THE DEVELOPMENT OF A SCHEMATIC DESIGN PRIMER TO AID ARCHITECTS IN DESIGNING FOR WIND

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As architects we were taught to use simple concept diagrams as a way of showing our design intentions, whether related to the design parti, the functional plan, or the building's response to sun and wind. We are not as well equipped to understand how our buildings will actually perform when exposed to the complex and dynamic forces of nature. The wind tunnel research program being initiated at Miami University is an attempt to bridge this gap through the development of a design guide or "primer" aimed at giving students and practicing architects the type of information that would be most helpful in the schematic design phase.

The AIA grant has allowed us to refurbish the department's low velocity wind tunnel, and to re-calibrate and automate the data acquisition systems. The grant also supported the initiation of a series of studies aimed at testing many of the standing assumptions about wind and how it moves over and through buildings. In these experiments airflow patterns in scale model studies are observed visually with smoke streams, as the effects of wind are measured through the use of pressure transducers and velocity sensors installed at appropriate points in the test model. Conceptual diagrams of how air *should* interact with buildings serve as the basis for many of these experiments. Through this research we hope to draw connections between the conceptual understanding we as architects have of wind and the kind of analytical tools that can be used to actually test our assumptions.

The Development of a Schematic Design Primer To Aid Architects in Designing for Wind

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I. Introduction to the Principles of Fluid Mechanics . . . *for Architects*

Of all the environmental forces that affect the performance of b-uildings, wind is arguably the most difficult for architects to understand. As designers we may have a fairly good mental picture of the path the sun takes across the sky on the summer and winter solstice and the equinox months. We may even have an idea how the magnitude of solar radiation incident on the exterior surfaces of buildings changes throughout the course of a clear day. And though we may not recall how to calculate the resultant heating or cooling loads, we all have an experiential appreciation for how diurnal and seasonal temperature swings affect human comfort and should affect the design of climatically responsive architecture.

Unlike daylight, however, which can be visualized as a vector or ray, air is a fluid. The affects of wind can be seen in the movement of tree branches, in the clouds overhead, or in the swirling snowflakes in front of our headlights; but the motion of the air molecules themselves is not visible. The inability to visualize air motion is only part of the problem. The way that an air mass moves over and around forms in the environment is a complex fluid flow phenomenon. Small changes in the size, shape and orientation of an obstruction can alter the pattern of the air motion dramatically. The fluid will be compressed in places, dispersed in others, and, if the velocity gradients in the moving air mass are great enough, the motion of the fluid will become completely disturbed or turbulent. In the field of fluid mechanics there are three "regimes" that are used to describe the dynamics of a fluid in motion. Laminar flow occurs when adjacent air molecules are moving in parallel, and their kinetic energy[i] could be represented by vectors all pointing in the same direction. Turbulent flow is when the motion of a fluid has been disturbed to the point where the direction of individual molecules is random. In this state their kinetic energy is dissipated as the molecules collide with each other. A transitional (or transient) regime occurs when fluid flow starts to oscillate, showing signs of instability, but does not break into turbulence. The molecules are all moving in the same general direction, but vectors representing their individual instantaneous kinetic energy would not be parallel. It is the kinetic energy of the air molecules that we feel as wind on our faces and that our buildings "feel" as differential pressures over the surface of the form. The three fluid flow regimes are a helpful construct for understanding how wind interacts with the building forms we as architect create. The greatest wind driven pressures will typically occur under laminar flows conditions, as the kinetic energy of the molecules of the air mass are all working in concert. Under turbulent flow conditions the direction and magnitude of the pressure on the building form will fluctuate, while much of the kinetic energy is dissipated within the disturbed field of flow itself.

Figure 1. Visible patterns of airflow in the natural environment.

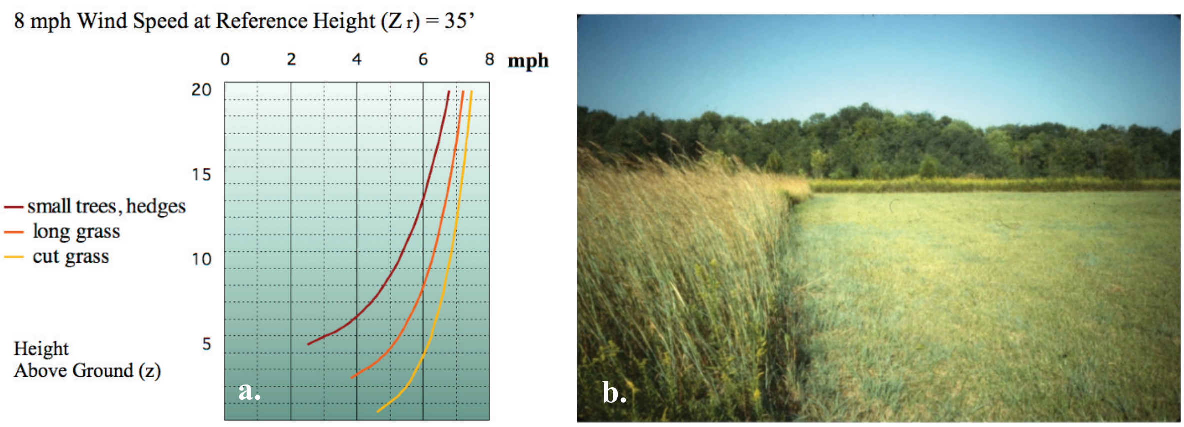


Figure 2. Wind velocity profiles and the varying ground plane conditions that create them.

2. Modeling Air Motion in the Natural Environment

As air moves over the ground, the lower portion of the air mass is sheared by the friction with the ground. At the interface with the ground plane there is little or no air motion. Moving up from the surface, the air velocity increases progressively until it reaches the velocity of the free stream flow. This is called the atmospheric boundary layer or ABL, and will extend 1000 feet above the ground for a flat terrain with few obstructions or higher in suburban or urban environments.[ii] While engineers studying the wind load on high-rise structures are concerned with wind velocities at higher elevations, for the great majority of the buildings only the wind velocities in the lowest portion of the ABL, or the surface boundary layer, are of relevance.[iii] Figure 2.a shows velocity profiles as a function of terrain roughness from 0 to 20 feet above the ground plane.[iv]

Along with velocity, the direction the wind is coming from will obviously change the distribution of wind pressure over a building form. Until recently the decision regarding wind angles to consider often defaulted to the monthly average "prevailing wind direction" for months when natural ventilation could be beneficial, or when wind shielding would be desirable. This statistic, published in the Normals, Means and Extremes charts of the National Oceanic Atmospheric Administration[v], gives an overly simplistic representation of the variability of wind directions. Probability distribution curves for wind speed and direction give a more complete picture, but still only tell where the wind is coming from, not when it would have a positive or negative affect on interior environments[vi]. One of the best tools for designing climatically responsive buildings is Climate Consultant, a program developed by Murry Milne at UCLA. The program "graphically displays climate data in dozens of ways useful to architects including temperatures, wind velocity, sky cover, percent sunshine, psychometric chart, timetable of bioclimatic needs, sun charts and sun dials showing hours when solar heating is needed and when shading is required. The new 'Wind Wheel' graphics shows velocity and direction correlated with temperature and humidity, and can be animated hourly or daily or monthly."[vii]

The wind wheel shown in Figure 3 gives the maximum, minimum and average wind speed by direction in 10° wind angle bands. The number of hours the wind is coming from each angle is shown (in brown) at the outer perimeter of the wind wheel. While this graphic way of representing wind data is in itself extremely helpful, of even greater value is the way climatic data related to human comfort is also shown. Graphically scaled color codes, in the middle two circles of the wheel, represent the temperature and relative humidity for hours when the wind is coming from each of the 10° wind bands. In the Climate Consultant program, architects now have a tool that gives precise information on wind speed and direction for those times when the outside temperature and humidity would either be a benefit or a detriment to the interior environments of buildings.

In addition to modeling the lower level of the atmospheric boundary layer, wind tunnel tests must accurately reflect the influence of objects extending up from the ground plane - landscape features and built forms. In real world environments this problem is complicated by the fact that the forms that make up the context surrounding a building are unique to that site. This dilemma represents both the unique value of wind tunnel modeling and one of the difficulties associated with creating accurate models of the airflow patterns that would be observed in real full-scale environments. A considerable body of research has been done on the techniques for modeling the dynamic effect of airflows for specific situations in a wind tunnel[viii]. The great majority of this work, however, has related to structural loads and cladding[ix]. Considerably less work has been done on the techniques for accurately modeling the influence of wind on buildings at lower velocities and smaller scales. The basic requirements for wind tunnel modeling, however, hold for large or smaller structures regardless of the velocity range of interest. The requirements are outlined in the ASHRAE Handbook of Fundamentals[x].

1) Accuracy of the scale model
2) Boundary layer similarity with velocity profiles for the actual terrain
3) Wind tunnel blockage of less than 5% of the cross sectional area
4) Model scale adequate to give good measurement resolution
5) Model scale adequate for full development of the surface boundary layer
6) Testing conducted at sufficient speeds to insure Reynolds number independence

The wind tunnel design issues associated with achieving similarities between model testing and full-scale environments for items 1 through 4 are not insignificant, but are mostly related to the physical size of the tunnel and the scale of the study models constructed within it. If the tunnel is long enough, ground plane roughness features can be installed to create tunnel velocity profiles that replicate the wind velocity profiles observed in the real environment (5). Pressure gradients and blockage effects can be alleviated by gradually sloping the ceiling of the tunnel to allow more free space in the cross section of the test area.

The last similarity noted, Reynolds number independence (6), is more complicated. The Reynolds number (Re) is a dimensionless parameter that is important in understanding any type of fluid flow where substantial velocity gradients are likely to occur (i.e., where wind shear is present). The Reynolds number characterizes whether inertial forces or viscous forces are dominant. “At low Reynolds numbers the viscous forces are so strong that they damp down any disturbances in the fluid motion. This means that the boundary layer remains laminar. At increased Reynolds numbers the inertial effects (mass × acceleration) become more dominant. These are strongly *non-linear* and tend to become unstable. Above a certain Reynolds number, boundary layer disturbances . . . grow and cause transition to turbulence.”[xi]

In wind tunnel studies the Reynolds number is useful in determining the velocity at which the airflows in a scale model will be representative of the flows observed in the full-scale environment. This work, pioneered by Jack Cermak at Colorado State University, identified four conditions that occur in wind tunnel modeling for which Reynolds number “independence” must be satisfied.[xii] The minimum values for achieving Reynolds number independence for each condition have been derived experimentally and are indicated in parentheses.

1) The approach flow of air moving up the tunnel (Re > 3)
2) Airflows around “bluff” or flat vertical walled build ings (Re > 2 x 104)
3) The flow of air discharging through a small window into a room (Re > 300)
4) The internal flow within a room (Re > 2 x 104)

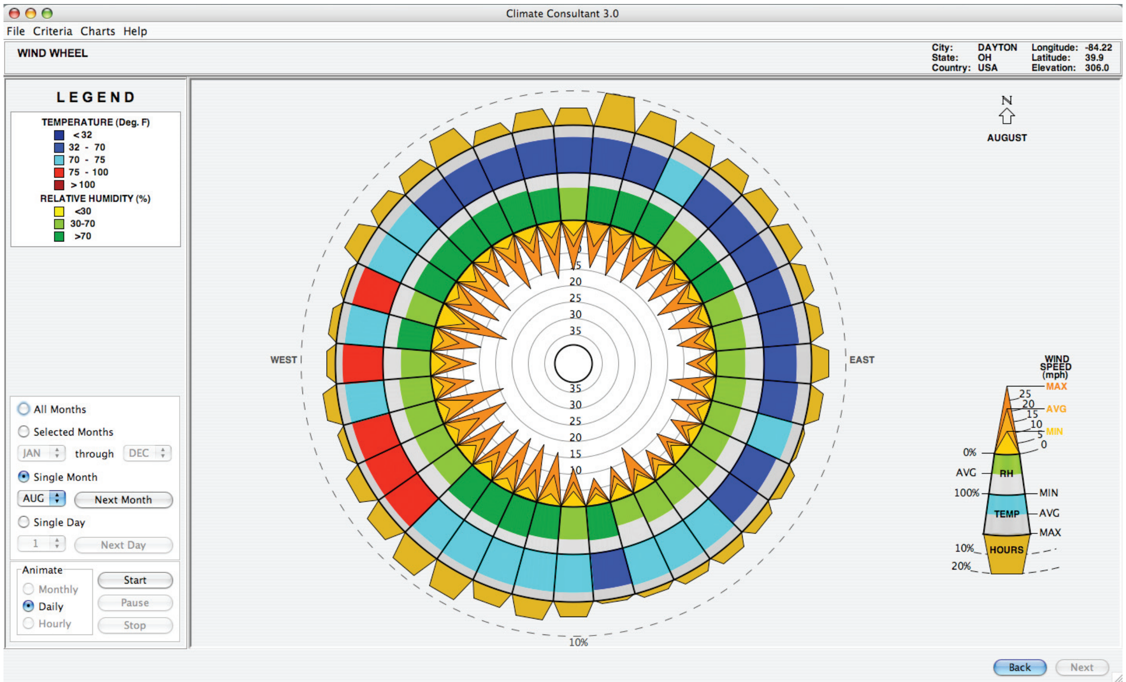


Figure 3. The Wind Wheel Page for Dayton, Ohio, for the Month of August.

In each of these cases a "characteristic" length – roughness length of the wind tunnel floor (1), building dimension in the direction of flow (2), window dimension (3), smallest room dimension (4) – are used to compute the Reynolds number for the velocity and type of flow occurring at that location in the model. If the calculated value is greater than the number for which local Reynolds number independence is achieved, a satisfactory correspondence between the scale model and the full-scale environment can be expected.

What does all of this mean for design architects, who may be much more interested in the form of the building for the visual impression it creates, than the form of the equations that describe the way air moves over it? With the growing use of wind tunnel testing in architecture, architects should have an appreciation for what this tool can actually tell us about the buildings we design. It is equally important to understand the limitations associated with conducting these tests and with the results that are derived from them.

Figure 4. Wind load tests for the 312 Walnut Office Building (1:300), Cincinnati, Ohio.

2. Architectural Applications for Wind Tunnel Testing

3.1 The Field of Wind Engineering

The use of wind tunnels to study the influence of wind on buildings is a relatively new field of engineering. The first United States National Conference on Wind Engineering was in 1970. Wind engineering evolved as a subset of the field of industrial aerodynamics and most of studies conducted to date have related to the structural aspects of building design and performance[xiii]. The types of wind tunnel studies that have been conducted and the related physical measurements are listed below.

1) Structural wind loads and building response – pressure tests
2) Wind pressure effects on cladding and envelope components– pressure tests
3) Dispersion of building exhausts – visual studies, velocity measurements
4) Pedestrian level wind patterns – visual studies, velocity measurements
6) The effect of wind on building interior environments - visual studies, velocity and pressure tests

The majority of the wind tunnel studies performed by private consulting groups relate to structural issues. Pressure tests are routinely conducted on high-rise structures to experimentally measure the wind pressures that will be observed across the surface of the building form. Small tubes are installed in a grid like pattern across the model surface with the end of the tube protruding through, but flush with, the exterior surface. These tubes are fed down through the model base and connected to a series of pressure transducers. Since pressure and turbulence intensity are both of interest, the frequency response of the transducer is important.

These tests are designed to understand how surrounding buildings will disturb the airflow approaching a structure under test. The airflow patterns in the wind shadow of an obstruction will generally be turbulent and lower in velocity. When multiple structures stand in close proximity, however, the wind eddies created can sometimes be of higher velocity than the approach wind. The effect of the surrounding structures on the wind pressures exerted on a building can be effectively modeled in a wind tunnel by creating a cityscape with all the major nearby building masses accurately modeled. Since design force winds could come from any direction, the test section of wind tunnels used for this purpose are constructed with a circular test platform that can be rotated 360°. In this way winds approaching the test structure from any direction can be studied.

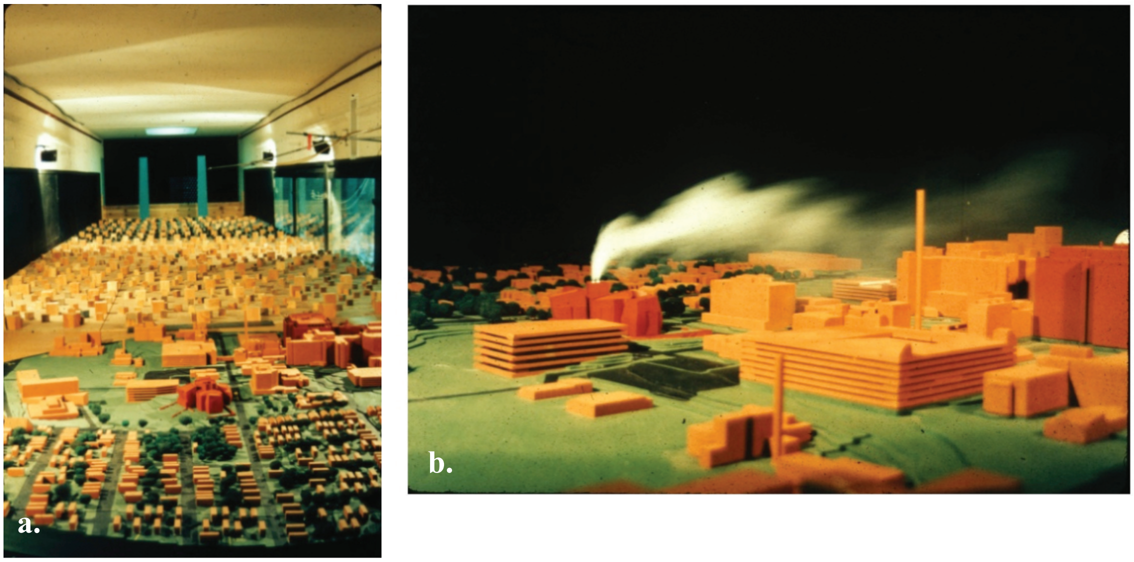


Figure 5. Diffusion testing for the Center for Molecular Studies (1:300), University of Cincinnati.

There is always a degree of uncertainty associated with how well scale model tests will reflect the wind forces and resulting building surface pressures that would be experienced in the real environment. The test procedures used for wind tunnel modeling have evolved over the years, however, to where the experimental results from wind tunnel studies can be used to accurately estimate the localized and overall wind loads on the structure. In some cases concentrated surface pressures that could not have been discovered through other analytical methods are identified and the building envelope systems and cladding can be designed accordingly. In high-rise structures the reduced pressure on the form, due to the screening effect and turbulence from surrounding buildings, will often allow for more efficient structural designs, reducing the overall cost of the building.

Diffusion testing is another type of study that is commonly performed in wind tunnels. As with high-rise wind load experiments, the building to be tested is placed in a scale model replication of its immediate context. A tube is used to pump smoke to a location on the surface of the building where exhaust vents would be located. The smoke provides a visible trail demarking the path that exhaust fumes will take after leaving the building. Of concern is the rate at which the exhaust gasses will dissipate into the atmosphere and whether the combined effect of the shape of the building under test and the surrounding context may cause exhaust air to be drawn down the face of the building to pedestrian levels before it can disperse. These tests are primarily visual, but hot wire anemometers can also be used to measure the air velocity at points of interest within the model.

Wind tunnels are also used to study ground (or pedestrian) level wind patterns. These tests try to identify situations were the shape and proximity of adjacent building forms may cause irregular wind patterns or higher than normal wind velocities. Studies of the potential for wind gusts created by the channeling effect of buildings are one case where this kind of testing is employed. Large outdoor sports venues are another situation where the shape of the stadium may create unusual airflow patterns on the field of play. As with diffusion testing, ground level wind patterns are studied using smoke streams, but air velocity sensors may also be used.

The studies noted above represent the great majority of the wind tunnel tests that are done by firms specializing in wind engineering. Structural wind load analysis and cladding pressure tests are routinely done for taller buildings where the consequences from not doing these tests can result in significantly over-sizing or under-sizing the structure, or can result in the failure of the building envelope systems at pressure points on the surface. The scale of the potential problems warrants wind tunnel testing, and the fee structure for larger buildings will normally include the cost of these services. Similarly, in special situations where understanding the dispersion of waste gasses from a structure (i.e., chemical labs, or industrial applications), or where building forms may cause abnormal or unsafe wind patterns, it is becoming more common to request wind tunnel testing.

3.2 Modeling the Influence of Wind on Interior Environments

Though wind can also have a significant impact on the interior environments of buildings, this aspect of the interaction between wind and buildings is less often studied. Reasons relate to the cost of the tests and issues of scaling. In smaller structures wind loads on the building are seldom seen as warranting the cost of conducting wind tunnel tests. At the lower air velocities that are relevant to the study of natural ventilations, the similarity between model and full-scale results is harder to achieve. Though it would be helpful to know how the shape of a structure and the design of the envelope will influence the infiltration or ventilation rates for a building, these kinds of tests are difficult to conduct in a wind tunnel with a high degree of confidence in the results.

There are few studies that relate wind tunnel tests to the actual measured ventilation of buildings. The studies that have been conducted would suggest that considerably more work needs to be done, particularly with respect to natural ventilation at lower velocities. One of the earliest tests was a collaborative research effort between the Florida Solar Energy Center (FSEC) at Coca, Florida, and the Wind Engineering and Fluids Laboratory at Colorado State University. The test building, called the Passive Cooling Laboratory or PLC, was located at the FSEC site about a mile from the Atlantic Ocean. The reconfigurable structure was 44' square in plan. Evenly spaced columns provided the support for the roof so that walls could be relocated or eliminated entirely. During the test period the exterior walls were changed to create four different configurations for the exterior envelope. The same four configurations were modeled by researchers at Colorado State University, in their meteorological wind tunnel, using a 1:25 scale model of the PCL structure. Wind velocities comparable to mean velocities measured on the actual site were used in the wind tunnel tests. In the experiments the effect of wind on ventilation was studied through the measurement of building surface pressures, approach and internal wind velocities, and through concurrent dilution or tracer gas sampling. Though the relative performance of the different building configurations studied was similar for the wind tunnel and full-scale tests, a number of discrepancies were noted in the test results[xiv]. There were several conclusions drawn by the principal investigators with respect to the use of wind tunnels to model natural ventilation that have guided much of the more recent work in this area. First, the wind patterns observed on a site will fluctuate, both in direction and wind speed, in ways that cannot be modeled with complete accuracy in a wind tunnel. As a consequence, low velocity wind tunnel studies of natural ventilation are best used to compare the ***relative effectiveness*** of design options for a single building, or between buildings of roughly similar size. Comparative test results, such as those described below, can provide valuable information to inform the way we design for wind. Though these results cannot be extrapolated to estimate the actual ventilation rate for a structure under real wind conditions, they provide a greater degree of confidence that the wind related design decisions being made will have a positive impact on ventilation effectiveness.

4. Miami Universities Low Velocity, Boundary Layer Wind Tunnel

4.1 Tunnel Design and Applications

Designing our wind tunnel was an education in climatology, fluid mechanics, and wind engineering. At the outset we sought the advice of researchers at the Wind Engineering and Fluids Laboratory at Colorado State University. We were fortunate to have had Jack Cermak, a pioneer in the field of wind engineering, serve as the advisor on our project. The Wind Engineering Lab at CSU has seven wind tunnels that are used for a range of applications, but the ones used for environmental testing are the largest, running 60' to 88' in length. The Environmental Wind Tunnel (EWT) is 60' long with a test section that is 12' across by 8' high.

By contrast the wind tunnel in the Department of Architecture and Interior Design at Miami is 35' in length with at 4' x 4' test section. The tunnel would be classified as an open circuit, low velocity boundary layer wind tunnel. It is used for observing the airflow patterns around building forms and to study the ventilation effectiveness of the building envelope. It was designed with the same features used in larger tunnels to condition the airflow in the tunnel in order to replicate the surface boundary layer. Though accurate modeling can be achieved, the small size of the tunnel limits the scale of buildings that can be tested.

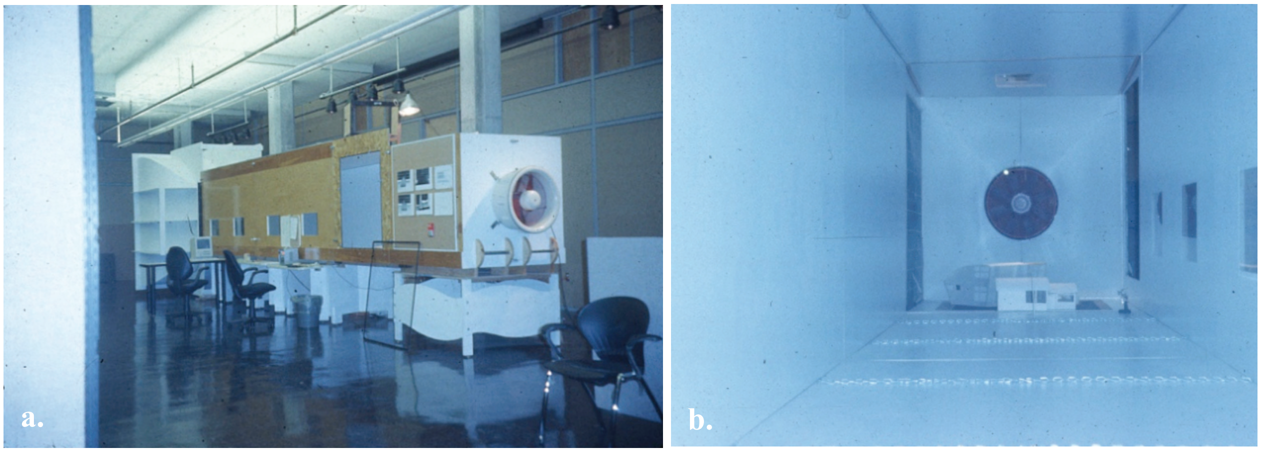


Figure 6. The low velocity boundary layer wind tunnel at Miami University.

The tunnel is powered by a fan that exhausts air from one end of the tunnel. This puts a negative pressure on the plenum, which in turn draws air down the length of the tunnel. The negative pressure creates a more uniform flow through the section of the plenum. The inlet end of the tunnel (far end in Figure 6a) has an opening cross section that is 4 times larger than the cross sectional area of the plenum. Two successive cubic parabolas form the shape of the inlet stage of the tunnel. The smooth curved shape of the inlet provides a 4:1 compression ratio, which increases the velocity while maintaining a more laminar flow along the length of the tunnel.

Several devices are used in the wind tunnel to condition the air entering and moving down the tunnel. A honeycomb screen establishes a slight pressure difference between the room and tunnel plenum and reduces the swirling effect at the edges of the inlet opening. A row of vertical spires, 10" apart running from the floor to the ceiling at the upwind end of the plenum, have a slightly flared bottom to slow the air velocity at the floor. Additional flow inhibitors are positioned over the tunnel floor to increase the resistance at the ground plane. This can be done using uniformly spaced small wooden blocks or by placing a series of evenly spaced chains across the tunnel perpendicular to the direction of airflow. The combined effect of the spires, and the use of chains or small blocks is to develop a vertical wind shear that approximates the profile of the surface boundary layer of air as it would move over the terrain of an actual site.

Determining the appropriate scale for wind tunnel modeling is always a tradeoff between achieving Reynolds number independence and the size limitations of the tunnel. Higher velocities will raise the Reynolds number and thereby provide better scaling. The higher velocity of the actual flow rate in the tunnel, however, would represent higher wind speeds at the scale of the model being tested. In studying how average winds influence the thermal environments in buildings, modeling abnormally high velocities for the sake of achieving Reynolds number independence would not provide useful results. If the scale of the study model is increased, the same tunnel airflow rates would represent more typical wind speeds. A third controlling factor is the requirement that the blockage of airflow by the test model not exceed 5 percent of the cross sectional area of the wind tunnel. In most applications it is also preferable that the horizontal model dimension not exceed half the width of the test section. If the actual physical dimensions of the model get too close to the side walls of the wind tunnel, the flow around the building model will be artificially restricted. In tests we have conducted we have found that a model scale of ½" = 1'-0" works well for visual studies of external flow patterns. In studying internal flows, as we do in the ventilation studies described later, a larger scale is desirable though the 5 percent blockage requirement then restricts us to studying smaller buildings.

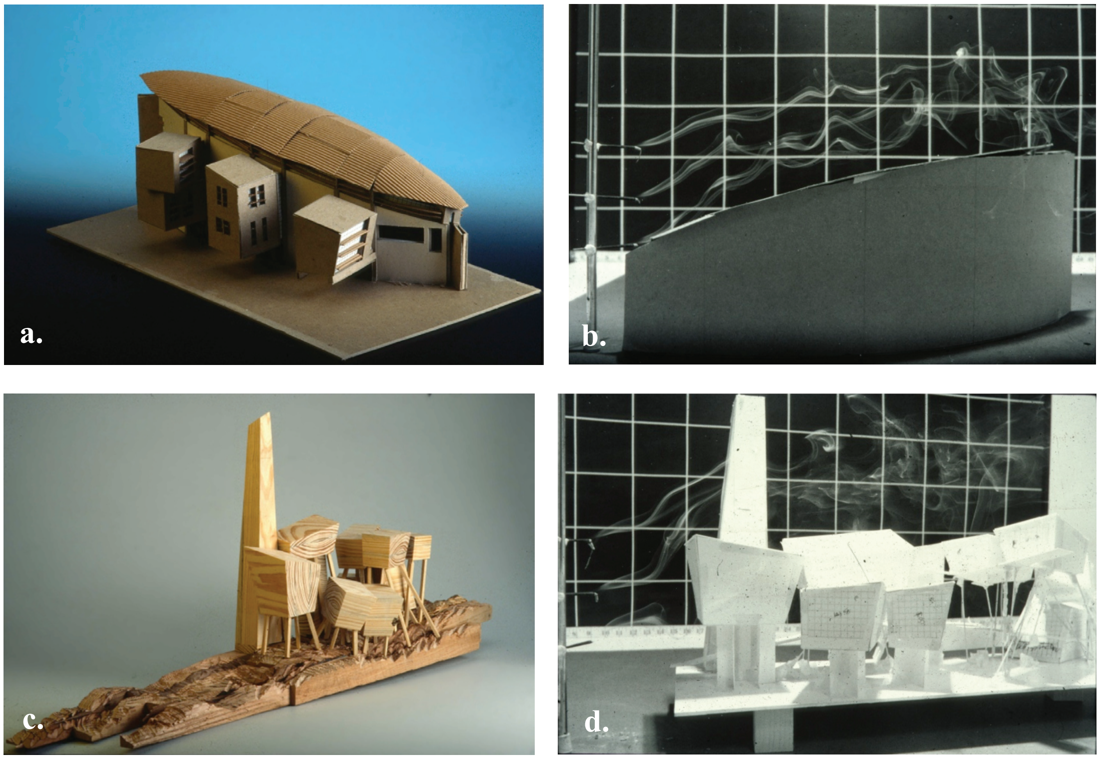


Figure 7. Student design and visual wind tunnel study models for a small vacation shelter.

In the projects shown in Figure 7 students were asked to design a small vacation cottage on the outer banks of North Carolina. The costal location made it possible to design for a more limited range of wind angles. The models of the two student designs reflect different strategies for increasing natural ventilation. The design in Figure 7a uses a curved roof shape to compress the flow over the form. Figure 7b provides a visual indication of how the design works. While some instability can be seen, the spacing of the three smoke streams is compressed from two units at the far left of the photograph to one unit at the peak of the roof. Since the velocity would be increased proportionally, roof vents located at the back edge of the peak would be more effective as a function of the shape of the roof. The design shown in Figure 7c elevates the building masses in an attempt to "catch" the breeze at the higher elevation. In theory the velocity should be slightly higher at 10-20 feet above ground (see figure 2a), but the abrupt form of the building masses disturbs the airflow causing it to break into turbulence. Though pressure tests were not conducted, the visual flow studies would suggest the obstructive shape of the form may be overriding the benefit of raising the building structure.

4.2 An Alternative Protocol for Studying Ventilation Effectiveness

Understanding the limitations of wind tunnel testing, particularly with respect to lower velocities, has led us to develop an alternative testing protocol to study ventilation effectiveness. The extreme variability of wind patterns and the high degree of uncertainty associated with modeling the resultant wind forces make the task of developing precise estimates of ventilation rates for an actual building on a specific site all but impossible. A more realistic goal is to study how the design of the building envelope can create the *conditions* for increasing wind driven natural ventilation of the interior volume. We make the assumption that the shape of the building and the location of openings can be studied as a separate issue from how the placement of interior partitions may enable or restrict airflow through the volume.

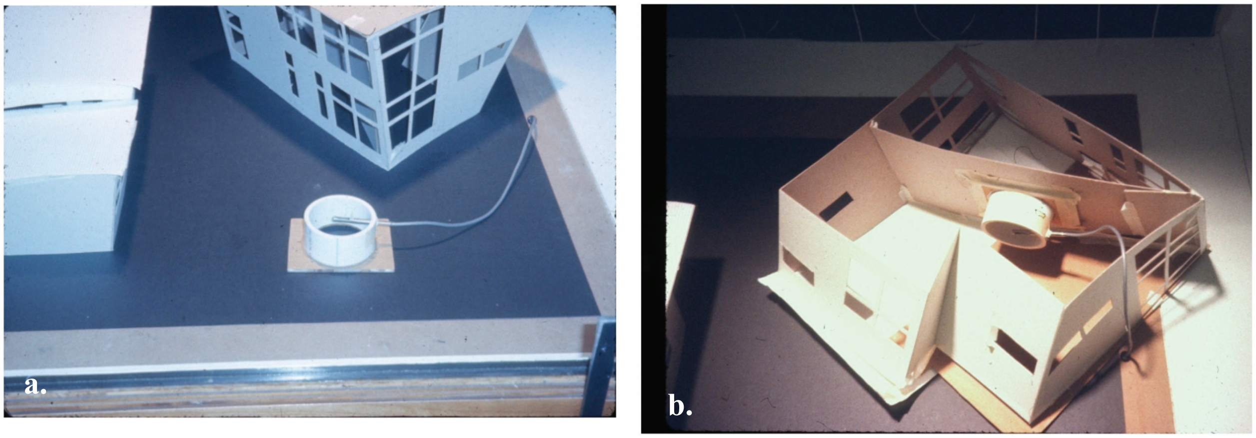


Figure 8. Installation of the internal velocity test port in a ventilation effectiveness study model.

Air motion through a structure is a function of the positive and negative pressures on the exterior envelope and, more specifically, on individual openings in the envelope. We start by building a study model of the shape of the exterior envelope with windows and vent locations cut out, but with no interior partitions. We then place an artificial "wall" across the interior of the test model to separate those openings that will be exposed to positive pressures from openings that will be exposed to negative pressures for the wind directions being studied. Preliminary smoke testing will show which exterior surfaces will be under positive and negative pressure. We then install a test port in the wall between the two zones. The port is a short cylindrical tube with a hot wire anemometer mounted at the center. Hot wire anemometers are used extensively in wind tunnel research because of their ability to measure airflows down to 10 standard feet per minute (SFPM). The sensitivity of these devices, however, also makes them highly responsive to turbulence. In our wind tunnel experiments we use anemometers that allow us to change the sensitivity by modifying the capacitance of the output circuit. By reconfiguring the anemometer circuitry we can electronically average the voltage output, which in effect dampens the fluctuations in the velocity readings.

With the cross wall in the model carefully sealed at the edges, the test port is the only path for airflow from the positive pressure to the negative pressure zones of the model. The velocity of the airflow through this opening will be a function of the magnitude of the pressure difference between the two zones. The internal velocity (Vint*) is divided by the approach velocity of the air mass in the tunnel, measured just to windward of the test section (Vref). This ratio (Vi/r) is used as a measure of ventilation effectiveness. The (*) is used to denote that the internal velocity measurement does not represent the actual velocity of air motion within the interior space of the model, but is the airflow through the test port.

$$\text{Ventilation Effectiveness Ratio}\ \ Vi/r = \frac{Vint^*}{Vref} \qquad (1)$$

Though this testing protocol is an artificial construct, the differential pressure between the two zones – as reflected in the velocity through the test port – has proven to be a good indicator of the potential for wind driven natural ventilation. Whether the potential is realized would of course be influenced by the openness of the actual plan. The ventilation effectiveness ratio is a useful number for comparing the relative performance between design options being considered. If the turbulence at the internal sensor is controlled, even small changes in the design of the external envelope can be seen in the ratio of internal to upwind velocities.

As with any analytical procedure it is important to acknowledge what the testing approach will not tell us. The testing protocol we have developed will not provide information on how air will move through the spaces of an actual building since the interior partitions are not modeled. It also cannot provide an indication of what the actual ventilation rate would be for a similarly designed full-scale structure. These kinds of results are out of the range of our research capability. Even for larger wind tunnels, the variability and fluctuation of wind forces and the uncertainties associated with modeling the effects of low velocity winds on internal flows simply precludes this level of real world correspondence. An additional limiting factor inherent in the testing protocol is related to the whole idea of interior positive and negative pressure zones. The Reynolds number for modeling discharge through a "small opening" is based on the assumption that the discharge rate will be driven by the differential pressure across the window. This will be true if the window is small enough that a pressure field is established over the exterior surface of the wall. In cases where the opening covers a large portion of the exterior wall area the airflow through the window will be momentum driven. The air movement through large openings will act more like airflow in an open field, where window mullions will only slightly disturb the flow. The zone separator wall will be the first plane obstructing the air approaching the structure. In effect this artificial wall, constructed to separate internal pressure zones, will be acting like part of the exterior envelope. The near side of the test model shown in Figure 8a has a series of adjacent windows. The flow through this part of the wall would be momentum driven if all of the openings were left uncovered during testing. The model was used to determine where operable window should be located by comparing the ventilation effectiveness with different patterns of window areas covered.

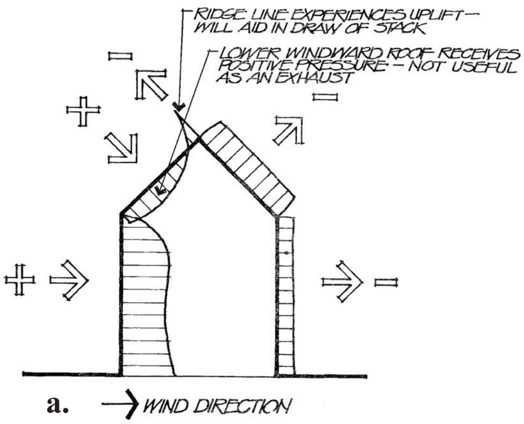
5. Designing for Wind – Intuition Informed by Analysis

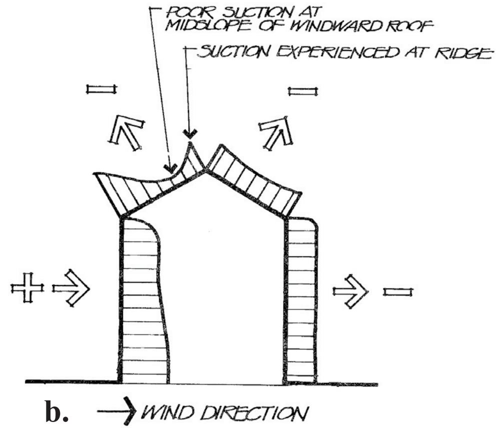
In addition to facilities upgrades and data acquisition software development, the AIA grant has allowed us to initiate a testing program that will continue over the course of the next academic year. We are using the wind tunnel to model a number of conceptual notions of how wind moves around and through buildings in order to show how these design idea will actually work. Many of the diagrams we are using were originally published by Don Watson in his book Climatic Design for Home Building[xv]. The book provides hundreds of graphic representations for ideas of how to design for climate, including sections on designing for wind. There are other books that could be referenced for their extensive use of diagrams showing architects how to design more energy efficient and environmentally responsive buildings. Some also contain detailed information on how to evaluate the performance and estimate the energy savings from doing so.

With respect to wind, however, there are few good design guides to rely on. There are no rigorously validated algorithms for calculating how decisions about the design of the exterior envelope will affect the rate of airflow through a building. Wind tunnel smoke stream studies can be used to visualize the patterns of airflow, but comparing the relative impacts of specific decisions is more problematic. The ultimate goal of the wind research program we have undertaken at Miami is to develop a resource to fill this gap. The document we are preparing, "Designing for Wind: A Schematic Design Primer for Architects", will present concept diagrams and sketches for designing with wind, alongside more quantitative data from wind tunnel tests using study models based on these concepts. Examples of how we intend to link conceptual understanding with research results to help architects develop a more informed intuition in designing for wind are shown in Figures 9 and 10. Visual smoke stream studies, surface pressure readings and ventilation effectiveness ratios were used to compare the performance of different roof shapes. Other studies being conducted as part of the larger wind research program are:

- The effect of building shape and proportions
- Combinations of wall and roof inlet/outlet locations
- The location, number and size of wall inlet/outlet openings
- Operable window types including the direction of op erability and degree of openness
- Sensitivity to small changes in aperture design and detailing
- The accuracy of using simple coefficients for window treatments such as screens or louvers
- Protocols for testing momentum driven ventilation
- The influence of turbulence created by surrounding context

Figures 9a and 9b show a sectional diagram of the wind pressures that would be exerted on two structures, one with a 30° roof slope and the other with a steeper 45° roof slope. The superimposed pressure graphs characterize what would typically happen. The projected area of the steeper roof will be more normal to the approach wind. With a less sharp angle at the top of the wall, the airflow at this location will be less disturbed by the air rising up the wall. The diagram indicates that the resulting pressures will be positive from the roof edge until separation occurs at the roof peak. The flatter roof (9b) will experience negative pressure over the entire windward slope. The airflow visualization studies (9c and 9d) show the actual pattern of air motion over a simple 45° roof form, similar to figure 9a, but with an additional aspect to the tests. Figure 9d shows the airflow patterns that result with a flush roof edge like the condition in the top two diagrams. In Figure 9c, however, the roof extends out over the building mass with a soffit returning back to the wall line. Though there is a correspondence between what the section pressure diagrams and the visual flow studies are showing, the juxtaposition of these two sets of images begins to hint at the underlying complexity of modeling wind. The soffit shears the approach wind into an upper and lower region at the roof edge. The lower flow is trapped below the soffit and moves along the wall horizontally to the corner or the structure. Undisturbed by rising air from below, the upper region of flow moves smoothly up the roof slope and makes a clean break with the form at the peak. By contrast, in the Flush Forward condition (Figure 9d), the rising air causes the airflow moving up the slope to switch to a transitional regime. The picture indicates, and the pressure tests in figure 9e and 9f verify, that the disturbed pattern of flow results in very different pressures along the windward and leeward slope of the roof.

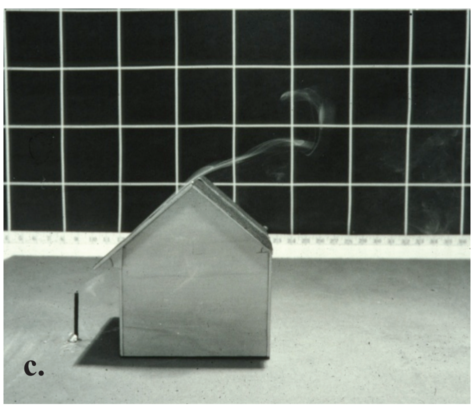


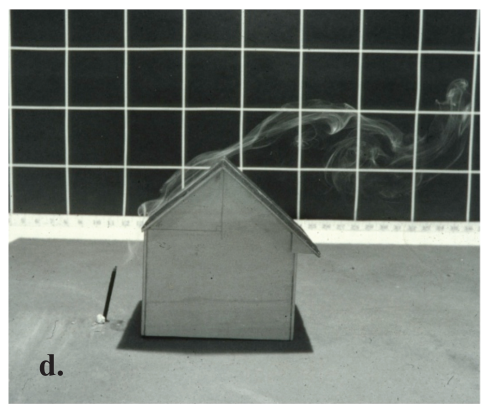


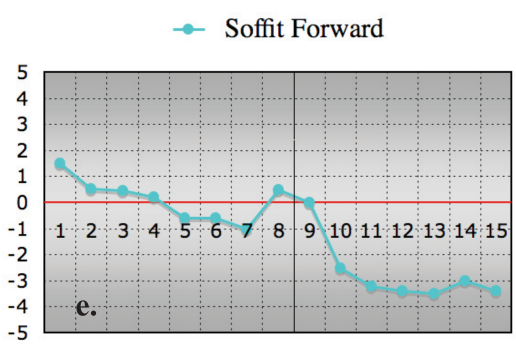
DESIGN NOTES:

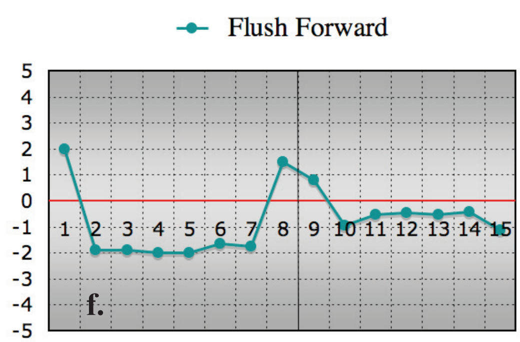
Steeper roofs {a} should have positive pressure on the windward slope and higher negative pressure at the peak, though other design variable will affect actual results {see c through f}.

Soffits {c} will tend to shear the approach wind into upper and lower flows. This can help create laminar flows over the windward roof slope and higher negative pressures at the leewarde side of the peak {e}.





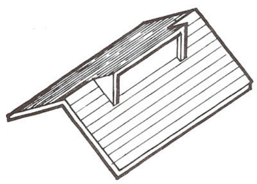




Pressure coefficients at evenly spaced points across the roof slopes

Figure 9. Sample page relating wind pressure diagrams to research results.

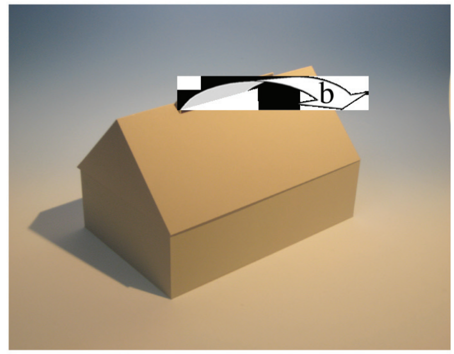
a. Ridge Hood



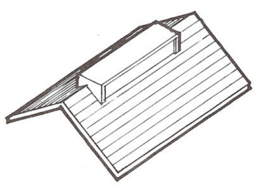
Highest ventilation effectiveness ratio. Less effective when located on windward side (bw)

Vi*/r (bl) = .95
(leeward side as shown)

Vi*/r (bw) = .71 (-25.3%)
(on windward side)



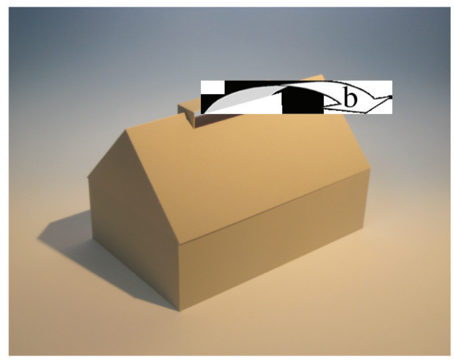
b. Ridge Monitor



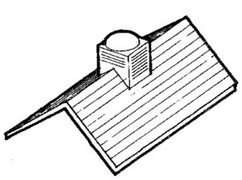
Second highest ventilation effectiveness, but is bidirectional. No change in ventilation effectiveness for wind angles 45° off normal.

Vi*/r (bl or bw) = .86
(with wind from either side)

Vi*/r (b for 60° angle) = .71
(-16.2 for wind 60° off normal)

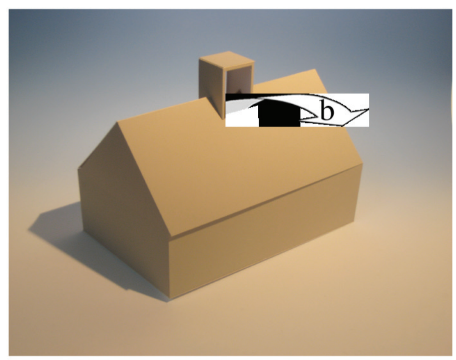


c. Cupola

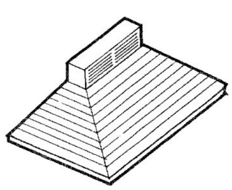


Third highest ventilation effectiveness, but is still bi-directional. No drop in ventilation effectiveness for wind angles 45° off normal, or up to 60° off normal with vents on all 4 sides

Vi*/r (bl or bw) = .65
(with wind from either side)



d. Hip Roof Monitor



Lowest ventilation effectiveness as wind moves around the side roof hips. No change in ventilation effectiveness for wind angles 45° off normal.

Vi*/r (bl or bw) = .53
(with wind from either side)

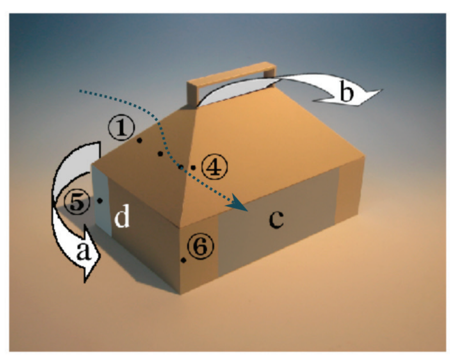


Figure 10. Sample page comparing roof shape ventilation effectiveness .

There are several important ideas communicated by relating diagrammatic conceptual information to the experimental results from testing identical or similar conditions. This study shows that the presence of a simple soffit can have a dominant influence on the way wind moves over the form, and on the pressures induced across the surface. Of greater significance is the way the actual results reflect the complexity of a physical phenomena which is often oversimplified in conceptual diagrams. For architectural designers, who by natural selection are visually oriented, the concept diagrams are a great place to start to understand the relationship between wind and the built environment. They should not, however, be the sole source of inspiration guiding our intuition as we work through the schematic phase of design. These kinds of conceptual representations need to be qualified through analytically based references that characterize the complexity of the forces at work and the relative influence of the design variables that will mediate the impact of these forces on the building.

The roof monitor tests shown in Figure 10 are another example of how we intend to make connections between design ideas – like those shown in the sketches - and the experimental studies needed to give some idea how these designs would actually work in a building. The sketches on the left show four different ideas for roof apertures, but from the sketches alone there is no way of knowing how they might actually perform. The photographs on the right are of the actual study models used in the ventilation effectiveness tests. This sample page shows the initial results from testing the different roof aperture designs in the wind tunnel. The results are also graphed in Figure 11. The experiments clearly show the relative effectiveness of the four options. The ridge hood has the highest ventilation effectiveness ratio, when located on the side away from the wind (bl), but will work less well when the wind is approaching it from the front (bw). The ridge monitor has a slightly lower ventilation effectiveness ratio, but is bidirectional. Tests with the wind coming at varying angles to the test model showed no reduction in ventilation effectiveness for wind angles of 45° off normal (45° from a perpendicular to the long dimension of the roof). At 60° off normal some fall off in Vi/r was observed. This would indicate that the ridge monitor would work better than the hip roof monitor and cupola designs at all wind angles, and better than the ridge hood for half the possible wind angles.

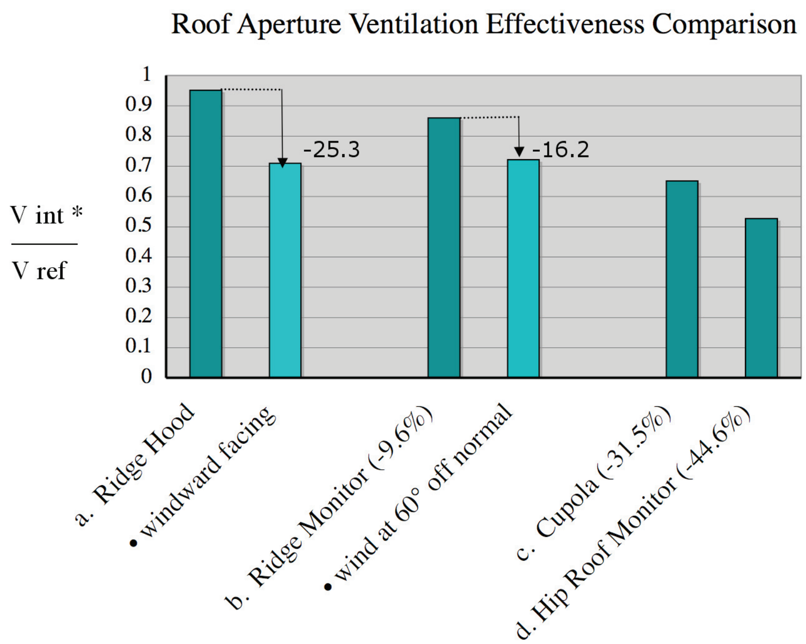


Figure 11. Ventilation Effectiveness for Roof Shapes a through d.

The right side of Figure 10d, at the bottom of the page, is an example of the way other test information will be presented over the study model photographs for this and similar pages of the design primer. The photographs will serve as a three dimensional diagram for showing the pattern of airflow over the form (as observed in smoke stream tests), and the location of data points where pressure and velocity readings were taken. Pressure test points are shown as solid dots and are identified by circled numbered symbols. Pressure tests can be made across a surface to show how pressure varies (1–4). They are also taken at individual points (typically where the form breaks) to indicate the potential of these points as locations for windows or vents (5 and 6). Arrows with letter symbols refer to velocity measurements that were taken. Velocity was measured at the corner (a) and the velocity was measured internally (b). Both of these readings are converted to a ratio of local to approach velocity. Letter symbols will also be used as a location reference for notes describing wind related design considerations. The gray area on the side wall (area d) is a location where windows or vents would be effective, due to the increased negative pressure occurring at this edge (pressure point 5). Conversely, windows located in the middle of the back wall (area c) would contribute little to the ventilation effectiveness, as the backside airflows are disturbed and the surface pressures will be low.

Figures 9, 10 and 11 are examples of the way the test results from the studies being conducting will be represented in the design guide. In both the pressure tests and the ventilation studies, the most important insights to be gained from relating conceptual design sketches to experimental results lies in appreciating the complexity associated with the physical phenomena being studied. The central idea behind the design guide we are developing is that truly sound environmental design practices will rely on an analytical, as well as an intuitive, understanding of the underlying physical principles that will ultimately affect, and should therefore shape, the forms we create on the landscape.

Acknowledgements

Figure 3 - Climate Consultant wind wheel page courtesy of Murry Milne, UCLA
Figure 4 - Photographs courtesy of Jack Cermak – Cermak, Peterka, Petersen Inc. Fort Collins, CO
Figure 5 - Photographs courtesy of Jack Cermak – Cermak, Peterka, Petersen Inc. Fort Collins, CO
Figure 9 - Figure 9a and 9b courtesy of Don Watson from Climatic Design for Home Building
Figure 10 - Roof sketches courtesy of Don Watson from Climatic Design for Home Building

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