11.1A On the Current Revision of the Enhanced Fujita (EF) Scale

Timothy P. Marshall, PE[1*], Tanya Brown-Giammanco, PhD[2], Samantha N. Krautwurst, PE[3], and [4]Nicholas L. de Toledo
[1]Haag Engineering Co., Flower Mound, TX
[2,4] NIST, Gaithersburg, MD
[3] AECOM, Germantown, MD

1. ABSTRACT

In 1970, Dr. Tetsuya (Ted) Fujita created a tornado rating system, which he called the F-Scale, based on the severity of building damage (Fujita, 1971, 1973). During the next decade, the National Weather Service (NWS) began using the F-Scale to rate tornado damage intensity from F0 to F5; F0 tornadoes represented minor, superficial damage while F4 and F5 tornadoes implied houses were completely destroyed with winds of 207 mph and greater. The NWS was tasked with documenting U.S. tornadoes in order to verify their tornado warnings and to establish a tornado climatology.

Since the 1970's, wind engineering studies revealed mounting evidence that the vast majority of constructed houses can be completely destroyed at wind speeds less than 207 mph (117 m/s), F4 level damage (Phan and Simiu 1998). In 2001, a team of atmospheric scientists and wind engineers assembled and developed the Enhanced Fujita (EF) Scale to address certain limitations and inconsistencies with the F-scale. The team was led by the Wind Science and Engineering Center (WSEC) at Texas Tech University (TTU) and funded by the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) (WSEC 2006).

In 2007, the EF-Scale was adopted by the National Weather Service (NWS). It kept the same 0 to 5 damage ratings but changed the range of failure wind speeds for specific degrees of damage (DoD) for certain damage indicators (DIs), based on how well a building or object was constructed. While the EF-Scale documentation was a great improvement over the F-Scale, the need for further detail was made apparent by the wide variations in assigned EF-ratings in the Storm Data record (Edwards et al., 2013).

In 2014, the American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI) and the American Meteorological Society (AMS) undertook an effort to develop a consensus standard for tornado wind speed estimation. The forthcoming ASCE/SEI/AMS standard, Wind Speed Estimation in Tornadoes, will officially standardize the EF-Scale and include chapters on new methods, including how to interpret treefall patterns, radar measurements, in-situ measurements, remote-sensing data and forensic engineering to estimate wind speeds. Requirements for data archival will also be included in the standard. This paper describes the proposed EF-Scale modifications in detail.

This standard will include much more descriptive information than in the original EF-Scale, including more DoDs, more DIs, a narrative describing various resistance levels of each DI, commentaries for each DI, additional guidance photographs, and references to damage surveys including those many of those conducted during the past 15 years. More than 80 scientists from various disciplines have volunteered their time to develop this standard. Thousands of hours have been put into this effort and it is anticipated the standard will be published within the decade. Public input will be requested through a public comment period once the draft standard has completed the committee balloting process – the objective of this paper is to provide an early public view of the proposed changes and process.

Corresponding author address: Timothy P. Marshall, Haag Engineering Co., 1410 Lakeside Parkway, Ste. 100, Flower Mound, TX 75028; email: tmarshall@haagglobal.com

2. INTRODUCTION

2.1 The Fujita Scale

Fujita (1971, 1973, 1981) developed the Fujita-Scale (or F-Scale) in order to rate various degrees of wind damage to buildings caused by tornadoes, hurricanes, and straight-line winds. The F-Scale (Table 1) is a subjective, visual interpretation of the severity of damage, which simply assigns a numerical value ranging from 0 to 5 based on increasing severity of damage primarily to "well-constructed" or "strong" wood-framed houses. Fujita divided the difference between Beaufort 12 (32.6 m s^{-1}), a mariner's scale (Met Office 2012), and Mach 1 (343 m s^{-1}), an aviator's scale, into 12 non-linear increments. He used the wind speeds in the lowest six divisions in his scale, noting that wind speed values of F6 through F12 were not practical for tornadoes, and therefore were not used. Fujita defined the wind speeds in the F0 to F5 range as being a "fastest 1/4-mile speed", usually in the five- to ten-second range for most tornadoes. Fujita deemed the wind speeds in this scale to be "experimental" and awaited engineering assessments of tornado damage to help "calibrate" the wind speed ranges.

***Table 1*. The Fujita Scale.**

F-Scale	Fastest ¼ mile wind speeds in mph, (m/s)	Description
F0	40-72 (18-32)	Light damage
F1	73-112 (33-50)	Moderate damage
F2	113-157 (51-70)	Considerable damage
F3	158-207 (71-93)	Severe damage
F4	208-280 (94-125)	Devastating damage
F5	261-318 (126-142)	Incredible damage

The empirical selection of 12 divisions between the Beaufort and Mach scales brought criticisms from many in the scientific community. Engineering assessments of tornado damage by Minor et al. (1977) questioned the accuracy of the empirical F-Scale wind speeds, especially above 125 mph (56 m s^{-1}). The F-Scale was an experimental concept that was popularized when NWS adopted and began using the scale to rate tornado damage. They were also tasked determining the path length and width. This information became part of a climatological database of tornadoes which is used by various entities. For example, certain businesses use the tornado database to determine design risk levels for building projects and establish insurance rates. Fujita (1981) was able to publish his F-Scale in scientific literature where it became the benchmark to rate tornado damage. Soon, other countries besides the United States adopted versions of the F-Scale, and it is still used today in parts of Europe.

Grazulis (1993) noted that the single-paragraph descriptions of damage given by F-Scale were vague and limited in scope and could introduce large errors in assigning F-Scale numbers. For example, homes "swept clean" from their foundations in the LaPlata, MD tornado initially were assigned an F5 damage rating but were downgraded to F1 when Marshall (2003) found those homes were not anchored and had slid off their split-level foundations as they collapsed.

Doswell and Burgess (1988) pointed out that building damage and tornado intensity are related but not correlated perfectly. 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 overrate them unless the strengths of the buildings were known. In contrast, tornadoes would be underrated if they remained over open country and did not cause damage. Schaefer and Galway (1982) found that tornadoes that strike populated areas are more likely to receive higher F-Scale ratings than those tornadoes that remain in open country. Fujita (1992) recognized that residences were not homogeneously constructed, and he devised corrections to compensate assigning F-Scale ratings. He indicated that a strong-framed house may sustain F2 damage, whereas the same wind might not damage a concrete building – or might totally destroy a poorly built outbuilding. Thus, he realized the relative strengths of buildings must be considered when assigning F-Scale ratings.

During their damage survey of the Jarrell, Texas tornado, Phan and Simiu (1998) determined that high-speed winds of longer duration resulted in greater damage to residences. Residences near the center of the Jarrell tornado experienced tornadic winds for about three minutes. This left several homes with nothing more than concrete slab foundations. Even the flooring and plumbing fixtures had been removed by flying debris during the tornado. In addition, there is a human factor in determining tornado intensity based on analyzing damage. An evaluator with knowledge of how buildings are commonly constructed (and fail) will likely rate a building differently than an evaluator without such knowledge.

2.2 *The Enhanced Fujita Scale*

Although the F-Scale had been used by NWS and the scientific community for several decades, limitations of the scale were well known to users. Primary limitations included a lack of damage indicators, no way to account for construction quality and variability, and no established relationships of building damage to wind speed. These limitations led to inconsistent ratings of tornado damage and, in some cases, overestimations of tornado wind speeds. By contrast, if a tornado did not strike a building, it was not rated, leading to underestimates of tornado hazards.

Recognizing the need to address some of these limitations, researchers at TTU WSEC proposed a project to re-examine the F-Scale, revise it where necessary, and attempt to develop a consensus between the meteorological and engineering communities, creating an Enhanced Fujita-Scale (EF-Scale) (WSEC 2006). According to McDonald and Mehta (2001) and Mehta (2013), a steering committee was first organized in 2001 to initiate the project.

A major challenge in creating the EF-Scale was addressing how to obtain correlations between damage and wind speed. There were no published studies where wind speed measurements were collected right at a damaged building. Additionally, there were few published scientific studies which calculated failure wind speeds to damaged structures. Minor et al. (1977) and Marshall and McDonald (1983) were among the few who found clean structures, with construction plans, with which to calculate a range of failure wind speeds and then compare them to their F-Scale ratings. Such calculations are tedious and time consuming. Additionally, calculations may not account for unintended overstrength or load paths inherent in many structures.

Thus, in development of the new EF-Scale, a panel of wind damage experts met in 2001 and assigned failure wind speed ranges to various “Degrees of Damage” (DoD) for 28 “Damage Indicators” (DIs) which included various building types, power poles, and trees (McDonald et al. 2003; McDonald et al. 2009). This process, known as expert elicitation, had previously been used successfully to estimate certain unknown parameters related to seismic hazard analyses, and was formalized by the Senior Seismic Hazard Analysis Committee (SSHAC 1997). Subsequently, Boissonnade et al. (2000) applied expert elicitation to estimate parameters for tornado hazard assessment.

The resulting estimated wind speeds could then be used to determine the appropriate EF-Scale, shown in Table 2. The baseline failure wind speed for the 2006 EF-Scale was a three-second gust, at 10 m above ground, in open, unobstructed terrain (for consistency with other wind speed measurements used by wind engineers). By contrast, the time averaging interval for the F-Scale was the fastest 1/4-mile wind speed. The EF-Scale still has the same number range from 0 to 5, but with much lower wind speeds at the higher categories.

Table 2. **The Enhanced Fujita Scale.**

EF-Scale	Three second gust mph, (m/s)
EF0	65-85 (29-38)
EF1	86-110 (39-49)
EF2	111-135 (50-60)
EF3	136-165 (61-74)
EF4	166-200 (75-89)
EF5	>200 (>90)

The number of DoDs for each DI depends on the complexity of construction. DoDs range from “threshold of visible damage” to “total destruction” of entire buildings, where the strongest winds topple all walls and could even sweep the foundation clear of debris.

In an attempt to account for variability in building resistance, ranges of failure wind speeds were determined for each DoD. These failure wind speeds were given the names “expected” (EXP), “upper bound” (UB), and “lower bound” (LB), as shown in Table 3 for an example DI (one- and two-family residences) from the 2006 EF-Scale (WSEC 2006). The expected failure wind speed caused damage under "normal" conditions. A weak connection, material deterioration, or a "fatal flaw" might result in failure at a lower-than-expected, or lower bound wind speed. On the other hand, stronger- than-normal connections (e.g., using steel "hurricane" clips instead of toe nailing), might require higher-than-expected, or upper bound, wind speeds to produce the damage. Thus, a damage evaluator applying the 2006 EF-Scale has the option to go above or below the expected failure wind speed depending on variations in construction while remaining within the range of upper and lower bounds.

gusts over extended periods of time, especially as the wind changes direction. That said, Forbes and Wakimoto (1983) used the F-Scale to map downburst damage in central Illinois while Stiegler and Fujita (1984) and Wakimoto and Fujita (1994) used the F-Scale to evaluate wind damage from Hurricane Andrew.

***Table 3*. The lower bound, expected, and upper bound failure wind speeds for one- and two-family residences for each DoD in the 2006 EF-Scale (WSEC 2006). Wind speed values are in mph and (m/s).**

DoD*	Damage description	Lower Bound	Expected	Upper bound
1	Threshold of visible damage	53 (24)	65 (29)	80 (36)
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding.	63 (28)	79 (35)	97 (43)
3	Broken glass in doors and windows	79 (35)	96 (43)	114 (51)
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	81 (36)	96 (43)	116 (52)
5	Entire house shifts off foundation	103 (46)	121 (54)	141 (63)
6	Large sections of roof structure removed; most walls remain standing.	105 (47)	122 (55)	143 (64)
7	Exterior walls collapsed	113 (51)	132 (59)	153 (68)
8	Most walls collapsed, except small interior rooms	127 (57)	152 (68)	178 (80)
9	All walls down.	142 (63)	170 (76)	198 (89)
10	Destruction of engineered and/or well-constructed residence; slab swept clean.	165 (74)	200 (89)	220 (98)

*DoD is degree of damage

The 2006 EF-Scale addressed some of the major limitations of the original F-Scale, while at the same time preserved the same six damage categories as in the original scale. In addition, the 2006 EF-Scale included various building types with failure wind speed ranges depending on the quality of building construction and lowered the failure wind speeds from the F-Scale (especially at higher EF-Scale numbers) as the result of expert elicitation.

Certainly, the 2006 EF-Scale has shortcomings, being a scale that simplifies wind speed-damage correlations. The problem of rating the strength of tornadoes in open country remains when no damage occurs. Additionally, wind duration is a problem not addressed in the EF-Scale, as a tornado might last a few seconds over a building, whereas a straight-line wind might last minutes, and a hurricane might last hours. These buildings can experience significant damage with longer duration winds. In addition, certain buildings also respond differently to turbulent

Additionally, the science behind the tree DIs in the 2006 EF-Scale was not well-developed, and several researchers noted instances where wind speed estimates derived from damage to tree DIs were not in agreement with those derived from damage to building DIs (Blanchard 2013). Another problem with evaluating building damage using the 2006 EF-Scale is the assumption that failure winds are horizontal when it is well-recognized that certain tornadoes have high vertical velocities near the ground. Marshall et al. (2012) found that heavy concrete parking stops were vertically lifted off rebar anchors and lofted substantial distances in the Joplin, Mo tornado on May 22, 2011. There are also videos on the Internet of tornadoes lifting cars (Leighton, AL on May 8, 2008) and trucks (Lancaster, Texas on April 3, 2012) which indicated that certain tornadoes have stronger vertical velocities than horizontal velocities. Wind tunnel studies by Haan et al. (2017) indicated it was difficult to loft vehicles as they tend to slide first.

As Womble et al. (2009) noted, buildings are likely to have greater wind resistance in hurricane-prone zones due to more stringent building codes with hurricane provisions, and/or an increased awareness of the need for increased resistance. In addition, newly constructed buildings constructed to more recent model building codes should theoretically sustain less damage, and consequently might be assigned lower EF-ratings. However, individual engineering-style examinations must be performed to confirm whether hazard-resistant construction best practices were implemented and whether there were any critical flaws in the structure that contributed to the overall wind damage. While users of the 2006 EF-Scale can vary wind speeds within the LB and UB speeds for a given DI and DoD, there is no information on wind resistance characteristics to inform this decision-making.

There have also been specific requests for updates to the EF-Scale by a diverse community of users. Specifically, requests for new DIs to be created, especially in rural areas where building DIs are not common, have been made, as has adding additional guidance, including example DoD photographs (FEMA 2012, Kuligowski et al. 2014).

2. ASCE/SEI/AMS TORNADO WIND COMMITTEE STANDARD

In 2010, an informal stakeholders' meeting of EF-Scale users and parties interested in discussing and potentially updating the EF-Scale was organized in Norman, OK (Edwards et al. 2013). By 2014, the organizer of the 2010 stakeholders' meeting, along with many of that meeting's participants and others undertook an effort to develop an American Society of Civil Engineers/Structural Engineering Institute (ASCE/SEI) consensus standard for tornado wind speed estimation. The American Meteorological Society (AMS) joined the effort a few years later. The forthcoming ASCE/SEI/AMS standard, *Wind Speed Estimation in Tornadoes*, will officially standardize the EF-Scale and provide a consensus process whereby changes can be implemented in future versions. One goal of the new standard was to preserve the 2006 EF-Scale numbers 0 through 5 with increasing amounts of damage, while providing updates to DIs and wind speed estimates based on the many damage evaluations that have been performed in the 15 years since the original EF-Scale was published. Another goal was to standardize other ways of estimating wind speeds in windstorms, including through treefall patterns, radar measurements, in-situ measurements, remote-sensing data and forensic engineering, and provide requirements for archival of data.

2.1 ASCE/SEI/AMS Standard Development Process

ASCE/SEI follows the American National Standards Institute (ANSI) standards development process (ANSI 2022), a consensus-based process which provides a framework for fair standards development. The process is intended to be neutral and requires openness, a balance of member types, and due process. Meetings of the ASCE/SEI/AMS standard's Main Committee are open to the public and announced in advance. Committee membership includes voting members, who are required to vote on proposals and have restrictions about the number of ballots that can be missed in a given time period, to ensure active participation. These voting members must represent a balanced population of producers of products, users of products or the standard, and general interest members which includes academics and government personnel. Associate members may also be designated on the committee, and these members do not have the voting requirements of voting members, but they may vote on ballots as they have time and expertise to contribute. All votes must be considered by the committee regardless of the membership type.

For new standards, the development process involves the creation of proposals for content, which must be balloted and approved. For existing standards, proposals are created to revise or delete existing sections or develop new sections; these must be balloted and approved as well.

Many committees operate with subcommittees, and they can develop their own processes to develop, vet, and ballot proposals before they go forward to the main committee. The EF-Scale subcommittee operates in a similar fashion to the main committee, described below. All proposals are balloted at the subcommittee first, before being revised and moved into the main committee's ballot process.

At the main committee, members may vote affirmative, affirmative with comment, negative, or may abstain from voting. There are published ASCE requirements about the percentage of votes and affirmative responses required for a ballot item to "pass". Regardless of whether an individual vote is affirmative with comment or negative, the ballot proposer must respond to all comments, finding them persuasive editorial, persuasive substantive, persuasive-new technical data/new business, non-persuasive or unrelated, or non-persuasive-previously considered, and must revise the proposal to reflect the persuasive changes. The proposal is then reballoted and each negative vote that was found non-persuasive must be balloted for the main committee's concurrence. This process continues until the committee reaches consensus about the proposal. Once all proposals for the version of the standard have reached consensus, the draft standard is posted for public comment. Any comments that come in during this process must also be reviewed and responded to by the committee, which may require additional changes to the draft before a final version is published.

As of mid-2022, various sections of the EF-Scale method, described below, have been balloted, while a few specific DIs have not yet been balloted. Some sections have gone through a single ballot, while others are on first, second, third, or even fourth revisions. More than 80 scientists, wind engineers, and others from various disciplines have volunteered their time to develop this new standard on wind speed estimation. Thousands of hours have been put into this effort and it is anticipated the standard will be published within the decade.

2.2 EF-Scale Method

The EF-Scale chapter of the ASCE/SEI/AMS standard will be limited to tornado-caused damage, as these winds are of short duration and accelerate/decelerate quickly, whereas tropical and extratropical cyclones, straight-line thunderstorm, and downslope winds can last for hours. The EF-Scale method in the standard will introduce the concept of "resistance" of a DI to withstand wind damage, ranging from "weaker-than-typical" to "typical" to "stronger-than-typical" resistance. The standard will include an extensive narrative explaining the different resistance levels of each DI, as well as a commentary, additional photographs, and references for each DI. Overall, failure wind speeds in the updated EF-Scale will remain similar to those in the 2006 EF-Scale with adjustments made to fit the linear increase in the DoDs. In the 2006 EF-Scale, each DI was treated separately which resulted in differences in the estimated failure wind speeds. For example, the expected failure wind speed for loss less than 20% of roof coverings is 79 mph (35 m/s) for residences, but it is 99 mph (44 m/s) for apartment buildings. However, the same roof coverings are typically used for these two DIs. Thus, for the new standard, DIs were cross correlated with each other using expert elicitation to make sure the same failure wind speeds were used for similar DoDs across DIs. In addition, damage descriptions in the new standard will include 25% increments of damage to key building components, such as roof covering, wall cladding, and roof decking, whereas in the 2006 EF-Scale, the damage description was divided at less than or greater than 20% for one- and two-family residences, as an example.

There will be a number of other changes to the 2006 EF-Scale in the ASCE/SEI/AMS standard. Estimated failure wind speeds will be rounded to the nearest 5 mph in the new standard, to convey the lack of precision in the estimates. A variance of 20% or greater in the expected failure wind speeds is also noted in each DI's DoD table, and a coverage probability for the wind speeds will likely be introduced. However, it is anticipated that future fragility studies will have an impact on both the expected failure wind speeds, as well as the variance. Currently, there are only a small number of published tornado-based fragility studies on a few DIs, mostly wood-framed residential structures, but this is expected to expand to other DIs in the coming years.

Additionally, some DIs will be merged with others. For example, the committee found little difference in failure wind speeds between single-wide and double-wide manufactured homes. Therefore, they were merged into one DI. Small Retail Buildings and Small Professional Buildings were merged for the same reason. Automobile Showrooms and Automobile Service Buildings were merged into other building types. The tree DIs from the 2006 EF-Scale will be changed from hardwood and softwood trees to single and multiple trees in the new standard. As Blanchard (2013) noted, the 2006 EF-Scale was overly simplistic for trees and did not address forests. His comparisons of tree damage with building damage suggested the EF-ratings were too low for trees. Additionally, Lombardo et al. (2015) compared tree damage with building damage and found that for individual structures, estimated tree-fall wind speeds were consistently higher than wind speeds estimated using the 2006 EF-Scale. The new tree DIs will address variability in tree type and maturity, soil conditions, etc.

Since many tornadoes occur in rural areas where there are no buildings, new DIs for Center Pivot Irrigation Systems (CPIS), Wind Turbines (WT), and Farm Silos and Grain Bins (FSGB) will be included in the new standard. Passenger Vehicles (PV) will also be included, although they have greater variability in wind speeds since they are small in size and can move, flip, or be lofted. Churches did not appear in the 2006 EF-Scale but will be included in the new standard as Religious Buildings (RB) and Classic Architecture Religious Buildings (CARB). Residences will be split into wood-frame and concrete masonry construction. Many of these changes are partially adapted from the Canadian EF-Scale (Environment Canada 2013). A list of the anticipated DIs for the upcoming standard is shown in Table 4.

***Table 4.* A list of DIs that are expected to be included in the initial publication of the ASCE/SEI/AMS Wind Speed Estimation standard.**

DI Number	Damage Indicator (DI)
1	Barns and Farm Outbuildings (BFO)
2	Wood-Framed Residences (WFR)
3	Concrete Block Stucco Residences (CBS)
4	Single- and Double-Wide Manufactured Homes (SDMH)
5	Apartments, Condominiums, Townhomes, Motels (ACTM)
6	Concrete Apartments, Condominiums, Townhomes, Motels (CACTM)
7	Passenger Vehicles (PV)
8	Small General Buildings (SGB)
9	Farm Silos and Grain Bins (FSGB)
10	Strip Malls (SM)
11	Large Shopping Malls (LSM)
12	Large Isolated Retail Buildings (LIRB)
13	Religious Buildings (RB)
14	Classic Architecture Religious Buildings (CARB)
15	Schools (SCH)
16	Roof-Top Units (RTU)
17	Low-Rise Buildings (LRB)
18	Mid-Rise Buildings (MRB)
19	High-Rise Buildings (HRB)
20	Institutional Buildings (IB)
21	Metal Building Systems (MBS)
22	Service Station Canopies (SSC)
23	Warehouse Buildings (WHB)
24	Electrical Transmission Systems (ETS)
25	Free-Standing Lattice Towers and Guyed Masts (FST)
26	Free-Standing Poles and Signs (FPS)
27	Single Tree (TREE)
28	Multi-Tree (MT)
29	Center Pivot Irrigation System (CPIS)
30	Wind Turbines (WT)

2.3 *Other Wind Speed Estimation Methods*

In addition to the EF-Scale method, there will be chapters included for several additional methods to estimate wind speeds. One such chapter is a forensic engineering method which is planned to include a procedure to analyze building damage by explaining what to look for when analyzing a particular DI. The hope is that connections with fatal flaws and broken links in load paths can be recognized by damage evaluators to help improve the accuracy in determining the failure wind speeds. The standard assumes the damage evaluator has some knowledge in building construction, particularly with how walls are attached to floors or foundations and how roofs are attached to walls. A treefall pattern wind speed estimation method will also be introduced as a chapter in the ASCE/SEI/AMS standard. This method will be based on publications by Karstens et al. (2013), Kuligowski et al. (2014), Lombardo et. al. (2015), Godfrey and Peterson (2017), and Rhee and Lombardo (2018).

The 2006 EF-Scale was strictly a damage scale and did not include in-situ measurements or remote sensing wind estimates, which occasionally created substantial discrepancies in wind speed estimations. For example, Wakimoto et al. (2016) indicated that dual-Doppler wind synthesis of the tornadic circulations at low levels in the May 31, 2013 El Reno, OK tornado resolved ground-relative wind speeds in excess of 90 m/s, greater than the minimum speed for EF5 damage, in open areas where there were no DIs. By contrast, the NWS survey team only found damage equivalent to EF 3 to a small number of DIs (Marshall et al. 2014) in areas between the peak winds. Thus, the peak intensity of tornadoes can be missed if there are no DIs directly in the path.

The new ASCE/SEI/AMS standard will include a chapter on radar measurements to estimate wind speeds. As of yet, there are no established correction techniques to compare instantaneous radial velocity components averaged at some height above the ground with three-second gust measurements at 10 m. But Kosiba and Wurman (2013) were able to measure tornado winds and have rapid in-situ measurements for the first time in the core flow of a tornado on May 25, 2012 near Russell, Kansas. From these data, they were able to plot cross section profiles of the wind velocities in a tornado. Interestingly, they found the maximum winds in this tornado were near 5 m above ground level (AGL). Their findings, as well as other publications will form the basis of the radar measurement wind speed estimation chapter in the new ASCE/SEI/AMS standard. In-situ measurements are also valuable but of course are point measurements and the instruments rarely survive a direct hit by a tornado. However, several field campaigns have been conducted to form the basis for an in-situ measurement method in the new standard.

Womble et al. (2018) found that remote sensing data are a valuable tool that can provide crucial and perishable evidence following a disaster before clean-up destroys it. Remote sensing imagery can quickly document tornado path length and width as well as intensities for later study. Womble et al. (2018) also noted there is a need for detection and estimation of tornado intensity especially in sparsely populated areas where tornado occurrences may otherwise go undetected. Therefore, the ASCE/SEI/AMS standard will also feature a chapter devoted to use of remote-sensing imagery in the study of tornado damage, including that collected by satellites, aircraft, or uncrewed aerial vehicles (UAVs).

3. SUMMARY

The ASCE/SEI/AMS *Wind Speed Estimation in Tornadoes* will standardize the EF-Scale and hopefully be published within the next few years. The name “EF-Scale” will remain unchanged and there will still be six damage rating categories from 0 to 5, with EF5 being the most severe damage. It is expected that the wind speeds associated with EF0, EF1, etc. will also remain the same. The EF-Scale will continue to rely on expert interpretation of the damage, but the new standard will hopefully lessen the subjectivity with its added details and commentary. The most accurate damage evaluations will come from evaluators who are familiar with building failures and construction. The standard will establish a methodology to evaluate tornado damage and will have more DIs than in the 2006 EF-Scale. Furthermore, the new standard is expected to include chapters on many new methods for estimating wind speed, including a forensic engineering method, a treefall pattern method, an in-situ method, a radar method, a remote-sensing method, and data archival requirements.

This standard will remain a work in progress and additional revisions through ASCE's standard development process are anticipated as additional research is published. It is also anticipated that data from future fragility studies will be incorporated into revisions. These may change the expected failure wind speeds as well as the ranges of wind speeds between weaker- and stronger-than-typical resistances.

A number of issues will remain debatable. There is the issue of wind duration, which the standard will not address at this time, despite the fact that it makes sense that a DI will exhibit more significant damage the longer the duration it experiences high winds. There is also an issue with the assumption that tornadoes impacting DIs have horizontal winds when in fact, there are various vertical components of the wind. Issues remain with regard to applying this standard to hurricanes and straight-lined thunderstorm winds. These and other issues may be addressed in future revisions of the standard.

4. DISCLAIMER

No formal investigation has been conducted to evaluate all potential sources of uncertainty or error associated with the wind speeds estimates being developed for the new ASCE/SEI/AMS standard.

5. ACKNOWLEDGEMENTS

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