Linking Survivor Stories to Forensic Engineering: How an Interscience Approach Reveals Opportunities for Reducing Tornado Vulnerability in Residential Structures

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ABSTRACT

When a tornado strikes a permanent or mobile/manufactured home, occupants are at risk of injury and death from blunt force trauma caused by debris-loaded winds and failure of the structure. Mechanisms for these failures have been studied for the past few decades and identified common weaknesses in the structural load path. Also under study in recent decades, much has been learned about how people receive and understand warnings and determine how, when, and if they will shelter in advance. Recent research, for example, shows most people do not shelter until close to impact, after seeing, hearing, or feeling the approaching tornado. To advance beyond these innovations, a new, multi-disciplinary approach was fielded in nine Southeast U.S. tornadoes between 2019 and 2022. For each tornado, 1) wind engineering assessments documented near-surface wind fields, 2) structural engineering assessments documented the primary wind load path for each structure, and 3) social science interviews captured the survivor’s narrative and asked several follow-up questions to assure key items of interest were addressed in each interview. When possible, the team was multi-disciplinary during the interview, enabling survivors to ask questions and better understand their experiences. Most survivors became aware of the approaching tornado with at least a few minutes lead time and most were able to reach a place of refuge. Most survivors recalled sensory experiences during the tornado and about half could describe direction or temporal sequences of damage. A case study

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of the Cookeville, Tennessee, Tornado of 3 March 2020 illustrates the power of the integrated data assessment.

CAPSULE
This multi-disciplinary work evaluated sheltering and survivability of residential structures and discovered many instances where information from survivors was invaluable for understanding how a tornado interacted with the residence.

SIGNIFICANCE STATEMENT
Linking an understanding of how tornadic winds interact with residential buildings with how human decisions affect survival has rarely been done due to the inherent complexity and cost of conducting joint social science, forensic engineering, and wind engineering assessments. Such work may reveal ways to reduce the number of injuries and fatalities caused by tornadoes. This study tested a multi-disciplinary protocol to holistically evaluate sheltering and survivability of individual homes for nine Southeast U.S. tornadoes. We found many instances where survivors’ stories, photos/video and access to structural elements were invaluable for understanding how a tornado interacted with the residence. Future efforts can advance these findings by focusing on severely damaged structures or severe injuries and through analysis of floorplans.

INTRODUCTION
Nearly 70% of the 2,237 confirmed tornado fatalities, and an untold number of severe injuries, since 1985 have occurred in homes (i.e., permanent or mobile/manufactured) (Ashley 2007; SPC 2023). Fatalities occur in homes when homes are severely damaged by tornado-induced wind loads and debris, putting occupants at risk of severe injury or death from blunt force trauma, crushing, and other mortality modes (Kuligowski et al. 2014; Chiu et al. 2013; CDC 2012). Given this well-known fact, there are two distinct paths towards achieving the societal goal of improving survivability in tornadoes.
The first is by recognizing that many homes, especially mobile and manufactured homes (Chaney and Weaver 2010; Strader et al. 2021), are vulnerable to severe tornado damage. On a long-term horizon, improving survivability would involve strengthening homes to resist EF2 or lower tornadoes and limit catastrophic damage in EF3+ tornadoes (Prevatt et al. 2012a). The intent of such performance goals is to keep sheltering occupants safe even if the home suffers some damage (van de Lindt et al. 2013). The engineering challenges of this path are not insurmountable, but the costs of strengthening to sufficient levels (Adhikari et al. 2020; Sutter et al. 2009; Kneifel et al. 2022), the legacy of existing vulnerable housing stock, enforcement of improved building code requirements, and other factors remain significant hurdles to widespread achievement, despite a few local successes (Simmons et al. 2015; Ramseyer et al. 2016; Malik et al. 2013). The most cost-efficient path forward might be to target specific locations within a range of home types and layouts, where strengthening a portion of the home or adding a wind-rated shelter would enable safer refuge on-site.

Thus, improving shelter-in-place survivability on relatively short time horizons would focus on identifying options for best available refuge or sheltering strategies when time available to shelter is minimal. Forensic engineering has long been a part of NOAA’s post-windstorm investigations (NRC 1993) and is particularly important following tornadoes. Forensic engineering assessments provide a means to quantify common damage mechanisms and infer correlations between the same (Roueche and Prevatt 2013), identify common weaknesses in the structural load path, and probabilistically assess physical damage conditioned upon wind hazard intensity, and are the primary means of estimating wind speeds for classification of tornado events (McDonald et al. 2012).

However, current scientific understanding of tornado-induced wind loads, debris impacts, and structural response remains fundamentally lacking (NIST 2016). Traditional post-tornado investigations are typically limited in that most only provide an assessment of the final, exterior condition of the building (McDonald et al. 2012; Burgess et al. 2014; Kuligowski et al. 2014; Prevatt et al. 2012b; Roueche et al. 2024b), which tends to bias the analysis and findings towards damaged buildings. Further, they are unlikely to be informed by video or other resident-provided evidence of damage sequence, especially in the most heavily damaged areas. Systematic access
to the interior of homes that served as shelters is needed to contextualize overall wind performance and sheltering performance within the context of the local hazards and the specific structural load path. Direct interaction with survivors can enable such access and provide opportunities for better informed assessment of survivability.

Regarding the second path towards improving survivability in tornadoes, NOAA NWS has recognized and prioritized the concept of an integrated warning team (IWT) whereby the publics are forewarned of danger through multiple channels of communication and urged to seek shelter in personal safe rooms or community shelters. As has been well-researched in the past, the effectiveness of such warnings in achieving safe sheltering actions is conditioned on factors such as the timing of the warnings (Simmons and Sutter 2008; Hoekstra et al. 2011), mode of dissemination by NWS and its partners (Fischer et al. 2022; Miran et al. 2019, 2018; Ash et al. 2014) mode of reception by the occupants (Golden and Adams 2000; Sherman-Morris 2010; Biddle 2007; Lindell et al. 2013), availability of safe sheltering options and access to them (Strader et al. 2019; Mason and Senkbeil 2014; Levitan 2013; Chaney and Weaver 2010; Schmidlin et al. 2009), language used in the warning (Sadiq et al. 2023; Donner et al. 2012; Nelson 2015; Perreault et al. 2014; Ahlborn et al. 2012), and social status of the warning recipients (Walters et al. 2020; DeWinter-Maciag and McPherson 2023; Phillips et al. 2005; Kashian et al. 2021). However, despite these investments in early warning systems, improved forms and channels of messaging, and increased numbers of community shelters in some locations, most warned residents remain in their homes during tornadoes and are not motivated to engage in sheltering actions until just before impact. For example, 77% of people in the path of the 2011 Joplin tornado did not take action until receiving a physical or environmental cue (Kuligowski et al. 2014). Klockow et al. (2014) found a similar situation in the Southeast during the 2011 April tornado outbreak, despite the event having been forecasted several days in advance. Most social science studies on sheltering focused on the presence, accuracy and receipt of warnings (Brotzge and Donner 2013; Sherman-Morris 2010; Simmons and Sutter 2008; Stokoe 2016); the decision processes taken by the residents (Klockow et al. 2014; Lindell and Perry 2012); and the timing of any actions taken (Kuligowski 2020; Nagele and Trainor 2012; Senkbeil et al. 2012). Survivors have rarely been used as a source of information to inform
engineering studies, despite their ability to recall the sequence of events even decades later (e.g., Johns 2012; Johns and LaDue 2014).

Despite the wide body of research on these two important paths toward increasing survivability of tornadoes, significant challenges remain in reducing the number of tornado fatalities occurring in homes. There is a critical need for further study explicitly linking human decisions and actions that affect vulnerability with the structural factors of the various types of homes occupants are seeking refuge in. Systematic study is needed of when and where survivors seek shelter in typical homes, how their homes are constructed with respect to mitigating wind damage, and how their homes, and specifically the potential sheltering locations within them, perform during tornadoes. This necessitates a multi-disciplinary approach linking the social sciences with forensic engineering and wind engineering / atmospheric science to holistically evaluate sheltering and survivability at per house levels.

The objectives of this study are to (1) present an integrated, interdisciplinary post-tornado assessment and interview protocol with social scientists and engineers working in concert, and (2) present findings from deployment of the protocol to characterize (a) the risk factors in relation to the tornado and surrounding environment, (b) efficacy of best available sheltering, (c) influences on decision-making regarding sheltering, and (d) the benefits of the interdisciplinary protocol to the represented disciplines.

DESCRIPTION AND DEPLOYMENT OF THE INTERDISCIPLINARY PROTOCOL

The interdisciplinary protocol developed and deployed in this study wove together elements important to the social sciences, structural engineering, and wind engineering. Specific methodological elements included survivor interviews, forensic structural engineering assessments, and documentation of wind speed and direction indicators, as illustrated in Figure 1.

Interviews were structured after Galea et al. (2007) and Kuligowski (2020), and began by asking the survivor for a narrative of events, beginning when they first became aware of the chance of tornadoes through when the storm impacted them. This helped them recall events and become more at ease. The authors then asked several follow-up questions to assure key items of interest
were addressed or addressed more completely, including: whether they were aware of the chance of tornadoes; what alerts or notifications they may have received; what they did just before storm impacted them; what the survivors heard, saw, and felt during the tornado; what they knew about the condition of their home prior to the tornado; and what they did to cope during and after the tornado. The survivor stories were collected mostly on-site through semi-structured interviews with the survivors, captured by a voice recorder. Interviewers had a check sheet to guide them on prompts and topics to engage the survivor and help maintain consistency between interviews. About one year after initial interviews were conducted, follow-up interviews were solicited with a subset of survivors to better capture coping and long-term recovery experiences.

The forensic structural engineering assessments focused on documenting the primary wind load path of the structure, any indications of the resistance of the various component and cladding elements (e.g., roof sheathing, vinyl siding), the component-level damage sustained by the structure, and the location and condition of interior sheltering options. Structural-focused data included images and videos captured by smartphones, GPS-enabled DSLR cameras, 360 cameras, and uncrewed aerial systems (UAS). Structural data also consisted of standardized survey forms that were collected on a smartphone via the Fulcrum app platform, which were based on the Structural Extreme Events Reconnaissance (StEER) data collection protocols (Kijewski-Correa et al. 2021). The survey forms prompted the documentation of the structural and geometric attributes of each structure. The extent of structural information collected for each interview site varied. Where possible, the structural assessments included interior inspections, utilizing attics and any accessible crawl spaces to evaluate the complete load path. In sites without interior access however, assessments were limited to exterior inspections that focused on quantifying overall damage levels. Additionally, the interviews queried survivors on structural details such as the year of construction of the residence and whether any retrofits or other wind mitigation measures had been performed. The survivor’s description and photographic evidence of the damage sustained to their own residence and surrounding residences was also solicited, as many times the damage state had been altered by the time the researchers arrived.

The wind engineering assessments focused on documenting the near-surface wind environment by means of available wind indicators, such as fallen poles, trees, signs, and other structures that could be used to infer wind speed and direction estimates. Wind indicators were documented
using GPS- and direction-enabled cameras that could record the precise location and direction of fall. The geometric and material properties of the wind indicators were also recorded when available to facilitate more precise wind speed estimates. During the interviews, information relevant to the wind engineering interests that could be solicited included timing and orientation of impact sequences (i.e., which side of the home was impacted first), mentions of pressure changes, and the duration of the event.

The decision to deploy the protocol described above was based on the location of the tornado, the density of structures impacted, the EF rating of the tornado, and the availability of the research team. For the study period, the authors prioritized events in the Southeast U.S. based on the source of funding. Priority was given to EF3+ tornadoes striking dense residential communities as this provided more opportunities to encounter and interview survivors and allowed for more representative characterizations of structural performance across a wide range of wind speeds. The team utilized purposive sampling that prioritized areas of interest within the tornado path from an engineering perspective, which typically included transects through the damage path, or areas with clusters of residences affected by the tornado. Social or demographic characteristics were not specifically targeted in the sampling. The goal was for the social scientists and engineers to be in the same location and interview the survivor(s) together, but sometimes it was necessary for the social scientist(s) or engineer(s) to conduct the interviews alone. Contact with survivors was made opportunistically while on-site, initiated by any members of the research teams. This sampling strategy typically yielded multiple homes with varying levels of damage and multiple opportunities to find survivors who nominally had the same amount of lead time, similar environmental cues, etc.

Data Handling and Synthesis
From the various engineering and social science data for each survivor, a synthesized dataset was curated for each residence that included such information as the total number of occupants, sheltering location(s), sheltering motivation, type of structure, type of foundation, number of
stories, whether a basement was present or not, year of construction, Degree of Damage\(^1\), location of the residence with respect to the start point and centerline of the tornado, what side of the tornado path the residence was located on, the time at which the first tornado warning included the residence, the time at which the tornado impacted the residence (based on analysis of radar images), and descriptions of what the survivors saw, heard, and/or felt. In addition, the recordings of the survivor stories were transcribed by a professional transcriptionist, and the transcripts were used to construct bulleted summaries of the events reported by participants in temporal sequence. The summaries and entire transcripts were coded for any comments relevant to the research questions. For all tornadoes, the interview summaries and transcripts were coded for any mention of any cues or communications that played a role in sheltering decisions, as well as for comments or responses that indicated which cue served as the precipitating factor in their decision to take shelter. Also analyzed were the relative importance of each factor and whether each factor had a positive or negative effect on the decision. The most common are reported below. Much of the data collected was beneficial to at least two disciplines (Figure 2). For four tornadoes, sufficient wind indicators were available and documented to facilitate generating a parametric tornado wind field conditioned to the wind indicator patterns following Rhee and Lombardo (2018), from which time histories of wind speed and direction could be estimated for any location of interest within the impact region.

\(^1\) Degree of Damage classifies the post-tornado condition of the building using a progressive damage scale unique to the type of building (e.g., school, one- and two-family residential). The Degree of Damage was assigned based on the guidelines of the Enhanced Fujita Scale (McDonald et al. 2004).
Figure 1. Geospatial components of data collection.
Figure 2. Interdisciplinary data collection and synthesis.

Interview Metadata

In total, the research team responded to nine individual tornadoes in four states in the southeastern United States (Figure 3) between 2019 and 2022, including two EF2 tornadoes, five EF3 tornadoes, and three EF4 tornadoes (Table 1). In responding to these events, the team conducted interviews and engineering assessments at 117 individual sites. The locations of the interview sites (i.e., survivor homes) collectively were scattered throughout the footprint of an idealized tornado path representing the various tornadoes, mostly within a region encompassing a quarter of the maximum tornado width (based on damage) on either side of the centerline (Figure 4). The majority (90%) of the interview sites experienced damage levels corresponding to EF2 or less, with 10% experiencing damage corresponding to EF3 or EF4 (Figure 5(a)), which is consistent with the distribution of intensities throughout major tornadoes (Banik et al. 2008). Many of the interview sites represented the behavior and experiences of multiple people who sheltered in the same location, as 85% of the interview sites had at least two people present at the time of the tornado (Figure 5(b)). The roles of the occupants varied, with 13% living alone, 40% living with other adult(s) (e.g., spouse, partner, or adult children), 46% living as caretakers of
dependents, and less than 1% being cared for by another adult. Most (55%) of the survivor interviews were conducted less than one week after the tornado event, and nearly all (89%) were conducted less than one month after the tornado event (Figure 5). A few (11%) were conducted more than 6 months after the tornado during follow-up deployments. Following the time of day classifications from Anderson-Frey et al. (2019), 57% of the interview sites experienced the first tornado warning during nighttime hours (more than 2 hours after sunset), and 16% in the early evening transition hours. Since 2000, 25% of all tornadoes and 33% of strong tornadoes (EF3+) in the Southeast (defined here as Georgia, Alabama, Mississippi, Louisiana, Tennessee, Arkansas, Kentucky, North Carolina and South Carolina) were nighttime tornadoes.

Figure 3. Geospatial summary of tornado events from which interviews were solicited and number of interview sites by county.
Figure 4. Standardized locations of interview sites with respect to the tornado centerline, and start and end points, by tornado event.
Figure 5. Select interview metadata, including (a) EF ratings of the residence at each interview site, (b) total occupants at interview site, (c) time of day of first warning issued at interview site; (d) delay between tornado impacts and first contact with interviewees.

Table 1. Tornado events from which survivor interviews were solicited.

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Event ID</th>
<th>Date</th>
<th>EF Rating</th>
<th>Path Length (miles)</th>
<th>Max. Path Width (yds)</th>
<th>Number of Interview Sites¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lee County #1</td>
<td>3/3/2019</td>
<td>4</td>
<td>26.6</td>
<td>1600</td>
<td>25 (9)</td>
</tr>
<tr>
<td>2</td>
<td>Lee County #2</td>
<td>3/3/2019</td>
<td>2</td>
<td>29.2</td>
<td>1300</td>
<td>2 (0)</td>
</tr>
<tr>
<td>3</td>
<td>Nashville</td>
<td>3/3/2020</td>
<td>3</td>
<td>60.1</td>
<td>1600</td>
<td>16 (1)</td>
</tr>
<tr>
<td>4</td>
<td>Cookeville</td>
<td>3/3/2020</td>
<td>4</td>
<td>8.4</td>
<td>900</td>
<td>12 (4)</td>
</tr>
<tr>
<td>5</td>
<td>Eufaula</td>
<td>3/31/2020</td>
<td>2</td>
<td>7.8</td>
<td>350</td>
<td>3 (0)</td>
</tr>
<tr>
<td>6</td>
<td>Fultondale</td>
<td>1/25/2021</td>
<td>3</td>
<td>10.4</td>
<td>900</td>
<td>3 (1)</td>
</tr>
<tr>
<td>7</td>
<td>North Shelby</td>
<td>3/25/2021</td>
<td>3</td>
<td>50.4</td>
<td>1100</td>
<td>3 (1)</td>
</tr>
<tr>
<td>8</td>
<td>Mayfield</td>
<td>12/10/2021</td>
<td>4</td>
<td>166</td>
<td>1760</td>
<td>33 (4)</td>
</tr>
<tr>
<td>9</td>
<td>Arabi</td>
<td>3/22/2022</td>
<td>3</td>
<td>11.5</td>
<td>320</td>
<td>20 (5)</td>
</tr>
</tbody>
</table>

Total: 117
Parentheses indicate the number of interview sites with multiple people present at the time of the tornado.

MAJOR OUTCOMES AND FINDINGS
Deployment of the survivor stories protocol provided a rich dataset linking survivor experiences, focused specifically on sheltering activities and decision making, with important contextual information on the structural resistance and performance, and the hazard characteristics. The following summarizes several key themes that emerged related to the objectives of this paper. Note that when statistics or counts of survivors are presented in the following sections, the numbers represent households of survivors, not individual occupants, unless specified otherwise.

Sheltering Actions and Shelter Performance
Sheltering actions varied among the interviewed survivors. Most of the interviewed survivors (N = 100) took some sheltering action, including 12% (N = 12) who initiated a sheltering action but were not able to complete it due to insufficient time. Regardless of whether a sheltering action was taken or not, most survivors (N = 101) ultimately were somewhere in their home or primary residence during the tornado. Only two survivors (~2%) sheltered in external storm shelters (both underground, residential shelters), while one left their home and sheltered in a community refuge area (courthouse). Only one reported sheltering in an in-home refuge\(^2\) in the basement. Five survivors left their own home to shelter in a neighbor’s home. Of those that sheltered in a home, most survivors (~65%) took shelter in what could be considered an a priori best available refuge area, described in FEMA (2011) as a small area on the lowest floor, in a small interior room without windows. Those that had time typically chose to shelter in an interior room (closet, bathroom, hallway) or basement (if available). Those that were not able to shelter in a best available refuge area knew that where they were sheltering was not ideal, but were unable to get to a better refuge area, primarily due to a lack of time. In the nighttime tornadoes, survivors were half as likely to reach their intended shelter relative to the daytime or early evening transition tornadoes.

\(^2\) Per Standohar-Alfano et al. (2015), refuge refers to a residential shelter consisting of a room that is hardened relative to typical construction standards, but does not meet the formal criteria of FEMA 320 (FEMA 2011) to be considered a safe room.
The survivors overall had good awareness of the best places to seek refuge in their home during the tornado to maximize their chances of survival given available options, potentially indicating that protective action messaging has largely been successful in this area. However, several survivors chose to shelter in optimal refuge levels (i.e., lowest floor), but non-ideal locations within the level (e.g., in a room with exterior wall and windows), suggesting more guidance may be needed on choosing the best area when all criteria for a best available refuge area cannot be met. For example, is it better to shelter in a basement where all rooms large enough to shelter occupants are exposed to exterior walls, or in the ground level floor above the basement in a room with no windows or exterior walls?

When survivors reached what could generally be considered a best available refuge area, the damage levels observed typically posed a low risk to life safety, with the greatest threat being from broken glass when survivors sheltered in refuge areas with a window. In seven instances, however, four of which were manufactured homes, and three were single-family homes built in 1985 or earlier, homes were pushed off the foundation and destroyed, compromising whatever refuge areas would have been available. In three of these seven instances, some or all occupants had left the home and sheltered elsewhere; however one occupant remained in a home and perished. In the other four instances, occupants sheltered in-home but survived the destruction.

**Influences on Decision-Making Regarding Sheltering**

For those that took some sheltering action (N = 100), 21% exhibited multi-stage sheltering of some kind, either shelter-based or occupant-based. In shelter-based multi-stage sheltering, some or all occupants sought shelter in one location first, before moving to another location later as the threat materialized. In occupant-based multi-stage sheltering, some occupants sheltered at one stage while one or more occupants sought shelter at a later time, for example after getting confirmation of a tornado through environmental cues or other threat indicators. These multi-stage activities were often associated with caregiving responsibilities such as trying to get children, pets, or elderly occupants safely into refuge areas.
For those that took some sheltering action (N = 100), multiple threat indicators were typically needed to motivate sheltering actions. Threat indicators included such events as a TV broadcast interrupting regular programming to cover a severe weather event, severe weather alerts (including tornado warnings) on a smartphone or weather radio, a friend or family member contacting the occupant to warn or inquire about plans, media partners mentioning specific local landmarks and directional information, radar images, environmental cues, and structural impacts. Most survivors mentioned multiple threat indicators during the sequence of events leading up to choosing to shelter, with a few having a negative impact on sheltering motivation, others having little to no impact, but most having a positive impact on sheltering motivation, meaning the threat indicators tended to at least heighten their awareness and readiness to shelter, even if they did not seek shelter right away (Figure 6). In 37 of the 74 survivor interviews (50%) from which the sheltering motivation was stated or could be explicitly inferred, environmental cues were the primary motivator for the initial sheltering actions. In many cases this led to incomplete or non-ideal sheltering actions as survivors did not have time to reach their intended refuge area.

Figure 6. Illustrative idealization of how various threat indicators work collectively to motivate sheltering behavior for (a) single stage, and (b) multi-stage sheltering.

Even if environmental cues were not the primary motivator for sheltering actions, most survivors reported a variety of sensory experiences during the tornadoes, either in response to interviewers’ prompts or offering details of the experience of their own accord. The primary sensory experiences included feeling pressure changes, hearing the tornado itself as well as its impacts to their structure, seeing a funnel cloud, flashes of light, or wind-borne debris, and feeling their
residence move or vibrate in response to the tornado. More specifically, 25 (21%) of survivors reported that their ears popped and 42% reported feeling pressure changes of some kind. Most survivors made comments about the loud noises during the tornado, due to the tornado itself (N = 71 reported the tornado sounding like a train, an engine roar, or other loud noise), and/or due to debris hitting the home (N = 84). A total of 42 survivors recalled that there was some form of movement of their home during the tornado, described as shaking and/or vibrating.

**Elements of Survivor Accounts Beneficial to Engineering**

Survivors offered various details that were useful to the engineers for better characterizing or understanding the tornado and its impacts. For example, about half of the survivors (N=58) described directional or temporal sequences of wind impacts that were of value in conditioning or validating wind field models of the tornado. Twenty-seven of the survivors offered an estimate of how long the tornado lasted, which helps in evaluating the size, translation speed, and location of the tornado core. Several survivors offered details on the construction of their home (e.g., the use of truss screws to fasten wood trusses to the walls) that helped explain its performance during the tornado or provided information on the expected resistance of the load path that would not have been captured otherwise. Many survivors were also willing to let the engineers conduct more thorough investigations of the load path through access to the attic or crawl spaces. Such access facilitated more in-depth load path assessments, particularly for homes that were less damaged than surrounding homes. An example of the structural and wind assessments that such access allowed can be found in Roueche et al. (2024a), which details structural findings from the March 22, 2022 Arabi, LA tornado that was a part of this study.

**CASE STUDY OF THE 2020 COOKEVILLE, TN, TORNADO**

The 2020 Cookeville, TN, tornado provides a case study of the interdisciplinary protocol and to resulting data. Cookeville, TN, was struck by an EF4 tornado just after midnight local time on 3 March 2020, causing 19 fatalities and destroying numerous homes and businesses. The authors deployed in Cookeville between 8–10 March 2020. Structural engineers initiated the deployment by imaging affected buildings within the entire tornado path using a vehicle-mounted 360 camera (NC Tech iStar Pulsar) and hand-held cameras. Using this imagery, along with public news reports and data in the NWS Damage Assessment Toolkit, the team selected a high-density cluster of homes within the path that also exhibited substantial treefall as a high priority area for
deployment of the interdisciplinary protocol. Once on the ground in the region, the engineers stayed in the same region as the social scientists so that interviews could be solicited from survivors encountered during the assessments. The wind engineering team focused on documenting tree-fall patterns in regions of the path with a high density of trees, using both ground assessments and an uncrewed aerial system. Exterior structural assessments were completed on representative structures within the cluster, and, when survivors were present, permission was requested to perform more detailed structural evaluations from all sides, including the interior if accessible. Asking permission provided a chance to talk with the survivor(s) and request an interview. If the survivor was agreeable, the interview was typically conducted immediately with both an engineer and social scientist present. At other times, contact was made, and a later time agreed upon to conduct the interview. At the end of each interview, the research team shared information on resilient construction practices from organizations and companies such as the Federal Alliance for Safe Homes (FLASH), the Insurance Institute for Business and Home Safety, and Simpson StrongTie, and answered questions from the homeowners, if any, on rebuilding. After completion of the deployment, data were processed as described in the previous section Data Handling and Synthesis. A parametric wind field was conditioned using observed tree-fall patterns, and wind velocity time series (with time step = 1 s) were generated for each location of a study participant in order to link the estimated hazard context with the survivor experience. In total, the research team conducted 12 interviews addressing 13 homes in close proximity to one another in Cookeville. Most survivors readily responded to the interview request. A few were hesitant, indicating they could only talk for a minute or two, but as interviews progressed, they became engaged and actively extended the interview. Most homes were built on-site between 2001 and 2006; two were built in the 2010s and one was a mobile home built in 1960. All participants were with at least two others, though one was initially alone in the mobile home and evacuated quickly to a relative’s home a block away. Nine participants had others within the home they were responsible for, mostly children under 18. All participants had homeowners' insurance.

The survivor stories were rich with details beneficial across disciplines, as illustrated by the select snippets from interviews provided in Tables 2–5. Despite the late hour, all but one person we spoke with attempted to shelter and many of them made it to a refuge location within their
home. About a third were already awake (Table 2), two of them for reasons other than weather. Another third woke up due to unusual environmental conditions in the minutes prior to the tornado and the remaining four woke up to warnings (phone alerts). Some of the warnings were received at the same time as environmental cues from the tornado itself (Table 3). Two participants received calls from friends or family. One was already beginning to shelter, but for the other, that call was the first she knew about the tornado and was the deciding factor when the first word she heard implored her with urgency: “Run!” Thus, all participants we spoke with were awake during the tornado and described a range of sensations (Table 4).

Many of the survivors were able to recount key moments in the timing and directionality of damage to their homes (Table 5). These details allowed for compelling comparisons between the survivor story and the engineering models, as illustrated by the example in Figure 7. In this home, the survivor recounted several damage sequence details that aligned with what was predicted by the wind field model. For example, the first window broke on the south side of the home that, according to the model, would have first experienced a rapid increase in wind speeds (windward wall) as the tornado approached. Other details challenged the engineering narrative of the damage sequence, including that a door on the north side of the home was blown in, rather than sucked out. Overall, the observed damage to this particular structure aligned well with the modeled wind velocity time series, with only minor damage on the east-facing side of the building and more severe damage on the west side which experienced the highest wind speeds. Similar comparisons for other homes would improve confidence in the accuracy of the parametric wind field model, which in turn would improve the hazard contextualization of all participants’ experiences.

Table 2: How study participants in Cookeville became aware of the impending tornado.

<table>
<thead>
<tr>
<th>Types of Ways Participants Became Aware</th>
<th>Quotation From the Interview</th>
</tr>
</thead>
<tbody>
<tr>
<td>A third of those we met in Cookeville became aware of the threat prior to environmental cues in their immediate area:</td>
<td>“I woke up, luckily. I was woken up with indigestion…and thought, it sounds kinda bad outside.” [CT007]</td>
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<td>“I had been up late playing video games…then turned on the news.” [CT003]</td>
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<td>A third woke from environmental cues:</td>
<td>“I work in Nashville and my team is in Nashville, so they were getting alerts indicating we had power outages all over.” [CT006]</td>
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<td>“I woke up…because it was just constant lightning…and my wife woke up because hail was hitting [the window].” [CT009]</td>
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<tr>
<td>“My wife saw the lightning. Really, really bright lightning. That’s what woke her up…” [CT010]</td>
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<td>“About 1:30 I heard some thunder. …I kept hearing thunder, and then all of a sudden, I heard the wind pick up…all of a sudden it just got really, really strong. …I’ve never heard anything like that.” [CT008]</td>
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<td>“…we had no warning, no notice. I believe that my phone warning went off at the exact moment that the tornado was here. My wife said, ‘what's that noise?’ I said, ‘that's a tornado, let's go.’” [CT012]</td>
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<td>The other four were awakened by the tornado warning:</td>
<td>“…there was only one warning on our phones. …We’re like, ‘oh, wow!’ We didn’t expect a tornado.” [CT005]</td>
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<td>“my phone went off, and before I could look at it, my phone rang. A buddy of mine…[got the warning before I did and] he said something didn’t feel right, so he called me.” [CT002]</td>
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<td>“I guess it was 1:45-ish. The phone started going crazy.” [CT001]</td>
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<tr>
<td>It was about 4 minutes from when we got the warning to when it hit. [CT004]</td>
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| One was awakened by a family member: | “[My brother] always calls me and says, ‘Hey watch the storm and keep an eye out or listen,’ …[or] he'll say, ‘There's a tornado. We've been watching it on the radar. It's coming your way.’
This time, he called and the very first word was, ‘Run!’ And that's all I had to know from him…” [CT011]

Table 3: Selected moments that illustrate sheltering decisions of Cookeville participants.

<table>
<thead>
<tr>
<th>Types of Sheltering Decisions Made</th>
<th>Quotation From the Interview</th>
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</thead>
<tbody>
<tr>
<td>Three decided to shelter with a just few precious minutes of lead time. This example also illustrates a multi-stage sheltering process we found in many interviews across the larger study:</td>
<td>“[My wife brought our son downstairs] because the weather was just spooking her. … [Then] I turned the TV on…and it said Bloomington Springs…and ‘Take cover.’ …So I [said], ‘Go get in the bathroom…in the tub.’” [CT010]</td>
</tr>
<tr>
<td>Most had little time to take action once they decided to shelter, with environmental cues a strong motivation. Two examples:</td>
<td>“I look outside [around 1:30-ish] and it's pouring the rain, which is generally a good sign as far as tornadoes go and I thought, well, maybe we're okay. …Ten or 15 minutes later. I mean I keep looking out the window and watching TV and [I hear], ‘Bloomington Springs take cover.’ And I look out the window and it was like everything was sucked out of sky. Water... Nothing's moving for a minute and then about that time I hear things blowing around and I can hear [fence panels] rattling around and I thought, okay, this is bad. …[I] run into the master bedroom to wake my wife up. …[Then] I ran…to her [my daughter's] bedroom, but by that time I didn't make it across the house.” [CT007]</td>
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<td>“…then our cell phone alarm went off. And for whatever reason, my wife grabbed her purse and her ring. …[After I tried to get my daughter up], I went and looked back out the back window, and by the time I was coming back to get her, I could hear it coming. I could hear the wind, just really</td>
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loud wind coming. And I told her. I said, ‘We got to go now.’ So, we had a little bit of time. Not much." [CT009]

This family received the warning at essentially the same time the tornado was starting to impact them:

“I was just trying to throw some clothes on. I was reaching for the bottom of my dresser, and I got slammed, and then I slammed into my bed and my bed broke. …I think I was getting sucked up, but everything fell on me. I remember I wasn't on the floor. I remember being in the air.” [CT005]

Two people we spoke with took essentially no sheltering action:

“after the explosion, I rolled off the bed for like... it didn't seem very long, like 15 seconds, and then it seemed like it was gone.” [CT008]

Table 4: Sensations described by participants. These participants were all in light wood-frame homes.

“you could hear that roar, a real deep roar. It was kind of like a train track jarred down into a five-gallon barrel going around. And then you could hear the rotation of it. It was going…I guess you hear it on the science fiction movies where they do that sound and it goes vooh, vooh, vooh, like that.” [CT011]

“The noise was, it was the loudest freight train you'll ever hear. And my wife said she heard a freight train and a whistle that never stopped. …It was both” [CT012]

“I don't know that freight train is the way I would describe it, but a very deep, ominous roar. You might not know that that's what a tornado sounds like, but you know you don't want to be around whatever's making that sound.” [CT001]

“the whole house is just doing [a steady shake] … it felt like everything was trying to come up[ward], to me, is what I sensed. By the time we get over there it's like woah woah woah whoh boom boom boom boom! and it just really... it's like a baffling effect. It's shuddering. I go over and it's getting very, very loud. ... and then we're hearing things like chunks of heavy rock debris, we can hear it hitting the side of our brick and there's impacts, and then we start hearing ‘Boom! (.5s) Boom! (.5s) Boom!’ I kept hearing huge booms with no reply.” [CT006]
“Your ears just instantly it's like you're going down a big hill. Instant pressure against ears. My wife said her shirt was actually moving. I didn't pay attention to that. At least not on me. You could actually feel the house moving but it was almost squeezing kind of more than just shaking side to side.” [CT003]

Table 5: Many were able to describe key moments in the sequence of damage.

<table>
<thead>
<tr>
<th>Ways Survivors Recalled Damage Sequence</th>
<th>Quotation From the Interview</th>
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| Here, family members are still piecing together their experiences a week after the tornado. A portion of this house collapsed which could also have contributed to the sensation of being airborne. | “Family Member 1: I think the roof came off first because I think that was when I was, like, before everything fell on me. 

Family Member 2: Oh, so you think maybe it was trying to suck you out and then everything fell down on you? 

Family Member 1: I really think so because I remember I was in the air and I was, like, ‘Oh, my God!’ And then I got slammed into my bed and my bed broke and then the dresser fell on me. So, I think that's the only reason I didn't get sucked up.” [CT005] |
| Some could describe what they heard and felt leading up to the initial damage: | “And the wind, I mean, all of a sudden it just got really, really strong. I was like, ‘I've never heard anything like that.’ And then right after that it started sounding like a softball-sized hail was just pounding my house. That lasted, I don't know, 30 seconds, a minute or something maybe. Maybe it was a little bit longer. Then all of a sudden it went ‘boosh,’ and our back window just exploded.” [CT008] |
| For some, the order of damage was easy to recall because it was tied to their sheltering actions. Two examples: | “as soon as we got into this back bedroom, shut the door, that window, the top window blew out and then blew me back through the door.” [CT009] |
“when [my wife] got out of the bed, the bedroom window blew out. And then we ran into the living room, and when we got to the living room, the living room window blew out. We ran upstairs … And when [my son] got out of the bed, his window blew out. … They were blowing out as we were running through the house.” [CT012]

Across our larger dataset, we identified how six factors impacted sheltering decision-making and whether our participants sheltered prior to the tornado impacting them. For Cookeville, all but one participant described at least two of these four factors as affecting their decisions: alerts (e.g., phone alert), TV coverage, a phone call from someone they knew, and environmental cues (e.g., seeing or hearing the approaching tornado; Table 6). These had positive impacts on sheltering in all but three instances. For example, one survivor initially thought the rain was a good sign (Table 3), delaying any sheltering actions until later environmental cues played crucial roles in his sheltering decisions.

Table 6: Factors that impacted decision-making of survivors we spoke with in Cookeville, TN.

<table>
<thead>
<tr>
<th>Interview ID</th>
<th>Impact of ALERTS</th>
<th>Impact of ENV CUES</th>
<th>Impact of TV COVERAGE</th>
<th>Impact of PHONE CALL</th>
<th>Sheltered?</th>
</tr>
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<tbody>
<tr>
<td>CT001</td>
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<td></td>
<td></td>
<td>Y</td>
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<td>CT004</td>
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<tr>
<td>CT005</td>
<td>✸</td>
<td>✸</td>
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<td>Y</td>
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<tr>
<td>CT012</td>
<td>✸</td>
<td>✸</td>
<td></td>
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<td>Y</td>
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<tr>
<td>CT009</td>
<td>✸</td>
<td>✸</td>
<td>✸</td>
<td></td>
<td>Y</td>
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<tr>
<td>CT010</td>
<td>✸</td>
<td>✸</td>
<td>✸</td>
<td></td>
<td>Y</td>
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<tr>
<td>CT003</td>
<td>✸</td>
<td></td>
<td>✸</td>
<td></td>
<td>Y</td>
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<tr>
<td>CT007</td>
<td>✸</td>
<td>⊗; ⬤</td>
<td>✷</td>
<td></td>
<td>Y</td>
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<tr>
<td>CT002</td>
<td>✸</td>
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<td>CT006</td>
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The Cookeville tornado data demonstrates several tangible discipline-specific benefits that emerged from the interdisciplinary approach. For the structural engineers, the interviews typically provided more in-depth knowledge of the structural load path and wind performance that otherwise would have been missed. For example, in one home that experienced less damage than surrounding ones, the homeowner offered that the contractor used truss screws to secure the roof trusses to the wall, providing a significantly stronger connection than the toe-nailed connections used in adjacent homes. Such information could not have been ascertained from an exterior inspection alone, and provided a plausible explanation for what was otherwise an anomalous performance. Survivors also frequently shared photographs of the damage as it looked immediately after the tornado, which was particularly helpful when significant repairs or cleanup was already underway by the time the research team arrived on site. For the wind engineers, information on the directionality of the wind loads and ensuing damage, and information on the dwell time of the tornado, were helpful in validating the wind field model, which was conditioned only on the tree-fall patterns. Similar benefits were also confirmed by Kuligowski (2020) following the Joplin, MO tornado. For the social scientists, the narrative and follow-up questions helped reveal sheltering choices, reasons and timing of them, and how environmental cues and warning messaging impacted what they did. Conducting the interviews with engineers helped ground the experiences reported by the survivors within standardized criteria of the exterior damage suffered and estimated hazard conditions. For example, homes that participants described as completely destroyed varied from having partial roof damage to the home being shifted and broken into units.
CONCLUSIONS AND LIMITATIONS

This study presents an interdisciplinary protocol for leveraging tornado survivor experiences to better understand sheltering actions and behaviors, and structural performance of these shelters, within the context of local hazard conditions. Over a four-year period, the authors successfully deployed the protocol with minor adjustments following nine different tornado events, producing a rich, interdisciplinary dataset. The authors found many benefits to deploying the interdisciplinary protocol, along with several challenges and opportunities for future improvements.

For the structural engineers, partnering with the social scientists and participating in the interviews provided access to data typically not available during forensic structural investigations. These included details of the structural load path for homes that were not severely damaged by the tornado, photographs and videos capturing perishable data on the immediate aftermath of the tornado prior to cleanup, and information on the sequence of damage experienced by the home. For the social scientists, having engineers present made it easier to engage survivors, made it easier to provide the occupants with information about why their home
performed as it did from both a structural and hazards context, allowed survivors the opportunities to ask questions about more wind-resistant building practices, and helped contextualize the survivor’s experiences within likely structural and hazards factors. For the wind engineers, the survivor stories provided important context on the timing and sequence of events that was useful to conditioning and validating parametric models of the tornado.

Collectively, the authors also found that one of the richest benefits was simply the interactions with the many survivors, who displayed the utmost resilience and kindness, often despite having experienced trauma and loss. With few exceptions, the survivors were interested in the study and seemed to benefit from telling their story, receiving validation of or context to their story from the researchers, and especially knowing that their experience was benefitting the advancement of science and ultimately the safety of future communities to tornadoes. Most participants also welcomed and seemed to appreciate the information on rebuilding to stronger wind-resistant standards, and several were able to implement elements of the information when rebuilding.

However, the authors also experienced several challenges from trying to implement the interdisciplinary protocol. The timing of the deployments was challenging because the engineers typically desired to get on site as soon as possible to capture perishable data (e.g., final damage state of homes before being fully demolished and cleaned up). However, arriving on site too early could conflict with access restrictions and the availability and emotional well-being of survivors. The timing of interviews was also challenging, as interviews would often last 30-45 minutes, which was longer than it would take for the engineers to perform a structural assessment of the home. Further, some structures which were a high priority for the engineers (e.g., due to anomalous performance relative to adjacent buildings) were unavailable for interviews, and vice versa.

Despite the challenges, the deployment of the protocol and analysis of the collected data produced the following observations and conclusions:

1. Survivors’ stories can be invaluable resources for understanding the tornado characteristics and impacts at a local scale, while simultaneously improving our knowledge of shelter-seeking activities and motivations.
2. Although survivors in the study were aware of the overall tornado threat and even the issuance of tornado warnings, most sought confirming evidence before actively seeking shelter. More specifically, 50% of survivors explicitly linked environmental cues (i.e., heard, saw, felt) with shelter-seeking actions. This behavior often led to incomplete or non-ideal sheltering actions, which was exacerbated in nighttime tornadoes. Communications from trusted friends and seeing local landmarks mentioned during live broadcast coverage were also highly influential motivators. However, it was also observed that survivors sometimes misinterpreted environmental cues (e.g., calmness, rain earlier in the day or in their first experience with the storm), producing negative impact on sheltering motivations. Given the importance survivors attributed to environmental cues, more education related to environmental conditions leading up to tornado impacts could benefit the public.

3. Largely because the sheltering decision-making process typically relied upon secondary confirmation, almost all survivors (~ 85%) in the study ultimately sheltered in place in a refuge area in their primary residence during the tornadoes, despite advanced warnings.

4. About 1 in 5 survivors who sheltered engaged in multi-stage sheltering, whereby either different survivors occupying the same residence sought shelter at different times, or occupants initially sheltered in one location before moving to a different location when they realized the tornado was about to strike.

5. Survivors all seemed generally to be aware of what to look for as a best available refuge area, despite not always having time to reach the area. More guidance may be needed on how to prioritize the different elements of a best available refuge area when not all criteria (based on (FEMA 2011)) can be met.

Finally, future studies looking to integrate survivor stories with engineering analysis to explore survivability during tornadoes would benefit from being aware of the following limitations of this protocol:

- Sheltering behavior and structural performance of shelters is perhaps most important to document in homes that experience severe damage, but with the purpose-driven, opportunistic sampling strategy deployed in this study it was difficult to find people willing to be interviewed in homes that experienced the heaviest damage. More
concentrated efforts to locate and interview survivors of the heaviest damage would be beneficial.

- Related to the above, the protocol as deployed also made it unlikely to encounter injured survivors, whose stories are perhaps most important to understanding survivability.
- The protocol would benefit from more structured documentation of the floorplan of survivor’s homes, the precise locations within the floorplan where occupants took refuge, and the structural performance of the refuge area and ensuing threat levels to occupants of the refuge area. Based on pilot studies conducted by the authors, sketching floorplans while capturing performance with 360 photographs would provide an optimal level of detail for further study.

ACKNOWLEDGEMENTS

Thanks to Tim Marshall, with whom the lead author first discussed a project along these lines, Jim LaDue for connecting our engineering team with our social team, and Erik Rasmussen and the VORTEX-SE program for providing the first opportunity to pilot this idea. Thanks to Erica Kuligowski for suggesting the interview structure we adapted from the NIST study she led in Joplin, MO, and thanks to her and Maria Dillard for helpful conversations about talking with survivors of natural disasters while we were preparing our proposal. Thanks are also due to Kim Klockow-McClain and Justin Sharpe for discussions about related work. The authors thank Alex Marmo for help in data collection. The authors also thank several students – Catherine Klop (Auburn University), Riley Johnson (Auburn University), Elizabeth Leslie (OU), Zachary Wienhoff (University of Illinois) – for their help in curating and organizing the data. This material is based upon work supported by the VORTEX-SE Program within the NOAA Weather Program Office under Grant Nos. NA16OAR4320115 and NA19OAR4590212 (OU), NA19OAR4590214 (UIUC) and NA19OAR4590213 (AU). Partial financial support from the Structural Extreme Events Reconnaissance (StEER) network for completing the structural assessments is gratefully acknowledged. Finally, the authors would like to thank the many tornado survivors who graciously participated in this study despite the personal trauma and challenging circumstances. Their positivity and resilience were inspiring.
AVAILABILITY STATEMENT
Due to ethical concerns, supporting data cannot be made openly available. Aggregated or non-proprietary data not provided directly in this paper can be provided by the corresponding author upon reasonable request.

APPENDIX

Survivor Story Question Prompts

First approved by the University of Oklahoma Office of Human Research Participant Protection (IRB) on 5 March 2019; minor revisions approved 2 Sept 2020

The primary goal is to have the tornado survivor describe the experience of preparing for the storm before it occurred, and the experience of sheltering during the storm. The participant will be allowed to first present their own unstructured narrative, and then some follow-up questions will be asked. Follow-up questions (below) are meant to home in on coping mechanisms before and during the storm, including things like information gathering, personalization of the risk, sheltering actions, and how their personal networks affected what their thinking and actions. We are also interested in anything they can recall about what they saw, heard, or felt during the tornado to inform forensic engineering analyses of damage.

Begin with an open-ended question:

- Can you walk me through your experience starting from when you first heard about the forecast of a tornado to the tornado hitting your home?

Follow-up questions for detail will be asked to build or fill in the timeline:

About preparing and information seeking prior to the storm:

- How did you first hear about the possibility of severe weather?
  - Was that how you usually hear about severe weather?
- Was there anything different about the alerts this time? More of them, more often, what the messages said...?
- When did you first know there was a chance of tornadoes?
- When did you first know this tornado was actually coming?
- Did you or other family members do anything in the days before the storm to prepare
  - For example, did you clean out a storm shelter? Buy supplies? Turn on the weather radio to turn on notifications from weather or news apps?
  - Did other family members say anything about the possibility of bad weather?
- Was there any discussion about the potential for severe weather at your workplace, or anywhere else you were, in the days leading up to the storm?

About their experience during the storm, focusing on cues they mention, how they interpreted those cues, and how those cues may have caused them to do something:

- What did you do just before the storm?
  - Is that what you usually do?
  - At some point did you feel like you needed a safer place? When was that?
- Did you hear or see the tornado approaching?
- Who was here with you?
  - Are they usually here with you during severe weather?
- Was there anything that was especially helpful during the storm, that made you feel better or more safe?
- Did you talk about the approaching storm? What did you talk about?
  - Did you talk about the storm during the storm?
- Have you been in a tornado before, what did you see/experience then?
  - In past 5 yrs where did you take shelter?
  - Did you have a plan and did you practice that? What did that plan look like?

About the structure:

- What happened first ... next ... last?
We are wanting to identify the sequence of damage, as well is identify items for further clarification: Cue -> Interpretation -> Action

- What was it about that [cue] that caught your attention?
- How did you decide to take that action?
- Can I go back to [point on their timeline]: why did you shelter in the bathroom?

- If manufactured or mobile home: Do you know how your home is anchored?
- Did you have any choice in how it was anchored?

- Clarification questions about order and actions:
  - E.g.:
    - Was the window bowing inward the first thing that you noticed as the storm started to hit?
    - What happened after you saw the window bow inward? Did it break?
    - Was the door latched or locked before it swung open from the wind?
- What did you see / hear / feel during the storm?
- Could you tell when the tornado started to hit?
- Was your shelter affected by the storm?
- Did you have any trouble getting out of your shelter?

REFERENCES


