3B.2 THE ENHANCED FUJITA (EF) SCALE

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1. INTRODUCTION

Although the Fujita Scale has been in use for 30 years, the limitations of the scale are well known to its users. The primary limitations include a lack of damage indicators, no account of construction quality and variability, and no definitive correlation between damage and wind speed. These limitations have led to inconsistent ratings of tornado damage and, in some cases, overestimates of tornado wind speeds. Thus, there is a need to revisit the concept of the Fujita Scale and to improve and eliminate some of the limitations.

Recognizing the need to address these limitations, Texas Tech University (TTU) Wind Science and Engineering (WISE) Center personnel proposed a project to examine the limitations, revise or enhance the Fujita Scale, and attempt to gain a consensus from the meteorological and engineering communities. A steering committee first was organized to initiate the project. The next step involved assembling a forum of users to identify the issues and develop strategies to improve the Fujita scale. A panel of wind damage experts met and assigned failure wind speed values to various degrees of damage (DOD) to buildings and other objects. Through this expert elicitation process, wind speeds corresponding to the DOD's were estimated. These estimated wind speeds then determined the EF (Enhanced Fujita)-scale category appropriate for the observed damage. This paper discusses the work to date in finalizing the EF-scale.

2. THE ORIGINAL F-SCALE

Fujita (1971, 1973, 1981) developed the F-scale in order to rate tornado damage to buildings. The F-scale is a subjective, visual interpretation of damage which simply assigns a numerical value ranging from 0 to 5 based on increasing severity of damage primarily to a “well-constructed” or “strong” wood-framed house. Refer to Table 1. However, as Grazulis (1993) noted, the single-paragraph descriptions of damage given by Fujita are vague and limited in scope and this can introduce large errors in assigning an F-scale number. For example, homes "swept clean" from their foundations initially were assigned an F5 damage rating but were downgraded to F1 as Marshall (2003) noted in the La Plata, MD tornado.

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Original Fujita (F) Scale		
No.	Wind Speed (mph and ms^{-1})	Damage Description with respect to housing
F0	40-72 mph 18-32 ms^{-1}	Light damage: Some damage to chimneys
F1	73-112 mph 33-50 ms^{-1}	Moderate damage: Peel surfaces off roofs; mobile homes pushed off foundations or overturned.
F2	113-157 mph 51-70 ms^{-1}	Considerable damage: Roofs torn off framed houses; mobile homes destroyed.
F3	158-206 mph 71-92 ms^{-1}	Severe damage: Roofs and some walls torn from well-constructed houses.
F4	207-260 mph 93-116 ms^{-1}	Devastating damage: Well constructed houses leveled; structure with weak foundations blown off some distance.
F5	261-318 mph 117-142 ms^{-1}	Incredible damage: Strong frame houses lifted from foundation and carried considerable distances to disintegrate.

Table 1. Original Fujita (F) scale with wind speeds and damage description with respect to housing (after Fujita 1971).

Fujita also assigned wind speed ranges to the numerical values in the F-scale. Wind speed ranges were derived empirically by dividing the gap between Beaufort 12 (73 mph/33 ms^{-1}) and Mach 1 (738 mph/330 ms^{-1}) into 12 non-linear increments. F-scale wind speeds were defined as the “fastest 1/4-mile speed” being longer in duration than a gust, usually in the five to ten second range for most tornadoes. Fujita deemed the assigned wind speeds as “experimental” and awaited engineering assessments of tornado damage to help “calibrate” the wind speed ranges. Engineering assessments of tornado damage by Minor et al. (1977a, 1977b) questioned the accuracy of the F-scale wind speeds, especially when they exceeded 125 mph (56 ms^{-1}). However, no formal changes to the F-scale have been made prior to the TTU effort.

As Doswell and Burgess (1988) pointed out, building damage and tornado intensity are related but not perfectly correlated. A destroyed building may have been built poorly leading to an overestimate of tornado intensity. Since tornadoes are rated by the worst damage they cause along their paths, there would be a tendency to over rate them unless the strength of the building was known. Additional difficulties in rating a tornado occur when it passes over open country and does not cause damage. Schaefer and Galway (1982) found that tornadoes that strike populated areas were more likely to receive a higher F-scale rating than those tornadoes that remain in open country.

Fujita (1992) recognized that residences were not homogeneously constructed and he devised corrections to compensate for assigning an F-scale rating (Table 2). He indicated that a strong-framed house may receive F2 damage whereas the same wind might not damage a concrete building or might totally destroy a poorly built outbuilding. Thus, he realized that the relative strength of the building must be considered when assigning an F-scale rating.

THE FUJITA TORNADO SCALE

Damage f scale		Little Damage	Minor Damage	Roof Gone	Walls Collapse	Blown Down	Blown Away
		f0	f1	f2	f3	f4	f5
Windspeed F scale		F0	F1	F2	F3	F4	F5
(m/s)		17 m/s – 32	32 – 50	50 – 70	70 – 92	92 – 116	116 – 142
(mph)		40 mph – 73	73 – 113	113 – 158	158 – 207	207 – 261	261 – 319
To convert f scale into F scale, add the appropriate number							
Weak Outbuilding	-3	f3	f4	f5	f5	f5	f5
Strong Outbuilding	-2	f2	f3	f4	f5	f5	f5
Weak Framehouse	-1	f1	f2	f3	f4	f5	f5
Strong Framehouse	0	F0	F1	F2	F3	F4	F5
Brick Structure	+1	-	f0	f1	f2	f3	f4
Concrete Building	+2	-	-	f0	f1	f2	f3

Table 2. The original F-scale shown with corrections for building strength (after Fujita 1992).

Phan and Simiu (1998) found that high-speed winds of longer duration resulted in greater damage to residences during their damage survey of the Jarrell, Texas tornado. Residences near the center of the Jarrell tornado were subjected to tornadic winds for about three minutes. By comparison, Marshall (2002) calculated that homes near the tornado center at Moore, Oklahoma were subjected to tornadic winds for about 30 seconds. Finally, there is the human factor in determining the tornado intensity based on analyzing damage. A person with knowledge of how buildings fail will likely rate a building differently than a person without such knowledge.

3. ENHANCED (EF) FUJITA SCALE

A forum of users and interested parties was organized by TTU to develop strategies for an Enhanced Fujita Scale. The forum convened in Grapevine, Texas on March 7-8, 2001. The steering committee invited 26 persons; 22 attended the one and one-half day meeting. Objectives of the forum were to identify key issues, make recommendations for a new or enhanced Fujita Scale, and develop a strategy for reaching a consensus from a broad cross section of users. A summary of the initial work on this project was published by McDonald et al. (2003).

Key issues included the need for additional and more specific damage indicators, a correlation between degrees of damage, and wind speed and a correlation between the original F-scale and the EF-scale so the existing tornado database could be preserved. At the close of the meeting, each participant was invited to submit written comments and suggestions. These comments were published in the forum summary report (McDonald and Mehta, 2001).

The Texas Tech project team was directed to develop an Enhanced F-scale that addressed the limitations and issues identified by the forum participants. They were to explore opportunities for workshops and symposiums to involve a more extensive audience with the goal of obtaining a general consensus.

The strategies pursued by the Texas Tech team included the following steps:

- Identify additional damage indicators.
- Define varying degrees of damage (DOD) for each damage indicator.
- Correlate degrees of damage with wind speeds expected to cause the damage.
- Propose an EF-scale and relate it to the original F-scale.
- Keep both meteorological and engineering communities apprised of the progress.

4. BUILDING DAMAGE INDICATORS (DI's)

Buildings and other objects, including towers, light poles, trees and crops make up the damage indicators (DI's). With each damage indicator, there are increasing degrees of damage (DOD's) caused by higher wind speeds.

The DI's and DOD's are selected to be recognizable by persons, who have little or no engineering training. Thus, specific uses of buildings, structures, and trees are selected for the initial set of DI's. Additional ones such as crops and missiles can be added to the DI list later as more information becomes available.

Twenty-eight DI's with various DOD's are initially defined. A few examples include one and two-story residences, single-wide manufactured homes, small professional buildings, elementary schools, large isolated retail buildings, institutional buildings, free-standing towers, and hardwood trees. A list of all 28 DI's is shown in Table 8 in the appendix. The type of construction for each building is carefully described. For example, typical construction for masonry apartments or motels is described as:

- Less than or equal to four stories.
- Facility made up of one or more multi-story rectangular buildings.
- Flat, gable, hip, or mansard roofs.
- Asphalt shingles, tile, slate, or BUR roofs.
- Light steel roof framing with metal deck and lightweight insulation.
- CMU load bearing and non-load bearing walls.
- Stucco, EIFS, or brick veneer wall cladding.

- Exterior walkways or balconies.

The number of DOD's for each DI depends on the complexity of construction. DOD's range from no visible damage to total destruction of the entire building. Table 3 shows an example of the DOD's for masonry apartments or motels. Wind speeds in the table are discussed in Section 5.

DOD	Damage Description	EXP	LB	UB
1	No visible damage	65	54	81
2	Loss of roof covering (<20%)	80	67	101
3	Uplift of metal roof	95	81	116
4	Uplift of pre-cast concrete roof decking	121	103	143
5	Collapse of top story walls	133	115	150
6	Collapse of top 2 floors of 3 or more stories	156	132	180
7	Total destruction of a large section of building	180	160	205

Table 3. Degrees of damage for masonry apartments and motels correlated with expected (EXP), lower bound (LB), and upper bound (UB) wind speeds in mph.

Initial visible damage in this case might be loss of cladding from the masonry walls. Higher wind speeds would involve loss of roofing material and then uplift of the metal roof deck. Still higher wind speeds would be required to lift up pre-cast concrete roof decking. Collapse of the building or its total destruction would involve even higher wind speeds.

The wind speed to cause a particular DOD varies because of conditions that affect the loading or the resistance of a structural element. That is why an expected (EXP), upper (UB), and lower bound (LB) wind speed is estimated for each DOD. The expected value of wind speed causes damage under "normal" conditions. A weak connection, material deterioration, or a "hot spot" of local wind pressure might result in failure at a lower-than-expected wind speed. On the other hand, stronger than normal connections, e.g. using hurricane clips instead of toe nailing, might require higher than expected wind speeds to produce the damage. Another factor is the duration of the tornadic winds. Thus, a person applying the EF-scale will have the option to estimate the wind speed to cause a DOD above or below the expected value but within the range of the upper and lower bounds.

5. EXPERT ELICITATION

The major challenge to the F-scale enhancement project was how to obtain a correlation between degrees of damage and wind speed. A search of the literature found very few definitive correlations. Mehta et al. (1976) estimated wind speed based on structural analysis of the damaged structure. Although the approach has merit, it requires more effort than the resources for this project allowed. Texas Tech personnel have the experience to estimate wind speeds, but without a detailed technical study, it would be simply the team's opinion, just like Fujita's original estimate. A more definitive solution was needed.

The concept of expert elicitation has been used successfully to estimate certain unknown parameters related to seismic hazard analysis. The Senior Seismic Hazard Analysis Committee formalized the process (SSHAC 1997), while working under the auspice of the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy, and the Electric Power Research Institute. Subsequently, Boissonnade, et al. (2000) at Lawrence Livermore National Lab applied expert elicitation to estimate parameters for tornado hazard assessment.

The SSHAC protocol specifies the following steps, which were followed in the present study:

- Assemble a panel of experts
- Discuss and refine the issues with the experts; provide all available data
- Train the experts for elicitation
- Conduct individual elicitations and group interactions
- Analyze and aggregate elicitations and resolve issues
- Document and communicate the process and final results

Members of the expert panel are listed in Table 4.

Name	Background	Affiliation
Don Burgess	Meteorologist	NSSL (retired)
Greg Forbes	Meteorologist	The Weather Ch.
Doug Smith	Engineer	Texas Tech U.
Tim Reinhold	Engineer	Clemson U.
Tim Marshall	Engineer/ Meteorologist	Haag Engineering
Tom Smith	Architect	Roofing Consultant

Table 4. Panel of experts selected for elicitation.

Each person listed has strong relevant expertise, professional reputations, academic training, experience, and peer-reviewed publications. All have specific knowledge of tornadoes and tornado damage. The experts met for a day and a half to initiate the elicitation process. After discussing the issues with the experts, providing all available data, and explaining the process, the experts were ready to perform individual elicitations.

Each expert estimated the expected wind speed to produce the degree of damage (DOD) to a damage indicator (DI) or building structure type. In addition, they estimated upper and lower bound wind speeds, taking into account the uncertainties in the damage. The wind speed standard was assumed to be a 3-second gust at 33 ft. (10 m) in open, unobstructed terrain. After the first round, results were tabulated and reviewed by the group. The DOD statements were refined and clarified. New DI's were added and others were eliminated. The experts went home with instructions to conduct a second round of elicitations. The second round results were tabulated and distributed to the group. The group was given the opportunity to refine its estimates a third time. Very few changes were made after the second round. The final elicitation results are tabulated and plotted as charts. The DOD's are ordered in ascending values of the expected wind speeds. Figure 1 contains the chart for Masonry Apartments and Motels. The numbers along the abscissa correspond to the DOD's in Table 3. The ordinate is wind speed. The range between upper and lower bound wind speeds is approximately 40 mph (18 ms^{-1}). The expected values fall about halfway between upper and lower bound values. All elicitation results for the 28 DI's are posted on the Wind Science and Engineering website at Texas Tech University (www.wind.ttu.edu).

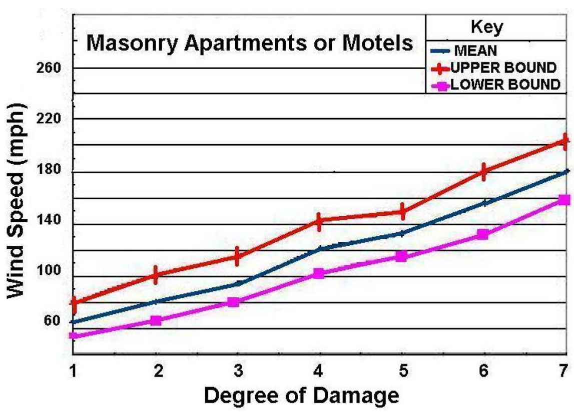

Figure 1. Wind speed as a function of the degree of damage (DOD) for masonry apartments and motels. Mean, upper and lower bound wind speeds were derived from expert elicitation.

6. EF-SCALE AND F-SCALE CORRELATION

In order to understand the relation between the EF- and F-scales and to preserve the historical database, a correlation is needed between the two scales. A panel of NWS meteorologists was assembled and asked to assign original F-scale ratings to each DOD. The six experts chosen routinely assign F-scale ratings to tornadoes based on observed damage. Persons from different parts of the country were invited to serve on the panel in order to incorporate the variation of construction practices around the country. Table 5 lists the NWS personnel on the panel and their geographic location.

Name	Affiliation	Location
Bill Bunting	NWS	Fort Worth, TX
Brian Peters	NWS	Calera, AL
John Ogren	NWS	Indianapolis, IN
Dennis Hull	NWS	Pendleton, OR
Tom Matheson	NWS	Wilmington, NC
Brian Smith	NWS	Valley, NE

Table 5. NWS expert panel members.

The F-scale rating of each DOD was expressed as wind speed by converting the median wind speed to a 3-second gust speed. The expected elicitation wind speeds and the F-scale wind speeds for each DOD are plotted as ordinate and abscissa, respectively, in Figure 2. A regression analysis was performed on the data points. A linear relationship with a 0.91 correlation coefficient gives the best fit. The regression equation is:

$$y = 0.6246x + 36.393, \qquad \text{(Eq. 1)}$$

where y is the EF-scale wind speed and x is the F-scale wind speed, both being 3-second gust speeds.

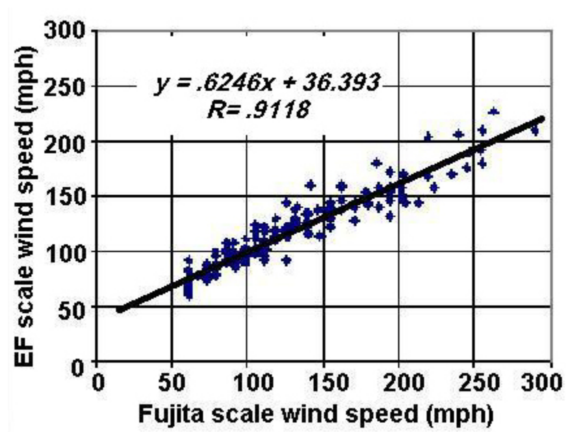

Figure 2. Correlation of F-scale and EF-scale wind speeds.

Now with the regression equation, the wind speeds that define the F-scale ranges were converted to equivalent wind speeds of the EF-scale ranges. Table 6 shows the original F-scale ranges and the equivalent EF-scale ranges corrected to three-second gusts. In order not to imply more accuracy than justified, the EF-scale values are adjusted to the nearest 5 mph (2.2 ms^{-1}) as shown in Table 6.

By correlating the F-scale wind speeds with the EF-scale wind speeds, a tornado rated by the F-scale will have the same "F-number" in the EF-scale, e.g. F3 translates to EF3, although the wind speed ranges are different.

Corrected F-scale		New EF-scale	
F scale	3-sec. gust speed, mph	EF scale	3-sec. gust speed, mph
F0	45-78	EF0	65-85
F1	79-117	EF1	86-109
F2	118-161	EF2	110-137
F3	162-209	EF3	138-167
F4	210-261	EF4	168-199
F5	262-317	EF5	200-234

Table 6. F-scale wind speed ranges corrected to 3-second gusts compared to EF-scale 3-second gust wind speeds.

Further refinement of the EF-scale was made to eliminate the upper bound wind speed at EF5. Refer to Table 7. This was done to allow for some flexibility in assigning future wind speeds in tornadoes as determined from building damage. In addition, having no stated upper bound for EF5 also limits the news media from selecting the highest wind speeds.

EF Categories	Wind Speed Ranges, mph
EF0	65 - 85
EF1	86 - 110
EF2	111 - 135
EF3	136 - 165
EF4	166 - 200
EF5	> 200

Table 7. Recommended EF-scale wind speed ranges.

7. APPLICATION OF THE EF-SCALE

The EF-scale is intended for application to an individual building or other damage indicator. Members of the forum were very specific in their opinion that no single DI ever should be used to rate the intensity of a tornado event. Therefore, items other than buildings were added to increase the likelihood that more than one DI will be struck by a tornado.

Each building or object is rated by the EF-scale in the following four steps. First, the building or object is chosen from one of the 28 DI's listed in the Appendix. Second, the degree of damage (DOD) is selected by visual examination of the building or object. Third, a wind speed is determined that caused the damage. Fourth and finally, the EF number containing that wind speed is selected.

Under normal conditions, the expected value is representative of the observed damage. However, there are factors that can cause a deviation (either higher or lower) from the expected value. The damage evaluator makes a judgment within the range of upper and lower bounds as to whether the wind speed to cause the observed damage is higher or lower that the expected value. The EF-scale rating is the one within the range of wind speeds that contains the estimated value for the DOD. For example, if the evaluator estimates the damaging wind at 140 mph (63 ms^{-1}), then, from Table 7, the rating for the damaged building or object would be EF3.

The rating of a tornado event should represent an estimate of the highest wind speed that occurred during the life cycle of the tornado. It is well known that intensity varies both along the length and across the width of a tornado damage path. Unless the DI is located in the damage path where the highest winds occurred, an estimate of wind speed will be low. Likewise, if actual wind speed is greater than the upper bound of the DOD being considered, the estimate based on the DOD will be too low. Thus, the rating of a tornado event must involve an aggregate of all available data, including nearby structures that were not damaged.

Ideally, the recommended approach for assigning an EF-scale rating to a tornado event involves the following steps:

- Conduct an aerial survey of the damage path to identify DI's and define extent of the damage path.
- Identify several DI's that tend to indicate the highest wind speeds in the path.
- Document specific locations of the DI's within the damage path.
- Conduct a ground survey and carefully examine the DI's of interest.
- Follow the procedure for assigning EF-scale wind speeds to the individual DI's and document results.
- Considering all information, arrive at an aggregate maximum estimated wind speed, and assign the corresponding EF-scale rating to the tornado event.
- Record the basis for assigning the EF-scale rating.
- Record other pertinent data.

8. IMPLIMENTATION

In an effort to gain consensus among users, every opportunity has been taken to present the EF-scale concept and to receive comments and feedback. Presentations, workshops, and symposiums have been held at both meteorological and engineering meetings:

- Fujita Symposium, January 2000
- National Severe Storms Workshop, March 2001
- U.S. National Conference on Wind Engineering, June 2001
- AMS National Conference, January 2002
- 21st Conference on Severe Local Storms, August 2002
- 11th International Conference on Wind Engineering, June 2003

A briefing was presented to the NWS upper management on June 28, 2004 in Silver Spring, Maryland. The concept was well received. The NWS leadership hopes to see endorsements from various organizations and agencies that would make use of the EF-scale. The project team, as well as some interested individuals, currently are working to obtain documented endorsements and approvals from various organizations. If the EF-scale is adopted, then, training courses and materials will be developed.

9. CONCLUSION

An Enhanced Fujita Scale (EF-scale) addresses major limitations of the original Fujita Scale first published in 1971. A set of damage indicators (DI's) is proposed along with degrees of damage (DOD's). Through an expert elicitation process, wind speeds corresponding to the described DOD's are estimated. The estimated wind speed determines the EF-scale category for the observed damage. The categories range from EF0 to EF5, just as in the original F-scale. This relationship preserves the historical tornado database if the EF-scale is adopted as the new standard.

However, the wind speed ranges of the two scales are different. The EF5 wind speed range is about 30% lower than in the original F-scale as determined by experts through the elicitation process. In other words, the wind speed needed to damage or destroy a building is lower than originally thought.

The problem of no damage in open country remains. Research currently is underway to identify other damage indicators and to obtain estimates of wind speeds to cause the damage. Of particular interest are damage to crops, farm equipment, silos, grain storage facilities, fences, and irrigation equipment. These indicators can be incorporated, as DI's in the EF-scale as reliable data becomes available. The technology of Doppler radar also should be a part of the EF-scale process, either as direct measurements, when available, or as a means of validating the wind speeds estimated by the experts.

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11. APPENDIX

No.	Symbol	Damage Indicator
1	SBO	Small Barn or Outbuilding
2	FR12	1- or 2-Family Residence
3	MHSW	Manufactured Home-Single Wide
4	MHDW	Manufactured Home-Double Wide
5	ACT	Apartments, Condos, Townhouses
6	M	Motels
7	MAM	Masonry Apartments or Motels
8	SRB	Small Retail Building
9	SPB	Small Professional Building
10	SM	Strip Mall
11	LSM	Large Shopping Mall
12	LIRB	Large, Isolated Retail Building
13	ASR	Automobile Showroom
14	ASB	Automobile Service Building
15	ES	Elementary School
16	JHSH	Junior or Senior High School
17	LRB	Low-Rise Building (1-4 stories)
18	MRB	Mid-Rise Building (5-20 stories)
19	HRB	High-Rise Building (> 20 stories)
20	IB	Institutional Building
21	MBS	Metal Building System
22	SSC	Service Station Canopy
23	WHB	Warehouse Building
24	ETL	Electrical Transmission Line
25	FST	Free-Standing Towers
26	FSP	Free-Standing Poles
27	TH	Trees: Hardwood
28	TS	Trees: Softwood

Table 8. Damage Indicators