two-dimensional surface. Stereographic and equidistant projections are the most popular for sun-shading analysis.

6.5 SHADING

Shading windows from solar heat gain is a key design strategy for passive cooling and to reduce cooling loads on active HVAC systems. Shading the opaque building envelope is also important, but since thermal resistance is usually greater through such elements than through glazing, the discussion in this section refers primarily to design strategies for shading windows oriented south, east, and west. Northern windows often also need shading devices, contrary to the myth that the north façade never receives direct beam radiation.

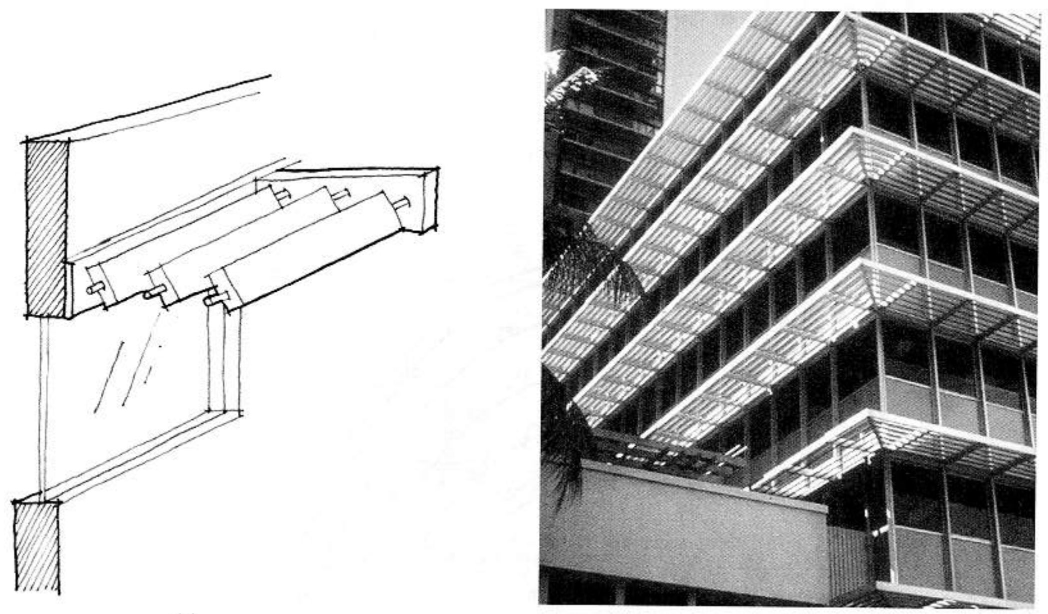
(a) Shading for Orientation

Because of the high altitude of the sun, the most effective shading device for south-facing windows during the summer is a horizontal overhang. On east- and west-facing windows, a horizontal overhang is somewhat effective when the sun is at high positions in the sky but is not effective at low-altitude angles. A variety of shading devices are illustrated by the diagrams and examples in Figs. 6.14–6.18.

Direct solar gain through east- and west-facing windows can be an extraordinary heat gain liability and produce thermal and visual discomfort. During the early design stages, it is best to orient spaces to face north or south to avoid the east/west sun's low angle. If this is not possible, vertical fins are an effective strategy for east and west orientations. Eggcrate shading devices (a combination of overhangs and fins) provide optimal shading particularly in hot climates (Fig. 6.19). North-facing windows receive direct solar radiation in the summer in the early morning and near sunset, when the altitude of the sun is very low. For shading on the north side at these times, vertical fins are most effective.

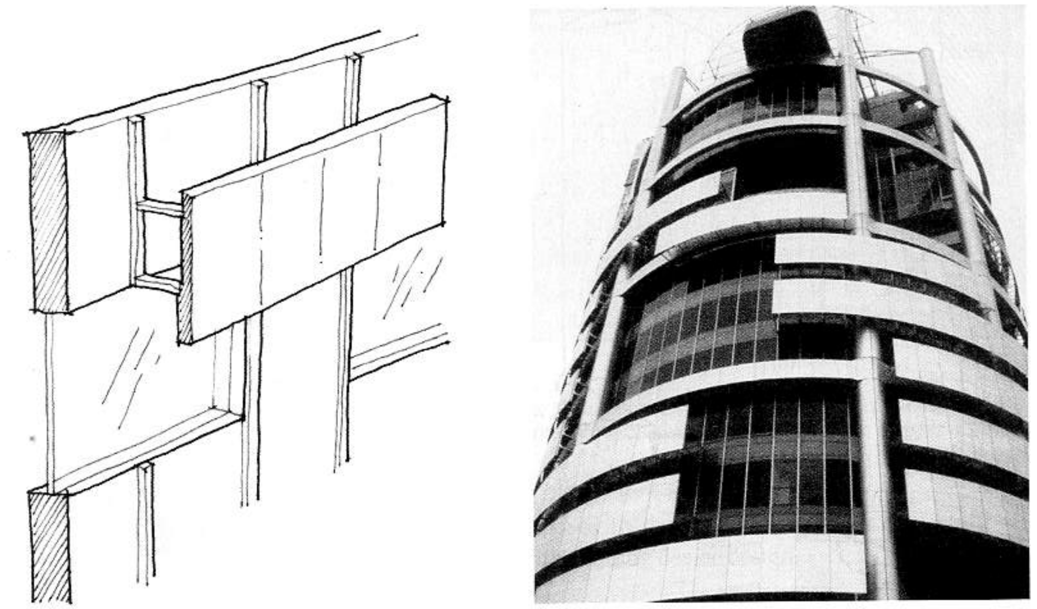
(b) Operable Shading Devices

Operable exterior shading devices are useful because they respond to daily and seasonal variations in solar and weather patterns in ways that fixed shading devices simply cannot do. The operation of a movable shading device can be as simple as twice-a-year adjustment—for example, manually extending roller shades, awnings, rotating fins, or louvers at the beginning of summer and retracting the shade after the hot season has ended (in fall). These devices are very effective at blocking low sun angles from the east or west. More complex movable devices are typically on automated daily and seasonal programs. Although many facility managers are of the opinion that movable exterior shading devices require high maintenance and are prone to malfunctioning, the designer can apply appropriate technology to provide a low-maintenance solution.



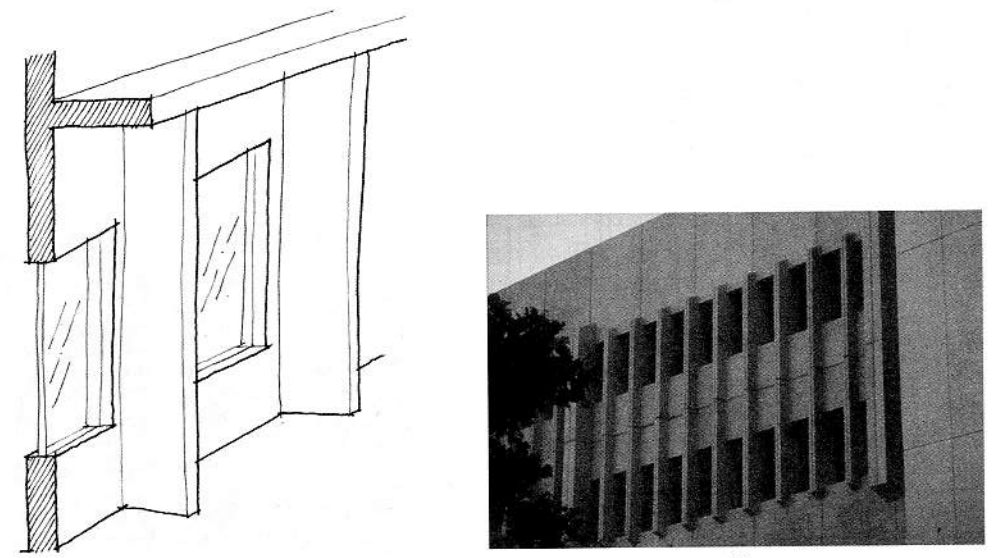
(a) (b)

Fig. 6.14 (a) Overhang with horizontal louvers. (b) Horizontal louvers allow free air movement—office building in Honolulu, Hawaii. (Drawing by Erik Winter, photo by Alison Kwok; © 2004 Alison Kwok; all rights reserved.)



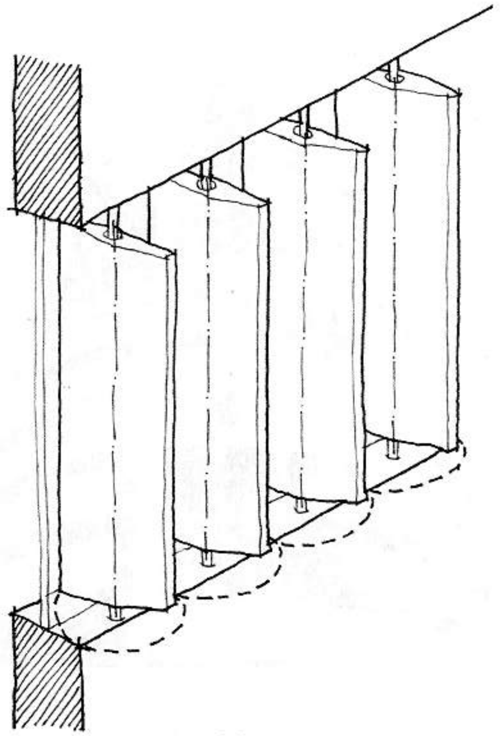
(a) (b)

Fig. 6.15 (a) Overhang using a series of vertical panels. (b) Application of horizontal overhangs at the IBM Tower in Kuala Lumpur, Malaysia. (Drawing by Erik Winter, photo by Alison Kwok; © 2004 Alison Kwok; all rights reserved.)

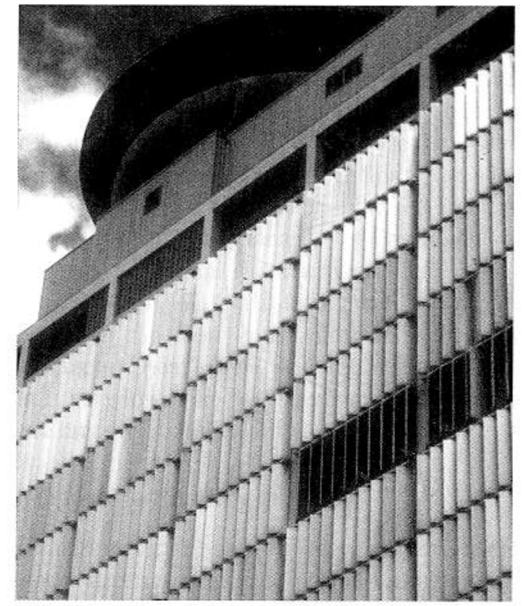


(a) (b)

Fig. 6.16 (a) Vertical fins. (b) Fixed vertical fins on a government building in Honolulu, Hawaii. (Drawing by Erik Winter, photo by Alison Kwok; © 2004 Alison Kwok; all rights reserved.)

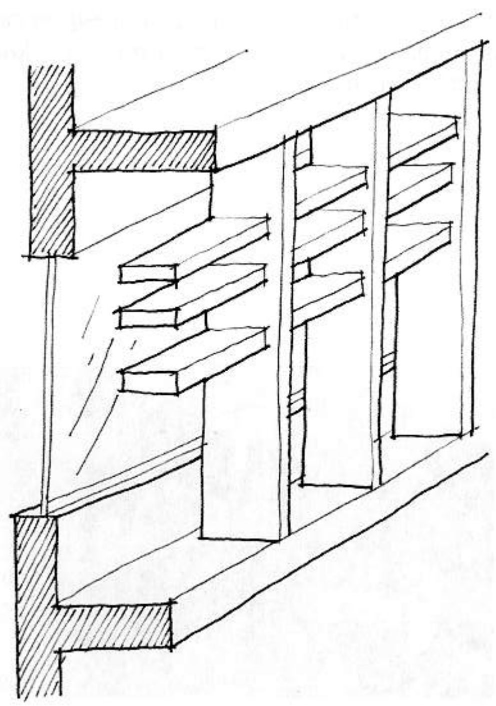


(a)

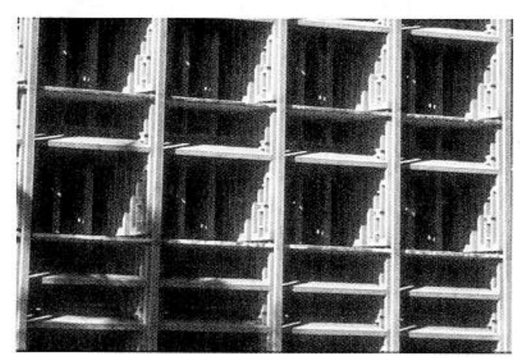


(b)

Fig. 6.17 (a) Movable fins. (b) Movable fins are positioned according to the sun's position at the Ala Moana office building in Honolulu, Hawaii. These effective shading devices were removed when the building was remodeled to make it look more contemporary. (Drawing by Erik Winter, photo by Alison Kwok; © 2004 Alison Kwok; all rights reserved.)

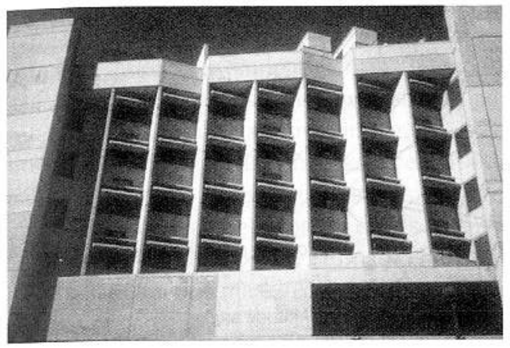


(a)

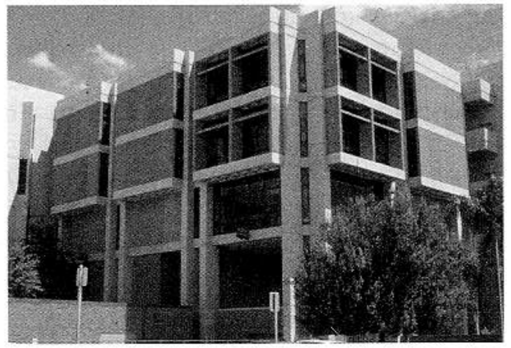


(b)

Fig. 6.18 (a) Eggcrate shading device. (b) Modified eggcrate to allow air movement and lighter structure at the Board of Water Supply in Honolulu, Hawaii. (Drawing by Erik Winter, photo by Alison Kwok; © 2004 Alison Kwok; all rights reserved.)



(a)



(b)

Fig. 6.19 Integration of eggcrate shading devices into the envelope at (a) the Hawaii Medical Services Association building in Honolulu, Hawaii, and (b) the University of Arizona library in Tucson. (Photos by Alison Kwok; © 2004 Alison Kwok; all rights reserved.)

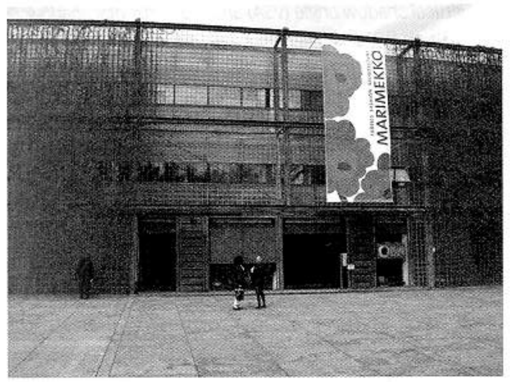


Fig. 6.20 Vines grow on an exterior structure at the Finnish Embassy in Washington, DC. (Photo by Alison Kwok; © 2004 Alison Kwok; all rights reserved.)

Designers can also situate deciduous trees and vines at key locations around a building, which will act as natural shading devices with a natural cycle for shade in the summer and loss of leaves in the winter (Fig. 6.20). Plants have the advantages of costing little, reducing glare, providing an attractive connection to nature, and reducing exterior surface (wall and ground) temperatures.

6.6 SHADOW ANGLES AND SHADING MASKS

Altitude and azimuth angles are very useful in understanding solar position and sunpath diagrams, but are much less useful in defining the shadow angles cast by a projection on a wall exposed to the sun. More angles come into play with shading device design.

(a) Shadow Angles

When designing shading devices, the geometry of the device itself and its relationship to the face of a building produce a number of angles relative to the desired shadow being cast. Since there is no universal nomenclature for these relationships, the angles involved in the design of shading devices will be very carefully defined. Refer to Fig. 6.21, which shows the shadow cast by a horizontal overhang on a wall exposed to sunlight. Note that the shadow is defined by two angles: the *vertical shadow angle* (VSA), which indicates the position of the leading edge of the shadow as defined from the leading edge of the overhang, and the *horizontal shadow angle* (HSA), which defines the leading edge of a shadow cast by a vertical element (indicated by a dashed line) as defined with respect to that element's leading edge. The terms *vertical shadow angle* and *horizontal shadow angle* are in use throughout the world, although in the United States the vertical shadow angle is also known widely as the *profile angle* because it is so designated on the Pilkington Sun Angle Calculator.

Figure 6.22 shows the same information in slightly different form; line *DA* is the shadow cast by line *DE*, which is the intersection between a horizontal projection and a vertical projection. This line is particularly important in determining the required extent of a shading element, as will be shown in the following sections.

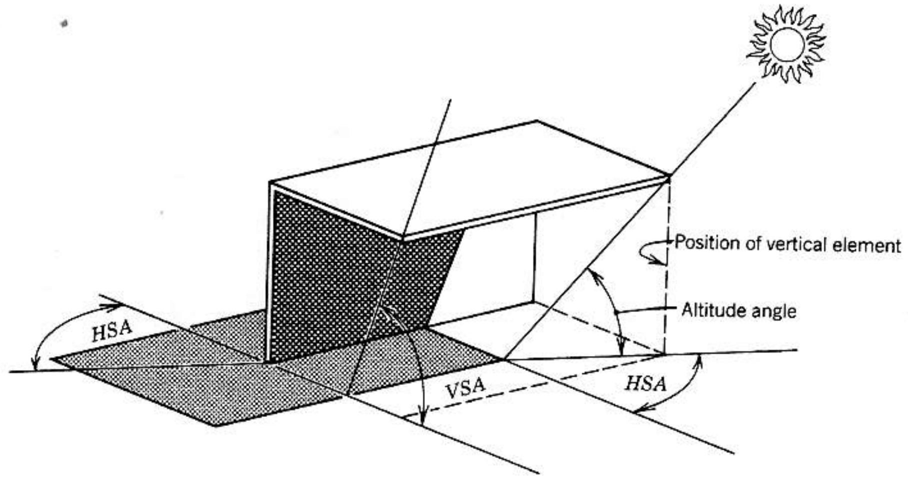


Fig. 6.21 The shadow cast by a horizontal overhang is best defined by the vertical shadow angle (VSA) and the horizontal shadow angle (HSA). The VSA is also known as the profile angle in the United States.

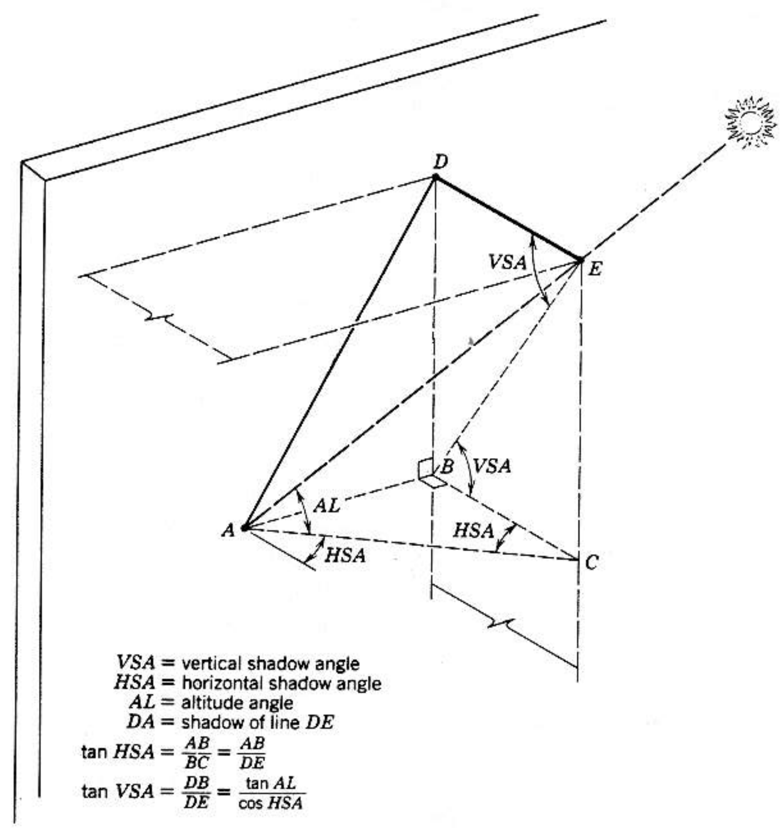


Fig. 6.22 The shadow DA cast by the intersection line DE between a horizontal and a vertical shading element defines the edge of each of these shadows. DE can also be thought of as a pin, normal to and extending from the wall, casting a shadow, DA, on the wall. The location and size of line DA are best defined in terms of angles VSA and HSA.

(b) Shading Masks

A shading mask is a sunpath chart (horizontal projection) that shows the shadow cast by a particular shading device, as shown in Fig. 6.23. For a horizontal shading device, the leading edge of the shadow cast by all horizontal elements with the same VSA (profile angle) projects as a segmental line, and when plotted on the sunpath chart, it is shown as a segmental mask. To draw this segment, a protractor is required. The Pilkington Sun Angle Calculator includes a profile angle protractor (an overlay to the sunpath chart) to draw the required segment. With no shading, there is no shadow, the VSA is 90°, and no segment exists. With a very deep overhang, the VSA approaches 0° and the *unshaded* area shrinks.

For vertical shading elements, such as fins (Fig. 6.23*b*), the leading edge of vertical shading elements forms a shadow, shown as radii projecting from the center, which forms an angle HSA, from a line normal to the wall. These radial lines can be drawn with the assistance of an ordinary protractor or by use of the protractor in Fig. 6.23*c*. The full segments and full radial lines of the shading masks are of *infinitely long elements*, which, of course, do not actually exist. Shading masks that appear in the literature (Olgyay and Olgyay, 1951; AIA, 1981) are frequently drawn as if for infinite elements, and the masks must be truncated for real-world shading design.

(c) Use of Shading Masks

A shading mask is drawn on some transparent medium (e.g., paper or plastic sheet) and laid on top of a sunpath diagram for the proper latitude *drawn to the same scale* (see Fig. 6.24, which illustrates the placement of a shading mask). Its center point is placed on the center point of the sunpath diagram, and it is rotated until its facing direction (the direction normal to the wall) is aligned with the appropriate azimuth line on the sunpath diagram. Assuming that the shading mask has been correctly drawn to provide shading for the window (typically 50% or 100% coverage), the shaded hours for the window and device in question can then be read directly from the underlying sunpath diagram as summarized in Table 6.1. (This is why the shading mask must be drawn on a transparent medium.)

It is extremely important to note that a horizontal overhang shading element the same width as a window can provide full shade for the window only when the sun is exactly opposite the window (when the solar-window azimuth is 0°). This situation occurs for only an instant (Fig. 6.25). At all other times, some part of the window will be exposed to the sun. To provide full shading for more than an instant with a horizontal element and no vertical (side) elements, *an overhang must extend beyond the sides of the window*. The amount of such an extension can be determined both graphically and analytically. Since graphic solutions are amply treated in the literature (Harkness and Mehta, 1978; Lim et al., 1979; Cowan, 1980), the focus here is the analytic solution. In reviewing this discussion, keep in mind the requirement that shading masks for 100% coverage must be prepared so that the extremities of the opening are shaded.

(d) Designing Finite Horizontal Shading Devices

Although any percentage of window shading coverage is possible, most shading devices are designed to give either 50% or 100% coverage. Deciding upon shading coverage is the first step in design. The second step is to establish the required *depth* of the shading device (the distance it projects from the wall). Figure 6.26 shows how the required depth and the corresponding segmental mask are determined. At times, because of window areas left unshaded by the original overhang, it is necessary to determine the required side extensions beyond the window's edges.

Due to the symmetry of solar motion about the ecliptic, the position of the sun is symmetrical on both sides of its maximum/minimum positions, that is, the solstices. Thus, the sun's position on May 21 is the same as on July 21, since both dates are 1 month from the summer solstice. As a result, any *fixed* shading device will give the same shade in the spring (before 21 June) as in the summer (after 21 June). Since in many locations spring is cool, desired late summer shading will produce spring shading that *may not* be desirable. Solutions to this apparent dilemma are either to use a movable or a variable-size fixed shading device or to compromise on the amount of shading, that is, to design for

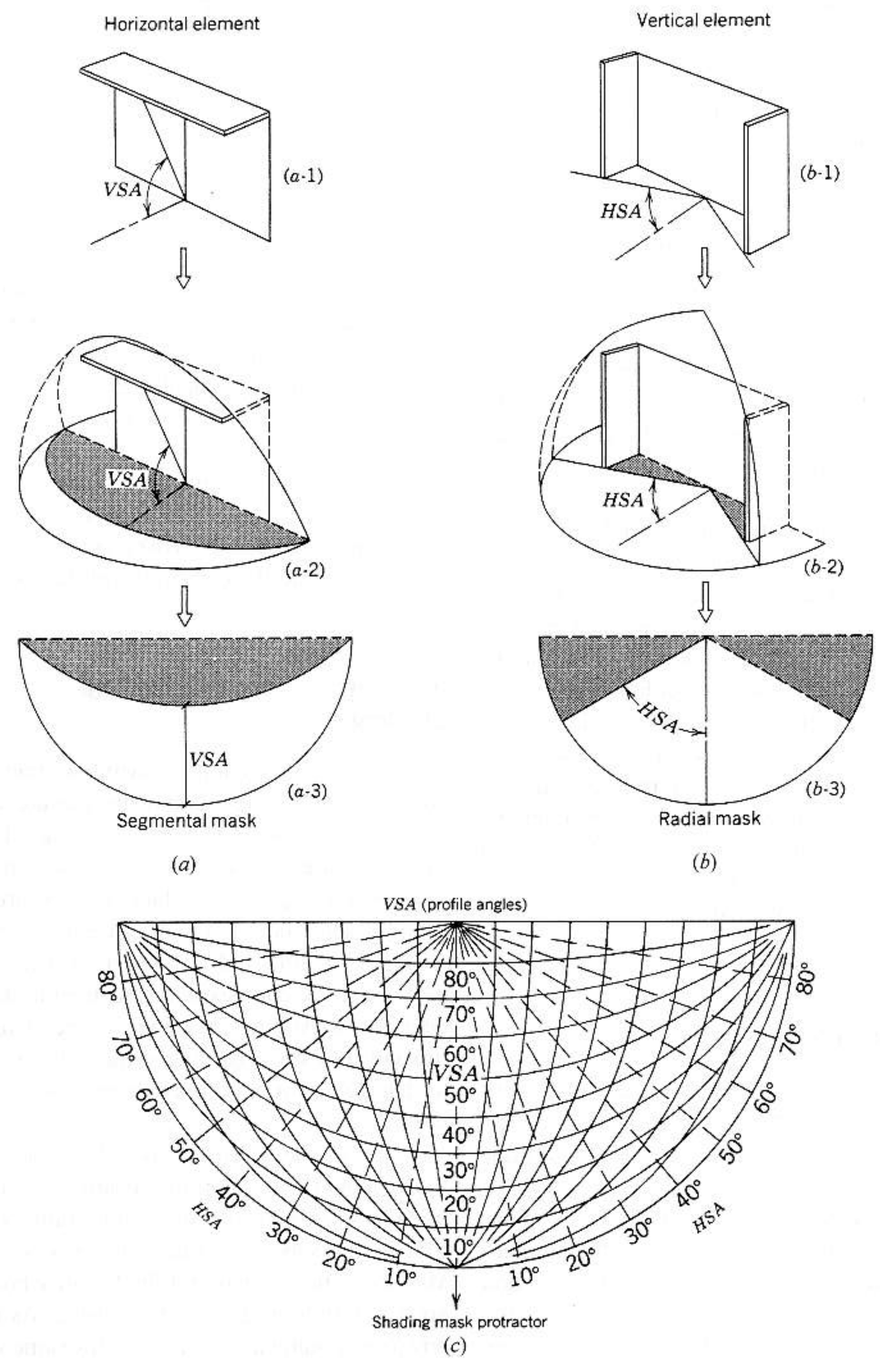


Fig. 6.23 A shading mask is the horizontal projection of the shadow cast by the elements with the same VSA or HSA. Thus, any infinitely long horizontal element with the VSA shown in (a-1) will have a shading mask, as shown in (a-3). Similarly, any infinitely high vertical elements with the HSA shown in (b-1) will have the shading mask shown in (b-3). A protractor (c) is required to draw the segmental horizontal element mask properly.

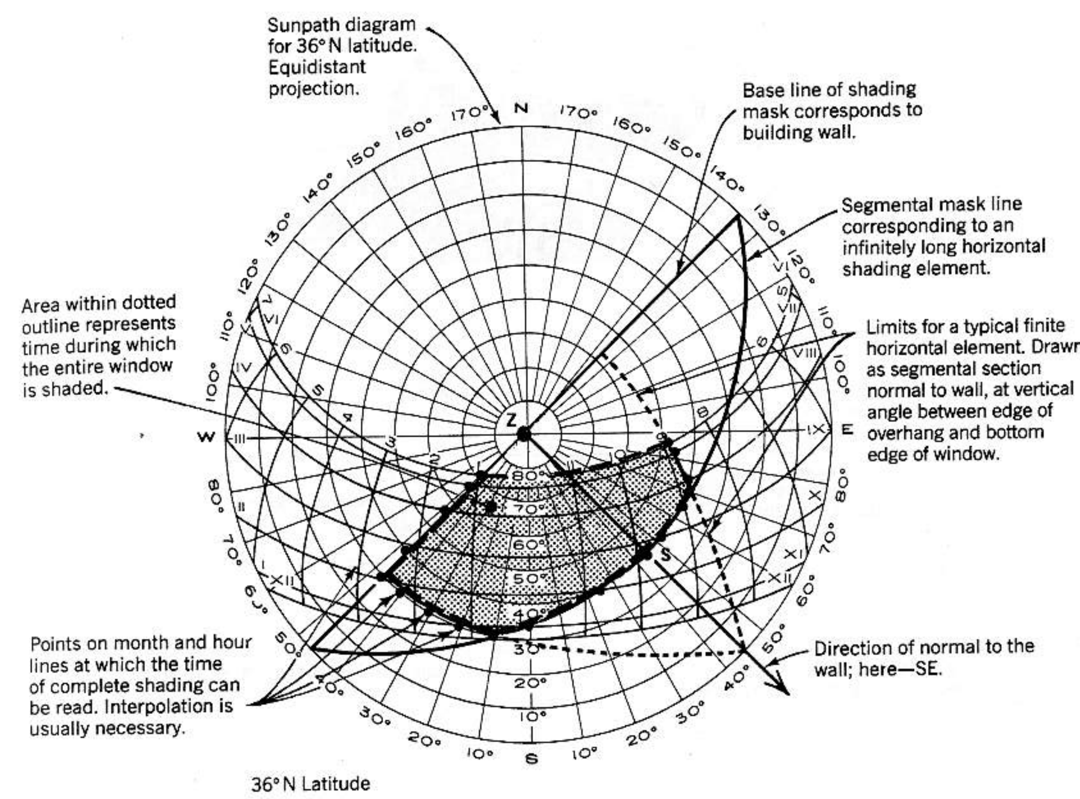


Fig. 6.24 A shading mask for a typical horizontal overhang on a window is laid over a sunpath diagram to permit determination of the shaded hours. The mask is drawn to provide 100% shading for the entire window. The hours during which the entire window is shaded are determined by the intersection of the mask perimeter with the date/hour lines of the sunpath diagram, and are tabulated in Table 6.1. Only during the hours falling within the dotted area is a window fully shaded by an overhang element that is as wide as the window. The shading element shown here is not symmetrical about the center, indicating that an extension to the left was used to provide a larger shade period after noon. This is typical for east-facing windows and is reversed for western exposures.

TABLE 6.1 Time of Day When Window Is Fully Shaded

With Required Overhang Extensions			With Element Same Width As Window
Date	From	To	Time
21 June	0900	1240	1115
21 July/May	0850	1250	1100
21 Aug./Apr.	0845	1330	1035
21 Sept./Mar.	0940	1400	0955
21 Oct./Feb.	1040	1410	—
21 Nov./Jan.	12N	1300	—
21 Dec.	1230		—

50% shading for late summer (and early spring) and 100% shading for early summer (and late spring).

(e) Design Approaches

In addition to the approach just described, design might start with conceptual sketches of an appropriate shading device. As the sketches are developed into scaled drawings, a sectional drawing will show the geometry of the building. The VSA for 100% shading would be an angle from the windowsill to the outer edge of the overhang. Once the VSA is established, a shading mask can be created and overlaid onto the appropriate sunpath chart to determine whether there is adequate shading during specific times of the day and year. A more detailed description of this design process is found in Olgyay and Olgyay (1951).

Shading devices can greatly enrich the aesthetics of a building as well as improve performance. Examples of shading device models for various orientations (Fig. 6.27) show a range of shading design solutions for a building in a temperate climate.

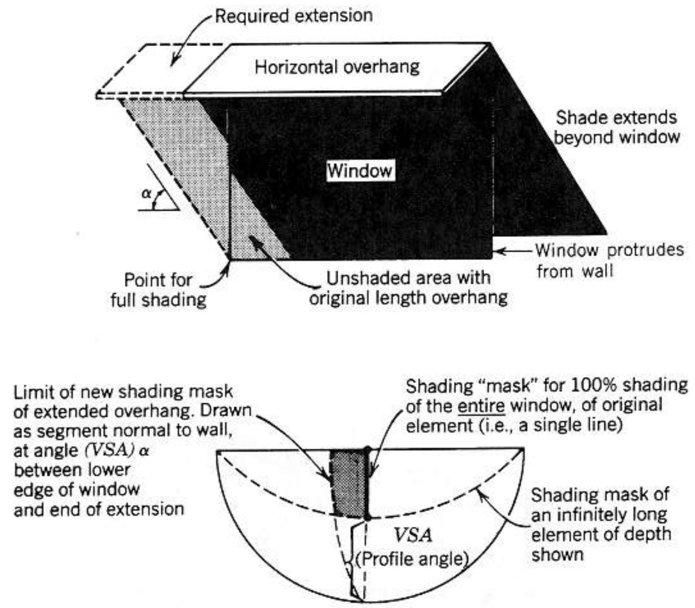


Fig. 6.25 *A horizontal overhang with sufficient depth to provide 100% shading can provide full shading only when the sun is exactly opposite a window. At any other time, part of the window will be exposed to the sun. Full shading from low early morning or late afternoon sun is not possible with horizontal elements.*

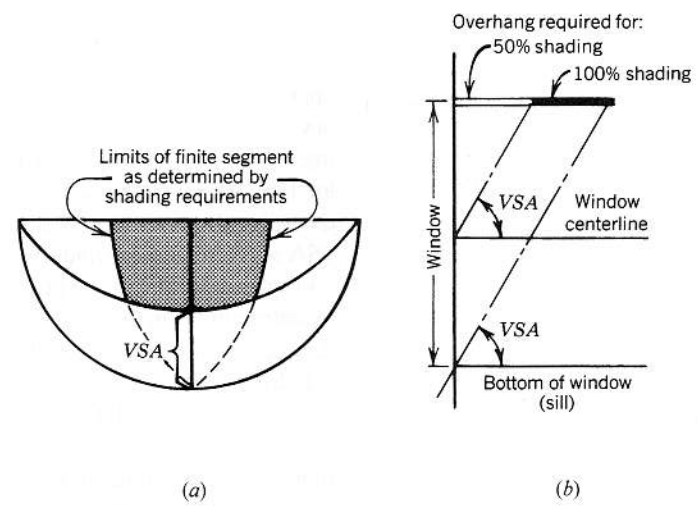


Fig. 6.26 *One way to find the required depth of a horizontal overhang is to establish the required segmental shading mask (a) and read the VSA (profile angle) off the protractor that corresponds to the segment. Draw a wall section (b) to scale with the VSA. The VSA can be drawn for 50% shading coverage, 100% coverage, or any other value. The depth of the overhang can be measured directly from the section. Alternatively, if the overhang depth is known, the segment can be drawn.*

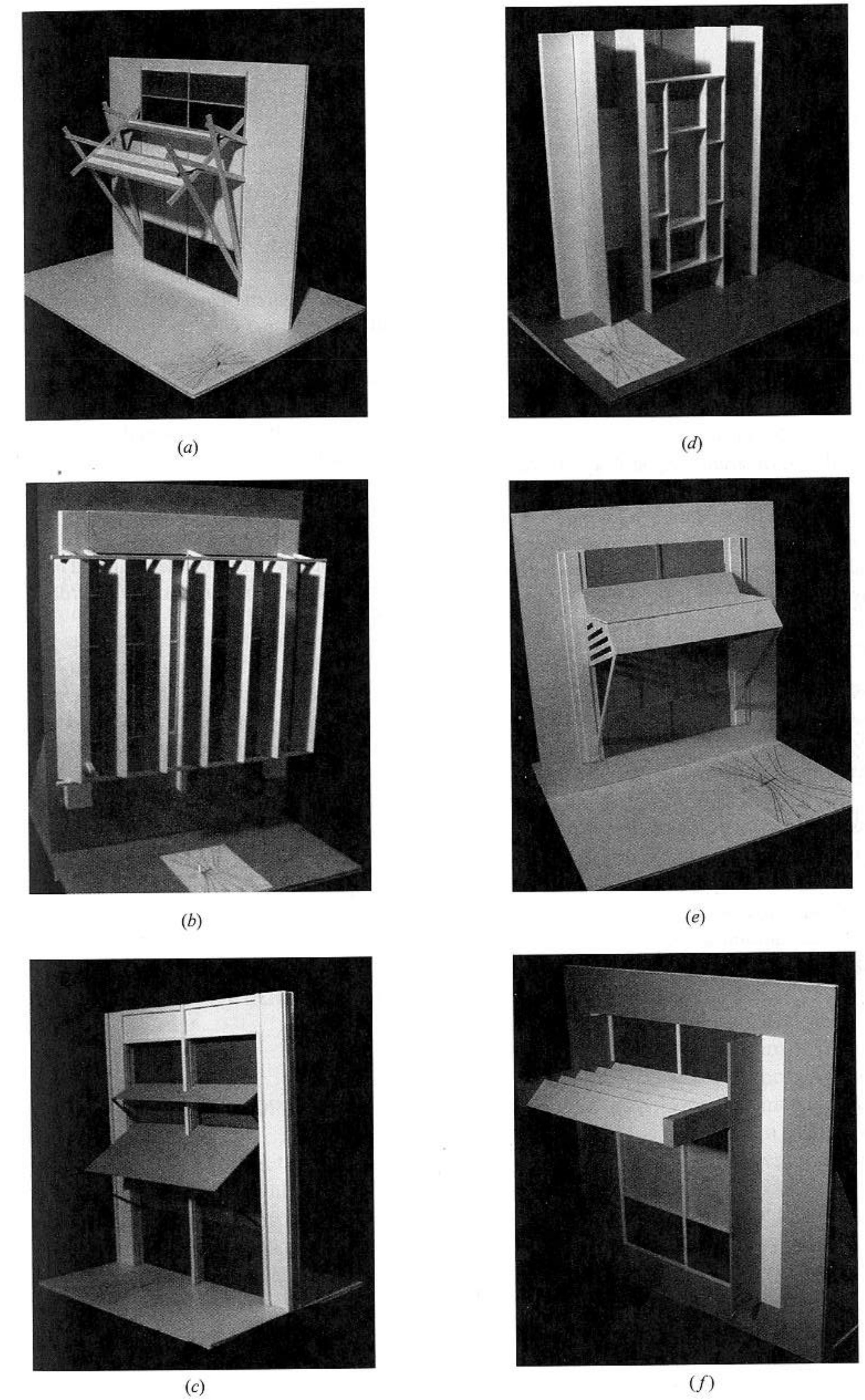


Fig. 6.27 *Examples of shading device models (a–f) illustrate a variety of design responses to orientation, shading requirements, and view for a university building located at 44° N latitude. (Photos by Fumiko Docker; © 2004 Alison Kwok; all rights reserved.)*

THERMAL CONTROL

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Pilkington Sun Angle Calculator. 1975. The Pilkington Sun Angle Calculator (formerly the Libbey Owens Ford Sun Angle Calculator) is available through the Society of Building Science Educators (SBSE). See http://www.sbse.org/resources/sac/index.htm/

Square One Research (solar position tutorial): http://www.squ1.com/archive/ (use menu for topics).

Sundials.org (information on clock vs. solar time): http://sundials.org/faq/tips.htm

Szokolay, S. V. 1980. *Environmental Science Handbook*. Halsted/John Wiley & Sons. New York.

University of Oregon (sunpath diagram software): http://solardat.uoregon.edu/SunChartProgram.html

U.S. Naval Observatory (complete sun and moon data for one day): http://aa.usno.navy.mil/data/docs/RS_OneDay.html

THERMAL CONTROL

CHAPTER 7

Heat Flow

UNDERSTANDING HEAT FLOW IS fundamental to all aspects of climate control. Chapter 4 addresses heat flows to and from the body that affect thermal comfort. Chapters 8, 9, and 10 deal in part with heat flows to, from, and within various elements of active and passive climate control systems. This chapter deals with heat flows through building envelopes, both through the materials of the building skin and by way of outdoor air that replaces conditioned indoor air. Basic concepts and calculations of heat flow are presented in this chapter, whereas applications of these concepts (passive solar heating, passive cooling, active HVAC system/equipment sizing, seasonal energy usage) are found in subsequent chapters. Numerous data tables that accompany this chapter are presented in Appendix E.

7.1 THE BUILDING ENVELOPE

From a building science perspective, the exterior enclosure (or envelope) of a building consists of numerous materials and components that are assembled on site to meet the intents of the owner and the design team. A building envelope typically includes some prefabricated components (such as windows and doors) that are available off the shelf and have well-defined and tested thermal performance characteristics. The typical envelope also includes materials in a variety of forms (sheets, blocks, bulk products, membranes, etc.) that have been site-assembled to meet design requirements. These components and materials may be assembled into commonly used configurations with generally understood performance or into configurations unique to a given project and of uncertain performance. The job of envelope thermal analysis is to ensure that a proposed envelope will meet the design intent and criteria (including building codes).

From a functional perspective, the envelope of a building is not merely a two-dimensional exterior surface; it is a three-dimensional transition space—a theater where the interactions between outdoor forces and indoor conditions occur under the command of materials and geometries. Sun and daylight are admitted or rejected; breezes and sounds are channeled or deflected; and rain is repelled or collected. This transition space is where people indoors can experience something of what the outdoors is like at the moment, as well as where people outside can get a glimpse of the functions within. Figure 7.1 shows an example of an envelope that is a transitional space, not merely a surface. The more suited the outdoors is to comfort, the more easily indoor activity can move into this transition space. At building entries, a person will be especially aware of the difference between indoors and outdoors during the passage between the two conditions.

The envelope has a fourth dimension: it changes with time. Seasonal changes have a marked effect on the façade shown in Fig. 7.1 and