Construction of Precast Prestressed Folded Plate Structures in Honduras

Precast prestressed folded plate roof elements are cast flat with hinges between panels; they are transported flat, then opened to the desired angle during erection, with joints formed and cast in place to unify the structure. The construction method and design rationale, as developed in China, are being widely used in Honduras for both public buildings and industrial buildings. This paper describes the several such buildings recently constructed, and explains how waterproofing and ventilation are handled in the tropical climate.

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Honduras, Central America, with an area of 112,000 km^2 (43,160 sq miles) and a population of approximately 4 million is a country located in the Caribbean basin. As in most developing countries, the majority of industrial shed-type buildings in Honduras have been built with imported steel roof framing systems. The rising cost of imports due to currency devaluation has generated a market opportunity for the concrete industry in this type of construction since Honduras has ample supplies of quality aggregates and local cement production.

After searching for a concrete building system that would be economical for the construction of industrial shed-type buildings, CONSHA, a concrete products company operating in Honduras, adopted a precast prestressed folded plate system developed in China (Fig. 1). The system, referred to as V-plate because of the shape of the elements, was described in detail by one of the authors in 1983.[1]

At the time the V-plate was introduced into Honduras, a comparison of its cost with the then-current prices of steel framing systems was made. Results of this comparison (Fig. 2) indicated that for a 20 m (65.6 ft) span, the producer's cost for the concrete plate system was 70 percent of the price of a steel truss system and about 57 percent of the price of a steel portal frame. If inflation of local cement prices is held at a lower pace than the devaluation of currency, the trend will be toward widening the cost gap between the V-plate system and imported steel structures.

Manufacture, Assembly and Structural Design

The entire procedure for the construction of V-plate roofs is divided into two operations: precasting and field erection.

Initially, the V-plate elements are manufactured in a flat position, hinged

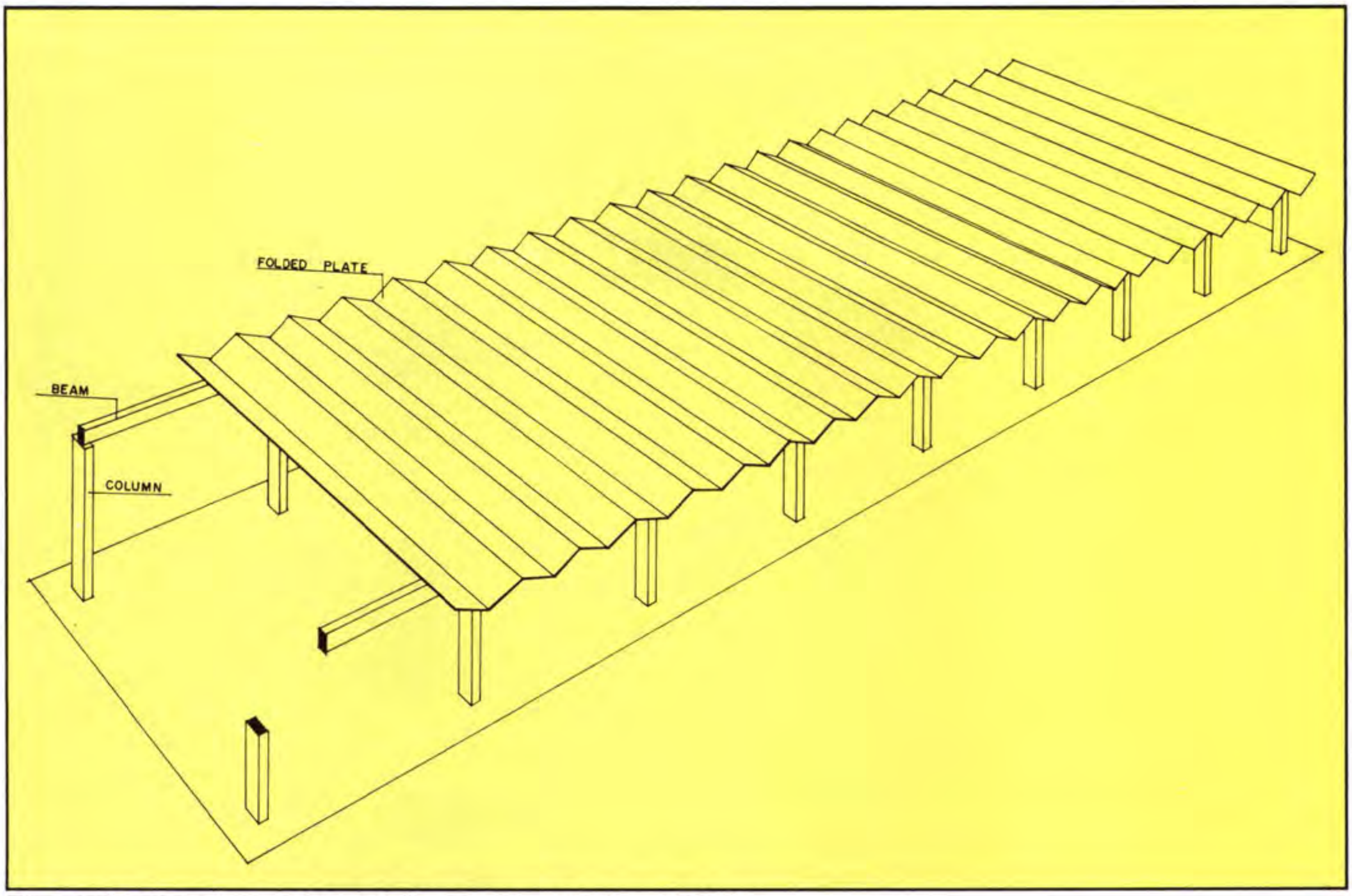


Fig. 1. Precast prestressed folded plate roof system developed in China.

together, and then they are folded over for handling, storage, and transportation. Thus, this phase of the operation is executed on two-dimensional elements.

In the second operation at the job site, the plates are opened to the design angle inclination, forming the V-shape. This makes the operation much simpler than handling three-dimensional elements would be. Although the construction system is simple, the success of the V-plate roof depends on the careful execution of each step, particularly during the erection phase.

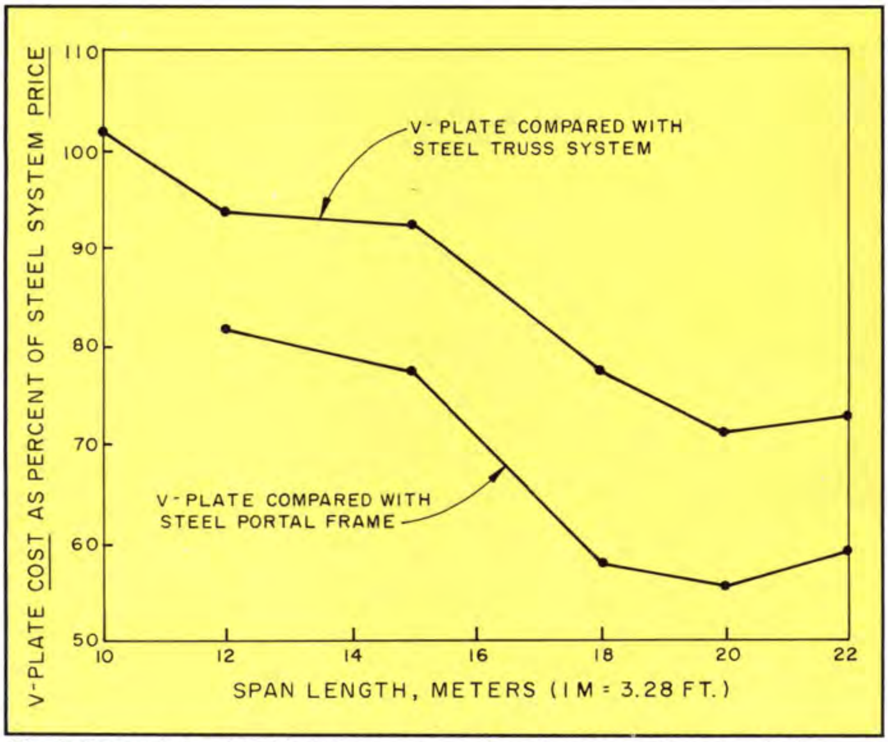


Fig. 2. Cost relationship, V-plate concrete and steel systems. Note that V-plate producer's cost is compared with selling price of competing steel systems.

Materials and Manufacture of V-Plate Elements

The prestressed V-plate elements are designed based on using the following specified materials:

Prestressing tendons: 250K, 1/4-in. (1,723,000 kPa, 6.35 mm) 7-wire strand with a 27,800 ksi (191,700 MPa) modulus of elasticity.

Concrete: 28-day compressive strength, 6000 psi (41,370 kPa) in both joints and panels; strength at transfer of the prestress, 4200 psi (28,959 kPa).

Reinforcing bars: yield strength, 40,000 psi (275,800 kPa).

Precasting is done in 4.2 x 40 m (13.75 x 131.2 ft) self-stressing steel forms with a bearing capacity of 150 tons (330,000 lb) (Fig. 3).

The basic steps in the manufacturing sequence are:

- Application of release agent to the forms.
- Laying the prestressing tendons.

Fig. 3. Self-stressing steel form used for V-plate fabrication.

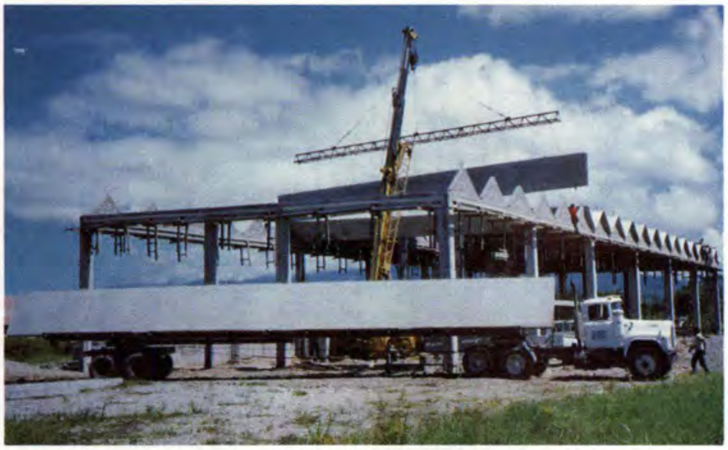


Fig. 4. Transportation and erection of 21.5 m (70.5 ft) V-plate elements in the city of La Ceiba, Honduras.

Fig. 5. Transportation of V-plates on the highway.

- Adjusting lateral forms to proper plate widths.
- Placing welded wire mesh fabric.
- Tensioning of the tendons.
- Placing of the concrete.

Surface vibration is used to consolidate the concrete and a smooth finish is provided.

Transportation and Assembly

In Honduras the principal land transportation is on highways, and so trucks are used to carry the V-plate elements. A steel rig is used to transport pairs of V-plates fastened together (see Figs. 4 and 5). Projects have been built in the cities of Ceiba and Tegucigalpa, as far as 250 km (155 mi) from the precasting plant in San Pedro Sula.

The erection procedure is very important for successful construction of the V-plate roofs. The geometric configuration as designed must be provided for exactly in the field, and this requires accuracy in erection. Several conditions must be considered before and during erection:

Fig. 6. Tapered V-plate roof elements during erection of the Good Shepherd Catholic Church.

(a) Convenience in opening the V-plate from the flat handling and transportation position to the correct angular spread in the roof.

(b) Ensuring proper balance and symmetry of both flat elements during the opening procedure.

(c) Stabilizing the V-plate once it is in place.

(d) Maintaining uniform width and shape in the lower joint.

(e) Correctly connecting the upper joints of adjoining V-plates once they have been opened.

When the V-plates are secured in position, turnbuckle tie rods are fixed simultaneously on the top ridge joints of the V-plates to stabilize the unit. After establishing uniform width and configuration, the upper joints of adjacent plates are welded at steel bars provided for this in the edge of the plates (see Fig. 6).

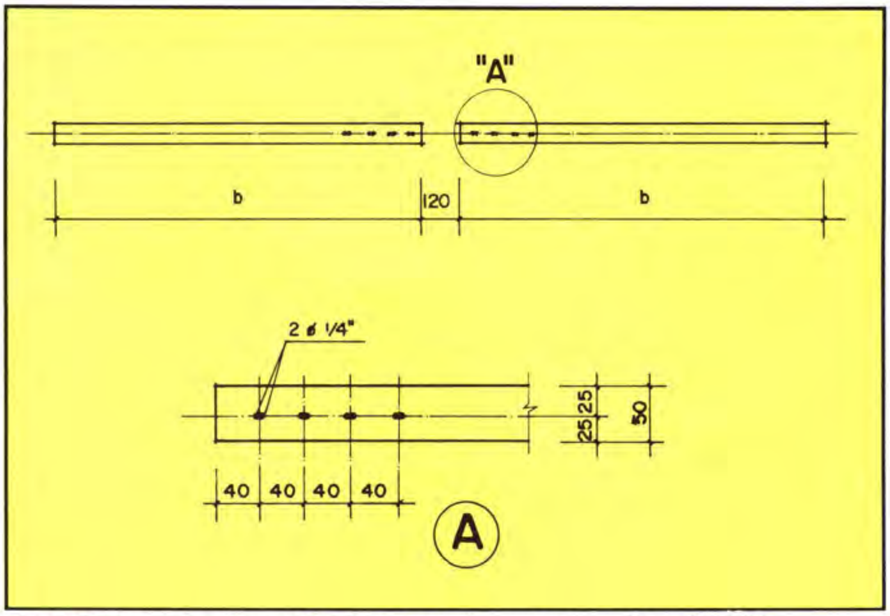


Fig. 7. Tendon arrangement in plates spanning more than 20 m (65.6 ft).

Structural Design

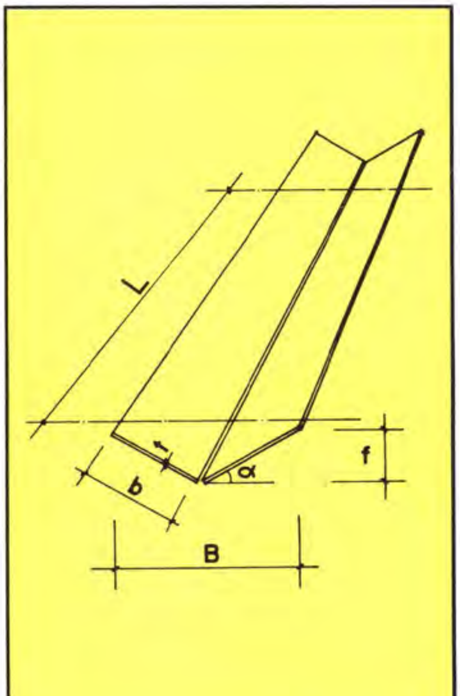
A folded plate structural system can be analyzed as a space structure; in the V-plate system the top and bottom joints become continuous and rigid after pouring the concrete. However, since a V-plate roof is generally a repetitive multi-folded continuous structure, some reasonable simplifying assumptions can be made in design.[1] The influence of space action can be neglected in the design of the final structure, and temporary supports (the turnbuckle rods) provide lateral stability during erection. Since the span L is much longer than the valley width B, the plate is assumed to act as a V-shaped beam in the longitudinal direction and as a simply supported beam in the transverse direction.

To establish a standard for V-plates, some practical rules have been incorporated to ensure a simple, economical structure. Table 1 has been developed for Honduras, taking into account the local conditions, the V-shape folded plate roof design-construction code of China,[2] and the ACI 318 Code.[4] The specifications for materials used to develop the upper part of Table 1 are given above with other construction details.

In general, the width used for arranging the main prestressing tendons is not more than one-fourth the total

Table 1. Dimensional configuration and limit ratios of folded plates used in Honduras.

Span	Valley width	Inclination	Thickness	Rise	Plate width ratio	Height to span ratio	Thickness/ width ratio	Width to length	Weight
L, m	B, m	α deg	t, mm	f, m	b, m	f/L	t/b	b/L	T
6	2.0	26	38.1	0.47	1.03	1/12.8	1/21.0	1/5.8	1.57
8	2.0	28	38.1	0.51	1.05	1/15.7	1/21.0	1/7.8	2.00
10	2.0	30	38.1	0.56	1.07	1/17.9	1/28.1	1/9.4	2.45
12	2.0	34	38.1	0.65	1.13	1/18.5	1/29.7	1/10.6	3.01
14	2.0	38	38.1	0.76	1.19	1/18.4	1/31.2	1/11.8	3.62
16	2.0	42	38.1	0.88	1.27	1/18.2	1/33.3	1/12.6	4.35
8	3.0	28	50.8	0.76	1.60	1/10.5	1/31.5	1/5.0	4.06
10	3.0	28	50.8	0.76	1.60	1/13.2	1/31.5	1/6.3	4.88
12	3.0	30	50.8	0.84	1.63	1/14.3	1/32.6	1/7.4	5.80
14	3.0	32	50.8	0.92	1.66	1/15.2	1/32.7	1/8.4	6.75
16	3.0	34	50.8	1.01	1.71	1/15.8	1/33.7	1/9.4	7.82
18	3.0	36	50.8	1.06	1.75	1/17.0	1/34.5	1/10.3	8.89
20	3.0	38	50.8	1.13	1.80	1/17.8	1/35.4	1/11.1	10.08
20	3.0	36	50.8	1.09	1.75	1/18.3	1/34.4	1/11.4	9.78
22	3.0	38	50.8	1.17	1.80	1/18.8	1/35.4	1/12.2	10.97
24	3.0	40	63.5	1.25	1.86	1/19.2	1/29.3	1/12.9	15.35
26	3.0	42	63.5	1.33	1.92	1/19.6	1/30.2	1/13.5	17.07
28	3.0	44	63.5	1.50	1.96	1/18.7	1/30.9	1/14.3	18.67
30	3.2	44	63.5	1.56	2.15	1/19.2	1/33.9	1/14.0	21.84



Metric (SI) conversion factors: 1 m = 3.28 ft; 1 mm = 0.04 in.; 1 T = 2200 lb. Element weights are calculated based on a length of $L + 2$ m. Sections above double line are designed using 6000 psi (41,370 kPa) concrete; below the double line design of sections is for 7000 psi (48,265 kPa) concrete.

Fig. 8. The Plaza de Sula Theater in San Pedro Sula, completed in June 1989, has a V-plate roof.

Fig. 9. Industrial building using the V-plate roof system in the Villanueva industrial zone.

Fig. 10. A typical industrial application is this factory building in the city of San Pedro Sula, roofed with a V-plate structure.

plate width. The spacing of the main prestressing tendons is 38 mm (1.5 in.).

For spans longer than 20 m (65.6 ft), the bottom section of Table 1 was developed based on a final concrete strength of 7000 psi (48,265 kPa) and 5600 psi (38,612 kPa) transfer strength, with pairs of 1/4-in. (6 mm) tendons spaced at 40 mm (1.57 in.) (Fig. 7).

The geometrical dimensions of V-plates are for simple spans with cantilevered ends of 0.5 to 1.5 m (1.64 to 4.92 ft) in length and with two valley widths — 2.0 and 3.0 m (6.6 and 9.8 ft) except for the 30 m (98 ft) span where the valley width is 3.2 m (10.5 ft). The angle of inclination of the plates from the horizontal varies from 26 to 45 deg. The ratio of height to length f/L varies between 1/10.5 and 1/20. The ratio of plate thickness to plate width t/b varies from 1/5 to 1/14, and the ratio of valley width to span b/L is from 1/3 to 1/10.

APPLICATIONS OF THE V-PLATE ROOF SYSTEM IN HONDURAS

Since 1988 the construction of buildings using the precast prestressed V-plate folded plate system has been growing in Honduras. With ten buildings already completed covering more than 15,000 m^2 (161,400 sq ft) and more than 100,000 m^2 (1,076,000 sq ft) planned, the system has already established itself in the country and its use will develop rapidly in the near future.

The V-plate roofs have been used on buildings with different architectural style, function, and appearance. Both industrial and commercial buildings have been built (Figs. 4, 8, 9, and 10).

A Commercial Building: The Plaza de Sula Theater Building

The 2556 m^2 (27,500 sq ft) theater building in the city of San Pedro Sula was completed in June 1989. The building has three distinct functional areas: three independent theater rooms, two concession areas, and a two-story lobby/projection room. The highest elevation of the building is at the staircase tower, which incorporates a water supply tank (Figs. 11 to 16).

The V-plate roof was used on both building wings and also to cover the external corridor on the west side. There are five different roof elevations in the building, the lowest at 3.2 m (10.5 ft) and the highest at 7.8 m (25.6 ft). The architectural composition and structural design required eight different spans, three different valley angles, and 24 different types of elements (Table 2).

To satisfy the architectural requirement, a basic constraint had to be dealt with in the design of the V-plate roof — the selection of the V-plate valley width. From an architectural perspective, a smaller valley width is called for in the lower levels and a larger width at the upper levels.

Structural considerations require a larger valley width for longer spans. In the lower level of the east wing there were a total of ten V-plate elements of which three spanned 13.5 m (44.3 ft) and the rest spanned only 3 m (9.8 ft). It was necessary to perform numerous analyses to establish the most adequate valley width. A 2.4 m (7.9 ft) valley width and a 34-deg angle were used for both spans.

Special details were incorporated to deal with two particular conditions. In one case since the main columns had a double height supporting a 7.8 m (25.6 ft) roof on one side and a lower roof elevation on the other side with the supporting beams concentric with the column axis (see Sections B-B and C-C in Fig. 15) the problem arose at the intersection of the column, beam, and V-plate. To provide sufficient support length for the V-plate, a blockout in the top of the V-plate was provided and its support was anchored into the beam (Fig. 17).

The second special detail was provided on the water discharge side of a V-plate at the intersection with the elevated water tank (Fig. 18). Covering this particular V-plate with precast prestressed flat plates permitted discharge of the rainwater to the adjoining V-plate.

Although the V-plate roof system in this project was not for a typical shed-type structure, its construction went smoothly and it proved that the system could be used in more complex buildings.

Fig. 11. The Plaza de Sula Theater building in the city of San Pedro Sula.

Fig. 12. Interior view of the concession area, Plaza de Sula Theater.

Table 2. Folded plate elements used in the theater building.

Type	Span, m	Valley width, m	Number of types	Number of elements	Roof area, m^2
1	16	3.0	7	9	490
2	15	3.0	4	9	468
3	14	2.4	2	4	170
4	14	2.0	2	15	510
5	12	2.4	3	12	432
6	11	3.0	2	6	234
7	4	2.0	2	15	180
8	3	2.4	2	6	80
Total			24	76	2556

Metric (SI) conversion factors: 1 m = 3.28 ft; 1 m^2 = 10.76 sq ft.

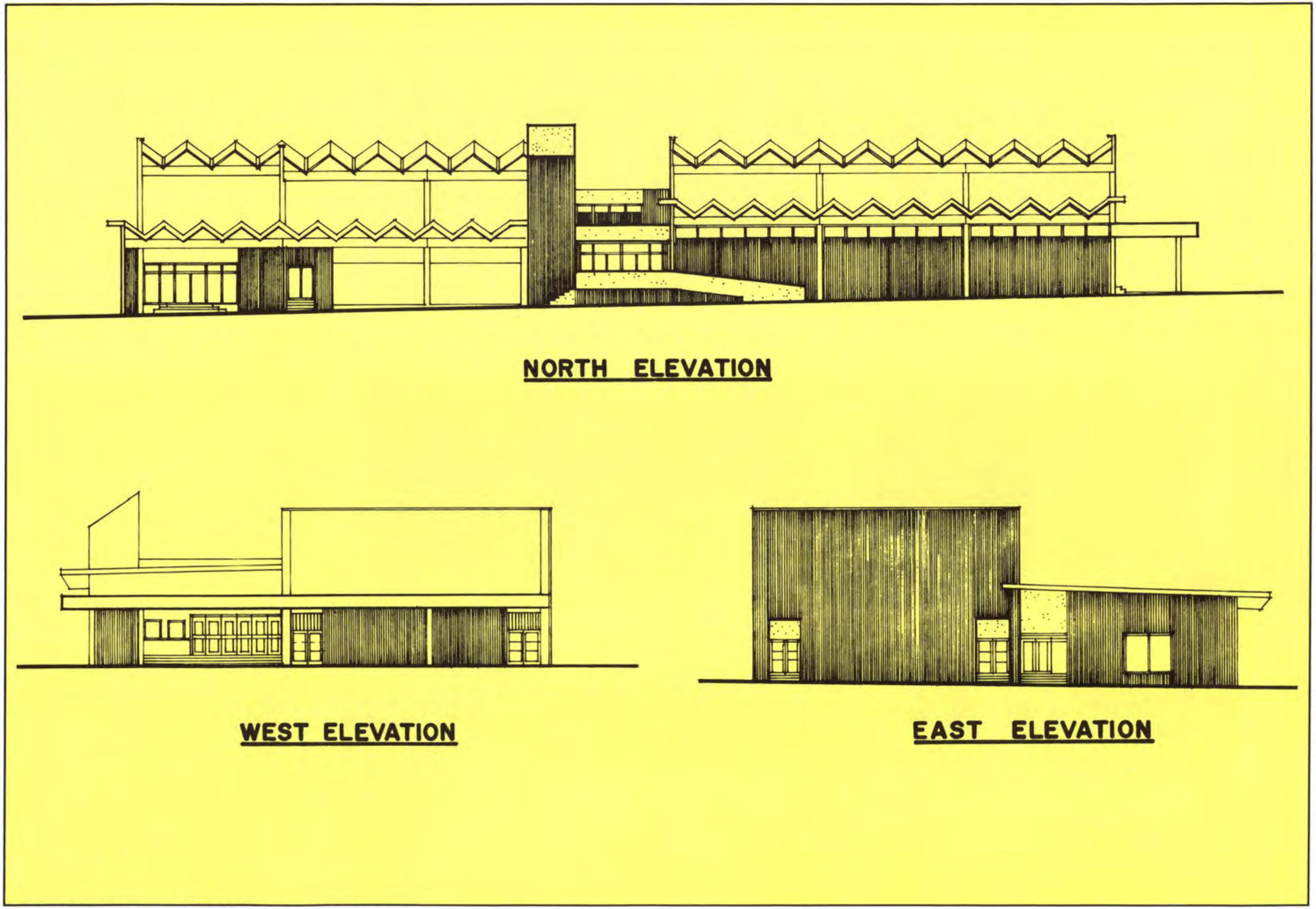


Fig. 13. Elevation views of the Plaza de Sula Theater.

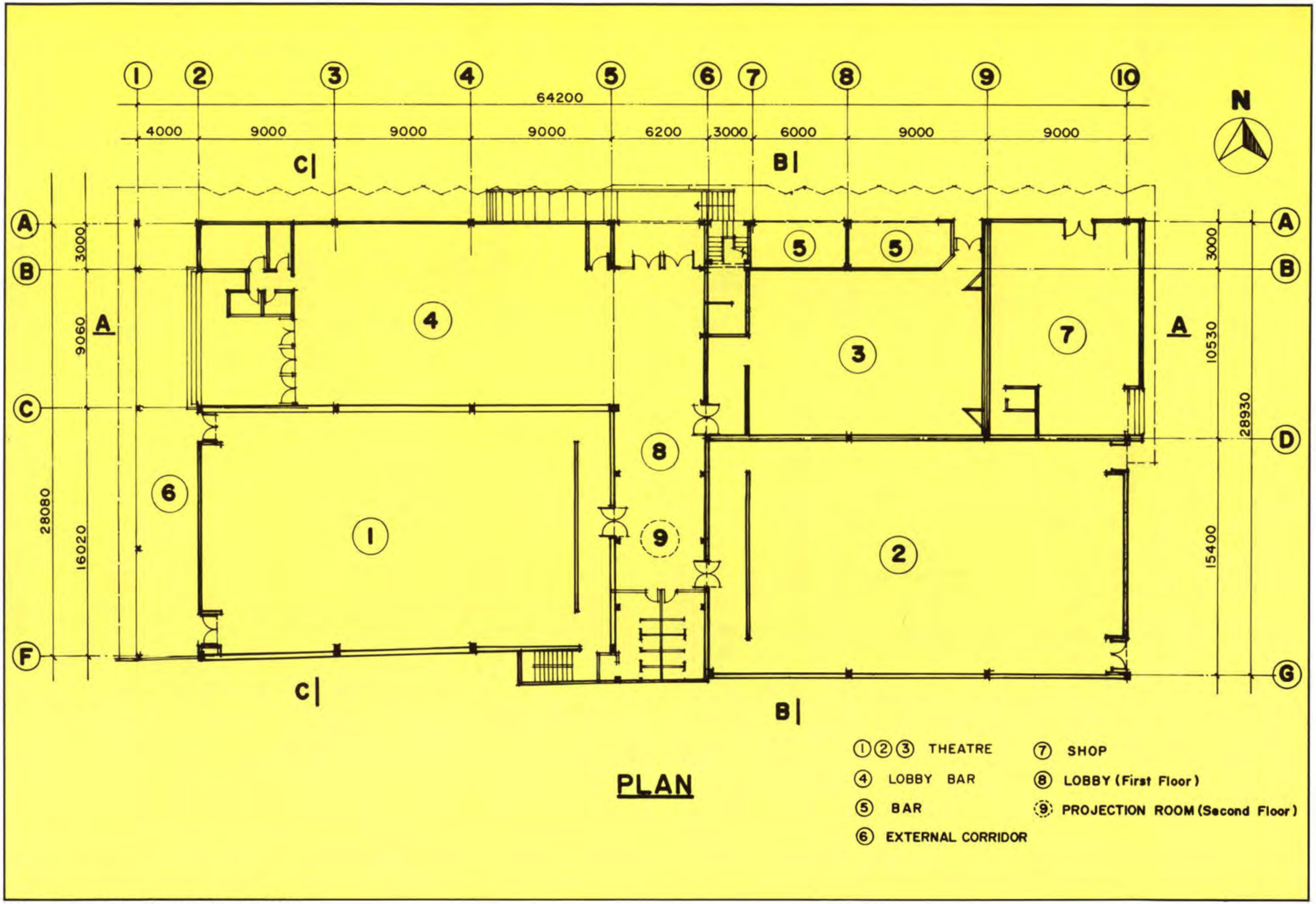


Fig. 14. Plan of the Plaza de Sula Theater.

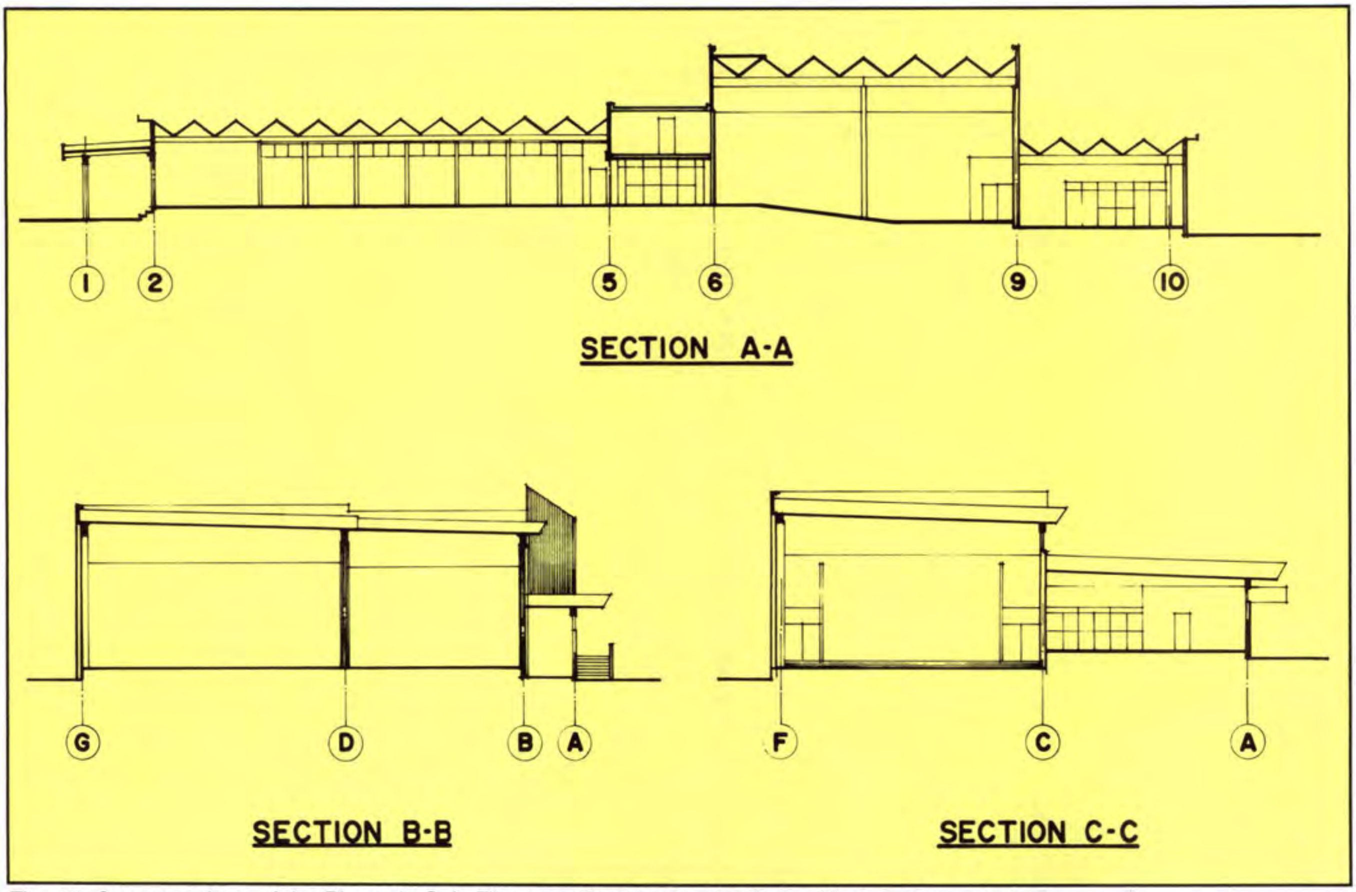


Fig. 15. Cross sections of the Plaza de Sula Theater. The theater features differing column heights.

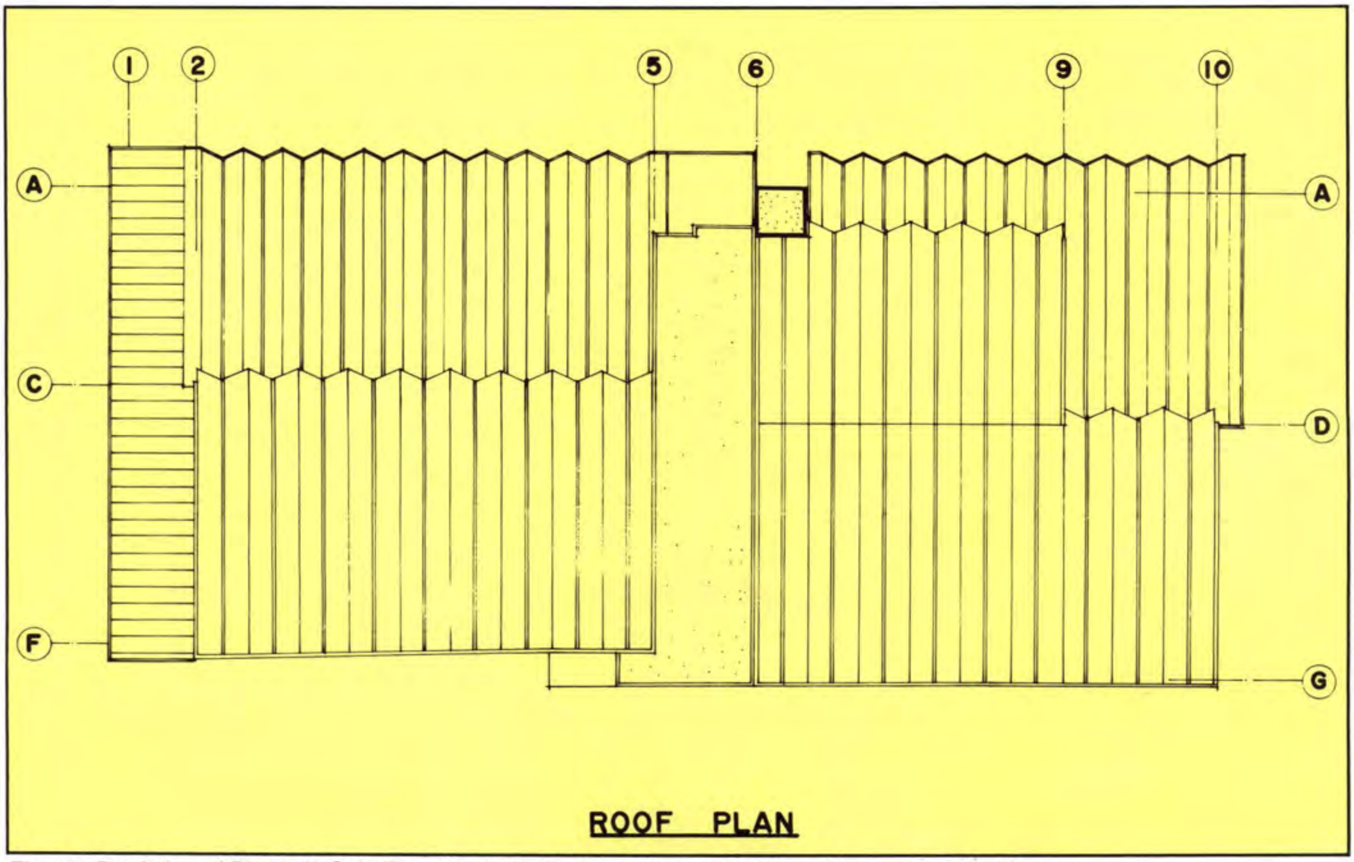


Fig. 16. Roof plan of Plaza de Sula Theater shows V-plates over external corridor on the left side.

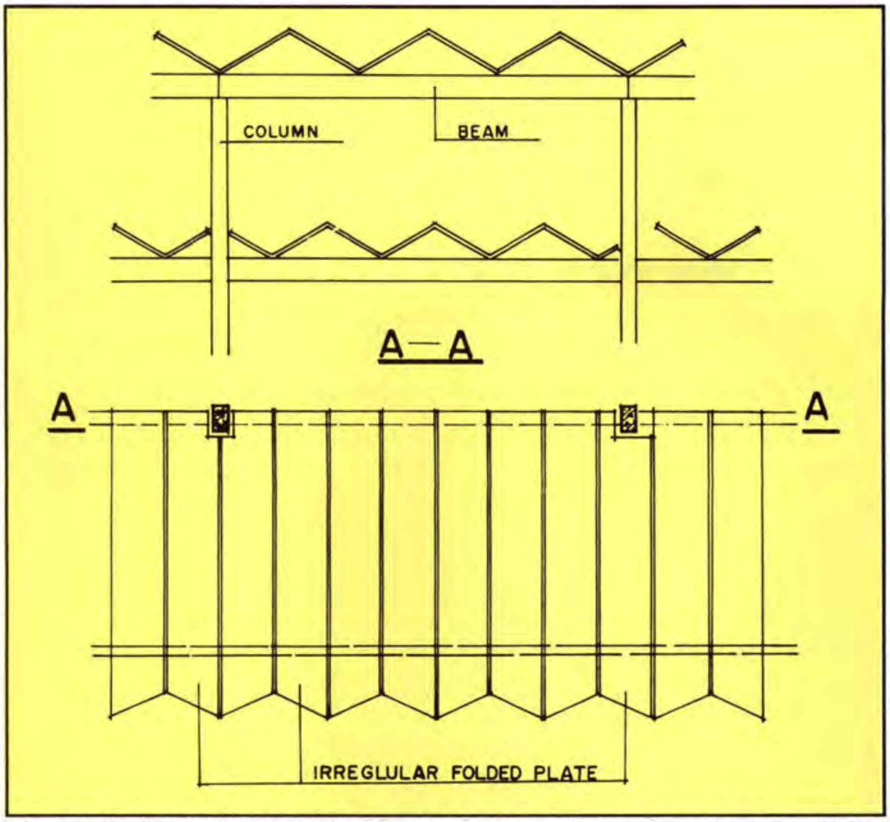


Fig. 17. Blockout in V-plate to facilitate connection at intersection of column, beam and plate.

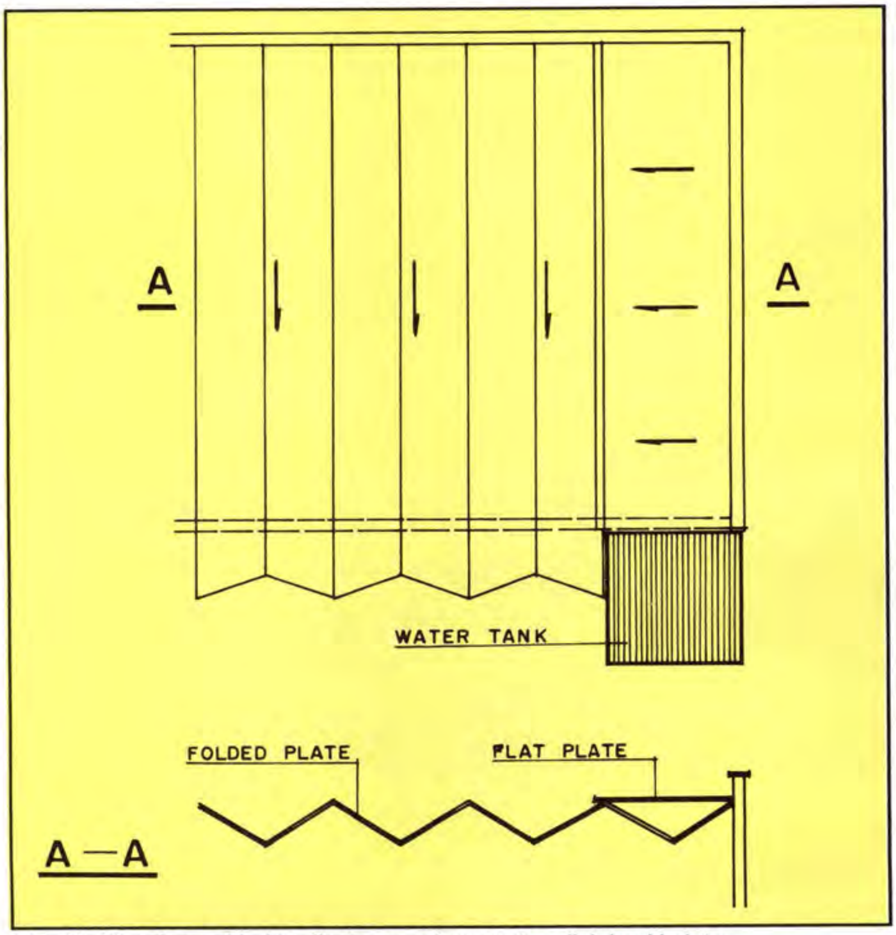


Fig. 18. Flat plate added to discharge rainwater to adjoining V-plate.

A Church Building: The Good Shepherd Catholic Church

This church building, under construction at the time of writing, also located in the city of San Pedro Sula, is cross-shaped in plan, is divided into five main areas focusing around an 8 x 10 m (26 x 33 ft) double height altar area (Figs. 19 and 20). Three fan-shaped roofs cover the main gathering areas, and two rectangular areas complete the plan. Seven different groups of V-plates were provided to make the roof for this project (Figs. 21 and 22).

The fan-shaped roof for this church demonstrates the inherent flexibility of the precast prestressed V-plate system. A seemingly complex as-built configuration was achieved simply by tapering the plates during fabrication in the plant. Sixteen different types of elements comprising a total of 37 elements are used to cover a total area of 835 m^2 (8976 sq ft) (Table 3).

Since each V-plate is precast in a flat position, tapering uniformly throughout its length, the various valley widths take form in the course of the erection at the job site. The actual erection of the V-plate for the tapering elements is the same as for a regular shaped V-plate (Figs. 6, 23, and 24).

This concept can readily be adapted to other projects since various plan shapes can be easily achieved with tapered V-plates. Fig. 25 shows some of the possibilities.

VENTILATION AND WATERPROOFING OF V-PLATE ROOFS

Honduras is in a tropical climate zone where two well-defined seasons occur — a dry season and a rainy one. The ambient temperatures vary between 16 °C and 40 °C (61 °F and 104 °F). Heavy rains fall almost daily during the rainy season. This must be considered when designing ventilation of a V-plate building, as well as when providing waterproofing for the V-plate roofs.

Ventilation for V-Plate Buildings

Nearly all buildings in the tropics require a design for natural ventilation

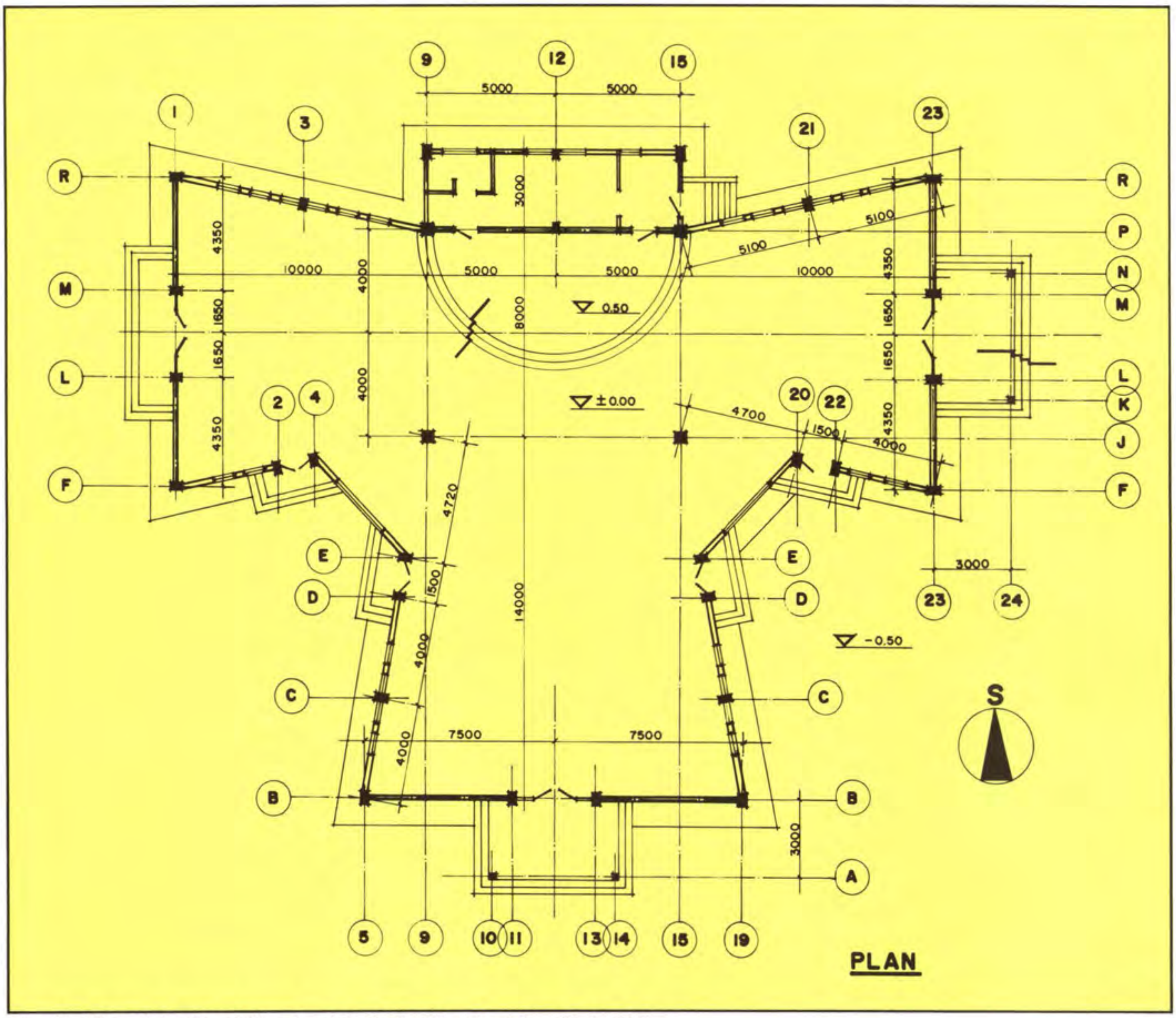


Fig. 19. Plan of the Good Shepherd Catholic Church at San Pedro Sula.

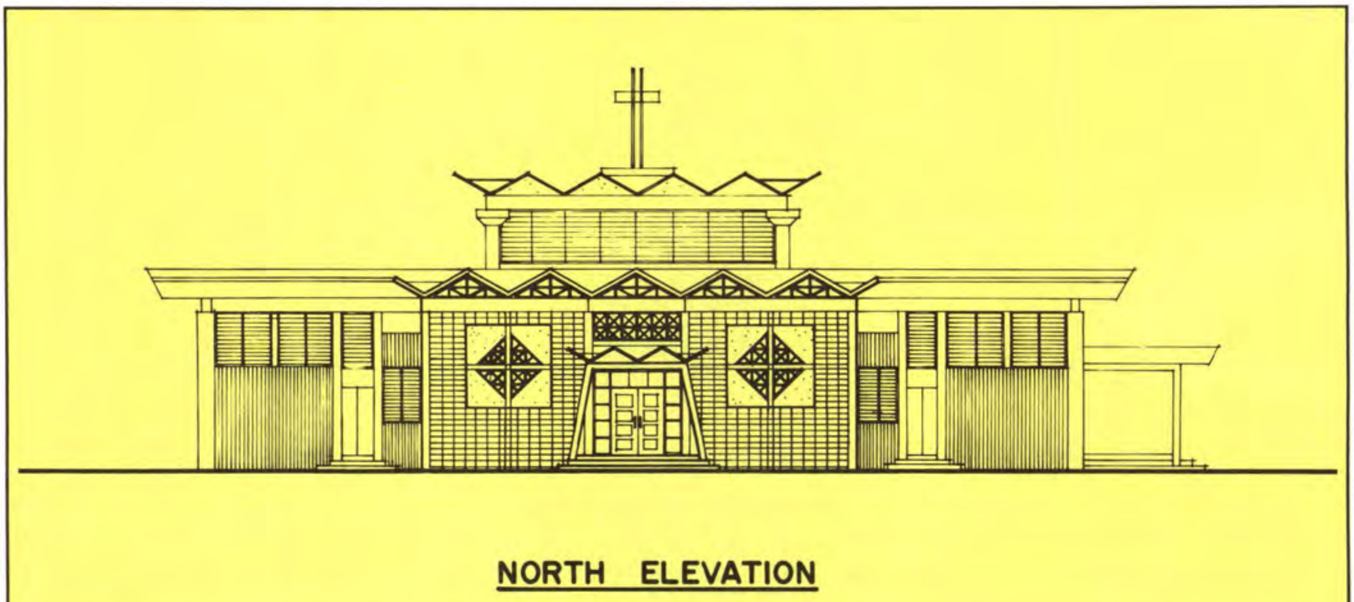


Fig. 20. North elevation of Good Shepherd Catholic Church.

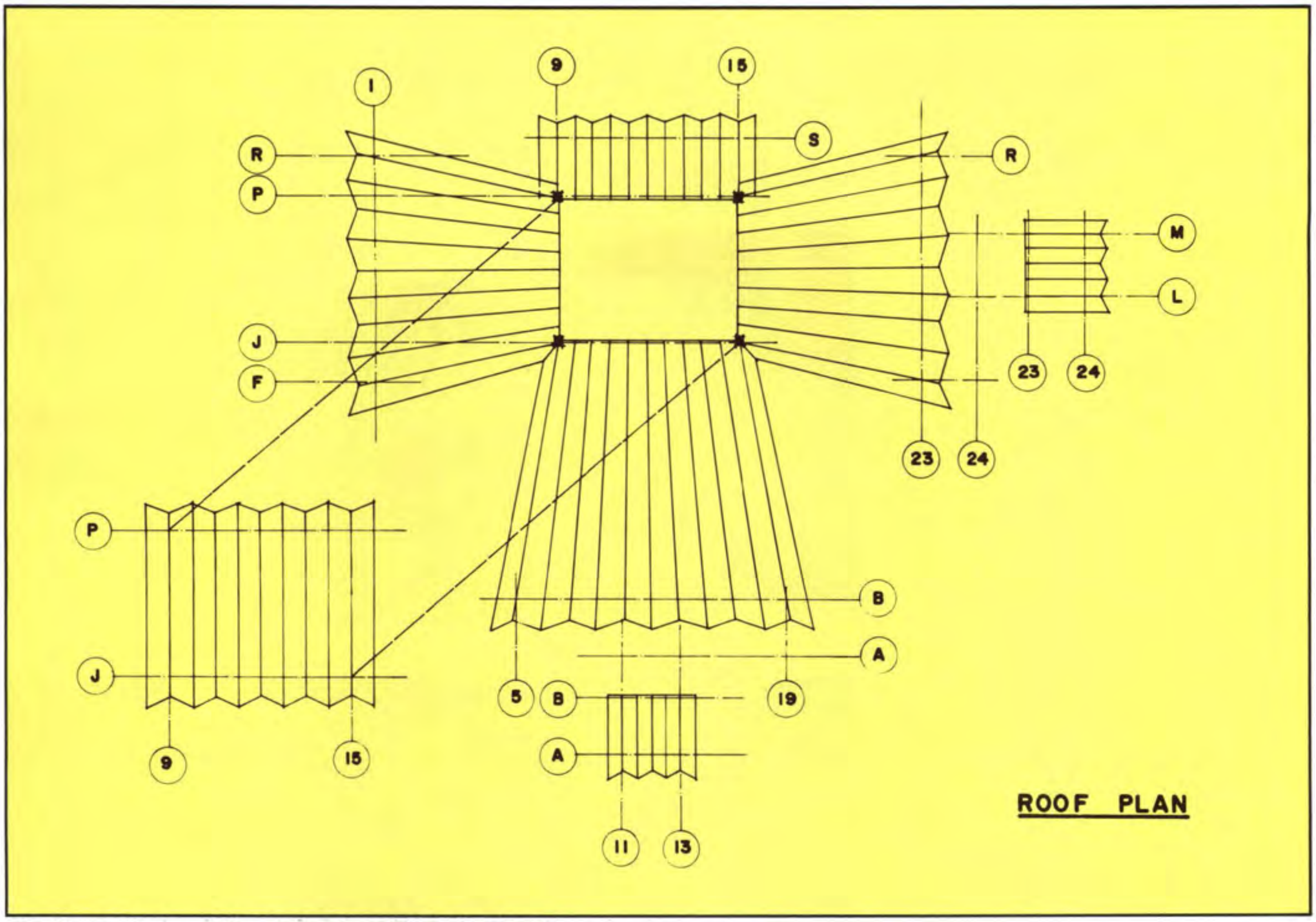


Fig. 21. Roof plan of Good Shepherd Catholic Church.

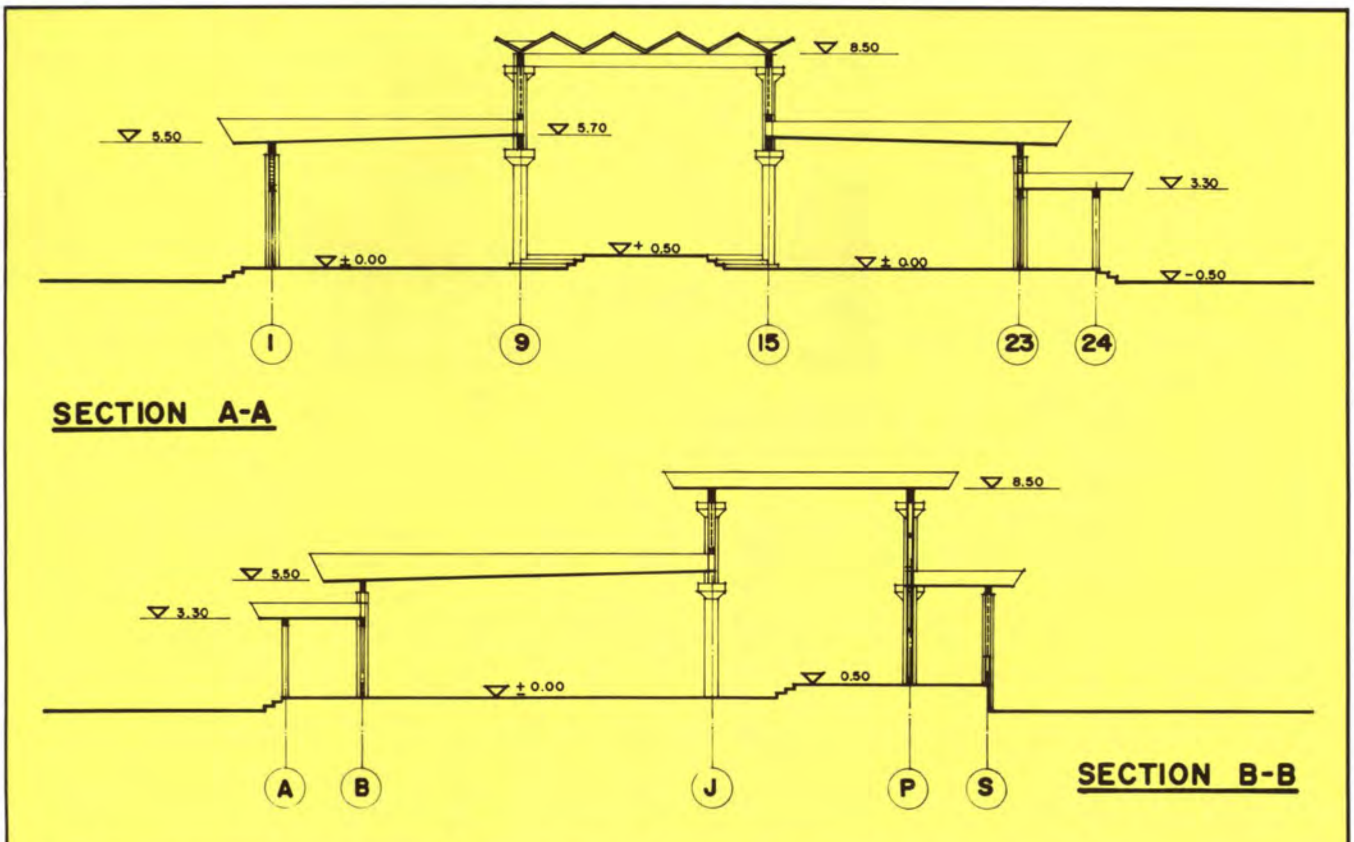


Fig. 22. Sectional views show multiple roof elevations at Good Shepherd Catholic Church.

except for buildings equipped with an air conditioning system. Natural ventilation can be provided by making an opening in the V-plate roof where a skylight-type window can be installed. For example, the 60 x 20 m (197 x 66 ft) Utility Building in La Ceiba, Honduras, has two skylight windows each 6 x 6 m (19.7 x 19.7 ft). Both natural light and ventilation were achieved with interior atrium type gardens (Fig. 26).

A strip skylight window in the longitudinal direction has been adopted for two-span or multispan buildings. In the skylight area, two supporting roof beams span a central axis of columns with double corbels. This concept was used in a project built in the city of Tegucigalpa. The two-span roof consisting of 12 m (39.4 ft) V-plates incorporates a 2 m (6.6 ft) double longitudinal skylight window (Fig. 27a).

A four-span roof with 20 m (65.6 ft) V-plates planned for San Pedro Sula uses an open strip skylight window along the two central longitudinal axes in the V-plate roof. To enhance the effects of lighting and ventilation, the top ends of the Y-shaped columns (Fig. 27b) were set at two different elevations, creating a 5 percent inclination of the V-plate roof and discharging water onto channels supported by the Y-shaped columns.

By setting different sections of the roof at different elevations, space is made available for natural ventilation and light, as in the church building described previously.

Fig. 28 shows three different versions of the V-plate roof using skylight windows. These three types were studied in China 10 years ago, and they have been widely used there. They offer several advantages:

Fig. 23. View during construction of the Good Shepherd Catholic Church.

Fig. 24. Interior view of the Good Shepherd Catholic Church building during construction.

Table 3. Folded plate elements used in the church building.

Type	Span, m	Valley width, m	Number of types	Number of elements	Roof area, m^2
1*	14	2-3	3	6	250
2*	10	2-3	5	10	300
3	8	2	2	5	135
4	3	2	4	12	110
5	3	1.65	2	6	40
Total			16	37	835

*Fan type.
Metric (SI) conversion factors: 1 m = 3.28 ft; 1 m^2 = 10.76 sq ft.

- Skylight windows may be placed anywhere in the roof.
- Light and ventilation can be adjusted in the interior.
- The overall V-plate structural system is not changed.
- Prefabrication and construction are simple and convenient.

These three types of skylight windows and other similar ones are being adopted for new projects in Honduras (Fig. 29).

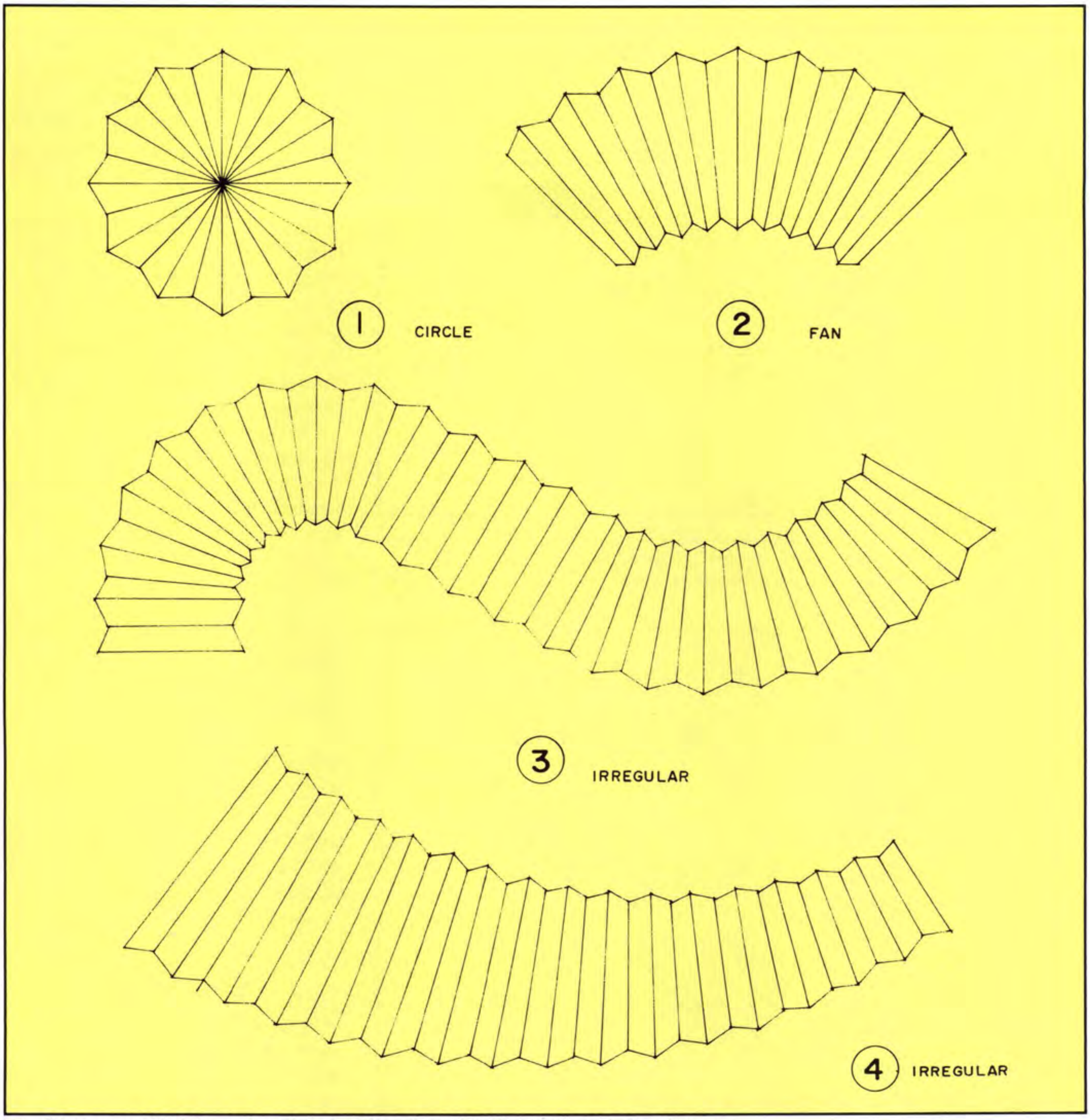


Fig. 25. Tapered V-plate roof sections can be adapted to fit various roof plan shapes.

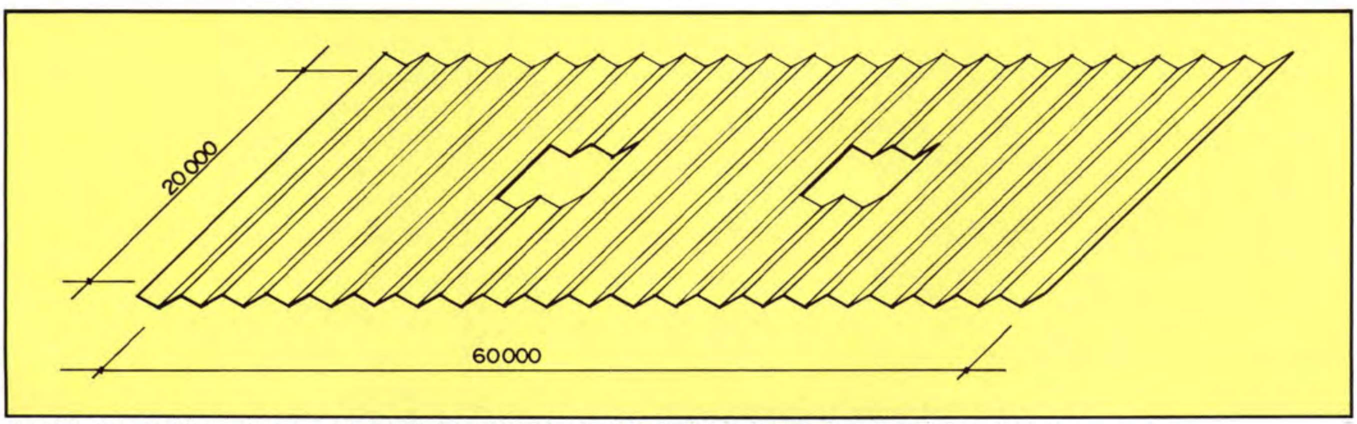


Fig. 26. Two skylight windows provide light and air for a utility building in the city of La Ceiba, Honduras.

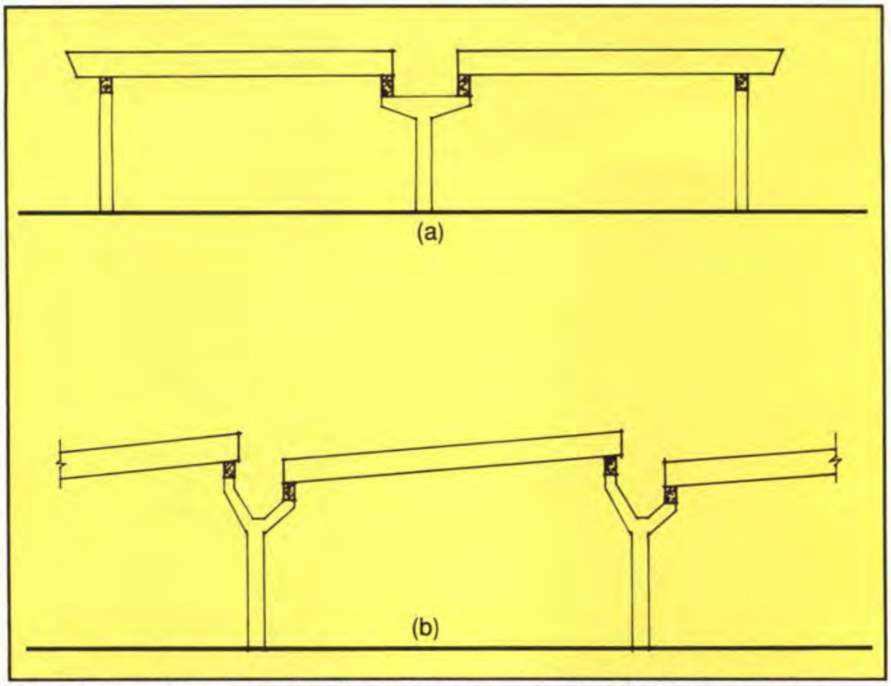


Fig. 27. Central longitudinal skylight (a) provided for a building in Tegucigalpa. Detail below (b) shows how V-plate roof sections were sloped to provide drainage.

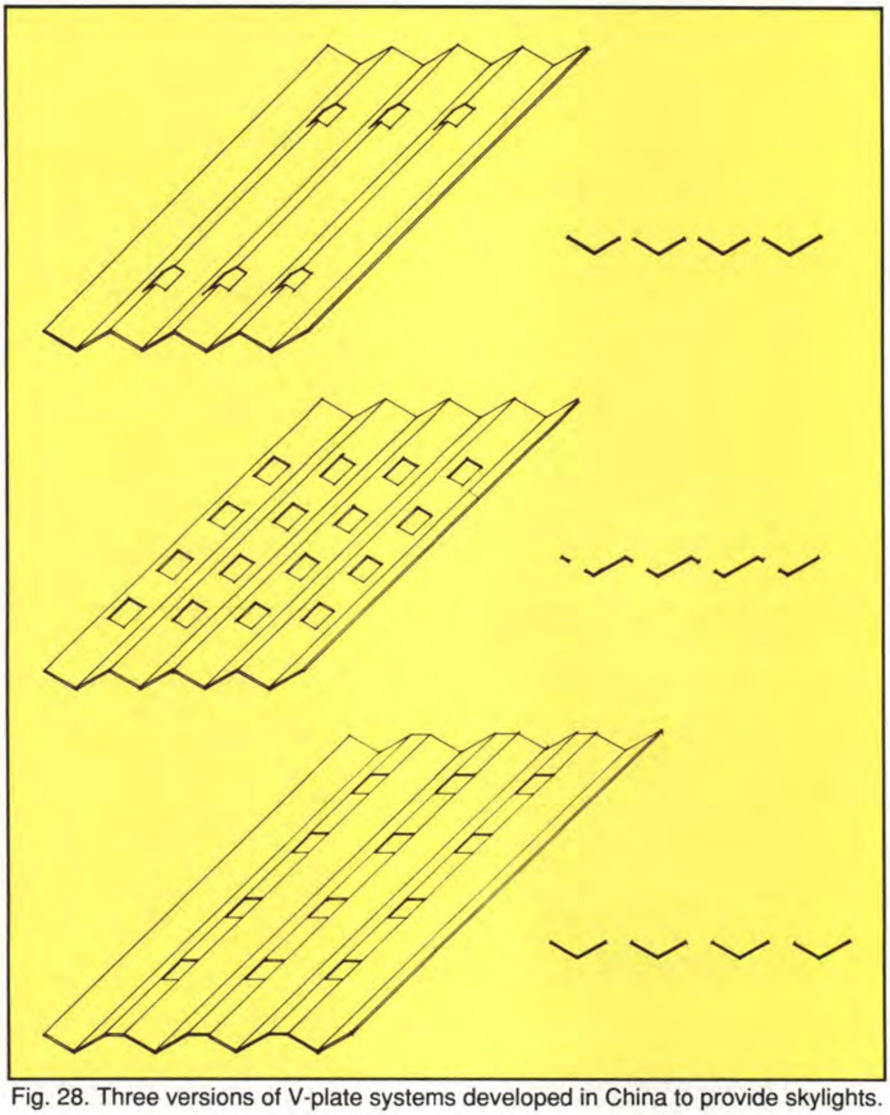


Fig. 28. Three versions of V-plate systems developed in China to provide skylights.

Waterproofing of V-Plate Roofs

Waterproofing is just as important for V-plate roofs as for any other system, particularly in the tropics. Since the V-plates are plant precast and the joints are cast in place, waterproofing extends to the entire process of construction.

High quality concrete is a good waterproofing material if rainwater is discharged rapidly. To insure the density of the concrete, good vibration is required with two to three smooth finishing passes after vibration. Addition of more water or cement to the mix during casting and finishing is not permitted.

During erection, the on-site casting of concrete at the joints is of prime importance. Density is achieved by vibration. Concreting of the upper joints must be done with particular care. Fig. 30 shows typical joint details of the V-plate system.

Waterproofness of V-plate roofs in the tropics will be ensured if a high quality concrete has been used for both the precast elements and the joints. Field investigations after heavy rains have shown that there were only a few permeable spots in the V-plate theater roof, none of which showed leakage.

Some of the V-plate roofs in Honduras have been given a waterproof coating of two or three applications of oil-based paint. The roof surface must be clean and dry for proper results.

CONCLUSIONS

Since 1988, architectural and structural systems using precast prestressed folded plate roofs have been developing rapidly in Honduras. Both the theater and church described in this article as well as numerous industrial shed-type structures have shown a successful application of the V-plate system. The projects described indicate that the inherent flexibility of the V-plate system for complex roof conditions makes it a very successful construction system not only in this country but can be adapted to other parts of the world.

ACKNOWLEDGMENT

Senior engineer Li Zhenqiang has been invited by CONSHA, a precast prestressed concrete company in Hon-

Fig. 29. Skylight window developed for roof systems in Honduras.

duras, to come to Central America from Beijing, China, to promote the development of precast prestressed systems. CONSHA has provided the necessary support for development of the folded plate systems in Honduras.

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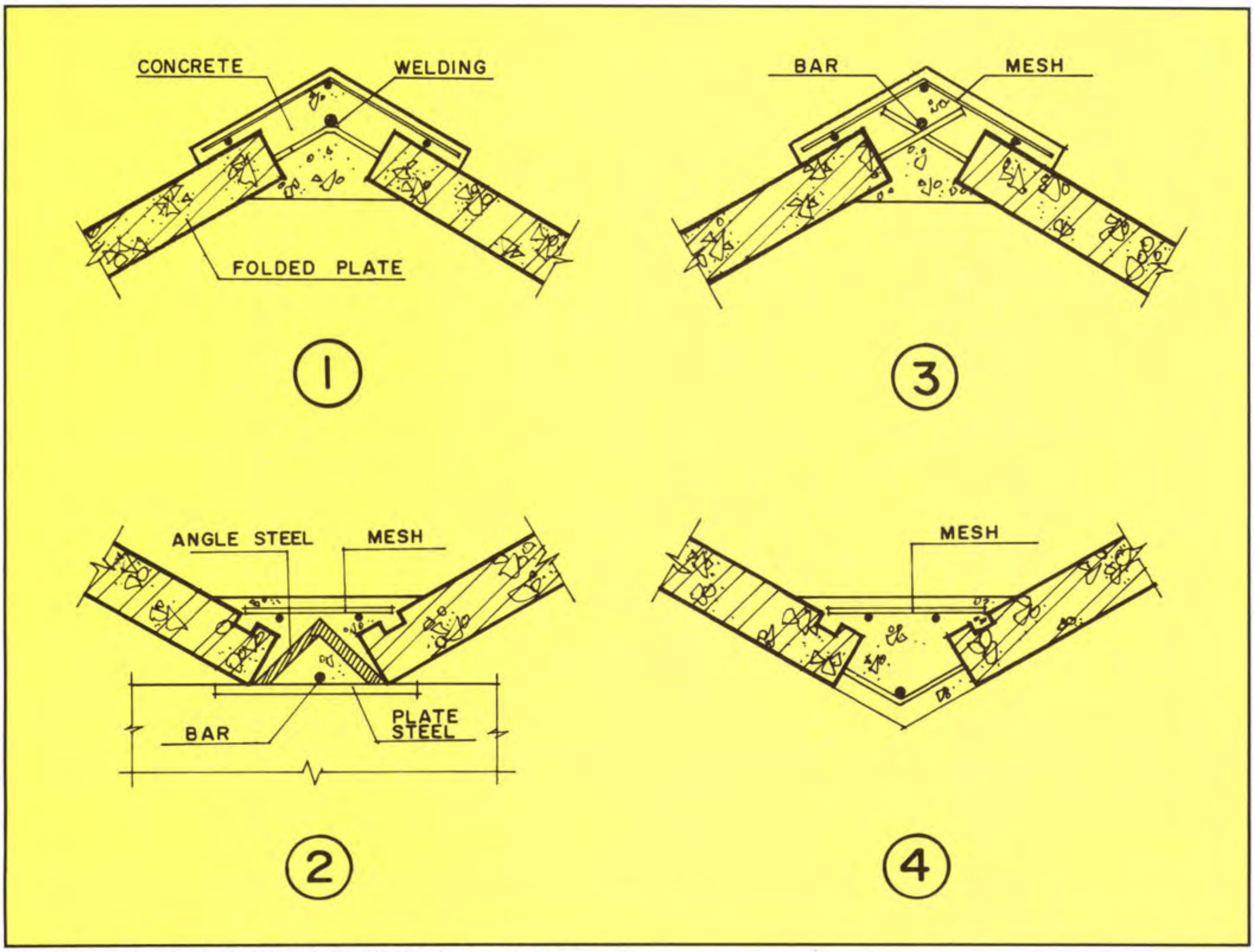

Fig. 30. Joint construction details for the V-plate roof system.