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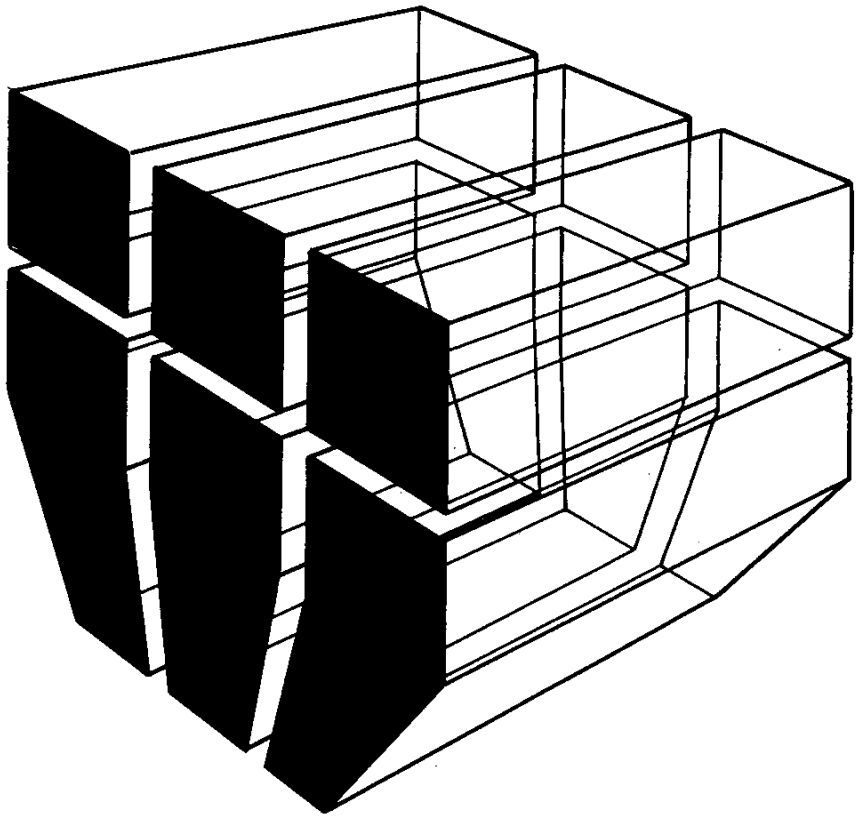
December 1984
Improved and New Roofing for Military Construction

SLOPED ROOF CONVERSIONS FOR SMALL, FLAT-ROOF BUILDINGS



by
Myer J. Rosenfield
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This study examines the cost-effectiveness of converting flat-roofed buildings to sloped-roof buildings as an alternative to repair or replacement of the existing roof. Projects were located, and designers, contractors, and owners were interviewed. This report includes case studies portraying methods, systems, materials, and costs for this type of reroofing.

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Converting flat-roofed buildings to sloped roofs proved to be a viable alternative to reroofing. This method was cost-effective when considering the life-cycle costs, particularly for smaller buildings. Sloped-roof conversions are being done in most areas of the country, regardless of geographic area or climatic region. Finally, this type of conversion often had the benefit of enhancing the appearance of the buildings and solving other problems associated with flat-roofed buildings.

FOREWORD

This investigation was performed for the Assistant Chief of Engineers, Office of the Chief of Engineers (OCE), under Project 4A162731AT41, "Military Facilities Engineering Technology"; Task A, "Facilities Planning and Design"; Work Unit 044, "Improved and New Roofing for Military Construction." The OCE Technical Monitor was Joel Seifer, DAEN-ZCF-B.

This study was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USA-CERL).

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SLOPED ROOF CONVERSIONS FOR
SMALL FLAT-ROOF BUILDINGS

1 INTRODUCTION

Background

Leaks in flat roofs are a source of many problems, costing the Army millions of dollars each year in repairs and replacement. The approach in the past has been to patch or reroof flat-roof buildings, but that has rarely been a permanent solution. However, the construction of a superstructure over the existing roof to provide an adequate slope for positive drainage appears to be gaining popularity, because it finally solves the leakage problem inherent in flat roofs. Sloped roof conversions, while initially costly, may prove to be a more practical solution to leaks on flat-roofed Army buildings than indefinite reroofing and repair.

Very little has been published on this approach, probably because it is only recently that this method has been used extensively.

This method of reroofing has several benefits. In addition to solving leakage problems, the building's energy efficiency can often be improved because of the ease of adding insulation, and overhangs can be easily provided for summer shading of window areas. Depending on the treatment used and the situation, other problems sometimes can be solved. For example, one-story schools often have problems with "foot traffic" on the flat roofs, but sloped roofs generally do not have this problem. In addition, careful treatment of a roof conversion can often enhance the building's appearance.

Objective

The objectives of this study were (1) to determine the cost-effectiveness of converting flat-roofed buildings to sloped roofs, particularly for use on U.S. Army buildings, and (2) to determine the effect of regional or climatic conditions on the decision to make this type of conversion.

Approach

A literature search was conducted, and titles of articles which discuss this form of reroofing are listed in the References section. Nearly 100 questionnaires were sent to wood truss manufacturers, major metal roofing manufacturing companies, and metal component manufacturers. About 20 percent of the questionnaires were returned, but only four respondents knew of, or participated in, roof conversions. These people were contacted and questioned about methods and materials. Also, a letter requesting information about roof conversion was sent to all of the Truss Plate Institute (TPI) engineers requesting information about roof conversion; no responses were received.

A notice requesting information was published in Peaks, a quarterly newsletter for the wood truss industry, distributed by the Lumbermate Company. It is unclear how many responses resulted directly from this publication. Other information was gained from members of the Building Research Council who made inquiries at meetings and conferences within the construction industry, requesting knowledge of roof conversions.

Mode of Technology Transfer

It is recommended that instructions for this method of reroofing small buildings be included in Army Technical Manual 5-617, "Maintenance and Repair of Roofs."

2 FRAME ROOF CONVERSION SYSTEMS

Discussion

In the case of retrofitting a sloped roof onto a flat roof, there is an existing structural system in place. The first step is to analyze that system to determine whether the building, which is designed for a specific set of loads that are already in place, can support an additional set of dead loads created by the new framing and roofing system. It must also be determined how to distribute the new set of loads to the existing structural system.

Roofs for conversions are constructed in the same basic shapes as any other sloped roof: gabled, hipped, shed, mansard, butterfly, and gambrel (Figure 1). With the possible exception of concrete (due to weight) most structural materials can be used to frame roof conversions. Converting a flat roof to a sloped roof allows the application of roofing materials such as wood or asphalt shingles or metal pans.

Wood Frame Systems

Because they are available, familiar, and economical, wood and steel are the most commonly used materials, and wood is the most popular choice. Roofs are built with one of these three basic systems: roof trusses, post and beam, and conventional framing (rafters and joists) (Figure 2). Each of these systems has distinct advantages, disadvantages, and applications.

Wood framing systems are covered with a variety of sheathing materials. The framing members usually are closely spaced (16-in. or 24-in. o.c.) (40 cm or 61 cm) and covered with plywood and shingles. Another commonly used system is wider spaced members (4 ft-0 in. [1.219 m] o.c.) and 2 x 4 in. (5 x 10 cm) purlins on top of the rafters. The purlins are normally spaced 2 ft-0 in. (61 cm) o.c. This system lends itself to covering with either plywood and shingles or some type of light-gauge metal roofing.

Truss Method

A truss is described by Webster as "an assemblage of members (beams, bars, rods) typically arranged in a triangle or combination of triangles to form a rigid framework (supporting a load over a wide area) that cannot be deformed by application of exterior forces without deformation of one or more of its members." The chief characteristic of a truss is that it is able to span large areas while being constructed with relatively small members. Trusses offer a lightweight, economical framing system and are in wide use in all facets of small-scale construction.

Since the advent of pressed galvanized-metal-plate connectors, wood trusses have proven very economical for most roof configurations. Wood trusses are generally fabricated in a shop or factory and trucked to the site. Wood trusses have been fabricated for spans up to 100 ft (30.5 m) long, but are normally limited in length and height by transportation restraints. The shipping height of wood trusses is limited to about 12 ft (3.66 m). When the desired slope or height of the truss exceeds this dimension, solutions

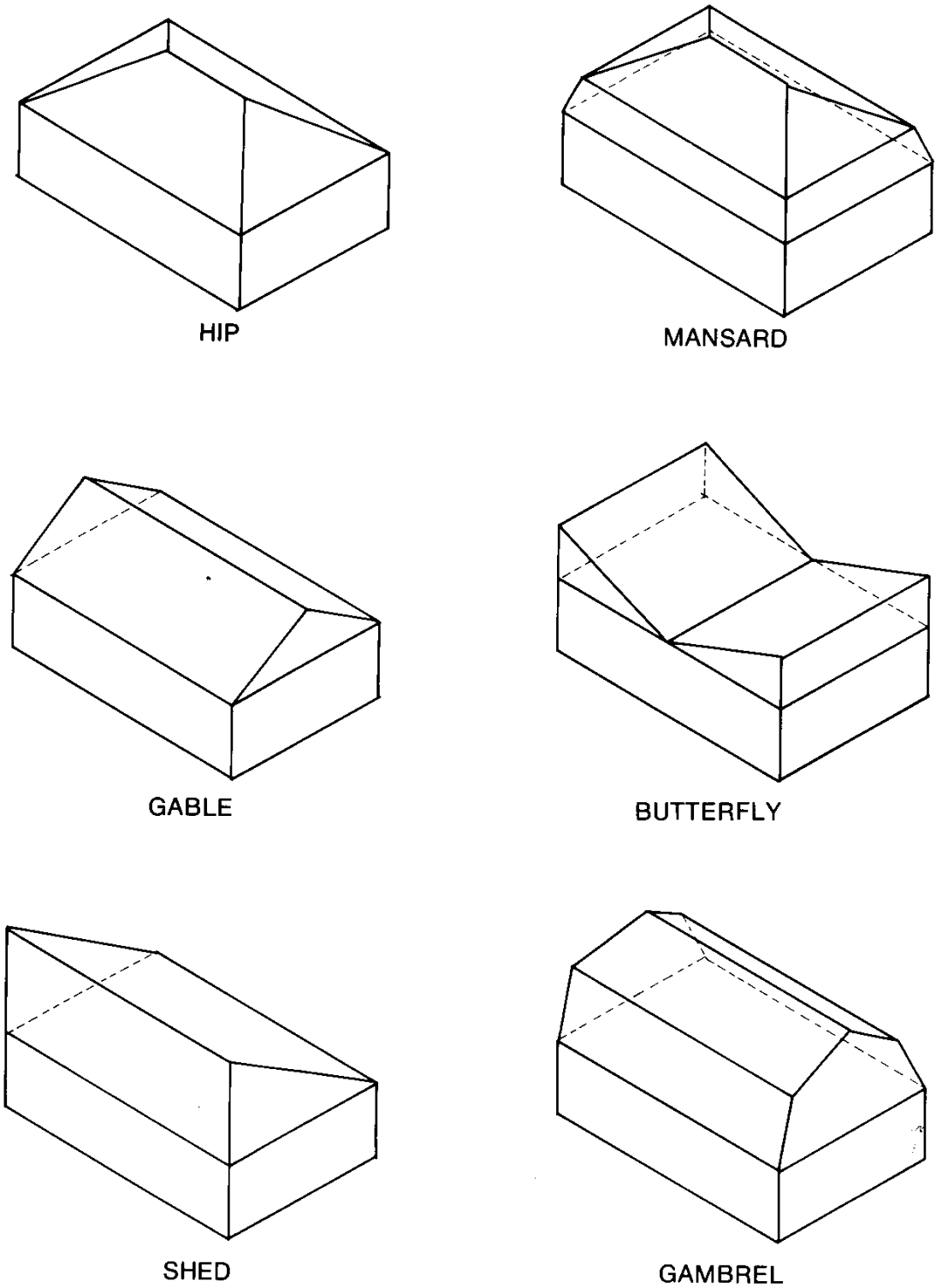


Figure 1. Roof forms.

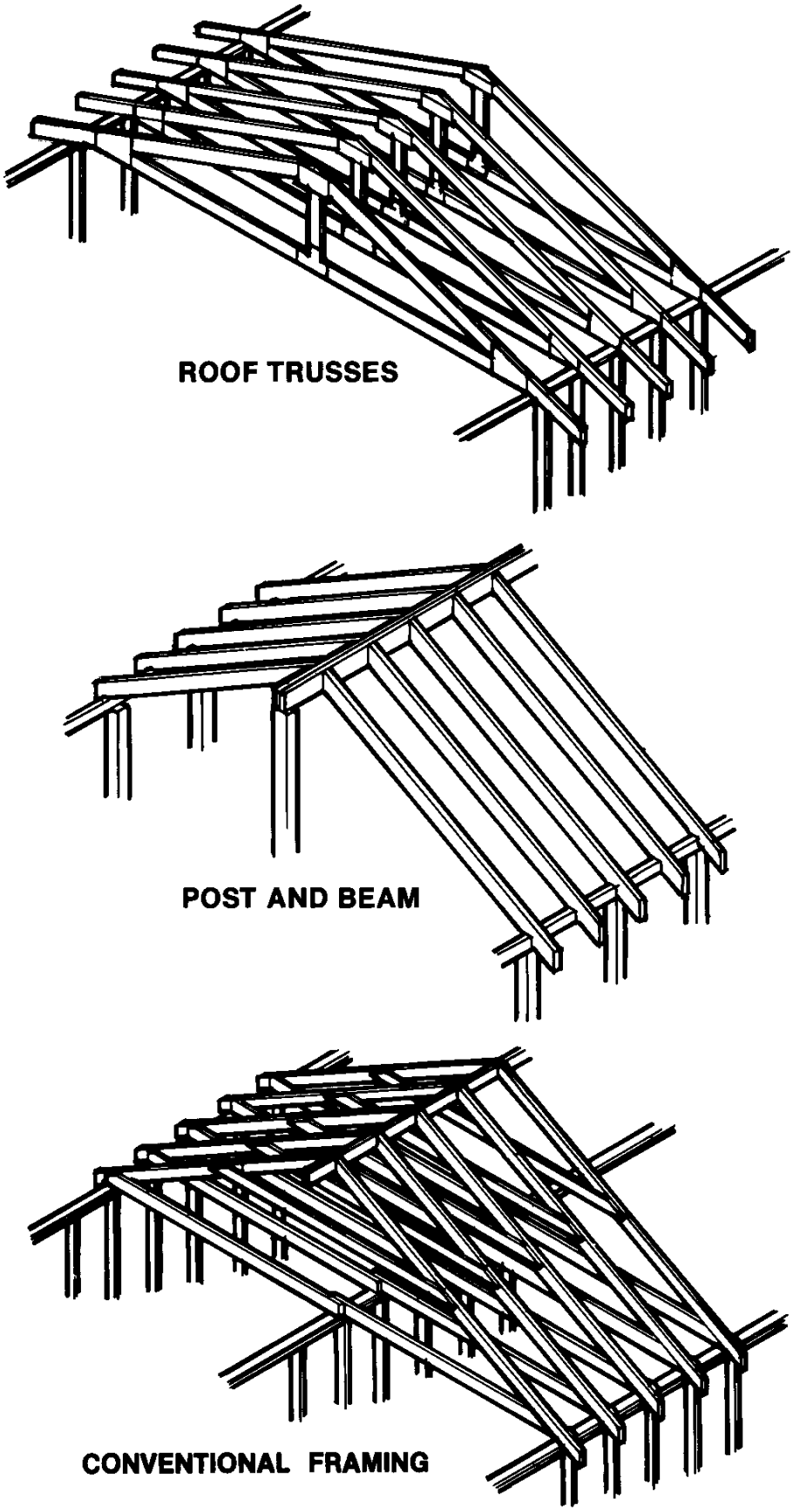


Figure 2. Roof framing systems.

like superimposing one truss on top of another can be used. The normal economical spans used range from 20 ft (6.1 m) to 60 ft (18.3 m) for wood trusses.

There are certain building types where trusses are required. A truss resolves all the horizontal loads within its members (primarily in the tensioned bottom chord), thus exerting only vertical loads on the structure below. This characteristic is essential in roof conversion for certain types of buildings. For example, a common type of flat-roof construction employs perimeter masonry bearing walls with parapets supporting wood joists or steel bar joists framed between the walls. In this case, conventional framing would apply excessive lateral or horizontal loads to the top of the parapet. Conventional framing would require that the parapets be torn down flush with the roof or that a horizontal tie be added that would restrain the lateral loads. In this case, trusses are the only logical and economical choice. Similarly, where the clear span exceeds the capacity of conventional framing, trusses would be required.

Post and Beam Method

Another type of roof construction system is post and beam. No examples were found of roof conversions using this system, although it could be used under certain rare conditions. The building would have to be capable of supporting a concentrated load at each end under the beam as well as uniform loads along both side walls. The deciding factor would be the beam spans. For most buildings, even small single-family residences, a single-span beam would be very large and therefore high in cost. If short spans are possible, post-and-beam framing might be acceptable.

Conventional Framing

The third basic roof system is conventional framing (rafters and joists). For this type of roof conversion, the existing flat roof joist can be used. The existing joists restrain the horizontal thrust caused by the rafters, so construction becomes a matter of erecting the rafters and tying them to the existing joists.

The usual way to attach the rafters to the joists is to fasten a wood plate around the perimeter. The plate is nailed or bolted into the existing joists and deck. The rafters can either rest on top of the plate or notch over it, forming a more secure connection.

Flat roofs often have one or more inches of rigid insulation on the structural deck below the roofing material. Various contractors treat this differently. Some fasten the plates on top of the existing roofing, through the insulation and into the joist and deck. Other contractors and architects feel this practice is unsatisfactory, because the insulation, which is a compressible material, could deform under long-term loading. Also, they feel it could deform unevenly from the amount of moisture in the insulation and different thicknesses. Their solution is to remove the roofing and insulation down to the structural deck. The plates can then be fastened directly to the existing deck.

This method assures secure fastening of the plates but creates another problem. To fasten the plates, a path several inches wider than the plate must be cut away to insure the plate will be straight and true. Depending on the complexity of the roof, it could be several weeks before the work is completed, during which time the building interior is extremely vulnerable to the weather. Temporary closures must be used, which add to the cost. The same problem occurs with similar applications of truss roofs, but is somewhat lessened due to the shorter time required for truss erection.

One of the major determinants indicating whether this system can be used is the length of the span to be covered. The size of the rafters and their spacing dictate the allowable span: the larger the rafter, the longer it will span. Similarly, the larger the piece of dimension lumber, the greater its cost per board foot. Thus, there is a point at which a truss system might prove less expensive. For example, with a 40 psf (193.7 kg/m^2) live load (L.L.) requirement, 2 x 10's (5 x 25 cm) spaced at 16 in. (40 cm) o.c. will span about 15 ft (4.57 m). Therefore, the maximum building width would be less than 30 ft (9.15 m).

If the building has intermediate supports, then the roof framing may not be limited to a single simple span. In small-scale frame construction there are often interior bearing walls. Bearing walls will support knee walls, which in turn can support the rafters, reducing their span. With a series of knee walls, the framing members can be small and cover fairly large areas. This makes a very economical system.

The dead loads imposed on a structure by this type of framing (wood rafters covered with shingles) are relatively light. Consequently, many types of existing structural systems can support the dead loads created by the roof conversion without the need for bearing walls beneath the knee walls. For example, a precast concrete deck (Case Study No. 1, Chapter 4) can support the relatively light loads imposed by knee walls.

The discussion of knee walls has been in regard to supporting rafters at about mid-span. Another situation arises in certain building types which require knee walls. Some flat-roofed buildings cantilever the roof out to form overhangs. The new rafters then concentrate a cantilevered load on the outermost point of the joists. Therefore, it is necessary to place a supporting knee wall above the exterior wall to take most of the rafter load. Then the only load carried by the existing cantilevered joist would be one-half the overhang load of the new roof.

Metal Conversion Systems

Several contractors used metal members to frame roof conversions. Although this approach is not as common as wood framing, the contractors that used this system used it almost exclusively.

Metal framing systems are generally covered with light-gauge metal roofing materials. Metal roofing is attached with sheet metal screws and neoprene washers. Metal framing members most often used were lightweight members such as rolled "c"-sections, bolted or welded together. The job-built metal framing is characterized by different spacing than wood. The rafters were

commonly 10 ft to 20 ft (3.05 m to 6.1 m) o.c. The intermediate members or purlins were normally 5 ft-1 in. (1.52 m) o.c.

The metal framing systems are generally characterized by lower roof slopes than wood framing systems. Metal framing systems with metal roofing materials normally range between 1/4 in 12 and 2 in 12 roof slope. Wood framing systems covered with metal roofing were found to slope from 2 to 12 and up. Wood framing covered with nonmetal roofing, like asphalt or wood shingles, generally began at 4 in 12 slopes. There are several reasons for this:

1. Asphalt shingles are not recommended (by their manufacturers) for use at slopes less than 2 in 12.

2. It is more advantageous to use metal on low-sloped roofs. The steeper the slope, the more roofing material required to cover it. The concern in metal roofing is not all economical. The longer the piece of metal, the more it expands and contracts from temperature change. This movement enlarges the holes around the securing screws or nails and can eventually cause leaks.

3. Covering a steep slope requires longer framing members, increasing the cost when metal framing is used.

4. It is difficult to restrain the lateral loads with metal framing systems. (This is not a problem with the lower slopes [1/4 in 12] because the horizontal components of the loads are small.)

Metal trusses have many of the same properties as wood trusses. They are fabricated in a shop or factory and delivered to the job site. They can span large areas exerting only vertical loads at their end points. The members are generally steel angles bolted or welded together, but a variety of standard steel shapes can be used. They can be used in conjunction with wood or metal purlins to support plywood and shingles or metal roofing material.

Steel is generally preferred over wood for long-span trusses, but steel trusses are more complicated and require more fabrication time, thereby increasing their cost. Also, the attachment of the steel trusses is a more complicated process in the field. In general, trusses using light-gauge sections are less expensive than trusses that use heavy rolled sections.

3 CASE STUDIES

Case Study No. 1

Type of Construction

10-ft (3-m) concrete block bearing walls with precast concrete (Flexicore) deck, no parapets.

Existing Roof System

Built-up, gravel surface over 1 in. (2.54 cm) of rigid insulation.

Building Size

108 ft x 33 ft = 3,564 sq ft (33 m x 10 m = 330 m^2)

Configuration

Two identical apartment buildings separated by a 12-ft (3.66 m) light well. At the roof level, the two buildings are connected at each end by a strip of roof 2 ft-6 in. (76.2 cm) wide. Only one roof has been converted at this time, but the owners plan to change the other roof at a later date.

Date

Construction begun January 15, 1983; completed February 15, 1983.

Reason for Roof Replacement

Leaking.

System Used

Two- by four-in. (5- x 10-cm) rafters at 2 ft-0 in. (61 cm) o.c. to create a hip roof with a slope of 4 in 12. The rafters are supported by 2- x 4-in. (5- x 10-cm) knee walls at the midpoint of their span. The existing built-up roofing and the rigid insulation were cut away from the precast concrete deck around the perimeter and under the supporting 2- x 4-in. (5- x 10-cm) knee walls to provide positive fastening of the 2- x 4-in. (5- x 10-cm) plates. One- by six-in. (2.5- to 15-cm) redwood fascia was fastened directly to the existing metal fascia, so there is no soffit.

Attic Ventilation

The attic space is ventilated with a continuous ridge vent. Ten circular mushroom vents were used at the base of the roof around the building.

Gutters

No gutters were used at this time. One long wall was previously guttered and the gutter remains.

Insulation Added

Unknown.

Cost

$8,068.84, or $2.26 per sq ft ($24.30/m^2).

Drawings and Photos

See Figures 3 to 8.

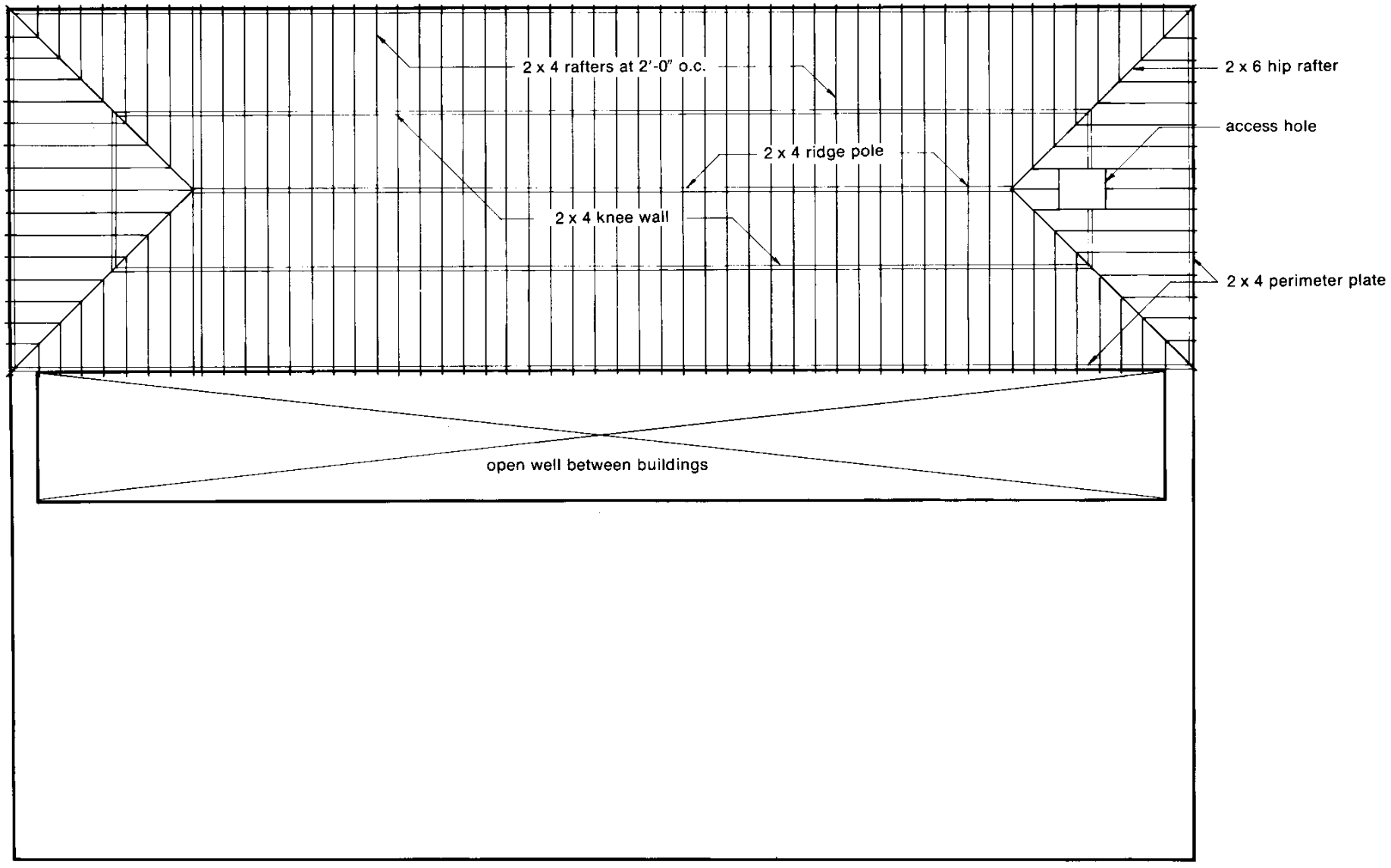


Figure 3. Roof framing plan, Case Study No. 1.

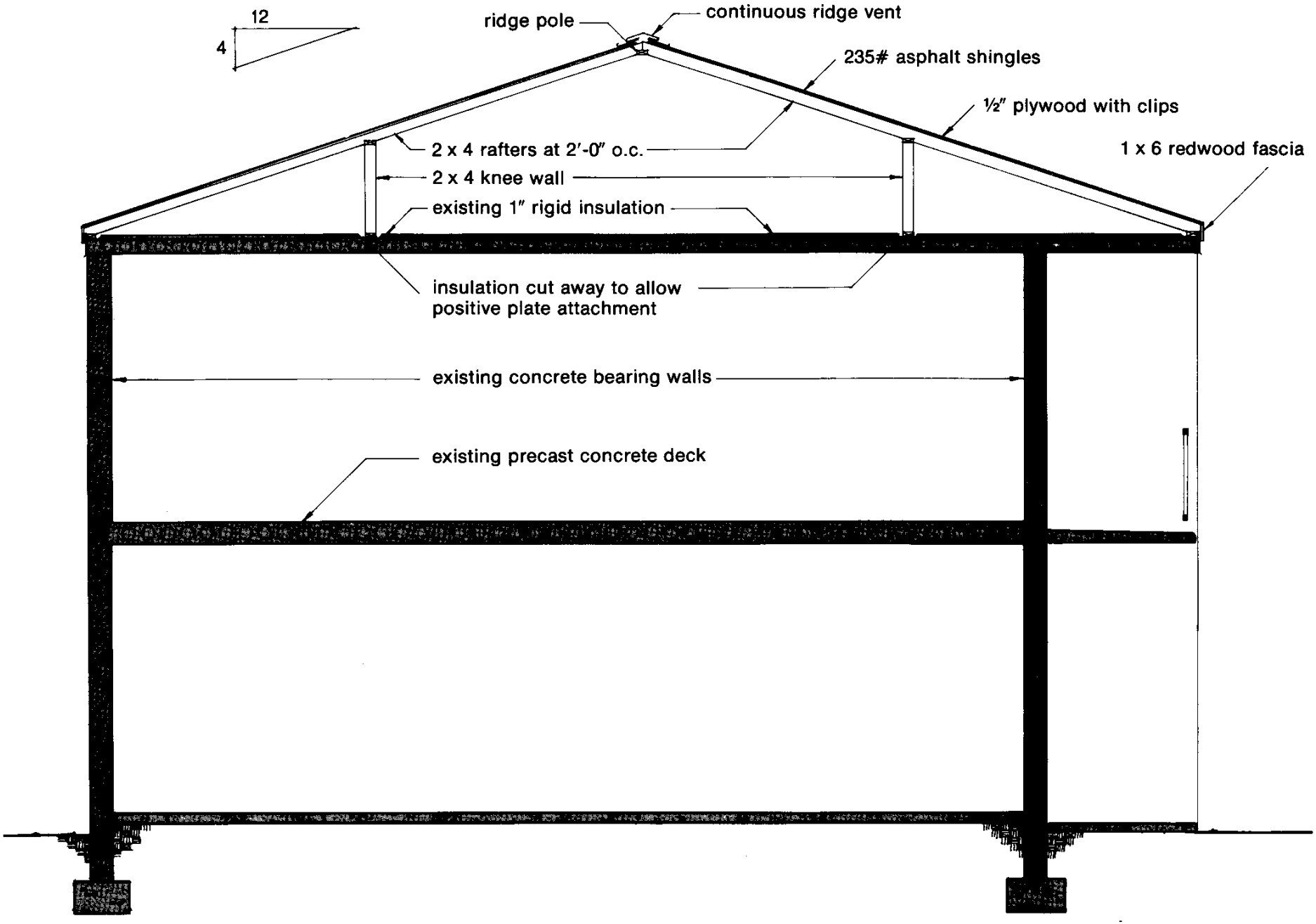


Figure 4. Section through building, Case Study No. 1.

Figure 5. View looking under framing, Case Study No. 1. The job was done during February so the knee walls were temporarily supported until it was completely roofed. Later the roofing and insulation on the existing roof were cut away to allow the 2- x 4-in. (5- x 10-cm) plates to be fastened.

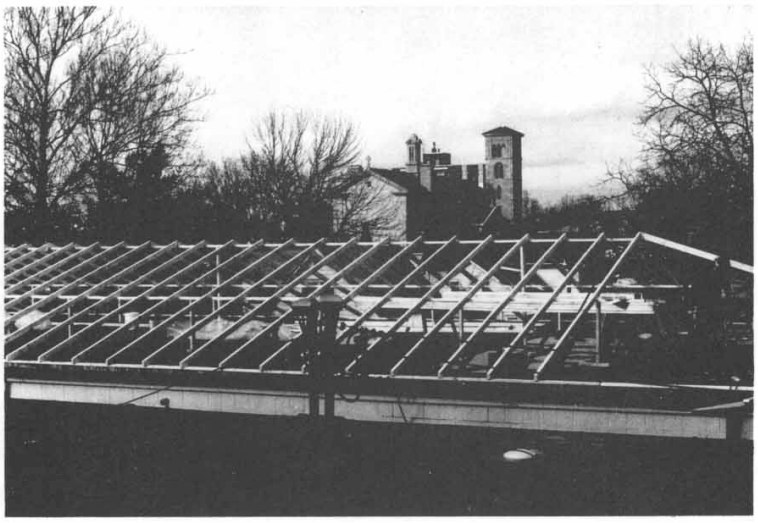


Figure 6. General view of framing, Case Study No. 1.

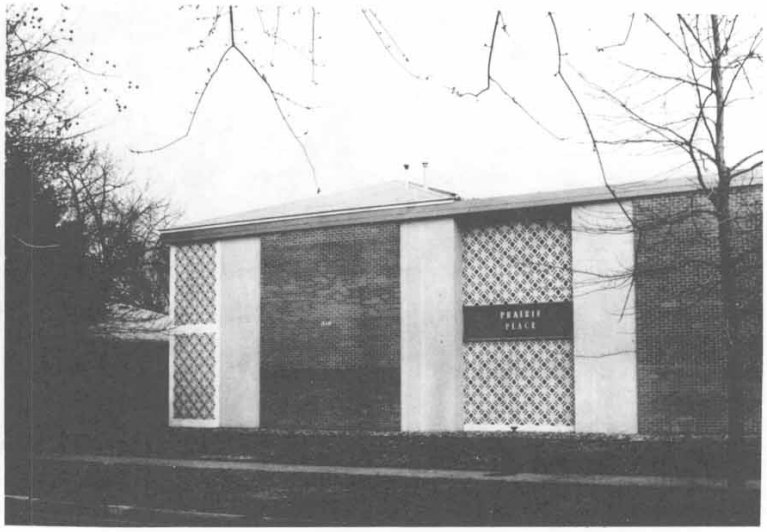


Figure 7. Completed roof from the front, Case Study No. 1.

Figure 8. Completed roof from the rear, Case Study No. 1.

Case Study No. 2

Type of Construction

Haydite concrete block bearing walls supporting steel bar joists and metal deck.

Existing Roof System

Built-up gravel surface over 1-in. (2.54-cm) insulation.

Building Size

52 ft x 32 ft = 1,662 sq ft (15.84 m x 9.75 m = 154.4 m^2).

Configuration

The main roof is rectangular. Also, a smaller roof (elevated 3 ft-6 in. or 1.07 m above main roof) covering an exterior loading dock.

Date

Work started February 7, 1983; completed February 18, 1983.

Reason for Roof Replacement

Leaking.

System Used

Two- x four-in. (5- x 10-cm) prefabricated step-down hip truss system. Existing roof left intact, as trusses were supported on a 2- x 6-in. (5- x 15-cm) plate anchored to the top of the parapet wall.

Attic Ventilation

Continuous ridge vent, 6-in. (16-cm) vent soffit (aluminum) around entire perimeter of building. Roof extended 6 in. beyond outer wall.

Gutters

5-in. (12.7-cm) aluminum (seamless).

Note

There are six similarly designed Post Office buildings in this area. Three of the buildings have been reroofed with sloped systems and the remaining three will be converted soon.

Cost

$6,277.08, or $3.74 per sq ft ($40.26/m^2).

Drawings and Photos

See Figures 9 to 14.

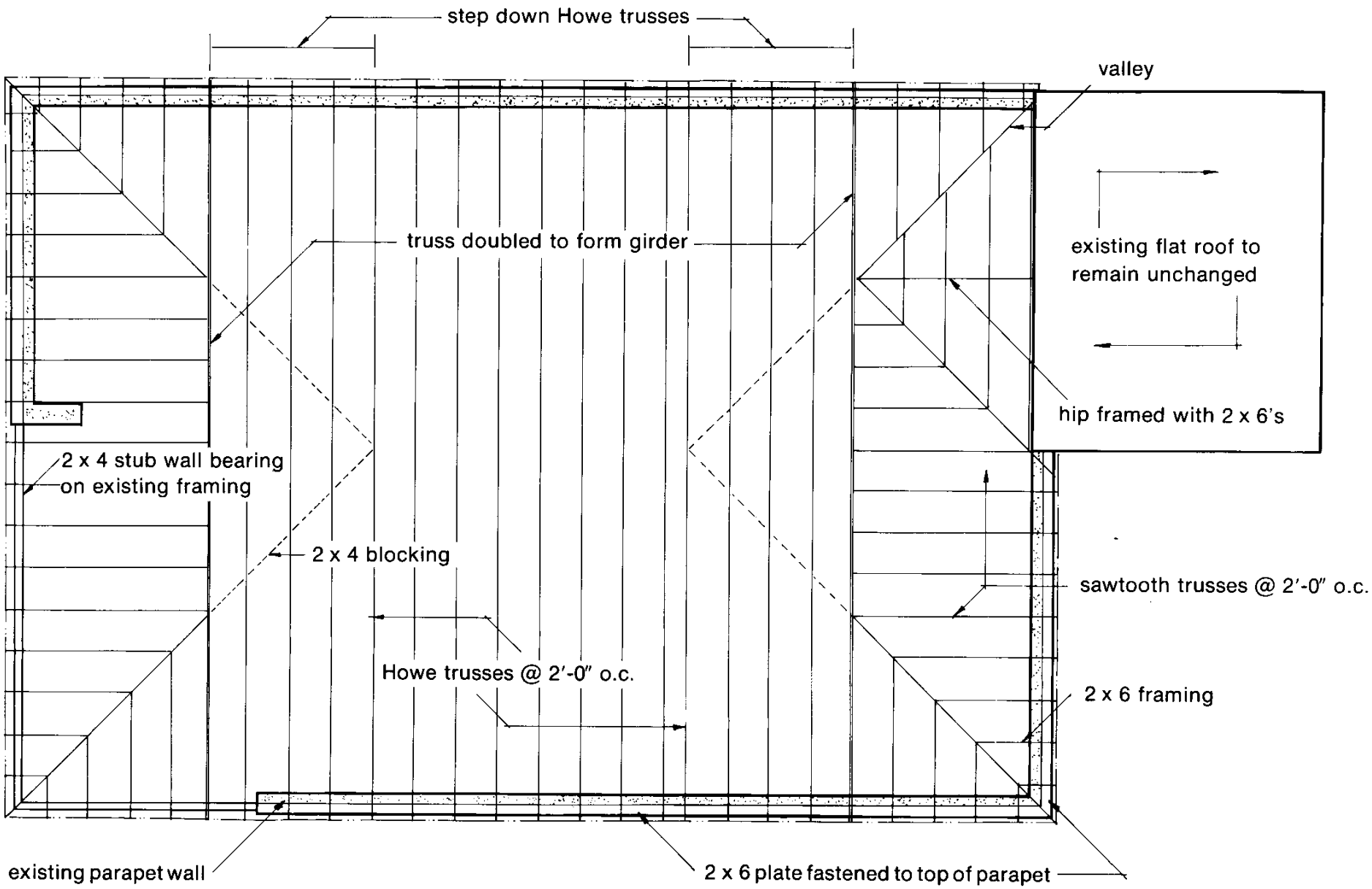


Figure 9. Roof plan, Case Study No. 2.

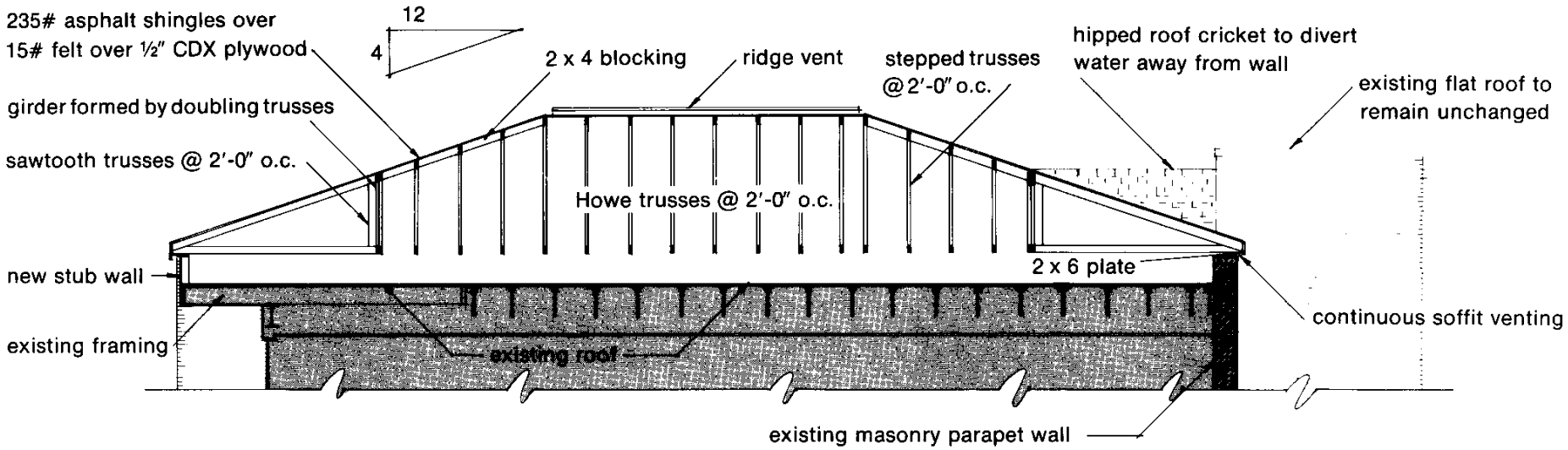


Figure 10. Longitudinal section through the roof, Case Study No. 2.

Figure 11. View on top of roof during beginning construction stage, Case Study No. 2. Note the 2- x 4-in. (5- x 10-cm) plate bolted to the top of the parapet wall and the allowable clear area for adding insulation.

Figure 12. Front view, Case Study No. 2.

Figure 13. View of the beginning of construction, Case Study No. 2. One full-length stepped truss and the front sawtooth trusses are in place.

Figure 14. Completed roof conversion, Case Study No. 2.

Case Study No. 3

Type of Construction

Wood frame; brick veneer and panel exterior, wood roof deck.

Existing Roof System

Built-up, gravel surface over 1-in. (2.54-cm) roof insulation.

Building Size

50 ft x 71 ft = 3550 sq ft (15.24 m x 21.64 m = 329.8 m^2).

Configuration

Rectangular with notches cut out at the corners and centered on one axis.

Date

Construction started February 20, 1983; completed March 30, 1983.

Reason for Roof Replacement

Leaking.

System Used

Two- x eight-in. (5- x 20-cm) rafters framed on 24 in. (61 cm) centers creating a hip roof with a slope of 4 in 12, covered with 1/2-in. (1.27-cm) wafer board, 15-lb felt under 235-lb asphalt shingles. Two- x four-in. (5- x 10-cm) knee walls were used for support at the mid-span of the rafters.

Attic Ventilation

Eighteen mushroom vents at the base of the roof and 20 lin ft (6.1 m) of ridge vent.

Gutters

Four-in. (10-cm) seamless gutter added around the perimeter.

Insulation Added

Six-in. (15-cm) of paper-faced fiberglass installed on top of existing roof.

Cost

$13,504, or $3.80 per sq ft ($40.95/m^2).

Drawings and Photos

See Figures 15 to 20.

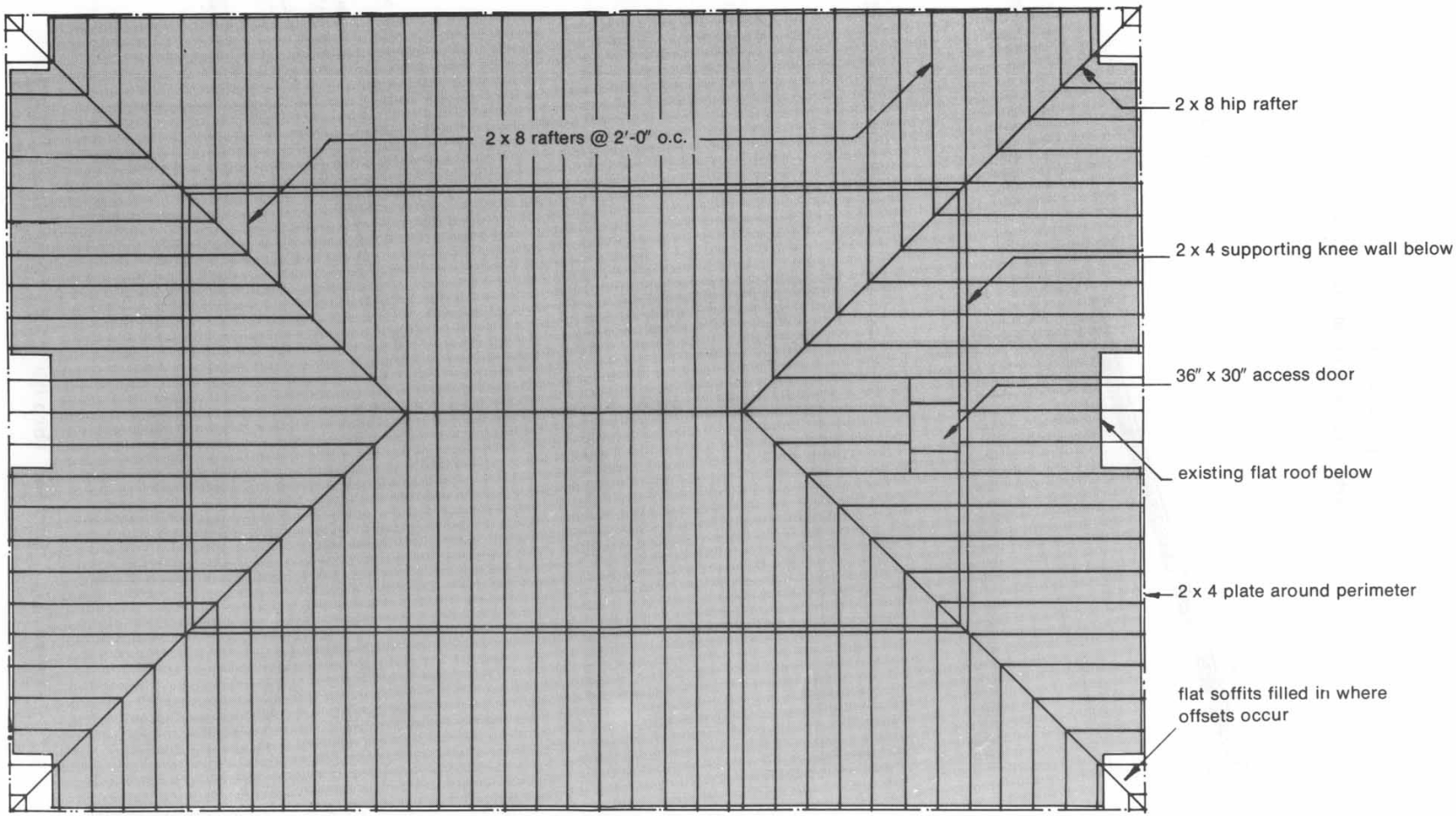


Figure 15. Roof plan, Case Study No. 3.

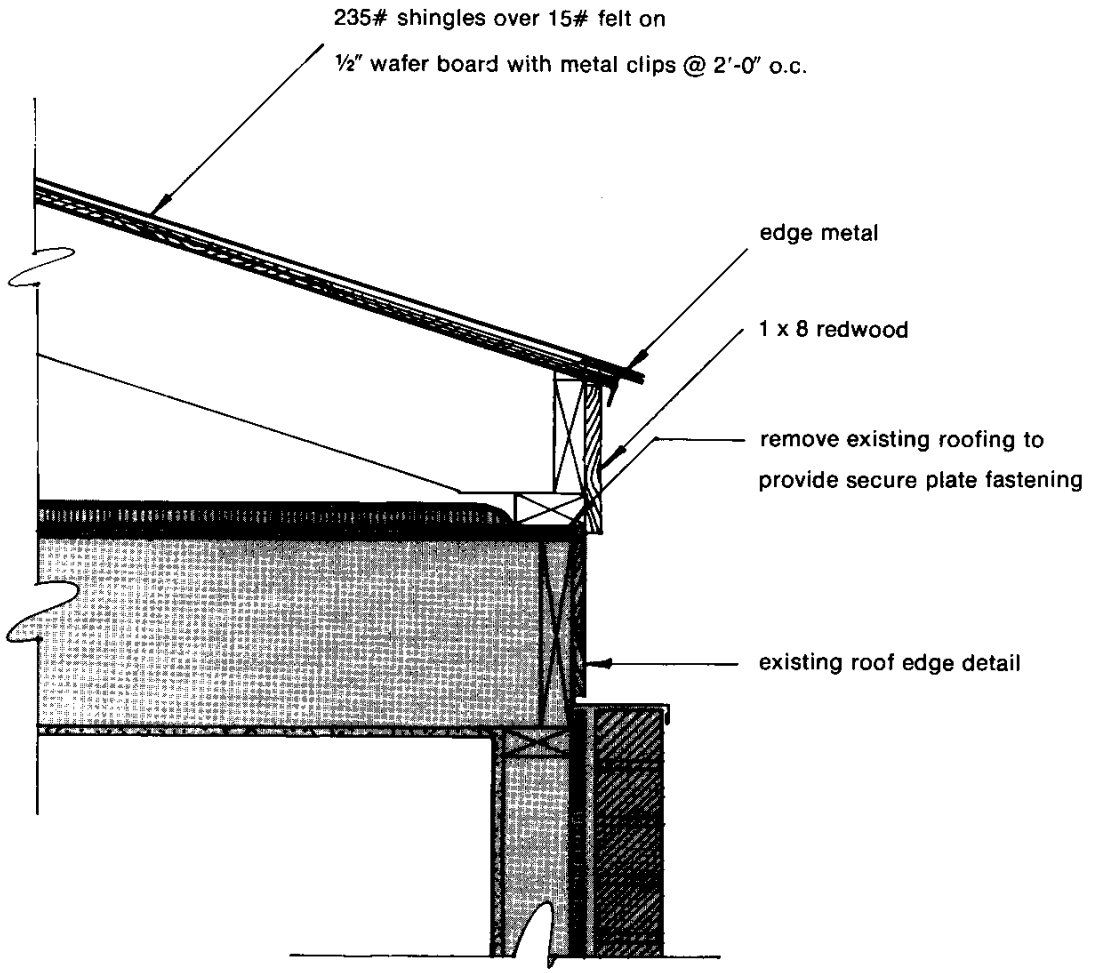


Figure 16. Typical cornice detail, Case Study No. 3.

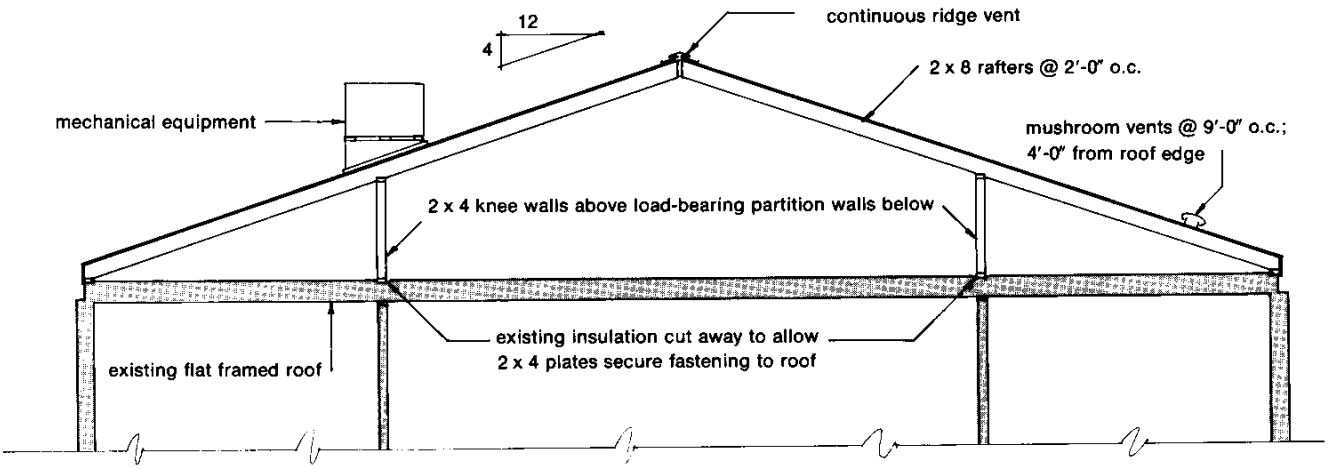


Figure 17. Section through roof, Case Study No. 3.

Figure 18. View of roof top before conversion, Case Study No. 3.

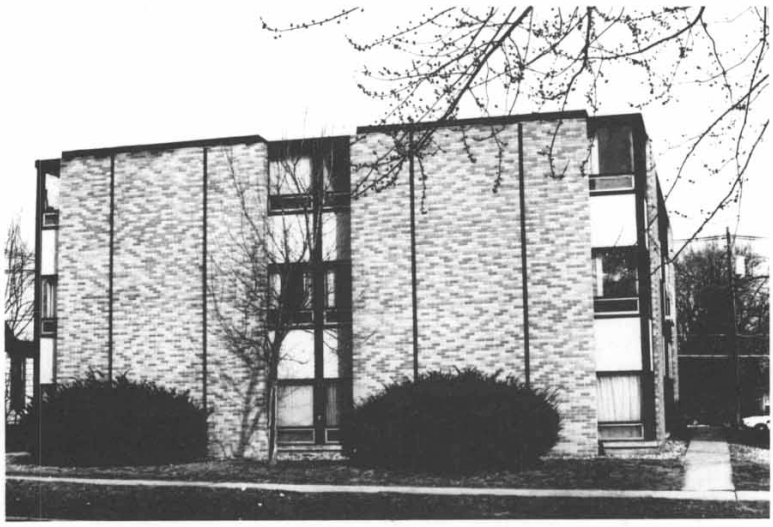


Figure 19. View of front of building before conversion, Case Study No. 3.

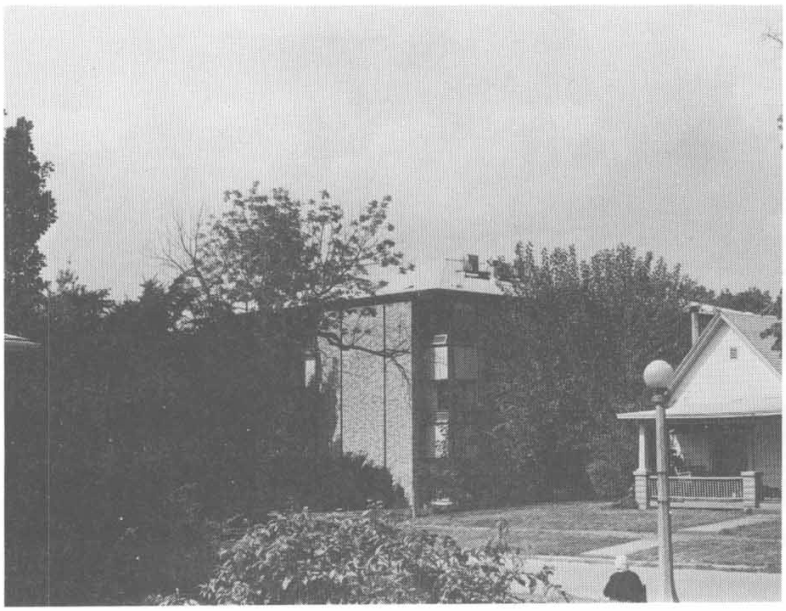


Figure 20. Completed roof conversion, Case Study No. 3.

Case Study No. 4

Type of Construction

Masonry bearing walls supporting a wood frame roof.

Existing Roof System

Built-up, gravel surface.

Building Size

4,882 sq ft (454 m^2).

Configuration

L-shaped.

Date

Winter of 1982-83.

Reason for Roof Replacement

Leaking.

System Used

A combination of wood scissors trusses, conventional framing, and Howe trusses was used because of the existing conditions and the design solution. The existing building had a portion of the roof raised to provide clerestory windows. The scissors trusses and conventional framing were used to raise the roof over this rather than removing it. Conventional Howe trusses were used elsewhere. The final 5 in 12 slope was covered with fiberglass-reinforced asphalt shingles.

Attic Ventilation

Continuous ridge vent and soffit vents were used.

Gutters

A complete new guttering system was added.

Insulation Added

Unknown.

Cost

$25,609, or $5.25 per sq ft ($56.50/m^2).

Drawings and Photos

See Figures 21 to 29.

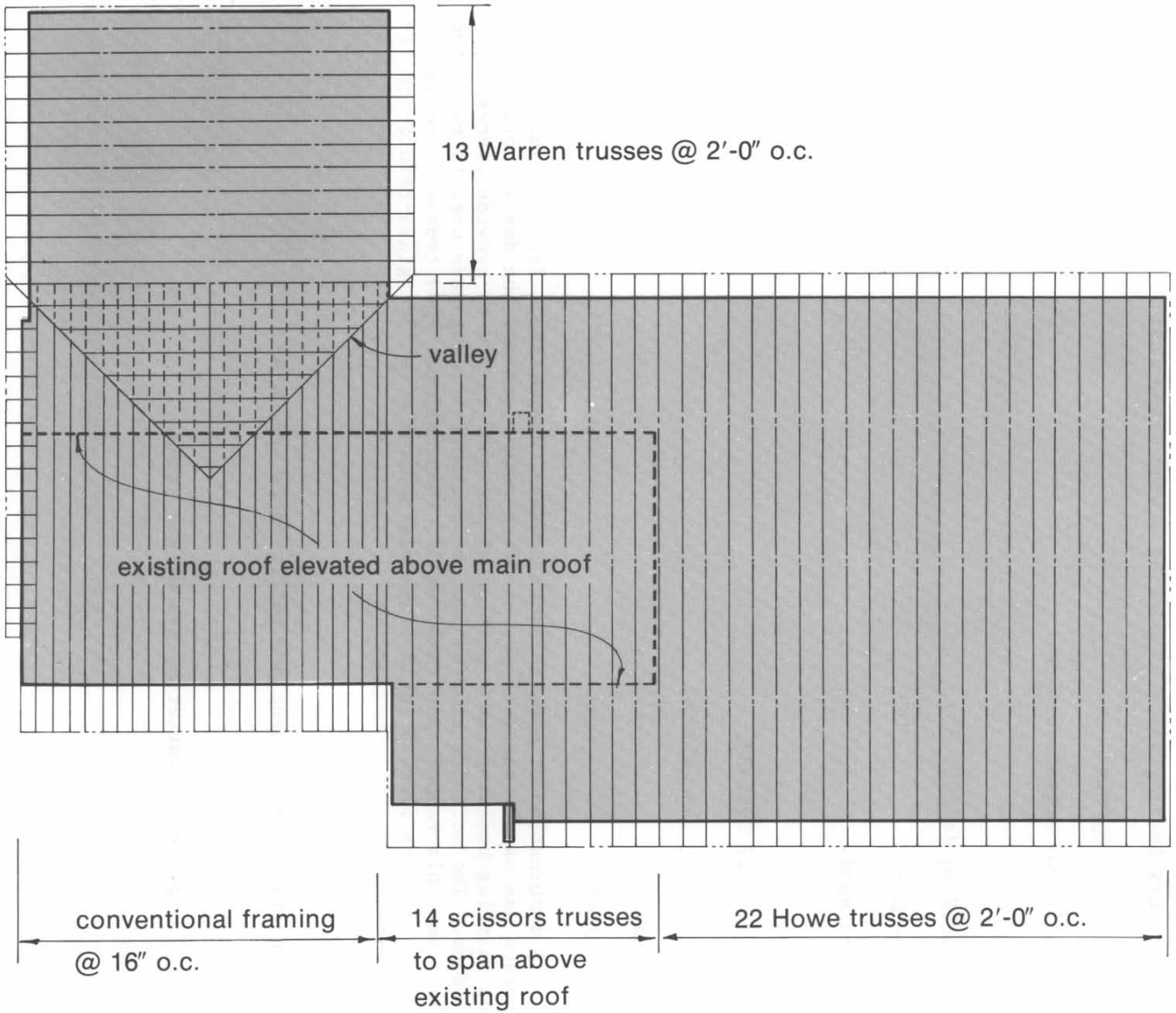


Figure 21. Roof plan, Case Study No. 4.

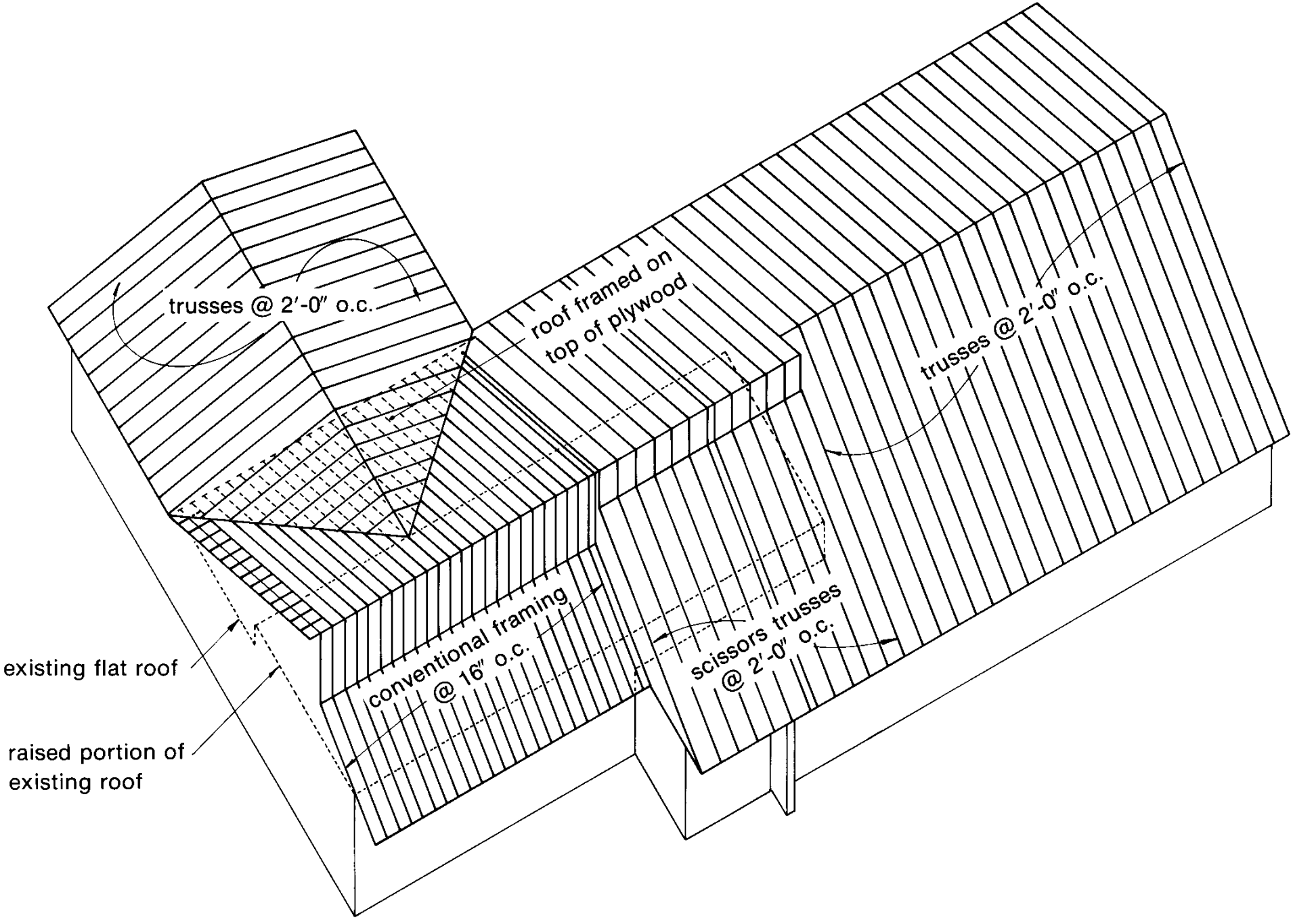


Figure 22. Diagrammatic isometric of roof framing, Case Study No. 4.

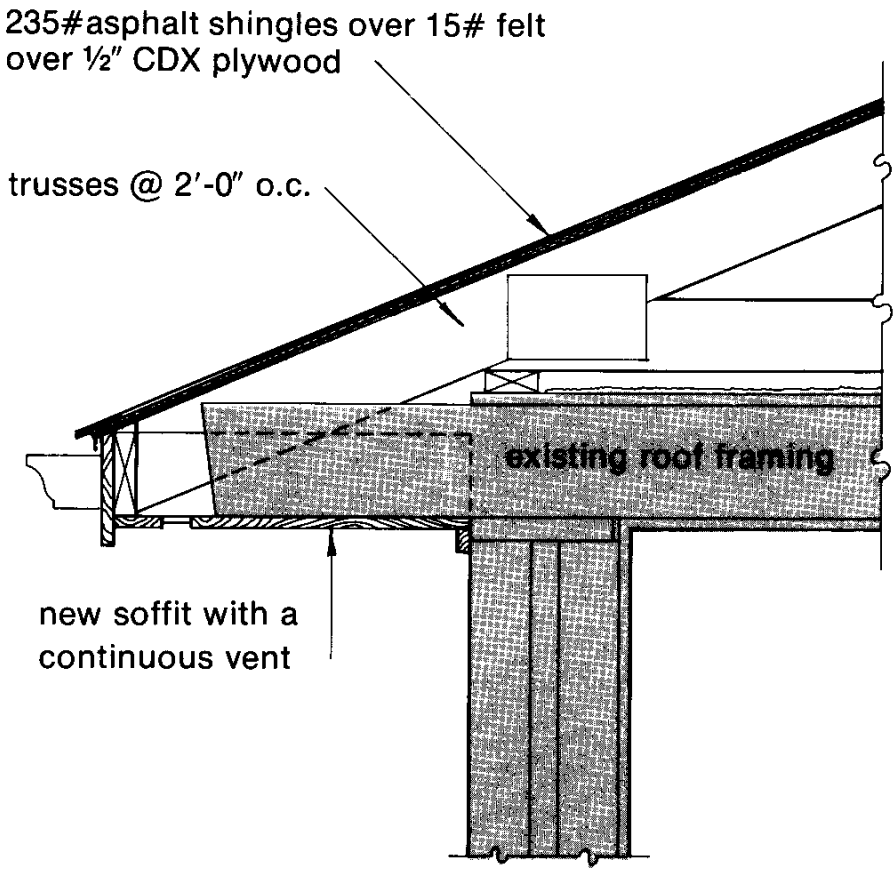


Figure 23. Roof edge detail, Case Study No. 4.

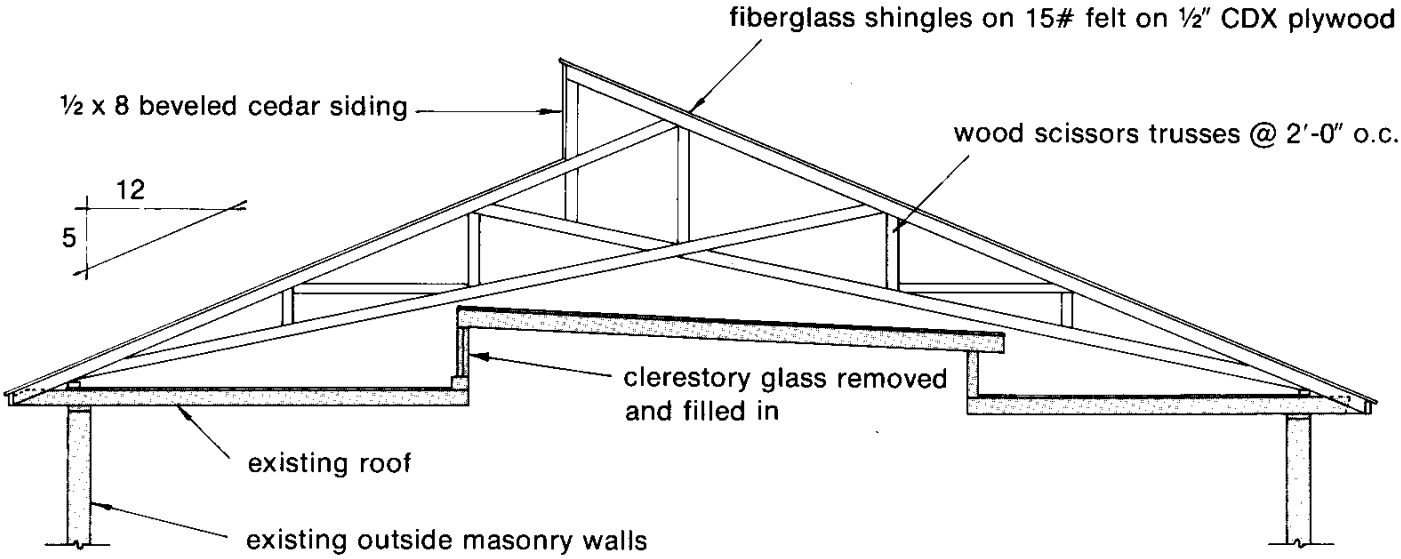


Figure 24. Section through roof, Case Study No. 4.

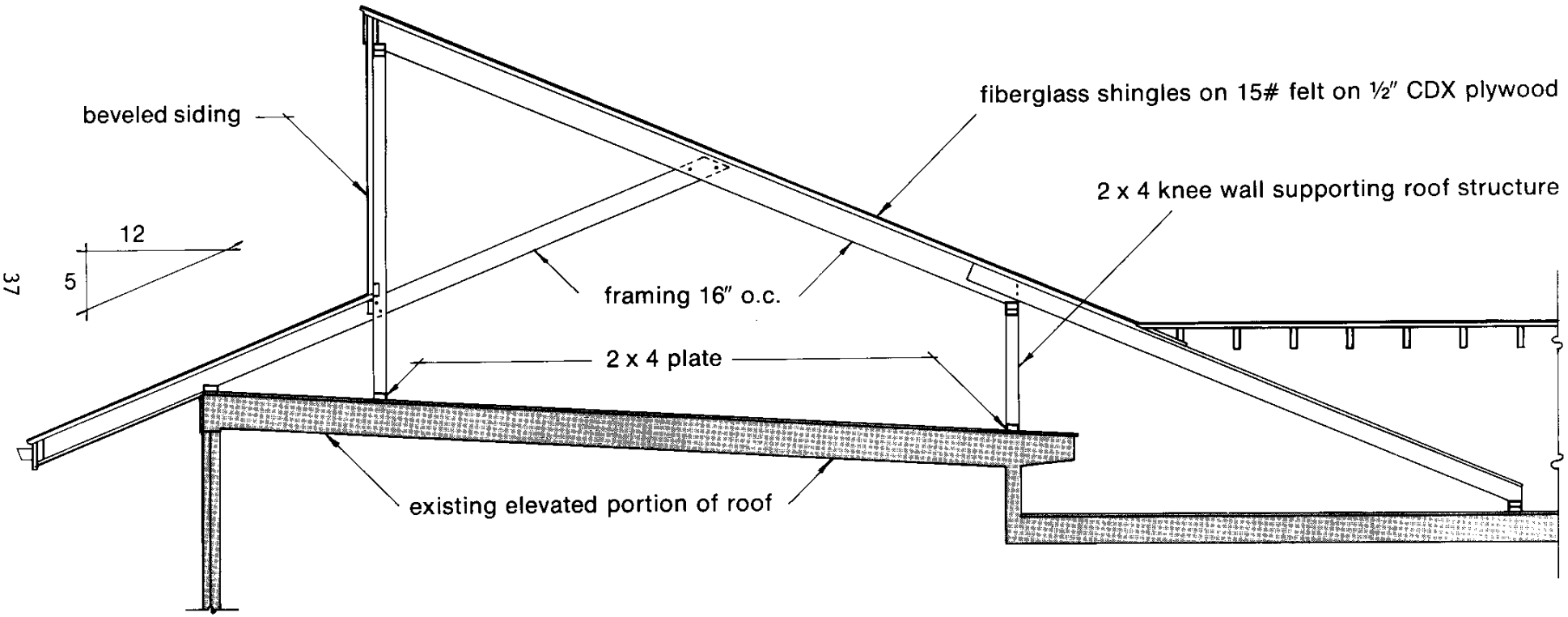


Figure 25. Detailed section through roof, Case Study No. 4.

Figure 26. General front view before conversion, Case Study No. 4.

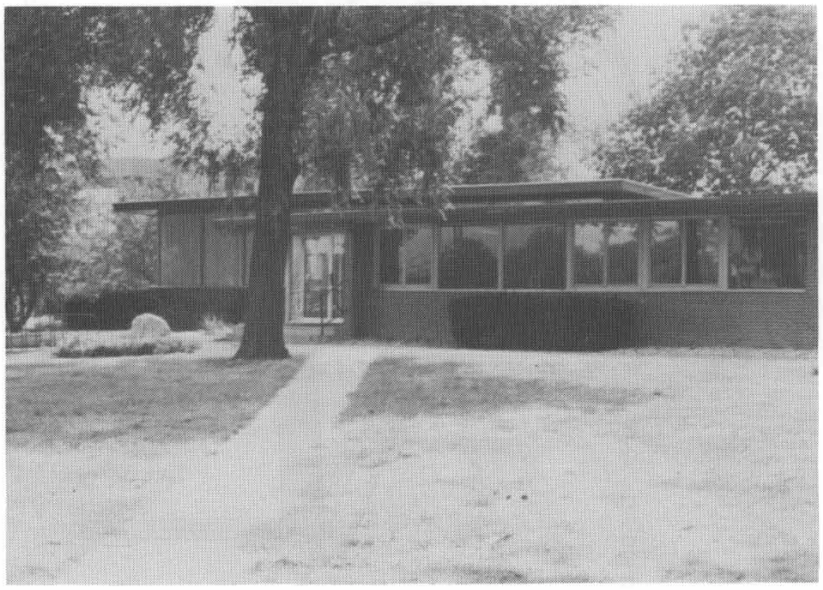


Figure 27. Close-up front view before conversion, Case Study No. 4.

Figure 28. Side view completed, Case Study No. 4.

Figure 29. Front view completed, Case Study No. 4.

Case Study No. 5

Type of Construction

12-ft (3.65-m) concrete bearing walls and wood ceiling joists framed between parapet walls.

Existing Roof System

Built-up, gravel surface.

Building Size

1,620 sq ft (150.5 m^2).

Configuration

Basically rectangular, with various offsets.

Date

February 1983.

Reason for Roof Replacement

Leaking.

System Used

Wood trusses at 2 ft-0 in. (61 cm) o.c. bearing on 2- x 4-in. (5- x 10-cm) plates attached to the top of the parapet walls. A parapet was on the back side to provide for drainage. A wood frame wall was constructed to the same level as the parapet walls to provide bearing for the trusses. The final 4 in 12 sloped roof was covered with asphalt shingles. The gables, soffit and facia were covered with prefinished aluminum.

Attic Ventilation

The attic space was ventilated with gable louver vents.

Gutters

Unknown.

Insulation Added

Unknown.

Cost

$7,614, or $4.70 per sq ft ($50.59/m^2).

Drawings and Photos

See Figures 30 to 35.

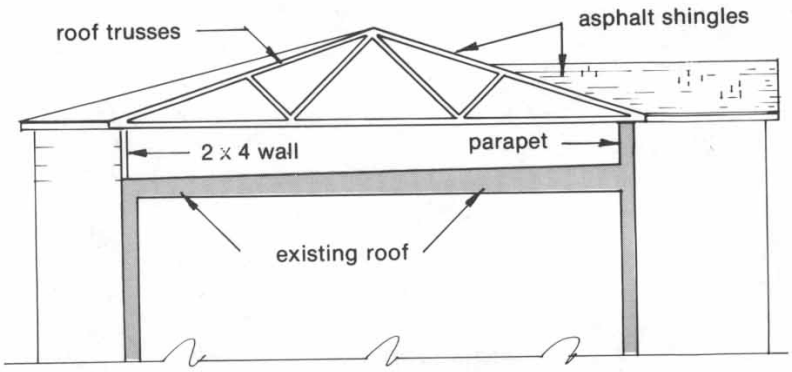


Figure 30. Section through roof, Case Study No. 5.

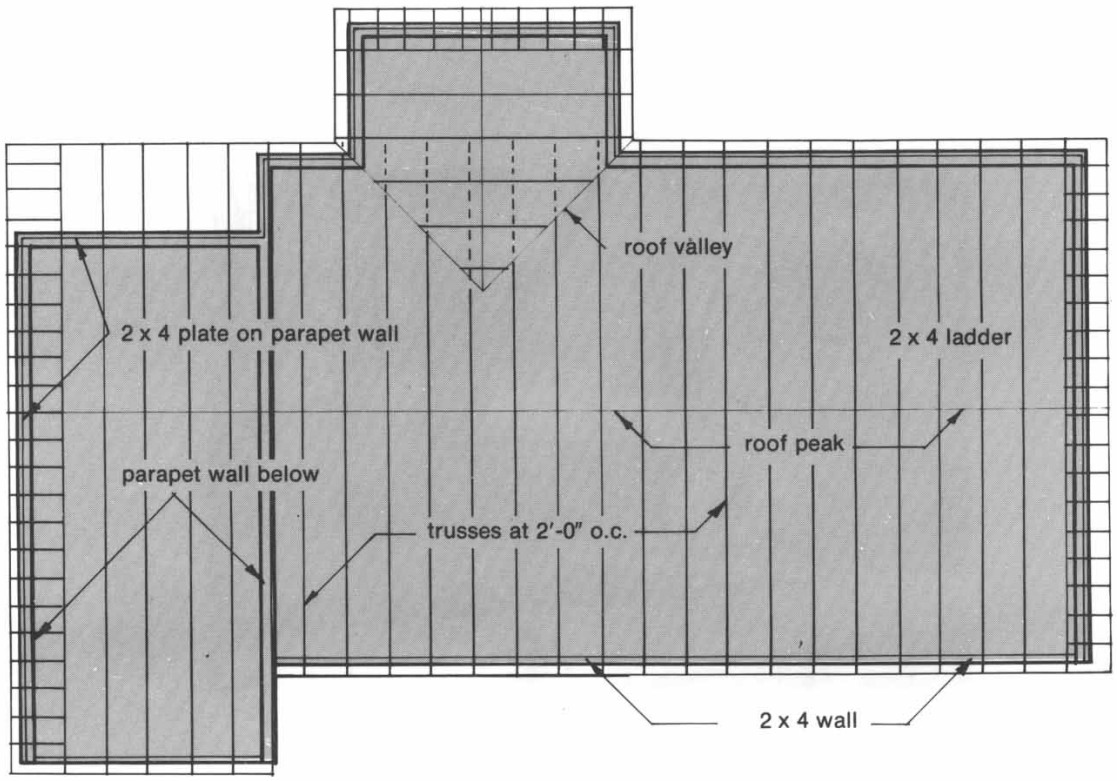


Figure 31. Roof plan, Case Study No. 5.

Figure 32. View under construction, Case Study No. 5.

Figure 33. View of completed roof, Case Study No. 5.

Figure 34. View of trusses in place during construction, Case Study No. 5. Note the frame wall; it is necessary for truss construction that supporting walls are level.

Figure 35. Rear view completed, Case Study No. 5.

Case Study No. 6

Type of Construction

This project is part of Camden County College, Blackwood, NJ, and consists of five separate buildings linked together. The buildings are different sizes and shapes, and are constructed from different materials. Several of the buildings had leakage problems. The architects proposed converting to sloped roofs on all of the buildings. Two of the buildings (Wilson West and East) are steel frame with concrete roof decks. Two other buildings (garage and Roosevelt Hall) have masonry bearing walls with wood frame roof structures. Wilson Center has steel columns supporting concrete barrel vaults.

Existing Roof System

Built-up, gravel surface was used on the garage, Wilson East, and Wilson West. Roosevelt Hall, which already had a sloped roof was reroofed with asphalt shingles. Since each building was slightly different, several will be looked at individually in more depth.

Building Size

See Case Studies 6a and 6b.

Configuration

Rectangular.

Date

Unknown.

Reason for Roof Replacement

Leaking.

Attic Ventilation

All buildings were provided with continuous soffit vent and gable vents or ridge vents.

Gutters

All buildings were guttered completely.

Insulation Added

Unknown.

Cost

Total $204,457, or $5.25 per sq ft ($56.50/m^2) for all three buildings.

Case Study No. 6a

Building

Wilson Center, Camden County College, Blackwood, NJ.

Type of Construction

Steel columns supporting a series of concrete barrel vaults.

Existing Roof System

A liquid-applied product that forms a membrane on the concrete.

Reason for Roof Replacement

Leaking.

Configuration

Rectangular.

Date

Unknown

System Used

Columns were located on the concrete roof directly above the existing structural columns supporting the roof. The new columns carry a beam running perpendicular to the vaults. The beam is made of four parallel-chord trusses tied together at the top with plywood. The two beams (one on each side of the building) in turn support the trusses which run parallel to the vaults.

Building Size

64 ft x 150 ft = 9,600 sq ft (19.5 m x 45.7 m = 891 m^2).

Attic Ventilation

Continuous ridge and soffit vents.

Gutters

Guttered completely.

Insulation Added

Unknown.

Drawings and Photos

See Figures 36 to 43.

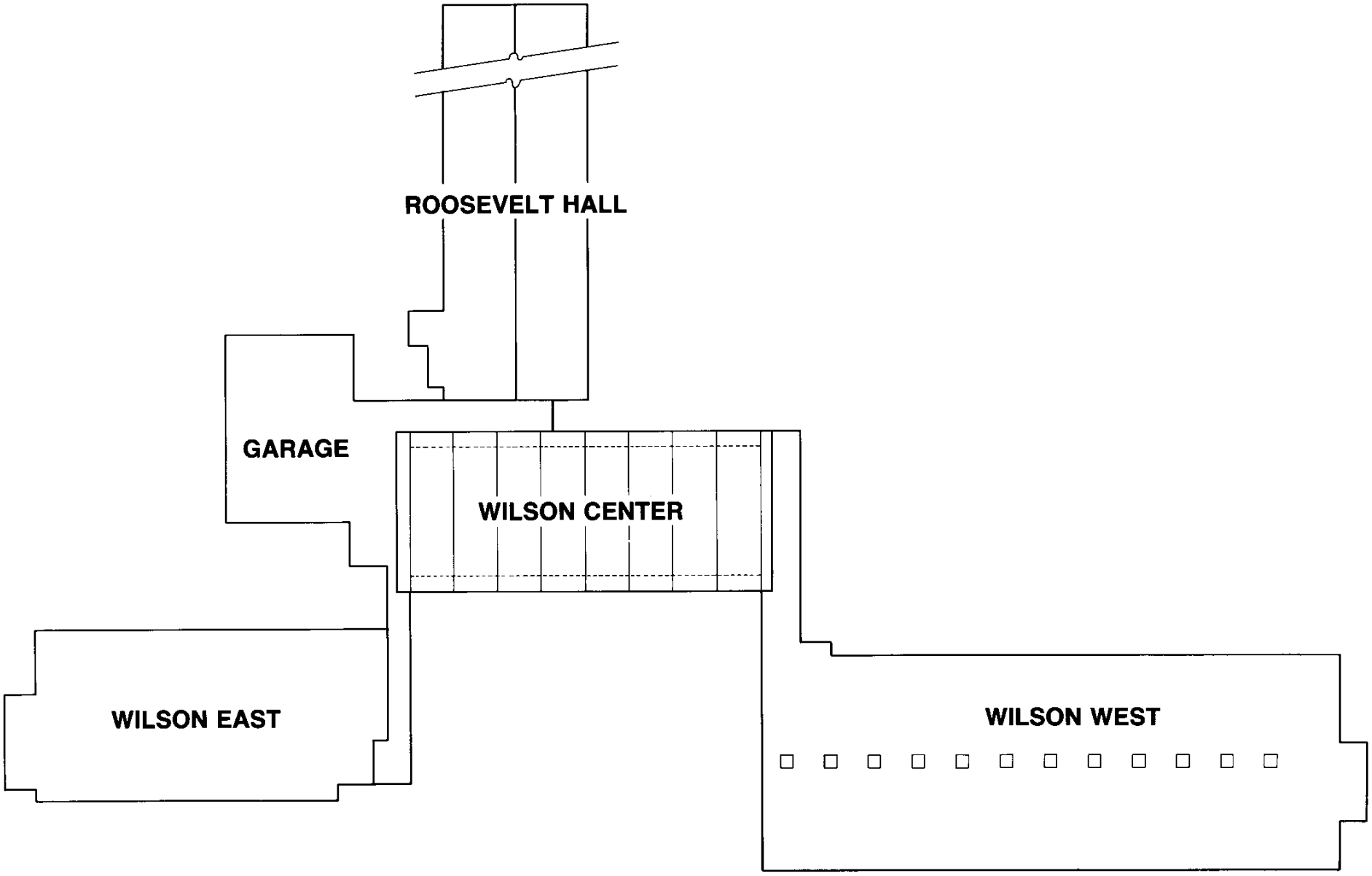


Figure 36. Premodified roof plan of Camden County College complex, Case Study No. 6a and 6b.

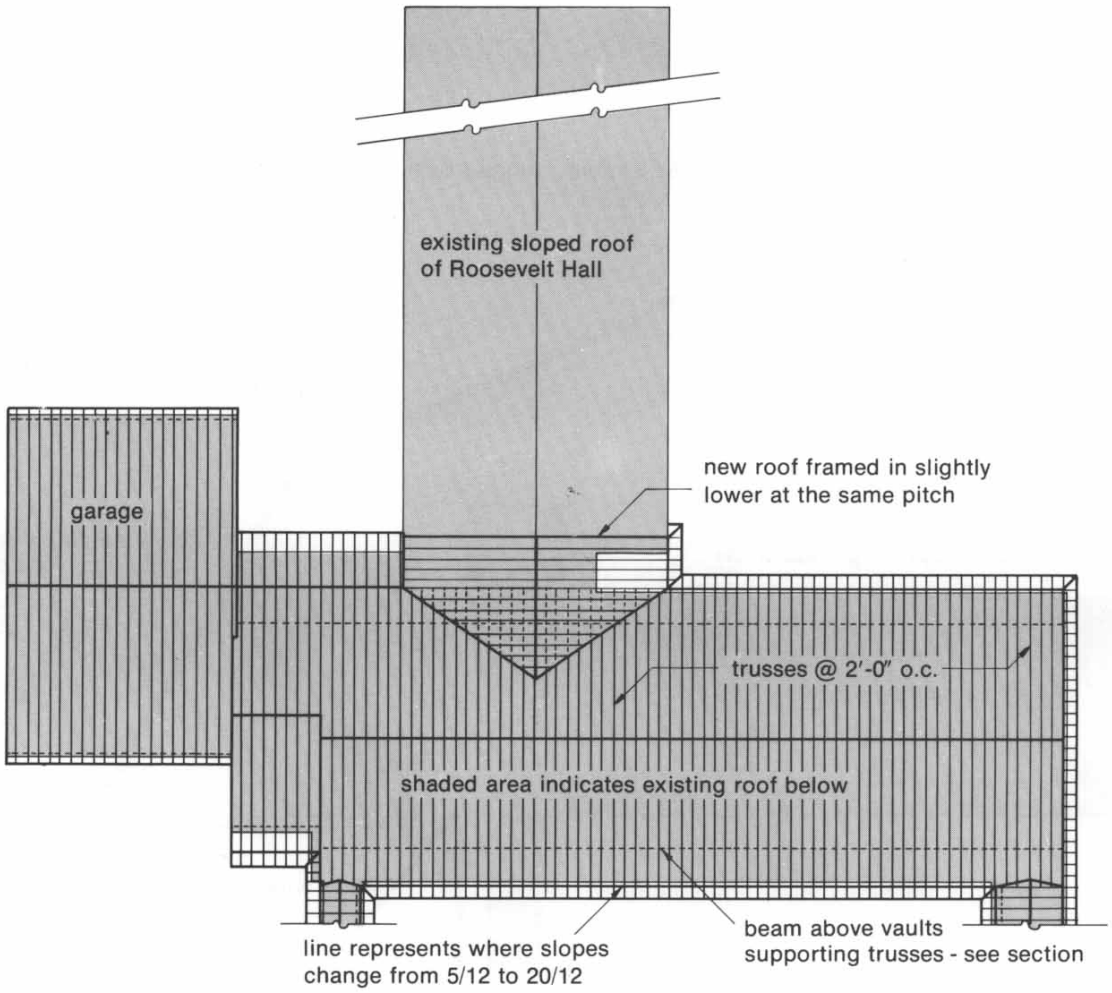


Figure 37. Roof framing plan for Wilson Center, Case Study No. 6a.

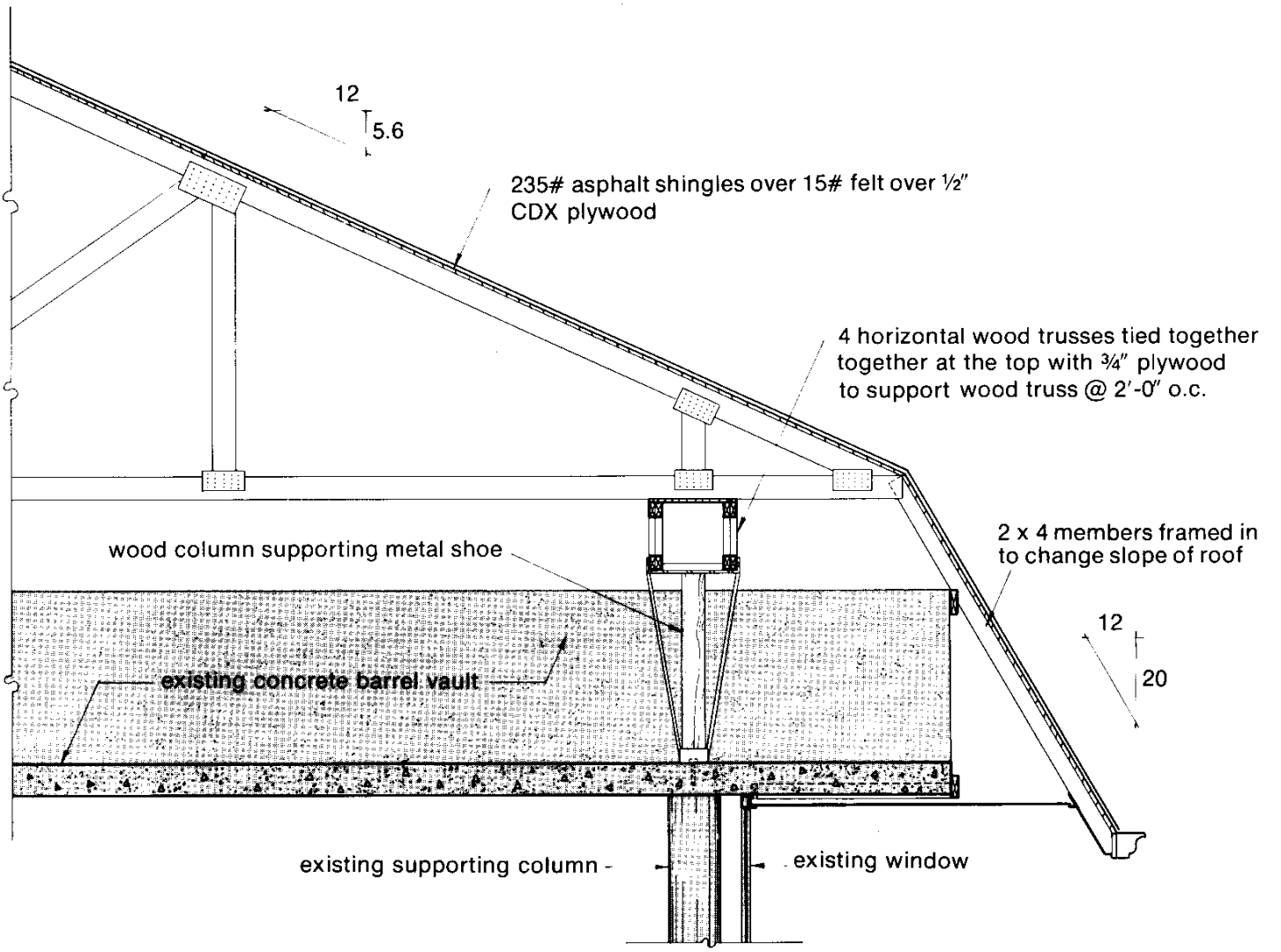


Figure 38. Section through roof edge, Case Study No. 6a.

Figure 39. View of Wilson Center before construction, Case Study No. 6a.

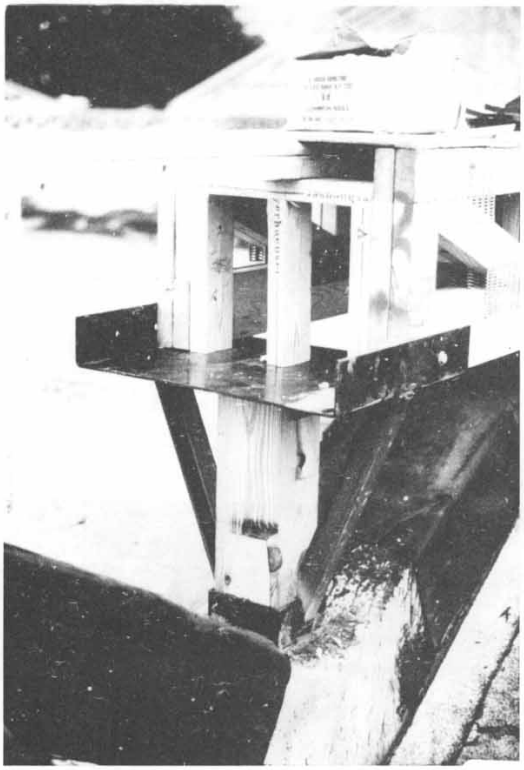


Figure 40. Detail of stub column supporting beam above barrel vaults, Case Study No. 6a.

Figure 41. View of trusses being erected, Case Study No. 6a. Note piggy-back trusses were used because a single full height truss would have been too tall to transport.

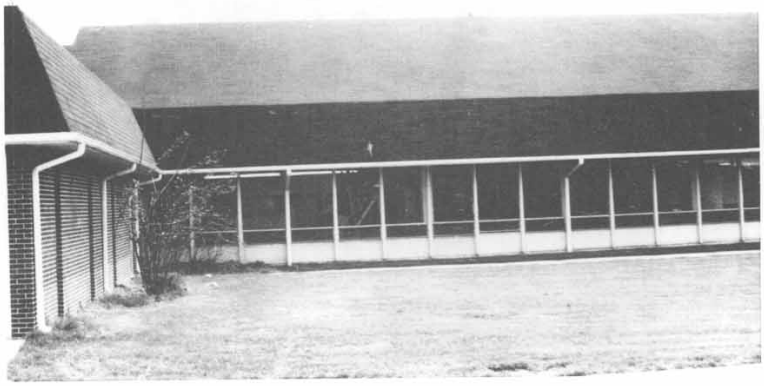


Figure 42. View of finished roof of Wilson Center, Case Study No. 6a.

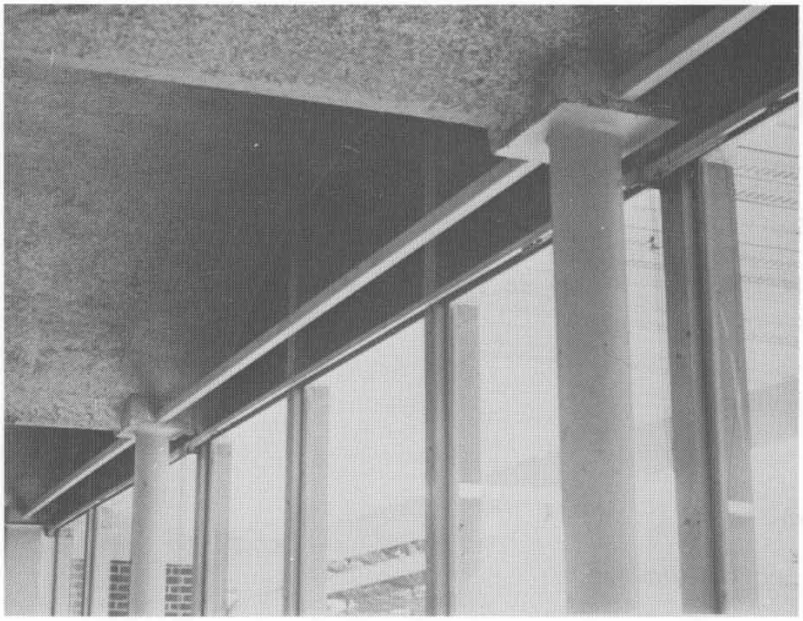


Figure 43. Inside Wilson Center looking out, Case Study No. 6a. Note, the soffit aligns with existing transom. The glass above the transom remains in place; it is painted black.

Case Study No. 6b

Building

Wilson West, Camden County College, Blackwood, NJ.

Type of Construction

Steel frame with concrete roof deck.

Existing Roof System

Built-up, gravel surface.

Building Size

56 ft x 184 ft = 10,304 sq ft (17 m x 56 m = 957 m^2).

Configuration

Rectangular.

Date

Unknown.

Reason for Roof Replacement

Leaking.

System Used

Wood trusses at 2 ft-0 in. (61 cm) on center bearing on 2- x 8-in. (5- x 20-cm) plates fastened through the roof. Due to the width of the building and a line of skylights running down the center of the building, two trusses were used. The two trusses were connected at the peak after they were in place. This solution allowed the skylights to remain (see building section). One-piece trusses would have required removal of the skylights and would have cost more.

Attic Ventilation

Continuous soffit vents, ridge vents, and gable vents.

Gutters

Guttered completely.

Insulation Added

Unknown.

Drawings and Photos

See Figures 44 to 49.

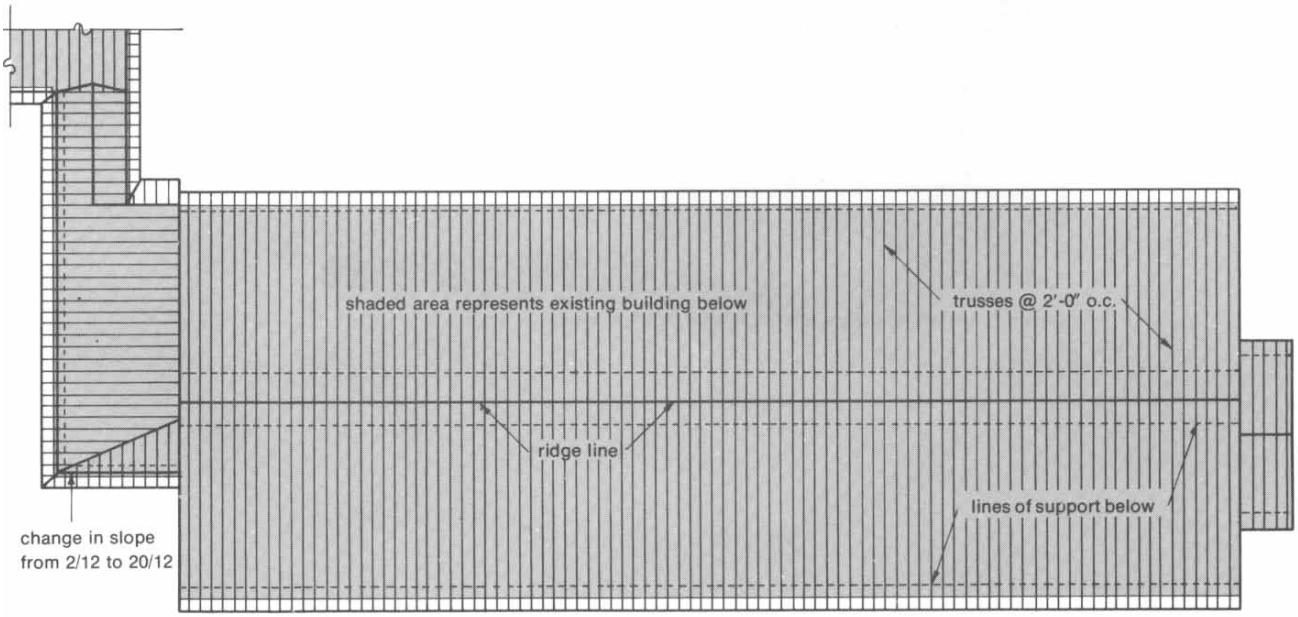


Figure 44. Roof framing plan for Wilson West, Case Study No. 6b.

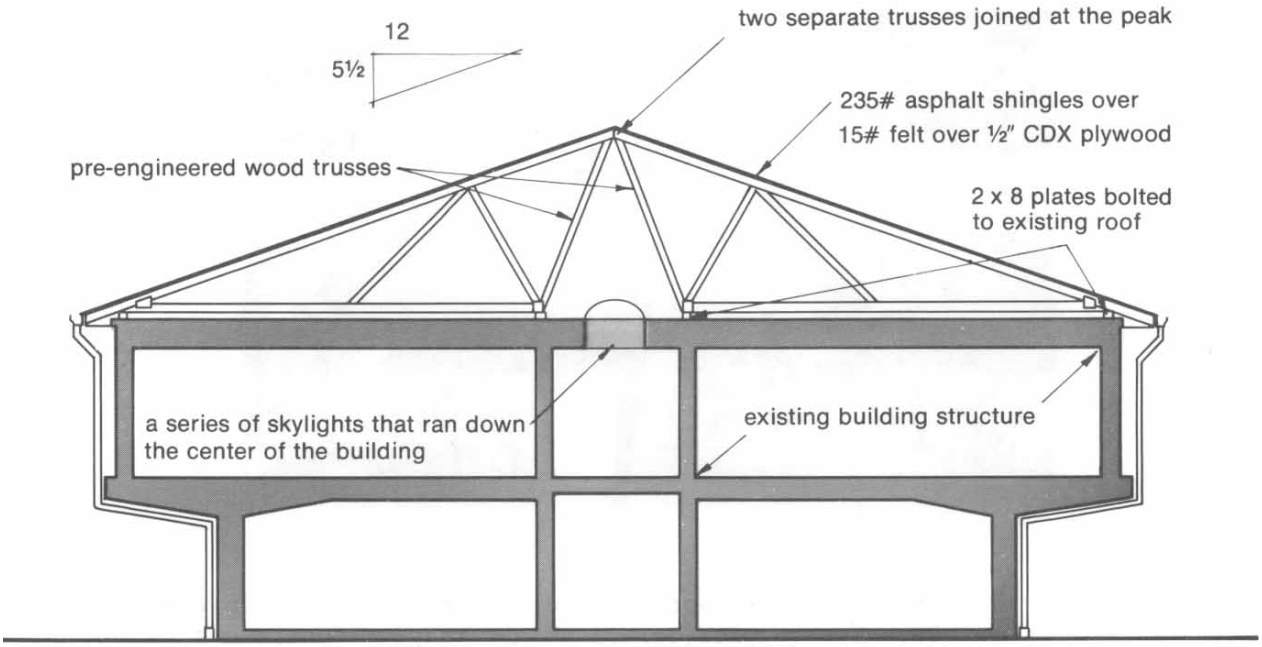


Figure 45. Section through Wilson West, Case Study No. 6b.

Figure 46. View of Wilson West before construction, Case Study No. 6b.

Figure 47. View of roof of Wilson West during construction, Case Study No. 6b. Two trusses joined at the ridge. Continuous bottom chords would conflict with the series of skylights down the center of the building.

Figure 48. Completed view of Wilson West, Case Study No. 6b.

Figure 49. General view of completed roof conversion of Camden County College, Blackwood, NJ, Case Study No. 6.

Case Study No. 7

Type of Construction

Concrete masonry bearing walls supporting precast concrete joists with masonry between.

Existing Roof System

Built-up, gravel surface.

Building Size

42 ft x 70 ft = 2,940 sq ft (12.8 m x 21.4 m = 274 m^2).

Configuration

Rectangular.

Date

December 1982.

Reason for Roof Replacement

Leaking.

System Used

A previous addition on the south side of the building had a sloped (2 in 12) metal roof. The new roof conversion tied into the existing sloped roof at the same slope to form a single continuous roof. The new metal roof is supported with wood trusses 4 ft-0 in. (1.22 m) o.c., which are bearing on 2- x 6-in. (5- x 15-cm) plates attached around the building perimeter. The 3-ft (0.9-m) wide, 26-gauge prefinished metal pans were nailed (with neoprene washers) into 2- x 4-in. (5- x 10-cm) purlins on 2 ft-0 in. (61 cm) centers which rested on top of the trusses.

Attic Ventilation

One 24- x 30-in. (61- x 76-cm) gable vent.

Insulation Added

Unknown.

Gutters

Unknown.

Cost

$9,125, or $3.10 per sq ft ($33.30/m^2).

Drawings and Photos

See Figures 50 to 52.

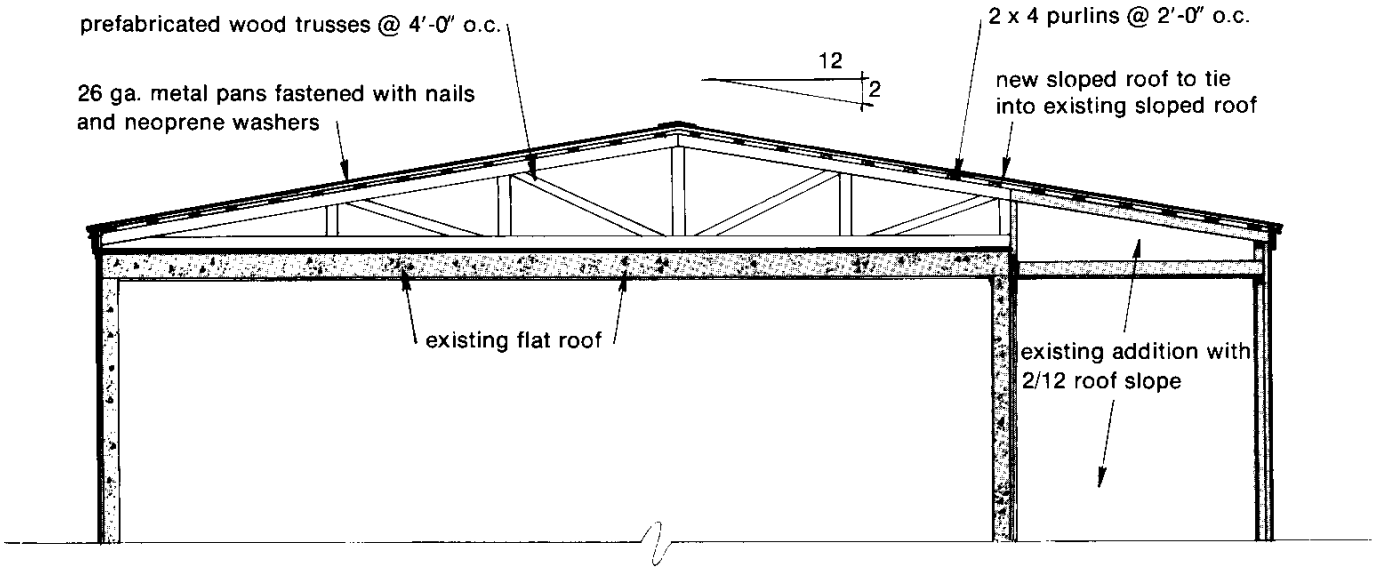


Figure 50. Section through building, Case Study No. 7.

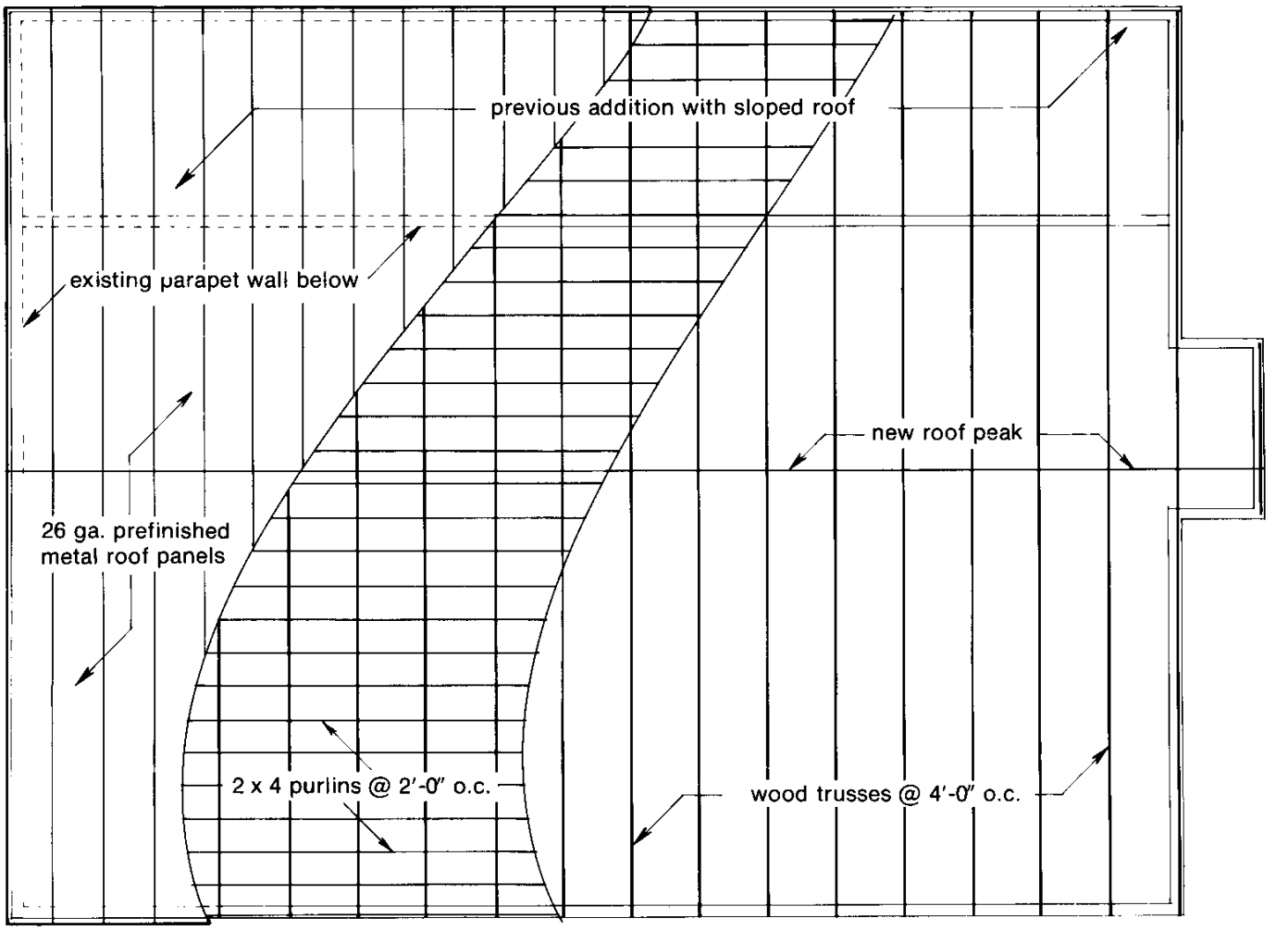
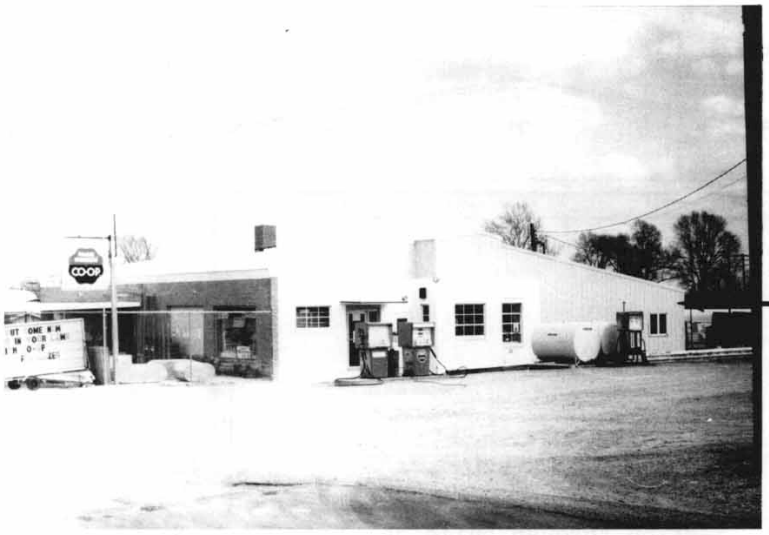


Figure 51. Roof plan, Case Study No. 7.



This is a previous addition with a sloped roof.

Figure 52. Completed view, Case Study No. 7.

Case Study No. 8

Existing Roof System

Built-up, gravel surface over 1-in. (2.54-cm) rigid insulation over steel deck supported by steel bar joists.

Building Size

31 ft x 132 ft = 4,092 sq ft (9.45 m x 40.25 m = 380 m^2).

Configuration

Rectangular.

Date

June 1982.

Reason for Roof Replacement

Leaking.

System Used

26-gauge, 3-ft (0.9-m) wide Tech-Rib (prefinished galvanized steel) panels were screwed to a supporting steel frame consisting of 7-in. (17.8-cm) steel "C"-channel rafters on 12-ft (3.65-m) centers with 7-in. steel "C"-channel purlins welded between at 5 ft-0 in. (1.52 m) centers.

Gutters

5-in. (12.7-cm) prefabricated gutters were added to the top and bottom. The top gutter was to divert water from a roof above.

Insulation Added

R-19 fiberglass batt insulation was added on top of existing roof.

Cost

$12,000, or $2.90 per sq ft ($31.21/m^2).

Drawings and Photos

See Figures 53 to 60.

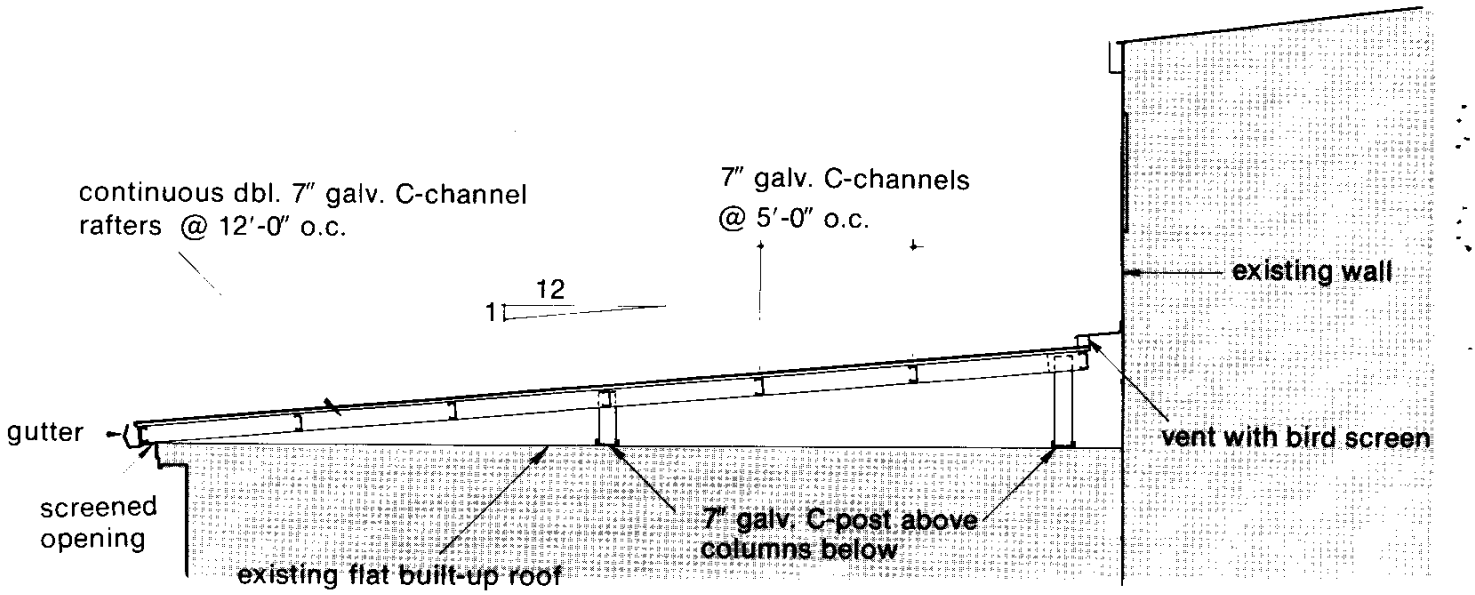


Figure 53. Section through roof, Case Study No. 8.

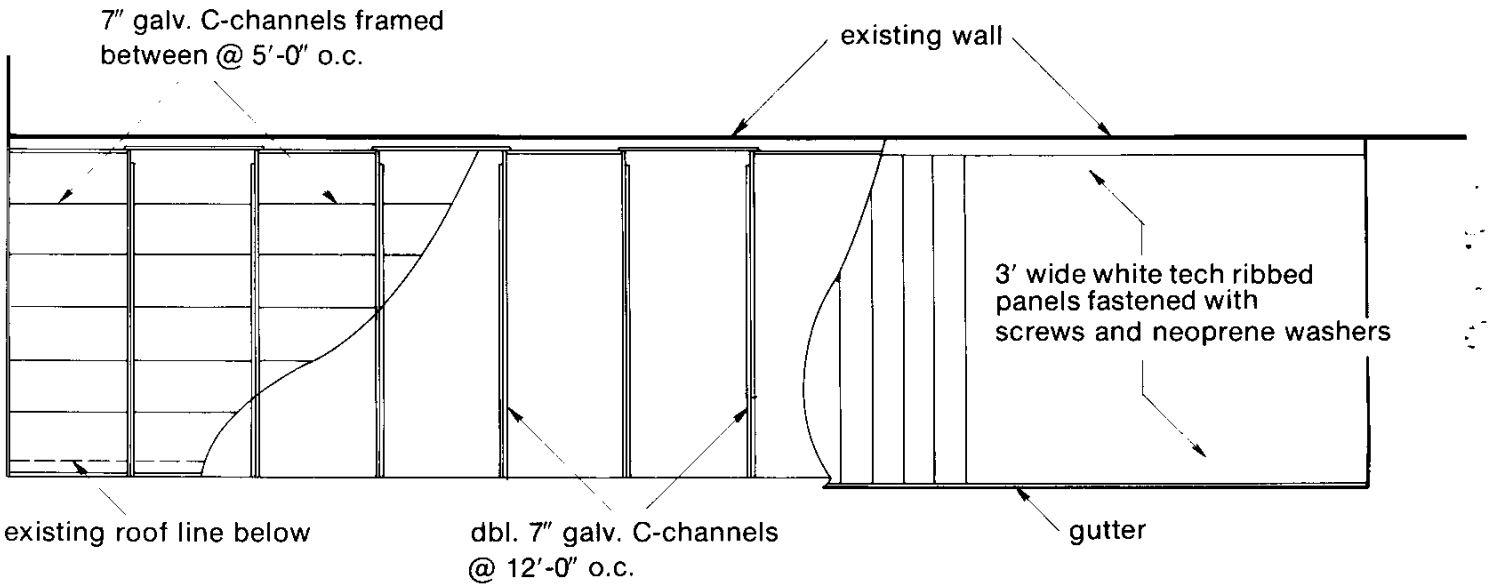
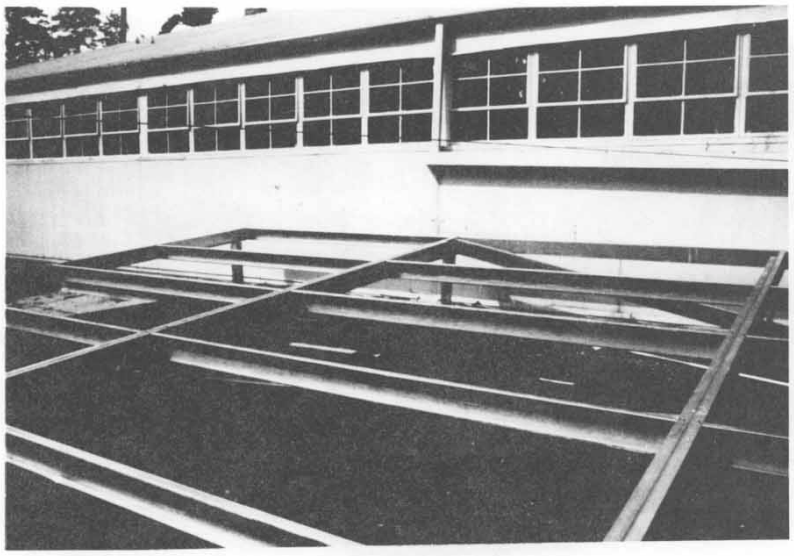


Figure 54. Roof plan, Case Study No. 8.



7-in. channels framed between rafter @ 5-ft-0-in. o.c.

Double 7-in. channel rafters @ 12-ft-0-in. o.c.

Figure 55. View of framing, Case Study No. 8.

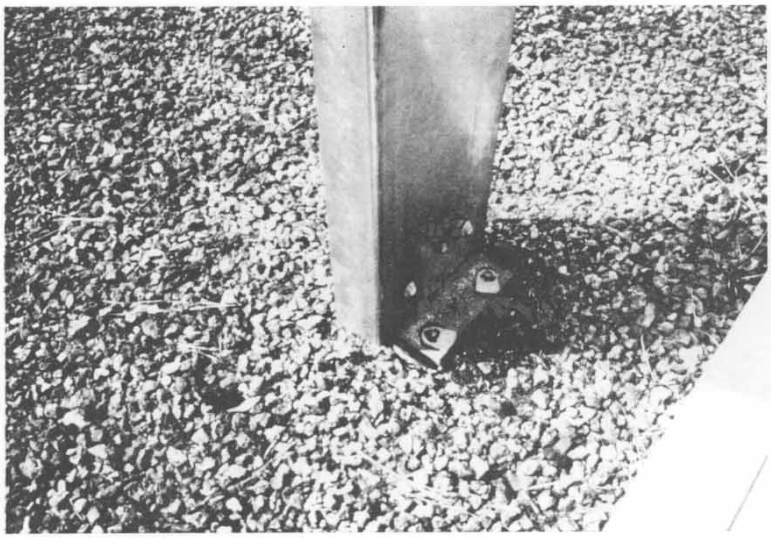


Figure 56. Detail of column connection to the existing roof, Case Study No. 8.

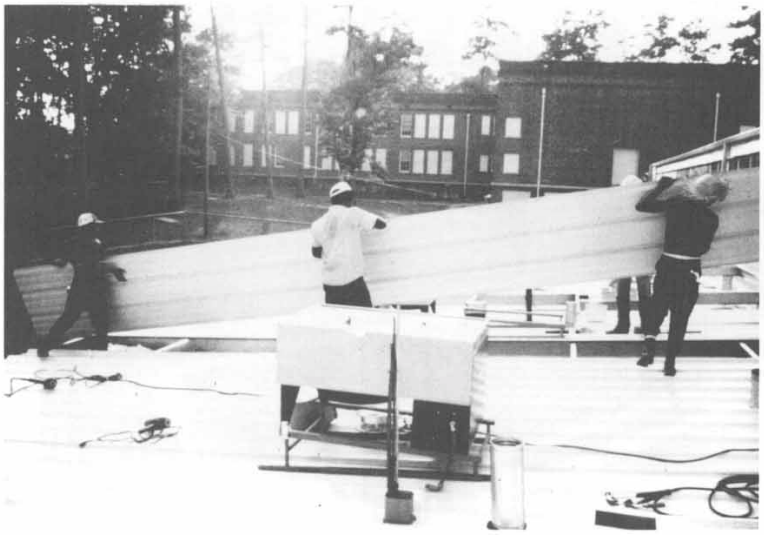


Figure 57. View during application of 3-ft wide by 31-ft long white Tech-Rib metal roofing, Case Study No. 8.

Figure 58. View of completed roof, Case Study No. 8.

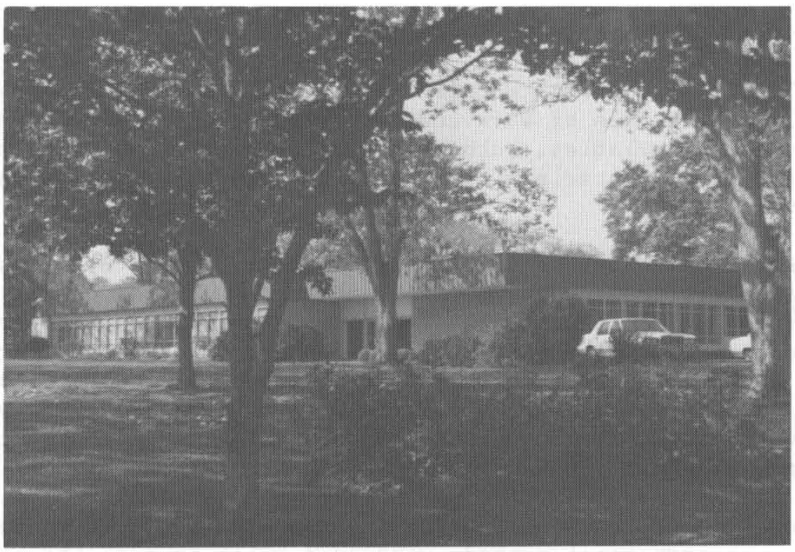


Figure 59. Completed view from the front, Case Study No. 8. Note the wide fascia covering the low sloped metal roof behind.

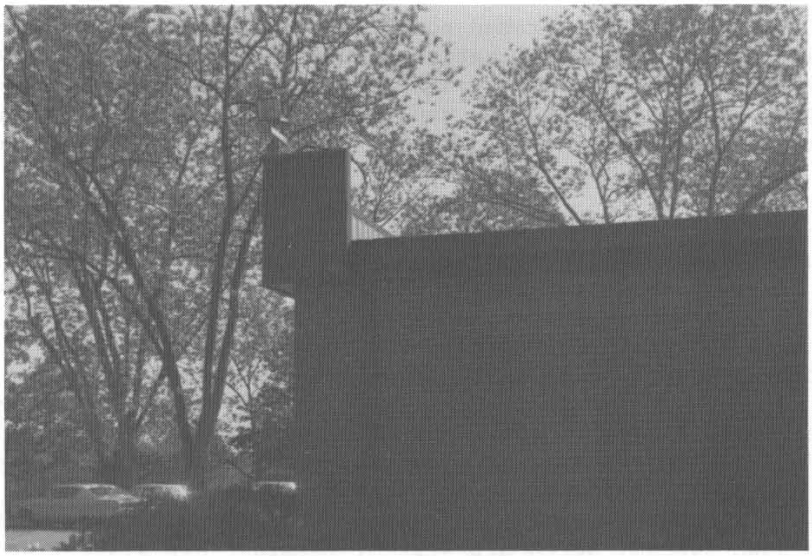


Figure 60. Edge detail at the rear of the building, Case Study No. 8, showing how fascia covers sloped roof and how roof drains to the rear.

4 COST ANALYSES

Construction Costs

The final cost of any construction work, including roof conversions, depends greatly on the type of work and each area's unique situation. The costs depend on many variables, such as the labor situation, price of materials, the distance materials have to be transported, and the nature and size of the work.

When wood was used for the structural material, for either trusses or conventional framing, the job was normally under the control of a general contractor or carpenter. In almost all cases the labor was nonunion and often by fairly small companies. Many of the larger jobs required prevailing wages be paid, but the construction companies were still nonunion. Sometimes the shingling was subcontracted to roof contractors; at other times it was done by the general contractor. In most cases, asphalt shingles were used instead of other coverings, presumably because of lower cost.

Conventional job-built wood framing superstructure proved to be very economical. The most economical methods used knee walls so that the size of the rafters could be reduced to 2 x 4's (5- x 10-cm) or 2 x 6's (5- x 15-cm). One case (see Case Study No. 1) was completed for \$2.26/sq ft (\$24.30/m^2). Others ranged upward to \$5.25/sq ft (\$56/m^2). The price most often encountered for this approach averaged about \$3.00/sq ft (\$32.30/m^2). Ending the top of the new sloped roof at the top of the existing fascia probably helped keep costs down. This eliminated any soffit and fascia work. Also, the final product looked less like a conversion and more as if it had originally been designed that way.

In general, conventionally framed conversions are less expensive than using trusses, but the local labor situation should be taken into account. The trusses themselves cost more than the material required to frame a roof conventionally; however, since trusses can be erected more quickly, the construction labor costs are lower. Consequently, in areas where labor costs are very high (and providing it is a simple roof) trusses might prove more economical.

A wood truss system costs less if identical trusses can be used. A greater number of truss types causes the price per truss to go up. When a building deviates from simple shapes such as a rectangle, the cost of the truss system begins to rise. When a reroofing job becomes a series of complex shapes, conventional wood framing probably will be less costly.

The most economical type of roof generally is a hip roof. The only areas to be finished (excluding the roofing material) are the soffit and fascia, and even these may not need replacement. A hip roof can be conventionally framed, or a wood truss system can be used. Four wood truss systems can generate a hip roof: step-down system, Dutch hip system, terminal hip system, and a combination of common trusses with conventional framing.

A step-down hip system (Figure 61) seems to be the most frequently used. It employs three types of trusses: a common truss, a step-down truss,

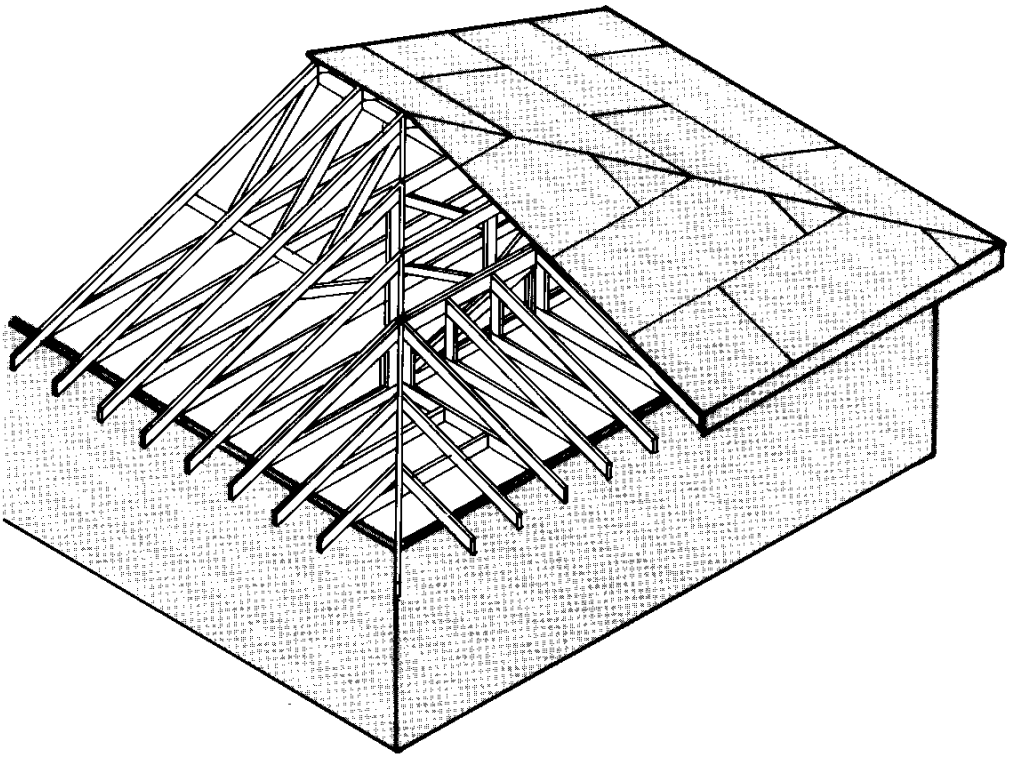


Figure 61. Step-down hip system.

and a mono truss (sometimes called a half or sawtooth truss). The common trusses are used to frame the main body of the roof. The step-down truss is the same span as the common truss but is truncated at the top to gradually decrease in height to form a sloping hip. A series of step-down trusses is used between the common trusses and the step-down girder. The step-down girder (two or more step-down trusses combined) carried the mono trusses which finish out the bottom of the roof (see Case Study No. 2). The cost of the step-down truss system in roof conversions generally averages between $3.00 to $4.00/sq ft ($32.30 to $43/m^2) with simple rectangular shapes.

The Dutch hip system (Figure 62) combines a hip end and a gable end. The gable can be for a louver or for appearances. This system uses common and mono trusses. The small hipped area is normally conventionally framed with a hip rafter and jack rafters. The cost of a Dutch hip system generally is slightly more than the step-down system because of the louver and/or gable finishes.

The terminal hip system (Figure 63) can be used for small span application only--32-ft (9.75 m) maximum. This system combines common trusses (for the main body) and long bottom chord mono trusses for the same application as jack rafters in conventionally framed hips. The hip rafter is a conventionally framed rafter and not a truss. The bottom chord of the mono truss is longer on one side of the hip rafter than the other, and the top chords are beveled to tie into the hip rafter. No examples were found using this system for a roof conversion, so costs are unknown.

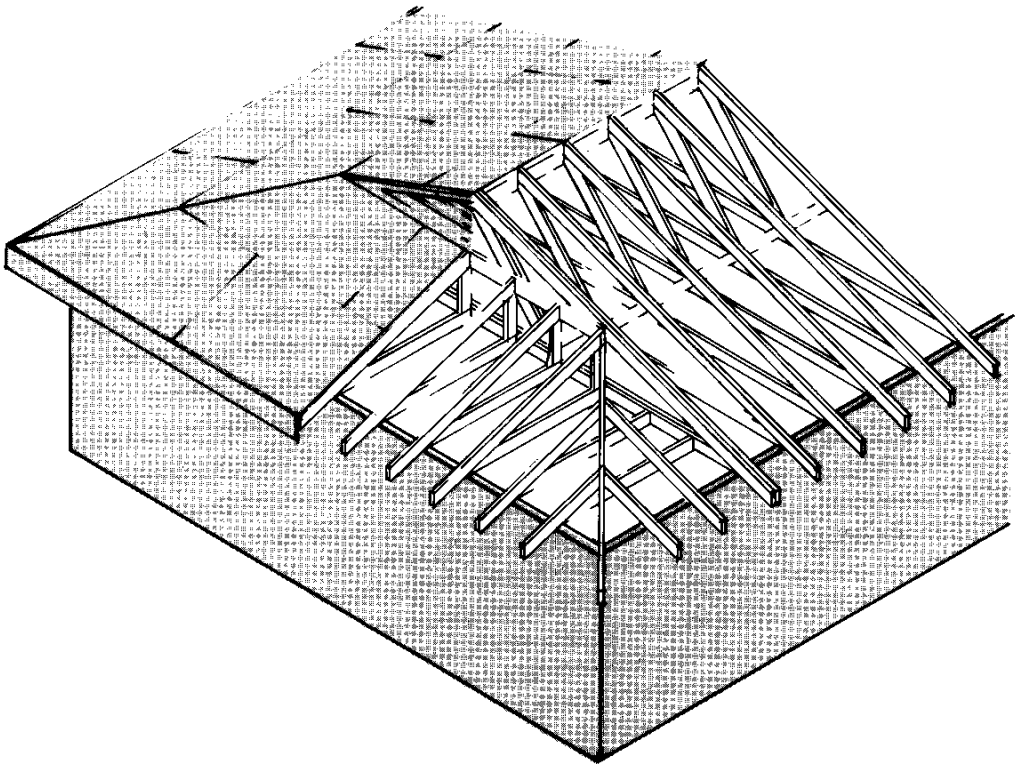


Figure 62. Dutch hip system.

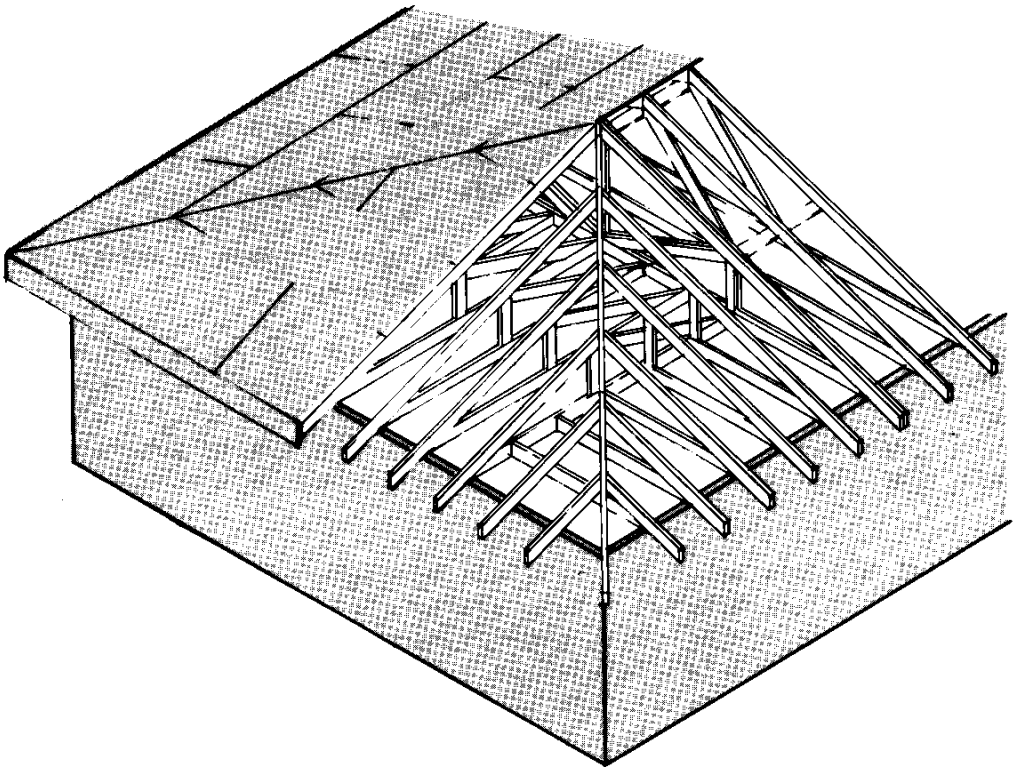


Figure 63. Terminal hip system.

The combination of common trusses and conventional framing (Figure 64) in some respects offers the best of both systems. Since common trusses are used to frame the main body of the roof, economy is maintained through the repetition. At the point where the hip begins, the trusses stop and the conventional framing begins. The hip rafter and the jack rafters are conventionally framed. This system is particularly economical for long roofs in which many identical trusses can be used. When the number of trusses is reduced, some of the economy is lost. Average cost of this system is $3.00/sq ft ($32.30/m^2).

Builders using metal as the framing material devised their own subpurlin structures to create a slope. Various light-gauge sections can be used, including hat sections, tubes, furring tubes, angles, "C's," and "C's" with flange tracks. Standing seam or some other type of lightweight metal roofing can then be attached to the frame. Various low-sloped framing systems were encountered. One of the systems used the members much the same as wood framing (see Case Study No. 8) using rafters and purlins. Another system ran a series of continuous purlins perpendicular to the metal roofing without any rafters. These job-built metal framing systems proved very cost-effective, generally averaging about $3.00/sq ft ($32.30/m^2). Average costs and comparison costs between wood and steel conversion systems can be found in Table 1.

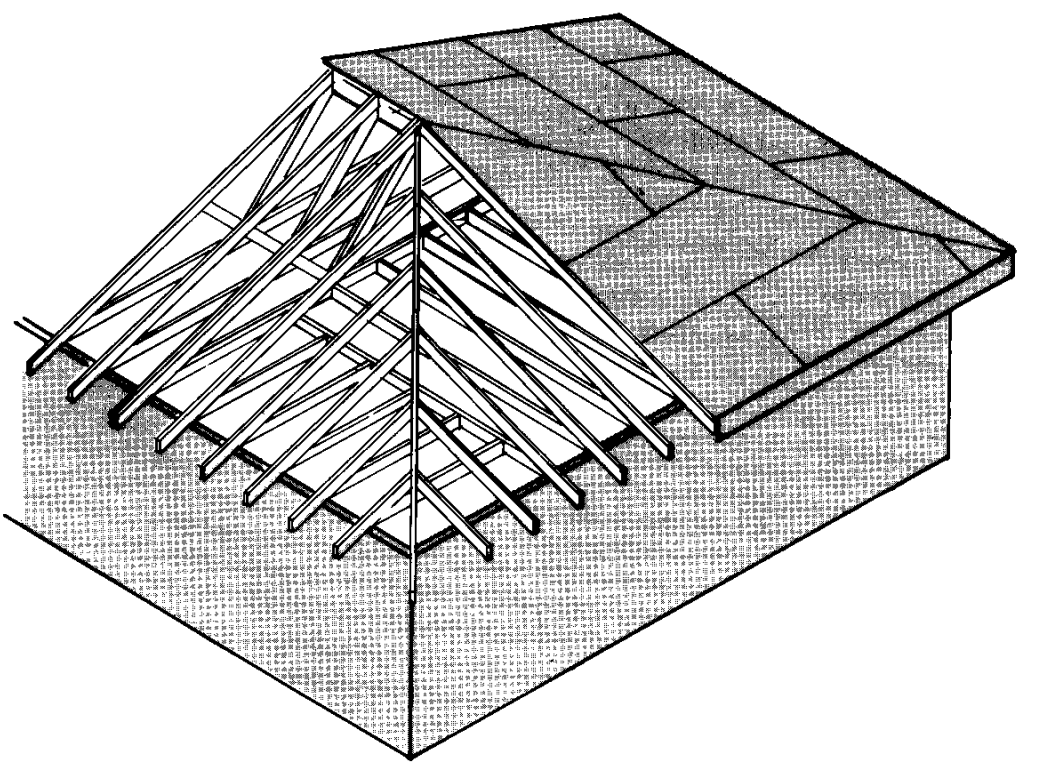


Figure 64. Common trussed/conventional framing hip system.

Table 1

Construction Costs for Roof Conversions

DESCRIPTION OF SYSTEMS	Range of Costs/Sq Ft (Costs/m^2)	Average Cost/Sq Ft (Cost/m^2)
Wood Framing Systems		
Conventional job-built wood framing with dimension lumber, covered with plywood sheathing and asphalt shingles	\$2.20-\$4.00 (\$23.70-\$43.05)	\$3.00 (\$32.30)
Wood Truss Systems		
Hip roof systems covered with plywood sheathing and asphalt shingles. Trusses are spaced on 2 ft-0 in. centers		
step-down hip system	\$3.00-\$4.00 (\$32.30-\$43.05)	\$3.50 (\$37.67)
Dutch hip system	\$3.25-\$4.25 (\$34.98-\$45.75)	\$3.00 (\$32.30)
terminal hip system	costs unknown	
combination of common trusses with conventional framing	\$3.00-\$4.00 (\$32.30-\$43.05)	\$3.00 (\$32.30)
Gable roof system covered wth plywood sheathing and asphalt shingles. Trusses spaced at 2 ft-0 in. o.c. Gable ends finished with siding.	\$3.50-\$5.00 (\$37.67-\$53.82)	\$4.25 (\$45.75)
Wood trusses spaced at 4 ft-0 in. o.c. with 2 x 4 purlins and covered with light-gauge prefinished metal roofing	\$2.00-\$4.00 (\$21.53-\$43.05)	\$3.00 (\$32.30)
Metal Framing Systems		
Job-built framing system using light-gauge (16 gauge or lighter) standard sections bolted or welded together. Framing covered with lightweight metal or standing seam roofing.	\$2.00-\$3.50 (\$21.53-\$37.67)	\$3.00 (\$32.30)
Steel trusses with members consisting of standard rolled sections (angles). Truss spacing at 20 ft-0 in. centers with standard rolled section (channel) purlins supporting roofing material consisting of light-gauge metal (prefinished galvanized or standing seam roofing).	\$5.00 (\$53.82)	

Only one case was found employing steel trusses to create a substructure. The roof was 42,000 sq ft (3,902 m^2). The prefabricated steel trusses were located on 20-ft (6.1-m) centers with "C"-channel purlins framed between at 5-ft (1.5-m) centers. Standing seam metal roofing with battens covered the 1/4 to 12 slope. The system cost $5.80/sq ft ($62.40/m^2). The contractor was unhappy with the system. He cited the inability to speed up the truss erection process as the major drawback. Insulation and roofing were removed under the trusses, leaving the existing structure vulnerable to water intrusion. The long erection time led to serious rain damage to the building and to a lawsuit.

Life-Cycle Cost Analysis

Case Study No. 1 was chosen as the model in this analysis primarily because the owner took competitive bids on several different systems, so accurate cost information is available for comparison. Cost will vary from area to area; however, it is assumed that local variations in labor and material costs will apply equally to roof conversions and conventional builtup roofing so that the comparison made in this example will remain valid.

The building in Case Study No. 1 is 33 ft x 108 ft = 3,564 sq ft (10 m x 33 m = 330 m^2). Before conversion the existing roofing system was a built-up system with gravel over 1 in. (25 mm) of rigid insulation. The roof structure is precast concrete deck supported by masonry bearing walls. There are no parapet walls. The edge detail consists of a sheet metal gravel stop. The roof had leaked for some time, so presumably the insulation was wet and needed replacment. With built-up roof replacement, the roofing and insulation would have to be torn off down to the structural deck before reroofing.

The building is about 15 years old. The Corps of Engineers projects a life expectancy of a building (for life cycle cost purposes) of 25 years; for this case, it is assumed the 25-year period begins with the application of the new roof. The possible roofing systems available for this building are: roof conversion-asphalt shingles, conventional built-up roofing, or a single ply system. Asphalt shingles can normally be expected to last for 15 years of trouble-free service. Built-up roofing with a gravel surfacing has a life expectancy of 15 years according to a recent ASTM-STP study.[1] Single ply roofing systems are relatively new and quantitative data are not yet readily available. A 15-year life expectancy is assumed.

The owners took competitive bids for different single-ply roofing systems and a roof conversion. Carlisle's single-ply roofing system, a 45-mil (1.14 mm) ballasted synthetic rubber membrane, was estimated at $2.36/sq ft ($25.40/m^2). The owners had so much trouble with the existing built-up roofing system they would not consider using a built-up system again.

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[1] Durability of Building Materials and Components, Special Technical Publication 691, First International Conference on Building Materials and Components, Ottawa, 1978 (American Society for Testing and Materials, 1980), p 652.

The owners selected the roof conversion system because it solved their problems and had the lowest initial cost. However, maintenance costs for the remaining 25 years of building life must be considered. Presuming that asphalt shingles last 15 years, they will need to be replaced only once after the conversion; similarly, so would the other systems.

Today's cost of asphalt shingle replacement = $0.60/sq ft.

Today's cost of single-ply replacement = $2.36/sq ft.

For comparison of Case Study No. 1 at today's cost, see Table 2.

To set up a fair life cycle cost model, built-up roofing should also be considered (see Table 3). According to the 1983 Means Cost Data[2] using the correct area multiplier, 3-ply built-up roofing with 2 in. of insulation cost $1.98/sq ft plus an estimated $0.75/sq ft for removal of existing roofing which totals $2.73/sq ft.

Today's cost of built-up replacement = $2.73/sq ft.

Normally when determining the life-cycle cost, a discount rate is employed. Often it is set by the prime lending rate. The discount rate set by the Army for military construction projects is equal to 10 percent. Money spent at some future date is worth less than money spent today. Therefore, the Net Present Worth (NPW) needs to be calculated. The NPW discounts future expenditures to today's terms by numerically prorating the future spending by the amount of 10 percent.

Table 2

Roof Replacement Cost For the Remaining 25 Years of Life
For the Building in Case Study No. 1

Roof Conversion	First Replacement in 15 Years (Excluding Inflation)	Total
$8,070.84	$2,140	$10,210
Single Ply Roofing		
$8,410	$8,410	$16,820
Built-up Roofing		
$9,730	$9,730	$19,460

[2] Building Construction Cost Data 1983, 41st Annual Edition (Robert Snow Means Co., Inc., 1983), p 139.

Table 3

Net Present Worth (NPW) of Roofing Systems for Case Study No. 1 (For a 25-Year Life)

	Initial Roof Replacement	NPW of First Replacement in 15 Years	Total NPW of Replacement
Roof Conversion	$8,070	$ 510	$ 8,580
Single-Ply	$8,410	$2,010	$10,420
Built-Up	$9,730	$2,330	$12,060

The formula is:

$$P = F \times \frac{1}{(1 + I)^N}$$

where P = the present value of the money spent in the future

F = the known (or approximated) future expenditure

I = 10.0 percent (standard discount rate used by the Army)

N = number of periods in years

$$NPW = INITIAL\ EXPENDITURE + P_1$$

where P_1 = present value of first roof replacement

Roof Conversion

$$P_1 = \$2,140 \times \frac{1}{(1 + 0.10)^{15}}$$

$$P_1 = \$510$$

$$NPW = INITIAL\ COST + P_1$$

$$NPW = \$8,070 + \$510$$

$$NPW = \$8,580$$

Single-Ply System

$$P_1 = \$8,410 \times \frac{1}{(1 + 0.10)^{15}}$$

$$P_1 = \$2,010$$

$$NPW = INITIAL\ COST + P_1$$

$$NPW = \$8,410 + \$2,010$$

$$NPW = \$10,420$$

Built-Up System

$$P_1 = \$9,730 \times \frac{1}{(1 + 0.10)^{15}}$$

$$P_1 = \$2,330$$

$$NPW = INITIAL\ COST + P_1$$

$$NPW = \$9,730 + \$2,330$$

$$NPW = \$12,060$$

Roofs require maintenance and repair which represents an expense over the life of the building; consequently, these costs should be incorporated into the life cycle cost analysis. The maintenance and repair cost for a conventional BUR roof is generally assessed at $0.02/sq ft annually. Single ply systems have not been around long enough to have quantitative data, so it will be assumed to be approximately the same value as BUR ($0.02/sq ft annually). Asphalt shingles have exceedingly low maintenance and repair cost, but a certain amount of inspection is necessary; this expense is estimated at 25 percent of the cost of BUR; therefore, $0.005/sq ft annually. The roof's size for Case Study No. 1 is 3,564 sq ft. Therefore, the annual costs of maintenance and repair are:

BUR	$0.020 [3,564 sq ft] = cost of M & R/year = $71.28
Single Ply	$0.020 [3,564 sq ft] = cost of M & R/year = $71.28
Conversion (asphalt shingles)	$0.005 [3,564 sq ft] = cost of M & R/year = $17.82

Because maintenance and repair costs are in the future, the expenditures must be discounted to today's value. It is assumed these occur at mid year for each of the 25 years.

$$\text{Discount Factor} = 1.0492 \sum_{k=1}^{k=25} \frac{1}{(1.1)^k}$$

$$= 1.0491 \times 9.077 = 9.524$$

where 1.0492 adjusts end of year factors to mid year. The discount rate is set at 10 percent (0.10). The results are:

BUR	$680
Single Ply	$680
Asphalt Shingles	$170

Table 4 is a life-cycle comparison of all factors.

Table 4

Life-Cycle Cost Compared

	Initial Cost	NPW of Replacement Cost in 15 yrs	NPW of M&R Cost for 25 yr life	Total NPW of Roofing System
Roof Conversion	8,070	510	170	8,750
Single Ply	8,410	2,010	680	11,100
Built-up	9,730	2,330	680	12,740

5 EFFECT OF REGIONAL AND CLIMATIC CONDITIONS

Regional Effects

One of the objectives of this research was to determine if regional or climatic conditions affect the frequency of these roof conversions. For example, are conversions done more in colder areas because they allow insulation to be added? The answer is inconclusive. Insulation was added in some projects in the northern, intermediate, and southern climates. Its use appeared to depend on the type of building rather than geographic location. For example, private residences normally added insulation, while rental properties did not. Public projects such as schools said they planned to add insulation at some future date, but because of budgetary constraints, the reroofing was all they were going to do that fiscal year. In all cases, roof leaks were cited as the reason for reroofing. Roof conversions appear to be used in most areas of the country; evidently flat roofs are a problem everywhere.

Conversions in Various Climates

In addition to the eight case studies described in Chapter 4, many other reroofing projects were investigated. Table 5 is a comprehensive list of the projects; the following text summarizes some of the findings.

In most cases the reroofing conversions were executed by general contractors who did all kinds of construction, not simply roof conversions. Several builders were found who did this type of work as their only business. Several others said roof conversions represented over 50 percent of their work.

One metal building contractor in southern Georgia has completed about 30 roof conversions over the past 5 or 6 years. They were all job-built framing systems using galvanized lightweight metal "C"-channels as rafters and purlins. Most of the roofs were covered with 26-gauge prefinished metal, screwed into the "C"-channels with neoprene washers. Over a dozen schools in this area, as well as commercial and residential buildings, have been converted. The firm, Metal Building Inc., does all its own design, engineering, fabrication, and construction. The costs range between \$2.00 and \$3.50/sq ft (\$21.53 to \$37.68/m^2) for completed roof conversions.

Another building contractor, based in Salt Lake City, UT, does only roof conversions. Most of this work is residential and is subcontracted through a very large Salt Lake City roofing business. This contractor frames the superstructures conventionally with wood then applies either asphalt or wood shingles as the roofing material. The firm does five to eight conversions a month at costs between \$2.75 to \$3.50/sq ft (\$29.60 to \$37.68/m^2). Insulation is added to most roof conversions afterwards.

The architectural firm of Goettelman and Associates has coordinated several larger scale roof conversions in the Philadelphia area (Case Study No. 6). They have done about a dozen school buildings using wood trusses and asphalt shingles. Their technique includes trying to solve other, unrelated

Table 5

List of Contacts Involved in Roof Conversion Projects

California
- AEP-Span, San Diego

Florida
- Duval County School Board, Jacksonville
- Gang-Nail Systems, Inc., Miami
- Metal Sales, Inc., Jacksonville
- R. B. Gay Construction Co., Jacksonville

Georgia
- Metal Buildings, Inc., Thomasville
- South Georgia Natural Gas Co., Thomasville
- Thomasville High School, Thomasville

Illinois
- Okaw Building Co., Chesterville
- Scott Buildings, Greenup
- Richard Carr Construction Co., Dieterich
- Doyle/Brotherson Arch., Savoy
- Stanhke Construction, Champaign
- Isaksen and Matzdorff Arch., Urbana
- Royse and Brinkmeyer Real Estate, Inc., Champaign
- Rantoul Public Library, Rantoul
- Dieterich Post Office, Dieterich
- Martinsville Post Office, Martinsville
- Andrews Lumber Co., Greenup
- Kurasek Construction Co., Champaign
- Doyle Construction Co., Savoy

Indiana
- Dye Lumber Co., Monon
- Hendrix County Farm Building Coop., Danville
- Lumbermate Truss Co., Remington
- River City Builders, West Lafayette

New Jersey
- Avon Elementary School, Camden
- Camden County College, Blackwood
- Culbertson Elementary School, Haddonfield
- Goettelman Associates, Haddonfield
- Perma-Clad Products, Tinton Falls

Ohio
- Gene Scherzinger Builder, Miamitown
- Retroframe Co., Randolph
- Wood Truss Co., Miamitown

Pennsylvania
- Joseph Callaghan, P.E., Philadelphia

Utah
- Great Basin Roofing Co., Salt Lake City
- Mike Florlio Builder, Salt Lake City

problems along with the roof conversions. For example, Goettelman's solutions normally provide maintenance-free finishes, properly designed overhangs (to give summer shading and winter penetration of sunlight), and a means to keep children off the roofs. This is done by drastically increasing the roof slope near the edge to about 20 in 12 (see Case Study No. 6). Most of their design solutions attempt to make the conversions appear as though they had always been there. This is done in part by attention to details, such as bringing the soffits in flush with the top of the window heads.

Yet another American firm, The Retroframe Co. of Randolph, OH, has developed a roof conversion system that is being marketed in the United States. The system, called the Retroframe Roof Retrofit, Facade and Re-side Components System, was invented by a metal building contractor and is competitively priced. It consists of 16-gauge galvanized framing components covered with a 16-gauge standing seam roof. The framing consists of a series of sub purlins (knee walls) running perpendicular to the new roof slope on 5 ft (1.5 m) centers. The different height knee walls are then diagonally braced. The framing is constructed from hat sections, tubes, furring angles, "C's," "C's" with flange tracks, and eight different connectors to provide the flexibility to cope with most situations.

The Retroframe system is particularly good for industrial and large-scale applications. The use of 1/4 in 12 slopes allows coverage of large areas economically. The system adds less than 3 lb/sq ft (15 kg/m^2) of dead load, which is about a third of the weight of a comparable wood system. The owner/-inventor states the total installed costs range between \$2.75 to \$3.50/sq ft (\$29.60 to \$37.68/m^2). The range of installed price varies, depending on the area labor costs.

The job-built framing system is fastened together with no. 12 self-drilling screws. The knee walls are constructed from hat sections for the top and bottom plates, and tubes as the vertical support members. A heavy layer of roofing cement is applied under the bottom hat section to provide a gasketing effect when the bottom plate is fastened to the existing roof. This technique helps eliminate leaking during construction. The whole system is prepunched for faster erection time. Standing seam clips are pre-attached on 2-ft (61-cm) centers. A 4-in. (10-cm) diameter air opening is provided in the rake trim, covered with bird screening, to provide ventilation. Examples of construction using the Retroframe system are seen in Figure 65.

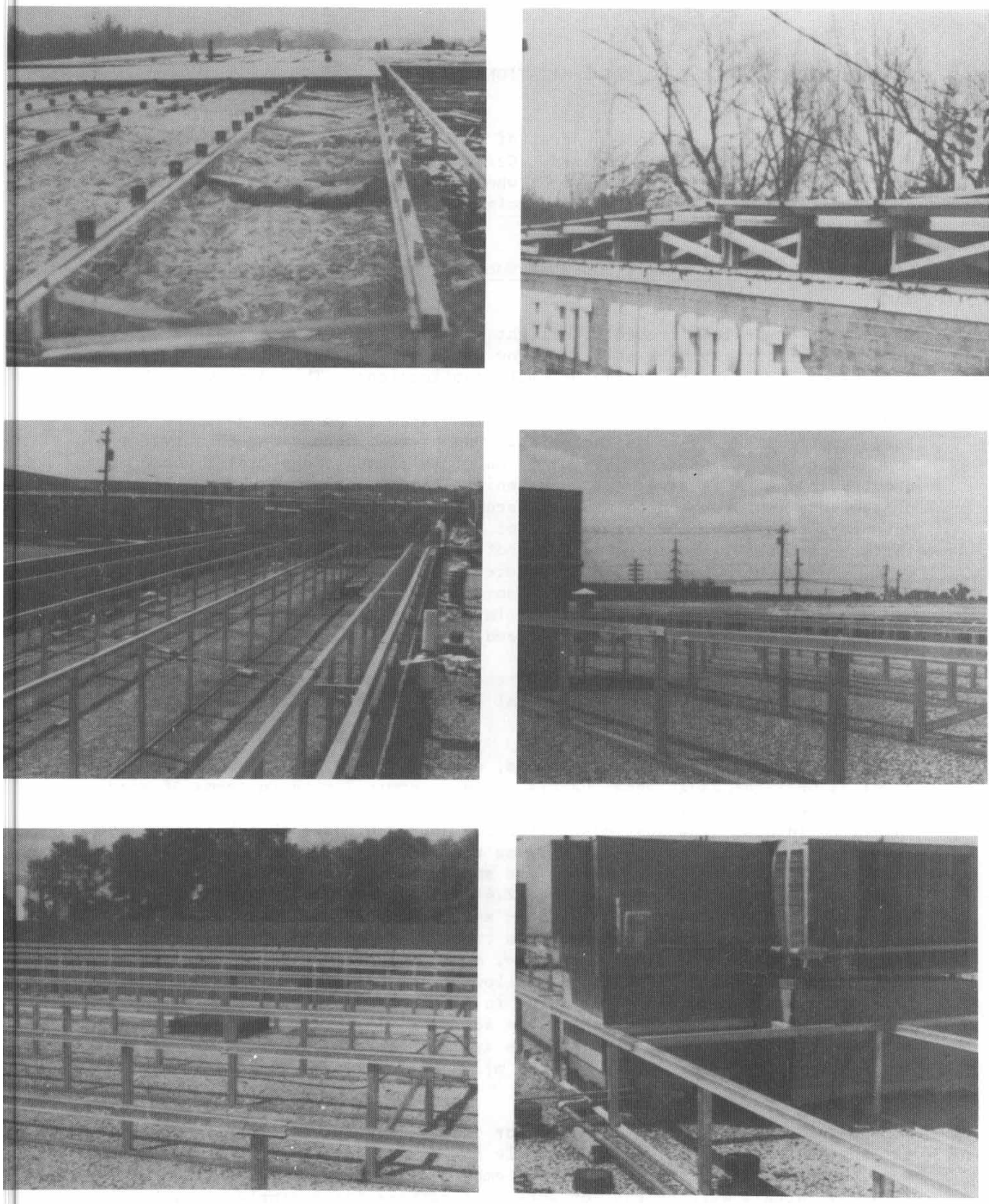

Figure 65. Examples of the Retroframe system.

6 ECONOMIC CRITERIA FOR SIZE LIMITATIONS

This chapter discusses the cost of roof conversion in relation to the size of the building being covered. Certain conversion systems shown in this report cost the same per square foot whether they are covering a large or small building while others vary in relation to the size of the building.

Cost Per Square Foot of Various Roof Conversion Systems Compared to Building Size

Roof conversions framed with light gauge rolled metal components covered with metal roofing panels at a very low slope (1/4 to 12) cost basically the same per square foot for large or small applications. This system can be framed either like conventional rafters or in a series of knee walls and can virtually go on forever, which is why this system is normally used for very large applications, such as factories. One of the reasons for this system's cost stability is its adaptability to multiple ridges and valleys; consequently, the work is always at a convenient height for the workmen. Because of the very low slopes attainable, there is a minimum amount of framing materials used below the roof. Most of the other systems' cost increase on larger buildings is because the new roof becomes too high above the existing roof; consequently, more labor is required, as well as more materials to support the new roof. Metal-framed conversions use basically the same system and amount of labor and materials for large or small buildings, which is the key to their economy for different sized jobs.

Roof conversion employing steel trusses as a superstructure have already been shown to be costly and impractical for any size building, so there is no point discussing them any further.

Job-built wood-framed conversions, covered with either plywood and shingles or light gauge metal panels, have economic limits in terms of size. These systems are very economical for small buildings but become expensive on larger buildings. The most cost-effective approach under this heading is to use small dimension lumber (2 x 4's) as the rafters in conjunction with 2- x 4-in. (0.5- x 1.0-cm) knee walls. The small sized rafters require closely spaced supports (approximately 8 ft [2.44 m] o.c. or less) due to the limited spans attainable with 2- x 4-in. (0.5- x 1.0-cm) rafters. Using small dimension lumber for the rafters has proven to be a very economical approach, but once a building reaches a certain size, multiple knee walls are required. Using asphalt shingles, the minimum allowable slope is 2 to 12 which means the roof rises fairly rapidly. This, in turn, means the second or third knee wall becomes taller; consequently, the additional material and labor required diminish the cost-effectiveness of the system. Case Study No. 1 exemplifies about the maximum size (33 ft [10.065 m]) a building can be economically framed using this system.

Using larger dimension lumber for the rafters is economically feasible as long as they are limited to a single span. Larger dimension lumber costs more per board foot than the smaller lumber. Therefore, 2- x 10-in. (5- x 25.4-cm) rafters will be cost-effective as rafters for a single span, but if additional knee walls are required, the material costs become prohibitive.

Wood trusses work well for roof conversions and can span great lengths. The cost-effectiveness of roof conversions with wood trusses is based on two factors: the type of truss (Howe, Fink, etc.), and the required span, which in turn dictates the size of the chord members. Different truss types are applicable to different spans and loading conditions. For example, a Fink or Howe configuration is normally used for relatively short spans, whereas a Double Howe or a Triple W configuration is normally used for longer spans. When a truss manufacturer gets an order, the most economical truss configuration is selected on the basis of specific span and loading conditions.

Once a particular truss configuration is selected, the cost is based on the required chord members size. For instance, if a Howe truss is selected, for 50 lb L.L., 15 lb D.L., 2- x 4-in. (5- x 10-cm) chord members will span up to 23 ft-10 in. (7.27 m) at a cost of $1.63/lin ft ($5.35/m); 2- x 6-in. (5- x 15.24-cm) chords will be required between 23 ft-11 in. to 35 ft-8 in. (7.30 to 10.88 m) at a cost of $2.05/lin ft ($6.70/m); from 35 ft-9 in. to 40 ft (10.9 to 12.20 m) 2 x 8's (5 x 20.32 cm) will be required at a cost of $2.48/lin ft ($8.14 m). Consequently, this means the larger the span for any given loading condition, the greater the cost per linear foot, which increases the cost per square foot for the roof conversion. Appendix A shows the five most common truss types used, different loading conditions and spacing, and their respective truss costs per linear foot and total cost per square foot for the entire roof conversion.

Since the other materials (plywood, shingles, etc.) remain basically the same for all roof conversions, the truss span becomes the critical factor when examining the relationship of a building's size to the cost per square foot. It is interesting to note that the opposite is true for conventional BUR roof replacement: the larger the building being reroofed, the less expensive it is per square foot. This is partially a result of additional expense of perimeter flashings, which are a smaller percentage of the cost per square foot on bigger buildings.

Figure 66 compares the relationship of the additional expense of larger sized buildings covered with trusses as well as the reduced cost of conventional 3-ply BUR. It should be noted the trusses which are depicted in the graph represent the bare essentials in terms of additional work, such as roof preparation or overhangs. These costs, beginning at $3.00/sq ft ($32.30/m^2), would apply when a minimum amount of roof preparation was required and there would be no overhangs (the new roof finishes flush with the existing). If fascia work and/or soffits were factored into the curve on this graph, the image would look basically the same except the curve would be shifted upward to $3.25 or $3.50/sq ft ($35 to $37.68/m^2) as the starting point.

The cost per square foot is based on the minimum width of the building. A building that is relatively narrow (even though it may be very long) will maintain the economy depicted on the graphs for the short span. The three graphs (Figures 67, 68, and 69) illustrate this point by showing the total cost per square foot for roof conversions using wood trusses for three loading conditions. These conditions represent the three basic loading conditions in the United States: southern, intermediate, and northern. The dead load is 15 lb/sq ft for all categories because there is not any ceiling load--only the trusses, plywood, and shingles. The live loads represent the various snow loads in the United States: 15 lb/sq ft, 30 lb/sq ft, and 50 lb/sq ft.

Again, these graphs represent the minimum costs, which in turn means the minimum work in existing building preparation and edge detail. If additional work is required in these categories, the cost per square foot shown on the graphs would shift upward relative to the amount of additional work required.

Other Factors Affecting Cost

In addition to the size relationship, other factors can drastically alter the cost per sq ft for any given roof conversion. First is the amount of mechanical equipment located on the existing roof. Obviously, the more equipment on an existing roof, the more it will cost to do a roof conversion. Any penetration through the existing roof will probably have to be dealt with; for instance, plumbing vents will have to be extended and re-flashed through the new roof. Most types of equipment cannot simply be covered up with a conversion; similarly, some conversion systems, such as trusses, make it difficult to cover up equipment. Therefore, existing mechanical equipment probably will have to be removed and resecured on the new roof, which requires moorings, flashings, and extension of mechanical components (electrical, piping, etc.).

Another factor affecting cost is the treatment of the edge detail. This depends in part on the existing situation as well as the desired final appearance. The least expensive approach is to terminate the new roof at the top of the existing fascia, if possible. Of course, any additional work to create overhangs, gables, soffits, venting, or fascia will increase the overall conversion cost.

The final aspect which can directly affect the conversion cost (excluding the structural system and the roofing material) is the preparation and means of attachment to the existing roof. For instance, in Case Studies No. 5 and 6a, additional structure was required to receive the superstructure. The different techniques of perimeter attachment can affect the cost, which depends in part on the existing building. For example, it is less expensive to merely nail a 2- x 4-in. (5- x 10-cm) plate on top of the existing roofing and insulation than it would be to cut away the roofing and insulation, nail some type of plate through a concrete deck, and then waterproof the entire assembly.

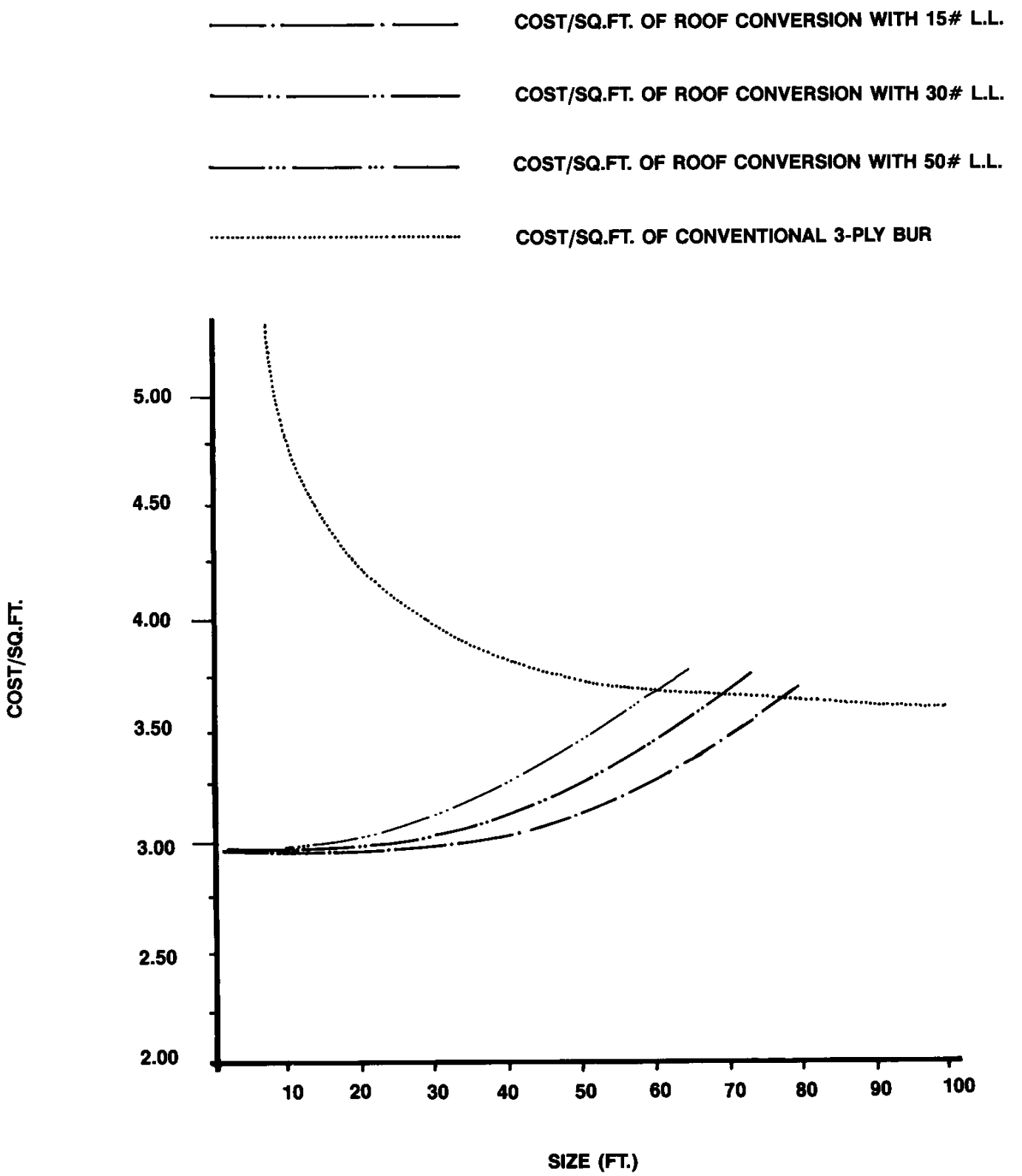

Figure 66. Comparison of cost per square foot vs. the size of the roof replacement.

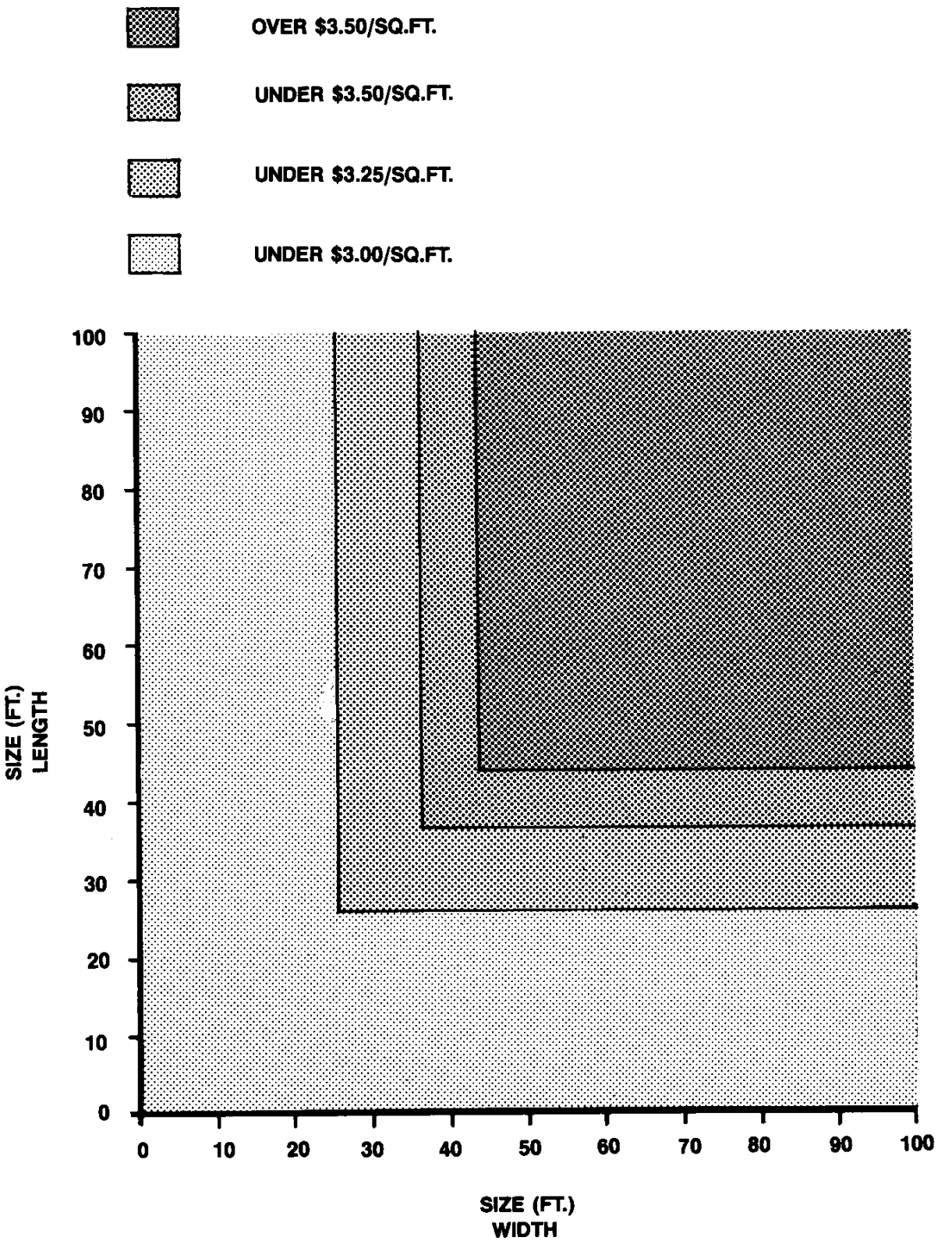

Figure 67. Cost per square foot vs. the size of a building for southern loading conditions (15 lb L.L., 15 lb D.L.).

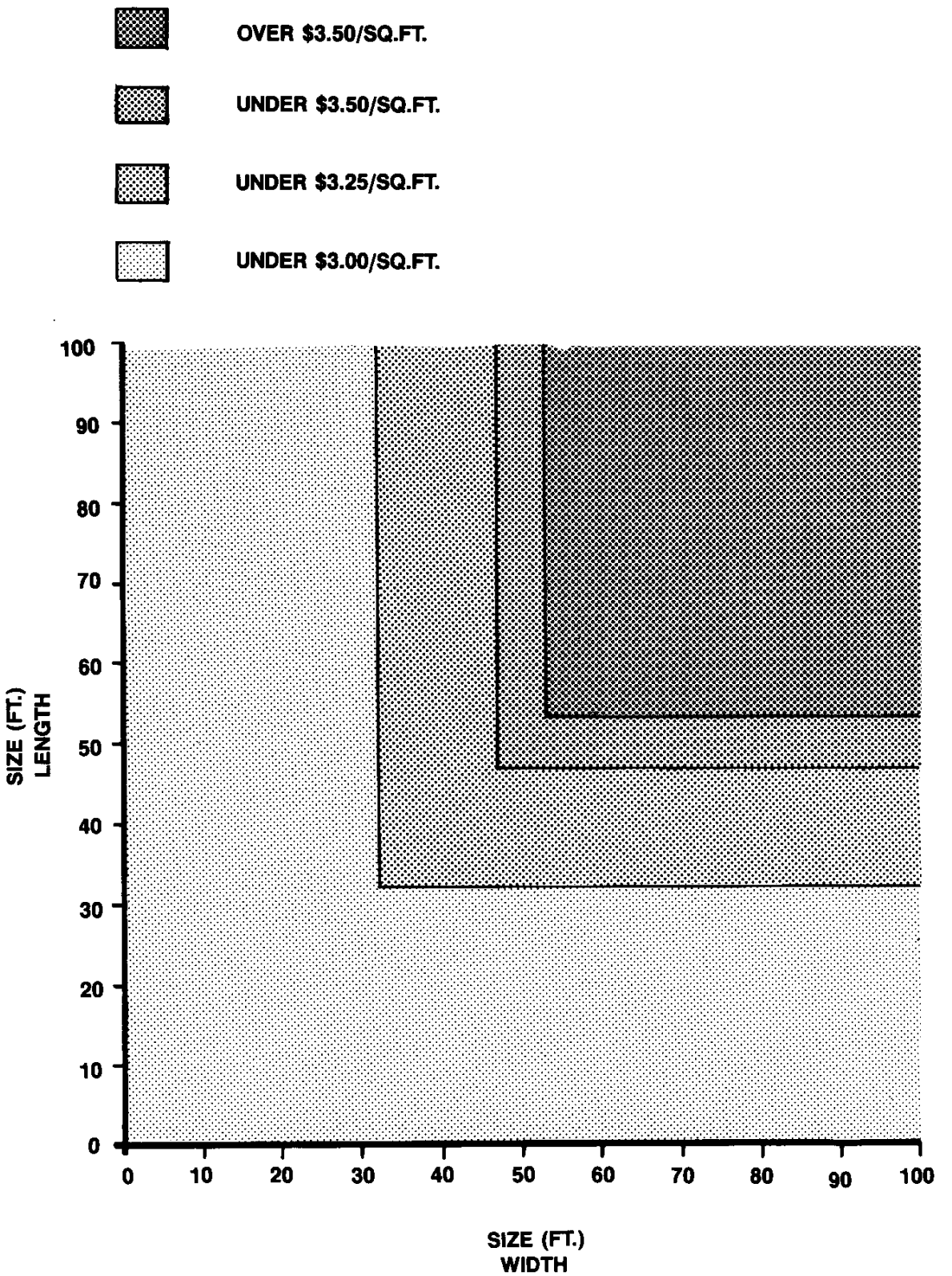

Figure 68. Cost per square foot vs. the size of a building for intermediate loading conditions (30 lb L.L., 15 lb D.L.).

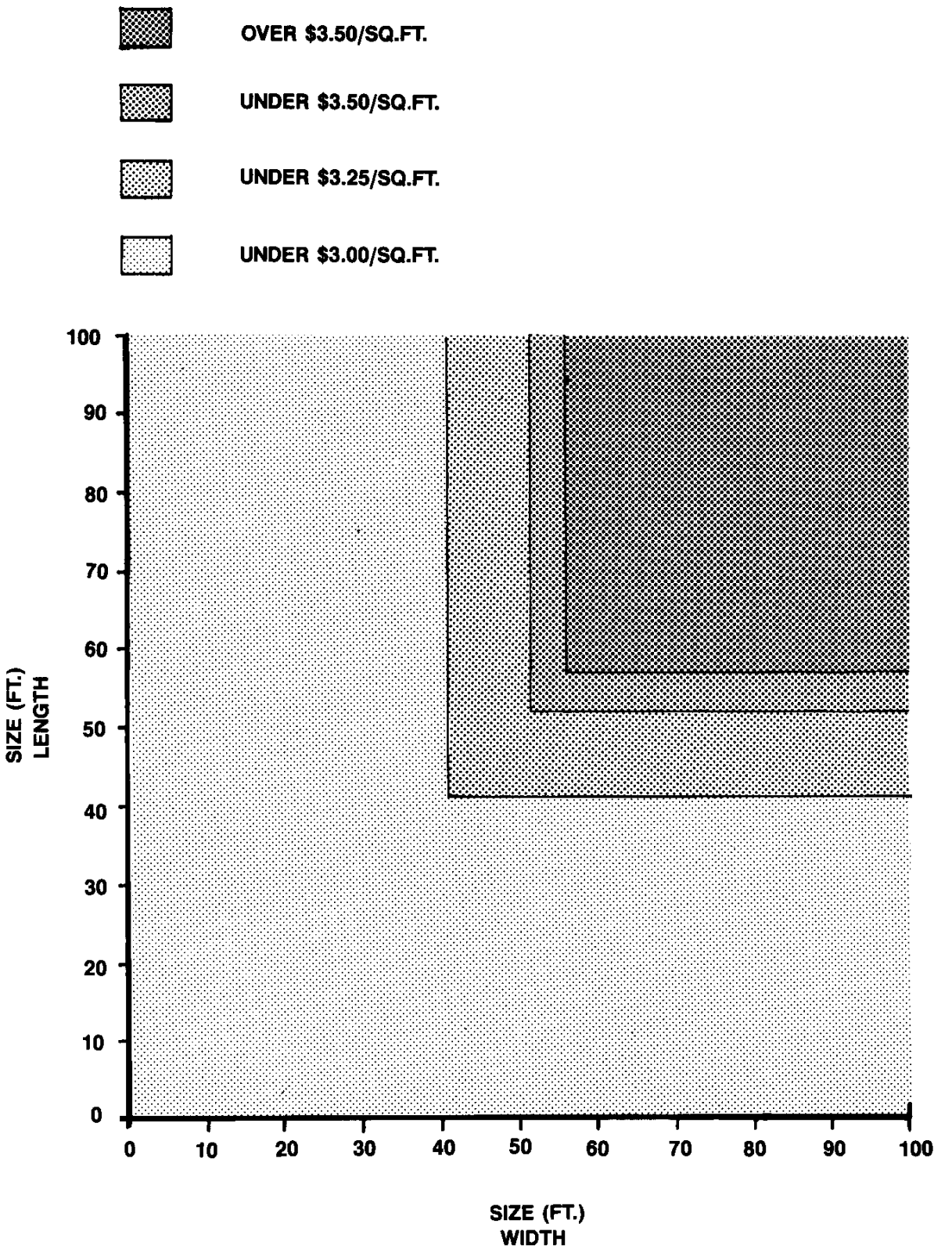

Figure 69. Cost per square foot vs. the size of a building for northern loading conditions (15 lb L.L., 15 lb D.L.).

7 CONCLUSIONS

Life-cycle cost analysis shows roof conversions can be cost-effective, particularly for small, relatively simple buildings, since labor for the smaller jobs is predominantly nonunion. Larger jobs are often done with union workers or prevailing wages are paid. Conventional methods of reroofing cost less per unit area, but only on larger applications. Most of the methods used for roof conversions become more complicated and costly when covering large areas.

The projected life of a sloped roof is longer, and its replacement cost is much lower than reroofing the building with conventional built-up systems. The total replacement costs today are between \$0.50 to \$0.60/sq ft (\$5.40 to \$6.45/m^2) for asphalt shingles.

In general, the conventionally framed roof conversions proved less expensive than the truss system. Conventionally framed roof conversions using wood as the structural material easily adapt to offsets in the building shape. This system is more economical if smaller dimension lumber can be used for the rafters, using knee walls to create shorter spans. Costs are between \$2.00 to \$4.00/sq ft (\$21.50 to \$43.00/m^2) with an average cost of \$3.00/sq ft (\$32.30/m^2). Conventionally framed roof conversions using lightweight metal structural members work well for larger applications because the roof slope does not become prohibitively steep. The completed costs range between \$2.00 to \$3.50/sq ft (\$21.50 to \$37.70/m^2) with an average cost of \$3.00/sq ft (\$32.30/m^2).

Wood trusses can span up to 60 ft (18.3 m) economically and offer fast erection time. This system works well covering very simple shapes such as a rectangle but loses its cost-effectiveness on complicated building shapes. The in-place cost of this approach ranges from \$3.00 to \$5.50/sq ft (\$32.30 to \$59.20/m^2) with an average of \$4.25/sq ft (\$45.75/m^2).

Steel trusses by comparison are not very cost-effective for roof conversions. One case was investigated which cost \$5.80/sq ft (\$62.43/m^2). The contractor felt that the time required to fabricate and erect the trusses was excessive.

Roof conversion is very competitively priced with respect to other forms of reroofing. This form of reroofing also allows insulation to be added, thus reducing energy consumption.

This research also showed that roof conversions are being done in most areas of the United States, regardless of geographic area or climatic regions. In every case encountered, the primary reason cited for reroofing was not to add insulation or improve the building's appearance, but to stop persistent leaking.

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APPENDIX:

COSTS FOR FIVE COMMON TRUSS TYPES

FINK TRUSSES

At 2'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chord), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	36 ft	$1.42	$2.86
2 x 6	40 ft	$1.82	$3.10
2 x 8	40 ft	$2.21	$3.33

At 4'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	24 ft-10 in.	$1.46	$3.25
2 x 6	37 ft	$1.87	$3.40
2 x 8	40 ft	$2.28	$3.54

At 8'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	16 ft-6 in.	$1.54	$3.36
2 x 6	24 ft-8 in.	$1.97	$3.43
2 x 8	31 ft-5 in.	$2.35	$3.50

FINK TRUSSES (Cont'd)

At 2'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	29 ft-11 in.	$1.46	$2.88
2 x 6	40 ft	$1.87	$3.12
2 x 8	40 ft	$2.28	$3.37

At 4'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	19 ft-2 in.	$1.51	$3.27
2 x 6	28 ft-7 in.	$1.93	$3.42
2 x 8	37 ft-8 in.	$2.36	$3.58

At 8'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	12 ft-7 in.	$1.60	$3.37
2 x 6	19 ft	$2.04	$3.45
2 x 8	25 ft	$2.42	$3.52

FINK TRUSSES (Cont'd)

At 2'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	23 ft-10 in.	$1.51	$2.91
2 x 6	35 ft-9 in.	$1.93	$3.17
2 x 8	40 ft	$2.36	$3.42

At 4'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	15 ft-2 in.	$1.55	$3.28
2 x 6	22 ft-9 in.	$1.99	$3.44
2 x 8	30 ft	$1.43	$3.24

At 8'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	9 ft-11 in.	$1.65	$3.38
2 x 6	15 ft	$2.10	$3.46
2 x 8	18 ft-4 in.	$2.50	$3.54

HOWE TRUSSES

At 2'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	36 ft-5 in.	$1.54	$2.93
2 x 6	40 ft	$1.94	$3.17
2 x 8	40 ft	$2.33	$3.41

At 4'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	24 ft-9 in.	$1.58	$3.28
2 x 6	36 ft-10 in.	$1.99	$3.44
2 x 8	40 ft	$2.40	$3.59

At 8'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	16 ft-5 in.	$1.66	$3.38
2 x 6	24 ft-7 in.	$2.09	$3.46
2 x 8	32 ft-4 in.	$2.47	$3.53

HOWE TRUSSES (Cont'd)

At 2'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	29 ft-1 in.	$1.58	$2.95
2 x 6	40 ft	$1.99	$3.19
2 x 8	40 ft	$2.40	$3.44

At 4'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	19 ft-1 in.	$1.63	$3.31
2 x 6	28 ft-6 in.	$2.05	$3.46
2 x 8	37 ft-7 in.	$2.48	$3.62

At 8'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	12 ft-7 in.	$1.72	$3.40
2 x 6	18 ft-11 in.	$2.16	$3.47
2 x 8	24 ft-11 in.	$2.59	$3.54

HOWE TRUSSES (Cont'd)

At 2'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	23 ft-10 in.	$1.63	$2.96
2 x 6	35 ft-8 in.	$2.05	$3.23
2 x 8	40 ft	$2.48	$3.49

At 4'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	15 ft-2 in.	$1.67	$3.32
2 x 6	22 ft-9 in.	$2.11	$3.48
2 x 8	29 ft-11 in.	$2.55	$3.64

At 8'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	9 ft-11 in.	$1.77	$3.40
2 x 6	15 ft	$2.22	$3.48
2 x 8	19 ft-9 in.	$2.62	$3.55

DOUBLE HOWE TRUSSES

At 2'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	46 ft-3 in.	$1.64	$2.98
2 x 6	60 ft	$2.04	$3.23
2 x 8	60 ft	$2.44	$3.47

At 4'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	31 ft-4 in.	$1.68	$3.32
2 x 6	46 ft-10 in.	$2.09	$3.48
2 x 8	60 ft	$2.50	$3.62

At 8'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	20 ft-2 in.	$1.76	$3.39
2 x 6	30 ft-6 in.	$2.19	$3.48
2 x 8	40 ft-2 in.	$2.50	$3.53

DOUBLE HOWE TRUSSES (Cont'd)

At 2'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	37 ft-4 in.	$1.68	$3.01
2 x 6	55 ft-9 in.	$2.09	$3.25
2 x 8	60 ft	$2.50	$3.50

At 4'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	24 ft-3 in.	$1.63	$3.31
2 x 6	36 ft-7 in.	$2.15	$3.49
2 x 8	45 ft-2 in.	$2.58	$3.65

At 8'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	14 ft-10 in.	$1.82	$3.14
2 x 6	22 ft-3 in.	$2.26	$3.49
2 x 8	24 ft-1 in.	$2.64	$3.56

DOUBLE HOWE TRUSSES (Cont'd)

At 2'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	30 ft-2 in.	$1.73	$3.04
2 x 6	45 ft-5 in.	$2.15	$3.30
2 x 8	59 ft-8 in.	$2.38	$3.55

At 4'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	24 ft-3 in.	$1.77	$3.36
2 x 6	36 ft-7 in.	$2.21	$3.52
2 x 8	45 ft-2 in.	$2.65	$3.67

At 8'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	10 ft-7 in.	$1.87	$3.42
2 x 6	16 ft-3 in.	$2.32	$3.50
2 x 8	17 ft-7 in.	$2.82	$3.59

DOUBLE W TRUSSES

At 2'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	46 ft-4 in.	$1.60	$2.96
2 x 6	60 ft	$2.00	$3.20
2 x 8	60 ft	$2.40	$3.44

At 4'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	31 ft-5 in.	$1.64	$3.31
2 x 6	46 ft-11 in.	$2.05	$3.46
2 x 8	59 ft-10 in.	$2.45	$3.60

At 8'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	19 ft-6 in.	$1.72	$3.40
2 x 6	29 ft-10 in.	$2.15	$3.47
2 x 8	33 ft-3 in.	$2.55	$3.54

DOUBLE W TRUSSES (Cont'd)

At 2'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	37 ft-5 in.	$1.64	$2.98
2 x 6	55 ft-9 in.	$2.05	$3.23
2 x 8	60 ft	$2.45	$3.47

At 4'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	24 ft-3 in.	$1.59	$3.30
2 x 6	36 ft-8 in.	$2.10	$3.48
2 x 8	44 ft-3 in.	$2.53	$3.64

At 8'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	14 ft-3 in.	$1.77	$3.41
2 x 6	21 ft-11 in.	$2.24	$3.48
2 x 8	23 ft-11 in.	$2.60	$3.55

DOUBLE W TRUSSES (Cont'd)

At 2'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	30 ft-3 in.	$1.69	$3.01
2 x 6	45 ft-6 in.	$2.11	$3.26
2 x 8	59 ft-9 in.	$2.53	$3.52

At 4'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	24 ft-3 in.	$1.73	$3.35
2 x 6	36 ft-8 in.	$2.17	$3.50
2 x 8	44 ft-3 in.	$2.61	$3.66

At 8'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	14 ft-3 in.	$1.82	$3.41
2 x 6	21 ft-11 in.	$2.28	$3.49
2 x 8	23 ft-11 in.	$2.78	$3.59

TRIPLE W TRUSSES

At 2'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	55 ft-5 in.	$1.86	$3.12
2 x 6	80 ft	$2.22	$3.34
2 x 8	80 ft	$2.58	$3.55

At 4'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	36 ft-3 in.	$1.92	$3.42
2 x 6	34 ft-9 in.	$2.29	$3.54
2 x 8	62 ft-1 in.	$2.66	$3.68

At 8'-0" o.c., 15 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	19 ft-10 in.	$2.02	$3.44
2 x 6	30 ft-6 in.	$2.40	$3.52
2 x 8	33 ft-3 in.	$2.79	$3.59

TRIPLE W TRUSSES (Cont'd)

At 2'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	43 ft-11 in.	$1.92	$3.16
2 x 6	66 ft	$2.29	$3.37
2 x 8	80 ft	$2.66	$3.60

At 4'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	26 ft-3 in.	$1.98	$3.43
2 x 6	40 ft-8 in.	$2.36	$3.58
2 x 8	44 ft-2 in.	$2.74	$3.71

At 8'-0" o.c., 30 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	14 ft-1 in.	$2.08	$3.46
2 x 6	21 ft-8 in.	$2.47	$3.61
2 x 8	23 ft-5 in.	$2.81	$3.58

TRIPLE W TRUSSES (Cont'd)

At 2'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	34 ft-8 in.	$1.98	$3.01
2 x 6	52 ft-8 in.	$2.36	$3.42
2 x 8	61 ft	$2.74	$3.64

At 4'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	19 ft-1 in.	$2.04	$3.46
2 x 6	29 ft-7 in.	$2.43	$3.60
2 x 8	31 ft-10 in.	$2.82	$3.79

At 8'-0" o.c., 50 lb L.L., and 15 lb D.L./sq ft, what is the maximum span attainable using 2 x 4, 2 x 6, and 2 x 8 members (top and bottom chords), and what are the respective costs at each of the maximum spans?

	Max. Span	Cost (Per lin ft)	Cost (Per sq ft of roof conversion)
2 x 4	10 ft-3 in.	$2.14	$3.47
2 x 6	15 ft-9 in.	$2.54	$3.54
2 x 8	17 ft	$2.96	$3.61

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