A Guide to F-Scale Damage Assessment

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service
Silver Spring, Maryland

Cover Photo: Damage from the violent tornado that struck the Oklahoma City, Oklahoma metropolitan area on 3 May 1999 (Federal Emergency Management Agency [FEMA] photograph by C. Doswell)

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April 2003

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Preface

Recent tornado events have highlighted the need for a definitive F-scale assessment guide to assist our field personnel in conducting reliable post-storm damage assessments and determine the magnitude of extreme wind events. This guide has been prepared as a contribution to our ongoing effort to improve our personnel's training in post-storm damage assessment techniques.

My gratitude is expressed to Dr. Charles A. Doswell III (President, Doswell Scientific Consulting) who served as the main author in preparing this document. Special thanks are also awarded to Dr. Greg Forbes (Severe Weather Expert, The Weather Channel), Tim Marshall (Engineer/ Meteorologist, Haag Engineering Co.), Bill Bunting (Meteorologist-In-Charge, NWS Dallas/Fort Worth, TX), Brian Smith (Warning Coordination Meteorologist, NWS Omaha, NE), Don Burgess (Meteorologist, National Severe Storms Laboratory), and Stephan C. Kuhl (National Warning Coordination Meteorologist Program Manager, NWS Headquarters, Silver Spring, MD) for their technical review of this manuscript. Thanks also to Neal Rasmussen, Jim Williams, Tim Marshall, and Dr. Joe Golden (Forecast Systems Laboratory) for allowing the use of their photographs within this guide. Dr. Harold E. Brooks (National Severe Storms Laboratory) generously provided data for some of the figures used.

I am confident that every one of our field personnel who are charged with assessing post-storm damage to determine final wind storm intensity will find this guide both useful and beneficial.

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I. The Fujita scale of tornado intensity

A. A short history

Prior to the adoption of T. Theodore Fujita's tornado intensity rating scale by the National Weather Service (NWS), there was no formal way to attempt to differentiate one tornado from another. With the interest and support of Allen Pearson, then Director of the National Severe Storms Forecast Center, the Fujita scale became the standard for estimating the intensity of tornadoes in the mid-1970s. Fujita originally envisioned this scale as a way to connect the Beaufort wind scale with the Mach speed scale (where Mach 1.0 is the speed of sound).

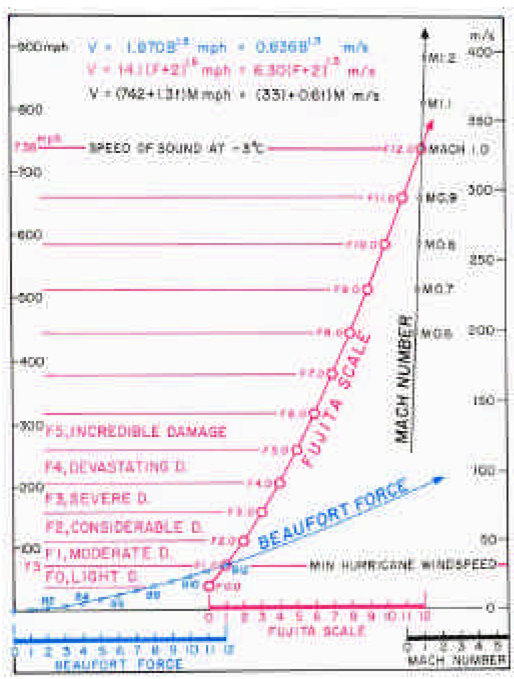

Figure 1. Illustration of the relationship of the Fujita scale as a connection between the Beaufort and Mach scales (Fujita 1987).

Dividing the difference between Beaufort force 12 (73 mph) and Mach 1.0 into 12 increments[1] (Fig. 1), the resulting scale for tornadic windspeeds became the now well-known Fujita scale:

[1] The reason for the choice of 12 increments has never been made clear. It might have been related to the fact that the Beaufort scale has 12 increments.

F-Scale	Windspeed (mph)	Damage description
F0	40-72	Some damage to chimneys and TV antennae; breaks twigs off trees, pushes over shallow-rooted trees
F1	73-112	Peels surfaces off roofs; windows broken; light trailer houses pushed over or overturned; some trees uprooted or snapped; moving automobiles pushed off road
F2	113-157	Roofs torn off frame houses leaving strong upright walls; weak buildings in rural areas demolished; trailer houses destroyed; large trees snapped or uprooted; railroad boxcars pushed over; light object missiles generated; cars blown off highway
F3	158-206	Roofs and some walls torn off frame houses; some rural building completely demolished; trains overturned; steel-framed hangar-warehouse type structures torn; cars lifted off the ground; most trees in a forest uprooted, snapped, or leveled
F4	207-260	Whole frame houses leveled, leaving piles of debris; steel structures badly damaged; trees debarked by small flying debris; cars and trains thrown some distance or rolled considerable distances; large missiles generated
F5	261-318	Whole frame houses tossed off foundations; steel-reinforced concrete structures badly damaged; automobile-sized missiles generated; incredible phenomena can occur

Table 1. The Fujita scale of windspeeds, as originally formulated (Fujita 1971).

Fujita added the F0 category to include the possibility of a tornado with marginally weak winds, perhaps even below the threshold normally considered to be “severe” by the NWS (50 kt or 58 mph).

Fujita (1971) specifically defined his “wind” as being measured as the “fastest 1/4 mile” whereas standard “surface” winds are defined as the “fastest mile” – at 60 mph, this corresponds to a 1 min average. At 200 mph, the fastest 1/4 mile windspeed corresponds to a 4 s average value. Although the *height* of the measurement is not specifically mentioned, Fujita’s intent with the F-scale was to be compatible to what an anemometer would measure (if it could withstand the winds!), so presumably the height above the surface is that of a *standard* anemometer (10 m).

Along with this windspeed scale, Fujita included a description of the damage associated with each category – those in Table 1 are taken from the original reference (Fujita 1971). In addition, Fujita used a set of damage photographs (Fig. 2) to illustrate the intensity categories. With the introduction of these materials, it became possible for someone surveying the damage from a tornado to estimate the F-scale (implying an estimate of the range of windspeeds). Further, using newspaper accounts and photographs, it became possible to assign an F-scale to historical events, a project which was undertaken by the National Severe Storms Forecast Center (NSSFC), with the support of the Nuclear Regulatory Agency in 1976. Students were hired to do the necessary research into old newspapers and other accounts of storms. They assigned an F-scale rating to as many historical events as possible based mostly on newspaper accounts and photographs.

Figure 2. Photographs of damage associated with F-scale categories taken from the Lubbock tornado of 11 May 1970 (Fujita 1971); no picture was originally provided for F0 damage.

In 1973, the official authority for doing *Storm Data* passed from the state climatologists to the NWS offices. From the late 1970s to the present, it has been expected that *all* tornadoes that become part of the *Storm Data* record will have an F-scale number assigned to them, as well as estimates of the path length and width.

In actual practice, the rating of tornado intensity is necessarily done by assessing the *damage*, rather than by *windspeed* estimates, whatever the original intent of the F-scale might have been. Given that tornadic windspeeds cannot be measured routinely, the only way to estimate tornado intensity for most reported events is to infer the windspeed from the damage. However, as discussed below, the relationship between windspeed and damage is not a simple one. With the involvement of structural engineers, it has become possible to use their knowledge of structural integrity and how structures react to the stress imposed by windstorms (e.g., tornadoes) to validate the damage-windspeed relationship assumed by the Fujita scale. Since Fujita's windspeed-damage relationship is essentially uncalibrated, engineers have questioned the windspeeds associated with the F-scale categories (e.g., Minor et al. 1977, Phan and Simiu 2002).

Moreover, the actual application of the Fujita scale has been complicated by the frequent absence of "standard" structures by which the intensity could be estimated. When a tornado passes through open country (or through vegetation for which no reliable standards exist) during some or all of its path, there is no obvious way to apply the standards developed by Fujita's work for those segments of the path. Therefore, it becomes challenging to know what the windspeeds were. Further, the F-scale estimate applies to the entire event, whereas the rating is based on what might only be a single point of the worst damage. Of course, Fujita recognized that a tornado damage path can be complex in terms of the variation in damage along it (Fig. 3)

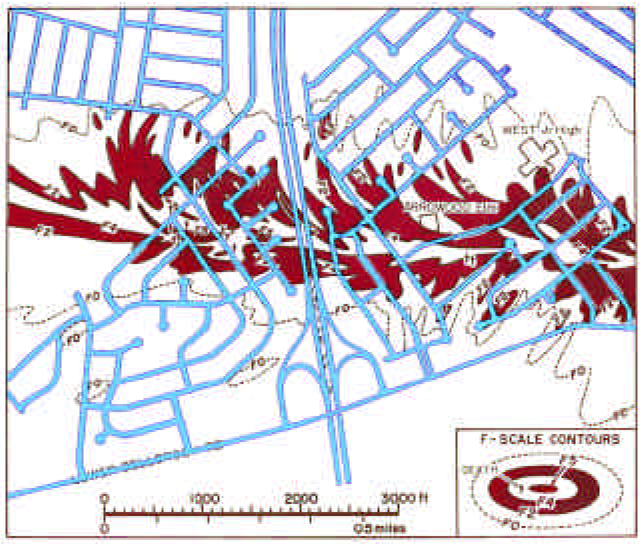

Figure 3. Sample of F-scale mapping in Xenia, OH, along a tornado damage path on 3 April 1974, showing complex debris patterns (after Fujita 1992).

The most intense damage usually is only a small portion of the whole damage swath. For example, Speheger et al. (2002) found that the F5 damage area in the major tornado that hit the metropolitan area of Oklahoma City, Oklahoma, was only 1.7% of the total damage path area.

Even as this is being written, the Fujita scale is under review by meteorologists and engineers, and its implied relationship between damage and windspeed is the object of considerable scrutiny. Alternative rating criteria are being reviewed and it is likely that in the future, a new scheme will be developed to replace the existing one. Whatever that scheme turns out to be, the same challenges discussed in what follows will be present for those doing storm damage surveys to assess the type of storm and its intensity after the event.

B. Damage and intensity (windspeed)

1. A nonlinear relationship

Clearly, damage and windspeed must be related. For each individual *structural element*,[2] there is a "threshold" windspeed that will cause that element to fail. Actually, the failure of a particular structural element is not at a fixed windspeed, for a host of reasons: for example, each structural element is not exactly identical in all its details to every other similar structural element. Therefore the probability of failure for a class of similar structural elements might look something like Fig. 4:

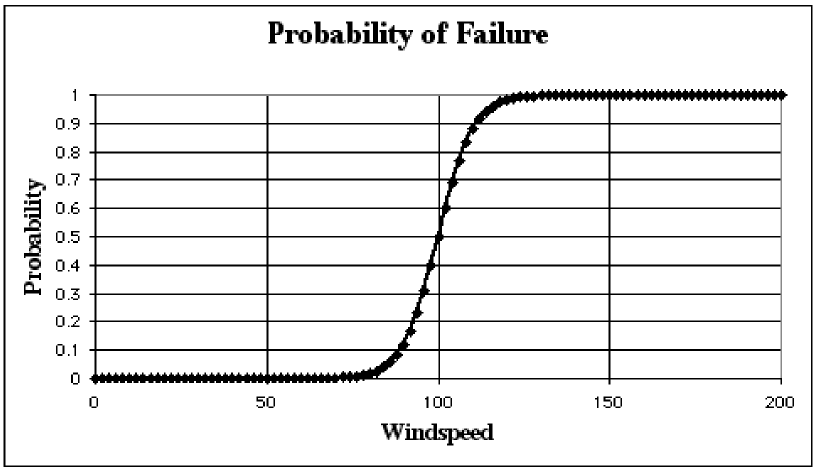

Figure 4. Schematic illustration of the probability of failure of a type of structural element as the windspeed increases.

For this simple example, there is a *range* of windspeeds from about 85 mph to 115 mph over which the failure point can range, such that the likelihood of failure below 85 mph is essentially negligible, whereas above 115 mph, failure is virtually certain.

Since it is unlikely we would ever know the details of this for every structural element in a damage zone, we can not know at precisely what windspeed a given failure occurred. In effect, for a given structural failure, there is a *range* of windspeeds associated with the damage that might look something like Fig. 5. The Fujita scale also gives a range of values for a particular item of observed damage, but it has "hard" boundaries. For example, according to Table 1, a 157 mph windspeed produces F2-type damage, whereas a 158 mph windspeed produces F3-type damage. This is, of course, not a plausible way to interpret damage. The challenge is that a given damage observation might well be produced by a range of windspeeds that could encompass two or more F-scale categories.

As if this isn't enough of a problem, consider that a tornado's windspeeds are constantly fluctuating in time and in space. Idealized models of a tornado envision a

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[2] A structural element is defined to be either a connection between one part of a structure and another, or an individual component part of that structure.

windspeed distribution like Fig. 6, relative to the tornado's axis of rotation, but reality surely is far more complex.

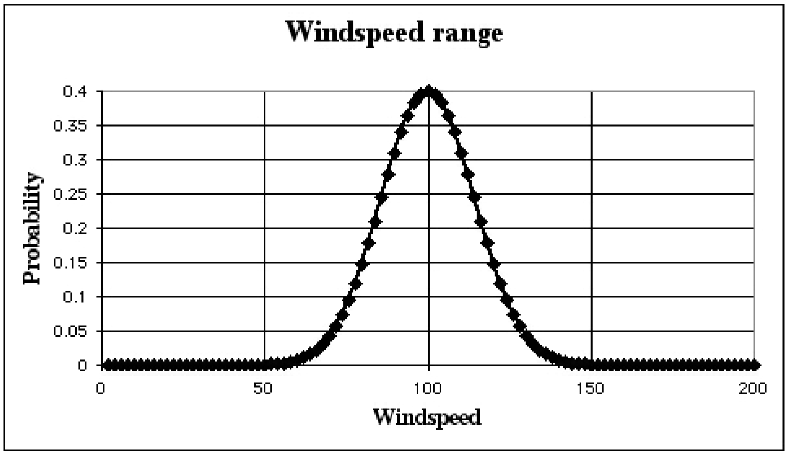

Figure 5. Schematic illustration of the probability that a particular damage event was produced by wind of a given value – the total area under the curve has a probability of 1.0. This distribution is symmetric about the most probable value and has only one peak probability, but in *real* examples, the distribution might not be so simple.

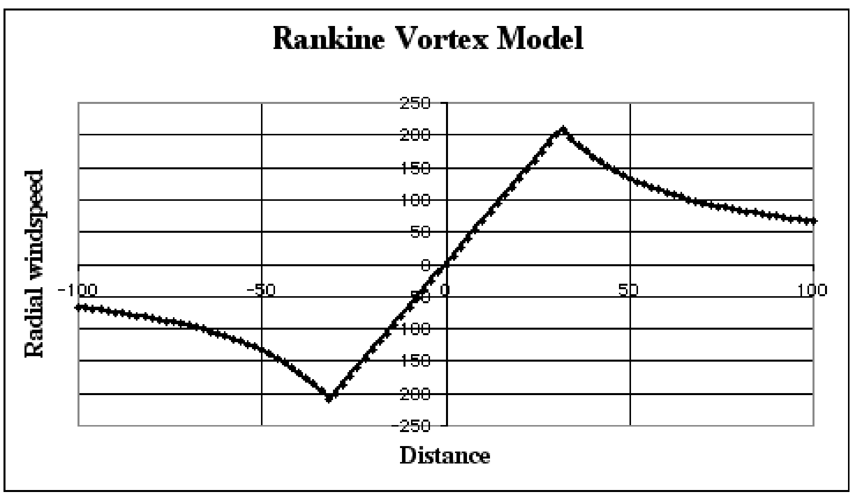

Figure 6. Radial wind profile in an idealized Rankine Combined Vortex Model, having a *radius of maximum winds* at a distance of about 30 units from the axis. Speed and distance units are arbitrary.

We already know that a tornado's speed of motion makes the windspeeds asymmetric about the axis, adding to the wind on the right side of the path of a cyclonic vortex (in the Northern Hemisphere) and subtracting from the wind on the left side. Moreover, there are almost sure to be many complexities beyond this, including the presence of multiple vortices. In any given tornado, it is likely that windspeed generally decreases with distance from the radius of maximum winds, but apart from that general statement, the true wind speed structure at any given instant is likely to be rather far from simple, idealized models. Add to this that the spatial structure of the windfield will change rapidly with *time*, and the overall picture of a tornado's windfield can be exceedingly complicated. This can be understood simply by watching tornado video and film footage, but since air is transparent, even such video cannot show all that is going on.

It also is known that the windspeed varies with *height*. In principle, the windspeed goes to zero right down at the surface, but even a few inches above the surface, it surely is not zero. Friction in the surface boundary layer generally acts to reduce windspeeds (see §I.B.5.c), and therefore the maximum windspeeds anywhere in a tornado are at some height above the surface (of order tens of meters), but the height of maximum winds is certainly not likely to be fixed in space and time – no doubt there are *multiple* maxima in the tornadic wind field from moment to moment. Depending on the "roughness" of the surface, the windspeeds (in the layer where structures and vegetation are found) will depend to some extent on the nature and distribution of structures and vegetation encountered along the path. The windspeeds within the surface boundary layer of a tornado passing over a grassy field are likely to be greater than those of one passing through tall trees and buildings. The energy of the wind in the latter situation will be reduced by the added friction and by the energy lost in causing damage to those structures and vegetation.

Figure. 7. Example of a strange effect caused by the Union City, OK, tornado of 24 May 1973. It is difficult to imagine how the wind accomplished this feat (Photograph © courtesy of C. Doswell, used by permission).

Near the surface, not only are the horizontal winds strong and highly variable in space and time, but so are the *vertical* winds. One of the reasons that the horizontal windspeed increases with height above the surface is that the pressure deficit associated with the vortex is largest somewhere *above* the surface. This intense decrease of pressure with height drives a powerful acceleration of the vertical wind, as well. This acceleration can exceed one full gravity [$g = 9.8$ m s^{-2}], which is sufficient to propel objects upward into the strong rotating winds aloft, and is accompanied by a powerful inflow very near the surface. That inflow may or may not be roughly symmetric – apparently, in some tornadoes it can be concentrated within one or more narrow inflow bands that spiral into the tornado instead of flowing inward from all directions.

As complex winds interact with structures and vegetation, additional complexities will be induced into the wind field (flow around solid obstacles creates "turbulent eddies", and so on). The interaction between the winds and objects embedded in that wind flow is usually quite complicated, often leading to strange effects, such as shown in Fig. 7. Nevertheless, neither the wind nor the associated damage is entirely random. Therefore, a proper description of the windfield along a tornado's damage path in a populated area is not that it is "chaotic" but that it may be challenging at times to infer the windspeed from the observed effects.

2. Variable resistance issues

In addition to variations in damage caused by variations in the windspeed, it is clear that the *resistance* of structures and vegetation to failure caused by winds also varies. In fact, as described in §I.B.1, the resistance can be thought of in terms of a probability distribution – any particular example is *most likely* to fail at the peak of that distribution, but that does not preclude the possibility of failure at a higher or lower windspeed than the peak of the distribution. If *all* the homes in a certain area were built according to the same standards, variations in damage will typically be observed from one home to another, even though they were all built in some standard way. Not all of this observed variability can be attributed to fluctuations in the wind. It usually is the case that individual homes, even in the same neighborhood, are built differently, introducing additional variations in resistance to the wind. Building codes, when in force, only provide *minimum* community standards. In general, homes built by different builders will have their own underlying probability distributions in terms of resistance.

Furthermore, methods of frame home construction differ from one geographic region to another, partly because of variations in the building codes and partly because methods of construction are just not uniform, owing to such things as regional soil types, climatic variations, cultural preferences, and so on. Different regional construction practices can be thought of as altering the underlying probability distributions. This also is a source of variability in resistance. Even the orientation of objects to the damaging winds can influence their resistance. The Fujita scale assumes (but does not *define*) a "well-constructed frame home" as the standard for judging the windspeeds needed to produce the observed damage. Anything that reduces the resistance of the home to wind-induced damage below that standard can reduce the F-scale rating.

A critical notion in the understanding of frame home construction is that of the *load path*. This is an engineering term for the path by which the weight of the building is transferred downward to the ground. A schematic illustration of the load path is shown in Fig. 8. The design of such a structure is intended primarily to deal with the loads imposed by the weight of the building. As we will see in the next section, the stresses imposed by interaction with a tornado (or other strong winds) are very different from this, and the method of construction has a large impact on the ability of the structure to resist tornadic winds.

There are many different types of structures with which a tornado might interact during its life. Although building codes exist in most metropolitan areas of the United States, they are primarily in force *only* in metropolitan areas – rural homes may or may not be built to some code. Building codes can vary from one community to the next, so knowledge of any relevant building codes is important in assessing storm damage. As

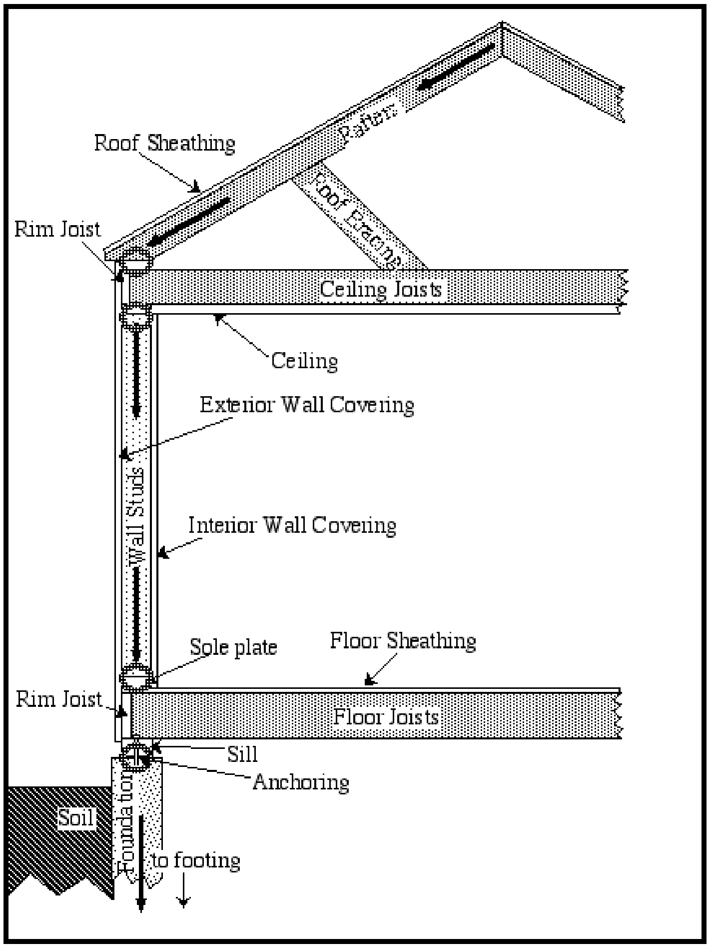

Figure 8. Schematic illustration of the load path for a single-story, wood-frame home, with arrows showing the transfer of the gravity load from the roof to the ground. Circles indicate locations for securing attachments (see BPAT [1999] for details).

noted earlier, building codes specify *minimum* standards. When meeting codes is the goal, actual construction practices can fall short of the codes.[3] It also may be the case that one part of a code conflicts with another. For example, one part of a building code might require meeting some general engineering standard (i.e., able to resist a specified

[3] It can be argued that a proper strategy to ensure that construction *meets* codes is to set a goal that will *exceed* the code requirements.

windspeed value), whereas another part of the same code could mandate a particular construction practice that would make it impossible to meet the previous standard. Of course, code enforcement can also be a problem.

Most of the codes have a windspeed threshold specified, and it is expected that a structure built to that code would have essentially no structural damage if the windspeeds don't exceed that threshold. This does not exclude other forms of damage: windows broken, projectile impacts, loss of non-structural elements, etc. Major structural damage can occur when trees or other large objects fall on the structure, but this would not imply that the threshold windspeed was exceeded.

Code violations can and do occur, as shown in numerous post-event surveys. Generally, communities have periodic code inspections during the process of home construction, but given limited personnel and resources, code enforcement can be variably rigorous. Exceptions and waivers to building code criteria are granted in some instances, at the request of builders, and these exceptions can result in reduced resistance to tornadic wind damage.

3. How structural damage occurs

In what follows, some considerable discussion of the processes by which damage to structures occurs is provided to facilitate recognition of structural failures during field surveys. The debris from a tornado might first seem to be chaotic, but it is possible to recognize key features in the damage that will reveal how the damage occurred, and this can give considerable insight about the range of windspeeds needed to create that damage.

a. Wind loading

First and foremost, it is important to remember that a tornado is a *wind* storm. What makes a tornado unique among windstorms is the intense *gradients* of wind speed and direction that can be found in most tornadoes. Clearly, a tornado is wind in strong rotation, but when objects are much smaller than the tornado, that airflow's rotation is not generally apparent. The rotation and movement of the storm mean that structures and vegetation in the path will typically experience variations in both wind speed and direction. These variations are important components in understanding what will be encountered during a survey.

Construction of structures also varies, and the strength of a structure typically depends on which direction and in what order the forces on it are operating. In ordinary situations, the weight of a structure is the dominant load on that structure. When the wind does not exceed the code-mandated threshold windspeeds, the structure should be able to resist those ordinary winds without structural failure. But when a tornado interacts with structures, the loads are very far from ordinary, and structural failures can begin. For *weak* structures, this might be at windspeeds as low as those associated with F1 on the Fujita scale. As structural integrity increases, it takes increasing windspeeds to initiate structural damage.

i. Lift forces

A major contributor to damage in tornadoes is the strong vertical acceleration of the upward motion near the surface, driven by the pressure field of the tornado itself. This is the "suction" associated with the tornado and its effect is to oppose the ordinary gravity loading of structures. That is, it acts to lift objects and structural elements into the air. Although most construction is designed to resist the ordinary effects of the downward gravity load, its design can be substantially less effective in resisting *lift* forces. For example, when wall studs are " straight nailed" (see Fig. A2.5 in Appendix 2) to the sole plate at the bottom of a wall frame (see Fig. 7), the connection does not resist an *upward* force very well; the wall studs are relatively easily pulled off the nails and the wall section is no longer attached to the structure.

Attachments all along the load path shown in Fig. 8 are potential weak points in the structure, and unless the structural integrity has been enhanced to increase its resistance to lift forces (see Figs A2.6-A2.8), these attachments are common failure initiation points. Unfortunately, it only takes one weak point along the load path to initiate structural failure. Generally, the wind seeks the weakest link in the chain. A wall that is not adequately attached to the foundation will allow the structure to slide off the foundation, no matter how strong the rest of the load path attachments are. A poor attachment of the roof allows the roof to "sail" off in the wind, and roofs are actually important in the structural integrity of the walls. When the roof is gone, the walls

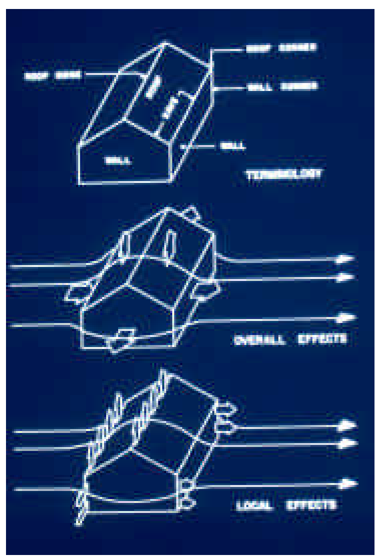

Figure 9. Schematic illustration of airflow interacting with a structure, showing the resulting pressure effects. The "local" effects arise because the increased airflow at corners due to the Bernoulli effect.

become "freestanding" and are more easily blown over than when the roof remains in place. Generally, any initial structural failures tend to spread under the forces imposed by tornadic winds.

ii. Horizontal forces

In addition to the lift forces associated with the pressure distribution of the tornado itself, the horizontal wind creates *dynamic* wind pressure forces. Consider Fig. 9: the flow of air over a building can create a dynamic pressure deficit wherever the horizontal wind is being accelerated and a pressure excess wherever the wind is decelerated. The pressure deficit associated with the acceleration of the wind in sometimes referred to as the *Bernoulli effect*. As the figure shows, the result is an upward pressure as the air accelerates over a roof. The *horizontal* airflow interacting with the structure can act to increase the lift forces being exerted on the roof by the tornado's pressure field.

As has been shown, as the wind interacts with a structure, the horizontal wind is forced to decelerate when approaching a wall. This results in a pressure excess that is the way the wall "feels" the effect of the wind. The faster the wind when it begins to interact with the wall, the stronger the resulting pressure excess. Generally speaking, the pressure excess increases as the *square* of the windspeed prior to impinging on the wall. Double the windspeed and the pressure goes up by a factor of four, not two. This nonlinear relationship is one of the reasons most people overestimate windspeeds. Their experience with windspeeds exceeding 60 mph is so infrequent, they just don't recognize how rapidly the wind-induced pressure force goes up as the wind increases. They "feel" the increased pressure and so overestimate the wind producing what they experience.

Structural attachment points are subject to failure during the extraordinary winds produced by tornadoes. A nailed attachment is more resistant to shearing forces (perpendicular to the nail) than it is to forces acting to pull it up. A wall that has been attached to the foundation with powder-driven cut nails (see Fig. A2.4) is much less resistant to those side loads than one where the wall is bolted to the foundation with nuts.[4] Wind-induced side loads act to "rotate" the wall inward, which creates forces that will pull out the nails, as well as shearing forces. Such nail attachments can create a "dimple" in the foundation when the nail is driven in, so the attachment is virtually nonexistent at that point. Weak attachments of the walls to the foundation allow the house simply to slide off the foundation when experiencing only moderately strong winds. Once the structure has moved off the foundation, it can collapse under its own weight – wind stresses will aid in its subsequent disintegration.

When the roof is removed, its loss promotes the failure of the walls, which are much more prone simply to rotate off the foundation in response to wind pressure, and collapse comes when the attachments pull out. As noted, the tilting of the wall means at least *some* of the force on the attachment is in the opposite direction as the gravity load – recall that pull-out is relatively easier than shearing the nail (or bolt). Sometimes, this can result in the failure of the sill plate itself, while the bolts (or nails) remain in place. The quality of the lumber used for framing can be an issue in some instances. Loss of the roof can be a major factor in wall failure during side loads induced by the wind.

[4] A survey team should be alert to the fairly common situation where the nuts have not been put on the bolts, and the sill plate is simply resting on the bolts. Without the nuts, the attachment of the wall to the foundation has virtually no resistance to lift forces.

b. Projectile impacts and the envelope and pressurization

Studies of tornado damage by structural engineers reveal that an important part of structural integrity is the integrity of the "envelope" of the structure. That is, the walls and roof create an "envelope" around the interior space that acts to deflect the winds around the structure, rather than into it. Of course, most homes have built-in weak points to their envelope: doors and windows. Glass windows can be broken readily, and doors may be poorly attached and unable to resist wind-induced side loads as well as the walls can. Adding to this potential loss of envelope integrity is the presence of projectiles (sometimes referred to as "missiles") in the debris generated by the tornado. Even in a relatively weak tornado, the air can be filled with objects that are sufficient to break windows: stones, sticks of wood, yard furniture, etc. A 2 x 4 framing stud moving at just 45 m s^{-1} (100 mph) has sufficient force to penetrate ordinary frame walls with standard interior and exterior sheathing materials quite easily.

Once flying debris punctures the envelope, wind can enter the structure and "pressurize" interior spaces. In effect, loss of external envelope integrity on the windward walls allows the home to "blow up" like a balloon. This augments any upward lift forces on the ceilings and roof, and creates outward side loads on all the interior walls. Recall that the wind is accelerated on those walls to the side of a windward wall, leading to pressure deficits on their exteriors. If the windward wall is breached and the interior is pressurized as a result, the outward side loads become large enough to "explode" the remaining structure (Fig. 10). This is the origin of the myth that the pressure field of the tornado causes structures to "explode". In reality, this apparent explosion is the result of dynamic pressure induced by the wind of the tornado, not the tornado's pressure deficit. Buildings can indeed "explode" but this result is only indirectly coupled to the tornado's pressure field: that pressure field drives the winds, which in turn, create the dynamic pressure effect producing outward forces on structures. Opening windows to "relieve" the pressure effect due to the tornado just increases the likelihood of interior pressurization!

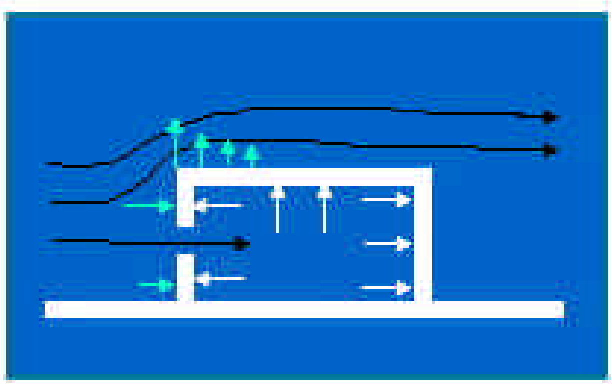

Figure 10. Schematic illustration of "pressurization" as impinging wind (black) enters through a puncture of a building's envelope, and the resulting pressure forces from both interior pressurization (white) and exterior airflow (turquoise).

c. Failure points and damage propagation

In a moving tornado, a fixed object can experience a rapidly fluctuating wind field, not just in speed but in direction. This changing wind field can act to "seek out" weak points in a structure. Structural integrity can have a strong directional dependence. For example, it has been found that garage doors are common weak points. When the windspeeds increase as a tornado approaches, garage doors facing the wind from an approaching tornado may be among the first failures. Failure of the garage door pressurizes the garage and since many garages are attached to their houses, the "explosion" of the garage can initiate failure of components like the roof of the home, compromising the structural integrity of the house itself. The initial failure of the garage door can cause the whole structure including the home to "unzip" and induce major structural damage.

The variability of the wind, combined with variations in the strength of a structure can combine to cause failure of the structure at any time during its interaction with the tornado. The final position and appearance of the debris remaining depends on when during the interaction the failure began. The complexity of this interaction can easily explain much of apparent capriciousness of tornado damage (Fig. 10). The particular sequence of wind speed and direction experienced by a particular structure can result in its destruction whereas nearby apparently similar structures are untouched (or vice-versa).

Figure 11. Path of a tornado in Xenia, OH, on 20 September 2000, showing near total destruction of one home (lower left) even as nearby homes have suffered virtually no structural damage. This is unlikely to be the result of extreme winds but is more likely to be a structural failure associated with that particular home, and is complicated by the damage to the home across the street, which surely produced many projectiles. (Photograph courtesy of J.H. Golden, used by permission).

It has been noted already that damage is the result of the interaction of a complex wind field in space and time with the characteristics of the objects experiencing that wind.

It is also important to keep in mind that the debris created by a tornado is also interacting with objects. When a tornado comes into a community from surrounding open country, it carries with it less debris than had it been in another community just before arriving. The character of that debris depends on the windspeed, of course, as well as the nature of the objects the tornado has just encountered. Further complicating the issue is that a tornado coming in from open country has been experiencing relatively small friction in its boundary layer. Structures and large vegetation (trees) can reduce the near-surface winds by friction. Therefore, a relatively weak tornado entering a community from open country might do its worst damage *early* in its track through the community and then seem to weaken. However, a relatively strong tornado would pick up a debris load as it interacted with structures such that damage could *increase* as it tracked farther into the community, even though the intensity of the tornado itself was *not* changing.

Failure points on a structure generally will propagate through the structure – the failure begins at a weak point and spreads from there. In an analogous way, weak structures can add to the debris load of a tornado and cause further damage as projectiles injected into the airflow hit other structures. Speheger et al. (2002) have suggested that this can cause "cones of damage" along the track (Fig. 12).[5]

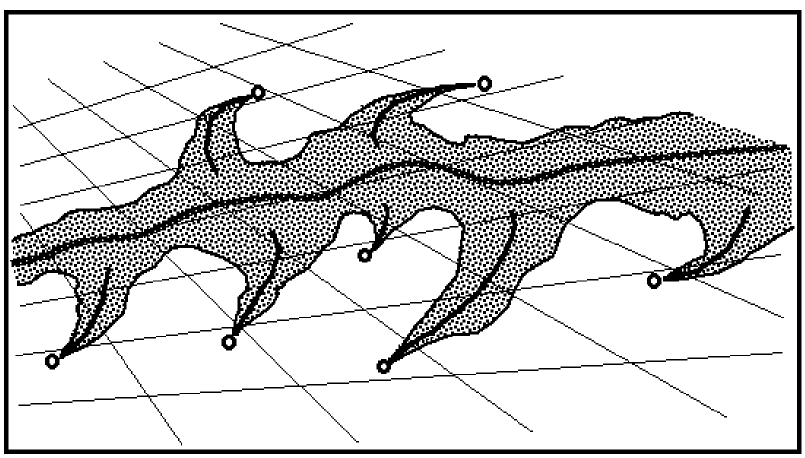

Figure 12. Schematic illustration how damage produced by the failure of a weak structure can create "damage cones" on the periphery of a tornado track (cf. Fig. 3) – from Speheger et al. (2002).

4. Duration of strong winds

The movement of the tornado is also a factor in the evolution of the wind field at some point in the path. A fast-moving, small diameter storm might interact with a given house for only a few seconds, whereas a slow-moving, large-diameter tornado would create an interaction of much longer duration. The effects of duration are not completely

[5] Similar patterns have been observed in hurricanes. In fact, many of the principles and practices described herein can be applied to hurricane damage surveys.

obvious. Some structural failures would be more likely if the interaction was rapid – if the forces on a structure increase rapidly, they might be more likely to create certain types of failures than if those same forces increased relatively slowly. On the other hand, the longer the damaging winds of a tornado have to work on potential failure points, the more likely a failure will become. More discussion of this follows later.

5. Windspeed variations

In order to be prepared to interpret the observations during a survey of storm damage, it is obvious that knowledge of how severe thunderstorms and tornadoes behave is essential. Most of this material is available in the references (see, e.g., Davies-Jones 1986; Lewellen 1993; Davies-Jones et al. 2001), but is reviewed briefly here for completeness.

a. Subvortices

Although an awareness of the possibility of multiple vortices has been present for a long time, it wasn't until Fujita connected this phenomenon to evidence at the surface that this awareness became a part of the scientific consensus understanding of tornadoes. Description of multiple vortex tornadoes by eyewitnesses and even photographs (Fig. 13)

Figure 13. Photograph of a tornado on 20 May 1957 near Ottawa, KS, clearly showing a multiple vortex structure (Photograph courtesy of Charles LeMaster, from Doswell and Ostby 1982).

have existed for some time, but research using a laboratory vortex simulator developed by Ward (1972) and a study by Fujita (1970) of the Lubbock, Texas tornado of 11 May 1970 made it clear that surface damage from tornadoes exhibiting a multiple vortex structure would be markedly different from those with a single vortex. Since then, the spread of inexpensive consumer film and video cameras has meant that *numerous* multiple vortex tornadoes have been documented.

The existence of multiple vortices means that the windspeed distribution in such a tornado departs considerably from the simple picture (Fig. 5) of a single vortex tornado. A snapshot of this can be illustrated by the detailed images captured from a mobile Doppler radar (Fig. 14).

The winds at the surface will involve the combination of four different contributions:

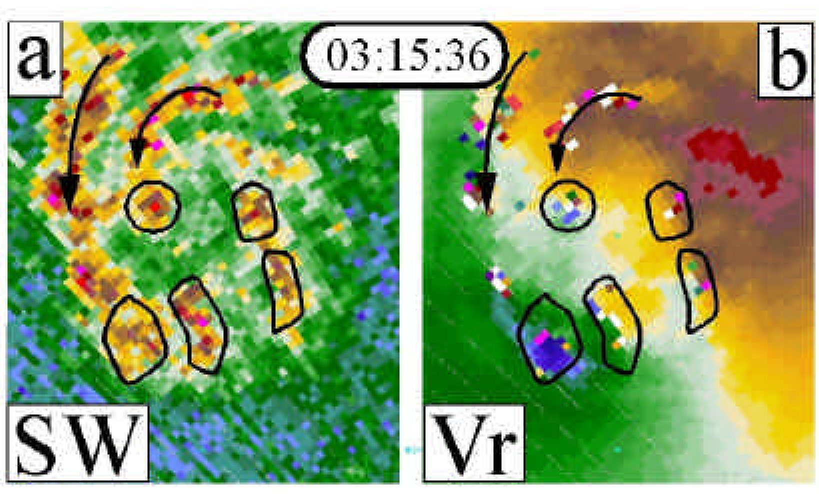

Figure 14. High resolution images from a mobile Doppler radar of the spectrum width (a – SW) and radial velocity (b – Vr) fields showing multiple vortices on 3 May 1999. The tornado is approximately 600 m in diameter (see the discussion in Wurman 2002) and the subvortices are rotating around the core at 50 m s^{-1}. (Image courtesy of Josh Wurman, University of Oklahoma).

1. Movement of the tornado as a whole, $\mathbf{C}_o$
2. Winds of the parent vortex, $\mathbf{V}_o$
3. Movement of the subvortex around the parent vortex, $\mathbf{C}_s$
4. Winds of the subvortex, $\mathbf{V}_s$

The complexity of this will be manifested in complex damage patterns. The most obvious of these are the debris streaks that are occasionally evident from aerial photographs (e.g., Fig. 15). Fujita showed that these marks are the result of the subvortices rotating about their common center, combined with the movement of the whole tornado (Fig. 16). These subvortices are relatively transient and almost never make a complete revolution around the tornado. Rather, they tend to form and dissipate in preferred locations relative to the moving parent vortex. This results in their leaving ground marks (typically, lines of accumulated debris) in the form of segments of a *cycloidal* curve. Each such streak marks the path of one subvortex. The existence of these also helps to explain many of the complexities of damage within populated areas – those locations in the path of a subvortex are subjected to stronger winds than in nearby locations that were not in the path of that subvortex.

Theory of such vortices indicates they develop in a region of strong radial shear, near (but not at) the radius of maximum winds in the main vortex (see e.g., Snow 1978; Gall 1985; Nolan and Farrell 1999). The cycloidal marks they produce can be related to their rotational velocity about the main vortex ($\mathbf{C}_s$, which does not necessarily equal $\mathbf{V}_o$, but these two velocities are not likely to very different), the radius of that rotation, and the speed of movement of the main vortex ($\mathbf{C}_o$), which probably is not too different from that of the storm producing the tornado. Unfortunately, the geometry of the marks can't be used to estimate the rotational speed within each subvortex, $\mathbf{V}_s$. The additional tangential windspeed of a subvortex could be on the order of 25-50 m s^{-1}, but there is no way to estimate this from the cycloidal marks.

Figure 15. Example of cycloidal debris marks associated with a multiple-vortex tornado (Fujita 1992).

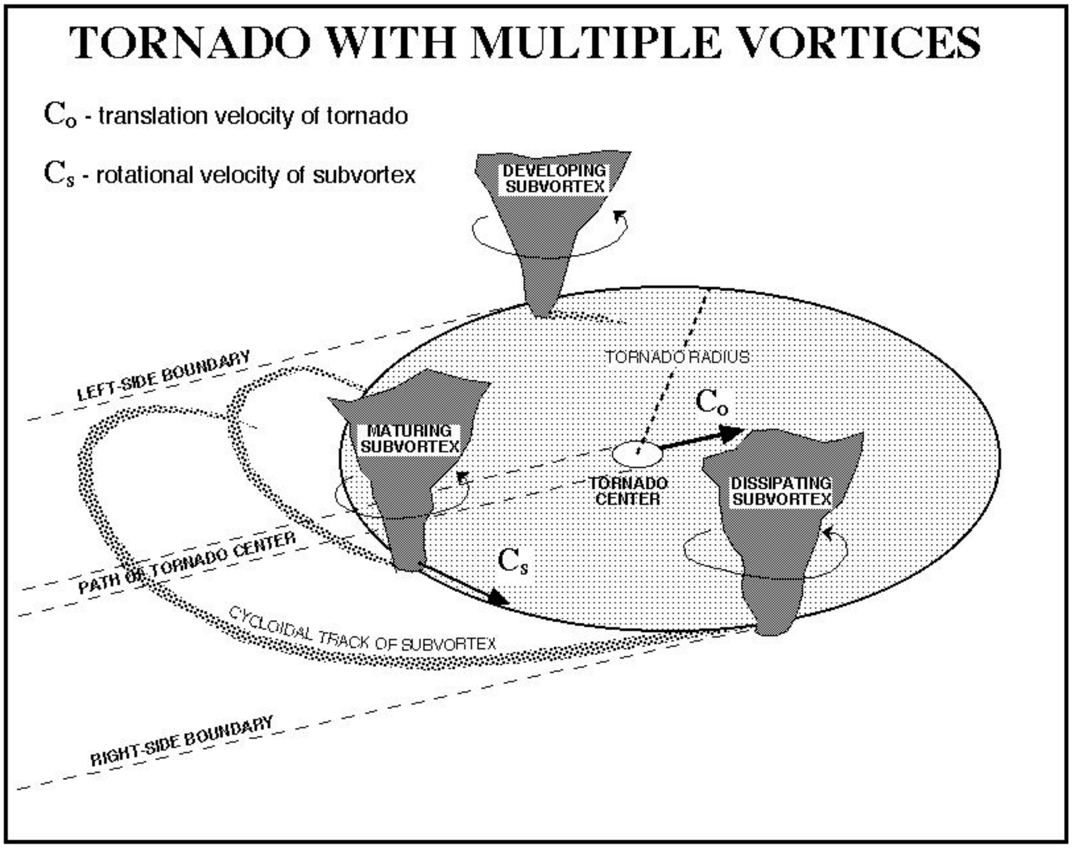

Figure 16. Schematic model of a tornado with multiple subvortices (adapted from Fujita 1971).

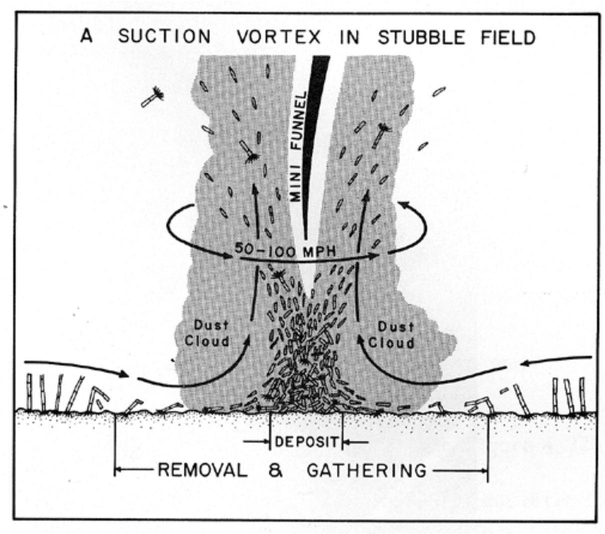

Figure 17. Schematic illustration of how debris would be deposited along the path of a subvortex (from Fujita 1978b), giving rise to the notion of a "suction" vortex.

Although debris tracks have been associated with individual subvortices of a parent tornado, a single vortex tornado can also produce them (Davies-Jones et al. 1978; Speheger et al. 2002). A single vortex tornado often produces a debris deposition trail, rather than cycloidal "swirl" marks. The deposition results from the radial inflow in the near-surface flow of a subvortex, as suggested in Fig. 17.

b. Satellite vortices

Figure 18. A satellite vortex (left) on the periphery of the large main tornado (center) near Chickasha, OK, on 3 May 1999 (Photograph © courtesy of N. Rasmussen, used by permission).

Multiple vortices are well known by now, but "satellite" vortices are relatively newly documented. It appears that within mesocyclone-associated tornadic storms, it is quite possible to have what are called "satellite" vortices (e.g., Fig. 18). The existence of these has been suspected from the damage revealed occasionally in detailed damage surveys, but had not been documented until recently. Like multiple vortex tornadoes, the spread of inexpensive consumer video cameras and storm chasing has given us indisputable evidence of their existence. Satellite vortices may be more common that suspected – at times, the vortex might not have such an obvious funnel cloud as shown in Fig. 18. That is, there can be a damage swath from a satellite vortex *without* a visible funnel cloud.

As with multiple vortex tornadoes, any survey team should be alert to the possibility of these satellite vortices. They are associated with the mesocyclonic circulation producing the main tornado and typically rotate around such tornadoes. These satellite vortices are distinct from the series of tornadoes that can be produced by a cyclic supercell storm, described below.

c. Boundary layer effects

Although friction inevitably reduces windspeeds, changes in the surface roughness can have unexpected consequences on a tornado. Above the boundary layer, the winds in a tornado approach a state of "cyclostrophic balance" where the inertial force (sometimes referred to as "centrifugal" force) is in approximate balance with the pressure gradient force. Cyclostrophic flow implies a small radial component, so the flow is nearly circular. In the boundary layer, however, friction acts to reduce the tangential windspeed. This reduction in windspeed causes the air to spiral inward because the inward-directed pressure gradient force is not affected by friction. But conservation of angular momentum means that this inward spiraling air must also increase its tangential velocity. The effect of friction, then, is to decrease the radius of maximum winds and to increase the inward-directed (radial) component of the wind. Hence, near the surface, the flow is dominated by intense convergence. A tornado traveling over a smooth surface that moves into a rough surface will have its force balance interrupted and the vortex near the surface should decrease its radius. There can be a transient increase in the peak windspeed after encountering rougher surfaces, resulting from an "overshoot" of the radial inflow (Fiedler 1993).

d. Tornado families

Research has made it clear that some supercells go through a cyclic evolution (Burgess et al. 1982; Dowell and Bluestein 2002; Adlerman and Droegemeier 2002), and the result can be a series of tornadoes. Fujita documented this in his classic study (Fujita 1960) of the Fargo, North Dakota, supercell storm (Fig. 19), among others, including Fujita et al. (1970) or van Tassell (1955).

Figure 19. Mapping of the tornado family in North Dakota on 20 June 1957 (from Fujita 1960).

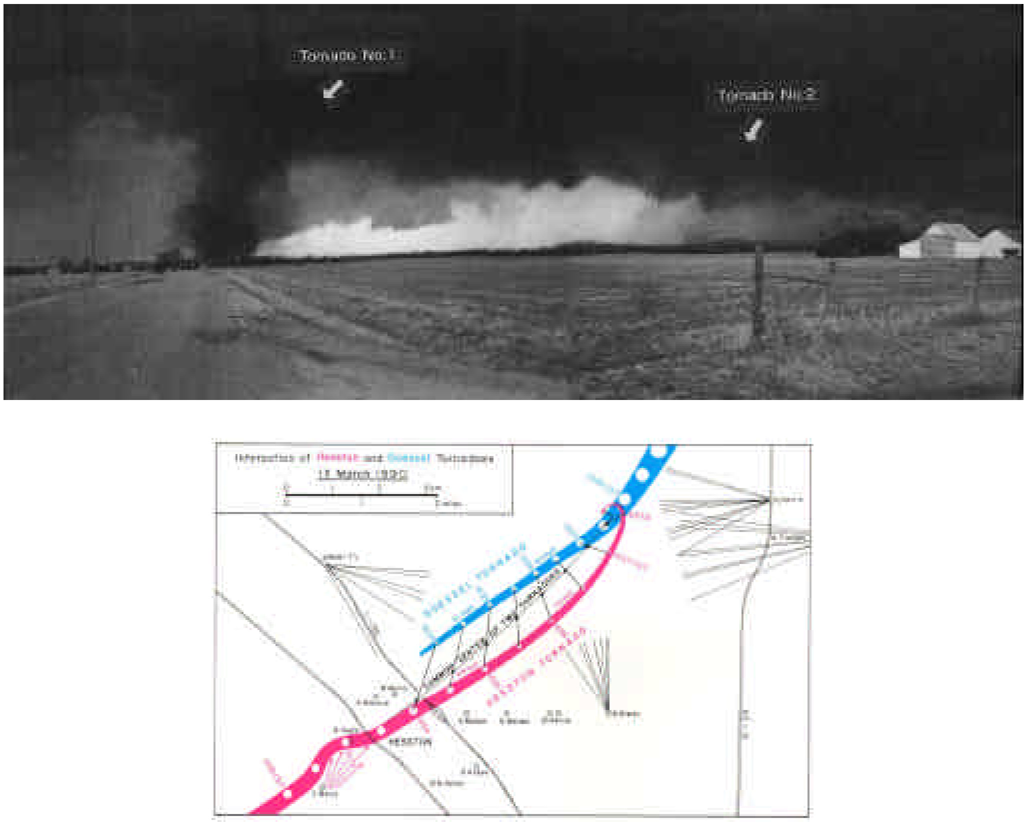

Figure 20. Example of the interaction of successive tornadoes on 13 March 1990. The final stage of the Hesston, KS tornado (top, left) became caught in the circulation of the rapidly-developing Goessel, KS tornado (top, right), eventually rotating around the latter and dissipating as it moved around the expanding Goessel vortex (bottom) [From Davies et al. 1994 (top) and Fujita 1992 (bottom)].

During major outbreaks of tornadoes, cyclic supercells producing tornado families are typical. Numerous examples can be cited. The intensity of the successive tornadoes within a family can vary widely, but it is during such outbreaks that violent tornadoes are most likely. Violent tornadoes during such outbreaks are usually members of a tornado family produced by a cyclic supercell storm. They are not always the *first* tornadoes produced within the family. In cyclic storms, it is not uncommon for new tornadoes in the series to be developing even before the dissipation of their predecessors. Thus, there can be more than one tornado in existence simultaneously, and their damage paths can overlap. A new tornado developing quickly can "absorb" its weakening predecessor, as illustrated by Fig. 20.

e. Downburst winds in supercells

Supercells that produce one or more tornadoes often produce strong *nontornadic* winds, as well. These are most commonly the result of *downbursts* within such a storm, but occasionally strong *inflow* winds can be damaging, as well. The inflow winds associated with the storm need to be distinguished from the inflow to a tornado – the latter is routinely capable of damage, whereas "parent storm" inflow winds produce damage only infrequently.

A simplified picture of the updrafts and downdrafts within a supercell storm is provided in Fig. 21: the most common location for downburst wind damage is with the

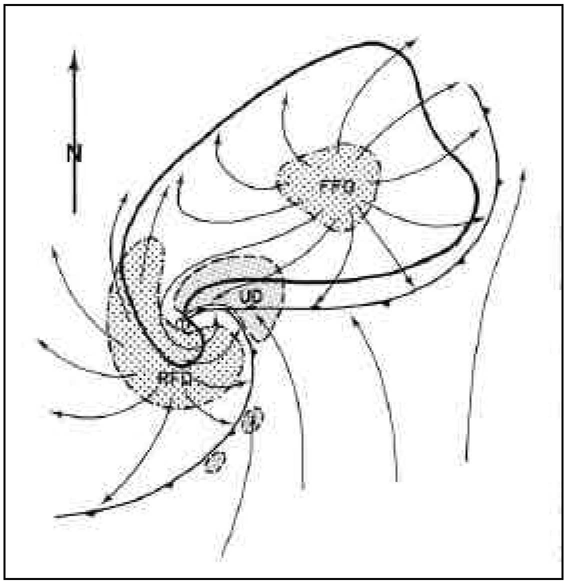

Figure 21. Basic airflow associated with a supercell storm (after Lemon and Doswell 1979), showing the forward and rear flank downdrafts, denoted "FFD" and "RFD" respectively. The updraft is indicated by fined stippling and labeled "UD" – the possible location of a tornado is indicated by the circled "T" symbol.

rear flank downdraft (RFD). It is notable that the RFD is closely connected in space to any mesocyclonic tornadoes. A "snapshot" image like Fig. 21 does not capture the time and space evolution of the storm; embedded within this structure can be a lot of complex variation. Neither updrafts nor downdrafts are likely to be constant for very long. Given this variability, it is important to be alert to the possibility that at least some of the damage along a tornado path can be the result of outflow associated with nearby downdrafts (i.e., downbursts) of varying scale.[6] In a real event, some of the damage from downbursts can be interspersed with tornado damage (as suggested by Fig. 22), adding considerably to the difficulty of attributing damage when doing a survey.

It should be clear from this example that it can be difficult to separate damage swaths from different events. This task of separation will be considered below.

[6] Technically, if the downburst size is < 4 km, it is a *microburst*, according to Fujita (1978a).

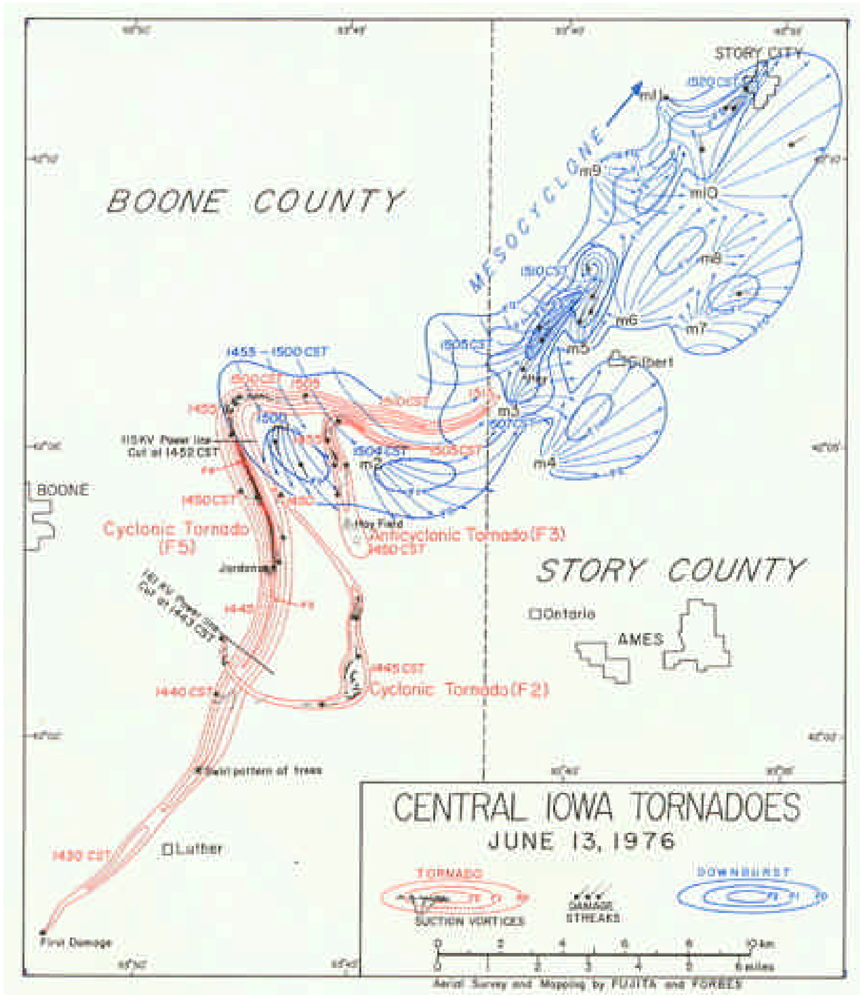

Figure 22. Survey of the 13 June 1976 tornadoes in Iowa by Fujita (1978a).

f. Size, appearance, and intensity relationships

It is true that size of the damage swath and tornado intensity are related, at least statistically. As width and, to a lesser extent, the length of the path increase, the most probable F-scale tends to increase as well (Fig. 23). Therefore, it would be logical to assume that tornado size is a way to gauge its intensity. This statistical relationship does not hold, unfortunately, for *specific* tornadoes. A statistical tendency does not equate to a general rule.

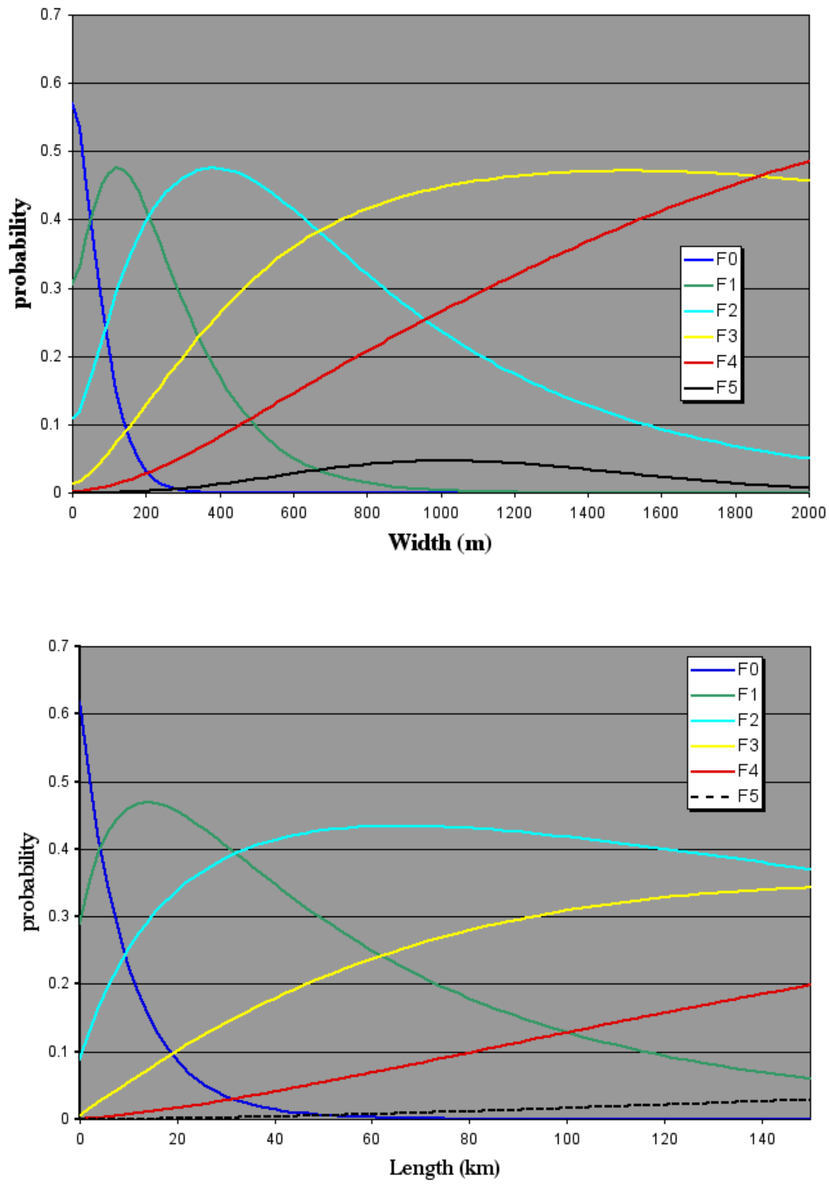

Figure 23. The probability of the F-scale rating, given (top) path width, and (b) path length (The figures were made from data provided by H. Brooks, NSSL).

Observe that as the path width increases, the most likely F-scale (the peaks in the probability distributions) shifts upward. For example, given a width of about 1600 m, around 45% of the tornadoes are violent (F4 – F5), whereas for widths of about 500 m, only 10% of the tornadoes are violent. At any given width or length, the sum of the probabilities must equal unity. It appears from these (and other) data that F5 events may be underrepresented in the historical record.

For any given tornado, the windfield is a complicated function of space and time, as already discussed. Since the tornado results ultimately from a process of conservation of angular momentum (sometimes referred to as vortex stretching), the closer the radius of maximum winds to the axis of rotation, the faster the associated windspeeds will be, all other factors being equal. Therefore, narrow tornadoes *might* even be more intense than wide tornadoes – but not *necessarily*. In cases of multiple vortex tornadoes, the fastest windspeeds would be associated with the subvortices. The windspeeds associated with the "parent" vortex in which the subvortices are embedded might be relatively weak compared to those in the transient subvortices. But the existence of multiple vortices is also not a reliable indicator of the possibility of high intensity. The occurrence of multiple vortices depends on the so-called *swirl ratio*, which is the ratio of the tangential velocity to the vertical velocity. Generally speaking, as the swirl ratio increases, the likelihood of multiple vortices increases – that is, the existence of multiple vortices is airflow that is increasingly dominated by the tangential winds over the vertical winds. Note that even dust devils can have multiple vortices, so a multivortex tornado need not be particularly intense.

With the widespread use of inexpensive consumer video cameras and the growth of storm chasing, it is now likely that a video record will exist for at least some portion of the life of many tornadoes. Therefore, those doing a survey may have access to such video. Unfortunately, the *appearance* of a tornado is not a reliable indicator of its intensity. Even the apparent speed of rotation may not be reliable, unless a careful photogrammetric analysis of the video is done. The apparent speed of rotation is strongly dependent on the distance of the vortex to the viewer, and the radius of maximum wind would only be coincidentally equal to the funnel or debris cloud boundary. Debris is not necessarily moving with the wind, so debris motion can also be deceptive. Generally speaking, while it is tempting to look to the appearance of a tornado, including its size, as an indicator of the windspeed, the relationship between appearance and intensity is just not reliable.

g. Other vortices

Although it seems rather obvious how to identify a tornado, it sometimes is not so easy (see Doswell and Burgess 1993). The atmosphere produces a wide variety of vortices, and separating the tornadoes from other types of vortices can be challenging on some occasions. There are at least three vortices, however, that should be considered tornadoes. A tornado, according to the newly-revised *Glossary of Meteorology* (Glickman 2000) is:

> A violently rotating column of air, in contact with the ground, either pendant from a cumuliform cloud or underneath a cumuliform cloud, and often (but not always) visible as a funnel cloud.

The first potentially confusing phenomenon is the so-called *landspout*. This terminology is intended to convey the similarity between events on land to those that can occur over the ocean. Most waterspouts are not associated with supercell storms, and so tornadoes that form in the absence of a mesocyclone have been given the colloquial name of "landspout" – technically, these should be referred to as *nonmesocyclonic* tornadoes. For purposes of classification, however, *all* such events should be considered tornadoes.

Nonmesocyclonic tornadoes can occur in clusters, with several of them ongoing simultaneously.

The second troublesome event is the *waterspout*. Currently, waterspouts are not reported as tornadoes unless they come on shore. They meet the criteria associated with the preceding definition and so whatever rationale might be offered to justify this policy, a waterspout is a tornado. The *Glossary* states explicitly that this is the case.

The final problematic convective vortex is the so-called *cold-air funnel*. This phenomenon has not received a great deal of research attention, but it is clear that a properly identified event (associated with convective storms developing near the core of a cold-core synoptic-scale cyclone aloft) that develops potentially damaging winds at the surface is a tornado. Such tornadoes are associated with regions having relatively weak ambient vertical windshear. Tornadoes that occur in the vicinity of a cold-core cyclone in regions of *strong* ambient vertical windshear are simply supercell-associated (perhaps with relatively low storm tops) tornadoes.

A different sort of commonly-encountered event is the so-called *gustnado*. This type of vortex, which is not interpreted as being a true tornado, occurs along gust fronts, as in Fig. 24.

Figure 24. Example of a gustnado on 23 May 1982, made visible by dust from plowed fields. It was one of a large number observed in the vicinity. No rotation was evident at cloud base, despite it being a relatively low cloud base above the vortex (Photograph © courtesy of C. Doswell, used by permission).

The primary distinguishing characteristic of a gustnado is that the intense vortex is *shallow* – on the order of 100 m. The intense vortex does not extend as far as cloud base, so no strong rotation will be observed in the clouds above such a vortex. Gustnadoes are generally weak and brief, and they can occur in swarms, with perhaps dozens of them occurring in a short time along a moving gust front. A troubling aspect of this sort of event is that true tornadoes also can arise in association with gust fronts. What makes them tornadoes is that the intense vortex is deep enough to be connected to strongly rotating cloud bases above the debris whirl at the surface. The observation of gustnadoes requires that some *tracer* be available to make the vortex airflow visible – gustnadoes might be relatively common along gust fronts, but without a tracer, they generally are not observed, and they would be too shallow to be seen on any operational radar. In situations involving downbursts, gustnadoes might be occurring episodically along the leading edge of the outflow, and each might create a local concentrations of damage, although the chances of a gustnado reaching even F2 intensity are small. If gustnadoes are *not* true tornadoes, in a post-storm survey it's certainly going to be difficult to sort out the difference between a gustnado and a brief, weak true tornado along a gust front. Without video documentation, it's not obvious how to make this distinction. Any eyewitnesses might well be adamant in considering these to be tornadoes.

C. Problems on the high end of the scale

The difficulty with providing ratings at the high end of the F-scale spectrum is associated with how much wind was required to produce the observed damage. The challenge has at least two primary components: (1) the actual resistance of the original structure or vegetation to the wind; and, (2) the role that factors other than the strength of the wind might have played in producing the damage. When structures are completely destroyed, it is difficult to gauge how fast the wind might have been – what *can* be done in situations meeting the F4-F5 damage criteria in Table 1 is that a *lower bound* can be assigned to the wind; the minimum value to cause that level of damage to the structure. If the structure is weak, that lower bound will be at a lower windspeed than if the structure is strong. Of course, when structures are *not* completely destroyed, it is often possible to estimate an *upper* bound to the windspeeds on the basis of what is left behind.

Since the Fujita scale has been closely associated with damage to frame homes, another important issue is the interpretation of damage to *other* structures or to vegetation, the carrying of objects by the wind, and other specific effects. At the high end of the F-scale, the relationship between damage and windspeed is essentially *uncalibrated* by any careful engineering studies. Therefore, the relationship between the windspeed categories and the damage attributed to each category by Fujita must be considered speculative.

1. F3 or F4?

According to the Fujita scale criteria, the dividing line between F3 and F4 is determined by whether or not interior walls are left standing in the wreckage of a frame home. Strictly speaking, F4 damage requires that no interior walls be left standing. Of course, there are gray areas: for instance, if a remnant of the interior walls is left but it is heavily damaged (as in Fig. 25), this might be seen either as "high" F3 or "low" F4 damage, depending on the structural integrity of what is left standing.

When there are *no* interior walls left standing, the most important issue becomes the structural resistance of that home and the process by which that damage occurred. In Appendix 1, an assessment form developed by Mr. Tim Marshall has been provided. This form is discussed in Marshall et al. (2003). The intent of the form is to facilitate the systematic gathering of information directly related to the integrity of the structure prior to the tornado. If there are major problems with the attachments along the load path, then much weaker winds could produce a given amount of damage. For instance, if the home

Figure 25. Example of a severely damaged, but still standing interior wall (FEMA photograph by C. Doswell).

is poorly attached to the foundation, then damage that nominally is associated with F4 (or F5) intensity winds could have been produced by much weaker windspeeds than those assigned to the F4 category in the Fujita scale (see Marshall 2003). A home with an inherently weak structure simply is inadequate to justify an F4 rating. Alternatives include: (1) rating the event F3 or even lower, in the absence of other examples of possible F4 damage, (2) basing an F4 rating on damage done to *other* homes that appear to have been truly well-constructed, or (3) basing an F4 rating on some other type of damage beside that done to that particular frame home.

Damage assessment should not focus exclusively on what has been destroyed. It is equally important to consider what was *not* destroyed. For example, it can be seen in Fig. 26 that an *engineered structure* (a water tower) survived relatively undamaged amidst what appears to be F4 damage to homes. An engineered structure has specified design criteria[7] that usually can be obtained by contacting the owner of the structure. When a structure survives the event without structural damage, this is a very clear indication of an upper bound for the windspeeds. If the structure was designed to be able to resist winds up to 150 mph, for example, then the fact that it successfully resisted the tornado winds is strong evidence that the winds did not exceed 150 mph. If a structure is damaged, but not completely, the windspeed might be close to the design criterion, assuming that some other factor, such as projectiles in the wind, are not involved. Recall that an F-scale rating can be based on a *single* point of damage. Clearly, if there are *many* instances of a given high level of damage, that is generally safer than a rating based on a single observation. However, even when there are numerous clear examples of apparent F4 damage to homes, care needs to be exercised. *All* the homes in a particular area might be characterized by weak attachments of the homes to their foundations. This turned out to be the case in a tornado that struck Omaha on 6 May 1975, producing particular devastation of homes in a subdivision. Post-event review of

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[7] Note that if a structure is designed to withstand a certain windspeed, the design likely includes a "safety factor" such that failure would actually be expected at a *higher* windspeed than the design criterion. When dealing with engineered structures, detailed information about the design has to be obtained to establish the likely failure threshold.

their structural integrity showed that all of them were inadequately anchored to their foundations, such that winds of 80-100 mph would have been sufficient to slide them off

Figure 26. A water tower still standing near homes with no standing interior walls (Photograph courtesy of J.H. Golden, used by permission).

those foundations. With the loss of structural integrity along the load path from sliding off their foundations, the homes were not sufficient to merit an F4 rating. That is, despite having left many homes in this area with no standing interior walls, the tornado could not be rated F4 on the basis of such evidence.

2. F4 or F5?

Giving a tornado an F5 rating is probably more contentious than it should be; in general, more scrutiny is given to an F5 rating than to an F4 rating. In fact, the reluctance to give tornadoes an F5 rating might well cause some events to be rated F4 that might well have been *deserving* of the highest rating. In effect, proposing an F5 rating focuses so much attention on the issue that storm survey teams will be hesitant to rate an event at that level unless they find the strongest possible evidence. Most F5-rated tornadoes have hit populated areas; a tornado passing through open country is unlikely to be given the highest rating.

In the event a tornado hits a populated area, survey teams can be under some substantial pressure to make an assessment before they have had time to give the issue the careful consideration it deserves. Formally, by the Fujita scale criteria, F5 damage to a frame home not only leaves no interior walls standing, but the debris from the home is swept away, leaving essentially a bare foundation. This sort of "incredible" destruction is as total as it is possible to be; it leaves essentially nothing of the home but a slab or an empty foundation. This criterion would seem to be relatively easy to evaluate but for a number of complicating factors.

As always, the structural integrity of the home prior to being hit is a critical element. When distinguishing F5 damage from lesser intensity storms, the attachments along the load path are potential weak points. As already noted, further complicating the issue is the question of the *duration* of the tornadic winds. The 27 May 1997 tornado that hit Jarrell, Texas, left a number of homes in a particular subdivision with nothing left but empty slabs (Fig. 27).

Figure 27. Empty slab left in the Double Creek Estates subdivision following the tornado of 27 May 1997 in Jarrell, Texas (Photograph © courtesy of T. Marshall, used by permission).

Even the debris was blown far away, making the F5 rating an apparently easy decision. However, a post-event survey by structural engineers revealed that there was some variability in the attachments. Some homes were rather strongly attached to their slab foundations, whereas others were not. Beyond that, however, an important question became the *duration* of the strong winds – this was a large, relatively slow-moving tornado (the damage path was estimated to be roughly 3/4 mile wide, moving at 5-10 mph). At the observed speed, homes would experience damaging winds for 5-10 minutes. Not only would the damaging winds have more time to put structures under stress, but the long duration would be more likely to sweep away the debris than if the tornadic windspeeds been of lesser duration.

Moreover, this subdivision was relatively isolated, surrounded by mostly open country. In the case of the tornado that hit the Oklahoma City, Oklahoma, metropolitan area on 3 May 1999, some of the F5-rated damage occurred in the suburb of Moore, Oklahoma. In this case, the tornado moved in from other populated areas, and its debris load was already substantial as it entered Moore. The result (Fig. 28) was large piles of rubble remaining on empty slab foundations. The tornado damage path was about 1/2 mile wide at this point and the tornado was moving around 35 mph. The damaging winds would last only about a minute in such a storm, and if debris from a particular home was swept away, other debris would fall in its place. In fact, that is just what was observed during a post-storm survey – the debris left in a particular location in the F5-rated damage area in Moore did not come from that location, but arrived from areas hit previously by the tornado. Hence, the *absence* of slabs swept clean of debris could not be taken as evidence of intensity levels below that of F5.

Figure 28. Debris piles left by the tornado of 3 May 1999 in Moore, Oklahoma (FEMA photograph by C. Doswell).

As with the F4, rating, it is important to consider carefully the role of other observations besides damage done to frame homes.

3. Nearby damage

Generally speaking, if an isolated piece of evidence suggests a certain range of windspeeds, it is important to consider *nearby* damage and other evidence suggesting the windspeed. [8] If there is a question about the validity of an F-scale estimate at any location, a look at the surrounding objects can confirm or deny the windspeed estimates. When the damage is associated with a structure of questionable strength, the surrounding trees and vegetation may suggest important clues, as in Fig. 29.

4. Projectiles

The generation of large projectiles is a commonly used factor in the decision to give a tornado either an F4 or an F5 rating. One somewhat controversial issue is the question of whether or not motor vehicles become airborne during tornadoes and, if so, at what windspeeds vehicles leave the ground. There is virtually no doubt that tornadoes can cause cars to be rolled and bounced along the ground. Other evidence, notably video documentation, provides convincing proof that cars *can* become airborne – there is some debate about at what windspeed this occurs. The wording of the Fujita scale (Table 1)

[8] It is probably true that meteorologists tend to regard variations in damage as evidence of variations in windspeed, whereas engineers tend to see the same variations in damage as evidence of variations in the susceptibility to wind. Reality almost always will lie somewhere in between these two extremes. It is useful, therefore, in any survey to have both meteorologists and structural engineers involved in damage surveys. This is only rarely possible, unfortunately.

Figure 29. Damage to a poorly constructed garage implies much stronger winds than the nearby tree, which has one broken tree branch but is otherwise not heavily damaged (FEMA photograph by C. Doswell).

suggests that Fujita believed automobiles became airborne at F3 windspeeds. Some preliminary work on this issue has been done by Schmidlin et al. (2003). Their work suggests that F4 and F5 tornadoes can, indeed, produce automobile-sized projectiles. It *may* be that F3 tornadoes can cause vehicles to become airborne, and F2 tornadoes might

Figure 30. A power pole propelled through a window during the 3 May 1999 tornado in Del City, Oklahoma. It clearly did not tip over and through the window, since the top of the window frame remains intact (FEMA photograph by C. Doswell).

be able occasionally to overturn vehicles. In any case, the impact of either a tumbling or airborne automobile on a structure would magnify considerably the effect of the wind alone. Although not specifically mentioned in the Fujita criteria, there is evidence that large power poles can become airborne, at least in violent tornadoes (Fig. 30). Fujita (1992) has shown that massive I-beams can apparently become airborne (see his Figs.

2.5-13-15). There is little doubt that heavy objects of all sorts have been moved without leaving evidence of being dragged or bounced along the ground.

Unfortunately, the absence of studies revealing at precisely what windspeeds a given object becomes airborne is a handicap to offering such events as evidence for giving a tornado a particular rating. Of course, when some objects do *not* become airborne, this also can be evidence for lesser windspeeds. The issue of windspeeds needed to loft some object is complicated by the fact that the object in question may have been attached to something else (with a large flat area to catch the wind) that facilitated its flight before detaching on impact or otherwise near the end of that time aloft.

Structures and vegetation that *remain* (even if damaged) within areas exhibiting possible F4-F5 damage can provide important clues about the windspeeds, especially engineered structures with well-defined windspeed design thresholds. Although strong variation in damage from one location to another can be an indication of the well-recognized strong gradients in windspeed (especially in multiple-vortex tornadoes), they can also be the result of variable resistance to a relatively uniform windspeed. Making this distinction is not easy and in many cases might come down to subjective judgment, rather than clear and direct evidence.

5. Damage to vegetation

Given that tornadoes are not always moving through populated areas with human-built structures to hit, it would be useful if we could establish some standards about the resistance of vegetation to windspeeds. This work has not been done, unfortunately, and so the relationship between vegetation and windspeed remains questionable. Fujita's verbal descriptions in Table 1 include some criteria associated with trees but, as everyone should be aware, the resistance of trees to damage from the wind varies considerably with the tree species, the size and health of the tree, antecedent precipitation (wet ground makes uprooting trees easier), whether or not the tree is isolated, orientation to the wind, the presence (or absence) of projectiles in the wind, and so on. Peterson (2003) has discussed a number of issues regarding tree falls in forests.

After particularly damaging tornadoes in populated areas, trees are usually observed to be stripped of most of their branches and even debarked (Fig. 31). Such damage is almost certainly due to the impacts of projectiles in the debris cloud of the tornado. The issue of whether or not a tree is uprooted depends on the tree type (conifers typically have shallow root systems), the season (for deciduous trees – the presence of leaves increases the chances of uprooting by increasing the wind load on the tree), the soil wetness, and the presence of other trees (which can fall on their neighbors and enhance the chances of uprooting other trees), among other factors.

In an effort to increase the range of events that could be rated, Fujita even developed a series of photographs showing damage to cornfields, purportedly relating the character of that damage to the F-scale. Again, there are many factors that influence how corn responds to the wind, so it is difficult to see how any such attempt to determine the

Figure 31. A debarked tree remnant in Moore, Oklahoma after the tornado of 3 May 1999 (FEMA photograph by C. Doswell).

relationship between damage to vegetation and windspeed can be made reliably quantitative. As with damage to structures, the relationship between winds and vegetation is complex and nonlinear; therefore, assignment of F-scale solely on the basis of damage to vegetation would be inherently difficult. It is even hard to imagine how a "calibration" of the damage to the windspeed could be done, given all the complex factors that can affect the way vegetation reacts to the wind. Guyer and Moritz (2003) have discussed some possible avenues for estimating windspeeds in rural areas, but clearly much research would need to be done to "calibrate" any proposed system.

6. "Scouring" of pavement

From time to time, there are reports of a tornado passage being associated with removal of pavement. This "scouring" of pavement is certainly unlikely with weak tornadoes, but it has been cited on occasion as evidence of "incredible" intensity. It is not known precisely how pavement scouring occurs – given a windspeed at ten meters above the surface, the wind at the height of pavement is surely much less, so the removal of pavement by wind action alone might seem to require very strong tornadic winds. Phan and Simiu (1998) have attributed the scouring of pavement to the pressure difference between air trapped beneath the pavement and the tornado. This does not seem plausible given the current consensus about the relative lack of importance of "suction" associated with tornadoes, but since it is not known how pavement damage actually occurs in specific instances, their hypothesis cannot be dismissed. It is quite possible that projectile impacts might be a factor, as well as the type of pavement and its exposure to the wind. Wind erosion of surrounding soil that undermines the pavement might be a major contributor in such examples. No instance of *concrete* pavement removal is known

– all examples of scouring have been asphalt or similar pavement material. It seems unlikely that pavement removal would be associated with a weak tornado (F0 – F1), but in the absence of a careful study of how much wind is needed to produce pavement failure, it is not known to what extent "scoured" pavement indicates the likelihood of F4 – F5 intensity. The occurrence of pavement scouring by itself probably should not be taken to imply F4-F5 intensity, but might be sufficient for a rating of F2-F3.

D. Problems on the low end of the scale

The challenges on the low end of the Fujita scale are very different from those at the high end. Rather than having structures completely destroyed, at the low end of the scale there is considerable evidence left behind that implies *upper bounds* on the wind speed. However, the challenge at the low end of the scale is generally deciding whether or not the damage was indeed produced by a tornado. The F-scale minimum threshold for an F0 tornado (40 mph) is not even sufficient to meet the NWS threshold criterion for a damaging wind (50 kt or 58 mph). It is indeed plausible to believe that a vortex might be present even with winds below 40 mph – the laws of vortex dynamics say that a vortex must either close on itself or end at a solid surface, so a vortex aloft (funnel cloud) is likely to also be present at the surface,[9] even when the windspeeds there are so weak that they cannot produce damage.

1. Tornado or downburst?

a. Evidence of rotation?

In doing a damage survey, it is common to look for evidence of rotation in the damage to decide whether or not a tornado was involved, if there is no other convincing evidence that the damage was caused by a tornado. It is important to keep in mind in searching for this evidence that the width of the damage path is a major factor in the reaction of structures and vegetation to the wind. If the vortex is much larger than a house or tree, then to the object being hit by the tornado, there is only "straight' wind. As has been said by structural engineers (e.g., Marshal 1993), "Wind is wind." What they mean is that for the most part, the objects affected by a tornado are not influenced by the rotation of the winds about the tornado. Only if the vortex size is comparable to the object being struck will that object reveal evidence of the vortex rotation. This can happen, perhaps with subvortices embedded within a multiple vortex tornado, but the *absence* of such twisting is not, by itself, direct evidence that the damage was not tornadic. Conversely, evidence of twisting on small scales – for example, in trees or traffic signs – can arise from various sources (such as asymmetric wind loading or off-center projectile impacts) and may not be direct evidence that the event was tornadic.

For a fast-moving tornado, traveling relatively rapidly, all the damage can be from wind that is nearly unidirectional. For a cyclonic (in the Northern Hemisphere) tornado, the counterclockwise rotation of the wind is *enhanced* by the tornado's motion to the

[9] Unless there is a strong stable layer between the vortex and the ground, which can act effectively as a "solid" surface.

right of its track and decreased by that motion on the left side of the track. A symmetric tornado with an axisymmetric tangential windspeed of 70 mph (nominally F0, but the F-scale is defined according to the *ground-relative* windspeed) traveling at 50 mph would have winds of 20 mph on the left side of its track and 120 mph on the right side (Fig. 32). In such an event, it is not hard to imagine damage indicating a nearly unidirectional wind. This might even be true for strong, fast-moving tornadoes (Reynolds 1957)

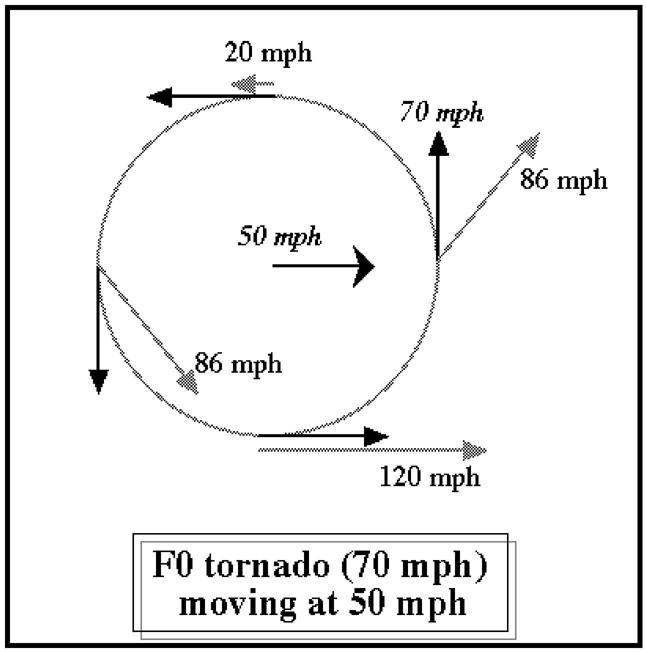

Figure 32. Schematic showing the winds resulting from a tornado with 70 mph peak tangential winds moving at 50 mph, such that most damage would be from winds from left to right on the figure.

b. Debris fall direction

The best evidence of rotation in damage is on the scale of the damage path. For tornadoes that are relatively strong, or moving relatively slowly, the orientation of the debris usually reveals that the winds in different parts of the path were from different directions. However, more important than direct evidence of rotation is whether or not the winds are diverging or converging. In a tornado, the airflow near the surface is predominantly inward, or *convergent*. The closer to the surface, the greater the predominance of this convergence over the rotational flow. When tornadoes move over mostly open country with few relatively tall objects to topple, the pattern of the winds can be mostly pure radial inflow. If this convergent flow is combined with the contribution from the movement of the tornado, the resulting near-surface flow will resemble Fig. 33, at least for a tornado without multiple vortices.

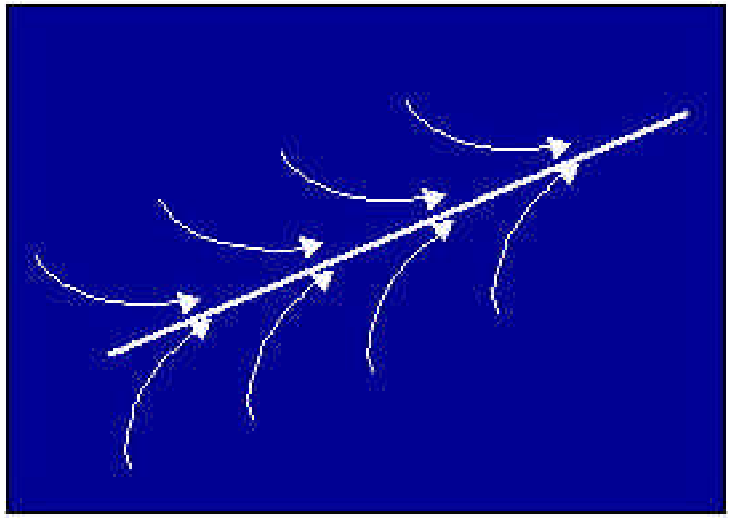

Figure 33. Schematic illustration of the near-surface flow directions produced by a moving, relatively long-lived source of convergence, such as a single-vortex tornado. When the tornado is moving rapidly, the centerline might be shifted toward the left of the track.

Figure 34. Example of a very narrow tornado track in a cornfield.

A tornado-associated damage track tends to be long and much narrower than it is long, as suggested by the damage in Fig. 34. This character of tornado tracks can be the most important clue that the event was a tornado, rather than a downburst.

On the other hand, damage produced by downbursts tends to be strongly *divergent*. A moving downburst typically will produce a divergent swath of damage, resembling Fig. 35. An example of a microburst in action is shown in Fig. 36. The divergent character of the airflow is revealed by the dust picked up along the leading edge of the outflow. Moreover, the damaging winds in a microburst are relatively short-lived. The resulting damage swath is typically relatively short and broad, more fan-shaped than linear. Note that "twisting microbursts" can appear on the right side of a cyclonic tornado path, probably associated with microbursts in the rear flank downdraft.

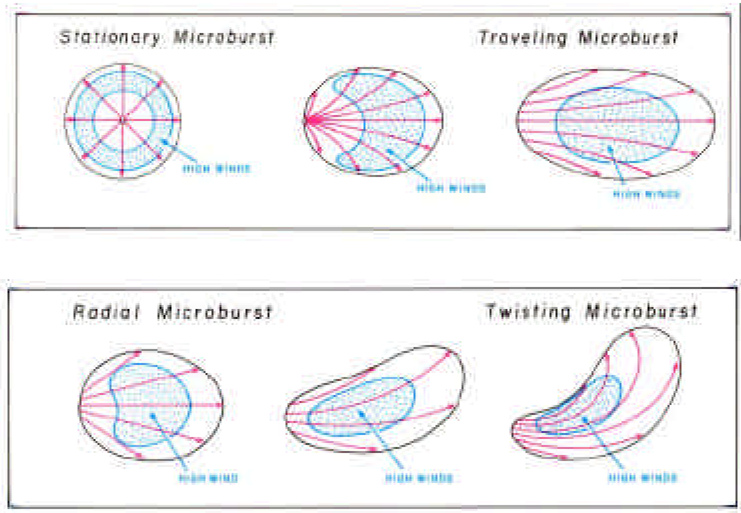

Figure 35. Schematic illustrations of the near-surface flow directions produced by a mircroburst (or a downburst). When the downburst is stationary, a circular pattern of symmetric outflow is observed; when the downburst is moving or is not coming down vertically, a fan-shaped outflow is observed, and some moving downbursts have vorticity, so that a "twisting" pattern of outflow is observed. What is common to them all is a pattern of diverging winds, so if the orientation of damage is diverging, the likely cause is a downburst (From Fujita 1985).

Figure 36. Photograph of a fan-shaped microburst in action, captured by T. Fujita during the Joint Airport Weather Study (JAWS) Project in Colorado, on 14 July 1982 (From Fujita 1985).

c. Storm sounds

Another commonly-used criterion for determining whether or not an event was a tornado was the "roaring" sound associated with the damage. In actuality, both tornadoes and downbursts can produce very loud wind noise that could be characterized as a "roaring" sound. Thus, there does not appear to be any way for those involved in such an event to be able to distinguish tornadoes from downbursts by the sound alone.

d. Radar signatures

When considering an event, a survey team should acquaint themselves with the radar data (as discussed below). However, radar alone is not sufficient information to distinguish tornadic from nontornadic events. There certainly are characteristic radar signatures associated with prototypical events. Not only does a supercell have dramatic

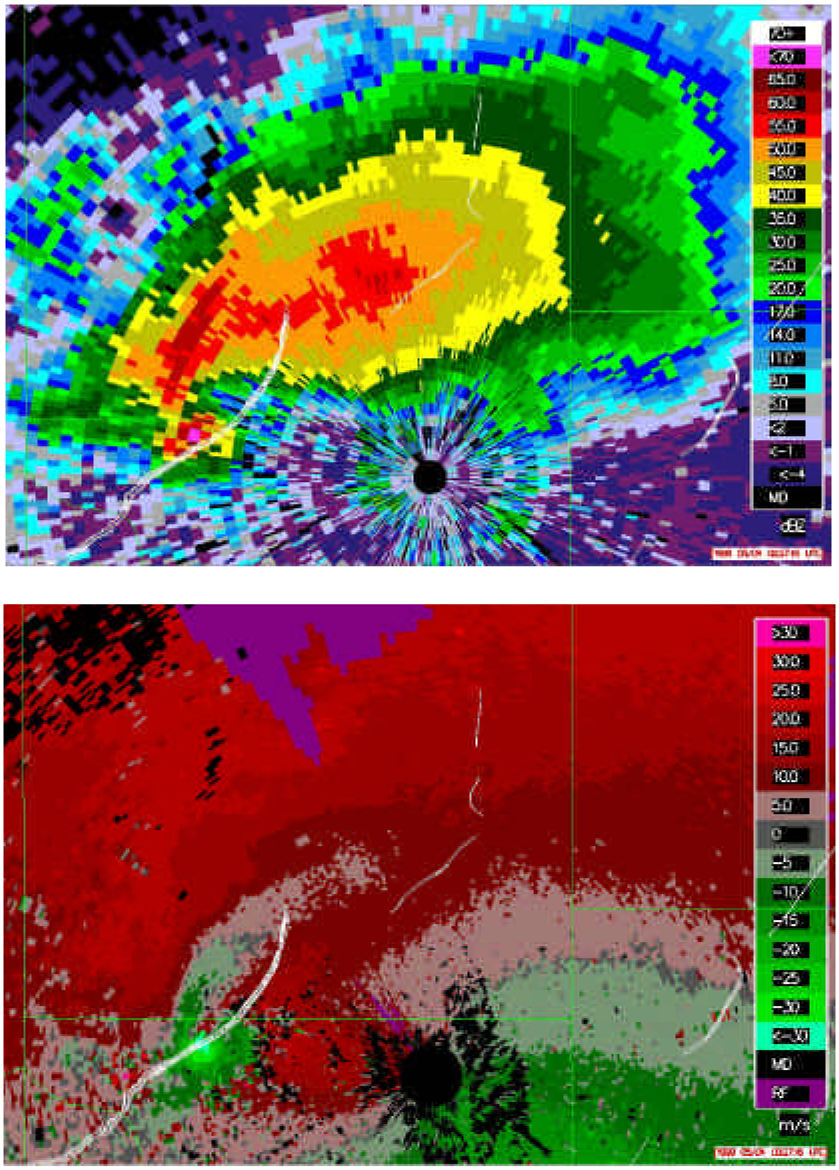

Figure 37. Reflectivity (top) and Doppler velocity (bottom) associated with the supercell storm that produced the tornado that struck the Oklahoma City, Oklahoma, metropolitan area on 3 May 1999. Tornado tracks from that day are superimposed (white). (Images courtesy of the National Severe Storms Laboratory).

radar reflectivity features (e.g., the hook echo, as shown in Fig. 37), but there are clear indications of strong rotation in the Doppler velocity fields.

The presence of a hook echo and Doppler velocity signature near and along the observed tornado track indicates that tracking features in the radar data can be helpful in locating possible tornadoes and establishing the timing of events along the storm path.[10] Unfortunately, not every real tornado can be associated unambiguously with such obvious radar signatures. This situation can result from several limitations that are inherent to all radars, or it can simply be that the event is not like the prototypical mesocyclonic tornado. We have already discussed the possibility of nonmesocyclonic tornadoes, and these may or may not have any recognizable signature in radar observations, depending on several factors – the distance from the radar, the size of the tornado, and so on.

The same can be said of downbursts and microbursts. The presence of strong airflow as seen in Doppler radar observations is no guarantee that those winds are reaching the surface. Conversely, the absence of strong airflow in Doppler radar

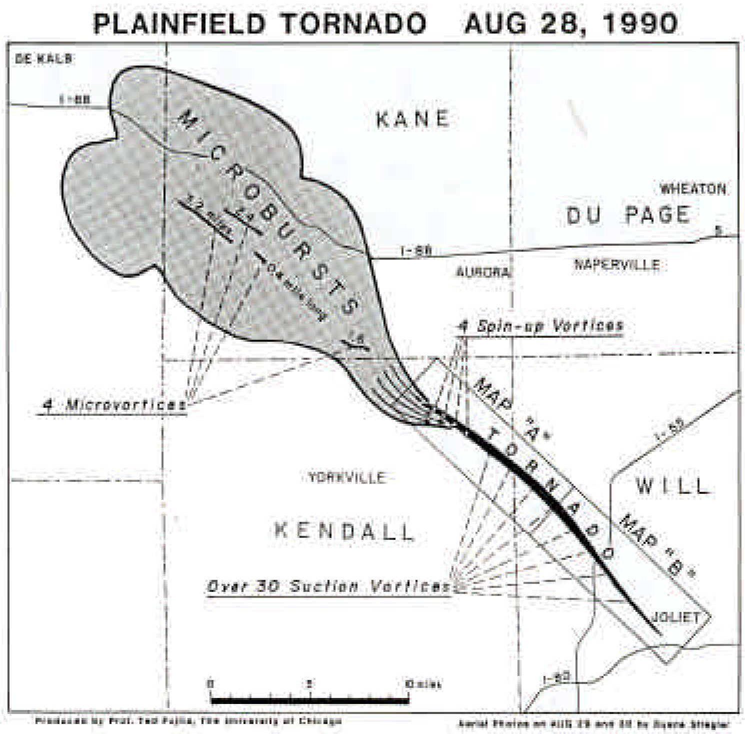

Figure 38. Results of an aerial survey (after Fujita 1993) showing the location of various events along the path of the supercell storm.

observations does not preclude the possibility of strong downburst winds at the surface. Nevertheless, the radar data may offer considerable value in locating possible events and

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[10] The location of a tornado at the surface is not necessarily consistently tied to some feature in the radar data. Radar data, even at the lowest elevation, are well above the surface, and tornadoes can be tilted, such that their surface contact point can vary relative to the radar features being tracked. The displacement of the surface track from, say, a vortex signature in the radial velocity field can be as much as a km or so, and will not be a constant over the duration of the tornado.

helping to establish the time of damage occurrence. Under ideal circumstances, as discussed in Speheger et al. (2002), it is possible to use radar data to help resolve many of the conflicting pieces of information about the details associated with a damaging event.

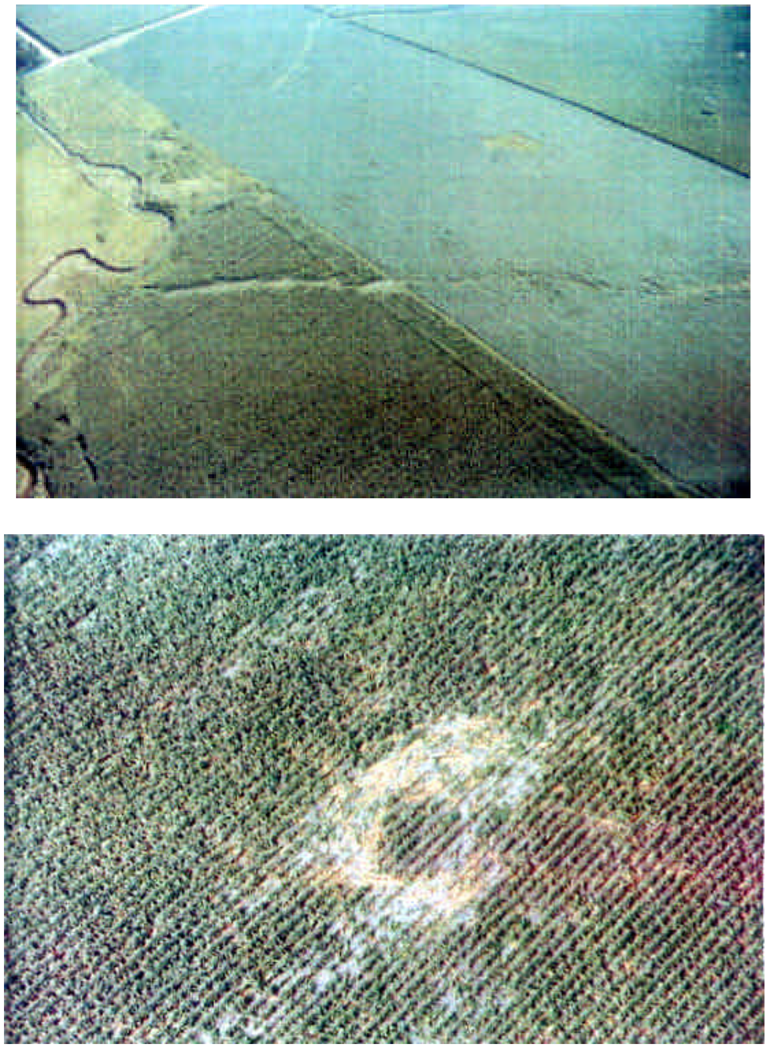

Figure 39. Photos showing the track of a “microvortex” (top) and a “spin up” (bottom) from Fujita’s aerial survey after the Plainfield, Illinois, tornado of 28 August 1990.

2. What is a tornado?

Some of the common issues with defining a tornado have already been discussed: gustnadoes, landspouts, “cold-air” funnels, and waterspouts. This does not exhaust all of the potential difficulties. For example, in his survey of the Plainfield, Illinois, tornado of 28 August 1990, Fujita (1993) shows what he has called “microvortices” and “spin-ups” in his mapping of the event (Fig. 38) – examples of these are shown in Fig. 39. Are these tornadoes or not? Since there were no eyewitness videos of these events and we only have evidence from the aerial photographs that something happened that almost certainly involved a vortex-like flow at the surface, these probably *are* tornadoes, but might possibly be gustnadoes, as well. These "microvortices" are quite narrow events (Fig. 39, top) but seem quite persistent (relatively long tracks), whereas the "spin-ups" must be brief vortices (and/or slow-moving). The "spin-ups" (Fig. 39, bottom) may be the first intermittent episodes of damage along the track of the developing Plainfield tornado (see below for a discussion of gaps in the path), made visible by the damage they produced in cornfields.

Eyewitnesses who claim to have seen a funnel cloud (or not) can be in error. This should not be taken to mean that eyewitnesses are necessarily unreliable, but they can easily be mistaken. Their range of experiences generally does not include an extensive sample of severe storms and tornadoes. For the example shown in Fig. 40, numerous false tornado reports were received. Although this certainly could easily be mistaken for a tornado, it simply is scud beneath a shelf-type outflow cloud.

Figure 40. Example of a tornado look-alike that generated numerous erroneous tornado reports on 27 May 2001 in southwestern Kansas (Photograph © courtesy of J. Williams, used by permission).

On the other hand, damage produced by a storm in which eyewitnesses did *not* see a funnel cloud *might* actually be tornadoes. This can occur when the tornado simply has no visible funnel cloud, or when the funnel cloud is obscured by dust or rain.

In some cases, identifying the character of an event can be a major problem – generally speaking, the greater the amount of damage, the easier it is to identify the nature of the event that produced it. A few isolated items of minor damage are much more difficult to associate with a particular type of event than a swath of extensive damage. Although the majority of events are relatively easy to identify as tornadoes or non-tornadoes, in real surveys of damaging convective storms, it is not always so straightforward.

3. Skipping and gaps in the path

An especially troubling problem is the existence of gaps along an extended damage track. Do these mark separate tornado occurrences or should they all be connected into a single "skipping" tornado? Unfortunately, this may not be an obvious decision, especially when all one has to work with is the damage. The best situation is when video evidence provides a visual record of a continuing vortex – in such a case, it might be satisfactory to ignore the gaps in the damage (which might arise either from a lack of objects to damage, or from transient fluctuations in the intensity of the vortex at the surface) and consider the event a single tornado. In the absence of documentary evidence for a continuing vortex circulation, this is basically a question of judgment.

a. Spatial and temporal variations in wind

Although the detailed structure and evolution of the wind field throughout a tornado's life cycle has never been documented, there are numerous reasons to believe in the complexity of that wind field. The damage itself offers some hints of this complexity, (cf. Fig. 3). The limited quantitative measurements of that wind field using photogrammetry and mobile Doppler radars suggest that tornadic windfields are far from simple. One consequence of all this complexity is that the windspeeds near the surface could decrease below some threshold from time to time, at some locations along the track. This could result in temporary cessation of damage, even though the vortex was continuously in existence. A strict interpretation of a tornado as requiring the presence of damaging winds at the surface would mean that each segment of a damage track with gaps would have to be attributed to a separate tornado. This seems to fly in the face of what we have learned from years of tornado films and video – the continuing vortex does not "skip" or "withdraw back into the clouds" but rather has a more or less continuous debris whirl at the surface, despite the presence of gaps in the damage. As already noted, unraveling the events associated with a "gappy" damage track is difficult in the absence of other evidence, so this suggests that *other evidence in addition to any survey of the damage track needs to be considered* in making this judgment. In the best of situations, fluctuations in the damage can be connected to changes in the radar depiction of the storm – for example, weakening of gate-to-gate shear signatures in the Doppler data, or the formation of new mesocyclones aloft prior to the occurrence of a new track with a gap separating it from the track of a tornado associated with a previous mesocyclone. Radar's ability to observe tornadoes can vary substantially with range, among other factors, so a comprehensive consideration of all the information available is an important part of arriving at a decision concerning whether or not damage path gaps indicate the presence of distinctly separate tornadoes.

b. Surface boundary layer character

A number of factors associated with the surface boundary layer (within a few tens of meters above the ground) can influence the damage produced by a tornado. Obviously, a major factor is the present of structures and vegetation that can be damaged. In some cases, a tornado can strip even short grasses from the surface, leaving behind a visible scar even though nothing substantial was present to be "damaged". As with the issue of pavement removal, such a track *could* be indicative of a tornado of significant (F2 or greater) intensity, but such an assertion is more speculation than established fact. It just is not clear how to interpret such a track in terms of an F-scale assessment if nothing that can be evaluated is struck within the track.

The presence of human structures and trees increases the "roughness" in the surface boundary layer and acts to reduce the near-surface winds within the area covered by such objects. If the tornado is not of sufficient strength to destroy those objects in its path, it may seem that the tornado is "at tree-top level" and not doing damage at the ground. Such an interpretation is not consistent with vortex dynamics – it simply means that the tornado is not strong enough to overcome increased friction near the surface.

4. Complex tornado tracks

Storm chasers and citizen videos have shown examples where the distinction between a continuing vortex and separate tornadoes can be difficult to make even when excellent video documentation is available and the event is not wrapped in rain or dust. Surveying a damage path after the fact is made even more complex by the fact that successive tornadoes in a tornado family can track along paths that are very close (cf. Fig. 20). In fact, distinctly different tornadoes have run over virtually identical ground on the same day. Recognition of the presence of overlapping tracks can be difficult unless survivors make a note of having been hit more than once (or video documentation of the two events exists). In such cases, having radar available (so that the passage of separate storms can be documented) makes it easier to recognize the possible existence of overlapping tracks. Even if it is known (or suspected) that more than one tornado has tracked along a very similar path, then partitioning the damage into different tornadoes can still be problematic (see the discussion of overlapping paths near Mulhall, OK, on 03 May 1999 in Speheger et al. [2000], their Fig. 7). If distinct tracks converge into (or

Figure 41. An aerial photograph showing an abrupt change in the direction of movement of a tornado (perhaps affected by a microburst) near Logan, Iowa, in May of 1999 (Photograph © courtesy of B. Smith, used by permission).

diverge from) a common path, then the likelihood of overlapping separate tornadoes is high. Making such distinctions can be quite challenging from the ground. An aerial survey is much more likely to uncover evidence of overlapping tracks than one done only on the surface. It is also much easier to document track complexities, such as abrupt path changes from an aerial view (Fig. 41)

E. Issues that will arise

1. Public reaction to damage

When doing a damage survey, the team needs to keep in mind that for many people, the event being surveyed is the most extreme example of a weather event most of the victims have ever seen. In their limited sample, its significance can be much greater than the objective evidence reveals. Survivors of such an experience may have many misconceptions and misunderstandings that characterize their perception of the event. It is counterproductive to attempt to correct their notions of what happened when discussing the event with them, no matter how wrong they might be, especially shortly after the event.

In particular, the public or local community leaders may be inclined to dispute the survey team's assessment of the F-scale rating. For various reasons, the local officials can also be unhappy with the team's evaluation of the data. If a careful analysis has been done, then there should be no need to alter the team consensus. In fact, it would be a mistake to modify a conclusion just to avoid negative pressure or publicity. Although some subjectivity is always going to be involved in reaching a final decision, when proper procedures (as described herein) are followed and evidence is available to support the team consensus, then the opinions of nonprofessionals (i.e., not meteorologists or engineers) should not be allowed to influence the survey team's assessment.

2. Media seeking an "instant analysis"

Another common experience for a survey team is the tendency of the media to want an "instant analysis" of a disastrous event. The National Transportation Safety Board is always careful to avoid drawing early conclusions about aircraft accidents – in the same way, a survey team should exercise comparable care to avoid being drawn into making premature statements about the intensity of an event. This does not mean a lack of cooperation with the media, of course. Indeed, many people want to know just what happened in a major event. Rather than succumbing to the pressure for a quick decision, the survey team should simply respond by saying that it is too early to draw any conclusions until all the available information has been gathered and analyzed.

II. Putting together a survey team

A. Prior preparation and fast response

The time to prepare for a survey is well before any event has hit. Possible team members need to be identified in advance of any event, and contact information about them should be available to team organizers. Generally speaking, clean-up begins within a few minutes after an event has happened. Removal and rearrangement of the debris makes a proper interpretation of the event increasingly difficult as time passes. Ideally, a survey should begin as early as possible on the morning after an event. In order to pull a team together and get them ready within less than 24 hr after a damaging storm, the arrangements simply cannot be done on the spur of the moment. The collection of survey materials, as well as getting team members prepared to leave, needs to be such that most of the preparation has been done well in advance, ready to be put to use at a moment's notice.

It is possible to begin a ground survey too soon, however. Generally speaking, tornadoes and damaging storms in general can block access to the damaged areas. First responders have to have time to remove victims and clear the roads to allow access before a team can be effective. That this also can destroy useful information is unfortunate.

If possible, an aerial survey should be done as soon as possible, and if that option is to be available, those arrangements absolutely would need to be made in advance. See below for some suggestions about obtaining aerial surveys. Aerial surveys can do several important tasks:

1. gaining access to locations that might otherwise be difficult to survey, either because of that access being blocked by storm damage, or by being located far from any easy access,
2. providing an indication of where the critical areas that need a ground survey are located,
3. determining track continuity or gaps in areas not readily accessible on the ground
4. documenting the presence of multiple vortices,
5. identifying convergence/divergence patterns to help distinguish between tornadoes and downbursts, and
6. mapping the variations in damage along the path.

See Fujita and Smith (1993) for more discussion of aerial surveys. An aerial survey is primarily useful for providing an overview of the event. As wide as possible an area needs to be searched for possible tornado damage, including areas that might be rather far from populated areas. It is only by air that such events are likely to be documented.

Doing ground surveys is also critical. Once the most intense damage areas have been identified, ground surveys are the only way to document the all-important details necessary to estimate the windspeeds associated with a particular piece of damage. Aerial and ground surveys complement each other, and neither is likely to be adequate by itself.

Ideally, it would be optimal to do *several* ground and aerial surveys (as described in Speheger et al. 2002). As a survey continues, questions inevitably arise whereby it would be best to go back and reexamine some locations, or go to some locations that had been overlooked or missed for some reason.. This may not be possible in a given situation, but the *option* to backtrack should be considered during the preparation phase, so that it would be possible to resolve questions that can arise.

B. Team capabilities

A major component of doing a proper survey is having the necessary capabilities on the team. In most instances, the majority of such a team would be meteorologists. Hopefully, the meteorologist team members would be well-versed on the structure and behavior of severe storms and tornadoes. Ideally, the members should have prior experience at surveying storm damage, and be able to focus on what are the relevant observations for coming to a plausible interpretation. For these purposes, having qualified structural engineers on the team can provide a critical component that is often missing from surveys conducted only by meteorologists. Limited survey training can not compensate for the insight provided by a professional structural engineer. Obviously, this may not be possible in every case. If some members have experience gained from prior surveys done with engineers, this might compensate somewhat for not having one or more engineers on the team.

Again speaking ideally, the team is likely to benefit from the participation of some local officials, perhaps law enforcement or someone identified with emergency management. This can be helpful in obtaining access to areas that may be closed, but it also provides those local officials with some first-hand experience about how the assessment process works. Having such a participant is potentially important in establishing local credibility for the conclusions of the team.

Another desirable team capability (but probably both difficult to achieve) would be someone with a professional sociology or psychology background who could conduct studies of the human side of a disastrous event. This would be helpful in learning about the interface between the weather community and the users of their information. Also, a medical doctor interested in the pathology of trauma caused by disasters would be helpful. Getting access to medical information about casualties can be a challenge as medical data are generally viewed as confidential. A medical doctor can provide an important interface between the team and the medical community.

Clearly, any team needs a local coordinator, who is likely to be available in most any circumstances. This is likely to be someone at the local NWS forecast office. A team coordinator has to be committed to providing a service that may never be requested. After all, most communities are not likely to be struck by a disastrous tornado event in a human lifetime. But if a team is to be ready to spring into action on short notice, there must be local commitment to being *prepared* to do so.

The reality of getting a team together rapidly enough to be able to start work on the morning after an disaster means that a pool of possible participants needs to be identified well in advance, ready and willing to go into action on short notice. The NWS has a Quick Response Team (QRT) that can be deployed within 18 to 24 hours of an event, to determine the final F-Scale rating for all tornadoes that are suspected of producing greater than F3 wind damage. At the local level, alternate team members for each of the capabilities envisioned have to be identified in order to be able to put a complete team together. Volunteers have to be sought and personal contact information available to the local team coordinator. Outside "experts" may or may not be available to survey a particular event, depending on the resources allocated to doing post-storm event damage surveys.

C. Tools

Although it may seem obvious that certain things are necessary for doing a survey, it is useful to list them. In the flurry of excitement after a severe weather event that produces significant damage, some items might be forgotten.

1. Equipment

a. Recording media

Cameras are essential documentation tools for a survey. Ideally, the cameras would be provided for the team by the agencies doing the survey. In practice, the cameras will often be those owned by the team members. Hopefully, the media (film, videotape, etc.) will be provided by the agencies, but again, this might or might not be so. Both still and video cameras are helpful, in different ways. Still cameras provide clear, high-resolution images that provide documentary evidence in support of an assessment. Video cameras can provide audio tracks, with verbal testimony from survivors and commentary from the survey team members as they go about documenting what they are observing. Video and still images from aerial surveys are also desirable.

Generally speaking, 35 mm still cameras of good quality are sufficient for the purposes of a survey. They should be capable of having exposure times of around 1/500 s, especially if they are to be used from the air (to reduce blurring from aircraft movement). Expensive professional equipment is not necessary. Ideally, each camera should have a *wide angle, normal, and telephoto* focal length lens. In many instances, zoom lenses can cover this range of focal lengths and reduce the number of lenses that need to be carried. Many zoom telephoto lenses have a “macro” setting that permits clear close-up photographs of structural details. A heavy “gadget bag” full of complicated camera gear is not generally necessary or even desirable – heavy gear can be a serious hindrance in scrambling through and over debris. Film for a 35 mm still camera should be moderately “fast” film (e.g., ISO 200) to permit clear, sharp images in light levels that might range from unlighted interior rooms to bright sunlight. It is useful to identify the sequence of film rolls in some way, to avoid potential confusion from arising after processing.

Another option is *digital* cameras – those capable of meeting resolution standards approaching that of 35 mm film images are preferred (on the order of 5-10 megapixels), but acceptable images can be obtained from digital cameras with resolutions of 1-2 megapixels. If digital cameras are used, then either the images need to be downloadable in the field (e.g., to a laptop computer), or there should be enough memory modules of sufficient size available to contain up to hundreds of full-resolution images. As with film, there should be some effort to identify the sequence of digital photographs. Those doing aerial surveys need to be sure to use a digital camera with exposure speed adjustable to 1/500 s, as with film cameras.

There should be a *flash unit* for each camera, to photograph structural details inside areas too dark for natural light exposures. If the lenses used have an *autofocus* capability, this can be a help in obtaining clear photographs but the user should be aware of the limitations of autofocus lenses (which can be “fooled” when looking through intervening materials like glass or screening). *Automatic exposure* still cameras can also have trouble with high-contrast scenes – when doing a survey in bright sunlight, the highlights may be overexposed and the shadows underexposed. When it doubt about the exposure, it is best to "bracket" the exposures to provide both highlight and shadow detail. Obviously, the more experienced each team member is with photography using the camera he/she has available, the more likely it is that useful documentary photographs will be obtained.

As with still cameras, it is not necessary to have professional grade video equipment. For most purposes, the autoexposure and autofocus capability of most consumer grade video cameras is acceptable. If using a video camera, the operator should provide audio documentation of such things as time and location. Some digital video cameras have a "time stamp" feature that indicates when the video was taken. If available, this feature should be enabled. When trying to capture audio tracks that contain eyewitness reports or commentary, wind can be an issue. It is best to have a wind "muffler" on the microphone, if possible. Digital video cameras have the advantage that the tapes can be downloaded into computers for incorporation in presentations, but there is no compelling need for digital versus analog video equipment. Most consumer video cameras have zoom lenses that cover a wide range of focal lengths, so it is normally only necessary to carry extra batteries and videotapes with the camera. The battery *charger* is also an important item to remember, especially if the survey extends over several days.

b. Proper footwear

Tornado debris contains many hazards: exposed nails and screws, broken glass, shattered framing lumber, and other potential sources of injury. A survey team arriving within the first 24 h after a major event will almost certainly be required to climb over debris piles to carry out their duties. Ideally, "safety" shoes with metal inserts to prevent puncture wounds to the feet ought to be available. Lacking that, tennis shoes don't offer a safe alternative – leather boots with deep tread are a possible alternative to true safety shoes.

c. Headgear

Proper hard hats should be considered *mandatory*. Entering damaged buildings puts the team at risk from falling debris. If the hard hats have an official logo to help to identify the team members, so much the better.

d. Local maps

The teams should obtain *detailed* street maps from local sources. If possible, individual structures should be identified on those maps, such as shown in Fig. 42. This facilities an accurate, detailed mapping of the level of damage along the storm track. Every effort should be made to identify sources of such maps well before the need to put together a survey team arises. There are maps available on the World-Wide Web in various locations that can provide detailed street-level maps (without identifying home sites). Local officials are likely to have detailed maps that might include home and structure locations. Getting teams into the field as early as possible after an event is important, as already noted; therefore, obtaining detailed maps needs to have been done as far in advance as possible.

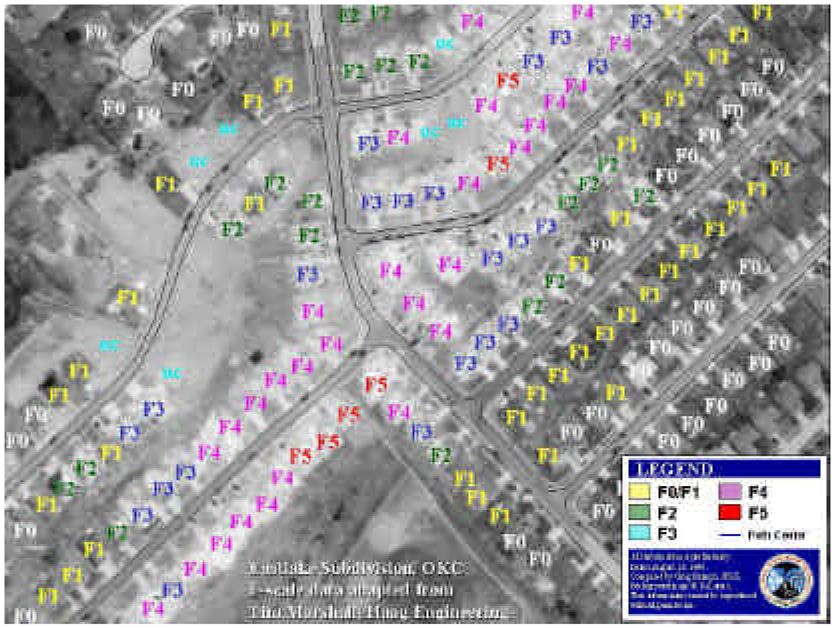

Figure 42. Example of detailed street map, showing home locations and F-scale estimates (Image courtesy of the National Severe Storms Laboratory).

e. Other gear

Everyone on the team should be carrying a flashlight, with extra batteries. This light is useful for identifying important clues in devastated structures, where it is virtually certain that there will be no power for building lights. A note pad and a clipboard, with pencils (with an eraser) and pens allows for documentation of observations. A supply of large capacity plastic bags with "zip" closure can be used to protect maps and notepads from precipitation. Drinking water and snack food, may or may not be available during a site survey – team members probably should carry a small amount of water and food. Rain gear is also an important consideration, as some of the survey may have to be done while it is raining. On the other hand, in case the survey is done in bright sunshine, sunglasses and sunscreen are helpful. A good pair of work gloves can be helpful if it becomes necessary to handle debris. A daypack to carry cameras, film, tapes, and the other gear is recommended to keep hands free during the process of scrambling over and through debris. The team should have one reasonably extensive first aid kit, with bandages, antiseptic creams, over-the-counter pain relievers, sunburn ointments, etc.

When documenting structural details (e.g., see Appendix 1), it is important to have a tape measure – the team as a whole should have at least one large tape measure capable of measurements up to about 100 ft, but 6-10 foot tape measures for individual team members will suffice. It is often useful to have the tape measure included in the documentation photographs, to provide an accurate scale.

f. Communication

It is common for the team to split up the tasks during a survey if a comprehensive review of the damage is to be done as quickly as possible. This means that some form of communication will be needed to coordinate the separated team members. Cell phones are a possibility, but experience after major disasters suggests that cell phone service might be erratic or non-existent. Ideally, short range, battery-powered radios are an ideal way for the team to stay in contact during times when they have split up. The usual range for these is no more than a mile or two, but the team should probably not get much more separated than their radios permit, anyway. These radios are relatively inexpensive and provide the team with added security in case someone has an accident. Typically, the batteries for these radios will need recharging at least once per day.

2. Credentials

As a way to prevent looting after disasters, the effected area is usually closed down and cordoned off for several days after a major event. Gaining access to the area for purposes of a damage survey requires that everyone on the team carry credentials that identify them as someone authorized to be present within areas of restricted access. The need for credentials as soon as possible after the event means that obtaining them is another task that cannot be done at the last minute. Although individual team members may not be known until a team can be organized after the event has occurred, *the coordination needed to get credentials for everyone should be worked out in advance*. Learning just whom it is that the team leader needs to contact in order to obtain credentials should not be put off until after the event occurs. Every NWS office should know how this is done and who the responsible authority is for all the communities within their County Warning Area (CWA). Depending on the circumstances, state, county, and city officials may need to be consulted. Ideally, NWS personnel will meet with those individuals for all the primary metropolitan areas within their CWA in advance, so everyone is prepared to obtain the team's credentials expeditiously after (or even before) a disastrous event.

3. Potential aerial survey opportunities

Given that aerial surveying is expensive, it might seem that many surveys would have to be done without the benefit of access to aircraft for the survey team. However, there are several options that can be considered to help secure this valuable resource at little or no cost. It already has been suggested that having an aerial survey can be a critical part of a thorough assessment of the situation, so these opportunities need to be pursued in advance. Again, trying to arrange for an aerial survey on the morning after a major disaster is going to introduce delays into the process, at the very least. In fact, if this has not been done in advance, it is likely to be very difficult to put something together at the last minute.

One option is to inquire about the possibility of securing a seat on an aircraft (fixed-wing or helicopter) operated by a local television (TV) station, if the community is large enough to support news aircraft. It is possible that TV stations will be willing to cooperate on such a survey in exchange for the favorable publicity. Although the team cannot be asked to provide an endorsement for that TV station, it can be argued that being cooperative with the survey team is good public relations. Be sure to make them aware that the needs of a damage survey are likely to be different from those of the station. A TV station may not be willing or able to help with a lengthy survey flight, but *any* aerial survey is better than none.

A related possibility is finding a seat on law enforcement aircraft. Again, this is only possible in communities large enough that the local law enforcement can afford to use aircraft. If the local community cannot afford it, the *state* might be able to offer a seat on state-operated law enforcement aircraft for purposes of a disaster-related damage survey.

In many communities, the Civil Air Patrol (CAP) can be contacted about securing an aircraft for purposes of a damage survey. They are committed to helping the NWS with this task, when asked – the NWS and CAP already have a Memorandum of Understanding (MOU) in place for this purpose.

If there is a military installation with aircraft nearby (Air Force, Army, National Guard, etc.), they also might be willing to provide aircraft after a local disaster. The "trick" to these options, of course, is to let them know *in advance* about the possible need for such a contribution. If the responsible authority is amenable to the idea, then the details for how that might happen should be worked out well before a storm-related disaster occurs, of course.

Finally, some citizen in the area might be willing to provide and pilot an aircraft. The number of people with private pilot's licenses is growing all the time and even someone on the local NWS staff may be able to obtain and fly an aircraft in support of a damage survey. Weather offices often have considerable interaction with the civil aviation community, so they might have contacts that would be ready to help out in case of an emergency.

Note that in requesting aircraft for use in an aerial survey, the best aircraft are helicopters and those with high wing attachments. Aircraft with low wing attachments will not provide adequate views downward.

D. Planning the survey

1. Multiple team coordination

In major weather-related disaster surveys, it is not uncommon for several survey teams to be sent in. In some communities, private sector aerial mapping teams are sent out under contract to provide local officials with information about the extent of the damage. Structural engineers (from federal agencies, universities, and/or private sector companies) may send in a survey team. The NWS may deploy a Service Assessment team following major weather-related disasters. The NWS also has a Quick Response Team (QRT) that can be deployed within 18 to 24 hours of an event, to determine the final F-Scale rating for all tornadoes that are suspected of producing greater than F3 wind damage. For major weather disasters, the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) will coordinate with all the federal agencies participating in the National Post Storm Data Acquisition Plan (NPSDAP). The OFCM will notify the appropriate NPSDAP members, if other agencies deploy a field survey team. Unfortunately at times, disparate survey teams may not even know of the very existence of the other teams, so communication and coordination among multiple survey teams can be minimal or even non-existent.

Hopefully, it is clear that this is a much less than optimal strategy in the face of the numerous challenges of doing a meaningful survey of a storm event. Without coordination, for instance, the same information may have been secured multiple times, and the different teams may arrive at different conclusions simply because they had not seen what another team used to draw its conclusions. The information may have been paid for several times, as well, which certainly is not a good use of limited survey resources. Moreover, even when the teams set about collecting different kinds of information, having access to data taken from different perspectives can be crucial in trying to understand the event. Therefore, the local team coordinator needs to make it a goal to find out as much as possible about who might be interested in information about a weather-related disaster, and seek out any and all local, county, state, and federal agencies, individuals, and private sector companies who might be involved in (or at least interested in the results from) a post-storm survey and therefore might be sending out a survey team.

2. Priorities

Not every survey team is charged with the same priorities. The team leader has to ensure that the mission objectives will be met in the time allotted for the survey. Typically, teams are made up of volunteers, which the team leader will need to keep in mind. In fieldwork, it is quite likely that a number of unanticipated issues will arise, some of which might be in conflict with the initial survey objectives. The team leader should be responsible to inform the team about the objectives and for decisions about *changing* priorities, after seeking input from all the team members and coordinating the process with the sponsoring agencies, if necessary.

For their part, team members need to be mindful of staying focused on achieving the goals for which they were brought in to accomplish during the survey. Each team member might well be providing expertise unique to that team, and that expertise will be necessary for achieving the survey objectives. Any other tasks done by individual team members should not compromise the mission objectives, but team members nevertheless should be encouraged to be creative during the survey. Various science and engineering "targets of opportunity" might present themselves that would significantly enhance the value of the survey, and team members should feel free to share these ideas with the team. The team leader must have the authority ultimately to decide how the team has to operate to finish their mission. For their part, team members will need to subordinate any special interests to the goals of the survey.

3. Comprehensive coverage

An important part of the team's priorities is to determine in advance just how comprehensive their survey can be in the time allotted. If the event is a major tornado outbreak comprising dozens of tornadoes, it might not be possible to survey every tornado with identical rigor. It is common to focus on those tornadoes that inflicted the greatest damage and casualties. In the event of a large outbreak, then, a decision will need to be made before the team even begins its fieldwork about which tornadoes will be given priority. For tornadoes that produce a large damage area (e.g., 10 km^2 or larger), it may be necessary to prioritize the work within a single tornado track, be it an isolated event or a member of an outbreak. If there are multiple teams in the field, it should be possible to coordinate the effort and minimize the redundancy of the surveys. This option depends on the individual team missions – if team missions are very different, then it might be necessary to have more than one team cover the same areas. This means that the team leaders should coordinate their missions with all other teams, in advance insofar as that is possible.

Clearly, the goal in damage assessment is to be comprehensive, and to avoid situations where a serious assessment error is made simply because the team failed to review the entire track. The time allotment for the survey and the size of the survey team should be matched to the event, ideally.

4. Coordination

a. Other survey teams

This issue has been mentioned several times, simply because it is a critically important component of a successful survey. Survey resources are typically limited, as is the time available. Coordination with other teams sent out by other agencies can be difficult. At times, the very existence of those other efforts may not be known during the survey. Therefore, it behooves the team leader to be aware of other possible groups who would do a survey. Coordination among Federal agencies has not always been well done in the chaos following a disastrous weather event, to say nothing of private sector groups, state and local authorities, and the local military. However, for major weather disasters in the future, the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) will coordinate with all the federal agencies participating in the National Post Storm Data Acquisition Plan (NPSDAP). The OFCM will notify the appropriate NPSDAP members, if other agencies deploy a field survey team.

In the absence of such coordination, it turned out after the 3 May 1999 tornado outbreak that a team of foreign national military officers was training in central Oklahoma and did an overflight of the main tornado track. This resulted in a high-resolution aerial mapping of that track, but no one knew that this flight was being done or that the aerial mapping images were available at the time some of the surveys were underway. The overflight was just something that happened, rather than being part of a coordinated plan. Hopefully, such valuable contributions after disastrous weather-related events in the future will be coordinated properly. The team leaders will need to make contacts well before an event, and when (and if) the event occurs, they will need to contact the responsible authorities to see if any survey-relevant activities will be undertaken. Just knowing whom to contact is the critical step.

b. Law enforcement

If the team is to do their job properly, coordination of the survey with law enforcement is a critical necessity. Do not assume that simply belonging to a responsible agency is enough to gain access to areas cordoned off. Those subordinate authorities who staff the barricades and decide who does and does not pass need to be aware that this specific team might at some time seek access to their area of responsibility. Subordinate authorities are generally only empowered to *refuse* requests for access – seeking approval of requests that have *not* been arranged beforehand is usually only possible if someone farther up the "chain of command" is consulted, and who is empowered to make the decision to grant access. Seeking this person is time-consuming and could be frustrating. If the team encounters some subordinate authority figure who is not willing to allow them access to an area, and it is not possible expeditiously to obtain the necessary approval, the team is advised to *avoid additional confrontation* with anyone barring access. Simply move on, and if the authority to pass can be conveyed to the local responsible authorities, the site can be reviewed later.

c. Emergency responders

If the team can begin their survey the morning after a major event, it is likely that access to some areas will still be blocked by debris. Those responsible for responding to such emergencies will be very busy dealing with the event, and may not be able to divert resources to assist the survey team. In such cases, it is likely that the team will simply have to make the best of the situation. An important part of coordination with emergency responders is to have up-to-the-minute information about the progress of the clean-up. Emergency responders put a high priority on clearing roads to allow access by emergency vehicles, so knowing the status of the roads is an important part of coordinating the survey. Areas may have to be surveyed in the order by which they become accessible. Team leaders should be aware of who are the local authorities responsible for emergency response. An awareness of the survey team's needs is helpful to emergency responders, who can incorporate those needs into their planning, but like many other aspects of a storm survey, the contact by the survey team leader needs to be made *well before* an event happens. Otherwise, emergency responders will have no input from the survey team and will establish their priorities without incorporating the survey team's needs.

E. Safety

1. On the ground

Safety on the ground during a survey must always be a major factor in deploying the survey team. Many hazards can be present in the immediate aftermath of a tornado (or other windstorms). These include, but are not limited to, such things as live power lines on the ground, gas leaks, hazardous material spills, aggressive or venomous animals in the debris, unstable piles of debris, sharp objects in the debris (glass, nails, broken timbers, etc.), and so on. Moving about through debris is a necessary part of doing a damage survey, but the team needs to be reminded constantly of the hazards they will encounter. Ideally, everyone should have a current tetanus booster shot, as puncture wounds are a very real possibility during a survey. Be aware of the possibility that a debris pile masks a hidden hazard, such as a swimming pool or a hole into which a team member could fall. Only a moment of carelessness can result in a serious accident.

Team members should not just wander about on their own; at no time should any team member ever be alone and out of contact with the team. In the event of an accident involving a team member, procedures need to have been planned in advance and arrangements for emergency treatment made. It's ideal to have *all* team members trained in first aid, but in the absence of this, the team should include at least one or more who are so trained. The team leader should be aware of the presence of emergency responders in the vicinity of the team's survey operation, since they will often have the capability to provide emergency treatment after an accident. This document cannot dwell on the details of first aid, but one rule that everyone on the team should know is that when people have been impaled by large objects (larger than nails or splinters), *those objects should not be pulled out* during first aid. Rather, the objects should be stabilized in place and the victims passed on to medical professionals as soon as possible.

Sanitation is also an important part of safety during a ground survey. Tornado damage swaths may be seriously contaminated with various hazardous materials and sources of infection. Wearing work gloves can reduce the possibility of contamination or infection when working in debris piles.

2. In the air

If one or more aircraft have been obtained for aerial survey purposes, the pilot should already be aware of the general requirements for safe aircraft operation. This will naturally include coordination with other aircraft operating in the vicinity. The team member(s) who will be riding on the aircraft need to work out (in some detail) with the pilot what the team's aerial needs are and the capability of the aircraft to meet those needs (see Appendix 4) before take-off. At no time should the survey operation compromise the safe operation of the aircraft.

Whatever the situation regarding aerial survey opportunities, it is useful to inquire about the pilot's background. Experience and Instrument Flight Rules (IFR) qualification are important to safety. If there is any doubt about the pilot's ability to accomplish the survey safely, seek another aerial survey choice. Note that during the aftermath of a damaging tornado, the airspace over the path can be crowded, so having an experienced pilot is a necessity, not a luxury.

Not all survey team members are equally good candidates for participation in an aerial survey. If the individual is prone to being airsick or has difficulty in aerial "navigation" this can lead to problems that could compromise the mission. Most people today have some flying experience, but often only in commercial aircraft. If someone on the team has experience in small private aircraft, such a person is more likely to be successful in the aerial part of a damage survey.

F. Courtesy

1. Interacting with victims

At all times, the survey team should be mindful of the impact that tornadoes can have on the victims. Their homes and possessions have been damaged or even swept away, they and their loved ones may have experienced serious physical trauma, and they will inevitably have suffered psychological trauma. In spite of all the devastation they may have experienced, many victims are surprisingly willing to provide information to the survey team. The victims should be made aware that information provided by them to the survey team will be of value in learning from the disaster – their assistance can help many others. Victims of natural disasters are often seeking to find meaning in what has happened to them, and that may explain why they are willing to cooperate with the survey team.

a. Sensitivity to their situation

It's possible that victims may say and do things that are known to be incorrect. They might believe erroneously that they have experienced the worst part of the event, or they thought they saw things that are physically impossible, for instance. You should avoid any arguments with victims about what they may have seen or experienced. If you disagree with them or don't believe their accounts, keep that to yourself. Listen to what they have to say about their experiences with the respect that you would hope to receive if your situations were reversed. For most victims, their first experience with a tornado or damaging windstorm will be the worst they've ever seen and have no basis for comparisons. The trauma of financial loss, in addition to physical harm to them and the people they know will be beyond your comprehension if you've not also experienced similar losses. Being a good listener is not only helpful to your team goals, but is also helpful to the victims.

b. Rendering aid

If the survey team is successful in commencing the survey on the morning after the event, it is possible that victims will be found who need medical attention. Team safety considerations suggest that at least one team member should have first aid training; this also is valuable in rendering medical aid to victims. Obviously, any such medical aid should be the minimum required to allow the victims to be passed on to medical professionals as soon as possible. In addition to medical treatment, victims may need other types of assistance. Generally speaking, the survey team is not in a position to provide much direct assistance. Instead, the survey team leader is responsible for providing the team members with information about where victims should be directed for various types of assistance. This will need to be coordinated with the emergency responders who are working the event.

2. Interacting with law enforcement

Law enforcement after a weather-related disaster is primarily concerned with keeping most people *out* of affected areas. At the level of the people staffing the "barricades," their default authority is to *deny* access. As already discussed, access for the survey team throughout the affected area should have been coordinated with all the relevant law enforcement authorities before the team begins its survey. At no time should any resistance that might be encountered to survey team access become confrontational – simply move on and attempt to find a higher authority empowered to grant access. In general, the team's survey operations are always subordinate to the needs of law enforcement authorities.

3. Interacting with the media

Various media representatives may be encountered during the survey. Generally speaking, the team leader should be the primary point of contact with all media representatives. Cooperation with the media is encouraged, wherever it does not conflict with the accomplishment of the survey mission. This may include granting recorded interviews at the discretion of the team leader and the individual team members, time permitting. The team should not be drawn into speculation about the event before all the information has been collected and evaluated. Discussion of any aspect of the situation that is not directly pertinent to the survey is strongly discouraged – the team is responsible only for their survey duties and should not engage in any discussion (positive or negative) about other issues associated with the event.

III. Evaluating the situation

Once the fieldwork phase of the survey is completed, a meeting of the team to discuss their findings will be necessary. Generally speaking, the assessment of the situation is not limited to determining an F-scale rating for the tornado(es). Although the F-scale rating is probably going to receive the greatest public scrutiny and attention, there are many facets to the survey, including both scientific and engineering contributions. The nature and extent of these issues (i.e., beyond establishing the F-scale) is determined when the objectives of the survey team are defined, naturally

A. Arriving at an F-scale

There are some general notions that can be used to provide a proper F-scale estimate, based on what has already been discussed herein (and within the references). As a *starting* point, the F-scale criteria (cf. Table 1) can be taken literally, at least with regard to the damage seen for frame homes. This initial evaluation then must be continuously re-evaluated on the basis of the detailed information about structural integrity obtained during the survey.

Any level of damage must be considered in the light of structural integrity, not just the extreme manifestations of damage where structures are leveled by the storm winds. If homes close to the extreme damage have similar construction but did not have comparable damage, it is *logically* possible that the most intense part of the tornado missed those nearby structures. However, there may be other explanations. For example, if a home has been unroofed, that is nominally at least F2 damage, but if it turns out that only one point of such damage can be found and that particular home has a notable weakness in the attachment of the roof, whereas nearby homes have lesser damage, then an F2 rating may not be appropriate. Another possibility is that the *orientation* of the home relative to the path of the tornado is different than those nearby homes, especially if it appears the damage was initiated by the failure of a weak point, such as a garage door. It's important to consider the construction details of nearby homes that did not experience the highest damage levels. If they're similar, that suggests the differences in damage are more likely to be associated with variation in the windspeed rather than variations in structural integrity, but this does not imply *certainty* in this regard, unfortunately. Even in cases with *similar* construction, minor detail variations in structural integrity might still be involved. Tornadic winds seek out the weakest link in a structure to initiate failure.

When attempting to determine F-scales from damage to something other than frame homes, it can become complicated. As already noted, *engineered* structures may have known failure thresholds – when they have been damaged but total failure did not occur, then those thresholds can be considered as estimates of the windspeed. When total failure occurs, the engineering thresholds can be considered as lower bounds to the windspeed. If failure does not occur, those thresholds are upper bounds to the windspeed. Note that some effort may be required to find the detailed information about engineered structures and their failure thresholds. This information will almost certainly only be found through some research.

When considering damage to something other than frame homes and engineered structures, F-scale estimation becomes much more problematic. If large, heavy objects have been moved, that movement can be a clue to intensity. If heavy objects have been dragged or have tumbled along the ground, this implies a lesser windspeed than if they become truly airborne for some distance. The *lack* of movement of some heavy object in the path is also a critical clue to the windspeed.

It's important to determine, when possible, if an object that has clearly become airborne was intact when it became airborne, or it was broken into smaller pieces prior to being lofted. It can difficult to sort out just what the sequence of damage was, as objects can disintegrate when striking the ground and the fragments scattered *after* impact, or the disintegration began while the object was airborne, or the object may even have begun to disintegrate *prior* to the pieces becoming airborne. Evidence from the survey should seek to make such distinctions, if possible, as they can have a direct bearing on the assessment of windspeed. It takes a stronger wind to make a large intact object become airborne than to loft the pieces of a disintegrating structure. Ground marks along the track from where an object was located before being moved (or the absence of any such ground marks) are the means by which the process of movement of an object can be understood. If an object were dragged, it would leave a more or less continuous scar along the track. If that object were tumbling, it would leave a series of impact marks along the track. Only if it was airborne would there not be a ground track showing the path of the object from where it was originally to where it was found. Often, objects are dragged or tumbled for a time before becoming airborne.

Pavement scouring, as discussed previously, seems to be associated with relatively high intensity storms, but that relationship is not clear. That alone would not be considered sufficient for an F4-F5 rating, but might justify an F2-F3 rating. Stripping of vegetation to the ground might imply similar things about a tornado's F-scale – insufficient to justify F4-F5, but perhaps supporting an F2 rating in the absence of any other information. It is not possible in this document to provide guidance for all such possibilities. The survey team will need to consider all the information available to make reasonable assessments.

Total destruction seems to establish a *lower* bound to the windspeed, but the structural integrity puts an *upper* bound on what a reasonable windspeed might be. For example, it is widely accepted that total destruction of a mobile home occurs at windspeeds comparable to F2 damage. In the absence of damage to objects other than a mobile home, total destruction of a mobile home usually cannot be used to rate the windspeeds higher than F2. In a similar way, roof removal seems to establish F2

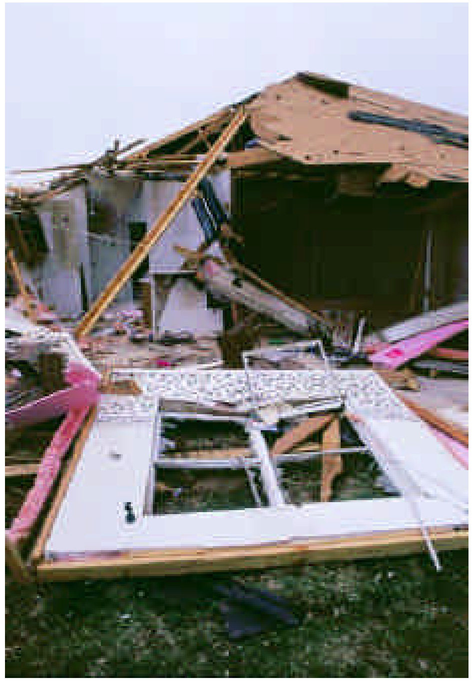

Figure 43. (Previous page) A frame home with little or no damage on its *front*, the side of the home facing the tornado. Note the damage to the home behind that in front, *farther* from the tornado (which has lost much of its roof), and the debris filling the space between homes in front. (Above) Damage to the *rear* of the home seen in the top photograph, caused by elements of the roof from the home across the street, behind it (FEMA photographs by C. Doswell).

windspeeds, but if the attachment is poor, that same damage cannot justify an F2 rating. Depending on the particular details, roof removal might occur at F1 or even F0 windspeeds. Consider the example shown in Fig. 43: This home's front side (facing the tornado) suffered only minor damage (supporting an F0 rating) as a *direct* result of the tornado, but was heavily damaged on its *rear* side by projectiles flying across the street from a house even farther from the tornado track that had a poorly-attached roof dormer. The roof damage to the home across the street, apart from the loss of the dormer, would not support an F2 rating, even marginally.

Using the information from a detailed documentation (Appendix 1 and 2) of structural details associated with frame homes permits some generalizations. If an attachment is weak, then the F-scale rating based on a superficial application of Table 1 needs to be reduced by one F-number (or possibly even two or three). On the other hand, if the structural integrity has been enhanced with such things as metal strapping, the F-scale number might have to be *increased* by one F-number in some cases. Such complexities virtually preclude an accurate F-scale rating from a *superficial* review of the damage – there are many things to consider and it does everyone a disservice to draw hasty conclusions before all the information has been reviewed and considered in the context of the full range of observations.

B. Mapping the damage

Any survey should produce a damage map for all the tornadoes surveyed, including an estimate of the F-scale along the track wherever possible. As discussed by

Speheger et al. (2002), the resources available to the survey team will determine the extent to which a detailed mapping of the event is possible. In some cases, only one or two of the tornadoes in an outbreak will be subjected to a detailed survey. If a comprehensive aerial survey is done, at least the damage tracks can be documented and mapped. In addition, an aerial mapping should document the *orientation* of the debris as extensively as possible. This can be helpful in distinguishing converging from diverging debris, which is helpful in distinguishing tornado tracks from downbursts (Fig. 44)

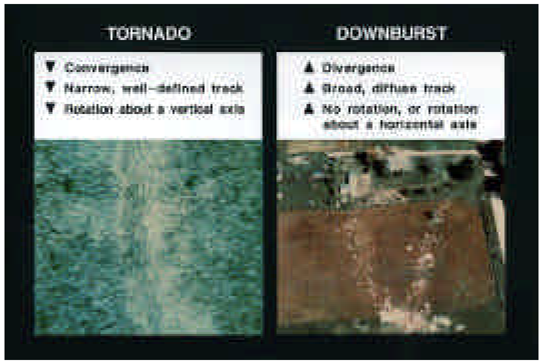

Figure 44. Illustration of the difference between tornado (left) and downburst (debris) damage from the air.

If only portions of the event can be surveyed from the air, other damage tracks may have to be estimated from whatever information about them is available. The team should be clear in its assessment about the extent to which each part of its evaluation has been carefully documented. If other survey teams were in the field, the survey team doing the assessment should make every effort possible to combine the results of other surveys with its own and to give appropriate acknowledgment for all its information sources.

Some discussion has already been offered about the possibility of overlapping tracks in a tornado outbreak. The team might need to be aware of recent other events. For example, the tornadoes of 3 May 1999 in Moore, Oklahoma, passed over some areas affected by a tornado from the previous fall – care should be taken during an aerial survey to learn of any recent damage tracks from earlier storms, to avoid confusing those earlier damage tracks with those from the event being surveyed.

Note that the damage path and the visible funnel are not likely to be exactly coincident, so video information does not necessarily have to be directly reconciled with the damage track. There is no scientific evidence to suggest that the edges of a condensation funnel or debris cloud coincide precisely with the radius of maximum winds or the boundaries of the damage. In fact, for fast-moving tornadoes, the funnel cloud axis most likely does not coincide with the center of the damage path, because the motion produces asymmetry in the ground-relative windspeeds of a moving tornado. Radar reflectivity can be enhanced by debris when the radar is close enough to the tornado, so operational radar data might offer some clues about the onset of damage, but operational radar data usually cannot offer much detailed information about the width and intensity of the damaging winds.

Storm chasers can provide considerable useful information to the survey team, but some effort to seek out and obtain their video and chase logs will be needed. The widespread availability of inexpensive consumer video cameras means that many tornadoes have been captured on video during some or most of their tracks through populated areas. As with storm chasers, some effort will be needed to obtain such documentation. In some areas, television stations operate chase teams and/or storm spotters. Their information should be sought to provide as complete a coverage of the event as possible. This can help document such things as multiple-vortex phases of the event and satellite tornadoes, which can be very helpful in sorting out the findings from a ground survey. It may even be possible to identify nearby downbursts from video and still images taken by chasers, citizens, or spotters.

The damage path is likely to be complicated by a number of factors already mentioned: asymmetries in the wind field, complex time and space structure to the windspeeds, structural characteristics of objects within the track of the tornado, "cones of damage" produced by weak structures on the margins of the damage path, subvortices, satellite tornadoes, downbursts occurring nearby the tornado, bands of damaging inflow to the base of the tornado, and so on.

C. Establishing the temporal sequence of events

It is not uncommon for severe storm reports to include erroneous information about the location and timing of tornadoes (see Speheger et al. 2002). This can cause various problems for the survey team: events can be missed; overlapping tracks can be confused; and, so on. The stopping of clocks does not necessarily determine the time of a damaging event; power might have been lost *before* the damage occurred, for instance. It's apparent that clocks in homes and in cameras will not be synchronized to a common time, so it's common for conflicting timing of events to be characteristic of the information going into a survey. It requires some considerable effort to come to a timing of events that is the most likely reconciliation of all the available information.

Radar data can be quite helpful in the task of producing a best estimate of the timing of events. Nevertheless, the team should be aware that even the radar data is not necessarily the ultimate standard. The timing and location of events relative to the radar echoes (and Doppler data, if available) is not a constant for all events or even from moment to moment during the same event. It will generally take several iterations, using *all* the available information, to develop what is a consensus solution to the timing of events. The team should seek to incorporate such information as the timing of power line breaks, but be aware that power line breaks may not pinpoint the location of the tornado in time and space – the lines may go down before the tornado actually reaches them, and falling lines can cause lines to break for some distance away from the tornado. Power line breaks are just another piece of the puzzle.

In some instances, good timing information can be obtained from the call logs to "911" or other emergency centers. In pursuing such a source, it's important to be able to distinguish the difference between the time of the call and the time of the event.

IV. The importance of accurate assessment

Obtaining an accurate assessment of the F-scale rating is important from a number of different perspectives. The F-scale represents an explicit recognition that not all tornadoes are the same; that is, not all tornadoes are equally capable of damage. In the absence of direct windspeed measurements, the F-scale is derived primarily from damage assessments. There have been some limited opportunities to compare windspeeds measured using mobile Doppler radars (e.g., Wurman 2002, Burgess et al. 2002), and it appears that those observations can be roughly consistent with the damage assessments leading to the F-scale rating. Forecast and warning accuracy and skill are dependent on feedback from verification. In turn, verification necessarily depends on having accurate and comprehensive information about actual events. Therefore, storm damage assessments are important contributors to forecast and warning improvement, by providing information about the storm events. If forecasts and warnings are to improve, then obtaining accurate storm damage assessments is a critical part of that improvement process.

Society also has a need for the information provided. If there is to be a positive result from storm damage, it is derived from the knowledge we gain from a careful and comprehensive assessment. This includes more than just a single number (the F-scale rating), of course. Thorough mapping of the damage, establishment of the temporal sequence of events, distinguishing between tornado and downburst damage, and so on – all these help to determine the meteorology of the event. The value of meteorology to society is considerably increased when it can be combined with the engineering, in an effort to develop strategies for minimizing casualties and property damage. For example, tornado safety rules have evolved over the years as we have learned more about tornadoes and their effects on structures. It is likely that the learning process will continue and, therefore, the safety rules may change as a result. As we learn more about the interaction between wind and structures, improved construction practices can lead to fewer casualties as well as reduced damage (Doswell and Brooks 2002, Marshall 2003).

Careful damage assessment also benefits the climatological record of events. This record is the basis for many scientific and engineering studies, whatever its shortcomings might be. It is recognized that the existing record of events is not perfect (e.g., Doswell and Burgess 1988, Kelly et al. 1978), but it is important for many users other than meteorologists.

The resources available for use in damage surveys are such that only a handful of events that represent the most devastating storms will be given a comprehensive assessment. However, the very infrequency of detailed surveys makes each one of them correspondingly more important. They are the benchmarks that provide the best information about significant events. Moreover, the cases chosen for comprehensive study set the standard by which routine, less detailed assessments are done. This has an impact on the whole record, not just the few cases per year that warrant a major effort. Generally speaking, it's a challenge to go back to the existing record and have the capability to improve the accuracy of the existing data set. This makes getting it right when doing surveys in the present even more important. If we can't fix the past very effectively, at the very least we need to set new standards for thoroughness and accuracy, so that the climatological record, as seen by our successors in the distant future, is a significant improvement over what we now have.

The challenge is clear: those doing surveys need to take it upon themselves to attempt to maintain high standards for their work. There may never be sufficient resources to do major surveys for more than a few cases in any given year, but each such survey team has an obligation to make their work as comprehensive and accurate as their resources permit. They need to be creative in seeking ways to magnify the resources at their disposal, and this necessitates substantial planning long *before* the event occurs. Everyone that is potentially involved in such a survey should consider what needs to be done to make that survey as successful as possible, even though the odds that they will actually be involved are relatively low. Surveys done on the spur of the moment, without prior "groundwork" to increase their capabilities and to get the team into the field expeditiously, will not be able to achieve much. The keys to a well-done survey are: planning, taking advantage of personnel with needed experience, and creative use of available resources.

Appendix A. Wind Damage to Residences Assessment Form

GENERAL INFORMATION ABOUT THE HOUSE
1) Name of homeowner
____
2) What is the house address?
____
3) What year was the building constructed? _____________ Building Code (if known) ______________________
4) What is the surrounding terrain?   Urban (Exp. A), Suburban (Exp. B), Open (Exp. C), On lake/ocean (Exp. D)
5) Where is the house located?   In a forest, In middle of the block, At a street corner, On a hill, In a valley.
6) What is the number of stories? 1, 1-1/2, 2, 3, split level. Describe ____________________________________
7) What direction does the front of the house face? N NE E SE S SW W NW
8) What is the shape of the house plan?   Rectangular, L-shape, U-shape, H-shape, Other _____________________
9) What type of cladding is on the house? Brick, Stone, Wood, Vinyl, Metal, Stucco/EIFS, Other_____________
10) Does the house have an attached garage? YES NO   If so, is it 1, 1-1/2, 2, 3.
11) What are the sizes of the garage doors? 1 car wide 2 car wide ___________feet
12) Where is the attached garage located on the house? N NE E SE S SW W NW
13) Which direction does the garage face?   N NE E SE S SW W NW.
14) What appurtenances are on the house? Awnings, Gutters, Shutters, Patio Cover, Antenna Other _________________
15) What is the number and location of windows? ________________ Sliding glass doors? ___________________
16) Is there a chimney? If so, what is the type and location on house? ____________________________________
17) What appurtenances are around the house? Storage Shed, Fence, Air conditioner, Other Type ___________________
18) What is the number and location of windows? ____
19) Location from tornado center N NE E SE S SW W NW   Estimated distance from tornado center _____ feet.

FOUNDATION COMPONENTS
20) What is foundation type? Slab, Pier & Beam, Concrete, CMU, Stacked brick/block, Timber piles, Masonry, Other __________________________________
21) How is the bottom plate or sill attached to the foundation? Bolted, Shot Pin, Strapped, Clipped, Nailed, None
22) Describe the number, type, interval, and length of fasteners in foundation ______________________________
23) Are fasteners installed correctly? YES NO If no, explain ____.

24) Did house fail at the foundation? YES NO If yes, explain where it failed.______________________________

WALL COMPONENTS

25) How is the wall cladding fastened to the framing? Nailed, Stapled, Brick, Ties , Other _________________________

26) Did cladding fail? YES NO If yes, explain where it failed

____

27) Are the walls standard 2 x 4's at 16 inches on centers? YES NO If no, explain__________________________

28) How is the bottom plate fastened to the stud? Straight-nailed, Toe-nailed, Strapped, or Clipped

29) Describe number, type, interval, and length of fasteners at base of wall________

____

30) Are nuts and washers secured properly on the bolts? YES NO If not, describe___________________________

31) Did walls fail? YES NO. If yes, explain where it failed____

ROOF COMPONENTS

32) What is the shape of the roof? Gable, Hip, Gambrel, Shed, Flat, Mansard, Other explain__________________

33) What is the type of roof covering? Asphalt shingles, wood shingle/shake, tile, metal, other ______________

34) How is the roof covering fastened? Nailed, Stapled, Clipped, Loose hung on battens, Mortared_____________

35) What is the age of the roof covering? ____ years

36) What is the type of roof deck? Plywood, Oriented strand board (OSB), Wood plank, Other________________

37) How is the roof deck attached and at what intervals? Nailed ___ inches apart Stapled at ___ inches apart

38) Did roof deck fasteners penetrate into rafters? YES NO. If no, explain________________________________

39) How is the roof framed? Rafters and joists or Pre-manufactured trusses Other

____

40) How are the rafters or trusses fastened to the top of the walls? Toenailed, metal straps, Other _______________

41) Describe number, type, interval, and length of rafter/top plate fasteners________________________________

42) Did roof fail? YES NO. If yes, explain where it failed

____

43) Did roof covering fail? YES NO. If yes, explain where it failed

____

Appendix B. Illustrations for Frame Home Damage Assessment Checklist

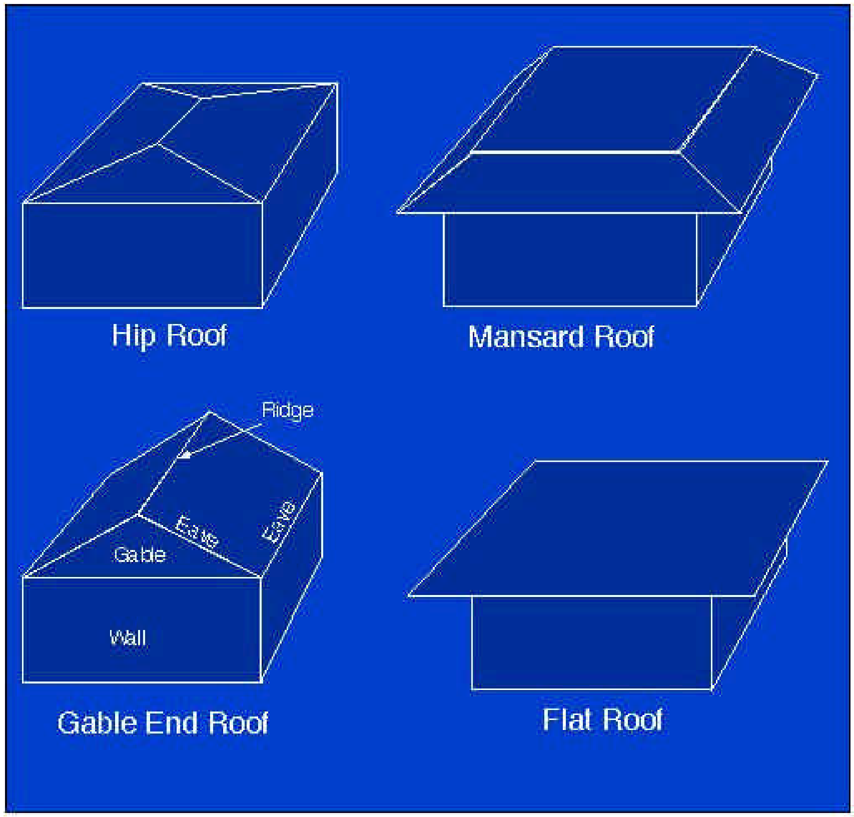

Figure A2.1. Illustration of roof terminology

Figure A2.2. Attachment of bottom plate by shotpins. [Photograph © T. Marshall, used by permission]

Figure A2.3. Attachment of wall studs by *toenail* connection. [Photograph © T. Marshall, used by permission]

Figure A2.4. Cut nail, often powder-driven, used to attach bottom plate to foundation slab after the concrete has hardened. Note the relatively shallow penetration of the cut nail. Often, the impact of the nail shatters the concrete, leaving the nail essentially unattached to the concrete beneath the bottom plate. [Photograph © T. Marshall, used by permission]

Figure A2.5. Bottom plate attached with strapping to the foundation, showing *straightnail* connection of wall studs to the bottom plate. The wall studs simply pulled out under lift forces, leaving the plate still attached to the foundation. [Photograph © T. Marshall, used by permission]

Figure A2.6. Example of a metal clip reinforcing the attachment of wall studs to the bottom plate. Note the bottom plate is bolted to the foundation with a nut and washer. [Photograph © T. Marshall, used by permission]

Figure A2.7. Example of metal clip reinforcing the attachment of the wall studs to the top plate. [Photograph © T. Marshall, used by permission]

Figure A2.8. Example of a metal clip reinforcing the attachment of the roof trusses to the top plates. [Photograph © T. Marshall, used by permission]

Appendix C. Procedure for Assessing Wind Damage to Wood Framed Residences

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Presented at THE SYMPOSIUM ON THE FUJITA SCALE AND SEVERE WEATHER DAMAGE ASSESSMENT, 83rd Annual Meeting, American Meteorological Society, Long Beach, CA., February 10, 2003.

1. INTRODUCTION

The authors have developed a procedure for assessing wind damage to wood-framed residences. This procedure has been utilized by the authors for the past twenty years when determining the extent of damage to buildings from tornadoes, hurricanes, and straight-lined winds. In order to develop the procedure, the authors have compiled information on various building construction techniques as well as analyzed how wind forces interact with buildings and their environments. There are a number of helpful references on the subject including papers by Minor et al. (1977) and Bunting and Smith (1990). Many myths associated with wind effects on buildings have been discussed by Minor (1976, 1982) and Marshall (1992).

This paper presents an overview of how wood-framed residences are constructed as well as how they fail. We will discuss how to recognize flaws or "weak links" in buildings that cause them to fail at relatively low wind speeds. It is hoped that this procedure will help inspectors better determine F-scale ratings (see Fujita, 1971). Although this paper is limited to wood-framed residences, the general principles can be applied to other types of buildings.

2. LOGISTICS

It is important to begin assessing the damage as soon as possible after the storm as cleanup operations begin immediately. Important weather information can be gathered and interviews with local National Weather Service Officials are helpful. Local officials can be contacted to obtain permission to enter the disaster area just after the event. Business cards and magnetic signs provide identification. Sometimes hard hats are required when entering damaged buildings. With major disasters, other storm damage teams from the Federal Emergency Management Agency (FEMA), National Association of Home Builders (NAHB), National Weather Service (NWS), National Roofing Contractors Association (NRCA), as well as various university-sponsored teams might be in the area. These teams eventually will publish storm damage summaries that may be helpful. An aerial survey can help provide an overall extent of the damage path quickly and interesting areas can be identified for later study on the ground.

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It is important to have proper equipment for inspecting damaged buildings. Detailed road maps are essential. Still and video cameras can be utilized to document the damage. A wide-angle lens helps capture the overall damage scene whereas a zoom lens captures specific details. A second camera is a good idea to serve as a backup in case the first camera malfunctions. Faster film speeds help freeze images when moving. Wearing dark clothes also limits camera reflections. A notepad with writing pens and a tape recorder are beneficial to record photograph locations and observations. A tape measure is helpful to determine the distances between objects and fasteners as well as obtain dimensions of building components and projectiles. A hand-held GPS (global positioning system) receiver can help pinpoint ground locations especially if road signs are destroyed.

3. GENERAL INFORMATION

There are many characteristics about a home and its surroundings that should be documented. An easy-to-use "questionnaire" summarizing essential information is included in Appendix A. The name and address of the homeowner are important to locate the house on a map. Also, the year the house was built can determine what building code(s) were in effect. First, walk around the house to determine how susceptible it was to the wind. Homes in urban, suburban, and forested areas may be shielded somewhat from the wind. In contrast, homes situated in open, unobstructed terrain, on hills, besides lakes or oceans, on street corners or at the end of city blocks may be more exposed to the wind. Document any debris (i.e. trees or other building components) that impacted the home.

Items susceptible to wind around the house include air conditioners, storage sheds, fences, trees, and backyard items like lawn furniture, portable spas, and trampolines. Items susceptible to wind on the house include awnings, gutters, shutters, patio covers, television antennas, chimneys, siding, windows, fascia and soffit trim.

Certain building configurations are more likely to sustain wind damage. In general, the higher the building, the more it is exposed to the wind and greater its potential for damage. Also, homes not anchored properly can slide off their foundations at relatively low wind speeds. Homes with attached garages sustain greater wind damage when the garage doors fail inward allowing wind pressure to lift the garage roof or push the garage walls outward. High profile gable roofs are more prone to wind damage than low profile hip roofs.

Wind interacting with a house is deflected over and around it. Inward pressure is applied to the windward walls and outward pressure is applied to side and leeward walls. Uplift pressure is applied to the roof especially along windward eaves, roof corners, and leeward ridges. The roof is particularly susceptible to wind damage since it is the highest building component above the ground. If the building is breached, wind enters creating internal pressures that can lift off the roof. Thus, damage to a home from wind typically begins at roof level and progresses downward and inward. The last place wind damage occurs is to the interior of the home. Catastrophic damage to a home usually occurs with failure of wall/foundation connections or roof/wall connections. Therefore it is important to examine these critical areas on a building.

4. FOUNDATION EXAMINATION

There are six common types of house foundations: 1) concrete slab, 2) pier and beam, 3) poured concrete wall, 4) concrete masonry wall, 5) stacked brick or block, and 6) timber piles or masonry and concrete columns. The inspector may encounter one or more of these foundation types in their damage survey. In general, homes on concrete slab foundations are usually found in the south and southwest U.S. Homes with basements or crawl spaces usually have poured concrete or masonry walls and are found in the upper Midwest and southeast. Houses on stacked brick or blocks typically are found in rural areas, especially in the southern United States. Timber piles and masonry or concrete columns are utilized to support homes in coastal and flood-prone areas.

4.1 CONCRETE SLAB FOUNDATIONS

Homes on concrete slab foundations usually are bolted or strapped to their foundations. However, some municipalities have adopted variances in the building codes that allow shot pins or cut nails. Figure 1 shows common types of foundation anchors.

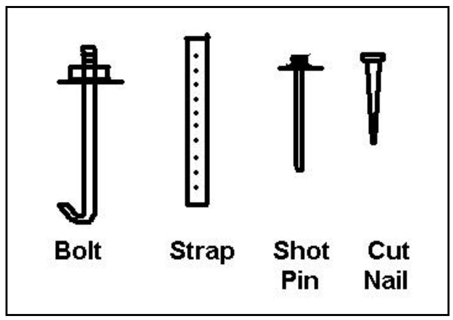

Figure 1. Common types of foundation fasteners.

Anchor bolts are at least 1.3 cm (1/2 inch) in diameter and 30 cm (12 inches) long and have a J-shaped profile that provides significant pull-out resistance. The anchor bolt is inserted into the concrete slab while it is poured with a depth of at least seven inches and must have sufficient height above the slab to pass through the plate and accept a steel nut and washer. Anchor bolts are spaced 1 to 2 meters (3 to 6 feet) apart and located within 30 cm (12 inches) of the end of the plate and wall corners (Figure 2).

Figure 2. Properly bolted bottom plate. However, note the weak straight-nailed connection between the wall studs and bottom plates.

Anchor bolts must be inserted properly into the concrete slab foundation. We have found anchor bolts placed too deep in the concrete to engage the nuts. We also have found bolts placed outside or inside of the wooden sills or bottom plates. Thus, these homes were not anchored to their foundations. Also, nuts and washers must be fitted on the anchor bolts and tightened snug to secure the plates. This might seem obvious, however, we have found numerous bolted plates and sills without nuts or washers. A properly anchored sill or bottom plate is a strong connection and rarely fails. Instead, failure of the home is more likely where the wall stud is nailed to the bottom plate (Figure 3). Therefore, homes that are bolted down to their foundations are not necessarily well-built or wind resistant.

Figure 3. Failure of this home occurred where the wall stud was nailed to the bottom plate.

The bottom plate is either straight-nailed into the wall stud and/or the wall stud is toenailed into the bottom plate (Figure 4). A pair of 16d (8.9 cm or 3.5 in) common nails often are used for this connection. Although such a connection will meet the minimum requirements in most building codes, it is inherently weak when uplifted (Figure 4).

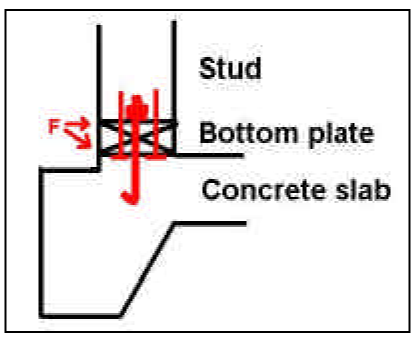

Figure 4. Typical wall cross section on concrete slab foundation showing a bottom plate bolted to the foundation and straight-nailed into the wall stud. Connections and failure points ("F") are in red.

Marshall (1983) conducted pull tests on pairs of 16d nails that connected plates to studs. For straight-nailed connections, the average pull-out strength was 984 N (220 lbs.) with a standard deviation of 375 N (84 lbs). For toenailed connections, the average pull-out strength was 1313 N (295 lbs) with a standard deviation of 304 N (68 lbs). Canfield et al. (1991) conducted similar pull tests with similar results. However, they could increase the average pull-out strength to 1842 N (414 lbs) if the wood did not split when nailed. By comparison, Canfield et al. (1991) also conducted pull tests on metal "hurricane" clips and found an average strength of 5341 N (1200 lbs) depending on the type of clip used. Thus, a metal clip can be about three times stronger than a 16d (8.9 cm or 3.5 in) toenailed connection (Figure 5).

Figure 5. A metal clip connecting the wall stud to the bottom plate provides considerably more uplift resistance than conventional straight- or toe- nailing.

Besides anchor bolts, bottom plates are attached to the concrete slab with metal straps, shot pins, or cut nails. Metal straps can be just as effective as bolts in anchoring the bottom plate to the foundation if they have proper thickness and are installed correctly (Figure 6). The straps are typically made from 18 gauge metal (1.2 mm or .0478 inches) and are perforated for the fasteners. Steel shot pins look like thick nails and literally are shot into the foundation with a powder actuated hammer. Shot pins are typically 7.6 cm (3 inches) long and have an accompanying washer (Figure 7). Unfortunately, cut nails sometimes are used to secure the bottom plates to the foundations. Cut nails are easily pulled through the bottom plate when the plate is uplifted or rotated. Building codes do not allow the use of cut nails, however, some building officials have allowed cut nails to secure interior (not perimeter) walls. Unfortunately, we have found many homes where cut nails were installed around the perimeter of the foundation (Figure 8).

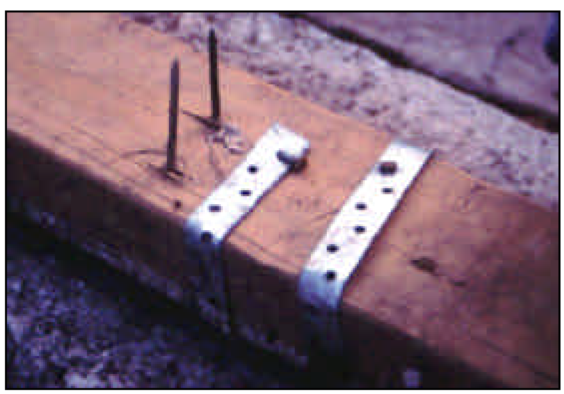

Figure 6. Metal straps held the bottom plate in place, however, failure occurred where the wall stud was straight-nailed through the bottom plate.

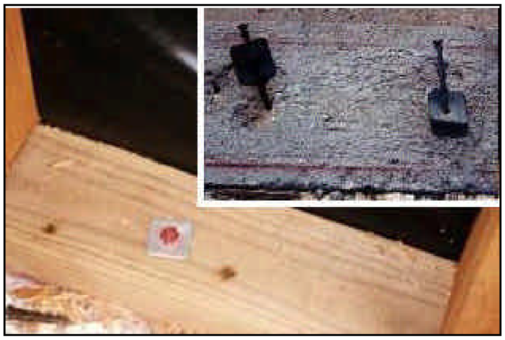

Figure 7. Shot pin with attached washer in the bottom plate. Inset photo shows aftermath of tornado where bottom plate broke around the fasteners.

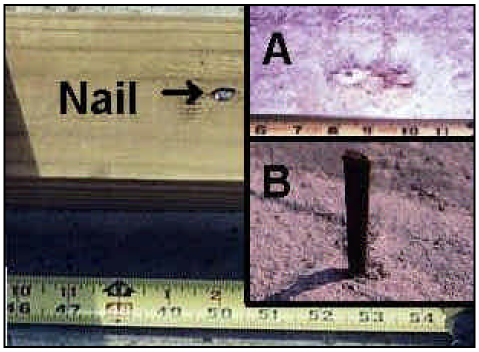

Figure 8. Cut nail in the perimeter bottom plate was a violation of the local building code. Inset photograph A shows scrape mark in the slab after wall slid off foundation. Inset photograph B is a cut nail left in the foundation after home was blown away.

4.2 PIER AND BEAM FOUNDATIONS

Pier and beam foundations usually are made of different materials. Piers can be wood, loose block, masonry, or concrete. Perimeter grade beams are usually poured-in-place concrete or masonry. The same types of anchors are used to secure the house to the beams as with concrete slab foundations. However, floors are supported by the piers and

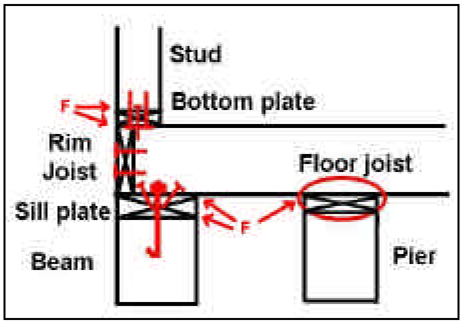

Figure 9. Typical pier and beam foundation showing connections and failure points (in red). However, piers are rarely attached to the flooring (circled).

rarely anchored (Figure 9). Note the floor platform separates the walls from the foundation, resulting in more nailed connections. In general, the more nailed connections in a foundation, the greater the chances for a poor connection. The authors have identified failures at each of the nailed location points in this type of foundation. Usually, the anchor bolted sill plate remains. Homes on pier and beam foundations tend to shift off their foundations and sustain more catastrophic damage (Figure 10).

Figure 10. This home shifted and disintegrated from its wooden pier and concrete beam foundation. Floor joists were not attached to the piers.

4.3 POURED CONCRETE WALL FOUNDATIONS

Poured concrete wall foundations are found in homes that have basements or crawl spaces. A concrete footing supports the foundation wall. The wooden sill plate is either bolted or strapped around the perimeter of the foundation. Floor joists typically are toenailed to the sill plate. A center beam extends across the middle of the basement or crawl space and is supported by columns and slotted into the perimeter wall. The center beam and columns are either wood or steel (Figure 11).

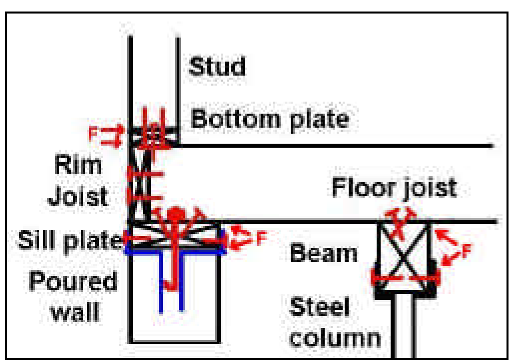

Figure 11. Typical cross section of a poured concrete wall foundation showing nailed and bolted connections with failure points (in red) and strapped connections (in blue). Center beam is wood or steel.

A common failure point is where the bottom plate is secured to the floor. The bottom plate is straight nailed to the floor at certain intervals and the nails usually miss the underlying floor joists. Thus, this connection has little resistance to lateral wind loads and the connection simply pulls apart as the wall is rotated (Figure 12). In many instances, the authors have found nails driven into the open joint between the rim joist and the floor joist leaving the wall virtually unattached. The floor platform usually remains if properly anchored to the foundation.

Figure 12. Straight-nailed bottom plate pulled out of the floor as the wall rotated. This was an inherently weak connection (circled).

A more catastrophic failure occurs when the connection between the floor joists and sill plate fails. This results in the entire home sliding off its foundation. The authors also have found no attachment of the center beam to the floor joists especially if the center beam was steel. Also, doors and windows in the foundation wall can weaken its lateral resistance leading to overturning of the foundation wall (Figure 13).

Figure 13. Exit door weakened the concrete wall foundation (circled). The foundation wall rotated and broke apart at the opposite corner. Steel rebar was used only at the wall corners. The house was pushed into the ravine in the background.

4.4 MASONRY FOUNDATION WALLS

Masonry wall foundations are constructed with concrete masonry units (CMU). These units have open cells that are stacked in a common pattern with mortared joints. The connection of the house to the foundation is similar to that of concrete foundation walls. However, the top cell is usually filled with mortar or concrete where the anchor bolts or straps are placed (Figure 14).

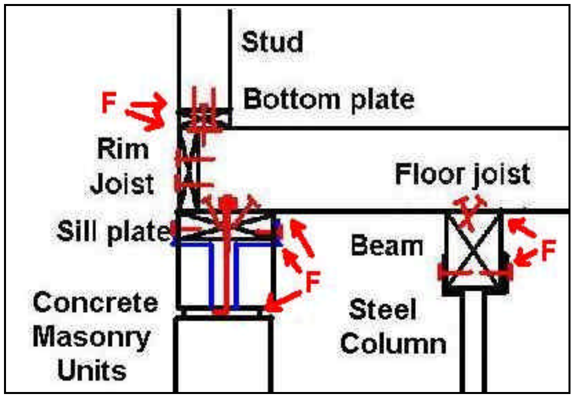

Figure 14. Typical cross section of a masonry wall foundation showing nailed and bolted connections (in red) and strapped connections (in blue). Center beam is wood or steel. Failure of this foundation type frequently occurs at areas denoted by the letter "F".

Unreinforced concrete masonry foundations are inherently weak in resisting lateral and uplift forces and frequently fail causing the house to slide along with the top row of concrete masonry (Refer to Figure 15). Interestingly, building codes in high wind areas require steel reinforcement to extend through the cells all the way down into the footing.

Figure 15. This home shifted off its foundation when the masonry foundation failed. Inset photograph A shows that the top row of masonry was attached with J-bolts as shown in inset photograph B. Note how little damage there was to the roof.

4.5 LOOSE BRICK OR BLOCK FOUNDATIONS

Homes constructed on loosely stacked brick or block foundations are not anchored and can be easily shifted from their foundations (Figure 16). Such homes can be "swept clean" from their foundations resulting in F-5 damage on the Fujita scale with wind speeds less than 45 m/s (100 mph).

Figure 16. Unanchored home on stacked CMU foundation slid 90m (295 ft) off its foundation.

4.6 PILE OR COLUMN FOUNDATIONS

Homes elevated on timber pilings, or concrete or masonry columns usually have substantial anchoring of the floor system. Weak points in this type of construction are where the bottom plates are nailed to the floors or where the wall studs are nailed to the bottom plates. Use of hurricane clips or straps can provide a much stronger connection provided they are installed properly and are protected from corrosion due to salt

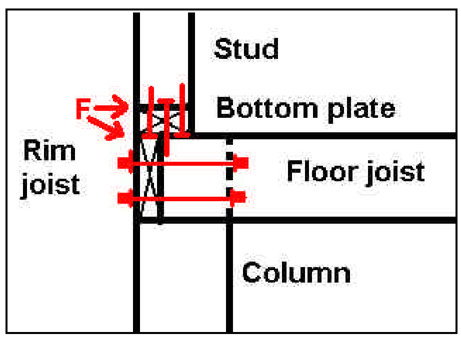

Figure 17. Typical cross section of home elevated on timber piles, concrete or masonry columns. Floors are usually bolted or strapped to the columns (in red). Common failure points are the nailed connections where the wall is attached to the floor.

Figure 18. Wind damage to a home elevated on timber piles. Failure commonly occurs where the walls are attached to the floor.

exposure. Wind damage to these homes usually involves loss of the walls leaving the floor intact (Figures 17 and 18).

Although rare, the pilings or columns can fail when they are not adequately braced or extend sufficiently below grade.

5. WALL EXAMINATION

Wood-framed walls need to be braced properly to stiffen the frame and resist racking from lateral loads. At a minimum, diagonal bracing or "let-ins" are required at all wall corners. Typically, wall studs are notched to receive a wooden board that extends diagonally from the top plate at the wall corner to the bottom plate and is nailed to the studs. Plywood or oriented strand board (OSB) is some times utilized at the wall corners, especially when diagonal bracing cannot be installed due to an intervening window or door (Figure 19).

Loss of brick veneer is a common problem due to improper attachment of the masonry to the wood- framed wall. Corrugated brick ties or wires must be imbedded at least two inches into the mortar joints and attached properly to the wall. Walls that are not attached properly are free-standing and can be moved even by applying hand pressure. Such walls can topple easily in relatively low winds (Figure 20).

Figure 19. Installation of solid sheathing at wall corners helps stiffen the frame. Top plate clips as shown in inset photograph A and diagonal bracing as shown in inset photograph B also stiffen the frame.

Figure 20. Brick ties (circled) were installed on this home but not engaged into the mortar joints. As a result, wind easily toppled this unanchored wall.

Weak links in wall systems are large windows or doors that interrupt the continuity of the framing. In addition, failure of windows and doors allows wind to enter the building increasing internal pressures that can help lift the roof and push out perimeter walls. Garage doors are inherently weak and often fail in wind speeds as low as 36 m/s (80 mph). The doors buckle or pop off the door tracks allowing the wind to enter the garage (Figure 21).

Figure 21. Inward failure of garage door led to outward failure of sidewall and collapse of the garage. Note little damage to remainder of home.

6. ROOF EXAMINATION

Roof systems typically are held in place by gravity. Thus, minimal attention is given to wind uplift effects. Typically, the rafters or trusses are toenailed to the wall top plates and this type of connection will meet most building codes (Figure 22). However, this connection is inherently weak when uplifted. Rafters or trusses will break away from the top plates. It is less common for the top plates to separate. Metal straps or clips can secure all of these members together.

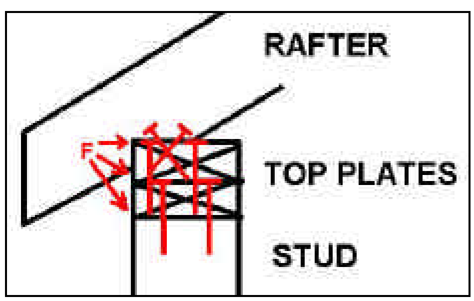

Figure 22. Typical cross section of roof/wall top plate showing nailed connections and common failure points (in red).

The authors have found numerous examples where rafters and trusses were not fastened adequately to the wall top plates. Nails had split the wood or were driven through knots or other defects in the wood (Figure 23). As a result, the entire roof was susceptible to being removed in relatively low wind speeds. Properly installed hurricane clips or metal straps can strengthen this connection greatly. A house that is missing its roof usually had poor attachments at the tops of the walls.

Figure 23. Nails driven through rafters and ceiling joists protruded through the top plate and split the wood. A better connection would have been to install metal clips as shown in the inset photograph that places the nails in shear (strong) instead of tension (weak).

Rafters and trusses require proper cross bracing to resist lateral wind forces. Installation of ridge blocking and metal brackets can prevent the trusses from falling down like dominoes. Although gable ends are non-structural components, they are susceptible to being blown inward or outward depending on the wind direction (Figure 24).

Figure 24. Toppled roof trusses due to a lack of lateral bracing. A metal bracket (inset photograph) along with proper wooden blocking between the trusses would have prevented rotation of the trusses.

The shape of the roof also will determine its wind resistance. In general, gable and flat roofs are not as strong structurally as hip roofs. Hip roofs are more streamlined and are structurally stronger as each slope is supported by intersecting planes of the roof. This is one reason why many homes in hurricane prone areas have low-pitched, hip style roofs.

Roof decking is typically plywood, oriented strand board (OSB), or wooden boards. The decking is fastened at six-inch intervals and fasteners must penetrate into the underlying rafters or trusses. Commonly, pneumatic guns are used to drive fasteners into the decking and in some instances, the fasteners miss the underlying framing. As a result, the roof deck is not attached and is quite susceptible to being removed in the wind. The authors have found entire sheets of plywood fully clad with roof shingles in the debris around the home. Exposure of the rafters and trusses usually indicates inadequate deck attachment (Figure 25).

Figure 25 House that lost all of its roof decking on the leeward slope. Close inspection revealed that staples missed the underlying rafters (inset photograph).

There are many different types of roofing materials on residences including asphalt shingles, tile, metal, wood shingles, shakes, etc. Each industry has guidelines available for proper installation of the roofing product. Installation instructions usually are printed on labels accompanying the roofing product indicating the proper size, number and spacing of fasteners. Roof coverings also must meet the minimum wind uplift requirements as stated in the building codes. However, the authors have found numerous deficiencies with installations of roof coverings that have led to their removal in relatively low wind speeds (Figure 26). Common roof installation errors include placing fasteners too high on the product, overdriving, under-driving, or orienting the fasteners incorrectly. Tile roofs secured with mortar tend to unbond leading to tile removal.

Figure 26. Poor installation of the roof covering on this home led to its complete removal. Staples were installed crooked and under-driven (inset photograph).

7. DETERMINING THE F-SCALE RATING

Fujita (1971) developed the F-scale to rate the severity of wind damage to buildings. He rated homes from 0 to 5 based on the increasing severity of damage to "well-constructed" or "strong" wood-framed houses. The terms "well-constructed" and "strong" are subjective and debatable. Most homes have nailed connections, and these connections are inherently weak especially when wood members are fastened together in tension. Also, homes are not homogeneously constructed, so rating them without regard to knowing how they are constructed (or failed) will introduce large errors. Fujita (1992) realized this and introduced corrections to the F-scale to account for variations in building strength but did not provide an explanation of how to employ such corrections. Therefore, the authors provide the following descriptors to aid the inspector in assigning F-scale damage ratings.

Homes rated F0 lost a few roof shingles, windows, some siding, a chimney, a garage door or carport. Homes rated F1 lost a small portion of the roof structure and/or suffered collapse of the garage. Homes with F2 damage lost most of their roof but the exterior walls remained. However, if the roof was not fastened properly to the walls, the F-scale rating is reduced one. F3 homes lost their roof and exterior walls. However, if the roof or walls were not fastened properly, the F-scale rating is reduced one. An F4 rating means the house was reduced to a pile of debris on the foundation. However, if the roof or walls were not fastened properly, the house damage rating is reduced by two F-scale numbers or to the damage rating of the adjacent house(s). An F5 rating still means a house was swept away from its foundation. However, if the roof and walls were not fastened properly, the house damage rating is reduced by three F-scale numbers or to the damage rating of the adjacent house(s).

Fujita (1971) also assigned wind speed ranges that would cause F-scale damage. The wind speed ranges were derived empirically and have been determined by Minor et al.(1977) and others to be too high, especially at the higher F-scale numbers. Marshall (2002) showed that most wood-framed buildings suffered significant damage with wind velocities of only 45 m/s (100 m.p.h.), and most wood-framed houses are leveled by winds exceeding 62 m/s (140 m.p.h.). Interestingly, the design wind speed for most of the U.S. is a three-second gust of 41 m/s (90 m.p.h.) at 10 m (33 feet) above the ground in open, unobstructed terrain (Exposure C).

8. SUMMARY

Inspecting a house for wind damage involves careful examination of the building components from the ground, up. This paper presented a procedure for inspecting wood-framed buildings for wind damage. Common weak links associated with nailed connections were discussed and many examples were presented. A questionnaire was developed by the authors to aid inspectors in assessing a house for wind damage and assigning an F-scale rating.

9. ACKNOWLEDGEMENTS

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Appendix D. Equipment Checklists

Team Equipment:

- Short-range radios ___
- Cameras
  - Still cameras for each member ___
  - Film for still cameras ___
  - Video cameras ___
  - Videotapes ___
- Credentials ___
- Detailed local maps ___
- Tape measure (100 ft) ___
- First aid kit ___

Equipment for individuals:

- Credentials ___
- Hard Hat ___
- Safety shoes or leather boots ___
- Sunglasses ___
- Flashlight ___
- Note pad ___
- Pencils and/or pens ___
- Sunscreen ___
- Rain gear ___
- Water ___
- Snacks ___
- Day pack ___
- Work gloves ___
- Camera(s) ___
- Camera supplies (film, tapes, batteries, etc.) ___
- Flash for camera ___
- Tape measure (10-12 ft) ___

Appendix E. Aerial Survey Operation Strategy

The most important reason for an aerial survey is to provide a comprehensive overview of the damage (an excellent discussion of aerial surveys can be found in Fujita and Smith [1993]). If possible, the aerial survey should begin as soon after the event as is possible. During an aerial survey, it is important to identify key locations that should also be surveyed from the ground; notably, areas of the most intense damage.

An important component of an aerial survey is to obtain a mapping of the location and orientation of debris; for example, the alignment of fallen trees, and the direction of debris deposition. This is important information for trying to distinguish between tornado and downburst damage.

Assuming that at least one aircraft is available, then certain strategies should be followed, if possible.

1. If a fixed-wing aircraft is used, it should be a single-engine, high-wing aircraft. A low-wing aircraft or one with multiple engines can obstruct downward viewing angles.

2. Wear a dark shirt to minimize the effect of reflections of your apparel in the windows.

3. Bring some means for cleaning the windows of the aircraft before takeoff, and be prepared to remove condensation from them during the flight.

4. Be certain that any still camera's shutter speed control is set to 1/500 s, in order to reduce the effect of movement on the sharpness of the images.

5. Go over the survey plan in detail with the pilot before take-off, and be certain that the pilot is willing and able to fly the survey as desired. Note that the sun angle can be a factor in the effectiveness of the aerial photographs. Since this changes during the day, sun angle might be important in planning.

6. If possible, an attempt should be made to overview as much area as possible, to attempt to find all the damage paths within the survey area and to determine which are likely to be associated with tornadoes. This will involve some sort of relatively high-level search pattern over the area to be surveyed.

7. Once tornado tracks are located, the plane should fly *along* the entire track at a height that makes it possible to see the entire path width. For narrow tracks, this generally will be lower than for wide tracks. During this overflight of the track, the damage path should be mapped as accurately as possible using detailed maps.

8. After mapping the track, fly along the entire track again to take high-level, oblique-angle photographs along the track, for reference when analyzing the damage. Again, be alert to the effect of the sun angle in revealing features along the track, especially ground markings and vegetation damage. This might require some circling to explore the best viewing angle at the time for making the subject stand out.

9. After obtaining the oblique reference photographs, yet another relatively high-level flight along the path should be done, this time with the aircraft banked so that photographs from a nearly vertical angle along the track can be obtained. The level of the flight should be as constant as possible, at a height such that the entire width of the track at its widest point fits entirely within the viewfinder, and successive photographs should overlap by about 20% or so. This permits a reconstruction of the entire track.

10. Finally, a low-level flight along the track should be done to obtain detailed photographs of various points of interest along the track: cycloidal multiple-vortex marks, severely damaged structures, severe tree damage, debris tracks where large objects have left ground marks from being dragged or tumbled along the surface, unusual damage, and so on., Be alert for areas of damage not directly in the main track, that might indicate satellite vortices, nearby downbursts, "cones of damage" leading into the main track, isolated vortex "spin-ups" , etc.

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