

## AN ENGINEERING ASSESSMENT OF STRUCTURAL DAMAGE IN THE ALTUS, OK TORNADO: MAY 11 1982

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### 1. INTRODUCTION

On the afternoon of May 11, 1982, several tornadoes touched down in southwestern Oklahoma. One of the tornadoes struck the east side of the city of Altus and traveled three miles in a northeasterly direction through the Altus Air Force Base, causing extensive damage. On the following day, a team of windstorm researchers from the Institute for Disaster Research at Texas Tech University went to the disaster scene. The purpose of the investigations was to define the tornado damage path and to assess the damage to structures on the base.

Our initial survey revealed that the damage path extended from the main gate, across the center of the base and ended just east of the main north-south runway (Figure 1). Gradations of damage were visually determined using the F-scale (Fujita, 1971). Buildings that sustained F1 damage or greater were shaded in the figure. Six buildings were severely damaged (F3), eleven buildings had considerable damage (F2), and seven buildings had moderate damage (F1). From the directions of fallen trees and debris trajectories, the center line of the tornado damage path appeared to be parallel to the northern periphery of the F3 damage track.

Construction plans were obtained for the Parachute Drying Tower, Dining Hall, Recreation Building, and Communications Building. From these plans, wind speed calculations were determined for damaged components of the structure and confidence limits were established using load and resistance statistics. Results of the wind speed calculations are presented along with their implications.

### 2. PREVIOUS WIND SPEED CALCULATIONS

Before 1950, the literature contained very few examples of wind speed estimates based on analysis of damaged structures. The Dallas, Texas tornado in

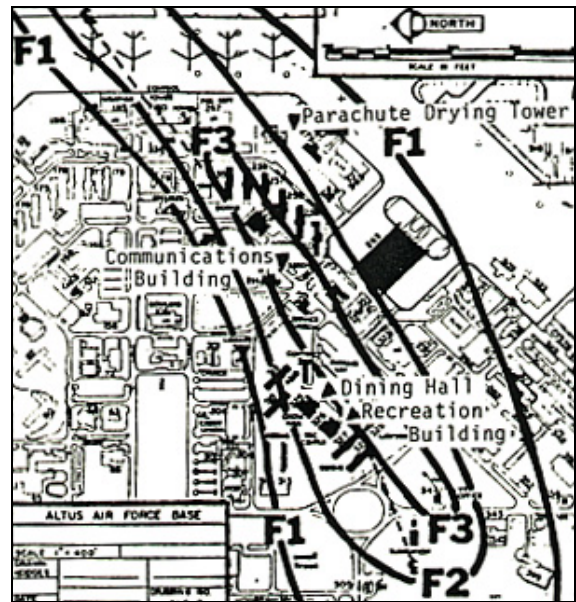


Figure 1. Tornado damage path through the Altus Air Force Base. Gradations in F-scale damage are shown along with pertinent buildings.

1957 provided the first significant opportunity to study damaged structures with different types of construction. Segner (1960) presented wind speed estimates from an engineering analysis of damaged structures. More recently, wind speed estimates have been derived from an engineering analysis of damaged structures caused by the Lubbock, Texas tornado (Minor et al., 1971) and the Xenia, Ohio tornado (Mehta et al., 1976). In all previous cases, a wind speed was calculated based on nominal characteristics of the structure.

A problem arises in that several variables may be responsible for deviations from the calculated wind speed. Material strength properties, construction practices, orientation of the structure and pressure coefficients are a few of the variables which are subject to uncertainties. These variables may, in turn, lead to an overestimate or underestimate of the calculated wind speed to cause the damage. In order

to quantify the degree of error in a wind speed estimate, statistical properties of the load and resistance characteristics of the structure must be known.

### 3. THE LOAD AND RESISTANCE CONCEPT

Within the past several years, a concept has emerged in the design of engineered structures which enables the engineer to account for the variations in material strength and types of loadings on structures. The concept is termed Load and Resistance Factor Design (LRFD). A further explanation of LRFD 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 2). In contrast, nominal strengths or loads are discrete values. In Figure 2, L and R describe the central tendency of the randomly applied load and structural resistance, respectively. When L equals R, a failure occurs. A brief summary is presented here using the load and resistance concept in wind speed calculations. Further explanation can be found in Marshall et al. (1983).

Ellingwood et al. (1980) recognized the uncertainties in the structural resistance as a function of variations in material strength, fabrication, and underlying design assumptions. They expressed the structural resistance by the equation:

$$R = R_n M F P \quad (1)$$

Where  $R_n$  is the nominal code-specified resistance and the terms M, F, and P represent ratios of the uncertainties of material strength, fabrication, and professional design assumptions, respectively. The expression for wind pressure is written by the equation:

$$q = c G C_p V^2 \quad (2)$$

where q is the wind pressure (psf), c is the air density, G is the gust response factor,  $C_p$  is the pressure coefficient and V is the wind velocity (mph). Let the total wind load, L, be represented by the product qA, where A is the area over which the wind pressure q is acting. Then, the wind speed to cause failure is calculated by seeing the structural resisting moment equal to the wind induced moment. Therefore, at failure:

$$V = \frac{\sqrt{\frac{R_n M F P d}{c A G C_p e}}}{\sqrt{\frac{R_n M F P d}{c A G C_p e}}} \quad (3)$$

where d and e are moment arms. In order to establish confidence limits on the failure wind speed, the uncertainty in each term must be known. These uncertainties are expressed in terms of coefficients of variation. When combining two or more probability distributions, the resultant coefficient of variation is determined using the equations of binary operations as shown by Haugen (1968). Therefore, the coefficient of variation of structural resistance is expressed by the equation:

$$V_r = \frac{1}{\sqrt{V_m^2 + V_f^2 + V_p^2}} \quad (4)$$

where the subscripts r, m, f, and p denote the coefficients of variation of the structural resistance, material strength, fabrication, and professional design terms, respectively. Similarly, the coefficient of variation of the wind speed can be expressed by the equation:

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

This equation expresses the coefficient of variation of the wind speed as a function of the uncertainties in air density, gust response factor, pressure coefficient, and structural resistance. Any degree of confidence can be specified for the calculated wind speed if the coefficient of variation is known. Ghiocel et al. (1975) have shown that, for a Normal distribution, the upper and lower bounds of the calculated wind speed can be expressed by the equation:

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

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

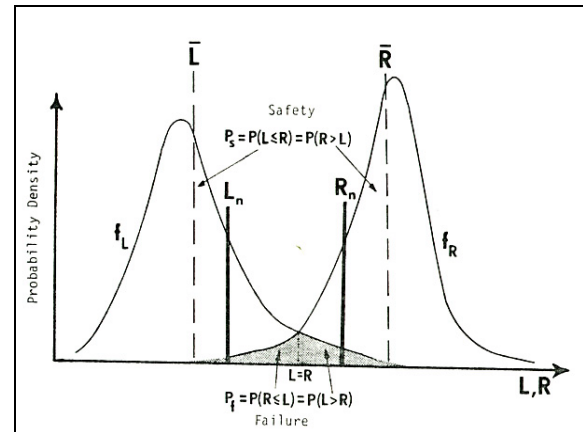


Figure 2. Typical load and resistance probability distribution. The shaded region indicates the probability of failure.

#### 4. LOAD AND RESISTANCE WIND SPEED

Wind speed estimates were determined for four structures that were damaged by the Altus tornado. Each wind speed estimate is based on information from construction plans and the following assumptions: a) the wind load is applied statically, b) the material strength distributes normally, c) internal pressures had a negligible effect on the structure, and d) the information on the construction plans is accurate. The following list is a summary of the procedures used to calculate the wind speed at failure:

- 1) Determine the average resistance of pertinent connections and anchorages as well as the dead load of the building components.
- 2) Calculate the mean resisting moment.
- 3) Calculate the overturning moment produced by the wind.
- 4) Equate the resisting moment to the overturning moment and solve for the mean wind pressure.
- 5) Determine the mean wind speed by Equation #3.
- 6) Determine the weighted coefficient of variation of the resisting moment using Equation #4.
- 7) Determine the coefficient of variation of the wind speed using Equation #5.
- 8) Establish the desired confidence levels using Equation #6.

The frame of reference for the calculated wind speed is one that describes a turbulent environment for a three-second gust in order to simulate a tornadic wind field. Procedures to modify the wind speed to reflect this appropriate frame of reference can be found in Marshall et al. (1983).

##### 4.1 Parachute drying tower

The parachute drying tower was located on the right side of the tornado path, approximately 650 feet from the tornado center (Figure 3). Apparently as the tornado passed, the 62 foot high tower overturned falling toward the northeast and pivoted about a line through two supporting columns of the structure. The longest side of the tower was normal to the strongest tornadic winds. Wind speed calculations are based on the tensile strength of A307 anchor bolts.

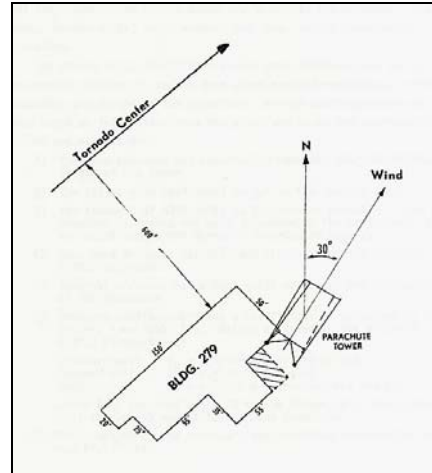


Figure 3. Plan view of the parachute drying tower that toppled to the northeast.

##### 4.2 Dining hall

The dining hall is a single story, masonry building with a timber roof structure (Figure 4). The center of the tornado passed 200 feet to the right of the building. The tornadic winds uplifted a portion of the roof over the cafeteria and office area. The roof consisted of 2 x 10 wooden joists spaced 12 inches on center and secured with 10d nails that were toenailed to a wooden top plate. Failure of the roof occurred when the nails pulled out. Wind speed estimates are based on the strength of the nailed connections.

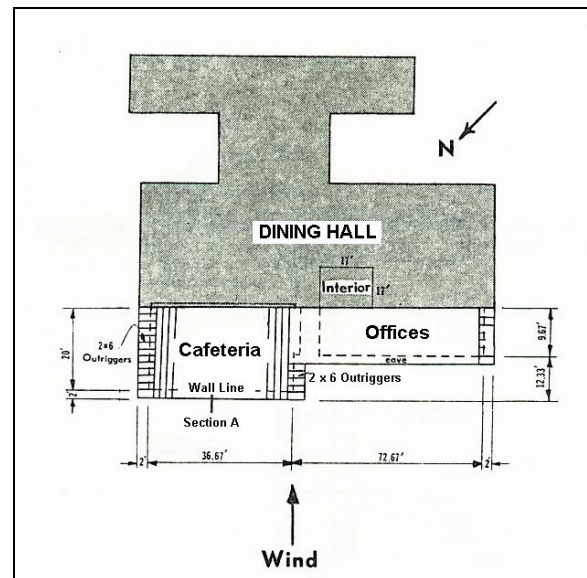


Figure 4. Plan view of dining hall showing windward roof damage (unshaded).

#### 4.3 Recreation building

The recreation building is adjacent to the dining hall and is similarly constructed (Figure 5). Most of the wind damage was confined to one corner of the roof. Two by eight wooden joists spaced 16 inches on center supported the roof. As the tornado passed, the roof uplifted as the nailed connections pulled apart. Wind speed estimates are based on the strength of the nailed connections.

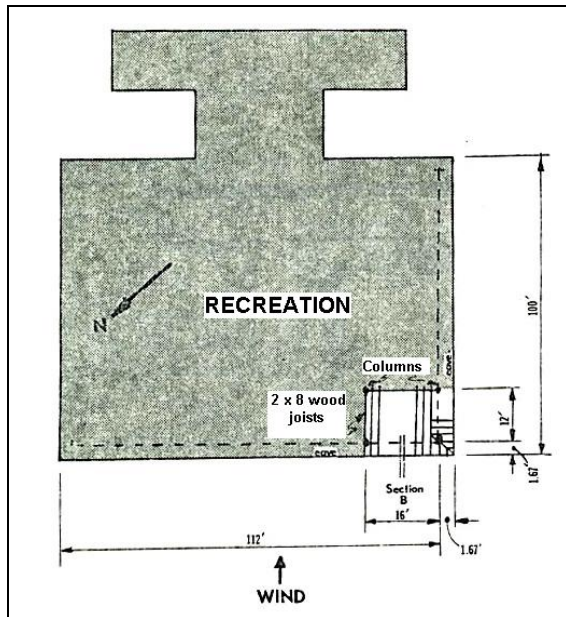


Figure 5. Plan view of the recreation building showing wind damage at roof corner (unshaded).

#### 5. COMPARISON OF CALCULATED WIND SPEEDS TO F-SCALE WIND SPEEDS

In this study, F-scale ratings were assigned to damaged structures before performing the detailed wind speed calculations. Care was taken to assign F-scale ratings without being influenced by the degree of engineering attention to a particular building. Table 1 compares the wind speed estimates from the calculations with the range of wind speeds assigned in the F-scale ratings. Two points are immediately recognized: 1) Three of four expected wind speeds from calculations fall within the assigned F-scale wind speed ranges, and 2) The range of calculated wind speeds at the 95% confidence level are larger than the F-scale wind speed ranges.

It should be mentioned that the errors involved in comparing the three-second gust calculated wind speed to the F-scale wind speed, which is a fastest quarter mile, is insignificant for wind speeds between

100 and 300 mph. Also, many more such calculations are needed to better "calibrate" the F-scale wind speed ranges.

#### 6. IMPLICATIONS OF THE LOAD AND RESISTANCE WIND SPEED TO THE F-SCALE WIND SPEED

The inherent variabilities in structural resistance and wind load will affect the wind speed bounds in several ways. To illustrate this point, load and resistance wind speeds were determined for selected coefficients of variation of resistance and then compared to the F-scale wind speeds (Table 2). This result raises two important points:

- 1) The load and resistance wind speed ranges *WIDEN* with *INCREASING* wind speeds. Using mean F-scale wind speeds for each F-scale category, note that the load and resistance wind speed ranges tend to overlap. This suggests that the damage intensity of a structure may actually lie in more than one F-scale category.
- 2) The load and resistance wind speed ranges widen as the coefficient of variation in structural resistance becomes larger. Therefore, the range in failure wind speeds will be larger for residential buildings than for public and more permanent structures.

#### 7. ACKNOWLEDGEMENTS

The cooperation of the personnel at the Altus Air Force Base in coordinating this damage survey was greatly appreciated. The assistance of the disaster team on the base helped our storm study team acquire the necessary information for this study. Funds for this tornado damage documentation effort were provided by the U.S. Nuclear Regulatory Commission Contract No. NRC-04-76-345. Robert F. Abbey Jr., serves as the contract monitor for this project.

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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 $\pm$ 19 mph	--
Dining Hall	Toenailed roof connection	200 ft left	F2	121 $\pm$ 27 mph 129 $\pm$ 34 mph	150 $\pm$ 38 mph
Recreation Hall	Toenailed roof connection	100 ft left	F2	120 $\pm$ 29 mph	147 $\pm$ 38 mph
Communications building	Twisted wire connection	0 ft	F3	--	107 $\pm$ 14 mph
* Three second gust with 95% confidence limits					

Table 1. Comparison of wind speed estimates between appearance of damage and structural calculations.

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 2. Comparison of F-scale wind speed to load and resistance wind speed.