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Standards to Resist Hurricane Wind Forces

by

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ABSTRACT

On August 24, 1992, Hurricane Andrew struck the coast of south Florida, and then proceeded across the Florida peninsula and the Gulf of Mexico before hitting Louisiana on August 26. Damages of over $30 billion, deaths exceeding 55, and over 200,000 people left homeless prompted the Department of Housing and Urban Development (HUD) to examine its wind design standards for manufactured housing and other residential construction. To review the adequacy of HUD's wind standards, the Department contracted for a study by the National Institute of Standards and Technology (NIST). Based on this study, a wind design and construction standard for manufactured housing, referencing the American Society of Civil Engineers (ASCE) Standard 7-88 was developed and published on January 14, 1994. Research is now being conducted by NIST to provide information so that HUD can further develop standards for wind and tornado resistant construction in other areas of the U.S.

KEYWORDS: anchorage, building codes, damage assessment, design standards, hazard mitigation, hurricane, manufactured housing, residential construction, structural engineering, tornado, wind, wind speed.

1. INTRODUCTION

The purpose of the National Manufactured Housing Construction and Safety Standards Act of 1974 is to reduce the number of personal injuries and deaths, and the insurance costs and property damage resulting from manufactured home failures, and to improve the quality and durability of manufactured homes. In 1993, manufactured housing accounted for approximately 25 percent of all new single-family homes sold in the U.S. Design and construction of this type of housing is covered by the Manufactured Home Construction and Safety Standards (MHCSS), administered by HUD. The MHCSS, which became effective in 1976, prescribes minimum loads for design against wind and snow.

Based on the performance of manufactured housing in Hurricane Hugo in 1989 and in Hurricane Andrew in 1992, it became apparent that the current provisions of the MHCSS were inadequate to ensure satisfactory performance under extreme wind conditions, and the Department undertook a comprehensive review of the requirements in 1992. This paper describes the current wind load requirements, the general types of failures experienced in south Florida during Hurricane Andrew, and amendments to the wind load provisions which are to become effective in July of 1994. Additional problems with ensuring the satisfactory performance of this type of construction in extreme winds are described in this paper.

Following Hurricane Andrew, HUD conducted field investigations of the damage experienced in the hurricane by manufactured housing, as well as other residences constructed under HUD subsidized or mortgage insurance programs. The primary goal of these investigations was to ensure that Federal standards provide adequate protection to manufactured home occupants during high wind conditions. In addition, damage surveys and assessments of single- and

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multi-family housing construction were made to evaluate the adequacy of building codes and HUD's Minimum Property Standards.

2. WIND SPEEDS IN HURRICANE ANDREW

The number of reliable wind speed records in a landfalling hurricane usually is quite limited, and Hurricane Andrew was no exception. In fact, no anemometers exposed to winds in the eyewall of Andrew survived long enough or had the recording capability to register the maximum wind speeds. In the months following Andrew, considerable effort was expended in locating records of wind speed and/or barometric pressure from which to reconstruct the wind field over the area of heaviest damage. The highest recorded gust speed, corrected for anemometer error, was 79 m/s (177 mph) at Perrine. There were no confirmed sightings of tornadoes in Dade County and subsequent aerial surveys did not show any evidence of tornado damage.

Reinhold et al. (1993) used a computer-based model that makes use of information on the storm track, barometric pressure data, and the radius of maximum winds. The transition from over-water to over-land exposure and reductions in speed as the storm moves inland are accounted for by an empirical decay model. The model was calibrated against partial records obtained inside the eyewall and complete records obtained outside the eyewall. Results of the analysis are shown in Figure 1 as fastest-mile isotachs. Estimates of fastest-mile wind speeds for standard conditions (10 m (32.8 ft) height in flat, open country) in the area of heaviest damage range from 55 m/s (122 mph) at Florida City to 65 m/s (145 mph) north of Perrine where the northern sector of the eyewall crossed the coastline. The upper-bound estimate of the fastest-mile wind speed in the Tamiami Airport/Country Walk area is 60 m/s (135 mph). A map of the affected area is shown in Figure 2 (Marshall 1993). The maximum recorded gust speeds at selected locations are given in the original units of knots.

3. PERFORMANCE OF MANUFACTURED HOMES IN HURRICANE ANDREW

Damage to manufactured homes in Hurricane Andrew ranged from minor loss of roofing materials to total destruction. In general, those units manufactured after the adoption of the MHCSS in 1976 suffered less damage than did those units manufactured prior to 1976. However, conventional residential construction located adjacent to manufactured home parks performed better, in some instances significantly better, than did manufactured homes, including HUD-labeled units. Based on damage surveys and a reconstruction of wind speeds over the affected area, it appears that HUD-labeled units began to experience damage to roof and wall coverings at fastest-mile speeds of up to 42 m/s (95 mph) and significant structural damage at wind speeds of from 45 to 54 m/s (100 to 120 mph). At wind speeds ranging from 54 to 60 m/s (120 to 135 mph), there were numerous instances of HUD-labeled units suffering total destruction.

Commonly observed failures included loss of roof membranes and failure of roof sheathing, failure of uplift straps at truss-to-wall connections where staple crowns pulled through the strap material, loss of cladding on endwalls and near corners where large negative (suction) pressures develop, loss of add-on construction such as expanded rooms or porches with resulting missile damage and damage to the parent unit at points of attachment, complete separation of superstructure from floor and underframe, and loss of the complete unit due to failure of tiedown straps or withdrawal of soil anchors. In Florida, some form of anchorage system had been installed in almost every case. The anchor failures that were observed involved helical anchors or rock anchors installed in the local coral which is covered by 150 to 300 mm (6 to 12 inches) of sand.

4. CURRENT WIND LOAD REQUIREMENTS OF THE MHCSS

The MHCSS wind load requirements in effect at the time of Hurricane Andrew identified two wind zones for the United States. Zone II (hurricane) included the Gulf and Atlantic Coast region, the coastal regions of Alaska, and Puerto Rico. All other regions of the United States were designated as Zone I (non-hurricane). Approximately, the boundary between the two zones followed the 40 m/s (90 mph) wind-speed contour of an early version of American National Standard A58.1 (Now ASCE 7 - Minimum Design Loads for Buildings and Other Structures). The basic wind load requirements of the MHCSS were as follows:

	Horizontal Load	Uplift
Zone I	718 Pa (15 psf)	431 Pa (9 psf)
Zone II	1,197 Pa (25 psf)	718 Pa (15 psf)

For the design of components/elements such as eaves and cornices, the MHCSS required uplift loads equal to 2.5 times the uplift loads listed above. For wind exposures in coastal and other areas where wind records indicated significantly higher wind speeds than are implied by the loads listed above, the Department could establish more stringent requirements for homes known to be destined for such areas.

There were no requirement in the MHCSS for permanent foundations, but it was recommended that windstorm protection in the form of soil anchors and tiedown hardware be designed to resist horizontal and uplift loads equal to 1.5 times the values listed above. However, specific requirements for windstorm protection devices and the enforcement of these requirements are left to the individual States. Recommendations for the design and installation of such devices are addressed in American National Standard A225.1 - Manufactured Home Installations.

5. REVIEW OF BUILDING CODES AND STANDARDS

Following Hurricane Andrew, the wind load provisions of selected codes and standards were compared. For Dade County, Florida, the basic wind speed (fastest-mile speed at 10 m (32.8 ft) in exposure category C) specified by ASCE 7-88 is 49 m/s (110 mph), and the corresponding design speed is 52 m/s (116 mph). In general, the wind load requirements of ASCE 7-88 exceed those of the other codes and standards included in this comparison.

Based on the requirements for structural stability (sliding and uplift), the design loads required by the MHCSS at the time of Hurricane Andrew corresponded to a basic wind speed of from 36 to 38 m/s (80 to 85 mph). A similar analysis of the South Florida Building Code (SFBC-88) provisions indicates that the specified design speed of 54 m/s (120 mph) was, in effect, a gust speed. The drag and uplift loads required by the SFBC-88 corresponded to basic wind speeds of 41 and 44 m/s (91 and 98 mph), respectively.

Although ASCE 7-88 and the Standard Building Code (SBC-91) reference the same basic wind speed of 49 m/s (110 mph) and the same source of pressure coefficient data, SBC-91 requires average drag and uplift loads that are approximately 75 percent of the values required by ASCE 7-88. The major reasons for this difference in design loads are a reduction factor of 0.8 applied to the pressure coefficients used in SBC-91 and disregard for the fact that the wind speed probability distributions for hurricanes and for extra-tropical storms are different.

6. PROBABILITIES OF FAILURE

Design wind speeds should reflect the local wind climate (distribution of extremes) and the consequences of structural failure. For ordinary buildings and structures it is generally accepted that the design wind loads should have as their basis the wind speeds associated with a mean recurrence interval (MRI) of about 50 years. Although the probability that these speeds will be exceeded in a 50-yr period is relatively high (64 percent), the use of load factors or allowable stresses in the design process reduces the risk of a structural failure to about 5 percent over the same interval (Gupta and Moss 1993). Generally, the available information from which to estimate the probability of failure of a building or other structure is very limited.

Nevertheless, it is useful to examine the relative risk associated with various design requirements and extreme wind environments. In the following, probabilities of failure implicit in the MHCSS wind load requirements in effect at the time of Hurricane Andrew are compared with those of ASCE 7-88 (Minimum Design Loads for Buildings and Other Structures) for Dade County, Florida; Omaha, Nebraska; and Tucson, Arizona. Extreme wind speeds for Dade County are due to hurricanes while the extremes for the other two locations are governed by extra-tropical wind events.

Implicit in the MHCSS wind load requirements in effect at the time of Hurricane Andrew are basic wind speeds (50-yr MRI) of 29 and 36 m/s (65 and 80 mph) for Zone I (non-hurricane) and Zone II (hurricane), respectively. According to ASCE 7-88, the basic wind speeds for Dade County, Omaha and Tucson are 49, 37 and 34 m/s (110, 83 and 75 mph), respectively. The ultimate load capacity or strength of the structure can be estimated from the design equation

$$\phi R \geq \gamma L \qquad (1)$$

in which R is the nominal resistance of the material or component under consideration, ϕ is the resistance factor, L is the nominal (code-specified) load or load combination, and γ is the load factor. If typical values of 0.8 for the resistance factor and 1.3 for the wind load factor are selected, the reference wind speed at or near the ultimate strength of the structure (ultimate limit state) will be $(1.3/0.8)^{1/2} = 1.275$ times the basic wind speed. In the case of Dade County, Florida, for example, the wind speed at failure should correspond to (49)(1.05)(1.275) = 66 m/s (147 mph). Note that the factor of 1.05 is a structure importance factor required by ASCE 7-88 for design in hurricane-prone regions. If it is further assumed that the coefficient of variation (COV) of structural strength is 0.1, then the distribution functions for load and ultimate strength can be plotted against a reference dynamic pressure, q, as is shown in Figure 3 for Dade County, Florida. By integrating the product of the load function, $Q_L(q)$, and resistance function, $p_R(q)$, it is possible to estimate the probabilities of failure with the results as shown in Table 1. The load function, $Q_L(q)$, for Dade County is based on the wind speed distributions developed by Georgiou et al. (1983), and for Omaha and Tucson on the distributions developed by Simiu et al. (1979).

Although the absolute values of the probabilities listed in Table 1 are reliable only to the extent that the simplifying assumptions represent the true relationship between load and resistance, it is their relative values (MHCSS/ASCE 7) that are of primary interest. It can be seen from Table 1 that, at the time of Hurricane Andrew, manufactured homes sited in Dade County had a risk of failure during a 10-yr exposure that was of the order of 10 times the risk of ordinary buildings designed in accordance with the wind load provisions of ASCE 7-88. This same ratio is seen to apply for Omaha, even though the corresponding probabilities are only about half those for Dade County. For Tucson, the probability of failure for manufactured homes during a 10-yr exposure is about 5 times that of ordinary buildings and structures designed in accordance with ASCE 7-88 and about 1/5 that of manufactured homes sited in Dade County. Not shown in Table 1 are the effects of variability of resistance on the calculated probabilities. In general, increasing the coefficient of variation of resistance will increase the probability of failure, particularly for lower mean values of resistance as is the case for the MHCSS wind load criteria. For example, the probability of failure during a 10-yr exposure at Tucson ranges from 0.27 to 0.42 for a corresponding range in COV of 0.05 to 0.20 in the case of the MHCSS design criteria.

7. REVISED STANDARDS

Based on the experience gained from Hurricanes Hugo and Andrew, on a comprehensive review of the wind load provisions of the model codes and of ASCE 7-88, and on the results of economic impact studies, an amended rule was published in the *Federal Register* in January, 1994. This amended rule is to become effective on July 13, 1994. The new wind zones are shown in Figure 4 with Zones II and III corresponding to basic wind speeds of 45 and 49 m/s (100 and 110 mph), respectively. Zone I retains the current MHCSS wind load requirements for non-hurricane regions. The new design wind load requirements for Zones II and III are summarized in Table 2.

8. FUTURE WORK

The MHCSS rule change is considered to be an interim measure as it is limited to the design and construction of manufactured housing units destined for hurricane-prone areas for which the basic wind speed is 45 m/s (100 mph) or higher. The rule change does not address construction in non-hurricane areas for which the current requirements still apply. As is indicated by the failure probabilities in Table 1, there are areas in the non-hurricane region for which the probabilities of failure remain unacceptably high. Specifically, improvements in the provisions for the design of cladding are required for wall corner zones, roof edge zones, and roof overhangs. In addition, it is doubtful that traditional approaches to windstorm protection (shallow soil anchors, tiedown straps and dry-stacked concrete block piers) will prove to be adequate or cost-effective in hurricane-prone regions. Alternative approaches using permanent foundation systems are being investigated. Finally, the significance of tornadoes as a design consideration is being examined.

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Table 1. Probability of Attaining Ultimate Limit State
$\phi = 0.8$ $\gamma = 1.3$ COV (R) = 0.1

Location	Design Criteria	Probability			
Exposure Period		1 yr	10 yrs	25 yrs	50 yrs
Dade County, Florida	MHCSS	0.037	0.313	0.609	0.847
U_{50} = 49 m/s (110 mph)	ASCE 7	0.003	0.033	0.081	0.155
Omaha, Nebraska	MHCSS	0.018	0.165	0.362	0.594
U_{50} = 37 m/s (83 mph)	ASCE 7	0.002	0.016	0.039	0.077
Tucson, Arizona	MHCSS	0.007	0.067	0.160	0.295
U_{50} = 34 m/s (75 mph)	ASCE 7	0.001	0.014	0.034	0.066

Table 2. MHCSS Revised Design Wind Pressures, January 14, 1994

ELEMENT	ZONE II (psf)	ZONE III (psf)
Anchorage for Lateral and Vertical Stability:		
Net horizontal drag	±39	±47
Uplift	−27	−32
Main Wind Force Resisting System:		
Shearwalls, diaphragms and their fastening and anchorage systems	±39	±47
Ridge beams and other main roof support beams	−30	−36
Components and Cladding:		
Roof trusses in all areas; trusses shall be doubled within 3'-0" from each end of roof	−39	−47
Exterior roof coverings, sheathing & fastenings; all areas except following	−39	−47
Within 3"-0" of gable end or endwall if no overhang is provided	−73	−89
Within 3'-0" of ridge or sidewall if no eave is provided	−51	−62
Eaves (Overhangs at sidewalls)	−51	−62
Gables (Overhangs at endwalls)	−73	−89
Wall studs in sidewalls and endwalls, exterior windows & sliding glass doors, exterior coverings, sheathing & fastenings:		
Within 3'-0" from each corner of sidewall and endwall	±48	±58
All other areas	±38	±46

Note: 1 ft = 0.3048 m 1 psf = 47.88 Pa

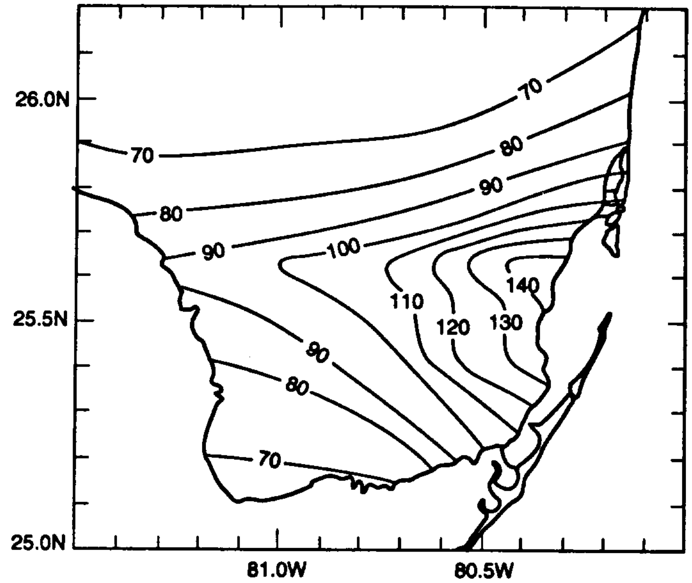
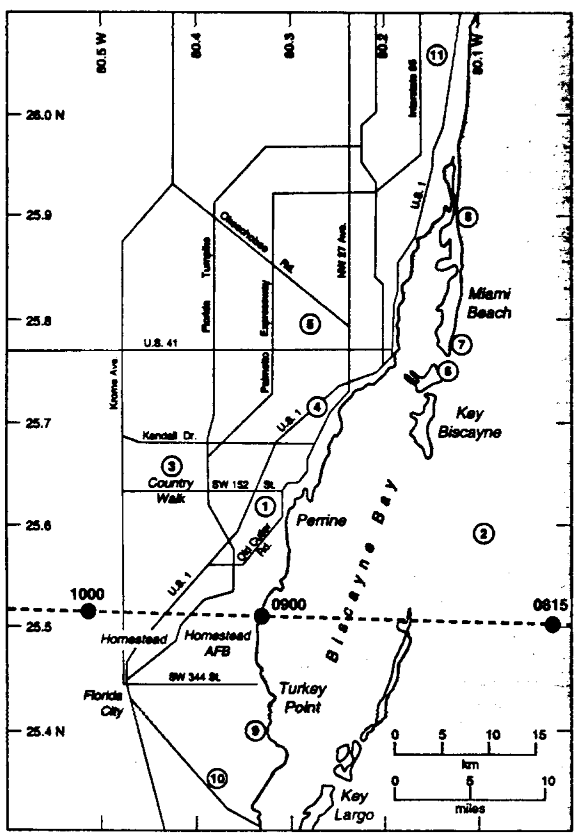


Figure 1. Isotachs of estimated maximum fastest-mile wind speeds (mph) in Hurricane Andrew. (Reinhold et al. 1993). Note: 1 mph = 0.447 m/s.



	LOCATION	Pk. Gust (knots)
1	Perrine*	154
2	Fowey Rocks C-MAN	147
3	Tamiami Airport*	108
4	Miami WSFO/NHC	142
5	Miami International	81
6	Virginia Key	98
7	Miami Beach DARDC	92
8	Haulover NOS	85
9	Turkey Point (10 m)*	85
10	Turkey Point (60 m)*	83
11	Fort Lauderdale	76

* Anemometer failed
1 kt = 0.514 m/s = 1.151 mph

Figure 2. Area map showing approximate storm track and key locations, Hurricane Andrew.

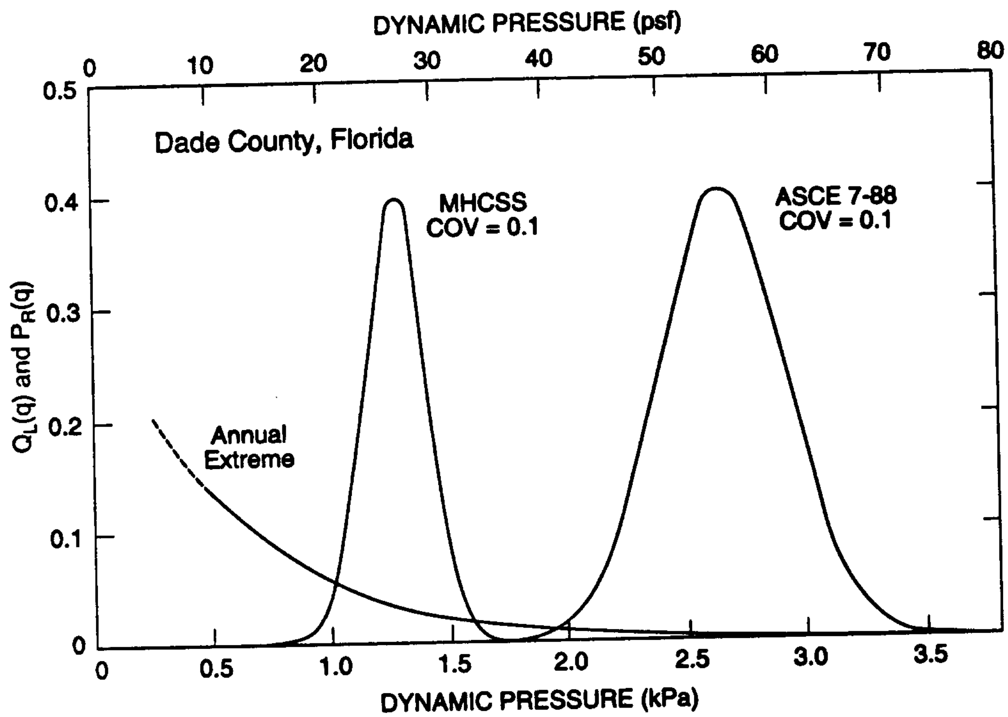


Figure 3. Probability functions for load and resistance, Dade County, Florida.
(Based on MHCSS wind load provisions in effect at time of Hurricane Andrew)

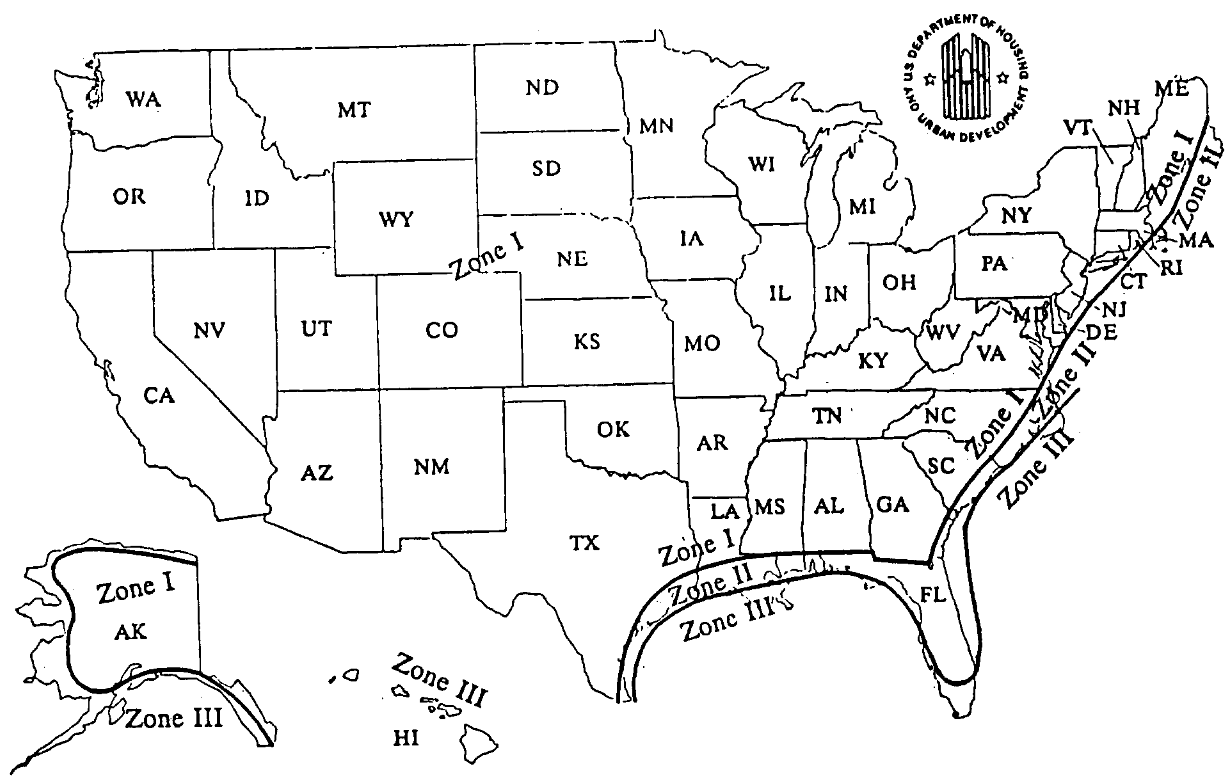


Figure 4. Basic wind zone map for manufactured housing, based on ASCE 7-88.
(Revised Manufactured Home Construction and Safety Standard, January 14, 1994)