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WIND DESIGN CRITERIA FOR FIELD SHELTERS - A STUDY

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This report presents a damage potential scale for storm winds (other than tornadoes and hurricanes) derived from storm damage reports in the NOAA monthly publication Storm Data by using threshold values in the scale. Wind design criteria are proposed for the design of the Army functional system of field shelters. An inherent advantage seen for the proposed criteria is that they are derived from storm winds most likely to be experienced in the field. Since the scale is based on storm data from

20. continued

a region known for its tornado activity, thunderstorm severity and cold front intensity and squall line passages, the wind criteria probably pose as severe design conditions as might be expected in any operational area in the world. Furthermore, normal engineering practices are believed to have the flexibility to allow design changes for various regions of the world, for criticalness of the shelter function, and for different service life expectancies.

PREFACE

This study was initiated at the request of the General Equipment and Packaging Laboratory, U.S. Army Natick Development Center, for information on environmental factors in support of the development of a functional system of field shelters. This report covers part of the study conducted at the Geographic Sciences Laboratory, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Va., under DA Project 1T162112A129 and, more recently, 1T162112A528 and 1F162112A528.

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Traditionally, the chief concern with the wind effect on building design has been to ensure stability against the overall overturning moment due to wind pressure, which is proportional to the square of the wind speed. The design wind is usually based on a very small expectancy of occurrence, such as once in 50 years. Recently, however, and by necessity, localized wind loads (from winds far less than design speeds) acting on the surfaces of buildings have also become of active concern to building design. Research, using models in wind tunnels, and actual measurements on buildings have shown that local negative loads on the outer surfaces resulting from disturbed air flow around the structure can be far more intense and variable than local loads due to the dynamic pressure. On rectangular or block type buildings, the negative loads are most intense just in back of the leading edges of the sides and roof and are particularly intense over the leading corner of the roof in a quartering wind.[1] Over spherical and cylindrical shapes the more intense negative loads are concentrated in a belt about 40 percent behind the leading edge.[2]

Concern with the overturning moment has been over the years the basic premise for specifying surface wind speed criteria for field shelter design.[3,4] The criteria have been based on life

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1 H.J. Leutheusser, "Influence of Architectural Features on the Static Wind Loading of Building," Proceedings of Technical Meeting Concerning Wind Loads on Buildings and Structures, Marshall and Thom, Editors, National Bureau of Standards, pp. 73-87.

2 A.E. Dietz, R.B. Proffitt, R.S. Chabot and E.L. Moak, Wind Tunnel Tests and Analyses for Ground Mounted, Air-Supported Structures (Revised), T.R. 70-7-6P, General Equipment & Packing Laboratory, U.S. Army Natick Laboratories, July 1969, pp. 199-203.

3 N. Sissenwine and A. Court, Climatic Extremes for Military Equipment, Report No. 146, Research and Development Division, Office of Quartermaster General, November 1951, p.39.

4 N. Sissenwine and R.V. Cormier, Synopsis of Background Materiel for MIL-STD 210B, Climatic Extremes for Military Equipment, AFCRL-TR 74-0052, Air Force Cambridge Research Laboratories, January 1974, pp. 73-81.

expectance of the shelter and degree of exposure. Values specified were those whose probability of being exceeded during the life expectance of the shelter was only 10 percent (once in 9.3 times the life expectance in years) plus a gust factor;[5] higher winds were given for mountain and seashore exposures. Although the above premise is valid and is still assumed in determining the overall wind stress on a building, it does not reflect recent findings concerning the intense negative pressures occurring on lee surfaces during disturbed wind flow.

Concern for generation of intense localized negative pressures may well lead to more successful field shelter designs. First, structures in the field shelter system are, essentially, shells, i.e. air and pole supported tents, vans, light warehouse type buildings, rigid foam and prefabricated modular panel structures. Thus, it is reasonable to expect the shell to be subjected to localized negative pressures due to disturbed air flow around the structure. With shells, local surface failure could lead to the loss of the shelter function. Second, field shelters are far more likely to be subjected to turbulent air conditions during severe thunderstorms and squall line and frontal passages than the comparatively much higher straight winds given on an extreme probability basis. Furthermore, with the exception of tornadoes and intense hurricanes, such turbulent winds may well be the most severe design conditions to be met in the field.

Damage potential scales have been devised for tornadoes and for Atlantic hurricanes. The dynamics and damage patterns of tornadoes have been a subject of study for the past number of years at the Department of Geophysical Sciences, the University of Chicago, and a damage potential scale was devised as an aid in reporting and classifying tornadoes. The Atlantic hurricane disaster scale was developed at the National Hurricane Center, Miami, Florida. What is presented here is a similar type of scale for turbulent storm winds. Results are discussed in the application to the design of field shelters and their use as design criteria for inclusion in the appropriate AR and MIL-STD.

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[5] N. Sissenwine and A. Court, Climatic Extremes for Military Equipment, Report No. 146, Research and Development Division, Office of Quartermaster General, November 1951, p.41.

II. APPROACH

The strongest natural winds are associated with tornadoes, and although its very localized nature limits the total area of destruction, an intense tornado is the most destructive of all wind storms. Because of the local nature and very small risk of exposure, tornado winds are not normally considered in establishing wind design criteria. However, the structural damages and the probable wind speeds have been studied for a number of years. Based principally on his own broad studies, T. Theodore Fujita, University of Chicago, has proposed a wind damage potential scale for tornadoes; the first 6 increments of the scale are given in appendix A.

Along similar lines, a damage potential scale for Atlantic hurricanes was proposed by R.H. Simpson, when Director of the National Hurricane Center. The wind section of the Simpson Disaster Potential Scale is given in appendix B. In comparing the two, the tornado scale shows a somewhat greater damage potential for like wind speeds, but much of the damage described commonly occurs during storms with winds of far less strength. What is of interest to this study is the lower range of wind speeds at which the described damage could occur.

To find this lower range of wind speeds, the NOAA (National Oceanic and Atmospheric Administration) monthly publication Storm Data, one source of input for both of the above scales, was searched for comparable data reported for storms other than tornadoes and hurricanes or storms associated with their occurrence. The objective was to develop a damage potential scale similar to those developed by Fujita and Simpson.

III. DEVELOPMENT OF STORM WIND DAMAGE POTENTIAL SCALE

Storm items included in the NOAA monthly publication Storm Data are submitted by State Climatologists, which insures uniformity of format and a degree of quality control. The property damage descriptions follow a rather standard format, and the descriptions were more or less used by both Fujita and Simpson in their scales. The following general damage descriptions are used in this study:

1. Trees and utility lines down and signs damaged.

2. House trailers overturned.

3. Farm barns and sheds damaged.

4. Cement or cinder block wall under construction blown down.

5. House trailers demolished.

6. Farm barns and sheds demolished.

7. Plate glass or other windows blown out or in.

8. Parked or tied down aircraft damaged.

9. Minor roof or building siding damaged.

10. Roof sections ripped off, chimneys blown down.

11. Warehouse or hangar type buildings, or outside walls severely damaged.

These descriptions cover practically all the described damages included in the hurricane scale of winds from 74 mph to over 155 mph and those in the tornado scale, up to and including category F (3), of winds from 158 to 206 mph.

As to be expected, many given wind speeds are estimated and are so stated; sometimes the wording is "up to" or, perhaps, a reference is made to gust speed. On the other hand, there are a good number of reports that give the wind speed as "measured" or "recorded." In most cases, this refers to measurement at a nearby airport station. As a check, two tabulations were kept for the wind category of thunderstorm or gusty winds; one for "estimated or up to" and the other for "measured or recorded." A third tabulation was kept for winds associated with low pressure systems, which were labeled "straight" or were not specified as "gusty."

Tabulations were kept also by regions on the premise that the data would reflect terrain roughness; specifically, wind speeds over the eastern section of the country would be lower than over the western plains for the same damage potential. Actual tabulation, however, was on a four region basis: (1) East of the Mississippi River and north of the Gulf States; (2) Gulf States of Florida west including Texas; (3) The plains states east of the Rocky Mountains; and (4) The region west of the Rocky Mountains including the west coast. Well over a third of all tabulated data were for the eastern states, with the plains area second. Data for the western United States were practically lacking, except for the category of estimated winds during thunderstorm and gusty conditions. As expected, much more data were available for estimated winds than for measured conditions and still less could be extracted for low pressure system winds.

For the eastern states the two thunderstorm tabulations show a greater frequency of 85 and 95 mph winds for measured or recorded than for estimated or up to despite the fewer overall reports. Similarly there are fewer tabulations under 55 mph. Both sets show a marked predominance in the 55 to 75 mph range. The third tabulation, low pressure systems and straight winds, differs little from either thunderstorm set. Similar conditions are shown by the three tabulations for the plains states, but with a general shift to an increase of 5 to 10 mph in the wind speeds. Thus, it should be reasonable to conclude that the roughness effect of the eastern states is less than 10 mph, or winds of equal damage potential are 5 to 10 mph less over the eastern states compared to those over the western plains.

The majority of data extracted for Gulf States are for estimated thunderstorm winds. The tabulated distribution follows that of the eastern states, but the concentration in the 55 to 75 mph range is not as pronounced. The data for measured thunderstorm winds is small; what there are spreads over the higher winds from 65 to 105 mph. Not much more data are available for low pressure system winds. However, the tabulation is more similar to the western plains than for the eastern states. For the western mountains and the west coast, the data are practically divided between estimated thunderstorm winds and low pressure systems. A characteristic of both tabulations is the marked decrease in the frequency of the higher wind speeds as compared to the western plains and eastern states.

All in all, the tabulations are consistent, which in some respects may just reflect control by the State Climatologists. However, consistency also exists between "measured or recorded" and "estimated or up to" reported winds under thunderstorm and gusty conditions. The estimated winds may even be slightly low. Therefore, in devising the wind scale, given wind speeds are not the lowest values at which the described damage was reported, but they are the values where the number of reports show a marked increase. The wind speeds may be slightly high for topographically rough states, such as New York and Pennsylvania, but slightly low for Kansas and Nebraska.

TABLE 1. DAMAGE POTENTIAL SCALE FOR STORM WINDS (OTHER THAN TORNADO AND HURRICANE)

Scale	
1	Winds 45 mph. Trees and utility lines down. Signs damaged.
2	Winds 50 mph. Minor damage to roofs and other surface areas of residences. Concrete or cinder block walls under construction blown down.
3	Winds 55 mph. House trailers overturned. Farm buildings and sheds damaged.
4	Winds 60 mph. Plate glass and other windows broken. Sections of roofs ripped off. House chimneys blown down.
5	Winds 65 mph. House trailers demolished. Farm buildings and sheds demolished. Outside walls damaged.

IV. DISCUSSION

For comparable damage potential, wind speeds in the storm scale are about half of those in the tornado and hurricane scales. Yet, this does not necessarily imply that the storm scale is inconsistent with the other two. One small problem recognized by Fujita and Simpson is definition. The threshold wind for tornado and hurricane classification is 74 mph; thus, their basic assumption could be valid that at this wind speed and higher the damage potential depends upon the dynamic wind pressure. Normally, such pressure is considered as a static load. Whereas, here the premise is that negative pressure loads resulting from disturbed flow around and over a structure are the primary cause for the type of structural failure described in the storm scale. Furthermore, surface storm winds are variable in both speed and direction, resulting in high fluctuation in intensity of the negative pressure loads.

There are some obvious variables in the damage potential scale. Tree damage depends somewhat upon species, foliage status, and soil conditions; and building damage depends upon type and state of repair. However, windows are a fairly standard item. Although there were a number of reports of windows being blown out, only a comparative few stated whether the glass had been blown into the structure or had actually been blown (or sucked) to the outside. Roof damage reports were common and many could only be attributed to development of a negative pressure loading. In one such report the loss of an apartment roof during a January storm was described by an observer thusly, "lifted straight up, remained stationary for a few seconds, then separated into big chunks and smashed into parked cars and an apartment house across the street." At the time, wind was described as gusting to 50 mph.[6] However, extensive damage may be caused by the intense downflow of air during turbulent conditions associated with strong squall lines and well-developed thunderstorms. These strong, narrow, straight-line winds are known as "plow" winds in the prairie states. Estimated speeds given in damage reports went to over 90 mph. A rarer reported storm damage mechanism is the sudden pressure drop. In what may have been related events at the Andrews Air Force Base, Maryland, a hangar wall collapsed during a severe thunderstorm, while windows were blown out on one side of 10 cars in the parking lot. The weather station reported gusts to 60 mph at the time although

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[6] Environmental Data Service, Storm Data, National Climatic Center, Asheville, NC, January 1963, p.6.

unofficial estimates placed the winds as high as 80 mph.[7] In a thunderstorm at Wrightsville Beach, North Carolina, the windows of 40 automobiles in a parking lot were blown out, and the occurrence was attributed to a sudden, unexplained, pressure reduction. At that time wind was gusting to 52 mph.[8] Similar damage has been reported at the Malmstrom Air Force Base in Montana. Even the fall of a suspended ceiling has been attributed to a sudden pressure drop occurring during a thunderstorm.

Windows popping out of store fronts and cars during the passage of an intense squall line over Martha's Vineyard off Cape Cod was attributed in the storm report to an internal local circulation cell, perhaps 1 to 2 miles wide, within a severe thunderstorm contained in the squall line.[9] During the same storm, an unusual .14-inch pressure jump was reported at Woods Hole. Surface wind gusts ranged from 60 to 98 mph in the area, while gusts to 110 mph were reported at the tower at the south entrance to the canal. Under what may have been similar conditions, "a three-story panel of windows 'exploded' out of the south side of the Student Center" on the Campus of the Arkansas State University during the passage of a squall line. Winds gusting to 80 mph were reported by the Jonesboro FAA Flight Service Station.[10]

V. APPLICATION TO DESIGN

The objective of the integrated field shelter system is to provide a controlled operating environment for essential military functions under three restraints: (1) transportability, (2) operational mobility, and (3) compatibility with available transport equipment.[11] Designer and user considerations are: (1) type of shelter, (2) criticalness of the shelter function, and (3) comparatively short service expectancy at any one site. How best may the design wind be brought into the life cycle of design, development, test, and use?

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[7] Environmental Data Service, Storm Data, National Climatic Center, Asheville, NC, March 1970, p.18.

[8] IBID., July 1972, p.125

[9] Ibid., July 1973, p.6.

[10] Ibid., June 1970, p.68.

[11] U.S. Army Natick Laboratories, QMDO Plan for Functional Field Shelter System, 30 June 1970.

Present design practice recognizes wind turbulence as expressed by gusts, but gust speeds are normally considered in relation to changing dynamic pressure loads on the windward face and only in the mean direction of the wind. Although the magnitude and frequency of fluctuations about the mean moment were far greater, the turbulence from upstream roughness, simulating flow over a built-up area, was found by Cermak and others[12] in wind tunnel studies to reduce by one-thirds the overturning moment. How much of this may be extrapolated to turbulence caused by terrain roughness or as a component of storm winds is a question; at least, it should indicate the direction. Under turbulent storm conditions, gust winds may have directional changes in the vertical as well as the horizontal components. Small directional changes should not materially affect the total dynamic pressure load on the face of the building, but could materially affect intensity and distribution of the local negative pressure loads in areas of critical flow near corners of sides and roof. Also, the possible magnitude and frequency of the directional changes may be related to the storm type and inversely to the wind speed.

The importance of a specified value or even a value for steady wind and another value for superimposed gusts depends principally on how it is used. Wind values are entered into the formula for determining the impact, or dynamic pressure, as the square of the speed. However, normal building design would also include a safety factor. The commonly used safety factor is 3 [13,14] (which is the equivalent of increasing

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[12] J.E. Cermak, W.Z. Sadeh, and G. Hsi. "Fluctuating Moments on Tall Buildings Produced by Wind Loading", Proceedings of Technical Meeting Concerning Wind Load on Buildings and Structures. Building Science Series 30. National Bureau of Standards, November 1970, pp. 45-59.

[13] ~~Where detailed information on fabric characteristics is not~~ available, Dietz ét al, indirectly through use of a reference, recommend using a safety factor of 3 for air-supported shelters. A.E. Dietz, R.B. Proffitt, R.S. Chabot and E.L. Moak. Design Manual for Ground-Mounted Air-Supported Shelters. TR 69-59-6P. General Equipment and Packaging Laboratory, U.S. Army Natick Laboratories, January 1969.

[14] For air-supported structures Dent proposes dividing the safety factor into two components. The first, varying between 2 and 4, would reflect the probable material strength loss over the life expectancy; the second, varying between 1 and 2, would reflect the intended use of the shelter whether for storage or for public use. As an example, he recommends a safety factor of 3 for an exhibition pavilion with a design life of 10 years and the expectation that the structure would be erected and dismantled many times. R.N. Dent. Principles of Pneumatic Architecture, The Architectual Press, 1971, pp. 81-84.

the design wind by over 70 percent. A safety factor of 4, is the equivalent of doubling the percent increase, and a factor of 2 is the equivalent of a 40-percent increase). The implication to overdesign has its limits; however, the design safety factor, as normally used, has a greater impact on the final product than the design wind. Thus, an acceptance of a variable safety factor would simplify the matching of design specifications for Army field shelters to operational needs of the various world regions.

The bulk of the damage reports used in developing the storm wind potential damage scale are from the area of the United States east of the Rocky Mountains. Certainly, it is a region buffeted by many severe storms. According to Fujita,[15] the region is the world core for frequency and intensity of tornado activity, which reflects the severity of thunderstorm development and intensity. The eastern slopes of the Rockies are swept by strong, persistent downslope winds and often are accompanied by snow in the winter. The Gulf and Southern States have the hurricanes, and the New England States have the "northeasterner." The region east of the Rockies also experiences the migration of intense frontal systems and squall lines.

Compared to other regions of the world, the winter winds of the open Arctic are characteristically persistent, moderately strong, and comparatively nonturbulent. Furthermore, in the Arctic, the snowload would not be greater as a design factor than for the northern tier of states, those east of the Rockies. Possibly, a more important factor to consider would be the element of blowing snow. In the tropics, maximum winds of the North Pacific typhoons are somewhat higher than for the North Atlantic hurricanes, but the maximum winds are not always attained in the tropics. Besides, the frequency in any single area is low compared with the number of violent extratropical cyclones and rapidly moving cold fronts and squall lines of the midlatitudes. Also, the numerous thunderstorms in the tropics are seldom accompanied by the type of violent surface winds that may accompany the well developed, midlatitude storm. Although moderately strong winds may occur during intense dust storms or dust devils, extreme wind speeds are not a characteristic of hot-desert climates. However, high winds can be expected around the desert edges when a source of moisture exists or during certain seasons of the year.

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[15] T.T. Fujita. Estimate of Maximum Windspeeds of Tornadoes in Southernmost Rockies, SMRP Research Paper No. 105, The University of Chicago, June 1972, p.4.

All in all, it is reasonable to conclude that storm wind conditions over the region of the United States east of the Rocky Mountains are as severe as in any area in the world and more severe than most. On the basis of wind stress, a general ranking could be: (1) midlatitudes, most severe: (2) Arctic and tropics, severe: and (3) hot deserts, least severe. If snowload is a factor, then the ranking becomes a simple one of (1) midlatitude and Arctic, severe, and (2) tropics and hot desert, less severe. Differentiation could well be regarded as a design factor in conjunction with or in lieu of the normal use of the safety factor. However, the mistake should not be made of regarding the rankings as simple ratios of 3:2:1, or 2:1. Pressure, whether positive or negative, is a function of the square of the wind speed, and energy exerted along a flapping fabric side or roof as the cube of the wind. Furthermore, the concept of regional differentiation is based on the premise of significant advantage, in this case, in transportability, mobility, or costs; all of which are the province of the designer.

The bulk of the storm winds east of the Rocky Mountains were tabulated in the 55, 65, and 75 mph classes with damage potential threshold values ranging from 45 to 65 mph. Assuming a general reference level of these winds of 30 feet, a reduction to the 10-foot level, as specified in AR 70-38 and MIL-STD 210B, would be from about 40 to 60 mph. Tentatively, then, the basic design wind would be from 40 to 60 mph with a mean wind of 50 mph. However, turbulence may also include directional changes; thus, the design wind would be further described by X degrees around a mean direction. Just as a basis of discussion, place X as 30 degrees. Storms involve time; thus, the third element becomes time, perhaps 15 minutes. Then the basic design wind becomes 40 to 60 mph around a mean wind of 50 mph varying directionally up to 30 degrees around the mean direction for a period of 15 minutes.

If the general premise and results of this study are acceptable to designers, the next step would be to research the velocity and directional profiles of the wind developed under severe storm conditions. Such profiles should be helpful in understanding the more probable extreme wind stresses that shelters may be exposed to under field conditions.

VI. CONCLUSIONS

Structures incorporated in the functional field shelter system are particularly affected by intense local negative pressure loads developed by disturbed flow around and over the shelters during turbulent storm winds. The damage potential scale presented for storm winds, excluding tornadoes and hurricanes, reflects such loads, and the wind criteria given should be used in the design of the field shelters. Additional research should be conducted to obtain velocity and directional profiles of winds that occur during storm conditions to understand the more probable extreme wind stresses that shelters may be exposed to under field conditions.

APPENDIX A. FUJITA WIND POTENTIAL DAMAGE SCALE

F0 - less than 73 mph, Light Damage.
Some damage to chimneys and TV antennas; twigs broken; shallow rooted trees uprooted.

F1 - 73 to 113 mph, Moderate Damage.
Roof damage; windows broken; light trailer houses pushed or overturned; some trees uprooted or snapped; moving vehicles pushed off the road.

F2 - 113 to 158 mph, Considerable Damage.
Roof torn off frame houses leaving strong upright walls; weak buildings in rural areas demolished; trailer houses destroyed; large trees snapped or uprooted; railroad boxcars pushed over; light object missiles generated; cars blown off highway.

F3 - 158 to 207 mph, Severe Damage.
Roofs and some walls torn off frame houses; some rural buildings completely demolished; trains overturned; steel-framed hangar warehouse type structures torn; cars lifted off the ground; most trees in a forest uprooted, snapped or leveled.

F4 - 207 to 261 mph, Devastating Damage.
Whole frame houses leveled, leaving piles of debris; steel structures badly damaged; trees debarked by small flying debris; cars and trains thrown some distances or rolled considerable distances; large missiles generated.

F5 - 261 to 319 mph, Incredible Damage.
Whole frame houses tossed off foundations; steel-reinforced concrete structures badly damaged; automobile-sized missiles generated; incredible phenomena can occur.[16]

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16 From SMRP Research Paper No. 91, Department of the Geophysical Sciences, The University of Chicago, February 1971, pp. 8 and 9.

APPENDIX B. SIMPSON'S DISASTER POTENTIAL SCALE FOR ATLANTIC HURRICANES

(The scale is actually composed of two elements, Wind and Storm Surge.)

1. Zero - Winds less than 74 mph. (all winds at standard anemometer height)
   No damage given since 74 mph is the threshold value for hurricane classification.

2. One - Winds 74 to 95 mph.
   Damage primarily to shrubbery, trees, foliage, and unanchored mobile homes. No real damage to building structures. Some damage to poorly constructed signs.

3. Two - Winds 95 to 111 mph.
   Considerable damage to shrubbery and tree foliage; some trees blown down. Major structural damage to exposed mobile homes. Extensive damage to poorly constructed signs. Some roofing material damage to buildings; some window and door damage; no major damage to building structures.

4. Three - Winds 111 to 131 mph.
   Damage to shrubbery and trees. Foliage off trees; large trees blown down. Practically all poorly constructed signs blown down; some roofing material damage; some window and door damage; some structural damage to small residences and utility buildings. Minor amount of curtain wall failures.

5. Four - Winds 131 to 156 mph.
   Shrubs and trees down; all signs down. Extensive roofing material damage; extensive window and door damage; complete failure of roof structures on many small residences. Some curtain wall failure.

6. Five - Winds greater than 155 mph.
   Shrubs and trees down; roofing damage considerable; all signs down. Very severe and extensive window and door damage. Complete failure of roof structures on many residences and industrial buildings. Extensive glass failures; some complete building failures; and small buildings overturned and blown over or away.[17]

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[17] U.S. Department of Commerce, National Hurricane Operations Plan, NOAA FCM 73-4, May 1973, pp. 16 and 17.