CHAPTER IV

EXPERIMENTAL DESIGN

4.1 SCHEMATIC APPROACH

The primary objective of this study was to investigate how atrium canopy systems affect the daylighting environment in atrium spaces which are already affected by the atrium structure itself. This schematic approach is the reverse sequence of the natural behaviors of daylight and sunlight in atrium buildings. As discussed through the literature reviews, the intensity of daylight and sunlight is first admitted by canopy systems; and then distributed by the atrium well structure. The current approach is based on the sequence of practice in atrium building design as follows:

1) The overall structural configuration (plan and height) of a building is determined by considering the site restrictions, building program requirements, economic factors, and urban context, etc.

2) Then, the designer determines arrangement of interior spaces, the areas of internal glass windows and solid walls, and wall material and finish, etc.

3) The final step is to make a decision on the canopy system to cover the atrium aperture by considering a prevailing climatic condition, required lighting conditions, and amenities. This step requires lighting evaluation criteria, appropriate evaluation tools, and information on the characteristic lighting performance of various canopy types. With the tools and information, the designer can predict the lighting conditions governed by the external conditions and the atrium structure itself. Then, the designer can decide upon a suitable canopy system to meet the criteria based on the final lighting conditions modified by the canopy systems.

Figure 4.1 shows the conceptual diagram of the schematic approach to the lighting measurements. As shown in the figure, the unobstructed illuminances on an exterior horizontal surface is measured first. Then, the illuminances on the floor and the luminance distributions on the interior wall surfaces are measured in the absence of canopy systems. These quantities are recorded as "base cases". Then, the same light quantities measured in the presence of canopy systems are used as identifiers of the lighting performances of canopy systems.

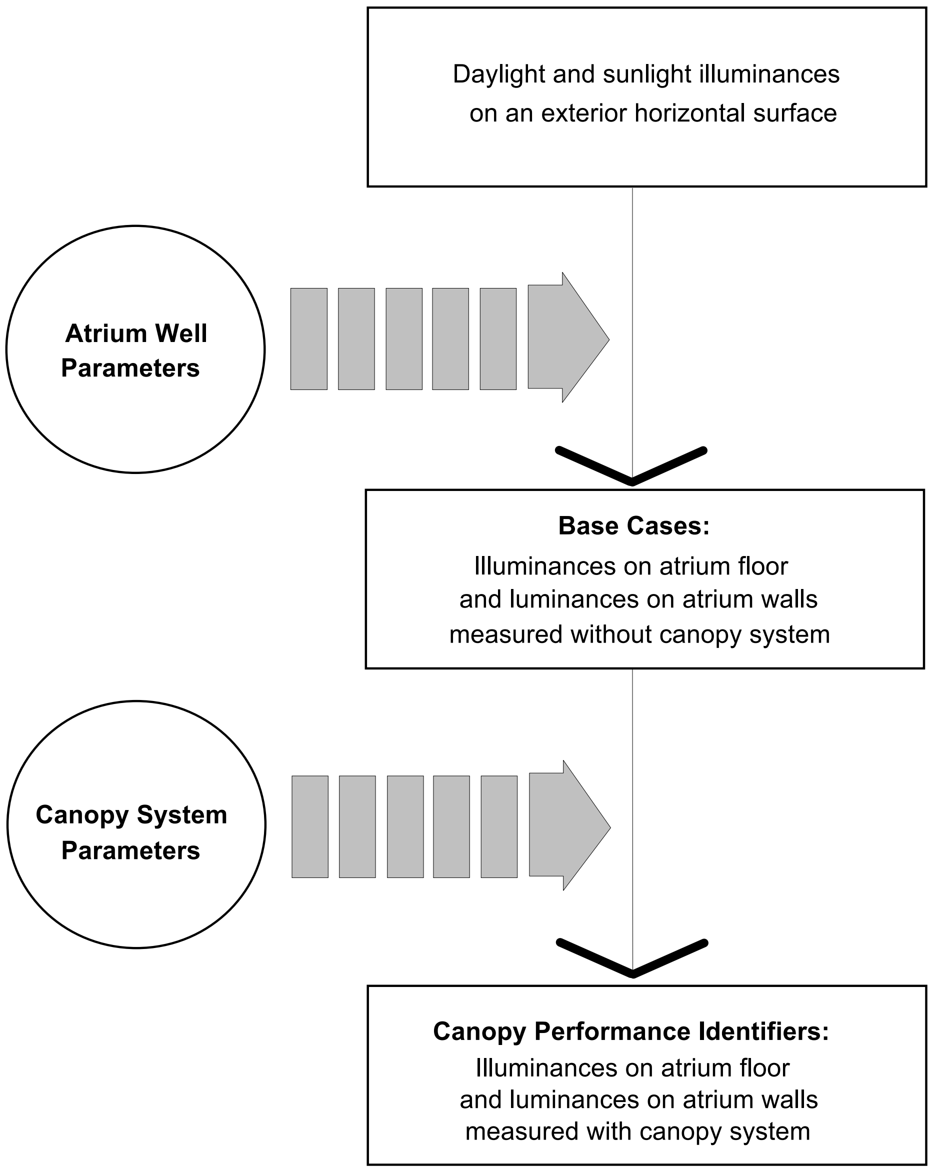

Figure 4.1 Schematic Approach to Lighting Measurements

4.2 RESEARCH VARIABLES

4.2.1 Dependent Variables

Two primary dependent variables concerned with interior illumination levels include Daylight Factor (DF) and Sunlight Illuminance Ratio (SIR). These two variables are the ratio of internal illuminances on the atrium floor to external illuminances from diffuse sky and direct sun as given in Equation 4.1 and Equation 4.2, respectively.

$$DF = \frac{E_{di}}{E_{do}} \tag{4.1}$$

where E_{di} = indoor horizontal illuminance measured under diffuse sky
E_{do} = outdoor horizontal illuminance from diffuse sky

$$SIR = \frac{E_{si}}{E_{so}} \tag{4.2}$$

where E_{si} = indoor horizontal illuminance measured under direct sunlight only
E_{so} = outdoor horizontal illuminance from direct sunlight only

A secondary dependent variable is Luminance Ratio (LR) on atrium walls calculated from wall luminances determined by the video-based luminance mapping system. Conventional Luminance Ratio is calculated with the average luminance of visual task area and the average luminance of remainder of the field of vision as given by Equation 4.3. However, in this study, since no specific task areas can be designated in atrium spaces, the Luminance Ratios between contiguous areas on atrium walls defined by solid walls and glass windows are considered.

$$LR = \frac{L_v}{L_s} \tag{4.3}$$

where L_v = average luminance of visual task area
L_s = average luminance of remainder of the field of vision (surrounding)

An additional dependent variable is concerned with the geometric properties of sunlight patches on the atrium walls as discussed in Chapter 2. The Sunlight Patch Locations (SPL), which are expressed by the elevation angles of sunlight patch areas, are examined in terms of the view angles of the human eye to test if the sunlit areas are located within the normal field of view. In addition, the Sunlight Patch Sizes (SPS) in terms of Configuration Factors of the sunlit areas are compared with the criterion recommended by a previous study (Boubekri et al. 1991). The previous study found that the size of sun patch area from 15 % to 25 % of total floor area was optimal for occupants' environmental satisfaction with 40 % as maximum. Even though the previous study dealt with a sidelighted room and sun patch areas on the room floor, the criterion might be applied to sun patches on the atrium wall areas.

4.2.2 Independent Variables

In this study, the primary independent variables are those concerned with the geometric configuration of the atrium space and the outdoor conditions.

The independent variable concerned with the atrium space is Well Index value (WI). With the geometry of an atrium shown in Figure 4.2, the Well Index is a measure of the well height relative to the width and length of atrium floor given by Equation 4.4. Using the relationship, for a cubical volume the value is 1.0, for two stacked cubes 2.0, etc.

$$WI = \frac{h\,(l + w)}{2\,l\,w} \tag{4.4}$$

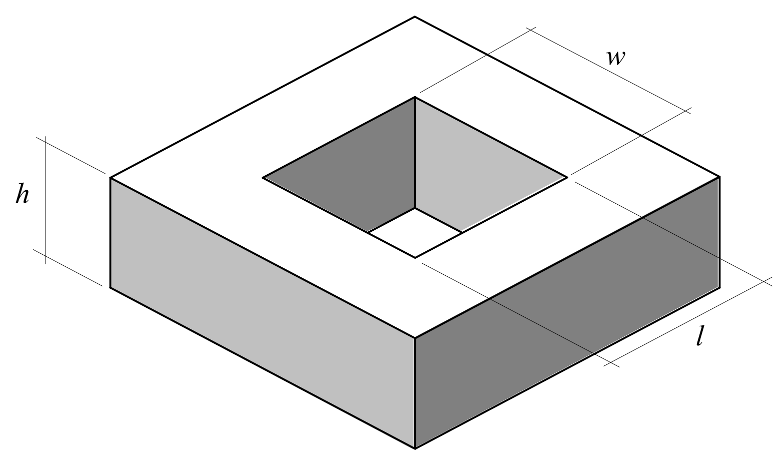

Figure 4.2 Geometry of Atrium

The independent variables connected with outdoor conditions include sky condition and sun altitude angle. In this study, three different outdoor conditions include: overcast sky, clear sky without sun, and direct sun.

A clear sky which has 1:3 of zenith-to-horizon luminance ratio was simulated with only the fluorescent lamps turned on, while an overcast sky which has 3:1 of zenith-to-horizon luminance ratio was created with half of the HID lamps turned on.

The variations in the sun altitude angle were decided by considering three different seasons (June 21, September 21, and December 21) for three different latitudes (high, middle, and low). Table 4.1 summarizes the geographic locations and sun altitude angles at solar noon hours.

TABLE 4.1
Three Geographic Locations and Sun Altitude Angles at Solar Noon

Location	Latitude	Longitude	Jun. 21	Sep. 21	Dec. 21
Houston, TX	29.5N	93.1W	84.0°	60.3°	37.1°
Oklahoma City, OK	35.3N	97.3W	78.2°	54.5°	31.3°
Minneapolis, MN	44.6N	95.2W	68.9°	45.2°	22.0°

4.2.3 Confounding Independent Variables

Since the illuminance levels and luminance distributions produced by the interactions between atrium well geometry and outdoor conditions will be affected again by the canopy systems, variables connected with canopy systems were defined as confounding independent variables. The variables in conjunction with the geometric and photometric properties of the canopy systems vary with canopy form types, which will be discussed later in detail.

4.2.4 Constants

Since there are too many variables involved in atrium daylighting design, certain features were set to constants. The wall and floor reflectances were set to constants by considering real situations in which atrium walls usually contain large areas of glass window and bright solid materials and the floor usually includes low-reflectance trees and ground-cover plants.

To determine the reflectances of the wall and floor material, illuminance and luminance on the materials were measured under a diffuse lighting condition in the sky simulator. Then, the reflectances were determined by Equation 4.5.

$$\rho = \frac{\pi L}{E} \times 100[\%] \tag{4.5}$$

where ρ = reflectance [%]
L = luminance [cd/m^2]
E = illuminance [lux]

The measured light quantities and the calculated reflectances of the materials are shown in Table 4.2.

TABLE 4.2
Measured Reflectances of Floor and Wall Materials

Material	Illuminance	Luminance	Reflectance
Bare cardboard for atrium floor	480 lux	46 cd/m²	30 %
White cardboard for solid wall area	480 lux	130 cd/m²	85 %

Since the reflectance of window glass varies with incident angles of light, instead of specifying the reflectance, the ratio of window area to total wall area was set to a constant which was 40 %.

Table 4.3 summarizes the variables and constants of daylighting design elements involved in the parametric lighting measurements.

TABLE 4.3

Variables and Constants for Parametric Lighting Measurements

Design Element	Name	Type
Interior lighting condition	Daylight Factor (DF)	Dependent variable
	Sunlight Illuminance Ratio (SIR)	Dependent variable
	Luminance Ratio (LR)	Dependent variable
	Sun Patch Location (SPL)	Dependent variable
	Sun Patch Size (SPS)	Dependent variable
Exterior condition	Clear sky	Independent variable
	Overcast sky	Independent variable
	Sun altitude angle	Independent variable
Atrium well	Well Index (WI)	Independent variable
	Solid wall reflectance	Constant (85%)
	Floor reflectance	Constant (30%)
	Window-to-wall area ratio	Constant (40%)
Canopy system	Varies with canopy type (discussed in the next section)	Confounding independent variables

4.3 ATRIUM AND CANOPY SCALE MODELS

4.3.1 Scale Models for Target Atrium Well

Four-sided square atrium spaces with different well heights were selected as target atria. The Well Index values range from 0.6 to 2.4 with an increment step of 0.3. This range considers the majority of real atrium buildings which have Well Index values ranging from 1 to 2 (Bednar 1986, p. 66).

In order to create atrium spaces with the varying Well Index values, a total of 32 rectangular atrium side modules measuring 20(*w*) x 6(*l*) x 6(*h*) in. were constructed in 1/2 in. = 1 ft scale using cardboard sheets. One of the four long-sided surfaces of each module has the 1.5 in. high window sill and the window area of 17(*w*) x 3(*h*) in. The window area was covered by 1/16 in. thick clear plastic sheet to simulate the specular effect of window glass. The remaining solid area was painted flat white. On the other hand, another long-sided surface was painted flat black to measure Sky Component (SC) by facing the black wall toward the atrium space.

As this study focused on daylighting and sunlighting in the atrium space itself, the inside surface of the modules were painted flat black so that light transmitted into the modules through the windows cannot be reflected back into the atrium space. This method ensures that the net effects of atrium canopy systems and atrium wall configurations can be measured and analyzed. Figure 4.3 shows the nominal dimensions of a unit of the atrium side module and the floor plan. Figure 4.4 shows an example of the atrium model. The atrium codes and Well Index values are shown in Table 4.4.

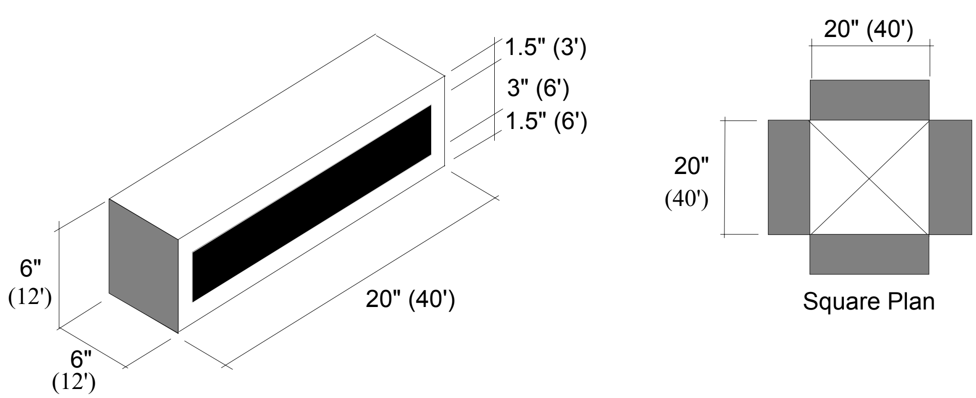

Figure 4.3 Atrium Side Module and Floor Plan

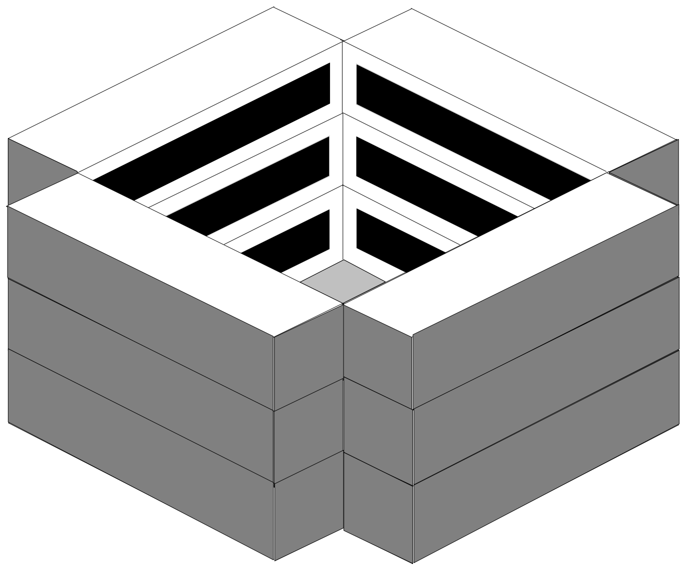

Figure 4.4 An Example of Atrium Model

TABLE 4.4
Seven Atrium Codes and Well Index Values

Atrium Code	No. of Stacks	WI
A2	2	0.6
A3	3	0.9
A4	4	1.2
A5	5	1.5
A6	6	1.8
A7	7	2.1
A8	8	2.4

4.3.2 Scale Models for Target Canopy Systems

The target canopy systems selected in this study included six different types: 1) sawtooth with vertical aperture, 2) sawtooth with sloping aperture, 3) flat horizontal, 4) barrel vault, 5) pyramid, and 6) multiple unit with waffle structure. All canopy systems were assumed to cover the entire area of the atrium opening of 20(w) x 20(l) in. By giving variations in geometric and/or photometric properties to each canopy system, a total of 36 canopy systems were tested. The following statements describe variations in each canopy type.

1) Sawtooth with vertical aperture: These canopy systems were constructed using 1/8-inch thick white cardboard sheets. The variations for this type were three different numbers of sawtooth units (2, 4, and 8) and four different slope angles (15°, 25°, 35°, and 45°) of the opaque panels. With the different slope angles of the opaque panels, the vertical-aperture-to-floor-area ratios became 0.3, 0.5, 0.7 and 1.0 for 15°, 25°, 35°, and 45° panel slope angles, respectively, regardless of the number of sawtooth units. Meanwhile, the horizontally-projected-aperture-to-floor-area ratio became zero. The glazing material for all sawtooth systems was assumed to be clear transparent. In addition, the reflectances of inside and outside surfaces were measured at 85 %. The geometric properties of this canopy type are given in Table 4.5. Figure 4.5 shows the top views and sections.

TABLE 4.5
Variations in Sawtooth Canopies with Vertical Apertures

Number of Units	Slope Angle of Opaque Panel	Vertical-Aperture-to-Floor-Area Ratio
2, 4, and 8	15°	0.3
2, 4, and 8	25°	0.5
2, 4, and 8	35°	0.7
2, 4, and 8	45°	1.0

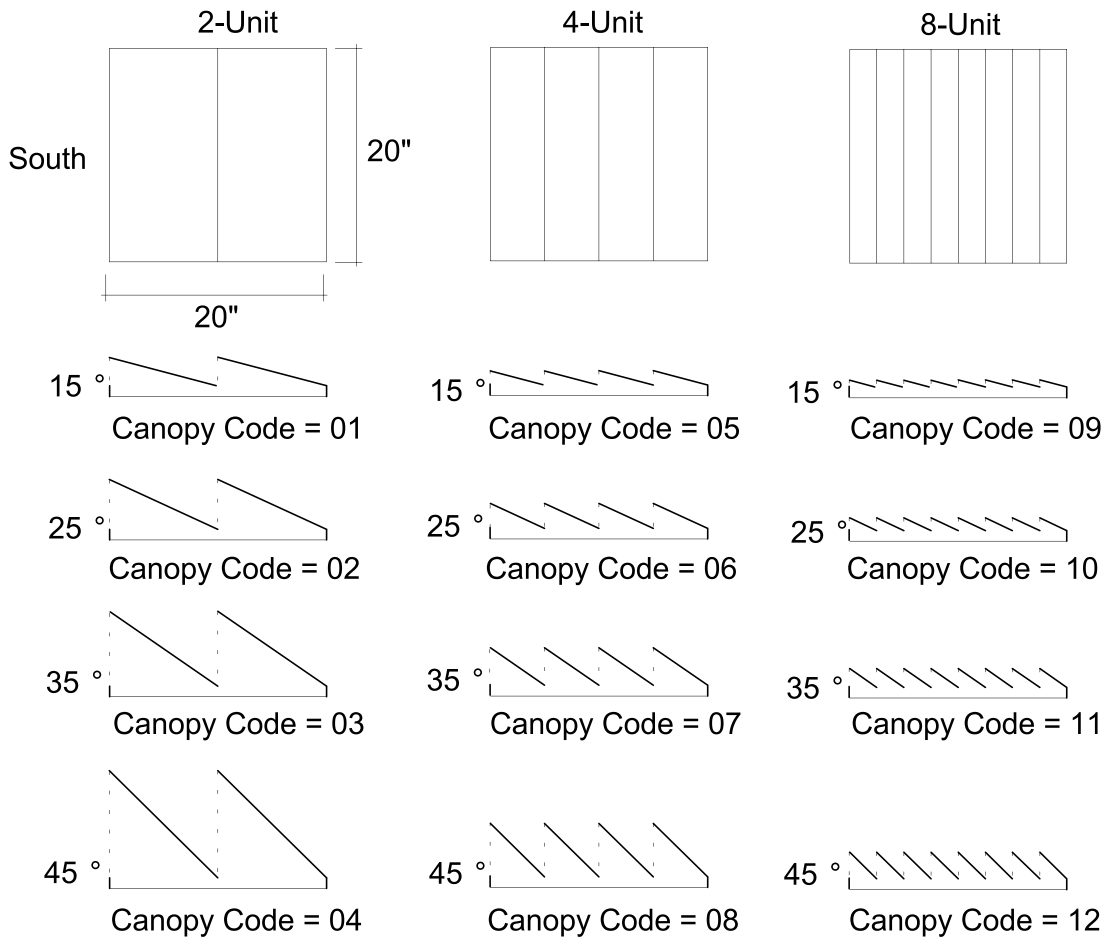

Figure 4.5 Top Views and Sections of Sawtooth Canopies with Vertical Apertures

2) Sawtooth with sloping aperture: These canopy systems were also constructed using white cardboard sheets. For this type, the number of sawtooth units was fixed to four. The aperture slope angles were 15°, 30°, 45°, and 60°. The total area of the sloping aperture was also fixed to 50 % of the floor area. However, differently from the previous sawtooth systems, this type had different horizontally-projected-aperture-to-floor-area ratios. With the given aperture slope angles, the ratio became 0.48, 0.43, 0.35, and 0.25 for 15°, 30°, 45°, and 60° slope angles, respectively. The geometric properties of this canopy type are given in Table 4.6. Figure 4.6 shows the top views and sections.

TABLE 4.6
Variations in Sawtooth Canopies with Sloping Apertures

Number of Units	Aperture Slope Angle	Sloping-Aperture-to-Floor-Area Ratio	Projected-Aperture-to-Floor-Area Ratio
4	15°	0.5	0.483
4	30°	0.5	0.433
4	45°	0.5	0.354
4	60°	0.5	0.250

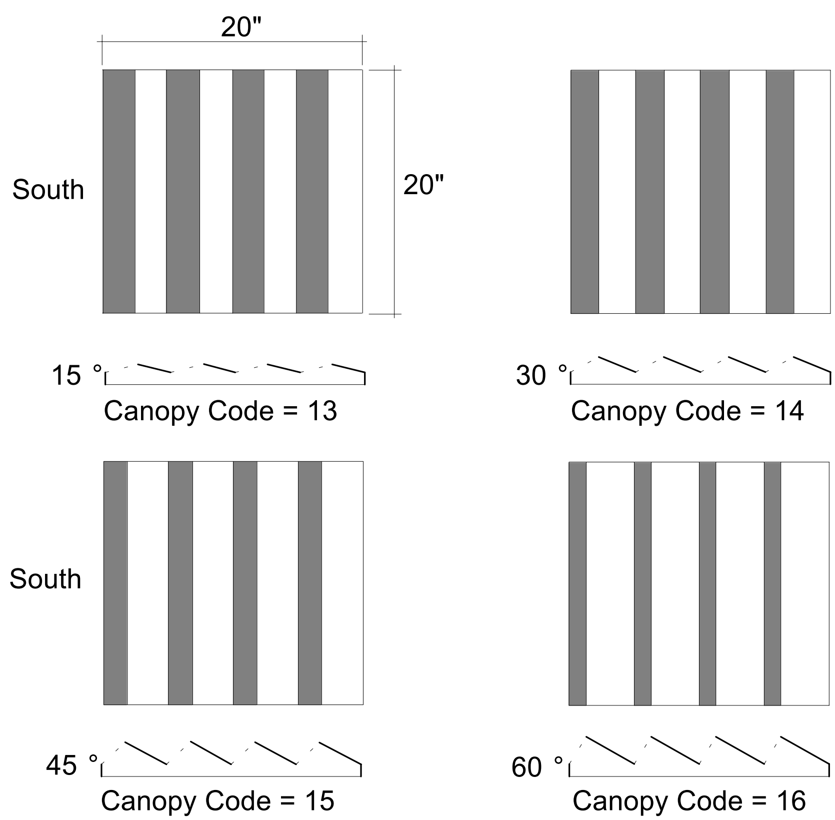

Figure 4.6 Top Views and Sections of Sawtooth Canopies with Sloping Apertures

3) Flat horizontal skylight: The most frequently used structure for this type of canopy system is a space frame which consists of linear members. The structural members were simulated by 1/8-inch thick linear wooden material as shown in Figure 4.7. Since this type always involves a large glazing area, glazing materials with different transparencies and transmittances were used as variations. The glazing materials and the manufacturer's specification of optical transmittance will be discussed later. A factor to be considered for skylight systems involving opaque linear material is the Framing Factor (FF). Since the FF varies with viewing direction, only that of horizontally projected structure was calculated as 44 % by the relationship given in Equation 4.6.

$$FF = \frac{\sum_{i=1}^{n} (l_i \times \delta_i)}{A} \times 100\,[\%] \qquad (4.6)$$

where l_i = length of each linear member
δ_i = thickness of each linear member
n = number of linear members
A = bottom area

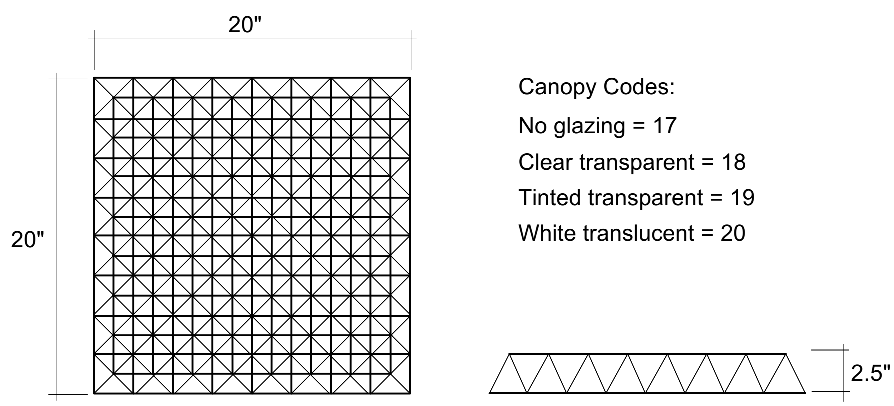

Figure 4.7 Top View and Elevation of Flat Horizontal Skylight

4) Barrel vault skylight: The structural members for this type was constructed by cardboard sheets measuring 1/8-inch thick and 1/2-inch high. The major variations were

also glazing materials. The horizontally projected Framing Factor (FF) was 36%. The top view and front elevation are shown in Figure 4.8.

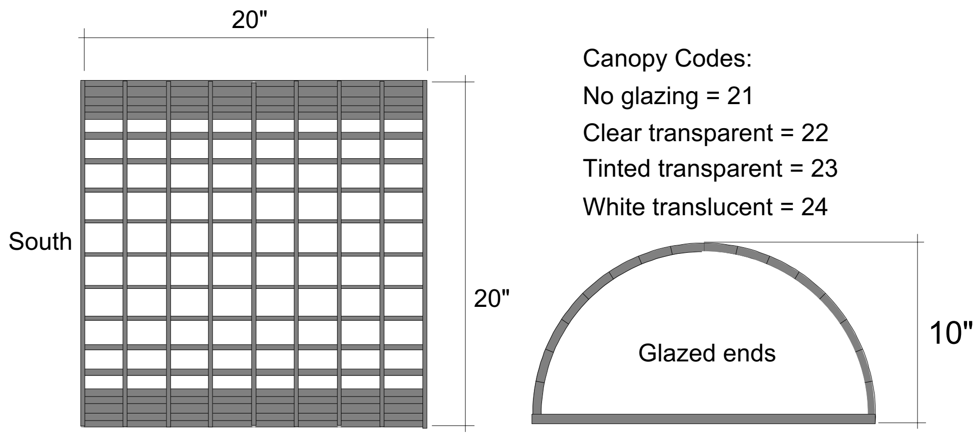

Figure 4.8 Top View and Front Elevation of Barrel Vault Skylight

5) Pyramid skylight: The structure for a pyramid skylight was constructed with a rectangular linear wooden material measuring 3/16-inch thick and 1/2-inch high as shown in Figure 4.9. The scaled dimension of the structural member represented 3-inch thick and 10-inch high in full scale. A variation in this type was also the glazing material. The projected Framing Factor (FF) was calculated as 17 %.

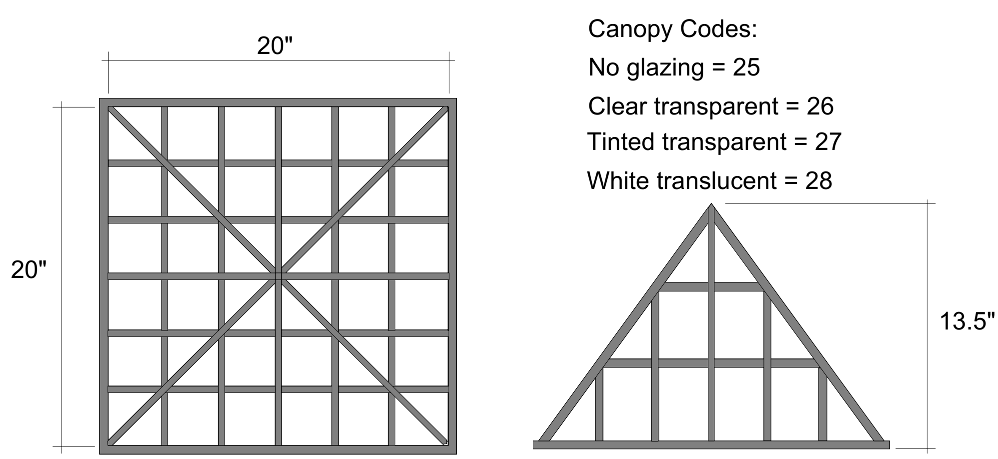

Figure 4.9 Top View and Elevation of Pyramid Skylight

6) Waffle skylight: Waffle skylights were constructed using cardboard sheets. Since this type involves mainly solid structures, the geometric configuration and reflectance of the panel surface were given variations. One compete waffle skylight system included a total of 100 skylight wells of 2(*w*) x 2(*l*) in. The geometric configuration of each skylight cell was then given by differentiating the heights of the cells varying from 1 in. to 4 in. with a step of 1 in. Similarly to atrium well geometry, the term Waffle Well Index (WWI) was used to characterize the geometric configuration of this canopy type. The reflectance of the structure was given two different values by using the raw cardboard (ρ = 30 %) and white cardboard (ρ = 85 %) sheets. Figure 4.10 shows the plan and elevations of waffle skylights with different WWI values.

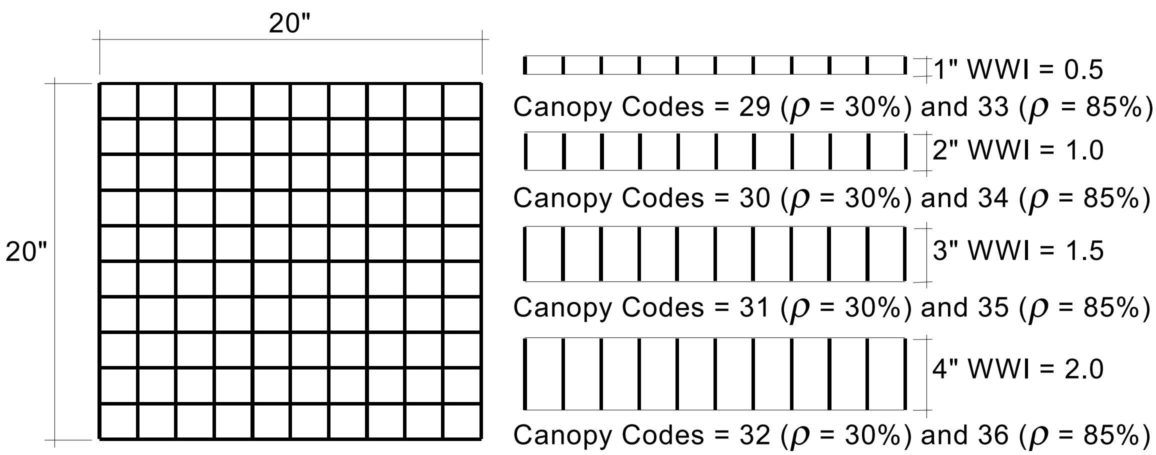

Figure 4.10 Top View and Sections of Waffle Skylights

4.3.3 Glazing Materials for Canopy Scale Models

The glazing materials to cover the scale models of canopy systems were 1/8-inch plastic products frequently used for real canopy systems in practice. The three different glazing materials included: 1) clear transparent Polycarbonate, 2) dark tinted transparent Polycarbonate, and 3) white translucent Acrylic. The optical properties and manufacturer-specified diffuse transmittances are shown in Table 4.7. The combinations of the canopy types and the glazing materials produced a total of 36 different canopy systems including skylight structures without glazing materials as described in Table 4.8.

TABLE 4.7

Optical Properties of Three Selected Glazing Materials

Material	Color	Transparency	Transmittance
Polycarbonate	Clear	Transparent	90 %
Polycarbonate	Dark tinted	Transparent	50 %
Acrylic	White	Translucent	40 %

TABLE 4.8

Description of 36 Canopy Systems

Canopy Code	Description *
00	No canopy (Atrium with open top)
01	2-unit 15° sawtooth with vertical aperture
02	2-unit 25° sawtooth with vertical aperture
03	2-unit 35° sawtooth with vertical aperture
04	2-unit 45° sawtooth with vertical aperture
05	4-unit 15° sawtooth with vertical aperture
06	4-unit 25° sawtooth with vertical aperture
07	4-unit 35° sawtooth with vertical aperture
08	4-unit 45° sawtooth with vertical aperture
09	8-unit 15° sawtooth with vertical aperture
10	8-unit 25° sawtooth with vertical aperture
11	8-unit 35° sawtooth with vertical aperture
12	8-unit 45° sawtooth with vertical aperture
13	4-unit sawtooth with 15° sloping aperture
14	4-unit sawtooth with 30° sloping aperture
15	4-unit sawtooth with 45° sloping aperture
16	4-unit sawtooth with 60° sloping aperture

* Note: All sawtooth and waffle canopies were examined without glazing materials.

TABLE 4.8
Continued

Canopy Code	Description *
17	Flat horizontal skylight without glazing (FF = 44 %)
18	Flat horizontal skylight with clear transparent glazing
19	Flat horizontal skylight with tinted transparent glazing
20	Flat horizontal skylight with white translucent glazing
21	Barrel vault skylight without glazing (FF = 36 %)
22	Barrel vault skylight with clear transparent glazing
23	Barrel vault skylight with tinted transparent glazing
24	Barrel vault skylight with white translucent glazing
25	Pyramid skylight without glazing (FF = 17 %)
26	Pyramid skylight with clear transparent glazing
27	Pyramid skylight with tinted transparent glazing
28	Pyramid skylight with white translucent glazing
29	0.5 WWI Waffle skylight with 30% reflectance
32	1.0 WWI Waffle skylight with 30% reflectance
31	1.5 WWI Waffle skylight with 30% reflectance
32	2.0 WWI Waffle skylight with 30% reflectance
33	0.5 WWI Waffle skylight with 85% reflectance
34	1.0 WWI Waffle skylight with 85% reflectance
35	1.5 WWI Waffle skylight with 85% reflectance
36	2.0 WWI Waffle skylight with 85% reflectance

* Note: All sawtooth and waffle canopies were examined without glazing materials.

4.4 MATRICES OF ILLUMINANCE MEASUREMENT CASES

Upon completion of variable definitions and scale model construction, two matrix diagrams of illuminance measurement cases were developed. As shown in Figure 4.11, a total of 1036 measurement cases were planned for daylight illuminance measurements under clear sky and overcast sky conditions. Meanwhile, as shown in Figure 4.12, with the reduced numbers of atrium Well Index values and canopy systems, a total of 648 measurement cases were planned for direct sunlight illuminance measurements.

Sky Condition		Atrium Well Index		Solid Wall Color		Canopy System		Total No. of Cases
2	x	7	x	2	x	37	=	1036
Overcast Clear sky		0.6 0.9 1.2 1.5 1.8 2.1 2.4		White Black		00 01 02 . . . 36		

Figure 4.11 Daylight Illuminance Measurement Cases

Climatic Zone		Season of Year		Time of Day		Atrium Well Index		Canopy System		Total No. of Cases
3	x	3	x	1	x	4	x	18	=	648
Hot		Jun. 21		Noon		0.6		00 Open		
Temperate		Sep. 21				1.2		04-South		
Cold		Dec. 21				1.8		04-North		
						2.4		08-South		
								08-North		
								12-South		
								12-North		
								13-South		
								13-North		
								16-South		
								16-North		
								19		
								20		
								27		
								28		
								33		
								34		
								36		

Note:
Sunlight measurements were conducted only with white wall areas with glazing. Measurements with black interiors were not conducted. See discussion in Chapter 5.

Figure 4.12 Sunlight Illuminance Measurement Cases