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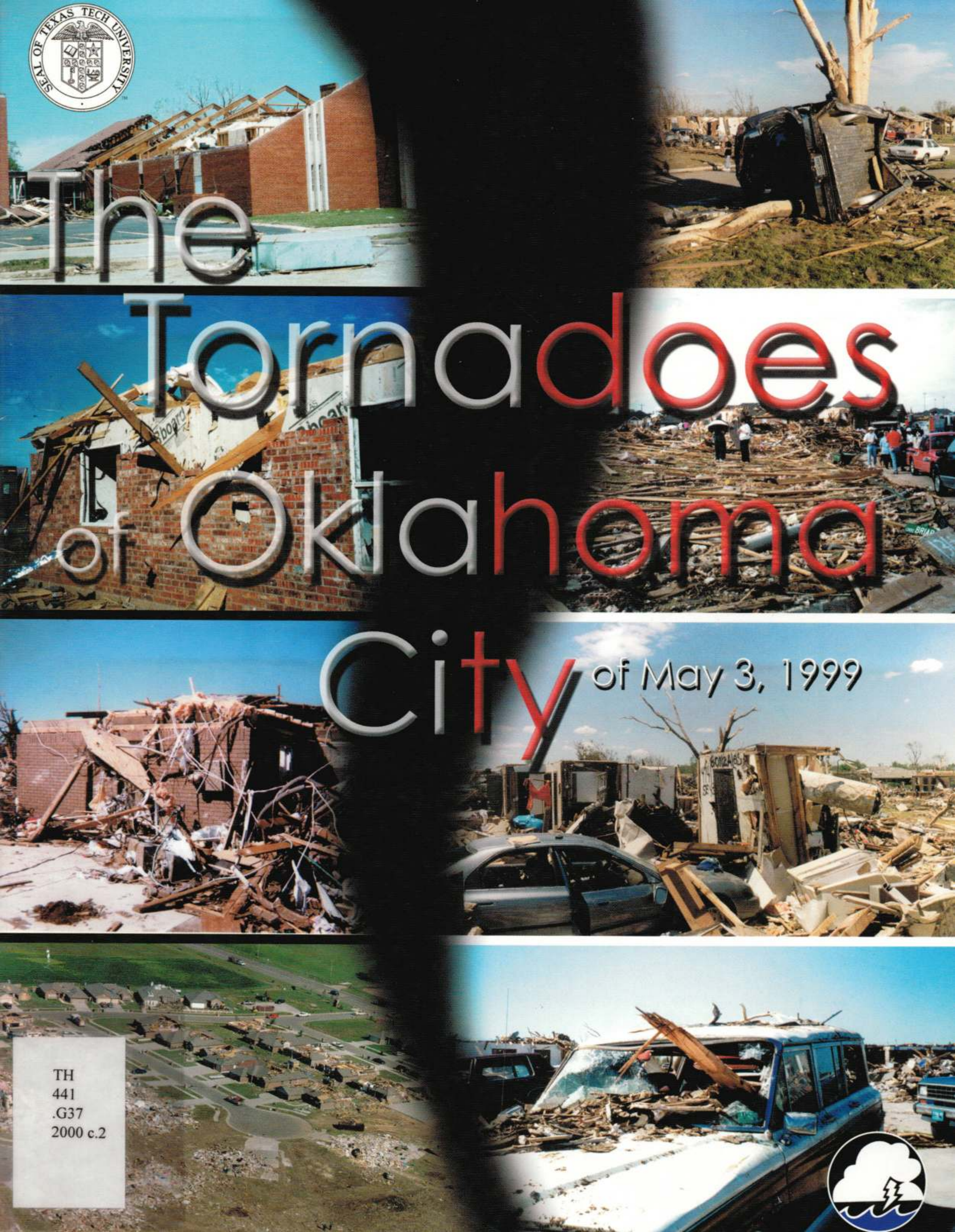

The Tornadoes of Oklahoma City

of May 3, 1999

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Executive Summary

On May 3, 1999, a series of tornadoes touched down in central Oklahoma. These tornadoes claimed 45 lives. The high death toll, along with the extensive damage, prompted Texas Tech University's Wind Science and Engineering Research Center to send three teams to the Oklahoma City area to investigate structure performance. This report describes the teams' observations. The content is directed toward architects, meteorologists, the construction industry, and others interested in a basic knowledge and general understanding of the observed tornado damage and the factors that govern the extent of damage. This report is not meant for the structural engineer and others requiring greater detail and associated calculations. Residential and non-residential building damage is consistent with previously observed damage, but in this investigation new strides are made in understanding residential damage, shelter performance and projectile characteristics.

Residential structure performance was of particular interest due to the severity and amount of damage and the 23 deaths that occurred in single-family residential suburban communities. The majority of single-family residences were wood frame construction with brick veneer. The consistency in their construction type, materials, and locality and the large number of residences experiencing all levels of damage provided an opportunity to establish a gradation scale of damage and associated wind speeds. The observed residential damage was classified into four categories: minor-moderate, extensive, severe, and destroyed. These categories were associated with estimated wind speed ranges capable of the ensuing damage. The following table gives the damage classification, associated estimated wind speed ranges, and the corresponding damage F-scale.

Residential Damage Classification	**Wind Speed (3-sec gust) m/s (mph)**	**Observed Damage F-scale**
Minor-Moderate	38-49 (85-110)	F0-F1
Extensive	50-58 (110-130)	F2
Severe	54-63 (120-140)	F3
Destroyed	58-72 (130-160)	F4-F5

Notice the wind speeds associated with the residential damage classification and the observed damage F-scale. The estimated wind speeds suggest that residential damage

is not a good indicator for wind speeds above 72 m/s (160 mph) and that F5 damage can occur at gust wind speeds as low as 58 m/s (130 mph). This suggests that wind speeds associated with the Fujita F3-F5 damage scale (74-143 m/s, 164-320 mph) are overestimated when they are based on residential damage.

Although damage ranged from minor to complete destruction, common modes of failure were observed and are consistent with previous damage surveys. The common failure modes observed in *residential construction* were:

- failure of wall to roof connections,
- failure of wall to foundation connections,
- breaching of the building envelope (particularly overhead garage doors), and
- failure of low quality materials.

Damaged non-residential structures included schools, banks, motels, and office buildings, with construction varying from heavy timber and steel to concrete and masonry. These types of buildings are normally designed by architects and/or engineers and receive more design attention than residential construction. The common failure modes observed in these *non-residential structures* included:

- failure of connections,
- breaching of the building envelope,
- failure of large overhangs, and
- total collapse with failure of load-bearing walls.

In both residential and non-residential structures, major structural failure seems to begin at the roof connections, which is often promoted by breaching of the building envelop, setting up a potential sequence of failures radiating throughout the structural system.

Breaching of the building envelope often results from debris impact. The storms generated and deposited massive amounts of debris in the suburban residential areas, particularly in the center of the damage path. The debris documented in this report were those projectiles still in place penetrating walls, roofs, automobiles, and other objects at the time of the damage survey. Broken wood board pieces were the predominant missile type. Projectiles penetrating brick veneer were typically 5 cm x 15 cm (2 in x 6 in) (cross section) wood boards. Projectiles found penetrating wood roof decks and automobiles included wood boards of 3 cm x 15 cm (1 in x 6 in), 5 cm x 10 cm (2 in x 4 in), and 5 cm x 15 cm (2 in x 6 in) cross sections. Smaller wood pieces penetrated interior walls. The average weights of the 5 cm x 10 cm (2 in x 4 in) and 5 cm x 15 cm (2 in x 6 in) (cross sections) documented wood projectiles were 13 N and 44 N (3 lbs. and 10 lbs.), respectively.

A crucial outcome of the damage survey was the discovery of an above-ground residential shelter (safe-room) located in the tornado path in Del City, Oklahoma. The reinforced concrete shelter survived in pristine condition, providing protection to the residents of the home. Both above- and below-ground shelters were inspected in damage paths. Shelter doors observed were under-designed with respect to material thickness and latching. Many outdoor underground shelters provided refuge for families, but their accessibility was limited due to small access doors and/or stairs leading to the shelter.

The end goal of damage documentation is to assess how to reduce fatalities and property damage. From this damage survey, 3 areas that can be improved to reach this goal were identified:

1. increased design attention to connections (particularly roof to wall and wall to foundation connections),
2. reduction in the amount of debris generated, and
3. increased awareness of residential shelters.

To reduce the loss of life in single family residential construction, the need for residential shelters should be emphasized. As observed in the report, most of the damage was caused by gust wind speeds in the range of 38-58 m/s (85-130 mph); only over small areas would the gust wind speeds have exceeded 58 m/s (130 mph). It is not cost-effective to design an entire home to resist these very rare extreme tornadic wind speeds, but strengthening one room (a safe room) can be feasible and life saving.

Introduction

On May 3, 1999, tornadoes were reported in 15 Oklahoma counties. The National Weather Service issued the first tornado warning on May 3rd at 4:47 pm. The warnings continued into the early morning hours. After the storms, the National Weather Service identified 68 tornadoes produced from 11 super-cell storms (Figure 1). The death toll reached 45, where 23 of the deaths occurred in site-built single-family residences (Table 1).

Table 1. Location of deaths*

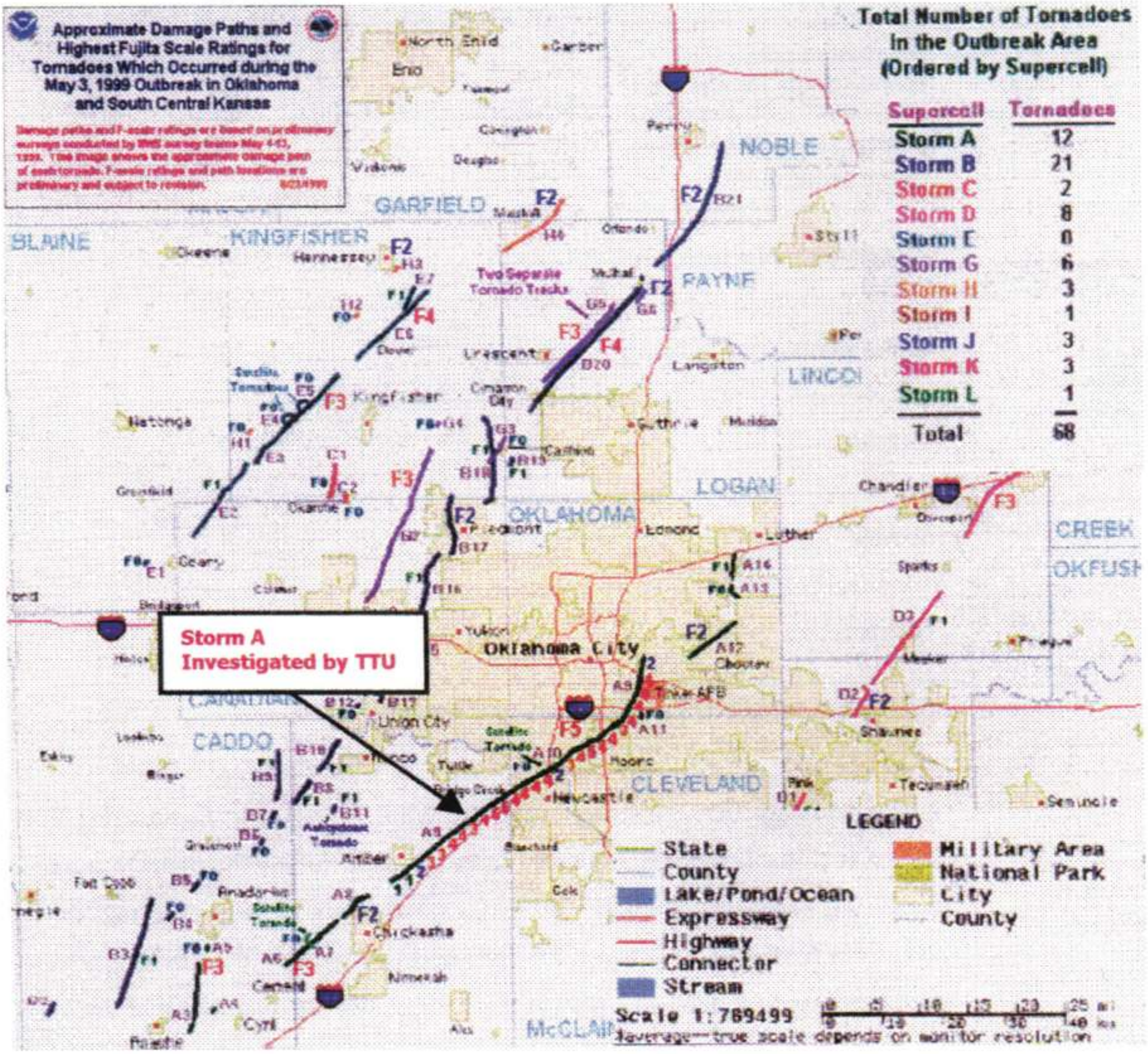
Location of Death	**Deaths**
Permanent (site-built) home (single family)	23
Permanent (site-built) home (apartment)	3
Mobile (manufactured) home	11
Other permanent building	2
Outside	2
Vehicle	1
Indirect	3

***National Weather Service (www.nssl.noaa.gov)**

Within 24 hours after the storm event, the Wind Science and Engineering Research Center at Texas Tech University sent three teams to survey the damage (most of the survey was performed on foot). The teams surveyed the damage resulting from supercell storm A (Figure 1) between Verden and Midwest City because this area experienced the severest damage. Due to the high number of fatalities and the high concentration of damage that occurred in the suburbs of metropolitan Oklahoma City, the damage documentation teams focused on the communities of Moore and Del City. The concentration of damage to suburban wood-frame brick veneer homes of similar construction provided an opportunity to classify the intensity of damage and to assess the variables affecting the extent of the damage.

The teams investigated the performance and failure modes of residential and non-residential structures. Shelter performance and their failure modes were also reviewed. A section on projectiles is included which discusses both common and unusual projectiles observed. The overall objective of the investigation was to learn from the damage how to improve the quality of the construction of structures to save lives and reduce property damage.

FIGURE 1. DAMAGE PATHS (NSSL.NOAA.GOV).



Housing Performance

Introduction

Practically all residential construction was one-story wood frame construction with brick veneer built on slab-on-grade foundations. Homes were 20 to 40 years old and 1200 to 1500 square feet in size. Damage to the homes varied from minor damage to total destruction. The variables affecting the extent of damage the homes experienced are outlined in this section. Discussion of these variables is important in order to view damage from an engineering perspective and permit classification of the damage with associated wind speeds. The residential damage is classified into four categories: minor/moderate, extensive, severe, and destroyed. Failure modes and associated wind speeds are discussed for each damage classification and mapped for the Moore and Del City communities.

Variables Affecting Damage

The extent of damage that a structure experiences during an extreme wind event depends on several variables (Minor et. al 1983). Some variables are storm-dependent, while others are structure-dependent.

Storm-Dependent Variables

Storm-dependent variables affecting the extent of damage are governed by meteorological parameters of the storm and include the magnitude and duration of the winds and the amount and speed of debris. **Lower** wind speeds of **longer** duration can produce damage typically associated with **higher** wind speeds of **shorter** duration. The higher wind speeds impart larger forces on the building, while longer durations cause progressive collapse of the building. Both phenomena can cause total destruction of buildings. The duration and magnitude of winds that a structure experiences not only depend on the meteorological parameters of the storm, but on the location of the structure relative to the storm. For example, a structure located in the center of a tornado path will be exposed to tornadic forces for a longer duration and experience higher wind speeds than a structure located along the edge of the path. Homes located in the center of the damage path associated with super-cell storm A (Figure 1) experienced high wind speeds for durations between 60-90 seconds, where homes located along the edge of the tornado path possibly experienced durations as low as 10 seconds or less.

Higher wind speeds and/or longer durations increase the ability of a storm to generate debris and higher velocity projectiles. Homes located in the middle of the tornado path, where higher wind speeds and a longer duration occur, generate more debris than homes located along the perimeter of the tornado path (Figure 2). The amount of debris also depends on the built-up environment. Sparsely populated rural communities typically do not have the structures which generate the massive amounts of debris seen in more densely populated areas (Figure 3).

FIGURE 2. DEBRIS COMPARISON

Debris comparison between locations at the middle of the tornado path (left) and locations at the perimeter of the damage path (right).

FIGURE 3. DEBRIS COMPARISON

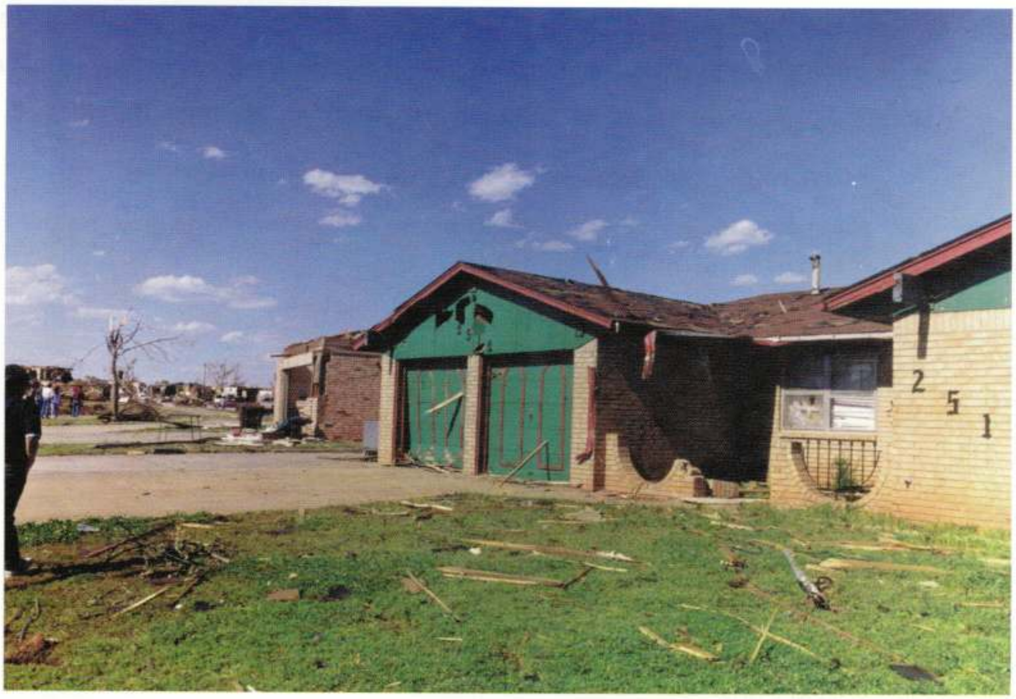
Debris comparison between rural (left) and suburban (right) areas.

Structure-Dependent Variables

Structure-dependent variables include the building's orientation, foundation, construction practices, and the condition of the building. Failure tends to initiate at points in the structural load path where structure-dependent variables are lacking in design, workmanship, material quality or maintenance.

Orientation of a building, relative to the direction of the approaching winds, can affect the extent of damage a building experiences. One of the most vulnerable areas of single-family residences (relative to orientation) is the attached garage. Garage doors are notorious for blowing inward during extreme wind events, allowing the wind to enter the building and increase internal pressures. The resulting uplift on the roof compromises the roof and eventually other parts of the building. Therefore, homes with garage doors oriented in the direction of the approaching winds typically fare worse than homes without the garage door oriented into the wind (Minor et. al 1983; FEMA 1992; FEMA 1999). Figure 4 shows two homes with two-car garages. Notice that the home with two **single** garage doors (foreground) has an intact roof structure, whereas the home (background) with one **double** garage door is missing its garage door and roof structure. Both garages were oriented towards the approaching winds (wind direction is established from the debris penetrating the single garage doors on the house in the foreground). The double garage door was breached due to its larger area and flexibility, which ultimately led to the loss of the roof structure.

FIGURE 4. GARAGE DOOR DAMAGE



The type of building foundation is another structure-dependent variable. There are three common foundation types found in residential construction: basement, slab-on-grade, and pier and beam. A basement foundation is typically constructed of reinforced concrete or concrete masonry (reinforced or unreinforced). A slab-on-grade foundation typically consists of a reinforced concrete slab placed on compacted fill or natural soil. A pier and beam foundation consists of masonry footings, concrete footings, or foundation walls with interior piers, which support the wood framing of the residence. The performance of slab-on-grade foundations has been observed to be superior in extreme wind events. Poor performance of basement and pier and beam foundations is often due to the absence of reinforcement in the concrete or masonry and/or poor connection practices (Minor 1983; Mehta and Carter 1999). Practically all the homes in the damaged areas had slab-on-grade foundations, and many of the homes were completely destroyed when the wall to foundation connections failed, leaving only the foundations intact.

Structural components in poor condition are typically a result of poor maintenance. The lack of adequate maintenance, varying from pest inspection to painting, can compromise the integrity of the structural load path. For example, a termite infested wall stud or weathered and water damaged sheathing can result in structural weakening or failure.

The extensive use of wood in residential construction also makes material quality integral to the structural integrity. Wood structural members tend to fail at locations where there are knots, wane, or other imperfections (Figure 5).

FIGURE 5. FAILURE AT KNOTS IN WOOD MEMBERS

The optimum orientation, foundation type, and materials, along with the most meticulous maintenance regiment, will assist little in maintaining the structural integrity if poor construction practices are used. Establishing minimum standards and requiring inspections during construction are integral parts of ensuring the use of quality workmanship and materials and the use of adequately designed components and connections. Rural construction practices are often inferior to construction practices within cities due to the absence of active building-code enforcement programs (Minor et. al, 1983).

Damage Classification

Residential damage in the Oklahoma City tornado is classified into four categories: minor/moderate, extensive, severe, and destroyed. Minor/moderate damage includes structures where exterior and interior walls are standing, and the envelope may be scarred from impact of debris; windows may be broken and 20% or less of the roof may be structurally damaged (Figure 6). Typical failure modes observed in this category were shingle damage along roof eaves, corners, and ridges (Figure 6, top left), projectile impacts (Figure 6, top right), windward gable roof truss failure (Figure 6, bottom left), and debris pitting of roof cover and cladding (Figure 6, bottom right). Minor/Moderate damage is repairable and the home can be lived in. This type of damage is believed to occur at gust wind speeds of 38-49 m/s (85-110 mph); this is comparable to 20-53 m/s (45-118 mph) wind speeds associated with F0-F1 Fujita damage scale.

FIGURE 6. MINOR/MODERATE DAMAGE (F0-F1 DAMAGE LEVEL)

Extensive damage includes structures with more than 20% of the roof structure damaged, most exterior walls remain standing, and 80% or more of the floor plan intact (Figure 7). The main failure modes associated with extensive damage are the inadequate connections of the roof cover to roof structure (Figure 7, top left and right) and the roof structure to the walls (Figure 7, bottom left and right). This type of damage is not considered a total structural loss, but uninhabitable until repaired. Extensive damage is estimated to occur with gust wind speeds in the range of 50-58 m/s (110-130 mph), as opposed to 54-73 m/s (121-163 mph) gust wind speeds associated with the F2 Fujita damage scale.

FIGURE 7. EXTENSIVE DAMAGE (F2 DAMAGE LEVEL)

Structures with no roof or exterior walls remaining, and only interior walls or rooms standing are classified as severe damage. Severe damage ranges from the majority of interior rooms surviving (Figure 8, top left and right) to only one small interior room surviving (Figure 8, bottom left and right). Severe damage is considered survivable by occupants because small interior rooms can provide refuge.

Structures wiped from the slab, leaving no roof or exterior or interior walls are classified as destroyed (Figure 9, all). Damage classified as destroyed is considered unsurvivable. Although essentially all of the homes in the storm path had the better performing slab-on-grade foundations and all slabs were intact, in both severe and destroyed classifications the dominating failure mode was the wall to foundation connections. The connections either failed due to the wall studs pulling out of the base-plate or the base-plate ripping away from the anchor bolts (Figure 10). Long durations of high winds are believed to be a significant factor in resulting in severe damage and complete destruction of residences, and was also considered the culprit for the devastating damage and loss of life experienced in the Jarrell, Texas, tornado on May 27, 1997 (Phan and Simiu, 1998). Residential structures classified with severe damages or as destroyed are considered a total loss. These types of residential damage are estimated to occur with gust wind speeds in the range of 54 to 72 m/s (120 to 160 mph), as opposed to the wind speed range of 74-143 m/s (164-320 mph) associated with F3-F5 Fujita damage scale.

FIGURE 8. SEVERE DAMAGE (F3 DAMAGE LEVEL)

FIGURE 9. DESTROYED (F4-F5 DAMAGE LEVEL)

FIGURE 10. WALL TO FOUNDATION CONNECTION FAILURE

The current wind load standard, ASCE 7-95 (ASCE, 1995), specifies design gust wind speeds of 40 m/s (90 mph, 3-sec gust) in the Oklahoma City area. Even though residential structures were not designed specifically for this wind speed (because residential structures are not engineered structures), their reserve strength would exceed design loads by a factor of 2 to 3. Since wind load varies with the square of the wind speed, the reserve strength would relate to wind speed by a factor of 1.4 to 1.7. This factor would suggest that gust wind speeds in the range of 58 to 72 m/s (130 to 160 mph, 3-sec gust) could overcome the reserve strength and totally destroy a structure. In addition to wind speeds, if a structure is located near the center of the tornado path, the long duration of winds can completely remove the home from its slab foundation (Simiu, 1998). Thus, the observation of destroyed homes and homes wiped from their slabs does not necessarily indicate wind speeds greater than 72 m/s (160 mph).

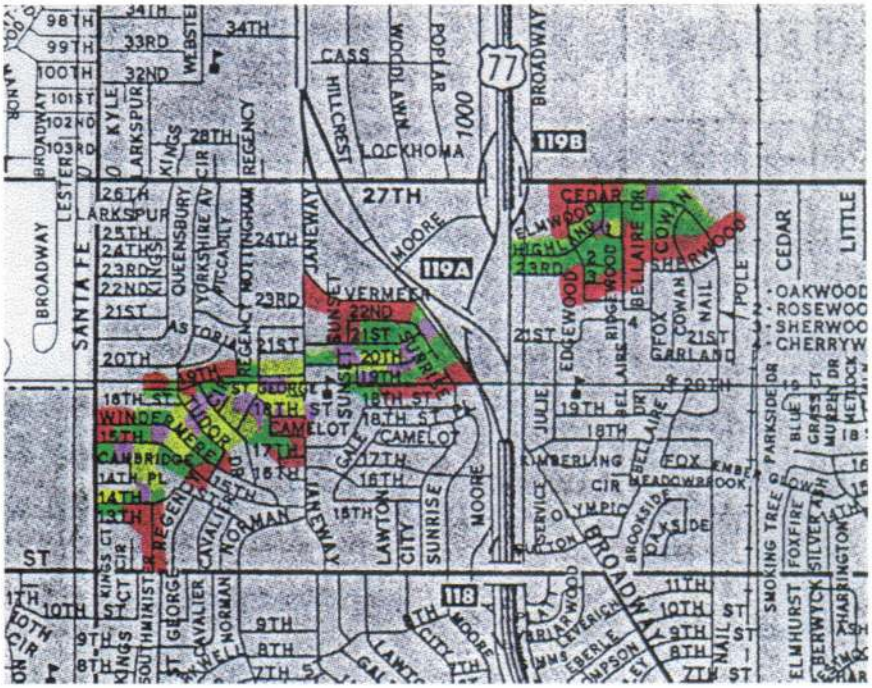
Descriptions of each level of damage, wind speeds associated with causing the particular level of damage, the associated Fujita damage scale, and the wind speeds associated with the Fujita damage scale are given in Table 2. Comparing wind speeds estimated by engineers from residential damage with the Fujita damage scale associated wind speeds, it is apparent that Fujita damage scale overestimates wind speeds in F3, F4, and F5 categories. This observation was initially reported by Texas Tech University researchers in the late 1970s (Minor et al, 1976).

Figures 11 and 12 show the locations of each damage classification (indicated in Table 2). documented in Moore and Del City, Oklahoma. These maps suggest that a large part of the damaged area experienced gust wind speeds in the range of 38-58 m/s (85-130 mph) at the ground level. The center part of the damage path likely experienced gust wind speeds in the range of 54-72 m/s (120-160 mph).

Table 2. Damage Classification

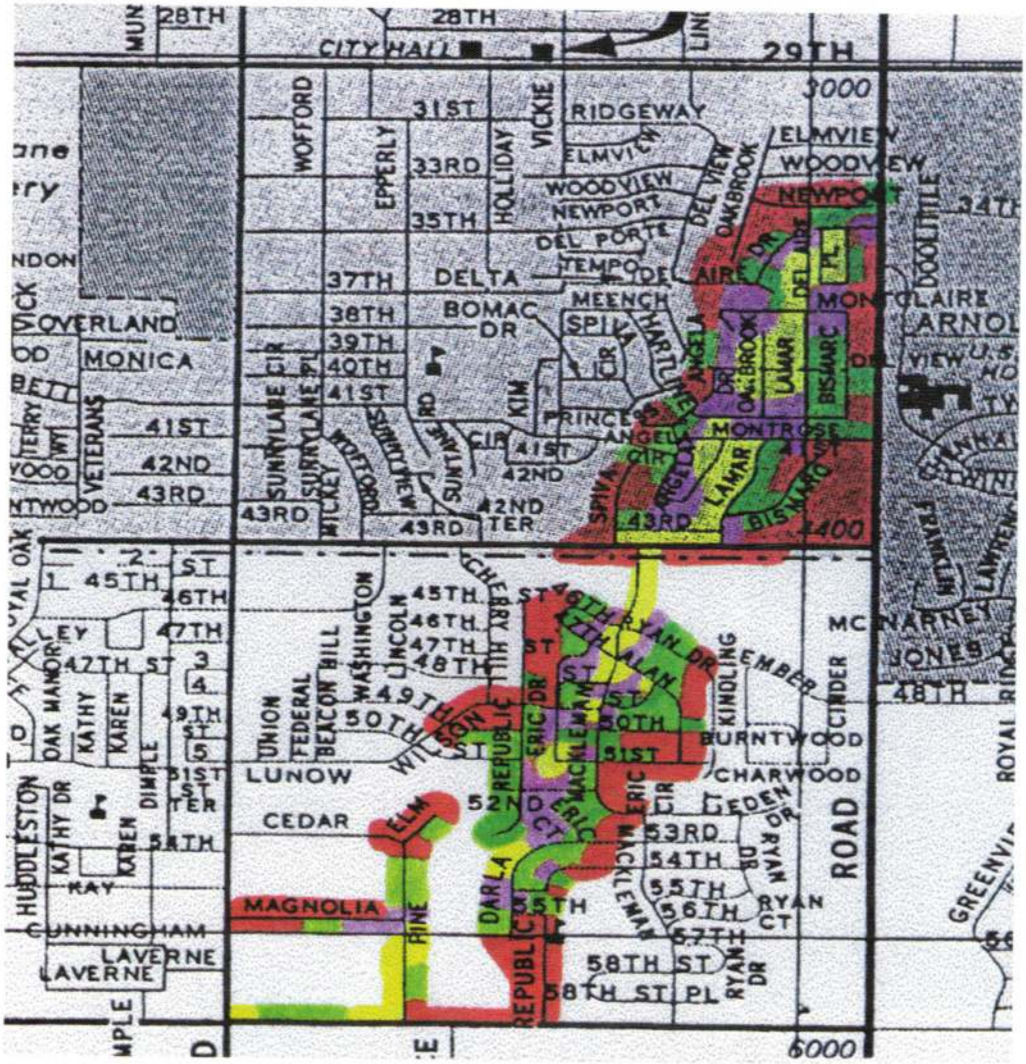
Damage Classification	Description	Wind Speed (3-sec gust) m/s (mph)	Fujita Damage F-Scale	Fujita Damage Scale Wind Speeds (3-sec gust) m/s (mph)
Minor-Moderate	Interior and exterior walls are standing, but the envelope may be scarred from impacts of debris; windows may be broken; 20% or less of roof experienced structural damage.	38-49 (85-110)	F0-F1	20-53 (45-118)
Extensive	More than 20% of the roof structure is destroyed; at least 80% of floor plan is intact; most exterior walls are standing.	50-58 (110-130)	F2	54-73 (119-163)
Severe	Roof is destroyed; almost all exterior walls destroyed, leaving only interior walls or interior rooms standing.	54-63 (120-140)	F3	74-94 (211-320)
Destroyed	Roof is destroyed; no exterior or interior walls are standing; only debris remains.	58-72 (130-160)	F4-F5	95-143 (211-320)

FIGURE 11. MOORE DAMAGE



Red-minor/moderate damage, Green-extensive damage, Purple-severe damage, and Yellow-destroyed damage.

FIGURE 12. DEL CITY DAMAGE



Red-minor/moderate damage, Green-extensive damage, Purple-severe damage, and Yellow-destroyed damage.

Summary

The wind forces experienced in the center of the damage path exceeded both past and current building code guidelines. It is not possible to delineate the failure modes from destroyed structures. However, homes sustaining lesser degrees of damage can give clues to possible failure modes.

Failure modes of components and connections were similar to those observed by previous damage documentation efforts (FEMA 1992; FEMA 1999). Some of the common failure modes observed were:

- failure of wall to roof connections,
- failure of wall to foundation connections,
- breaching of the building envelope (most commonly observed was failure of garage doors: particularly double doors),
- failure of lower quality materials, and
- debris impacting the exterior walls and roofs and often breaching the building envelope.

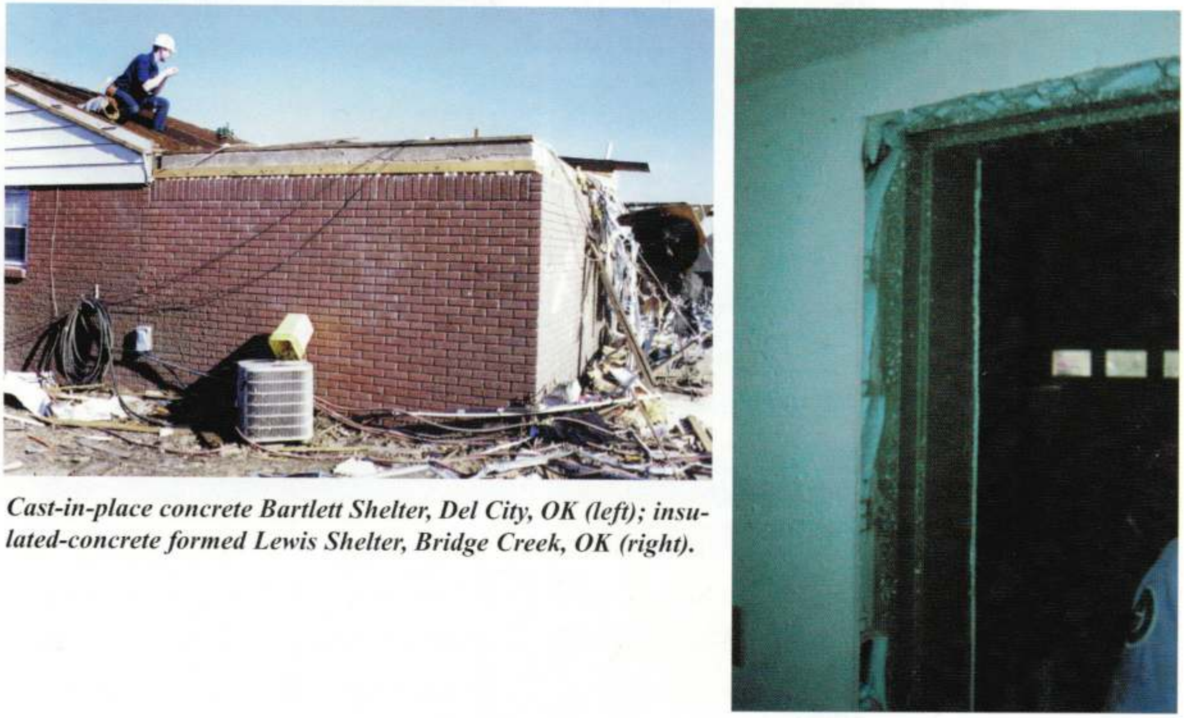
Wind speeds necessary to cause severe damage and destruction of residential structures in the center of the damage path are estimated to be in the range of 54-72 m/s (120-160 mph). This damage fits in the description of the Fujita damage scale of F3, F4, and F5, but the Fujita damage scale associated wind speeds for F3-F5 (74-143 m/s; 164-320 mph) are overestimated when based on damage or destruction of single family residential structures.

Residential Shelters

Introduction

Both above- and below-ground shelters were found in the damage path of the tornadoes that struck Oklahoma City on May 3, 1999. Above-ground shelters included cast-in-place concrete, i.e., the Bartlett Shelter (Figure 13, left), and insulated concrete formed, i.e., the Lewis Shelter (Figure 13, right).

FIGURE 13. ABOVE GROUND SHELTERS



Cast-in-place concrete Bartlett Shelter, Del City, OK (left); insulated-concrete formed Lewis Shelter, Bridge Creek, OK (right).

Although common in many parts of the country, residential basements are not common in Oklahoma and were not observed by the damage documentation team. However, self-contained shelters located below-ground and out of the building footprint, commonly referred to as cellars, were observed. These storm cellars were constructed of cast-in-place concrete (Figure 14, left) or prefabricated steel with a concrete cover (Figures 14, right).

FIGURE 14. SELF-CONTAINED BELOW-GROUND SHELTERS

Cast-in-place concrete (left); prefabricated steel (right).

Shelter Performance

Above-Ground Shelters

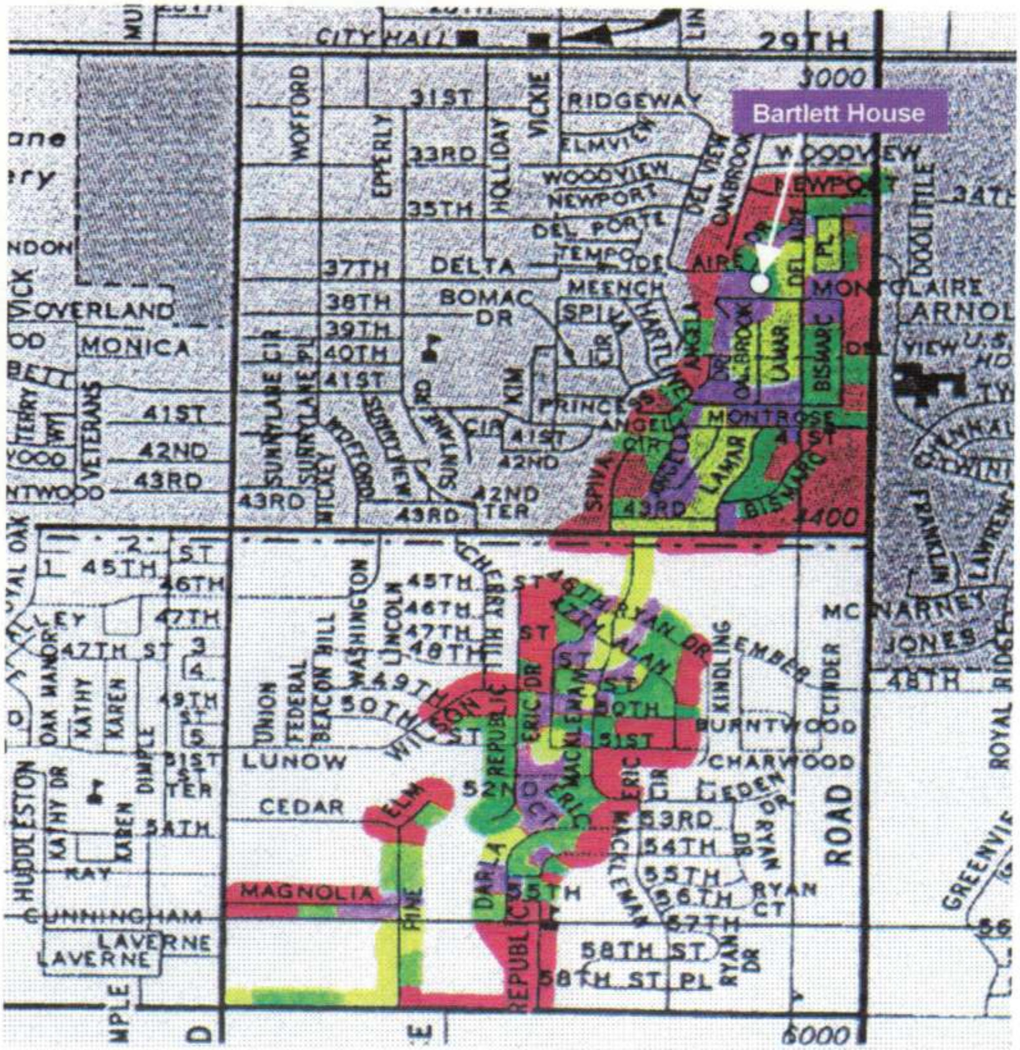
The Bartlett Shelter was located in Del City, Oklahoma. The Bartlett neighborhood experienced extensive to severe damage (Figure 15). The Lewis shelter was located in the Bridge Creek Estates in Bridge Creek, Oklahoma, an area which experienced minor/moderate damage. Both shelters survived without any damage, even though the Bartlett home was classified as having severe damage (Figure 16).

The construction of each shelter was consistent and somewhat excessive compared to the Texas Tech shelter (FEMA Safe Room, FEMA, 1998) guidelines. The Bartlett Shelter had 12 in. thick concrete walls and ceilings (FEMA, 1998). The doors on both shelters were 16 gage (or less) steel set in hollow metal frames and locked with a single deadbolt (Figures 17). This door construction setup is not sufficient to resist direct impacts from flying debris. Fortunately, the doors did not show signs of impact by debris and provided protection to the occupants. The owners of both shelters were informed that the lighter gage doors should be armor plated with a layer of 14 gage steel and that two additional locks should be added to meet shelter guidelines.

Below-Ground Shelters

Countless families found safety in outdoor underground cellars. To our knowledge, people seeking shelter were not injured, though the occupants of the shelter pictured in Figure 18 could have been injured when the door was removed by the storm. Many of the observed cellars suffered from maintenance problems, such as waterproofing of walls and roofs, which resulted in a musty and damp environment. Poor selection of materials and maintenance of painted items such as hinges and latches led to rusting, which

FIGURE 15. BARTLETT NEIGHBORHOOD

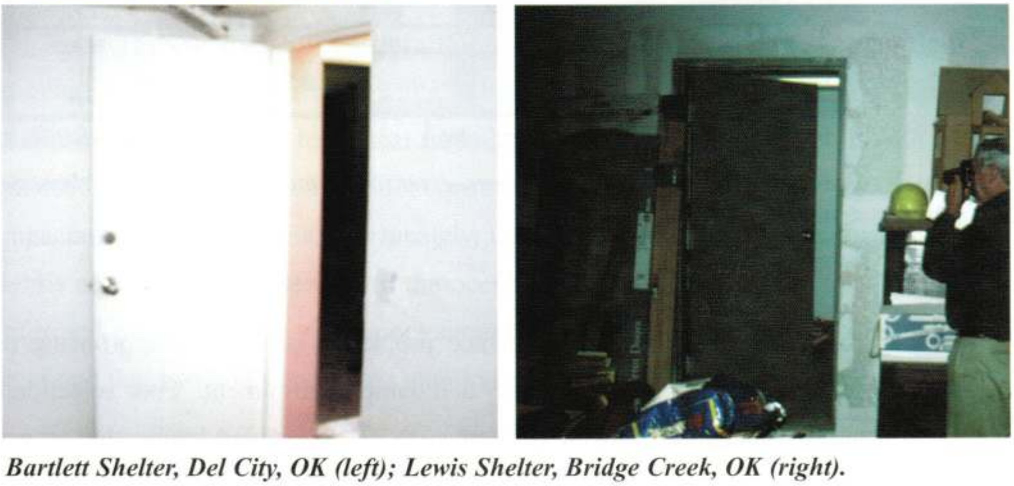


Red-minor/moderate damage, Green-extensive damage, Purple-severe damage, and Yellow-destroyed damage.

resulted in failures or poor performance. Cellar doors normally consisted of a single sheet of plywood covered with thin gage sheet metal, which exhibited deterioration of the zinc galvanization resulting in rust (Figure 18). The plywood backing was often found to be highly deteriorated from moisture (Figure 19). The older cellars were vented with substantial heavy steel pipe vents that performed well in the storm event (Figure 20).

FIGURE 16. BARTLETT HOME

FIGURE 17. SHELTER DOORS



Bartlett Shelter, Del City, OK (left); Lewis Shelter, Bridge Creek, OK (right).

FIGURE 18. BRIDGE CREEK CELLAR DOOR

FIGURE 19. MOORE CELLAR

FIGURE 20. CELLAR VENT

Shelter Accessibility

The observed above-ground shelters were easily accessible. The door widths would have allowed access by a wheelchair or otherwise disabled occupants. Storm cellars were located either in the front yard or the rear yard of the homes, and access to these shelters would have been difficult for the physically challenged. In each cellar case, front yard and rear yard locations, the cellar entrance was insufficiently raised above the existing grade and would have allowed floodwaters to enter the shelter.

Summary

Both above- and below-ground shelters were observed. The Bartlett above-ground shelter, constructed of cast-in-place concrete, and its occupants survived wind speeds that severely damaged the entire neighborhood. The Bartlett shelter door, along with other shelter doors observed, was under-designed with respect to material thickness and latching. The FEMA publication on safe room provides details for door material and latching details to resist wind forces and debris impact (FEMA, 1998). Doors should be accompanied with at least 3 dead bolt locks to withstand impact forces. Many outdoor underground cellars provided refuge for families. Unlike above-ground shelters, underground cellars limit accessibility and increase opportunities for injury from flying debris and flooding.

Non-Residential Building Performance

Introduction

The damage documentation teams investigated several non-residential buildings damaged by the May 3, 1999, tornadoes. The non-residential buildings observed included a church, a bank, a motel, a warehouse, an industrial park, an office building, and two schools. The buildings various construction types included light steel, heavy timber, pre-cast concrete elements, reinforced concrete, and masonry. These types of buildings are typically designed by architects and/or engineers and usually have more reserve strength than residential buildings, which typically do not have the input of architects and/or engineers.

Steel Structures

Kelly Elementary School

Kelly Elementary (Figure 21) had a load-bearing concrete masonry wall construction with light steel columns and beams with bar joists supporting a built-up roof over metal roof deck. The 1960's vintage building had low roof slopes and large overhangs. The strong wind forces produced uplift on the overhangs and the storm debris compromised the building envelope allowing internal wind forces coupled with the external wind forces, to remove the roof decking . Initial structural failure occurred at the roof deck to joist connections. The sequential failure of the decking probably produced eccentric loading on the structural steel frame causing racking of the frame (Figure 22) and eventual failure of the beam blocks in the bearing wall (Figure 23). It is of interest to note that the planned areas of emergency refuge within the building were the corridors, each of which was filled with toppled masonry walls and twisted building elements.

Bank Building

The second steel structure investigated was a bank building (Figure 24) located approximately four blocks from Kelly Elementary. Wind uplift accounted for the removal of the drive-through roofing material. Windborne debris compromised the building openings allowing internal pressures to combine with the external pressures, resulting in the removal of sections of the metal roofing. The steel structure was composed of heavy wide-flange beams and columns with high-strength bolted connections and stiffened beam webs. The building frame exhibited no signs of torsion or racking.

FIGURE 21. KELLY ELEMENTARY SCHOOL, MOORE, OK

FIGURE 22. KELLY ELEMENTARY SCHOOL, MOORE, OK

FIGURE 23. KELLY ELEMENTARY, MASONRY BEARING WALL

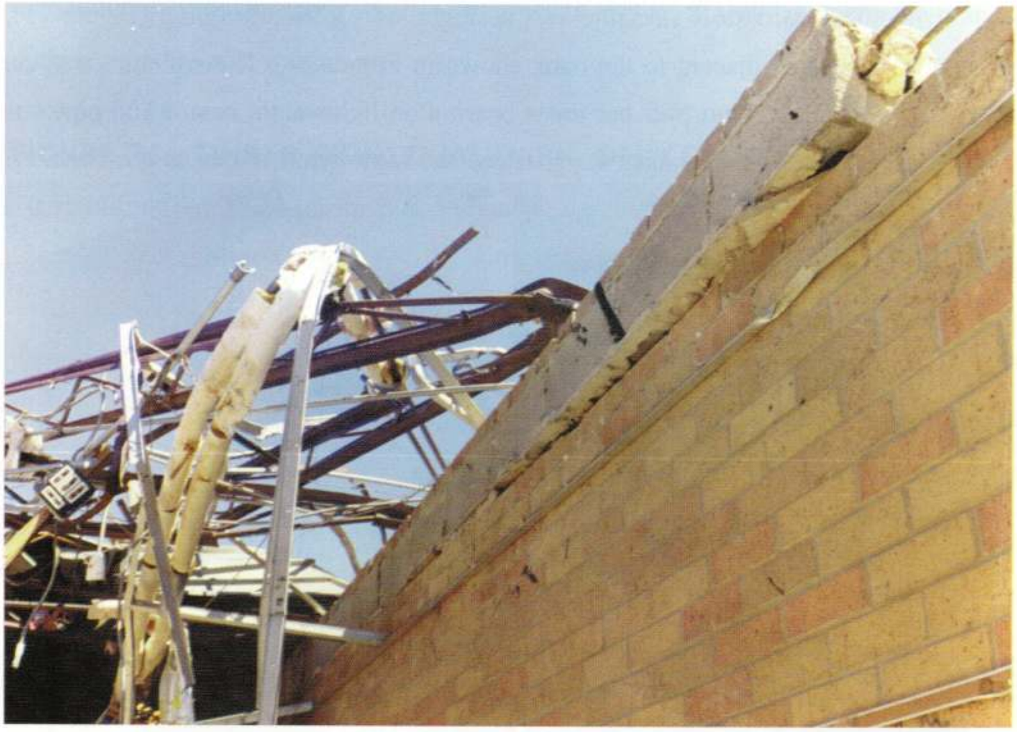


FIGURE 24. MOORE BANK, MOORE, OK

Office Building

The third steel structure was a single story office building (Figure 25), which was located adjacent to the bank shown in Figure 24. The structure was constructed of metal decking over bar joists bearing on lightweight beams and pipe columns. This structure would have experienced the same wind forces as the bank. However, the lighter steel structure was incapable of withstanding both the internal and external forces. Failure occurred at virtually all structural connections.

FIGURE 25. OFFICE BUILDING, MOORE, OK

Tinker Industrial Park

The last steel structure investigated was at the Tinker Industrial Park. The office complex consisted of three separate long buildings. The buildings were constructed of a light steel frame with metal decking supported by bar joists and load bearing walls. Typical failure included debris compromising large windows on the narrow west end and the channeling of wind through the entire length of the buildings resulting in failure of the leeward walls. The most significant damage occurred to the building nearest to the storm path. A longer span and taller building addition had been added to the leeward end of this building. This portion of the building experienced considerable uplift causing the disconnection of the structural elements (Figure 26, left) and total collapse of the building addition (Figures 26, right). Storm damage in the immediate residential area was severe.

FIGURE 26. TINKER INDUSTRIAL PARK, DEL CITY, OK

Disconnection of structural elements (left); collapse of the building addition (right).

Heavy Timber Construction

Regency Park Baptist Church

Regency Park Baptist Church was located approximately one block from Kelly Elementary shown in Figure 21. The damage in the surrounding residential areas was extensive. The sanctuary's long span roof experienced the majority of the damage. The sanctuary was constructed of stick framed roof joists bearing on glued laminated timber arches with a heavy masonry wall. Wind forces removed the toenailed roof joists (Figure 27) with the nails failing in withdrawal. The heavy timber structure and walls were virtually undamaged.

Precast Element Concrete Construction

Tilt-Up Concrete Warehouse

The warehouse constructed of tilt-up concrete experienced numerous overhead door failures, thereby allowing internal pressures coupled with the external pressures to remove the roof decking and set up a chain of failure events. The roof decking was tack welded to the top of the end walls in order to provide lateral bracing of the walls. Lateral support of the load-bearing walls was provided by the bar joists bearing top chords and the extended bottom chords, that were welded to plates embedded in the wall panels (Figure 28, left). The chain of failure after the decking removal included loss of the end wall panels and the subsequent weakening and failures of the welds of the bar joist top and bottom chord connections (Figure 28, right).

FIGURE 27. REGENCY PARK BAPTIST CHURCH, MOORE, OK

FIGURE 28. TILT-UP CONCRETE WAREHOUSE, MOORE, OK

Lateral support failure of load bearing walls (left); failure of bottom bar joist chord connections (right).

Best Western Motel

The Best Western Motel was constructed with pre-cast hollow core concrete floor slabs supported on masonry walls. The architectural design consisted of back-to-back rooms stacked two stories with wide exterior corridors and roof overhangs ringing the building exterior. The wind forces acted on the top and bottom surfaces of the overhangs, and windborne debris compromised the large guest room windows. Many of the structural systems failed, including removal of some of the wood roof structure (Figure 29).

FIGURE 29. BEST WESTERN MOTEL, MID-WEST CITY, OK

Concrete and Masonry Construction

Westmoore High School

Westmoore High School was constructed with a metal deck over bar joists bearing on beams and columns and load bearing concrete and masonry walls. Observed failures of the components and cladding included removal of the roof membrane, some decking, ornamental steel wall cladding, and window glazing (Figure 30).

FIGURE 30. WESTMOORE HIGH SCHOOL, MOORE, OK

Summary

Non-residential construction types included steel, heavy timber, pre-cast concrete elements, concrete, and masonry. These types of buildings (i.e. schools, banks, motels, and office buildings) are normally designed by architects and/or engineers. The architectural/engineering calculations include an inherent reserve strength, which increases the load capacities. This reserve strength normally enables non-residential structures to withstand extreme wind events better than residential structures. However, some of the structures observed (i.e., the Tinker Industrial Park Buildings, Best Western Motel, Kelly Elementary, and the tilt-up concrete warehouse) actually performed more poorly than expected. In each case, the connections were insufficient to withstand the extreme wind forces. The buildings failed when large openings (overhead doors or large windows) were compromised. In most cases, failure appears to have initiated at the roof connections, setting up a sequence of failures radiating throughout the main structural system, including the load bearing walls.

Projectiles

Introduction

Debris of different materials, shapes and weights may or may not become windborne. Some building parts may become windborne and disintegrate into several components. Documentation of debris would include original and final locations of debris pieces and the size and shape of debris pieces. The documentation teams did not document general debris (Figure 31), but focused on projectiles: pieces of debris that impacted and were found penetrating walls and other surfaces and objects. Note that projectiles are a small subset of debris. Since the sample size is relatively small, no attempt is made to perform statistical analysis of debris or projectiles.

Figure 31. Debris Field

This section discusses the parameters governing the ability of a piece of debris to become windborne and penetrate objects and materials. The projectiles observed during the damage survey are described and characterized.

Windborne Debris

From basic principles of mechanics, a debris piece displaced from its original position can be carried by airflow over a significant distance only if the aerodynamic lifting force overcomes gravity. The aerodynamic lifting forces are exerted upon the surface of an air-borne object. From this observation, it is easy to conceive that the **specific gravity, shape,** and **weight** of a debris piece, along with **wind speed,** are the primary factors determining whether the debris will take flight. In general, debris of high specific gravity with a relatively small surface area are not likely to become windborne. For example, solid bricks are not likely to become flying debris. Commonly observed windborne debris include, but are not limited to: roofing materials, plywood board, gypsum board, lumber, broken tree branches, and small, lightweight household items.

Projectiles

Obviously, a certain amount of momentum is required for a piece of debris to penetrate a specific building component. Ordinary window glass is very vulnerable to impact damages, even by small flying debris such as gravel, while it might take a 60 cm (2 ft) long 5 cm x 15 cm (2 in x 6 in) wood board to penetrate brick veneer. More accurately, the momentum (speed x mass), impact angle, material type, and geometry of the projectile head govern the behavior of the impact. Presumably, a minimum momentum is required for a particular projectile to penetrate a certain building component.

The majority of buildings surveyed were residential buildings of wood-frame construction, thus most of the debris and projectiles observed were broken wood boards. **Wood board projectiles** consisted of a wide variety of shapes, from small 3 cm x 3 cm (1in x 1 in) pieces to a 4 m (14 ft) long 5 cm x 15 cm (2 in x 6 in) member. Out of the 27 wood projectiles documented, there were two 3 cm x 15 cm (1 in x 6 in), nine 5 cm x 10 cm (2 in x 4 in), and sixteen 5 cm x 15 cm (2 in x 6 in) members. The average weights of documented 5 cm x 10 cm (2 in x 4 in) and 5 cm x 15 cm (2 in x 6 in) projectiles were 13 and 44 N (3 and 10 lbs), respectively. An unusually large 5 cm x 15 cm (2 in x 6 in) projectile (4 m, 14†ft long) with an estimated weight of 151 N (34 lb) was observed (Figure 32). Wood projectiles penetrating brick veneer were typically 5 cm x 15 cm (2 in x 6 in) wood boards (Figure 33). Wood projectiles penetrating wood roof decks (Figure 34) and automobiles included 3 cm x 15 cm (1 in x 6 in), 5 cm x 10 cm (2 in x 4 in) and 5 cm x 15 cm (2 in x 6 in) wood boards (Figure 35). The weights of documented wood projectiles ranged from 9 to 151 N (2 to 34 lbs), with lengths from 25 cm (10 in) to 4 m (14 ft).

Figure 32. Large 2x6 Wood Projectile

Figure 33. Wood Projectiles

Figure 34. Wood projectile

Figure 35. Wood Projectile

Steel projectiles were rare since steel components were not widely used in residential construction. Failed steel buildings were normally found in agricultural areas, and their components typically did not completely separate from each other. Steel members were often found twisted and tangled in a mound (Figure 36). A short, lightweight **C-section steel** piece, 64 cm (25 in) long and 8 cm (3 in) wide, was found stuck in grass-covered ground (Figure 37). A **steel gas pipe** segment, about 1.5 m (5 ft) long, was found penetrating a wood roof deck (Figure 38).

Figure 36. Steel Building Failure

Figure 37. C-Section Steel Projectile

Figure 38. Steel Gas Pipe Projectile

Summary

The observations made in this report are based on the limited number of documented projectiles still in place, penetrating walls, roofs, automobiles, and other objects at the time of the field survey. The battered condition of homes is evidence of the large mass of debris generated by the tornado (Figure 39) even though relatively few projectiles impaling structures were observed. In wood framed, single-family, residential construction, the debris overwhelmingly consists of wood material. Projectiles penetrating brick veneer were typically 5 cm x 15 cm (2 in x 6 in, cross section) wood boards. Projectiles found on wood roof decks and automobiles included wood boards of 3 cm x 15 cm (1 in x 6 in), 5 cm x 10 cm (2 in x 4 in), and 5 cm x 15 cm (2 in x 6 in) cross-sections. The average 5 cm x 15 cm (2 in x 6 in) and 5 cm x 10 cm (2 in x 4 in, cross section) documented projectile weight was 44 and 13 N (10 and 3 lbs), respectively.

There is a great need for damage documentation focused on characterizing debris and projectiles. Further research in this area should include detailed documentation of debris/projectiles in a specified area. Characteristics to be documented include, but are not limited to, original and final location, weight, cross-section, length, and material. Careful selection of the site and detailed documentation of debris/projectile characteristics can produce statistically significant debris/projectile parameters.

Figure 39. Homes Battered by Debris

Summary of Observations

The damage observed from the Oklahoma tornadoes of May 3, 1999, was consistent with previous damage surveys (FEMA 1992, FEMA 1999), although a greater emphasis was put on documenting shelter performance and projectile characteristics. Both residential and nonresidential structures suffered from inadequate connections. The wall-to-roof and wall-to-foundation connections failed most frequently. Many of the failures were initiated and/or increased due to breaching of the building envelope. The excessive amount of debris observed was most likely the main compromiser of the building envelopes.

The massive amounts of debris generated and deposited in single-family residential communities and the catastrophic damage observed indicates that wind speeds experienced in the center of the tornado path exceeded the capacity of the typical residential construction. The damage observed in residential communities was classified into 4 groups, and associated wind speed ranges were estimated and are listed in the following table. Observed damage F-scales associated with the residential damage classification are also listed below.

Table 3. Damage Classification

Residential Damage Classification	**Wind Speed (3-sec gust) m/s (mph)**	**Observed Damage F-scale**
Minor-Moderate	38-49 (85-110)	F0-F1
Extensive	50-58 (110-130)	F2
Severe	54-63 (120-140)	F3
Destroyed	58-72 (130-160)	F4-F5

Notice the wind speeds associated with the residential damage classification and the observed damage F-scale rating. The estimated wind speeds suggest that residential damage is not a good indicator for gust wind speeds above 72 m/s (160 mph), that F5 damage can occur at gust wind speeds as low as 58 m/s (130 mph), and that the Fujita damage scale gust wind speeds are overestimated for F3-F5 tornado categories.

Projectiles resulting from the massive amounts of debris ranged in size from small pieces of wood to long sections of steel pipe. The most common projectiles were remnants of 5 cm x 10 cm (2 in x 4 in) and 5 cm x 15 cm (2 in x 6 in, cross-section) wood boards, with the average 5 cm x 15 cm (2 in x 6 in) projectile weighing 44 N (10 lbs) and the average 5 cm x 10 cm (2 in x 4 in) projectile weighing 13 N (3 lbs).

Many families sought protection from the winds and flying debris in shelters. The teams documented above- and below-ground shelters. The shelters provided adequate refuge to occupants, though shelter doors were under-designed in respect to material, material thickness, and latching, and the accessibility of many outdoor shelters was limited due to stairs and small entrances.

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