The Fujita Tornado Intensity Scale: A Reassessment from Structural Engineering Perspective

by

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ABSTRACT

On May 27, 1997 the town of Jarrell in central Texas, and on May 30, 1998 the town of Spencer in South Dakota were hit by two violent tornadoes. We evaluated the structural damage caused by the Jarrell tornado and concluded that the worst damage can be explained by wind speeds corresponding to an F3 rating on the Fujita tornado intensity scale (wind speeds of 71 m/s to 92 m/s). An F4 (93 m/s to 116 m/s) rating, or the F5 (117 m/s to 142 m/s) rating officially issued by the National Weather Service (NWS), need not be assumed to explain that damage. We also present assessments of damage in the Spencer tornado, and suggest there is an inconsistency between the NWS ratings of the Jarrell and Spencer tornadoes. We ascribe the NWS ratings to the failure of the Fujita scale to account explicitly for the dependence of wind speeds causing specified types of damage upon two structural engineering factors: (1) the basic design wind speed at the geographical location of interest, and (2) quality of construction, defined as degree of conformity to applicable standards requirements. We address the need for a stronger involvement of the structural engineering profession in nationwide efforts to develop an improved tornado classification scale and a more realistic tornado windspeed database.

KEYWORDS: Building technology; Fujita tornado intensity scale: meteorology; standards; structural engineering; wind engineering; tornadoes.

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1. INTRODUCTION

On May 27, 1997 a violent tornado swept through a housing area on the outskirts of Jarrell, Texas (population 410) in Williamson County, approximately 60 km north of Austin, Texas, destroying about 40 single family residences and killing 27 people. A year later, on May 30, 1998 a violent tornado struck the town of Spencer, South Dakota, a small farm community approximately 72 km west of Sioux Falls, leaving 6 dead, more than 150 injured, and nearly 90 percent of a total 195 structures in the six-by-seven blocks community destroyed. Immediately following the passages of these tornadoes, structural engineers of the National Institute of Standards and Technology (NIST), in collaboration with meteorologists of the National Weather Service (NWS), conducted post-storm inspections to document structural damage and to assess tornado intensities. (Both NIST and NWS are agencies of the U.S. Department of Commerce.) This paper (1) describes the most severe structural damage observed for the Jarrell and Spencer tornadoes, which served as the basis for the NWS official rating of F5 and F4, respectively (see Appendix I); and (2) assesses the tornado wind speeds in Jarrell based on engineering considerations. From this assessment it was concluded that the damage caused by the Jarrell tornado may be explained by wind speeds corresponding to an F3 rating. An F4 rating, or the F5 ratings officially issued by the NWS, need not be assumed to explain that damage. The apparent misclassification of the Jarrell tornado can be ascribed to two shortcomings inherent in the current Fujita tornado intensity scale. The first shortcoming is that the damage descriptors for tornado categories F3 to F5 include ambiguous terms referring to construction quality, such as "well constructed houses," "structures with weak foundation," and "strong frame houses." These

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descriptions are open to subjective interpretations and can lead to inconsistent field applications, especially by non-engineers who normally cannot be expected to have the requisite technical knowledge needed for ascertaining whether or not houses destroyed by tornadoes were well-constructed or strong. Evidence of subjective application of the Fujita tornado intensity scale is further illustrated by comparing the damage caused the Spencer tornado and that of the Jarrell tornado. While similar damage to similar structures was observed in Spencer and Jarrell, the Spencer tornado was rated as an F4 tornado instead of F5, as was the case for the Jarrell tornado The second shortcoming is that the Fujita tornado intensity scale does not reflect the dependence of the tornado wind speeds causing various types of damage upon the design wind speed specified for the zone of interest. For example, a tornado wind speed that tears down the roofs of well constructed houses may be assumed to be larger by a factor of roughly 1.6 for zones in which the design wind speed is 63 m/s than for zones where the design wind speed is 40 m/s; that is, damage that in a 63 m/s zone could be attributed to an F5 tornado could be explained in a 40 m/s zone by F3 tornado winds.

2. THE JARRELL TORNADO

2.1 Post-storm Survey

Shortly before 3:45 PM CDT on May 27, 1997, the Jarrell tornado first struck areas of Bell County causing minor damage to trees and the roofs of a few residences. The tornado then crossed the Bell/Williamson county line into Williamson County where the town of Jarrell was located. The locations where the tornado crossed county roads were clearly marked by strips of scoured asphalt road surface. The top layer of the asphalt pavement was about 20 mm thick. The scouring of asphalt road surface is ascribed to differences between the atmospheric pressure in pockets of air trapped underneath the asphalt and the lower atmospheric pressure at the tornado center. The tornado path length was estimated to be 12.2 km and the maximum path width was measured to be approximately 1.2 km. Witnesses estimated that the Jarrell tornado was moving at a slow speed of between 2 m/s and 4 m/s.

The NIST-NWS post-storm survey team conducted ground surveys, on May 29 and June 1, 1997, and two aerial surveys: one on May 30, 1997 using a fixed wing aircraft flying between 760 m and 910 m, and the second on May 31, 1997 using a helicopter flying between 150 m and 300 m. A commercial Global Positioning System (GPS) was used to obtain the coordinates defining the tornado path.

2.2 Main Damage Observations

The first structural damage in Jarrell occurred at the corner of County Road 305 and County Road 307, where a culvert plant collapsed in place (Figure 1). The plant was a light steel frame construction with non-reinforced masonry and steel tube columns supporting steel pipe, gable roof trusses. The steel tube columns were cast into a concrete mat foundation on grade. The roofing, supported by wood purlins, consisted of corrugated sheet metal. An identical plant located approximately 15 m away from the collapsed culvert plant, and a mobile home located about 150 m north-northwest of the plant sustained only very minor damage. As the tornado continued its track south-southwestward, a barn located just southwest of the culvert plant and just north of the Double Creek Estates subdivision in Jarrell was destroyed. The tornado then moved through the Double Creek Estates subdivision and the surrounding areas, where the destructive path widened to its maximum of 1.2 km and the tornado became most deadly.

Figure 2 shows a portion of what remained of Double Creek Estates subdivision after the tornado passage. The structures in the subdivision consisted mainly of single family residences built over the last 15 years or so, of the typical slab-on-grade construction type. Owing to the presence of a limestone bedrock most houses had no basements or underground shelters. The houses, which consisted mainly of wood frame construction, were completely swept off the concrete foundations. Inspections of the concrete slab-on-grade foundations performed during the ground surveys revealed that, in many cases, even the sill plates that connect the wood frames to the concrete slab-on-grade foundations were blown away (see Figure 3). There was evidence that the sill plates had been connected to the foundations by explosive-driven nails. Figure 4 shows a nail that remained in the foundation but pulled through the sill plate. Figure 5 shows nails, spaced 0.9 m apart, that pulled out of the foundation. The Council of American Building Officials (CABO): One and Two Family Dwelling Code and other nationally recognized model codes require that sill plates of exterior walls for wood-frame construction be anchored to the foundation by anchor bolts not more than 1.83 m apart, but no evidence of anchor bolts was found by the team. It should be noted that Williamson County *has not adopted a building code*, even though Jarrell was also hit by a tornado on May 17, 1989.

3. THE SPENCER TORNADO

3.1 Post-storm Survey

The Spencer tornado struck at 8:38 pm CDT on May 30, 1998 and moved through the town of Spencer at a speed of approximately 15-20 m/s. The tornado left a ground track about 34 km long and close to 1.5 km wide at its broadest. An aerial survey using fixed wing aircraft flying at between 760 m to 910 m was conducted on the following day, and was followed by a ground survey one day later.

Based on surveys of the most severe structural damage, the NWS assigned it an F4 rating. Reportedly, a Doppler-On-Wheels (DOW) radar, operated by the School of Meteorology of the University of Oklahoma as part of the Radar Observations of Tornadoes and Thunderstorms Experiments (ROTATE-98) program, was able to record wind speeds of this tornado and indicated wind speeds of up to 110 m/s. These measurements, if validated, would be consistent with the wind speed range associated with an F4 tornado (93-116 m/s).

3.2 Main Damage Observations

Figure 6 shows an overview of the town of Spencer after the tornado passage. Within the town of Spencer, the observed damage ranged from total disintegration of structures in the direct path of the tornado, to light damage to envelopes of structures in the outlying areas. The structures affected varied in age and structural systems. Completely destroyed structures included one and two-story wood-frame, heavy timber, and engineered metal frame constructions. Among these were wood-frame constructions that were either poorly connected or totally unconnected (i.e., relying on gravity alone) to the concrete or brick foundations. However, structures that were totally destroyed also included some (post office, fire department, gas station, antique and other stores) that were properly anchored to the concrete slab-on-grade foundations by 12.7 mm (½-in) anchor bolts with proper spacing as required by CABO (1995) and other nationally recognized model codes (see Figures 7 (a) and (b)). Many heavy trucks, some reportedly fully loaded, used in transporting grains to and from the town's grain processing and storage warehouses, were lifted and carried more than 30 m away by the wind. Trucks and houses exhibited widespread evidence of missile impacts from broken wooden power poles, tree branches, and other debris.

4. TORNADO INTENSITY ESTIMATES

The Jarrell and Spencer tornadoes offered an opportunity to assess subjective tornado intensity estimates based on Fujita scale damage descriptions. Our assessments are based on structural engineering considerations.

The basic peak gust wind speed specified in the ASCE 7-95 Standard (1995) for the design of buildings in central Texas is 40 m/s. Building designs for central Texas before 1995 should be roughly compatible with this basic speed. Design and construction practices of buildings such as those destroyed by the Jarrell tornado are normally based on experience and judgment rather than formal engineering calculations. When they are sound, such practices are consistent with the requirement that buildings should be capable of withstanding wind speeds higher than the basic design wind speed, with a safety margin with respect to wind loading of at most 1.5 to 2. Assume that in areas with a 40 m/s basic design wind speed buildings would collapse under winds loads twice as large as the loads induced by the 40 m/s speed. It follows from the proportionality of the wind loads to the square of the wind speeds that those buildings would be expected to collapse under wind speeds in excess of $40 \times (2)^{1/2} = 56.6$ m/s. The expectation would be even stronger that wind speeds corresponding to wind loads 3 times as large as those induced by the 40 m/s speed (i.e., 69 m/s wind speeds) would leave no buildings standing, especially if the construction is mediocre or poor, as appears to have been the case for buildings destroyed by the Jarrell tornado.

Speeds assigned to F3 tornadoes in the Fujita classification are about 72 m/s to 94 m/s. For a building to resist such speeds its safety margin with respect to wind loads would on average have to be about 3.1 to 5.5. There is no reason to believe that any of the buildings destroyed by the Jarrell tornado were that strong. We note that 90 m/s wind speeds, which in the Fujita classification are associated with F3 tornadoes, would likely destroy residential homes not only in a 40 m/s basic design wind speed zone, but in hurricane-prone areas with 63 m/s basic design wind speeds as well.

In fact, based on evidence that code compliance with respect to the connections between the upper wood frame and the concrete foundation was better in Spencer than in Jarrell, one may conclude that buildings that were completely destroyed were stronger in Spencer than in Jarrell. Nevertheless, the NWS tornado ratings were F5 and F4 for the Jarrell and Spencer tornadoes, respectively. In our opinion this is a clear indication of possible inconsistencies inherent in subjective tornado speed assessments by non-engineers.

5. CONCLUSIONS

Our conclusions are:

1. The strongest damage caused by the Jarrell tornado can be explained by wind speeds corresponding to an F3 rating (i.e., 71 m/s to 92 m/s).

2. The Fujita tornado intensity scale has two major shortcomings that can lead to misclassification of tornadoes by non-engineers:

(a) It does not reflect the dependence of the tornado wind speeds causing various types of damage upon the design wind speed specified for the zone of interest.

(b) The damage descriptions include ambiguous descriptions of structural quality such as "well-constructed houses" and "strong frame houses." Non-engineers normally cannot be expected to have the requisite technical knowledge needed for ascertaining whether or not houses destroyed by tornadoes were well-constructed or strong.

These conclusions are of significance insofar as:

1. Tornado misclassification corrupts the database used to develop design criteria for structures whose performance must be unaffected by strong tornadoes.

2. Ascribing failures to unrealistically high wind speeds when the actual speeds are in fact lower discourages the application and enforcement of standards, such as ASCE 7, that are capable of reducing loss of life and property caused by most tornadoes.

3. A stronger contribution of the structural engineering profession to efforts aimed at assessing tornado wind speeds could help improve the knowledge needed to protect the public from tornado-induced losses.

For these reasons, we recommend the followings:

1. Engineers, meteorologists, disaster relief workers, and representatives of standards organizations, regulatory bodies and the insurance industry should work together to develop a tornado intensity classification scale wherein damage descriptions make specific reference to basic design wind speeds and to quality of construction as defined by degree of conformity to standards requirements. As a basis for discussion, it is suggested that wind speed ranges included in tornado intensity classifications be affected by numerical factors related to the basic design wind speeds and to quality of construction. Factors related to quality of construction could be specified in accordance with matrices of the type considered for development by insurance companies, wherein conformity to various standards requirements is estimated both qualitatively and quantitatively.

2. ASCE, in collaboration with other interested parties, should consider organizing and training local ASCE chapter volunteer engineering teams that could join in expeditiously with local NOAA and other specialized personnel, and promptly record from the strength of their professional knowledge significant evidence on tornado intensities. This recommendation is based on experience which shows that evidence of tornado effects is often removed from the site less than a day after a tornado occurrence, that is, *before* survey teams can reach the site.

3. The documentation for the approximately 150 tornadoes (about 0.5% of the total number of recorded tornadoes in the U.S.) that were classified as F5 should be revisited in an attempt to reassess their classification. Such reassessment would involve a relatively small effort and would, even if only partly successful, allow some updating of the database from which probability distributions of tornado wind speeds have been estimated so far. This recommendation follows a proposal by K. Mehta of Texas Tech University.

4. Continuing efforts to develop procedures for obtaining direct, scientific tornado wind speed measurements should be encouraged. On the one hand such measurements would add valuable data to the database, even though the effect of such addition to the more than 25,000 data currently available would be small: many years of data would have to be collected for that effect to be significant. On the other hand, scientific measurements can help to assess estimates of tornado wind speeds based on observations of damage. This would in turn help to effect corrections to the existing database by allowing the use of Bayesian or other updating techniques.

6. REFERENCES

ASCE 7-95, Minimum Design Loads for Buildings and Other Structures, ASCE Standard, American Society of Civil Engineers, New York, New York.

The Council of American Building Officials, *CABO One and Two Family Dwelling Code*, 1995 edition, Falls Church, Virginia.

Long T. Phan and Emil Simiu, *The Fujita Tornado Intensity Scale: A Critique Based on Observations of the Jarrell Tornado of May 27, 1997*, NIST Technical Note 1426, National Institute of Standards and Technology, July, 1998.

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APPENDIX I. FUJITA TORNADO INTENSITY SCALE

Category-Definition-Effects

F0 Gale tornado (Approximate wind speeds 18-32 m/s (40-72 mph)): Light damage. Some damage to chimneys; break branches off trees; push over shallow rooted trees; damage sign boards.

F1 Moderate tornado (Approximate wind speeds 33-50 m/s (73-112 mph)): Moderate damage. Lower limit is the beginning of hurricane wind speed; peel surface off roofs; mobile homes pushed off foundations or overturned; moving autos pushed off the roads.

F2 Significant tornado (Approximate wind speeds 51-70 m/s (113-157 mph)): Considerable damage. Roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light-object missiles generated.

F3 Severe tornado (Approximate wind speeds 71-92 m/s (158-206 mph)): Severe damage. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forests uprooted; heavy cars lifted off ground and thrown.

F4 Devastating tornado (Approximate wind speeds 93-116 m/s (207-260 mph)): Devastating damage Well constructed houses leveled; structures with weak foundation blown off some distance; cars thrown and large missiles generated.

F5 Incredible tornado (Approximate wind speeds 117-142 m/s (261-318 mph)): Incredible damage Strong frame houses lifted off foundations and carried considerable distance to disintegrate; automobile-sized missiles fly through the air in excess of 100 yards; trees debarked; incredible phenomena will occur.

(From National Post-storm Data Acquisition Plan, Federal Coordinator for Meteorological Services and Supporting Research, National Oceanic and Atmospheric Administration.)

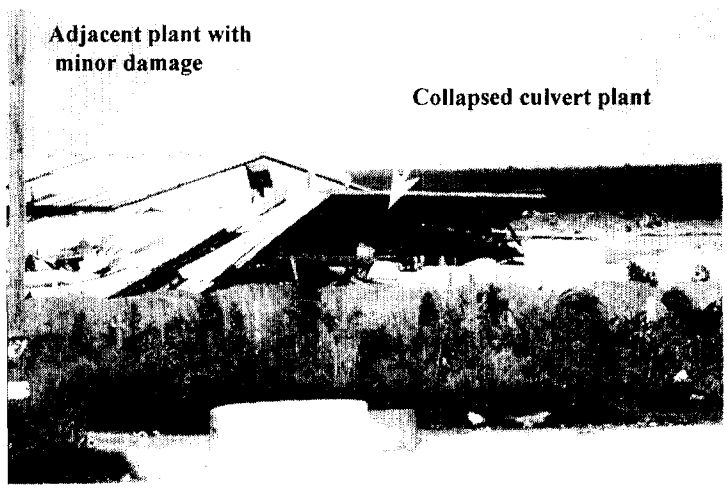


Figure 1. Ground view of collapsed culvert plant.

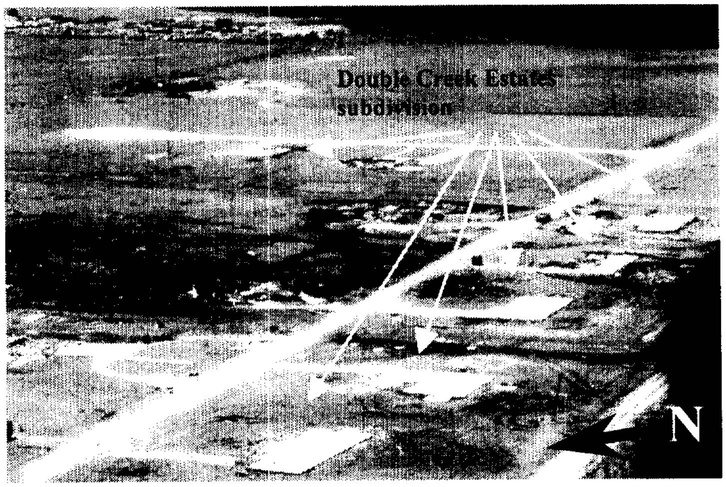


Figure 2. Aerial view of portion of the Double Creek Estates subdivision after tornado passage

Figure 3. Close-up view of a typical slab-on-grade foundation of houses in Jarrell. Only one sill plate remains connected to the concrete foundation.

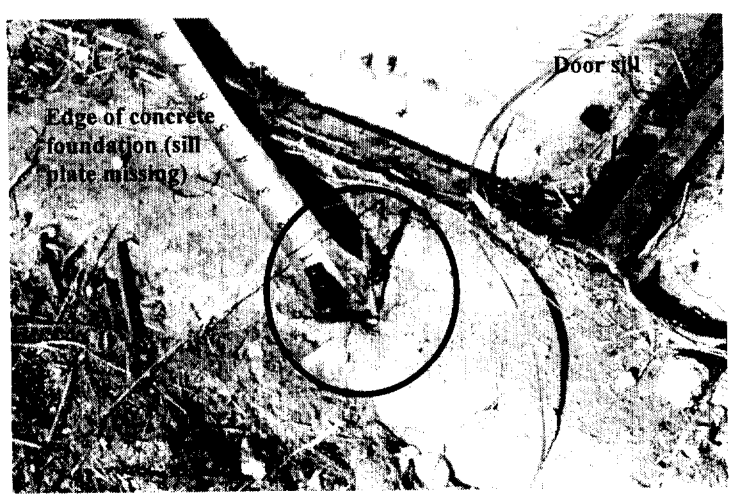


Figure 4. Evidence of nail that was used for connecting sill plate to concrete foundation.

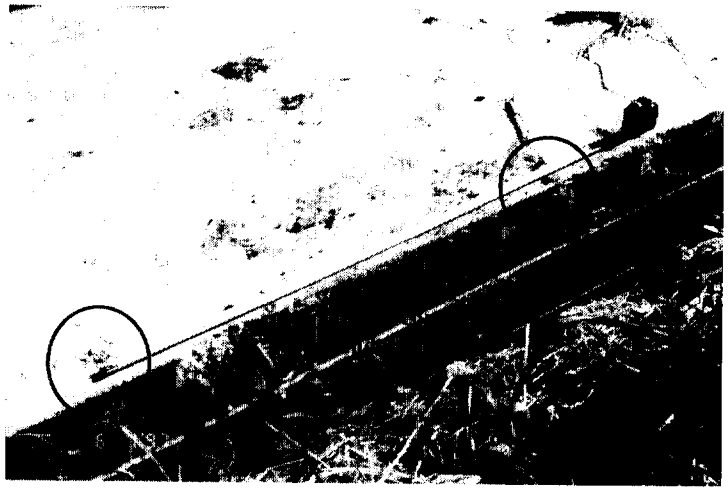
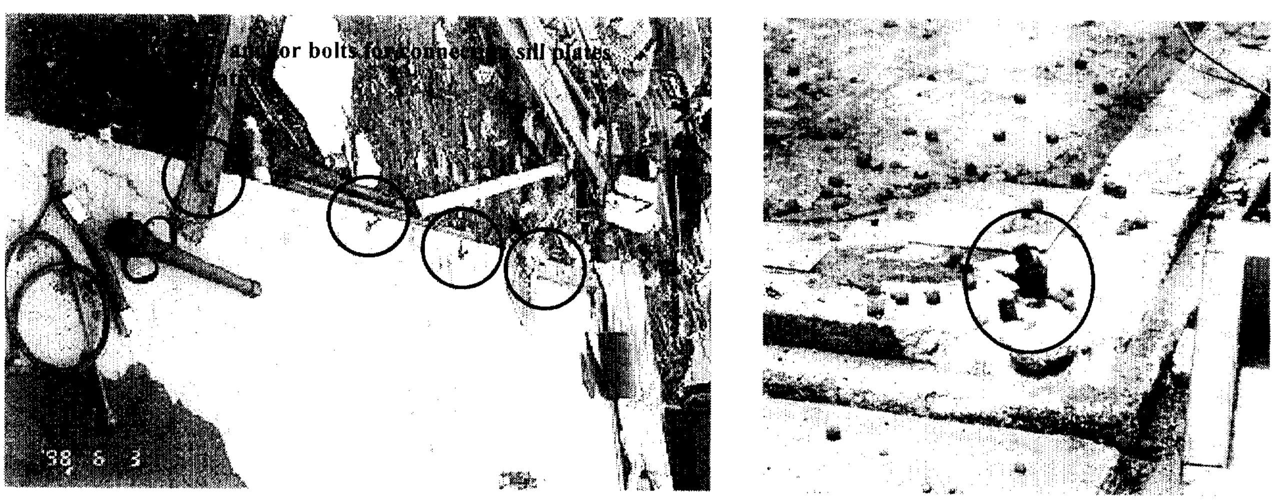


Figure 5. Evidence of pullout of nails used to fasten sill plates to concrete foundation.

Figure 6. Aerial view of portion of the town of Spencer, South Dakota, after tornado passage.



(a) (b)

Figures 7 (a) and (b). Evidence of anchor bolts used to connect upper structure to concrete slab-on-grade foundation in Spencer, South Dakota.