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Designing for an acceptable wind environment

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DESIGNING FOR AN ACCEPTABLE WIND ENVIRONMENT[a]

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(Reviewed by the Aerospace Division)

INTRODUCTION

Tall or exposed buildings adjacent to public open spaces may cause local winds at ground level that are much more intense than winds found elsewhere at ground level. These winds may affect the comfort and safety of pedestrians and thus reduce the usefulness of the outdoor open spaces. In recent years, wind problems have become more common, as more tall buildings are built and as cities and building owners place increasing emphasis on public plazas and open space. Since both the cost and economic benefits of such plazas and open space may be very high, significant financial losses may occur when such spaces are rendered unusable due to wind.

The designers of buildings and their sites would benefit from being able to anticipate, in the planning stage, the possibility of local wind flow zones that cause unacceptable discomfort to users of outdoor space. If such zones are found, appropriate design decisions can eliminate them or direct pedestrians away from them.

This paper reviews present knowledge of pedestrian comfort in the wind and outlines how to design projects that avoid unacceptable wind environments.

NATURE OF PROBLEM

Designers concerned with acceptable outdoor environments will have to address the following issues during the design of a building and its surrounding open space:

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1. How does the wind affect comfort and safety? What are the wind descriptors that measure comfort and safety? What are the limits of these descriptors at which the wind becomes uncomfortable or dangerous? These physiological and psychological questions can be answered by research in laboratories and in the field.
2. At any outdoor site, wind will probably exceed comfort or safety limits for a certain number of hours, minutes, or seconds during the year. The time during which the limits are exceeded, measured as a percentage of the total time that the project is occupied, indicate the users' probability of discomfort or danger. How large should these probabilities be? It is up to the designer and owner to decide acceptable probabilities for any given project, but certain levels have been suggested by researchers for use as design criteria.
3. How strong are the regional winds (as measured at the weather station) when local wind flows on site exceed comfort or safety limits? The relationship between the project's local wind and the wind of the surrounding region is a ratio based on the aerodynamic configuration of the project and its surroundings. The ratio varies with wind direction. Certain generalizations can be made, but complex configurations are best modeled in an appropriate wind tunnel.
4. How often do these excessive regional winds occur? This information, extracted from climatological records, determines the probability of the local wind on the site exceeding the limits for comfort or safety.
5. If local winds exceed the comfort or safety limits an unacceptable percentage of time, what design measures will reduce their strength so that the velocity limits are exceeded less often? These measures are devised by a combination of common sense, experience, and wind tunnel testing.

The following sections address these five issues, summarizing the state-of-the-art in acceptability criteria and design procedures.

WIND AND PEDESTRIANS

Wind influences comfort both mechanically, through its pressure effects and particle transport, and thermally, through wind chill. Pedestrian safety in the urban pedestrian environment is affected by mechanical pressure. Both mechanical and thermal effects are reviewed in the following to establish the wind speed limits above which comfort and safety are jeopardized. These limits form the basis for acceptability criteria used in design.

Mechanical Influences of Wind.—Wind influences comfort mechanically through pressure effects and particle transport. Wind pressure causes disturbance of clothing and hair, resistance to walking, and buffeting of the body and carried objects such as umbrellas. Comfort also is affected when the wind lifts dust and grit particles to eye level, or drives rain laterally into the eyes or beneath clothing. At higher velocities, wind interferes with walking and endangers people by causing them to lose their balance. At such velocities, eye damage from dust or possibly from flapping hair is also a safety problem. Some of the effects described are caused by the wind on a continuing basis, while others are precipitated by sudden unexpected peak gusts: a summary of such effects is provided in Refs. 1 and 18.

Wind at pedestrian level is accompanied by turbulence, and perceived as varying velocity, gusts, or eddies. The intensity of turbulence for any given wind speed varies from place to place, tending to be greater in urban or built-up surroundings than in open countryside. The effects of turbulence on pedestrians may be described as an addition to mean velocity. An "equivalent steady wind" defined as giving the same comfort or safety effect as the turbulent wind was introduced by Hunt, Poulton, and Mumford (9):

$$u_s = \bar{u}(1 + a \cdot \mathrm{TI}) \quad \ldots \quad (1)$$

in which u_s = the equivalent steady wind; $\bar{u}$ = the mean wind speed; a = an empirically determined coefficient; and TI = the relative turbulence intensity (the root mean square of the instantaneous deviations from the mean velocity, divided by $\bar{u}$).

Hunt et al. found $a \simeq 3$ in experimental observations of the performance of pedestrians in a wind tunnel with controllable turbulence characteristics. The steady wind, u_s is a value greater than the mean, reflecting turbulent fluctuations superposed on the mean speed.

Jackson (12) used this relationship in defining a "standard equivalent mean wind speed" $\bar{u}_{se}$, in which terms he assembled a wide range of previously observed wind effects into a table combining the effects caused by steady uniform winds, turbulent wind fluctuations, and infrequently occurring peak gusts (see Table 1).

Certain standardized conditions were necessary to compile Table 1:

1. The standardized equivalent wind speed, $\bar{u}_{se}$, is measured at a height of 2 m over an averaging time of 5 min. Published observations for different averaging times are corrected to this time.
2. The horizontal relative turbulence intensity is 18%. Observations for which TI is unspecified are assumed to have occurred with a TI of 18%. Observations with specified TI values different from 18% are converted by the following relationship:

$$\bar{u}(1 + 3\,\mathrm{TI}) = \bar{u}_{se}(1 + 3 \times 0.18) \quad \ldots \quad (2)$$

3. For effects caused by a maximum gust of some minimum required duration, a value of $\bar{u}_{se}$ is calculated that would be expected to produce one such gust in the 5-min averaging period under 18% TI.

Wind effects observations as summarized in Table 1 and Ref. 17 are the basis for making judgments about wind acceptability in buildings and open space. Recommended acceptability criteria will be described later.

Thermal Influences of Wind.—The familiar concept of wind chill reflects the thermal influence of wind. In cool climates, wind increases the rate of cooling of the body by removing the insulating film of still air found next to skin and clothing in calm conditions. The increased rate of cooling may cause discomfort. In hot climates, the increased wind-induced convection and evaporation may be beneficial to comfort.

Thermal comfort is influenced by the following climatic variables: air, temperature, radiation (solar and terrestrial), humidity, and wind. The pedestrian's clothing and activity level are also important variables. Thermal comfort is a function of body and skin temperature, the rate of heat transfer, and in overheated conditions, of skin wettedness as well.

To date, attempts to develop thermal models of human comfort outdoors have been confined to steady-state thermal balance models (1) in which thermal equilibrium is assumed to assure comfort. Such models have not been useful in practice primarily because thermal equilibrium with the surroundings requires 1 h–2 h continuous exposure to the outside environment. This is a rare situation for pedestrians, although such exposures may be experienced at bus stops and sports stadia. The average exposure is much shorter.

TABLE 1.—Wind Effects Versus Standard Equivalent Mean Wind Speed Under Standard Conditions[a]

Standard equivalent mean wind speed, in meters per second (1)	Effects observed or deduced (2)
0	Calm, no noticeable wind
2	Wind felt on face
	Clothing flaps [5]
4	Newspaper reading becomes difficult (1)
6	Hair disarranged [5], dust and paper raised, rain and sleet driven (1)
8	Control of walking begins to be impaired
	Violent flapping of clothes [5], progress into wind slightly slowed
10	Umbrella used with difficulty
12	Blown sideways [2], inconvenience felt walking into wind, hair blown straight
	Difficult to walk steadily, appreciably slowed into wind [10]
	Noise on ears unpleasant
14	Generally impedes progress
	Almost halted into wind, uncontrolled tottering downwind [10]
	Difficulty with balance in gusts [2]
16	Unbalanced, grabbing at supports [2]
18	People blown over in gusts [3]
22	Cannot stand [3]

[a] The minimum gust duration required for each effect to be experienced is given, in seconds, in brackets [ ].

A computer program that iteratively calculates the thermal response of the body over a series of 1-min intervals shows promise for providing thermal design criteria for the wind environment (6). The effect of any period of exposure to outdoor climates on body temperature, heat transfer, thermal sensation, and comfort sensation can be predicted in this way. This model currently suffers from lack of experimental information on wind penetration or infiltration of clothing, and requires validation in outdoor conditions.

DESIGN CRITERIA: COMFORT, SAFETY, AND PROJECT ACCEPTABILITY

With an understanding of wind effects on people, it is possible to suggest limits above which wind should not be permitted or is not desired. The Building Research Establishment, in England, recommended the following well-known values for mean wind at pedestrian height over an unspecified averaging period, in cool conditions (20): at 5 m/s, there is an onset of discomfort; at 10 m/s, it is definitely unpleasant; and at 20 m/s, it becomes dangerous.

Hunt et al. (9) refined these recommendations to the velocities given in Table 2.

Murakami et al. (17) corroborated Hunt's limits, with some values somewhat more restrictive, finding control of walking difficult in the 10 m/s–15 m/s range. Nonuniformity of wind in time and space greatly affects walking and can cause the observed effect "walking difficult to control" in wind speeds as low as 3 m/s.

TABLE 2.—Wind Velocity Limits

Wind and effect (1)	Criterion[a] (2)
Steady uniform wind:	
For comfort and little effect on performance	$\bar{u} < 6$ m/s
For ease of walking	$\bar{u} < 13$ m/s–15 m/s
For safety of walking	$\bar{u} < 20$ m/s–30 m/s
Nonuniform winds ($\bar{u}$ varies by at least 70% over a distance less than 2 m):	
To avoid momentary loss of balance and to be able to walk straight	$\bar{u} < 9$ m/s
For safety (for elderly people this criterion may be too high)	$\bar{u} < 13$ m/s–20 m/s
Gusty winds[b]:	
For comfort and little effect on performance	$u_s < 6$ m/s
Most performance unaffected	$u_s < 9$ m/s
Control of walking	$u_s < 15$ m/s
Safety of walking	$u_s < 20$ m/s

[a] $\bar{u}$ is averaged over short periods, on the order of seconds.

[b] u_s is defined in Eq. 1.

With a wind speed limit in hand, the designer must judge what percentage of the time (or with what frequency in a year or season) it may be exceeded. The percentage of time exceeded equals the probability of discomfort or danger. For comfort limits, 10%–20% may seem reasonable. For safety limits, lower percentages of time exceeded (say 0.1%) should be applied to the higher velocities. Various researchers have suggested limits and acceptable frequencies for the limits. These have been summarized and compared by Melbourne (15).

Fig. 1 is a reproduction of a figure from Ref. 15, with some additions as noted later. The figure compares the various criteria using the probability of exceeding various hourly mean speed limits in any given year. The probabilities are adjusted to apply to half the hours in the year representing the daylight hours when most buildings are occupied. The curves imply a relative turbulence intensity of 15%.

Legend for Comfort Criteria Graph

CRITERIA		SYMBOL
MELBOURNE (16)		—
Acceptable below for:		
Walking		1
Stationary, short exposure		2
Stationary, long exposure		3
Unacceptable, dangerous above:		4
DAVENPORT (5)		
Acceptable for:		
Walking fast	If $P[\bar{u} > 10] < 0.05$	D
Strolling	If $P[\bar{u} > 7.5] < 0.05$	D
Standing, Sitting, Short Exposure	If $P[\bar{u} > 5.5] < 0.05$	D
Standing, Sitting Long Exposure	If $P[\bar{u} > 3.5] < 0.05$	D
PENWARDEN AND WISE		
Acceptable	If $P[\bar{u} > 5] < 0.2$	P
LAWSON (13)		
Acceptable	If $P[\bar{u} > 6 \text{ to } 8] < 0.04$	■
Unacceptable	If $P[\bar{u} > 11 \text{ to } 14] < 0.02$	■
HUNT, POULTON & MUMFORD (9)		
Acceptable for Strolling	If $P[u > 6] < 0.1$	H
Acceptable for Walking	If $P[\bar{u} > 9] < 0.01$	H
COHEN, ET AL (3)		
Data from Table 3.		C

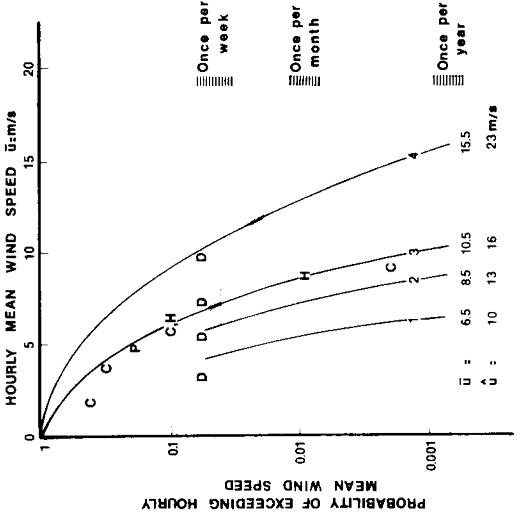

FIG. 1.—Comparison of Various Criteria for Environmental Wind Conditions for Daylight Hours, for Relative Turbulence Intensity of 15%

Isyumov (10,11) presents a plot of comfort and safety versus hourly mean wind speed similar to Melbourne's but expressed in terms of number of occurrences per year where the hourly mean wind speed is greater than the comfort limits indicated. The return periods are calculated using a method by Davenport (4).

Cohen et al. (3) recommends a number of acceptability criteria based on their extensive field observations (see Table 3). These findings have been incorporated into Fig. 1 correcting for daylight hours for consistency with Melbourne's method. The safety-related values show lower wind speed limits in the acceptability criteria than the other researchers, almost certainly because the peak gusts recorded per hour in this investigation tended to three times the hourly mean, whereas such gusts in Melbourne's assumed turbulence would be only 1.5 times the hourly mean. Because the turbulence intensity was not reported with Cohen's data, it is not possible to adjust these values to make them fully comparable. The comparison does show the significance of assumed turbulence intensity in these acceptability criteria for safety purposes, where the influence of the peak gust predominates.

TABLE 3.—Pedestrian Safety/Comfort Standards for Urban Winds

Activity area (1)	Hourly mean wind speed, in meters per second (miles per hour) (2)	Permitted occurrence frequency, as a percentage (3)	Permitted frequency considering only daylight hours, as a percentage (4)
All pedestrian areas—limit for safety	9.1 (20)	0.1 (≃10 h/yr)	0.2
Major walkways, especially principal egress path for high-rise buildings	9.1 (20)	0.1	0.2
Other pedestrian walkways, including street and arcade shopping areas	6.4 (14)	5	10
Open plazas and park areas walking, strolling activities	3.6 (8)	15	30
Open plaza and park sitting areas, open-air restaurants	2.3 (5)	20	40

Penwarden (18) analyzed cases of shopping centers that had experienced wind complaints. He found that in centers where the single limit of 5 m/s hourly mean wind speed was exceeded 20% of the time or more, the owners invariably spent money to add protective screens or roofs. Centers with frequencies of 10%–20% caused complaints but no remedial action was taken. Few complaints were registered at centers with frequencies below 10%. Penwarden's study gives the most concrete economic evidence in support of specific acceptability criteria to date.

Caution should be exercised in applying such criteria to wind data available from the United States National Oceanic and Atmospheric Administration (NOAA). In a nonsteady wind, the length of the averaging interval will affect the value of $\bar{u}$ associated with the maximum wind effect observed during that interval. This is because most wind effects are sensed by the pedestrian over very short intervals of time, 1 sec–10 sec, while wind is usually observed and recorded for longer intervals, of 1 min or more. Melbourne's and Cohen's effects on the chart are either observed against hourly menas, or converted to be so. The actual effects, however, may refer to instances that may have occurred only once, during a gust, within that hour.

The NOAA wind records available in the United States are termed hourly mean wind speeds, but are actually 1-min means measured once an hour. This means that the distribution of windspeeds from NOAA data will show greater variability than would true hourly means. The pedestrian effects specified for gusts implied within Melbourne's hourly mean wind speeds would therefore occur at higher mean wind speeds when using NOAA data, speeds closer to those of the gust itself. Fig. 2, reproduced from Lawson (14), gives an example of the variation of wind speed with averaging time at a relative turbulence intensity of 0.28. One may estimate from this that the hourly mean criteria should be 25% higher when using NOAA data; that the 5-min mean wind speed limits described above should be 20% higher; and that criteria based on direct peak gust measurement (2 sec–3 sec), should be 25% lower.

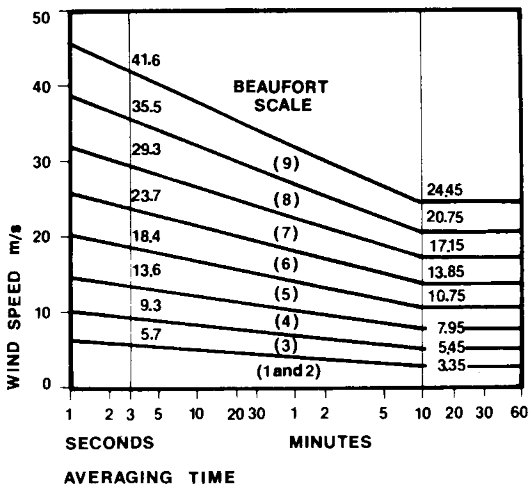

FIG. 2.—Variation of Wind Speed with Averaging Time, for Velocity Ranges of Beaufort Scale

Finally, caution is needed when using any of the criteria based on mechanically-caused wind discomfort, for thermal discomfort in cool environments usually begins at lower velocities than mechanical discomfort. Reliance on these may underestimate the actual discomfort, especially for prolonged or relatively inactive outdoor activities.

DETERMINING SURFACE WINDS IN PROPOSED BUILT ENVIRONMENT

The designer should consider outdoor comfort and safety early in the design process. Because the relationships between the physical form of a building and site, the climate, and resulting comfort and safety around it are complex, he or she may have to follow a climatic design process in order to find a satisfactory solution. The process, basically: (1) Determines the climatic characteristics of the site and the preliminary project, partly by model tests; (2) assesses its effects on the acceptability of the project; and (3) modifies the project design and tests the climate until a solution is reached.

Winds at pedestrian level often will be strongly affected by the building, planting, and grading configuration of the project. Briefly, there are basically three flow fields that cause enhanced wind at pedestrian level: (1) Vortices at the base of the windward face of a building caused by greater pressures on that face at higher elevations; (2) flows caused by pressure differences between low pressure regions at the sides and lee of a building and the relatively higher pressure regions at the windward side (open passageways between these regions will experience greatly enhanced winds); and (3) flows through constrictions between buildings. Two publications by Gandemer (7,8) provide visualizations of wind flow around a wide variety of building configurations. They are very useful for obtaining an intuitive feel for wind behavior around buildings.

Penwarden and Wise (19) have provided generalized rooftop-to-ground-level velocity ratios for such configurations that have been widely quoted. However, note that these ratios do not apply when buildings of similar height are located in the upwind direction.

If the configuration of a yet-unbuilt project seems likely to cause high local winds, it should be tested in model form in a wind tunnel. This technique is also useful for defining winds on existing sites, since the flow strength and direction can be controlled during the tests. Physical modeling with limited field verification is most desirable.

Physical modeling requires the use of a specialized wind tunnel that reproduces the boundary-layer conditions above the actual site. Both the velocity and the turbulence intensity profiles should be modeled to scale. The most satisfactory means of achieving this at present is to generate the boundary layer with turbulence generators and long fetches of roughness similar to that of the terrain upstream of the project site. The testing of architectural models for environmental wind conditions may be carried out at low wind speeds (5 m/s–10 m/s) because turbulent flow patterns around bluff (sharp-edged) objects do not vary over a wide range of velocities. This is fortunate, for it allows tests to be performed at costs comparable to other design consulting fees.

Velocities measured in the wind tunnel are nondimensionalized and are expressed as a percentage of a reference velocity. The reference velocity in the tunnel is measured at a reference height, often chosen as the height (at model scale) of the wind instrumentation of the weather station providing climatological wind data. By relating wind tunnel measurements to climatological data, wind speed frequency distributions are found for important locations within and around the proposed project.

Measurements are normally made at a network of grid points on the project model. A hot-wire anemometer is used to measure wind speed and turbulence at each grid point. Its small size allows it to measure speeds within distances of the order of millimeters above the surface, representing pedestrian height at model scale. In addition, when the wire is held vertically, the hot-wire anemometer is insensitive to the azimuth angle of approaching wind (within a sector of about 270°). Since the wind turbulence at pedestrian level near buildings often results in rapid lateral directional changes, it is important that the measuring instrument exhibit minimal directional sensitivity in the horizontal plane.

The entire network of points on the model is tested separately for each wind direction, the number of directions normally corresponding to the number of points of the compass considered in the meteorological wind data base.

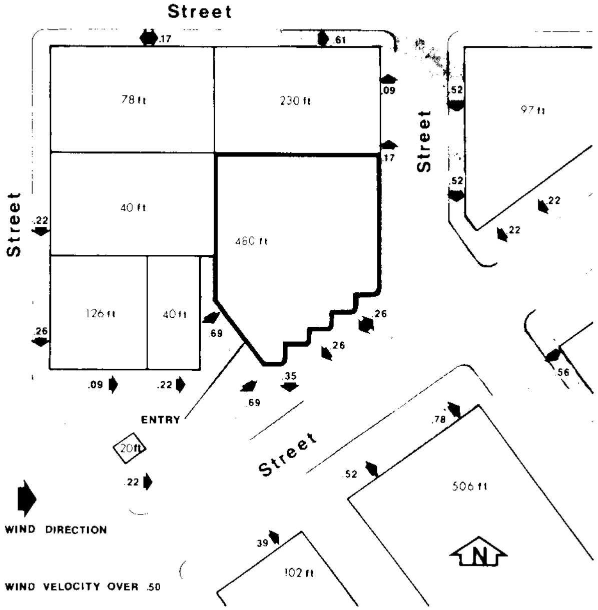

FIG. 3.—Street-Level Wind Directions and Velocities during West Wind, High-Rise Project

Fig. 3 is a representation of a strong air flow pattern occurring around a wind tunnel model of a San Francisco high-rise project during exposure to west winds. The building's entrance is located on the southwest side of the building. The wind directions at several grid points are marked and the velocities expressed as decimal fractions of the velocity at the reference height, which in this case is 132 ft, the height of the anemometer at the local weather station in the city.

DETERMINING FREQUENCIES OF UNCOMFORTABLE OR DANGEROUS WINDS IN PROPOSED BUILT ENVIRONMENT

Wind data are usually recorded at airports in open terrain. For most sites wind information must be extrapolated geographically from the recording station to the vicinity of the site. The effects of topography, vegetation, and structures must be carefully considered in this extrapolation.

The meteorological data base should provide information necessary to determine the amount of time that pedestrians will be uncomfortable or endangered on the site. This requires predictions of expected winds preferably by time of day, and if thermal comfort is being estimated, coincident data on temperature and sun. The most useful data format is a cumulative directional frequency distribution providing the percentage of time that each wind velocity is exceeded for each wind direction. The National Climatic Center of the NOAA may have this information in existing published summaries, although most locations have not been analyzed in detail. The Center will prepare such summaries from original hourly observations upon request. It also provides magnetic tapes with the hourly observations, usually with 10 yr/tape. The data from the tape is then commonly fitted to a model such as the Weibull distribution to provide a smooth frequency distribution.

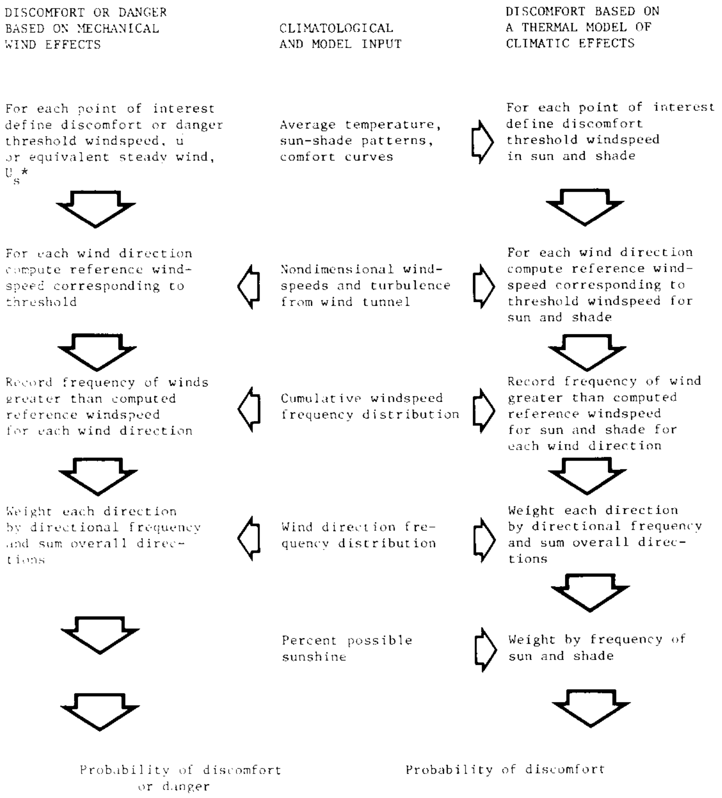

FIG. 4.—Process for Determining Probabilities of Discomfort or Danger

The frequency of discomfort may then be determined for either thermal or mechanical wind effects by following the procedure in Fig. 4 taken from Ref. 1. The same approach may be used to predict dangerous wind velocity frequencies. The procedure for thermal comfort is carried out for selected hours of the day to incorporate sun/shade patterns and temperature data into the comfort determination.

Fig. 5 shows the probability of discomfort around the high-rise project considering all wind conditions expected in San Francisco in the early afternoon during the autumn season. The predominance of west winds over other winds during this period causes the discomfort values to closely follow the wind patterns shown in Fig. 3. The threshold velocity used here for determining discomfort is 5 m/s. The shadow patterns for this period are also shown, to give a suggestion of the thermal environment.

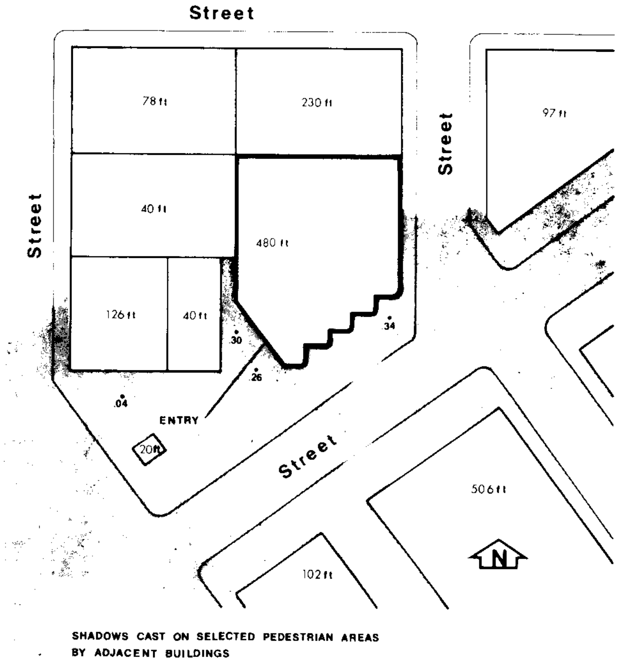

FIG. 5.—Probability of Discomfort at 1:00 P.M. Autumn Season

Avoiding and Mitigating Wind Problems

If the expected comfort levels are unacceptable, design modifications to improve conditions may have to be investigated. The following measures are appropriate for tall buildings (2,3):

1. Large slab buildings should not be oriented in a direction normal to the prevailing wind to avoid downwash on the windward face. Circular and polygonal towers tend to have advantageous wind climates at ground level because of reduced downwash.

2. Tall buildings benefit from significant horizontal projections to break up downward-directional winds. Protective awnings and canopies near ground level need to be large to influence wind over appreciable areas around buildings.
3. Important pedestrian thoroughfares and building entrances should not be planned at the windward corners of tall slab buildings as these are regions of accelerated corner flows.
4. Openings through buildings near the ground, especially with openings facing the prevailing wind, will experience strong winds unless revolving doors are used.
5. Vegetation may be used to absorb horizontal wind energy in pedestrian areas. Trees and shrubbery are not usually effective at protecting appreciable areas from downdraft winds.

Based on trials with wind tunnel models, design modifications within the site and budgetary limitations of the project may be selected. Modifications to reduce winds can range from changes in building height, bulk, or orientation, to the provision of vegetation or landscaping.

For any given problem there is a range of possible solutions varying in effectiveness and cost that should be optimized. For example, roofing over a shopping mall would surely reduce winds, but construction of wind deflectors or latticework or use of vegetation may yield the same results at far less cost.

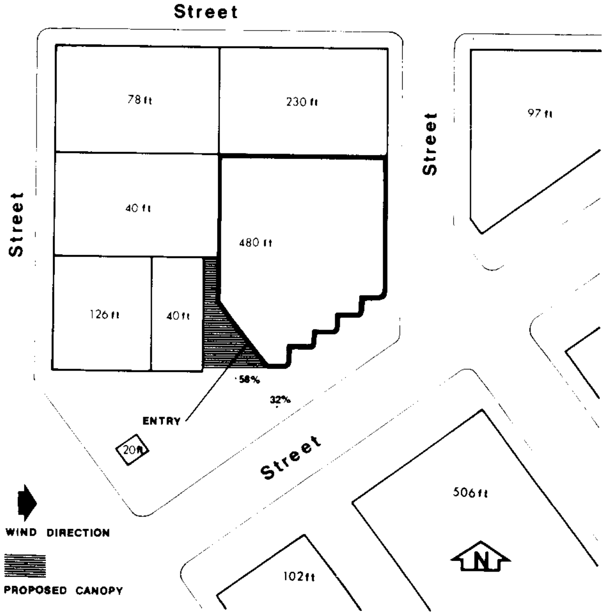

FIG. 6.—Percentage Reductions in Wind Speeds Near Entry due to Proposed Canopy above Entry

The influence of such devices on sunlight also should be considered.

A model of the modified design is tested in the wind tunnel and the analysis of comfort repeated. Further modifications are again suggested and the process is repeated until a satisfactory design is obtained.

Fig. 6 shows the reduction in the wind speeds at the sidewalk for the west wind case when a canopy is extended over the entrance. The reduction in expected discomfort on the sidewalk may be determined from this, allowing the designer to assess the feasibility of the canopy.

Conclusions

Wind effects on comfort and safety have been described and limits for acceptable velocities proposed by various authors have been summarized. These limits are strongly influenced by the averaging interval selected, and by the turbulence component of the wind. The paper presents suggested design criteria for the amount of time that these velocity limits may be exceeded.

The designer of a project affecting pedestrians outdoors may estimate whether the project meets these criteria by synthesizing information on the aerodynamic characteristics of the project and climatological information on wind frequency distributions for the region. Some general problem-causing building geometries can be identified, but many urban sites are sufficiently complex to justify model testing in a wind tunnel. A procedure for determining project acceptability through model testing is outlined.

Acknowledgments

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16132 DESIGN AND ACCEPTABLE WIND ENVIRONMENT

KEY WORDS: **Aerodynamics;** Buildings; **Climatology; Comfort;** Microclimatology; Pedestrians; Pedestrian safety; **Wind;** Windblast; Windbreaks; Wind chill; Wind forces; Wind pressure; Wind speed; **Wind velocity**

ABSTRACT: The comfort and safety of pedestrians has been neglected by designers because few criteria exist on acceptable wind velocities and it is difficult to predict the climatic characteristics around proposed buildings. Available information on wind effects on pedestrian comfort and safety are summarized. The mechanical effects of wind on comfort are now better understood than the thermal effects of climate. Limiting values of wind speed become the criteria to determine whether a space is comfortable or safe over time, and allow judgments to be made about project acceptability. Microclimatic-prediction techniques are explored, as are procedures for determining the probability of a proposed pedestrain area being uncomfortable or unsafe.

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