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UTILIZATION OF LOAD/RESISTANCE STATISTICS IN A WIND SPEED ASSESSMENT

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ABSTRACT

A methodology for computing failure wind speeds is presented using a probabilistic approach which incorporates load and resistance statistics. This approach allows upper and lower bound wind speed estimates to be obtained with a desired degree of confidence. Load and resistance variables of a structure are treated in terms of continuous probability distributions. Failure wind speeds were calculated using the load/resistance approach for four structures damaged by a tornado. Results are shown and appear to be consistent with the type of damage observed. Comparison of the results to the F-scale wind speed rating shows good agreement.

INTRODUCTION

Over the past several decades, there have been numerous advancements in wind engineering research. Before 1950, few studies appeared in the literature deriving wind speed estimates from analysis of structural damage. Windstorms were perceived by many as a hazard for which buildings could not be economically designed. The Dallas, Texas tornado, in 1957, gave engineers an opportunity to study windstorm damage to a variety of structures. Segner, (1960), derived credible wind speed estimates from studying the structural damage in the wake of that tornado.

Since then, there have been a numerous studies estimating failure wind speeds on buildings struck by tornadoes and hurricanes. However, there are still several questions which have not yet been addressed. What effect does the variability in wind load and structural materials have in building response? How credible is the calculated failure wind speed? What degree of confidence is there in the failure wind speed estimate? These questions and others are explored further in this paper.

THE ALTUS, OKLAHOMA TORNADO

A tornado struck Altus Air Force Base in Oklahoma on May 11, 1982. The tornado traveled in a northeastward direction across the base, causing substantial damage to many buildings. One structure, heavily damaged by the storm, was the communications facility. Although this building was engineered and hardened for blast, the roof failed with wind velocities below 150 m.p.h. exposing the building contents to rainwater. A damage survey by the author initially categorized damage intensity using the F-scale rating developed by Fujita, (1971). On a scale from zero to five, five being the most severe, six buildings suffered heavy damage (F3), eleven, moderate damage (F2), and seven, light damage (F1).

Construction plans were obtained for several heavily damaged buildings. Information from these plans was used to calculate the wind velocity needed to cause structural failure.

Parachute Drying Tower

A parachute drying tower was located on the right side of the tornado path approximately 650 feet from the tornado center. As the tornado passed, the tower overturned falling toward the northeast, pivoting about a line through the two leeward supporting columns. Anchor bolts, securing the tower to the foundation, failed in tension. Failure wind speed was calculated based on the tensile strength of the anchor bolts.

Dining Hall and Recreation Buildings

Both buildings were single-story masonry structures with flat timber roof. The center of the tornado passed about 200 feet to the south of the buildings. The strong winds lifted eaves along windward sides of the building. The dining hall roof structure consisted of 2" x 10" wooden joists spaced 12 inches on center. Roof framing on the recreation building consisted of wooden joists spaced 16 inches on center. Roof joists were toenailed with 10d nails to the top plate of the walls. Failure of the roof systems occurred when nails were extruded and the dead weight of the roofs was overcome by aerodynamic uplift. Failure wind speeds were calculated using the pullout strengths of the toenailed connections and weight of the roof structures.

Communication Building

The communication building was a one-story, steel reinforced, block masonry building with steel roof joists. Roof joists were spaced 30 inches on center, and were bolted to a bond beam with two half-inch diameter bolts. The roof deck had a two inch thick lightweight concrete deck poured over a fabric-backed wire mesh. The mesh was anchored to the steel joists by twisted galvanized wire. The tornado passed directly over the building. Applied wind loads caused failure of the twisted galvanized wire and the entire roof literally "rolled" off. Failure wind speed was determined using tensile strength of the wire.

LOAD AND RESISTANCE METHODOLOGY

Within the past several years, a concept has emerged in the design of engineered structures which enables engineers to account for the variability in material strength and types of applied loadings. The concept is termed Load and Resistance Factor Design (LRFD). Further explanation of the LRFD method can be found in Ellingwood et al., (1980). LRFD essentially treats the load and resistance properties of structures in terms of continuous probability distributions (Figure 1). In contrast, nominal strengths (or loads), as specified in building codes, are discrete values. Codes include safety factors which need to be excluded when determining failure wind speeds. If safety factors and uncertainties in load-resistance behavior of the structure are NOT considered, failure wind speeds can be overestimated or underestimated.

In reference to Figure 1, L and R describe the central tendency of randomly applied loads and material resistance, respectively. When L equals R, failure results. A brief summary of the procedure used to calculate failure wind loads employing the load-resistance concept is presented. Further explanation can be found in Marshall et al., (1983). Uncertainties in structural resistance include variations in material strengths, fabrication, and underlying design assumptions. Ellingwood et al., (1980), recognized the uncertainties in structural resistance as a function of:

$$R = R_n \; M \, F \, P \qquad (1)$$

where R_n is the nominal code-specified resistance, and the terms M, F and P represent ratios in the uncertainties of material strength, fabrication and professional design assumptions, respectively.

The simplified expression for wind pressure can be written as:

$$q = c \, GC_p \; V^2 \qquad (2)$$

where q is the wind pressure in pounds per square foot (psf), c is the air density term, G is the gust response factor, C_p is the pressure coefficient and V is the wind velocity in miles per hour (mph). The total wind load, L, is represented by the product qA, where A is the area over which the wind pressure q is acting. Then, the failure wind speed can be calculated by setting the structural resisting moment equal to the wind induced moment. At failure:

$$V = \sqrt{\frac{R_n \; M \, F \, P \, d}{c \, A \, GC_p \, e}} \qquad (3)$$

where d and e are moment arms. In order to establish confidence limits on the failure wind speed, the coefficient of variation (c.o.v.) in each term must be known. Quantifying these uncertainties is difficult, especially for M, F, P and GC_p terms. Although Ellingwood et al., (1980) has presented some data estimating the variability in these parameters, they are just estimates and more research is needed to quantify these uncertainties.

When combining two or more probability distributions, the resultant c.o.v. is determined using the equations of binary operations as shown by Haugen, (1968). Using this approach, the c.o.v. in resistance terms can be expressed as:

$$V_r = \sqrt{V_m^2 + V_f^2 + V_p^2} \qquad (4)$$

Similarly, the c.o.v. in the wind speed terms can be expressed as:

$$V_w = 1/2 \sqrt{V_c^2 + V_{cp}^2 + V_r^2} \qquad (5)$$

A degree of confidence can be selected for the calculated wind speed if the c.o.v. is known. Ghiocel and Lungu, (1975) has shown that, for a normal distribution, the upper and lower bounds of the calculated wind speed are expressed as:

$$WS = V \, (1 + K \, V_w) \qquad (6)$$

where K represents the number of standard deviations from the mean which are selected.

Load and Resistance Statistics

Statistical data on load and resistance variables were assembled from numerous sources. These data were categorized and arranged into Table 1. Categories entitled good, acceptable, and questionable were designed to help rank the variability of load and resistance data. These categories were initially developed by Mehta, (1976) as an attempt to establish some degree of credence in a failure wind speed estimate. Construction materials in the good category are most reliable for wind speed calculations. Under wind loading, these materials will yield failure wind speed estimates with narrow confidence bands. Widest confidence bands will result with questionable structural materials.

Wind Load Examples

Using the methodology described above, failure wind speeds were calculated for four buildings which were heavily damaged at the Altus Air Force Base. The structures were a parachute drying tower, dining hall, recreation center, and communications facility. Results are presented in Table 2. In each case, structural failure initiated at a connection. The parachute drying tower overturned when anchor bolts failed in tension. The remaining buildings had roof failure which initiated from uplift of nailed or tied connections at the roof/wall intersection. Calculations for structural portions which did not fail were completed to provide an upper bound estimate of the failure wind speed. Although each building was considerably different in construction detail, the calculated wind speeds proved consistent and reasonable for the damage observed.

USE OF THE F-SCALE

The F-scale is used frequently to rate the intensity of damage to structures. The scale is easy to use and is readily accepted by the National Weather Service and others in the scientific community. One of the shortcomings of the F-scale is that it assumes all structures are homogeneously constructed. Variations in structural strength simply aren't considered. In essence, a leveled steel-reinforced concrete building would be assigned the same F-scale rating as a demolished outbuilding. Incorporation of load-resistance principles in the F-scale rating would result in the modifications listed below:

1) As the mean wind speed increases, confidence bands widen. As a result, wind speed ranges will overlap between F-scale categories. Therefore, damage intensity of a structure may actually lie in more than one F-scale category.

2) Confidence bands widen with increasing variability in the resistance of a structure. Since this is related to the degree of engineering attention in design of a building, a better degree of confidence in estimating the failure wind speed can be obtained.

These two points are illustrated in Table 3.

SUMMARY

A methodology to calculate failure wind speeds on buildings was presented. The method incorporates load and resistance statistics to obtain a certain degree of confidence in wind speed assessment. Information can be used from construction plans to calculate the possible range of failure wind speeds. The probabilistic approach shown here is new since advancements using the LRFD method are still being developed. Future research will provide additional load and resistance data which can improve failure wind speed estimates.

ACKNOWLEDGEMENTS

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REFERENCES

Ellingwood B., Galambos T., MacGregor J., and Cornell C., 1977, Development of a Probability Based Criterion for American National Standard A58, National Bureau of Standards, 577, 222 pp.

Fujita, T., 1971, Proposed Characterization of Tornadoes by Area and Instensity, SMRP Research Report #91, University of Chicago Press, 15 pp.

Ghiocel D., and Lungu, D., 1975, Wind, Snow, and Temperature Effects on Structures Based on Probability, Abacus Press, Turnbridge Wells, Kent, 411 pp.

Haugen E., 1968, Probabilistic Approaches to Design, John Wiley and Sons, New York, NY, 323 pp.

Marshall T., McDonald J., and Mehta, K., 1983, Utilization of Load and Resistance Statistics in a Wind Speed Assessment, Institute for Disaster Research, Texas Tech University, #67D, 91 pp.

Mehta, K., 1976, "Wind Speed Estimates Engineering Analysis," in Proceedings of the Symposium on Tornadoes, Texas Tech University, pp. 89-103.

Segner, E., 1960, "Estimates of Minimum Wind Forces Causing Structural Response to Natural Wind," in Proceedings of Wind Effects on Buildings and Structures, University of Toronto Press, pp. 595- 630.

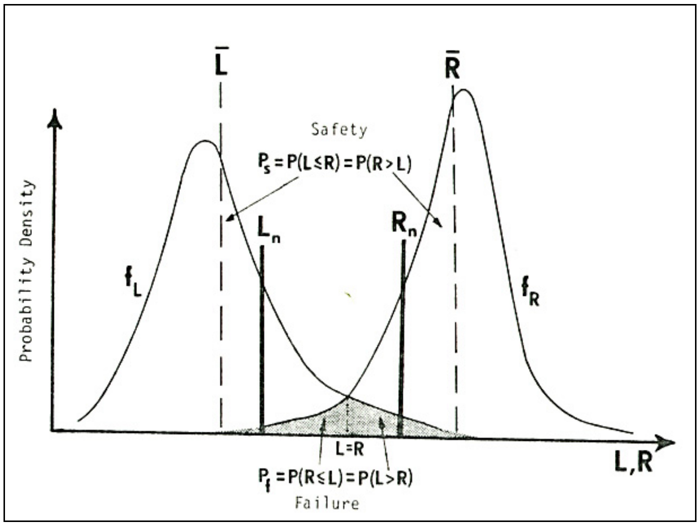
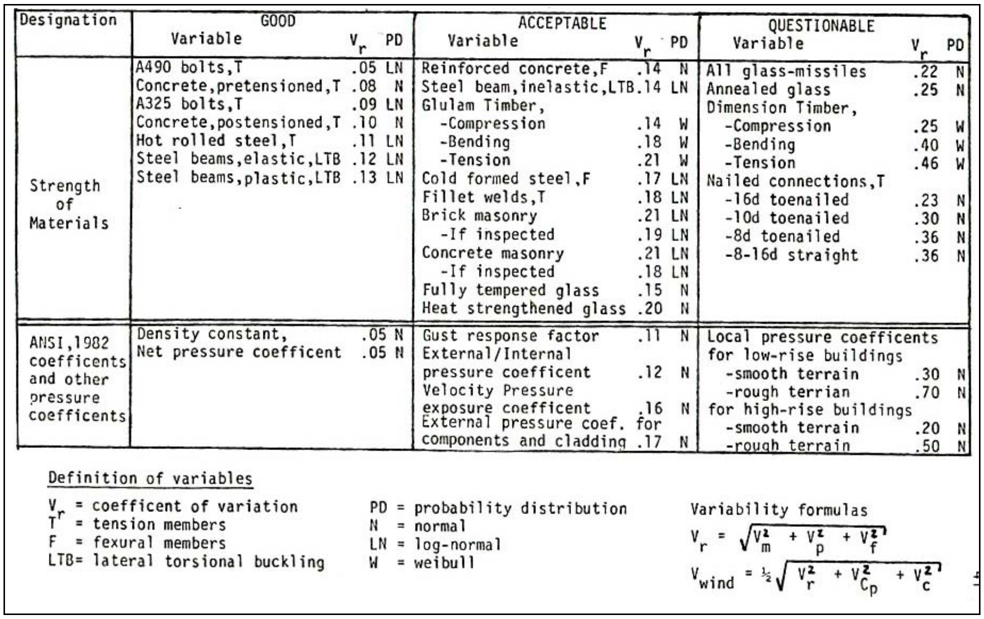


Figure 1. Typical load and resistance probability distributions.
Shaded area indicates a probability of failure.



Designation	GOOD Variable	V_r	PD	ACCEPTABLE Variable	V_r	PD	QUESTIONABLE Variable	V_r	PD
Strength of Materials	A490 bolts,T	.05	LN	Reinforced concrete,F	.14	N	All glass-missiles	.22	N
	Concrete,pretensioned,T	.08	N	Steel beam,inelastic,LTB	.14	LN	Annealed glass	.25	N
	A325 bolts,T	.09	LN	Glulam Timber,			Dimension Timber,		
	Concrete,postensioned,T	.10	N	-Compression	.14	W	-Compression	.25	W
	Hot rolled steel,T	.11	LN	-Bending	.18	W	-Bending	.40	W
	Steel beams,elastic,LTB	.12	LN	-Tension	.21	W	-Tension	.46	W
	Steel beams,plastic,LTB	.13	LN	Cold formed steel,F	.17	LN	Nailed connections,T		
				Fillet welds,T	.18	LN	-16d toenailed	.23	N
				Brick masonry	.21	LN	-10d toenailed	.30	N
				-If inspected	.19	LN	-8d toenailed	.36	N
				Concrete masonry	.21	LN	-8-16d straight	.36	N
				-If inspected	.18	LN			
				Fully tempered glass	.15	N			
				Heat strengthened glass	.20	N			
ANSI,1982 coefficents and other pressure coefficents	Density constant,	.05	N	Gust response factor	.11	N	Local pressure coefficents		
	Net pressure coefficent	.05	N	External/Internal			for low-rise buildings		
				pressure coefficent	.12	N	-smooth terrain	.30	N
				Velocity Pressure			-rough terrian	.70	N
				exposure coefficent	.16	N	for high-rise buildings		
				External pressure coef. for			-smooth terrain	.20	N
				components and cladding	.17	N	-rough terrain	.50	N

Definition of variables

V_r = coefficent of variation
T = tension members
F = fexural members
LTB= lateral torsional buckling

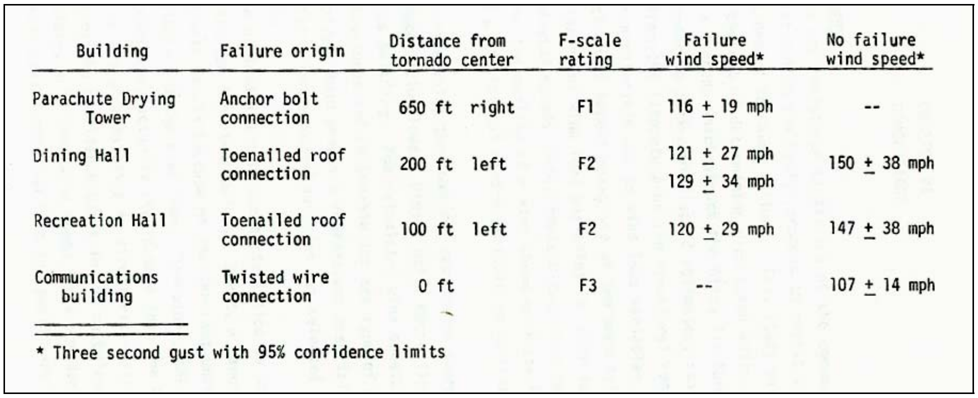
PD = probability distribution
N = normal
LN = log-normal
W = weibull

Variability formulas

$$V_r = \sqrt{V_m^2 + V_p^2 + V_f^2}$$

$$V_{wind} = \tfrac{1}{2}\sqrt{V_r^2 + V_{C_p}^2 + V_c^2}$$

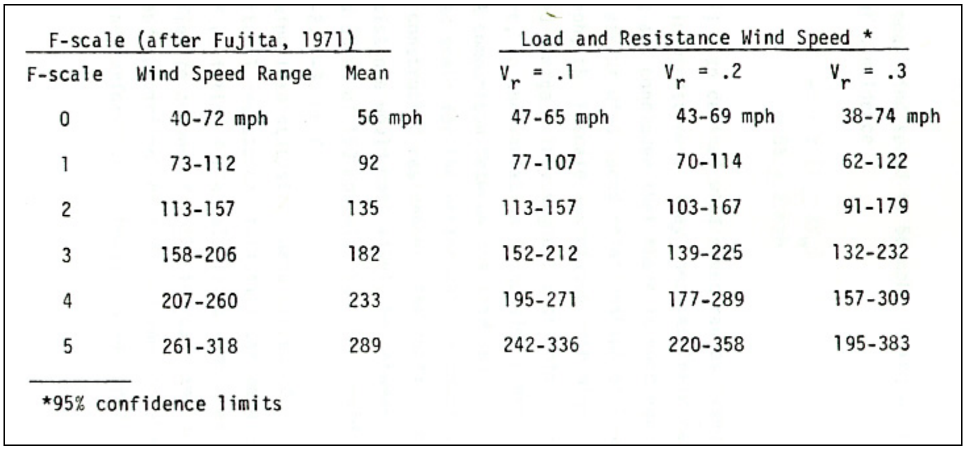
Table 1. Credence levels for wind speed calculations based on variability.



Building	Failure origin	Distance from tornado center	F-scale rating	Failure wind speed*	No failure wind speed*
Parachute Drying Tower	Anchor bolt connection	650 ft right	F1	116 ± 19 mph	--
Dining Hall	Toenailed roof connection	200 ft left	F2	121 ± 27 mph 129 ± 34 mph	150 ± 38 mph
Recreation Hall	Toenailed roof connection	100 ft left	F2	120 ± 29 mph	147 ± 38 mph
Communications building	Twisted wire connection	0 ft	F3	--	107 ± 14 mph

* Three second gust with 95% confidence limits

Table 2. Summary of wind speed estimates in the Altus, Oklahoma tornado.



F-scale (after Fujita, 1971)			Load and Resistance Wind Speed *		
F-scale	Wind Speed Range	Mean	V_r = .1	V_r = .2	V_r = .3
0	40-72 mph	56 mph	47-65 mph	43-69 mph	38-74 mph
1	73-112	92	77-107	70-114	62-122
2	113-157	135	113-157	103-167	91-179
3	158-206	182	152-212	139-225	132-232
4	207-260	233	195-271	177-289	157-309
5	261-318	289	242-336	220-358	195-383

*95% confidence limits

Table 3. Comparison between load/resistance wind speed and F-scale wind speed.