia for steel column.

$$I = \frac{P_{cr} \cdot \ell^2 \cdot S}{n \cdot \pi^2 \cdot E}$$

$$= \frac{[illegible] \text{ lbs} \times (102)^2 \times 5}{[illegible] (3.14)^2 \times 30 \times 10^6}$$

$= [illegible]154 \text{ in}^4$

Chosen section:

3" x 2" steel box section with wall thickness of 1875 in.

$I_x = 1.06 \text{ in}^4$

$A = 1.73 \text{ in}^2$

Weight and cost:

Weight = 5.59 lb/ft x 68 ft/dwelling

= 380 lbs/dwelling

= 1520 lbs/unit

Cost = 1520 lbs x \$.20/lb

= \$304/unit

APPENDIX B

SPAN CALCULATIONS FOR THE SANDWICH PANEL WITH VARIOUS SKIN MATERIALS

1. Span Calculations

1.1 Load: $W = 40$ psf

Maximum deflection:

$$\delta = \frac{5W\ell^3}{384\ EI} + \frac{W\ell}{8bcG}$$

where: ℓ = span in inch

EI = stiffness factor in lb/in^2

c = core thickness in inch

G = modulus of rigidity of core in lbs/in^2

1.2 Sandwich Material:

1.2.1 Skins: Inside 1/4 in plywood; outside 26 gauge steel sheet.

Core: 2.5 in thick Styrofoam SI

$$EI = \frac{b(E_1t_1E_2t_2)d^2}{E_1t_1 + E_2t_2}$$

where: b = sandwich width = 12 inch

E_1 = modulus of elasticity for plywood

$= 1.2 \times 10^6\ lb/in^2$

E_2 = modulus of elasticity for steel

$= 30 \times 10^6\ lb/in^2$

t_1 = thickness of plywood skin

$= 0.25$ in.

t_2 = thickness of steel skin = .0179 in.

d = distance between centroids of the skins

= 2.625 in.

$$EI = \frac{12(1.2 \times 10^6 \times .25 \times 30 \times 10^6 \times .0179) \times 6.29}{1.2 \times 10^6 \times .25 + 30 \times 10^6 \times .0179}$$

$$= 16.03 \times 10^6 \text{ lb-in}^2$$

$$\delta = \frac{5W\ell^3}{384\ EI} + \frac{W\ell}{8beG}$$

$$= \frac{5 \times 40 \times \ell^4}{384 \times 12 \times 16.03 \times 10^6} + \frac{40\ell^2}{8 \times 12 \times 12 \times 2.5 \times 1200}$$

$$= \frac{\ell^4}{369.2 \times 10^6} + \frac{\ell^2}{86400}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{369.2 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{180}$$

$\ell \simeq 120$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{369.2 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{240}$$

$\ell \simeq 102$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{369.2 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{360}$$

$\ell \simeq 90$ in.

1.2.2 Skins: Inside 1/4 in. plywood; outside 30 gauge steel sheet.

Core: 2.5 in. thick styrofoam SI.

$$EI = \frac{12(1.2 \times 10^6 \times .25 \times 30 \times 10^6 \times .0120)6.90}{1.2 \times 10^6 \times .25 + 30 \times 10^6 \times .0120}$$

$$= 13.53 \times 10^6$$

$$\delta = \frac{5 \times 40 \times \ell^4}{384 \times 12 \times 13.53 \times 10^6} + \frac{40\ell^2}{8 \times 12 \times 12 \times 2.5 \times 1200}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{311.73 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{180}$$

$$\ell \simeq 108 \text{ in.}$$

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{311.73 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{240}$$

$$\ell \simeq 96 \text{ in.}$$

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{311.73 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{360}$$

$$\ell \simeq 84 \text{ in.}$$

1.2.3 Skins: Inside 1/4" plywood; outside .0253 inch thick aluminum sheet.

Core: 2.5 inch thick Styrofoam SI.

$$EI = \frac{b(E_1 t_1 \times E_2 t_2) d^2}{E_1 t_1 + E_2 t_2}$$

where

$E_1 = 1.2 \times 10^6$ lb/in^2

$E_2 = 10 \times 10^6$ lb/in^2

$t_1 = 0.25$ in.

$t_2 = 0.0253$ in.

$b = 12$ in.

$d = 2.625$ in.

$$EI = \frac{12(1.2 \times 10^6 \times 0.25 \times 10 \times 10^6 \times 0.253) \times 6.89}{12 \times 10^6 \times 0.25 + 10 \times 10^6 \times .0253}$$

$$= 11.35 \times 10^6 \text{ lb-in}^2$$

$$\text{Maximum deflection} = \frac{5W\ell^3}{384\ EI} + \frac{W\ell}{8beG}$$

$$= \frac{5 \times 40\ \ell^4}{384 \times 12 \times 11.35 \times 10^6} + \frac{40\ \ell^2}{8 \times 12 \times 2.5 \times 1200}$$

$$= \frac{\ell^4}{261.5 \times 10^6} + \frac{\ell^2}{86400}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{261.5 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{180}$$

$$\ell \simeq 102 \text{ in.}$$

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{261.5 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{240}$$

$$\ell \simeq 90 \text{ in.}$$

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{261.5 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{360}$$

$$\ell \simeq 78 \text{ in.}$$

1.2.4 Skins: Both 26 gauge steel sheet

Core: 2.5 in. thick Styrofoam SI.

$$EI = \frac{Ebtd^2}{2}$$

$E = 30 \times 10^6$ lb/in^2

$b = 12$ in.

$t = .0179$ in.

$d = 2.5$ in.

$$EI = \frac{30 \times 10^6 \times 12 \times .0179 \times 6.25}{2}$$

$$= 20.115 \times 10^6 \text{ lb-in}^2$$

$$\delta = \frac{5 \times 40\ \ell^4}{384 \times 12 \times 20.11 \times 10^6} + \frac{40\ \ell^2}{8 \times 12 \times 12 \times 2.5 \times 1200}$$

$$= \frac{\ell^4}{463.33 \times 10^6} + \frac{\ell^2}{86400}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{463.33 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{180}$$

$\ell \simeq 126$

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{463.33 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{240}$$

$\ell \simeq 114$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{463.33 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{360}$$

$\ell \simeq 96$ in.

1.2.5 Skins: Both 30 gauge steel sheet

Core: 2.5 in. thick Styrofoam SI

$$EI = \frac{30 \times 10^6 \times 12 \times .012 \times 6.25}{2}$$

$$= 13.48 \times 10^6 \text{ lb-in}^2$$

$$\delta = \frac{\ell^4}{310.57 \times 10^6} + \frac{\ell^2}{86400}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{310.57 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{180}$$

$\ell \simeq 108$

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{310.57 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{240}$$

$\ell \simeq 96$ in.

$\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{310.57 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{360}$$

$\ell \simeq 84$ in.

1.2.6 Skins: Both .0253 in thick aluminum sheet.

Core : 2.5 in. thick Styrofoam SI.

$$E = \frac{Ebtd^2}{2}$$

$$= \frac{10 \times 10^6 \times 12 \times .0253 \times 6.25}{2}$$

$$= 9.48 \times 10^6.$$

$$\delta = \frac{5 \times 40 \times \ell^4}{384 \times 12 \times 9.48 \times 10^6} + \frac{40 \times \ell^2}{8 \times 12 \times 12 \times 2.5 \times 1200}$$

$$= \frac{\ell^4}{218.4 \times 10^6} + \frac{\ell^2}{86400}$$

$\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{218.4 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{180}$$

$\ell \simeq 96$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{218.4 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{240}$$

$\ell \simeq 90$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{218.4 \times 10^6} + \frac{\ell^2}{86400} = \frac{\ell}{360}$$

$\ell \simeq 75$ in.

1.3 Load: W = 30 psf.

Sandwich material:

1.3.1 Skins: Inside 1/4 in. plywood; outside 26 gauge steel sheet.

Core: 2.5 in. thick Styrofoam SI.

$$EI = 16.03 \times 10^6 \text{ lb-in}^2$$

$$\delta = \frac{5W\ell^3}{384\ EI} + \frac{W\ell}{8beG}$$

$$= \frac{\ell^4}{492.889 \times 10^6} + \frac{\ell^2}{115{,}200}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{492.889 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{180}$$

$\ell \simeq 126$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{492.889 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{240}$$

$\ell \simeq 114$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{492.889 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{360}$$

$\ell \simeq 96$ in.

1.3.2 Skins: Inside 1/4 in. plywood, outside 30 gauge steel sheet

Core: 2.5 in. thick Styrofoam SI.

$EI = 13.53 \times 10^6$

$$\delta = \frac{\ell^4}{415.5 \times 10^6} + \frac{\ell^2}{115{,}200}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{415.5 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{180}$$

$\ell \simeq 120$

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{415.5 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{240}$$

$\ell \simeq 108$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{415.5 \times 10^6} + \frac{\ell^2}{115,200} = \frac{\ell}{360}$$

$\ell \simeq 93$

1.3.3 Skins: Inside 1/4 in. plywood; outside .0253 in thick aluminum sheet.

Core: 2.5 in. thick Styrofoam SI.

$EI = 11.35 \times 10^6$ lb-in^2

$$\delta = \frac{5 \times 30 \times \ell^4}{384 \times 12 \times 11.35 \times 10^6} + \frac{30\ell^2}{8 \times 12 \times 12 \times 2.5 \times 1200}$$

$$= \frac{\ell^4}{348.7 \times 10^6} + \frac{\ell^2}{115,200}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{348.7 \times 10^6} + \frac{\ell^2}{115,200} = \frac{\ell}{180}$$

$\ell \simeq 114$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{348.7 \times 10^6} + \frac{\ell^2}{115,200} = \frac{\ell}{240}$$

$\ell \simeq 102$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{348.7 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{360}$$

$\ell \simeq 90$ in.

1.3.4 Skins: Both 26 gauge steel sheet.

Core: 2.5 in. thick Styrofoam SI.

$EI = 20.115 \times 10^6$ lb-in^2

$$\delta = \frac{\ell^4}{617.66 \times 10^6} + \frac{\ell^2}{115{,}200}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{617.66 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{180}$$

$\ell \simeq 138$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{617.66 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{240}$$

$\ell \simeq 126$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{617.66 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{360}$$

$\ell \simeq 108$ in.

1.3.5 Skins: Both 30 gauge steel sheet.

Core: 2.5 in. thick Styrofoam SI

$EI = 13.48 \times 10^6 \text{ lb-in}^2$

$$\delta = \frac{\ell^4}{414.03 \times 10^6} + \frac{\ell^2}{115,200}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{414.03 \times 10^6} + \frac{\ell^2}{115,200} = \frac{\ell}{180}$$

$\ell \simeq 120$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{414.03 \times 10^6} + \frac{\ell^2}{115,200} = \frac{\ell}{240}$$

$\ell \simeq 108$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{414.03 \times 10^6} + \frac{\ell^2}{115,200} = \frac{\ell}{360}$$

$\ell \simeq 93$ in.

1.3.6 Skins: Both .0253 in thick aluminum sheet.

Core: 2.5 in. thick Styrofoam SM.

$EI = 9.48 \times 10^6 \text{ lb-in.}^2$

$$\delta = \frac{\ell^4}{291 \times 10^6} + \frac{\ell^2}{115,200}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{291 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{180}$$

$\ell \simeq 108$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{291 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{240}$$

$\ell \simeq 99$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{291 \times 10^6} + \frac{\ell^2}{115{,}200} = \frac{\ell}{360}$$

$\ell \simeq 84$ in.

1.4 Load: $W = 20$ p.s.f.

Sandwich material:

1.4.1 Skins: Inside 1/4 in. plywood;

Outside 26 gauge steel sheet.

Core: 2.5 in. thick styrofoam SI.

$EI = 16.03 \times 10^6$ lb-in^2

$$\delta = \frac{5 \times 20 \times \ell^4}{384 \times 12 \times 16.03 \times 10^6} + \frac{20\ \ell^2}{8 \times 12 \times 12 \times 2.5 \times 1200}$$

$$= \frac{\ell^4}{739.16 \times 10^6} + \frac{\ell^2}{172{,}800}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{739.16 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{180}$$

$\ell \simeq 144$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{739.16 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{240}$$

$\ell \simeq 132$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{739.16 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{360}$$

$\ell \simeq 120$ in.

1.4.2 Skins: Inside 1/4 in. plywood; outside 30 gauge steel sheet.

Core: 2.5 in. thick Styrofoam SI.

$EI = 13.53 \times 10^6$ lb-in^2

$$\delta = \frac{\ell^4}{623.1 \times 10^6} + \frac{\ell^2}{172{,}800}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{623.1 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{180}$$

$\ell \simeq 141$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{623.1 \times 10^6} + \frac{\ell^2}{172,800} = \frac{\ell}{240}$$

$\ell = 126$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{623.1 \times 10^6} + \frac{\ell^2}{172,800} = \frac{\ell}{360}$$

$\ell = 108$ in.

1.4.3 Skins: Inside 1/4 in. plywood; outside .0253 in. thick aluminum sheet.

Core: 2.5 in. thick Styrofoam SI.

$EI = 11.35 \times 10^6$ lb-in^2

$$\delta = \frac{\ell^4}{523 \times 10^6} + \frac{\ell^2}{172,800}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{523 \times 10^6} + \frac{\ell^2}{172,800} = \frac{\ell}{180}$$

$\ell = 132$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{523 \times 10^6} + \frac{\ell^2}{172,800} = \frac{\ell}{240}$$

$\ell = 120$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{523 \times 10^6} + \frac{\ell^2}{172,800} = \frac{\ell}{360}$$

$\ell = 108$ in.

1.4.4 Skins: Both 26 gauge steel sheet.

Core: 2.5 in. thich Styrofoam SI.

$EI = 20.11 \times 10^6$ lb-in^2

$$\delta = \frac{\ell^4}{926.66 \times 10^6} + \frac{\ell^2}{172,800}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{926.66 \times 10^6} + \frac{\ell^2}{172,800} = \frac{\ell}{180}$$

$\ell = 162$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{926.66 \times 10^6} + \frac{\ell^2}{172,800} = \frac{\ell}{240}$$

$\ell = 144$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{926.66 \times 10^6} + \frac{\ell^2}{172,800} = \frac{\ell}{360}$$

$\ell = 126$ in.

1.4.5 Skins: Both 30 gauge steel sheet.

Core: 2.5 in. thick Styrofoam SI.

$EI = 13.48 \times 10^6$ lb-in^2

$$\delta = \frac{\ell^4}{621.15 \times 10^6} + \frac{\ell^2}{172{,}800}$$

For $\delta = \frac{\ell}{180}$

$$\frac{\ell^4}{621.15 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{180}$$

$\ell = 144$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{621.15 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{240}$$

$\ell = 126$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{621.15 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{360}$$

$\ell = 108$ in.

1.4.6 Skins: Both sides .0253 in. thick aluminum sheet.

Core: 2.5 in. thick Styrofoam SI.

$EI = 9.48 \times 10^6$ lb-in^2

$$\delta = \frac{\ell^4}{436.8 \times 10^6} + \frac{\ell^2}{172{,}800}$$

For $\ell = \frac{\ell}{180}$

$$\frac{\ell^4}{436.8 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{180}$$

$\ell \approx 126$ in.

For $\delta = \frac{\ell}{240}$

$$\frac{\ell^4}{436.8 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{240}$$

$\ell \approx 114$ in.

For $\delta = \frac{\ell}{360}$

$$\frac{\ell^4}{436.8 \times 10^6} + \frac{\ell^2}{172{,}800} = \frac{\ell}{360}$$

$\ell \approx 99$ in.

2. Weight and Cost Per Square Foot of Panel

2.1 Skins: Inside 1/4 in. plywood

Outside 26 gauge steel sheet.

Core: 2.5 in. thick Styrofoam SI.

Weight $= 1 \times 1 \times \frac{1}{4} \times \frac{1}{12} \times 34$ lbs/cu. foot plywood

+ .75 per square foot steel sheet

$+ 1 \times 1 \times \frac{2.5}{12} \times 2.2$ lb/cu. foot Styrofoam SI

$= \frac{34}{48} + .75 + .4583 = .7083 + .75 + .4583$

= 1.9166 lbs/sq. ft. panel

Cost = $0.20/sq. foot plywood + $0.1125 per square foot steel + $0.3750 per square foot styrofoam SI = $0.6875 per square foot panel.

2.2 Skins: Inside 1/4 in. plywood
Outside 30 gauge steel sheet
Core: 2.5 in. thick Styrofoam SI
Weight = .7083 + .5 + .4583 = 1.67 lbs/sq. foot panel
Cost = 0.20 + 0.075 + 0.3750 = $0.65/sq. foot panel.

2.3 Skins: Inside 1/4 in. plywood
Outside .0253 in. aluminum sheet
Core: Same as above
Weight = .7083 + .3671 + .4583
= 1.53 lbs/sq. foot panel
Cost = .20 + .483 + .3750 = $1.06/sq. ft. panel

2.4 Skins: Both sides 26 gauge steel sheet
Core: Same as above
Weight = 1.5 + .4583 = 1.9583 lbs/sq. ft. panel
Cost = .225 + .375 = $0.600/sq. ft. panel

2.5 Skins: Both sides 30 gauge steel sheet
Core: Same as above
Weight = 1.0 + .4583 = 1.4583 lbs/sq. ft. panel
Cost = .150 + .3750 = $0.525/sq. ft. panel

2.6 Skins: Both sides aluminum sheet

Core: Same as above

Weight = .7342 + .4583 = 1.1925 lbs/sq. ft.

Cost = .966 + .375 = $1.341/sq. ft.

APPENDIX C

THE ANNUAL REQUIREMENTS FOR THE SANDWICH PANEL

Panel area required to meet annual production of 500 homes is based on the basic two storey quadruplex unit with floor area of 768 square feet per floor per home.

1. Wall System

1.1 Thirty two feet exterior and party walls

Required panel area = [32 ft. x (22 ft. + 18 ft)/2] x 5 walls per unit x 125 units per year

= 32 ft x 20 ft x 525 = 400,000 square feet per year

1.2 Twelve feet exterior walls

Required panel area = 17 ft x 48 ft x 2 walls per unit x 125 units per year

= 204,000 square feet per year

1.3 Interior Walls

Required panel area

= 12 ft x 8 ft x 5 walls per unit x 125 units per year

= 60,000 square feet per year

2. Roof System

Required panel area

= 17.5 ft x 50 ft x 2 x 125 units per year

= 218,750 square feet per year

Total panel area required

= 400,000 + 204,000 + 60,000 + 218,750

= 882,750 square feet

Plus 20% to meet the fluctuation in demand and wastage total area required.

= 1,059,300 square feet

Designed production per year = 1,100,000 square feet