Damage Survey and Assessment of Fort Worth Tornado, 28 March 2000

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Contents

1. Introduction

A tornado, designated as F2, passed through the downtown region of Fort Worth, Texas, in the early evening of Tuesday, March 28, 2000. Severe damage to glass clad buildings in the downtown area was reported. A second tornado from the same storm system touched down in Arlington some fifteen miles farther east about thirty minutes later. A team of five researchers from the Wind Science and Engineering Program at Texas Tech University was dispatched to survey damage on Wednesday, March 29. The team members were faculty members Joseph Bilello, Chris Letchford, and Scott Norville and graduate students Alok Kumar and Mark Martinez. Norville arrived mid-afternoon on March 29 but was unable to gain access to the restricted areas until the following day, when the full team surveyed damage on the eastern side of the Trinity River and into the downtown. Bilello spent March 30 in the Fort Worth and Arlington areas, while the other team members spent the following day documenting damage on the western side of the Trinity River. A brief visit to the Arlington Tornado site was conducted late in the afternoon of March 31.

2. Tornado details

2.1 Tornado path estimate

The preliminary path estimate for the first tornado produced by the National Weather Service (NWS) is shown in Figure 1. They estimated the path length to be 3 miles extending to a width of one-quarter mile and rating from F0 to F2 damage along the path. The tornado path started near Monticello and just north of West 7th Street and ended near Spur 280 just to the east of the downtown area.

Figure 1. NWS preliminary estimate of Fort Worth Tornado path. (source: NWS)

2.2 Timing of the tornadoes

The National Weather Service has given the following timings for the Fort Worth and Arlington Tornadoes.

2:53 p.m.: Tornado watch issued.

5:33 p.m.: Severe thunderstorm warning issued.

6:10 p.m.: Tornado warning issued after a rotating storm is spotted 5 miles west of Meacham Field, heading east.

6:11 p.m.: Fort Worth sounds emergency sirens. (Sirens are repeated at 6:22, 6:23 and 6:26.)

6:18 p.m.: Tornado sighted west of Fort Worth, near Castleberry High School.

6:22 p.m.: Tornado reported just west of downtown, near Montgomery Ward building on 7th Street.

6:25-6:26 p.m.: Tornado sweeps through Fort Worth central business district.

6:28 p.m.: Tornado dissipates.

6:37 p.m.: Tornado indicated at I-35 and Riverside.

6:40 p.m.: Tornado warning re-issued.

7:05 p.m.: Tornado detected 5 miles west of Arlington Airport, moving east.

7:07 p.m.: Tornado observed near I-20 and Collins in Arlington.

7:20-7:24 p.m.: Tornado touches down in southwest Grand Prairie.

7:26 p.m.: Tornado dissipates.

(Sources: National Weather Service, Grand Prairie Fire Department)

2.3 Radar images of the tornado

Figures 2 and 3 show radar images of the Fort Worth Tornado. Figure 2 shows the radial velocity at the lowest elevation as inferred from the radar. It is seen that there is significant convergence of flow towards the supercell and tornado.

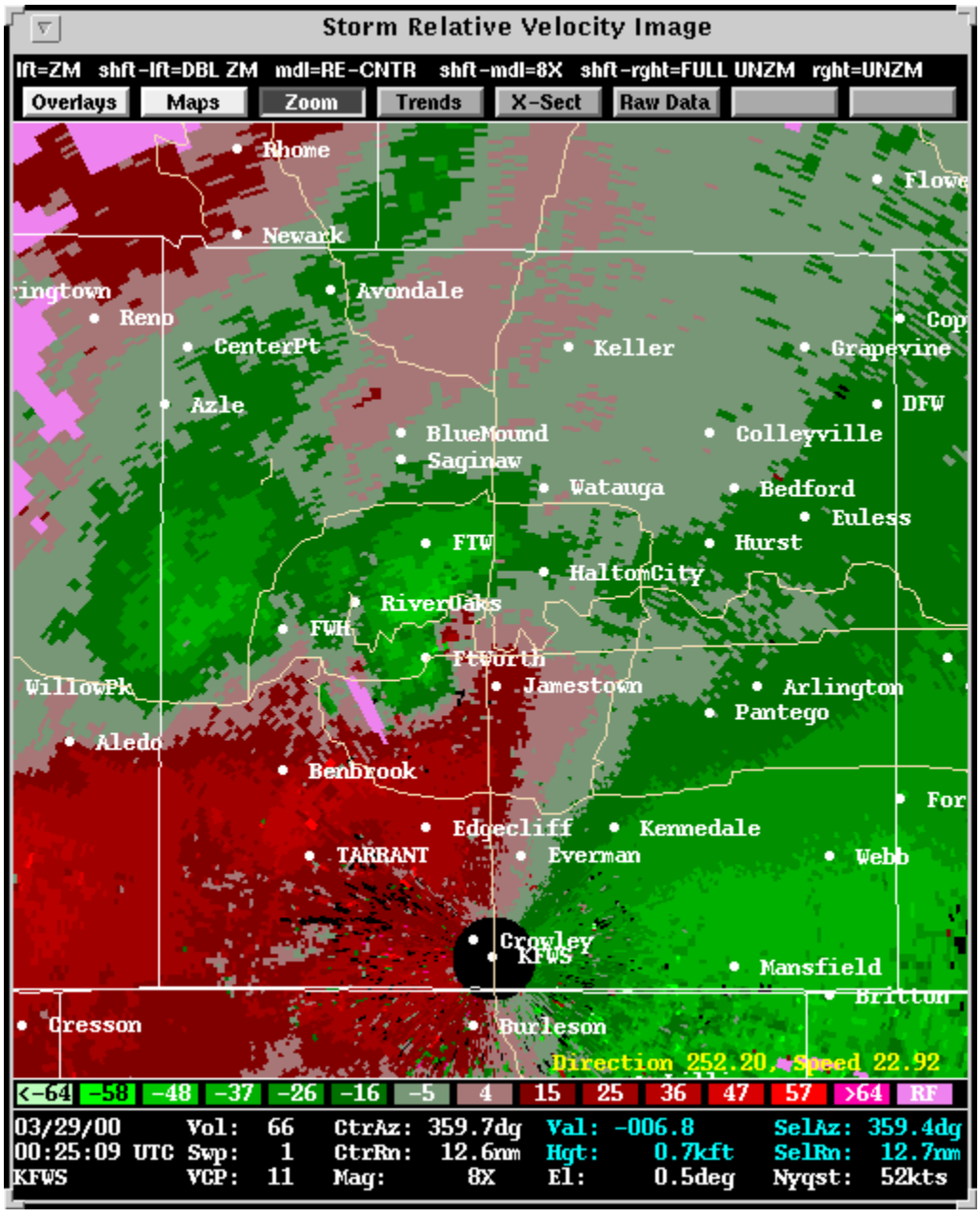

Figure 2. Radial velocity at 0.5 deg elevation angle, at about the time the tornado is hitting the downtown area. (source: NWS)

Figure 3 shows the storm reflectivity as measured by the radar and a blowup of the radial velocity in the vicinity of the tornado. It is seen that the highest reflectivity is near the tornado and to the north, where large hail was reported.

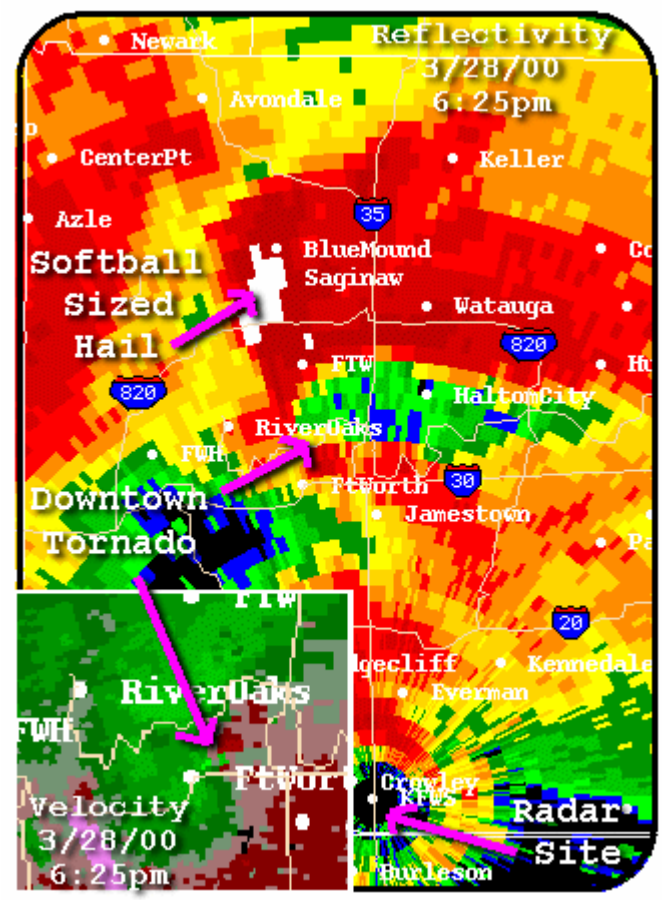

Figure 3 Radar reflectivity and blowup of radar radial velocities in tornado. (source: NWS)

Figure 4. Fort Worth tornado approaching Mallick Tower. Towers of First Methodist Church on left. Significant debris is evident in the flow field. (source: Fort Worth Star-Telegram)

3. Documented damage

The major buildings damaged in the Fort Worth tornado are shown on the map in Figure 5, with a more detailed map of the downtown in Figure 6. The damage documentation team surveyed the general damage area on the eastern side of the Trinity River on March 30 in two groups, and several buildings were documented in detail. The western side of the Trinity River was documented on March 31 as a single team.

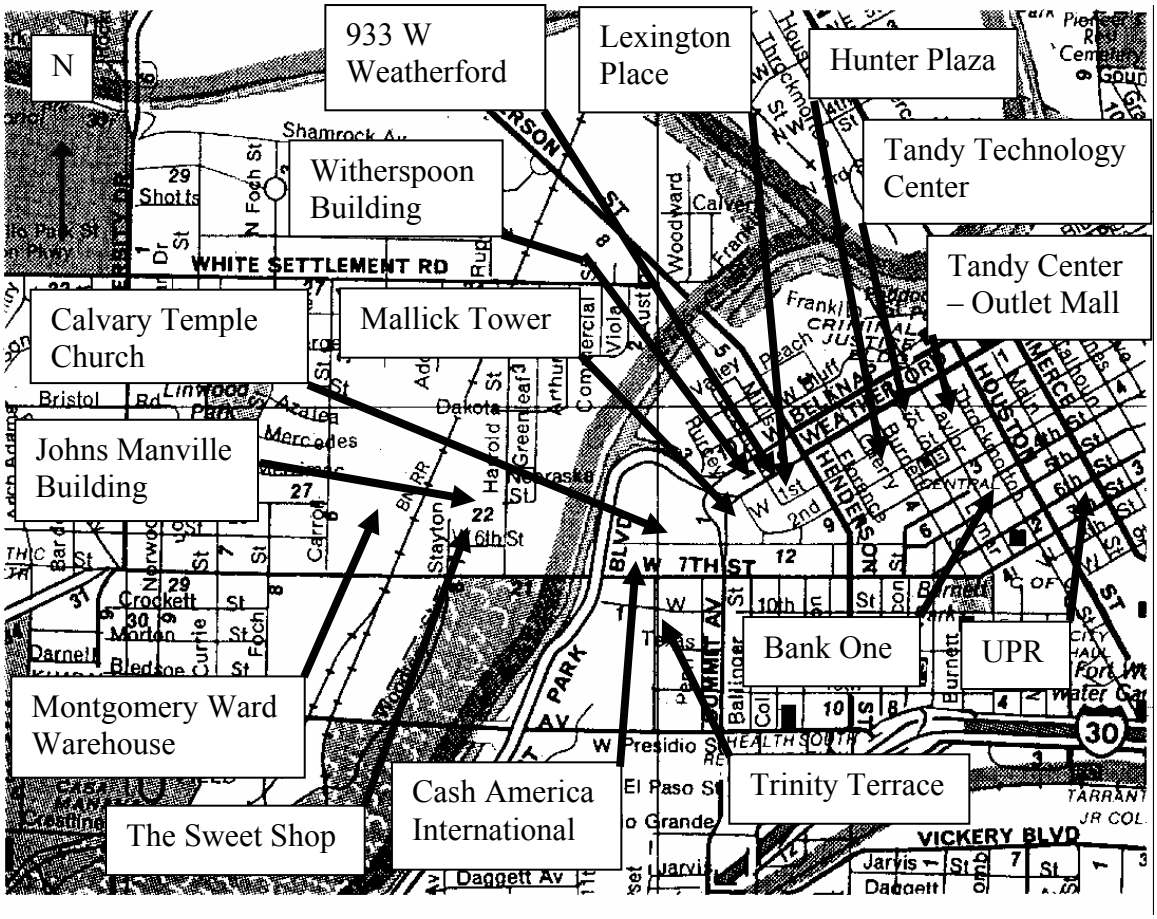

Figure 5. Map of the region affected by the tornado showing the major buildings damaged.

3.1 Summary of damage

The following table summarizes building characteristics and tornado damage surveyed by the Texas Tech investigators. It is not exhaustive, but is believed to be representative of non-domestic buildings within this tornado. A detailed discussion of the failure mechanism for some specific buildings follows the table. Appendix A shows photographs of typical damage.

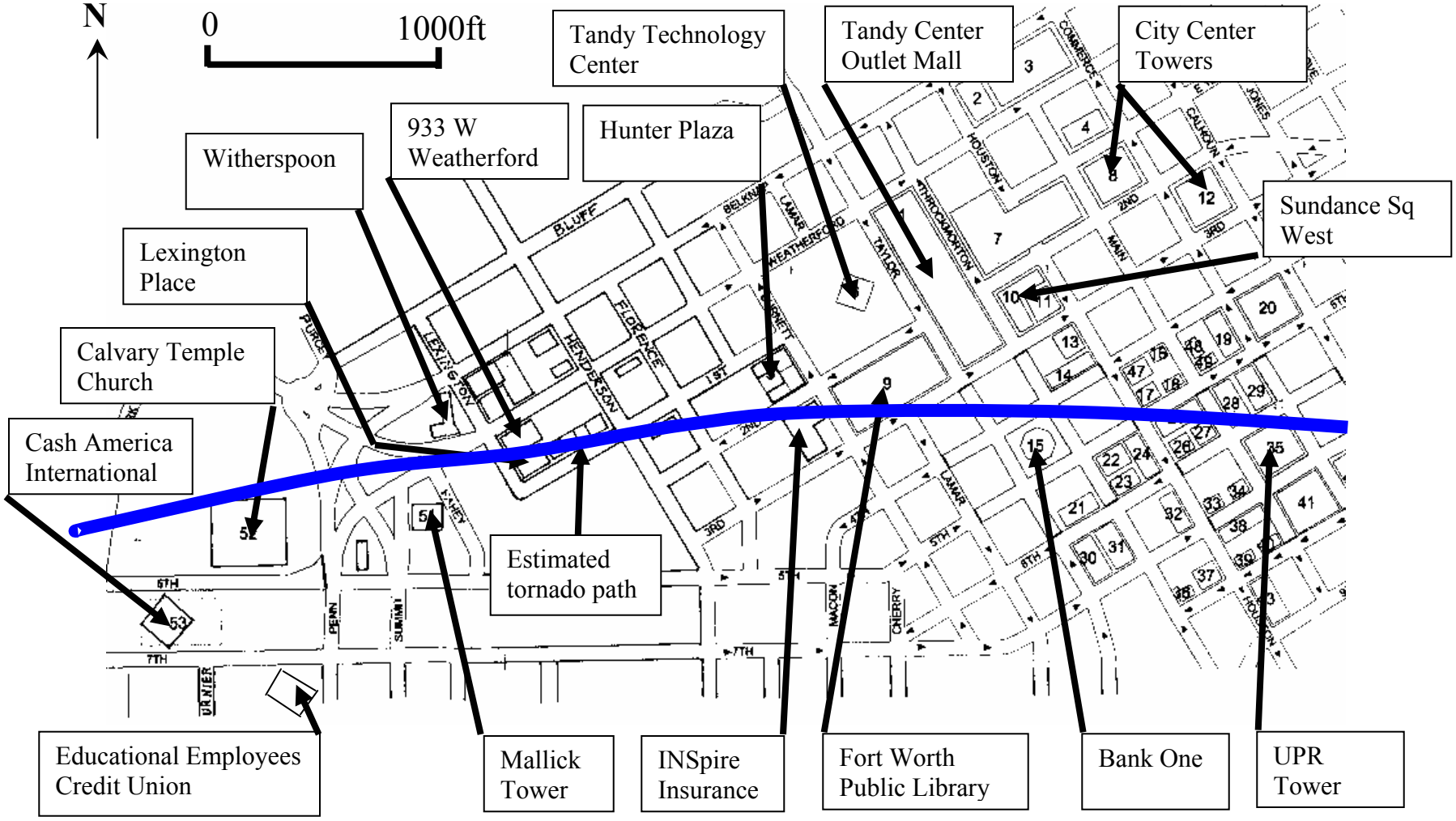

Figure 6. Map of downtown Fort Worth.

Building Name	Occupancy	Location	Construction Type	Cladding Damage	Roof Damage	Structural Damage	Evidence of Debris Impact
Trinity Terrace	Retirement complex – Multiple apartments, Public assembly, Parking	1600 Texas St	Steel and concrete tower, 15 floors Above Ground Level (AGL)	Insulating Glass (IG) unit windows broken, in quite a few cases only the outer pane is broken W face (~3%)	no	No	Yes, roofing from upstream impacted on west facing balcony windows on 7th and 15th levels
Cash America International	Office – Multiple tenancy Public assembly, Parking	West 7th St	Steel and concrete tower, 9 floors AGL -window and spandrel glass and travertine skin at corners and roof level	Severe damage to all but NE face with major damage on that face SW face – already broken out NW face ~ 100% lites and spandrels SE face – Lites ~ 80% Spandrels ~ 35% evidence of suction failure on S corner of SE face NE face – Lites ~ 35% Spandrels ~ 25%	Membrane peeled off roof from SE face	?	Evidence of suction failure on windows adjacent to W corner on NE and SE faces. Mostly likely due to overpressure from debris impacted NW and SW faces.
Calvary Temple Church	Church complex – Public assembly	West corner of Penn & 5th	Steel frame clad in brick. Auditorium to 3 floors AGL, steeple to 6 floors AGL	Brickwork removed from steeple and E & W parts of the auditorium walls and parapets. Ground level windows broken on W, S and E (~100%) faces.	Membrane peeled off towards S from office complex to west of church, roof sheeting lost from auditorium A/C unit ends up S across 6th St	Yes, plastic hinges form in steel framing of steeple.	Yes, S face shows extensive debris impact marking
Office Building	Office – for lease	Summit, Penn & W 5th	Brick clad 2 floors AGL	Bricks peeled off E face, W wall falls out extensive glazing damage to E and W walls	Roof pulled off W wing	W wall falls out, probably after roof is pulled off	Debris markings on wall and Rose window probably broken by impact

Building Name	Usage	Location	Construction Type	Cladding Damage	Roof Damage	Structural Damage	Evidence of Debris Impact
Educational Employees Credit Union	Office – Single tenancy	South corner of Penn and 7th	Steel and concrete to 4 floors AGL	Window failures on SW face and on NE and SE faces near E corner, Exterior insulated finishing system (EIFS) removed from top 2 floors of NW face and 2rd floor only, just above a podium, on SE face.	Membrane peeled off on western and southern corners. A/C units blown over.	no	Either suction removes rockwall on SE face or window breakage on NE or SW corners lead to over pressure blowing off rockwall.
Mallick Tower	Office – Multiple tenancy	Between Summit, Fahey, Weatherford and 5th St	Steel frame to 10 floors AGL.	Severe damage to glazing E face Lites ~ 45% Spandrels ~ 25% N face Lites ~ 45% Spandrels ~ 70% W face Lites ~ 85% Spandrels 100% S face ~ 100%	Membrane peeled from SW corner (from video)	?	Some windows in the middle of the eastern face are bowed outward – internal impact? Evidence of suction failure at W end of N face.
Witherspoon	Advertising Agency	West corner of Lexington & Weatherford	Brick clad wood frame some steel bracing, 2 floors AGL, plus underground parking	Many windows broken, on W (~20%) and E faces ~33%). Brick facing collapsed on western and southern walls. Ties from brickwork to stud wall not effective.	Pea sized roofing gravel piled up under conical vortices, membrane bubbled	Collapse of western corner due to internal pressurization blowing out SE wall	Several safety glass doors broken and IG units blown in on western sides. Skylight and window damage on eastern side due to impact

Building Name	Usage	Location	Construction Type	Cladding Damage	Roof Damage	Structural Damage	Evidence of Debris Impact
933 Weatherford	Office	East corner of Lexington & Weatherford	Steel frame precast concrete panels, 2 floors AGL with ground floor open as parking	Severe window damage on SE and SW (~70%) faces	Membrane and insulation completely removed from entire roof. A/C units blown off	Western corner lost roof sheeting and trusses	
Lexington Place	Office	North corner Lexington & 1st	Brick clad precast concrete 4 floors AGL	Windows severely damaged on S corner, SE face NE face has framing removed as well, and window and brickwork blown out on NW face	None, some impact damage to air-conditioning ductwork and equipment.	No	?
Hunter Plaza	Retirement complex	West corner Burnett and 2nd St	12 floors AGL. U shaped Brick clad opening to SW	Severe window breakage on all faces within the U facing SW. Older style single glazed casement windows. NE face ~ 40% NW face ~ 40% SW face ~ 85% SE face ~ 85%		None	
INSpire Insurance	Office	SW side of Burnet between 2nd and 3rd	Precast concrete panels and glass	Trees along SW face prevented a lot of damage; however, several outer panes of ground level IG units broken as well as windows in the top floor. SW face top floor ~ 80% Roller garage door on NW face blown out.	Skylight broken, evidence of conical roof top vortex removing gravel.	None	Pitted windows

Building Name	Usage	Location	Construction Type	Cladding Damage	Roof Damage	Structural Damage	Evidence of Debris Impact
Tandy Technology Center	Office	Weatherford 2nd, Burnett and Taylor	6 floors AGL	Window damage on S (~2%) and E (3%) faces	None	None	
Tandy Center – Fort Worth Outlet Square North Tower	Office	Weatherford between Throck-morton & Taylor	Mostly glass clad 20 floors AGL	Window breakage SE face (~20%) Mostly near SW corner SW face (~5%)	None	No	
Tandy Center – Fort Worth Outlet Square South Tower	Office	3rd between Throck-morton & Taylor	Mostly glass clad 20 floors AGL	Window breakage SE face (~15%) Mostly near SW corner and at ground level SW face (~95%)	None	No	
Tandy Center – Outlet Square	Retail	Taylor St	Glass clad to 3 floors AGL	Significant ~ 50% window breakage on Taylor St	?	?	
Fort Worth Central Library	Library	Taylor, Burnett, 2nd & 3rd	2 floors AGL	Glazing damage on most faces	Skylights broken, 6 A/C units dislodged	?	
Sundance Sq West	Accommo-dation	N corner of Throckmort on & 3rd	14 floors AGL	Glazing damage on south and west faces SE face (~ 50%) S 1/3 portion of SW face (~50%) NW face (0%) NE face (~10%)	?	none	

Building Name	Usage	Location	Construction Type	Cladding Damage	Roof Damage	Structural Damage	Evidence of Debris Impact
Bank One Tower	Office	Taylor, 4th, 5th & Throck-morton	Glass clad to 35 floors AGL	Extensive damage to glazing N chamfer ? NW face (~60%) W chamfer (~100%) SW face (~90%) S chamfer (~40%) SE face (~15%) E chamfer (~20%) NE face (~40%)	?	no	Many broken windows
Union Pacific Resources Tower (UPR)	Office	Main, Commerce, 6th & 7th	Glass clad to 38 floors AGL	Extensive damage to glazing NE face (~0%) N face Lites (~1%) Spandrels (~10%) NW face Lites (~1%) Spandrels (~5%) SW face Lites (~65%) Here only 30% had both panes of IG unit broken Spandrels (~95%) S face Lites (~35%) Spandrels (~25%)	?	no	Yes, only outer panes broken on many IG units on SE face
City Center Towers	Office	Two towers on eastern & western corners of Commerce and 2nd	Glass clad to 40 floors AGL	Each Tower similar with W face (~8%) S face (~8%) Negligible damage on N and E faces	?	no	

Building Name	Usage	Location	Construction Type	Cladding Damage	Roof Damage	Structural Damage	Evidence of Debris Impact
The Sweet Shop	Chocolate factory	Between Stayton & Harrold Sts north of 6th	Precast concrete wall panels 24'x24'x5", light steel trusses 22" deep and spaced at 14.5', metal deck roof overlain with insulation and membrane, building floor area was ~60,000 ft^2 with dimensions, 144'x408'.	24ft high concrete panel walls collapse both inward and outward, apparently after loss of roof support.	Would appear roof fails under uplift with a lot of debris shed. Some portions end up upside down and under sidewall panels.	Total structural failure. 9 people lucky to escape alive	Some debris impact evident on steel shed on Stayton St on W and S faces. The abutting single story building to the south on Stayton St suffered some roof damage but no other significant cladding damage.
Johns Manville Warehouse	Shipping warehouse with large overhangs at loading docks on S (road) & W (rail) sides	End of Stayton St adjacent to railway, Main entrance off Harrold St, this section remains standing but has roof sheeting removed.	Heavy steel frame ~30' to ridge line column 8"x7.24" beams 20"x6" purlins 10"x6" and white metal deck roof and wall cladding ~1/8" screws at 1' spacing	Metal deck walls pull off small self-tapping screws (no washers?)	Metal deck roof pulls off leaving (~3/16") self-tapping screws in purlins (no washers?)	Total structural failure. Initiated by pullout of base plate bolts through base plate on W wall columns (?)	Broken windows

3.2 Low-rise buildings

Low-rise buildings are defined as being fewer than three stories in height and this class of building performed the worst in terms of structural damage. The buildings in this class discussed in detail here are:

- The Sweet Shop Factory building
- Johns Manville Warehouse building
- Witherspoon building
- 933 Weatherford building

The Sweet Shop Factory

The Sweet Shop Factory lay between Stayton and Harrold Streets, just north of West 6th Street. Constructed of tilt-up concrete wall panels, this building suffered catastrophic failure and generated a large amount of debris. Figure 7 shows a schematic of the collapsed state of this building. The debris varied in size and weight from portions of tar covered roofing insulation to full 20'x 2' sheets of metal roofing with the former observed approximately one-half mile to the SSE on the fifteenth floor of Trinity Terrace facing Fournier Street, just south of West 10th Street. The larger roofing sheets were observed on the ground on Fournier Street between West 7th and West 10th Streets and on the seventh floor of Trinity Terrace.

The postulated failure mechanism is as follows:

- Debris marking on the intact steel building fronting the factory on Stayton Street, indicated that the wind approached the building from the south and west. The 10' high chain mesh fence on the western side of Stayton Street blew over to the east.
- Roof decking on the southern side and particularly near the western corner detached from the roof trusses (as evidenced by upside down roof portions in the adjacent debris and wall panels lying on top of roofing - in particular the southern and western wall panels fell inward (to the north and east respectively) on top of the awning that covered the front (western) entrance while the northern walls fell outward (to the north) also on top of roofing.
- The building had several openings; a front entrance safety glass single door in the southern end of the western wall and loading bays in the middle of the northern wall and the eastern end of the southern wall. These openings were sealed as the tornado hit and appeared to remain so during the building's collapse. Thus, it is not expected that internal pressurization lead to failure of the roofing.
- The wall panels in the vicinity of the roofing failure were exposed to the full windward pressure and the full negative pressure that removed the roofing.
- Without the diaphragm action of the roof decking, the walls lost their upper support and fell. Figure 5 indicates that the western half of the building fell northwards, while the eastern half fell southwards.
- The western end wall fell inwards on top of the already collapsed southern wall.
- The eastern end wall fell outwards onto Harrold Street.
- An interior wall, which divided the building approximately in half, fell toward the east.

By and large, the concrete panels remained intact upon falling, but the three fillet-welded joints (~4" long at 6' spacing) up each side between adjacent panels failed. This failure would have occurred after the loss of the roof and during the fall of the wall. The concrete wall panels had similar short fillet welds at their bases and some of these showed significant corrosion. The upper cords of the roof trusses were tack welded to a metal plate set into the top of the concrete wall panels. It is anticipated that this connection failed once the walls began to fall. Some cases failed as the roofing and trusses were removed intact, as evidenced by the upside down trusses toward the middle of the building.

Nine staff, members of the cleaning crew, were lucky to escape with their lives. They had attempted to move away from the southwest corner, which was fortunate, as this corner collapsed inwards.

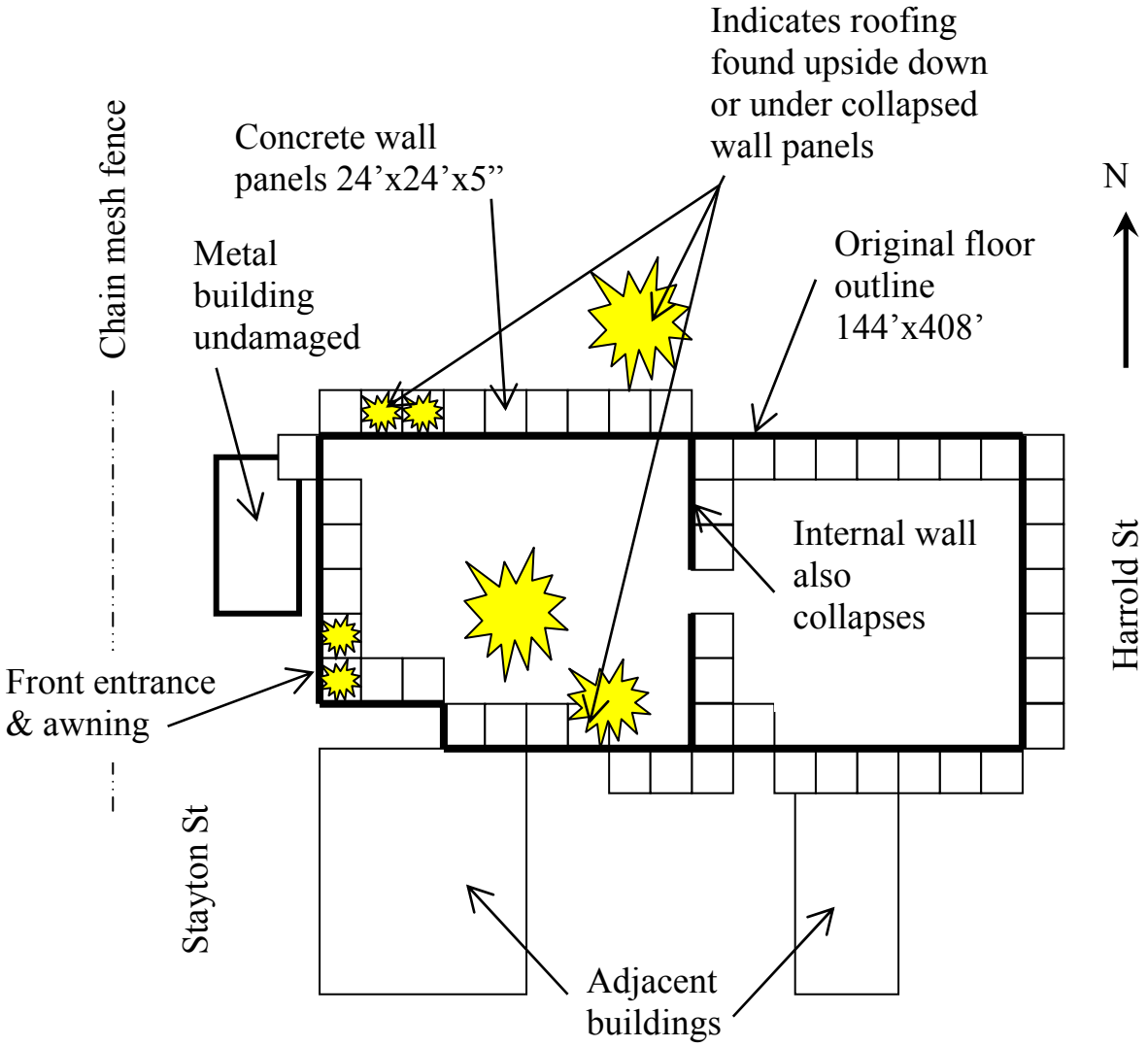

Figure 7. Schematic of damage to Sweet Shop Factory.

Johns Manville Warehouse building

The Johns Manville Warehouse complex is located between Stayton Street and Harrold Street and is separated by about 75' of asphalted loading zone from the Sweet Shop Factory to the south. Figure 8 shows a schematic of the collapsed state of the building. The western end of the building appeared to be of much newer construction than the eastern end. The western end consisted of a single large gable roof running east/west and overhanging a loading bay for railway access to the west and a vehicular loading bay to the south. The eastern end of the building had three parallel gable roofs also running east/west and providing a covered loading area to the eastern end of the building. The distinctive white metal roofing sheets from this building were observed on light poles and in trees in Greenleaf Street and in the Trinity River some one-quarter mile to the east.

The western half suffered catastrophic collapse, while the eastern end appeared to suffer only loss of roofing. The postulated failure mechanism is as follows:

- The 5 columns at the western end of the building supporting the roof to the open loading bay were all pulled through their ¼" base plates and two ½" bolts holding them down. The 8"x7¼" columns were 26' high and spaced at 42'. The roofing remained attached at this stage.
- The white roofing metal sheets started detaching from the purlins at the western end of the building, and this loss progressively moved eastwards. The roofing was attached to the purlins with 3/16" self-tapping screws at 1' spacing. The wall sheeting to the western end of the southern wall was also lost during this stage. This loss of sheeting led to insufficient lateral bracing for the frames.
- The building frames then collapsed to the east. The horizontal frame members were typically 20"x6" beams; the purlins, which remained attached to the beams, were 10"x6" beams at 6' spacing.
- The northern wall fell inward to the south and also suffered failure of the column-base connection, this time spalling the concrete plinth. This was most likely a result of the frames falling.
- The southern wall collapsed more or less in the plane of the wall towards the east.
- It is expected that large uplift forces were also exerted on the overhang to the southern loading bay as wind was directed from the west and the south during the passage of the tornado, as evidenced in the collapse of the adjacent Sweet Shop Factory.

It was unclear whether any material was in storage in the warehouse or whether any staff members were on duty at the time of the tornado; however, the two-story office building did not suffer any noticeable structural damage.

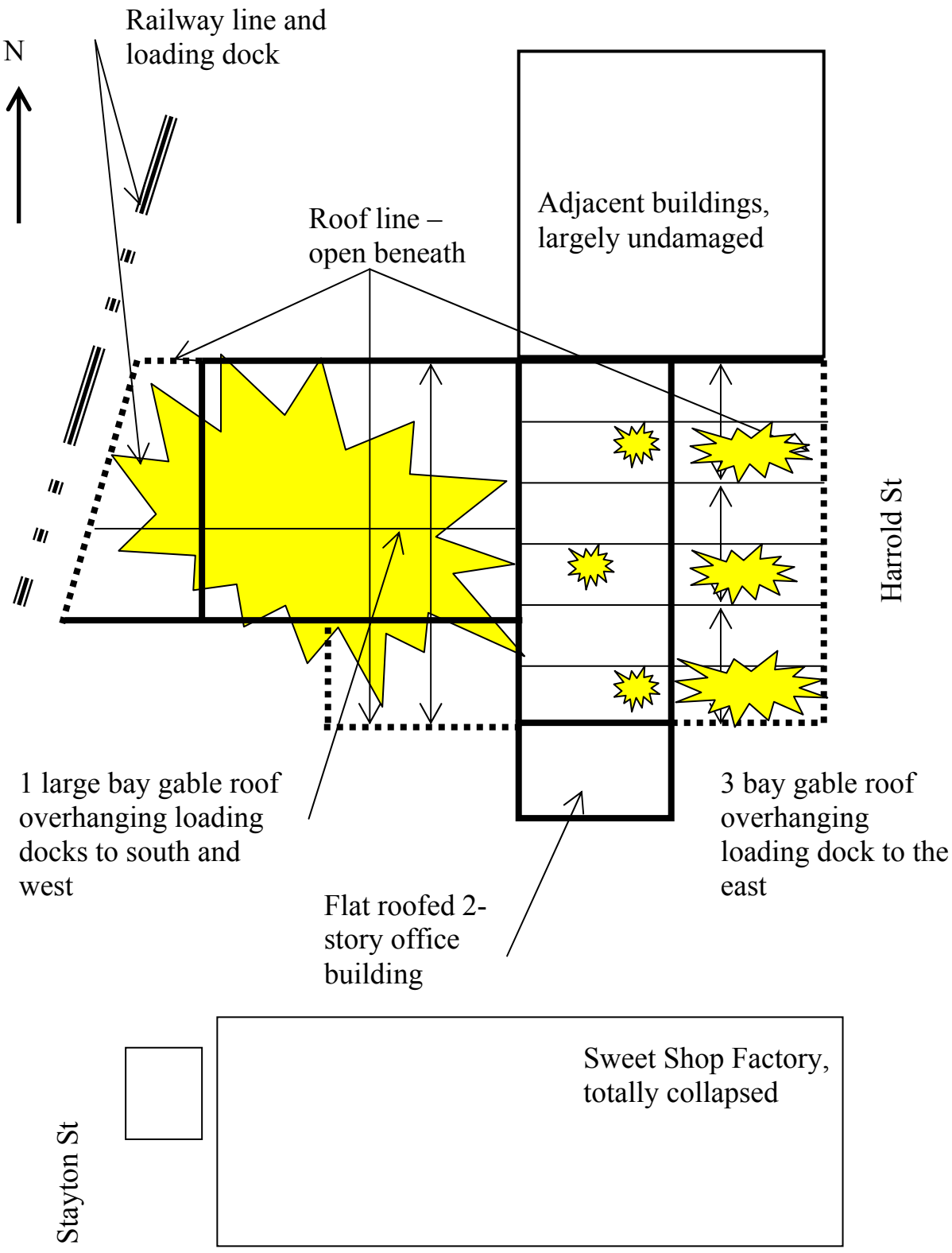

Figure 8. Schematic of damage to Johns Manville Warehouse

Witherspoon building

The Witherspoon building is a two-story L-shaped structure occupying the southwestern side of Lexington, between Weatherford and Belknap Streets. Figure 9 shows a schematic of the damage to the building. This building suffered major structural failure of the southwest corner including removal of the brick cladding on the southeast face and collapse of the roof over the southwest corner. In addition, there was significant debris damage to glazing on both western and eastern facing walls as well as east facing skylights. The building was very exposed to the west with no structures between it and the river some one-quarter mile to the west. Some trees in the interior of the L afforded some protection from that direction but not sufficient to prevent debris damage particularly at the western and northern extremities of the arms of the L. The postulated failure mechanism is as follows:

- Debris breaks windows on the interior of the L particularly on the northwest face near the western corner, from whence the tornado approached. The evidence for this was the glass-strewn drawing office, which occupied the western end of the second floor. In addition a north-facing skylight had glass and framing sucked outward, rather than blown inward.
- This debris damage on the positive pressure face led to a high internal pressure which, when combined with suction on the Weatherford Street (southeastern) face, lead to failure of the cavity brick wall.
- The external brick wall and parapet fell into Weatherford Street and also from the southwestern face. The brick ties in some cases did not attach to the stud framing but only to the rockwall sheeting.
- The loss of cladding lead to loss of support for the roof in the southwestern corner and subsequent collapse of the roof.
- There was almost complete breakage of skylight windows on the eastern face along with two highly recessed windows, also on the eastern face. This would indicate that wind approached the building from this direction at one stage during the passage of the tornado. In all cases only the outer pane of the double glazed unit failed. The inner panes were safety glass, and although some showed impact markings, the building envelope was not penetrated here.

The building had only two occupants at the time of the tornado, and they were able to take refuge in the basement parking area. The drawing office was severely damaged, and many offices on the northern wing had significant glass debris, although surprisingly little other damage was evident.

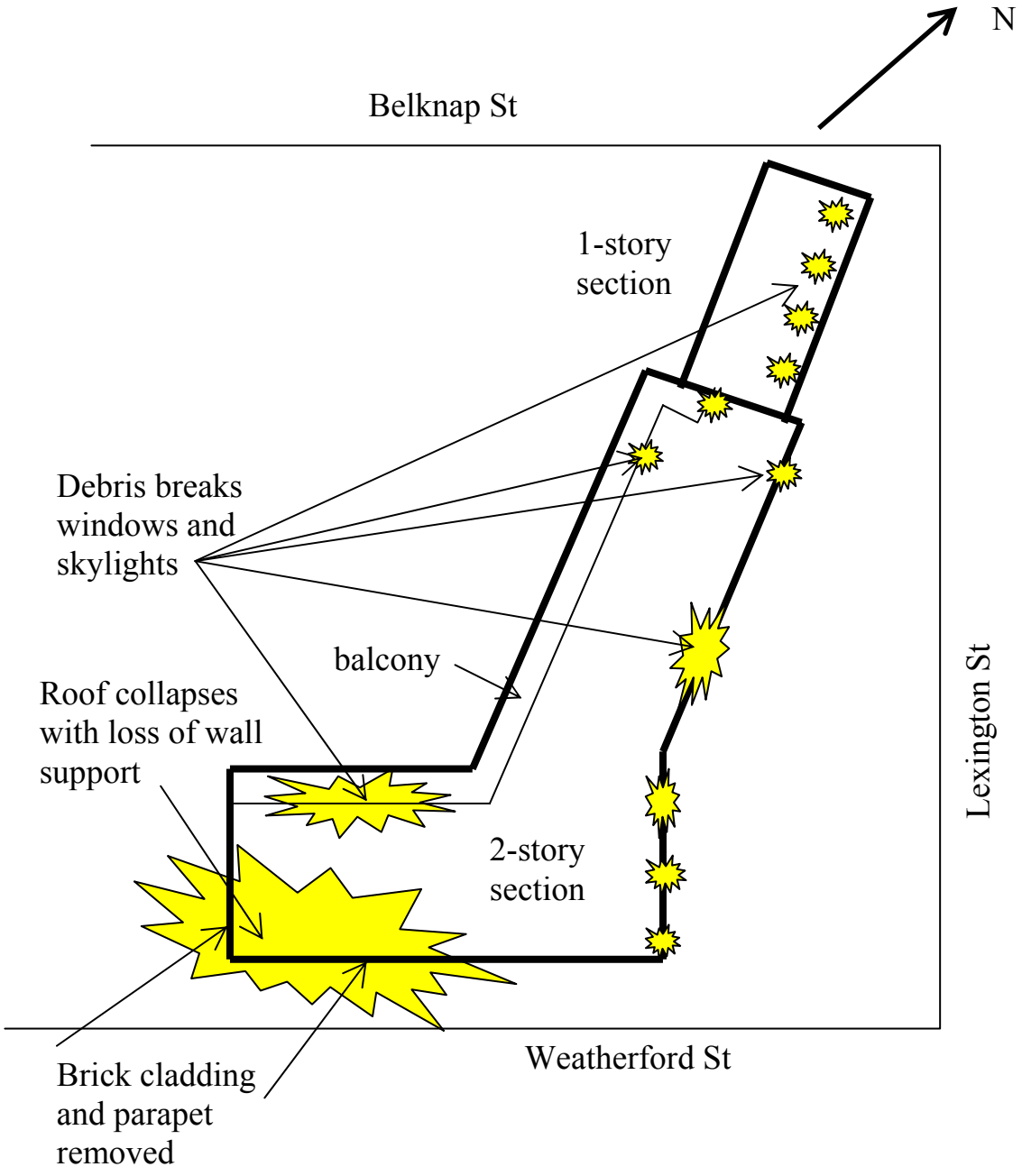

Figure 9. Schematic of damage to Witherspoon building.

933 Weatherford building

The two-story building at 933 Weatherford is located on the eastern corner of Weatherford and Lexington Streets, directly opposite the Witherspoon building. Figure 10 shows a schematic of the damage to the building. This building suffered catastrophic failure of the complete roofing membrane and insulation and of the roof deck and roof trusses in the western corner. There was significant glazing damage on the Lexington and Weatherford road frontages. The ground floor level was an open parking area.

The postulated failure mechanism is as follows:

- Debris impact breaks windows on western corner of building from whence the tornado approached. Apart from the Witherspoon building and across the street to the northwest, there is clear exposure for this building upwind to the river some one-quarter mile to the west.
- This debris damage on the positive pressure face led to a high internal pressure which, when combined with suction on the roof, lead to failure of the complete roof system, covering and trusses, in the western corner bay.
- Subsequently the complete covering was stripped off the roof.

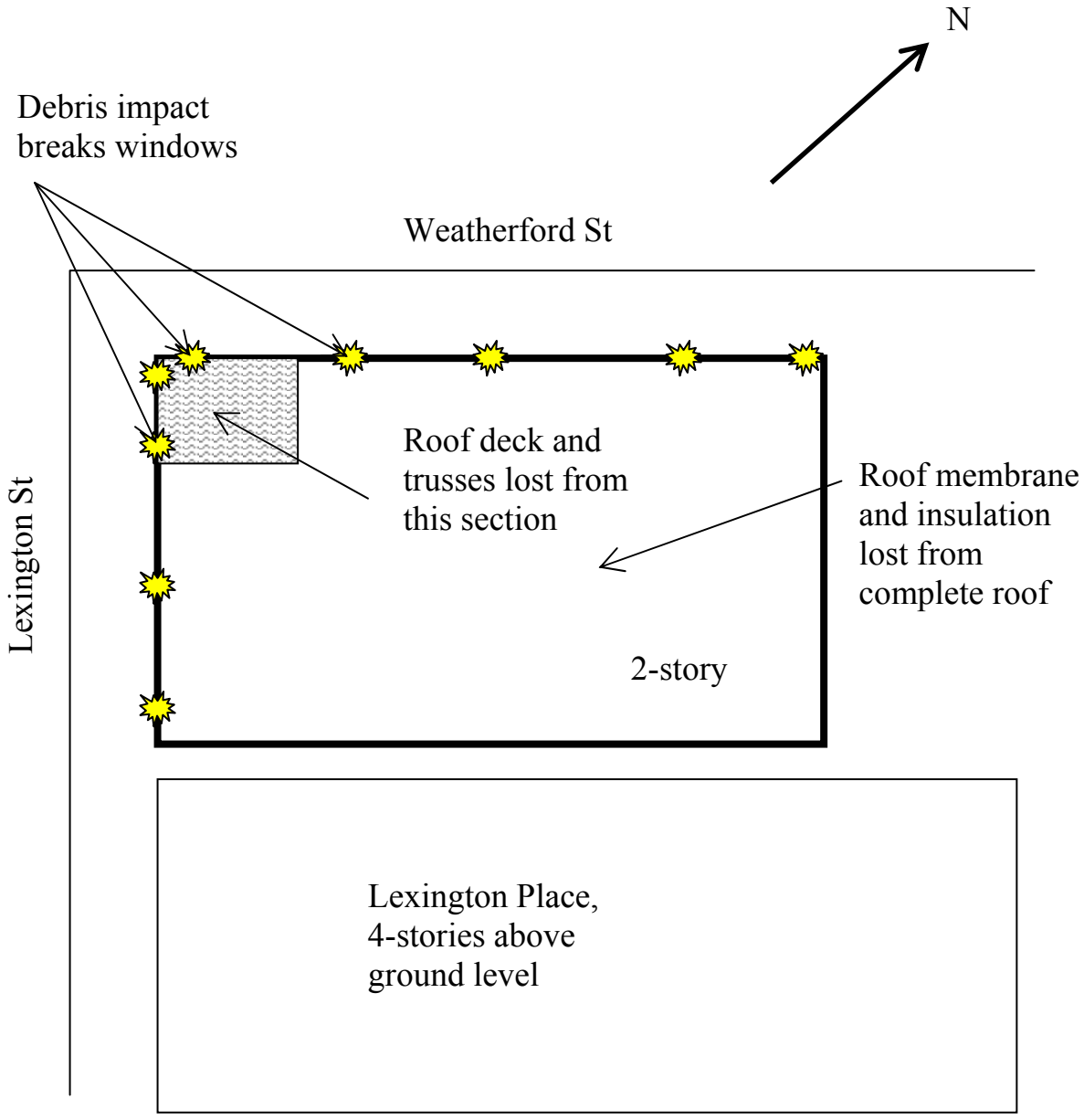

Figure 10. Schematic of damage to 933 Weatherford Building

3.3 High-rise buildings

This class of building, ranging from four to thirty-five stories, suffered significant cladding failure, with many broken windows. A significant cascade effect inflicted by debris was evident, commencing on the western outskirts of the downtown at Cash America International and finishing with the UPR Tower, about one mile to the east. These buildings are located in Figures 4 and 5.

The most heavily damaged buildings commenced with Cash America International, which appeared to bear the brunt of the debris generated by the collapse of the Sweet Shop Factory and the Johns Manville Warehouse some one-third mile upwind. This was followed in-order downwind to the east by: Educational Employees Credit Union building and the Calvary Temple Church about one-fifth mile, Mallick tower and Lexington Place another one-quarter mile, Hunter Plaza a farther one-quarter mile, then Tandy Center Outlet Mall Towers and Bank One another one-quarter mile. The major cladding damage finished at the UPR Tower a farther one-fifth mile to the east. The debris field continued to gain material from each of these failures.

Buildings outside the main tornado/debris path suffered lesser cladding damage. These were: Trinity Terrace, which was approximately one-fifth mile south of Cash America International; the County Jail buildings, one-tenth mile north of Hunter Plaza on the northern side of Belknap Street; City Center Towers, one-fifth mile north of Bank One on Commerce and 2nd Streets. These buildings suffered broken windows and marking left by flying tarred roof debris.

Two failure mechanisms were clearly evident in the cladding of these buildings. The first was inward due to debris impact on a windward face during the passage of the tornado. The second cause of failure was outward most likely due to internal pressurization leading to outward failure at side corners and, in some cases, rear faces where strong suctions combined to have large net pressure differences across the cladding. Another potential cause of the outward window failure was from internal debris impact.

Both types of failures were clearly evident in Cash America International and Mallick Tower, where western and southern faces suffered inward failure under debris loading, while eastern and northern faces showed clear signs of corner windows failing outward, as evidenced by the piling up of internal building furnishings in these regions.

In the Cash America International building, monolithic glass having nominal 6 mm (¼") thickness glazed both the vision and spandrel areas. The spandrel lites consisted of heat strengthened glass. As the tornado passed, the southwest façade suffered the first impacts. The glass from virtually every fenestration on the southwest façade fractured. Breakage on the southeast façade most likely resulted from several causes as outlined above. These include impact from interior debris, impact from exterior debris, and increased cladding loads because the inside of the building became pressurized as soon and the southwest façade windows fractured. Primarily vision glass fractured on the southeast façade. The vast majority of glass remained in place on the northeast façade, indicating that fewer

impacts occurred. Although window glass breakage resulted on this façade for basically the same reasons as on the southeast façade, investigators surmise that the high incidence of breakage near the northeast corner resulted from a combination of internal pressurization and negative loading as the tornado passed. The northeast façade was subjected to positive wind forces and impacts and virtually every lite, both vision and spandrel, has fractured. Investigators believe debris impact caused most breakage on this façade.

The Cash America building provided office space for the Federal Bureau of Investigation and the Bureau of Alcohol, Tobacco, and Firearms. At the time of damage investigation, the building was cordoned off, and investigators could not enter. Even so, the figures in Appendix A indicate the chaos that occurred in the interior space after the glass broke and wind and rain entered the building.

For Mallick Tower, the south and west faces had almost complete fracture of both vision and spandrel lites, while approximately half of the vision lites were broken on the north and east faces. Monolithic annealed glass with nominal 6 mm (¼") thickness glazed the curtain wall of Mallick Tower. The vision lites consisted of annealed glass and the spandrel lites consisted of heat-strengthened glass. Oddly, slightly more spandrel glass than vision glass fractured on the north face, while this was reversed for the east face. Investigators received permission to enter Mallick Tower. The interior suffered very significant wind and water damage. Tenants were moving damaged belongings from their offices. Scrape markings on the top of the Mallick Tower parapet from built-up roof construction indicated that the debris field was populated with large pieces and the glazing had little chance of survival.

The Calvary Temple church suffered major structural damage to the steeple, with plastic deformation of the steel frame and loss of brick cladding to the top portion and also to the eastern wall of the worship hall. Extensive broken windows and scaring of the brickwork indicated an intense debris field at this point in the tornado. The roof of the extensive two-story classroom section was largely stripped of its membrane cladding and several roof-mounted air-conditioning units traveled across West 5th Street to adjacent parking areas.

The four-story Educational Employees Credit Union suffered debris impacted broken windows and also loss of EIFS cladding on most of the northwest face and also on the southeast face adjacent to the east corner. It is likely that a combination of suction and internal pressurization lead to the EIFS cladding failures due to the extensive stripping of the cladding from the wall studs. Roof mounted air-conditioning units were also displaced from mounts and the roof membrane was heavily damaged adjacent to corners where conical vortices induced high suctions.

Hunter Plaza, a twelve-story accommodation building, U-shaped in plan, appeared to suffer window damage to all faces and all levels. Here the glazing was only 1/8" single pane, while Insulating Glass (IG) units on the adjacent INSpire Insurance building, made up of two ¼" panes separated by ½", suffered breakage of outer panes only. This

effective redundancy of the IG units has major implications for recoverability of building function, as the building membrane was not breached for this building.

Bank One is a chamfered square in plan-form with the chamfers being approximately one-quarter of the side length of the enclosing square. The northwest face (~60% broken), southwest face (~90% broken) and the intervening west chamfer (~100% broken), sustained heavy impact damage. The northeast face had about one-half the number of breakages on the southwest face, while the southeast face received approximately one-eighth of the southwest face. The intervening chamfers had intermediate numbers of breakages and these tended to be concentrated along the corners, indicating that they may have failed under internal pressurization. Interestingly, the internal partitions around the lift core appeared to withstand these pressure gradients. This was most noticeable on the top floor restaurant level where there was significant window failure around the entire floor level. Access to corner offices was not possible to confirm whether this was typical for all partition walls.

The Union Pacific Resources Tower (UPR), located approximately one-fifth mile to the east of Bank One Tower suffered the heaviest impact damage to its southwest and south faces, with hardly any damage to the other faces. Corner windows appear over-representative for pure impact damage and indicate that internal pressurization may have lead to outward failure of these windows. The Bank One Tower is likely to have been a primary source of debris for this building.

Almost all the buildings in the central business district suffered some degree of window glass breakage with consequential interior damage from wind and rain. Investigators had only a few hours in the central business district with their main purpose being to visit the Bank One building.

4. Discussion

4.1 Lower bound wind speed estimates

There would appear to be no direct anemometer measurements for the Fort Worth tornado. Hence, wind speeds must be obtained via indirect means. Here, lower bound estimates of wind speed have been obtained from the plastic collapse of several chain mesh galvanized iron (GI) pipe fences and gates. The potential to use similar methods for street signs is also being investigated. The actual calculations are shown in Appendix B.

The calculations determine the wind speed required to form a plastic hinge in the base of the fence posts, assuming a unidirectional drag coefficient of 1.2 for fence posts, rails, and wire and assuming the fence was free of debris. The later assumption was based on observations of the actual wind-damaged fences. In all cases examined here, the fences surrounded asphalted parking areas, and little or no debris was observed to be stuck in the fences. The calculated wind speeds have been converted to an equivalent 10m height in Exposure C terrain using the approach of ASCE 7-98.

The first fence formed the western border to Stayton Street just upwind of the Sweet Shop Factory.

- The estimated lower bound gust wind speed at 10m here was 70 – 80 mph.

The second fence formed the southeast and southwest borders to a parking area on 2nd Street and Florence in the downtown area.

- The estimated lower bound gust wind speed at 10m here was 90 – 100 mph.

The third estimate came from a GI sliding gate on 2nd Street adjacent to Hunter Plaza.

- The estimated lower bound gust wind speed at 10m here was 80 – 90 mph.

Thus, gust wind speeds in excess of 100mph at 10m in standard exposure could be postulated. However, given the extent of damage (mostly fractured window glass) and cause of damage (largely through debris impact leading to internal pressurization), it is unlikely that wind speeds reached significantly above these estimates. Lack of attention to connection details are largely thought to have caused the structural failures at the Sweet Shop Factory and the Johns Manville Warehouse.

4.2 Debris source and paths

Debris ranged in size from small ¼" roof gravel, medium pieces of tarred roof insulation, to large 20' by 2' roofing sheets and roof-mounted air-conditioning units. The larger pieces of debris were sourced from the warehouse and factory areas around Stayton Street and included the Montgomery Ward warehouse, the Sweet Shop Factory, and the Johns Manville Warehouse. Further along the path, the debris became smaller, typically because the buildings became better constructed, with only windows failing. An exception to this was a roof-mounted air-conditioning unit from the Calvary Temple Church, which ended up in the parking area of the Cash America International building. Perhaps the longest-traveled debris were the lightweight tarred roofing insulation pieces, which were found in trees and some fences in Lexington and 2nd Streets. In addition, these materials left scrape markings at high levels on the County Jail and Hunter Plaza, amongst other buildings in the downtown area.

Roofing debris, sheets and tarred insulation, from the Sweet Shop were tracked to Trinity Terrace giving a direct line of flight of one-half mile and an increase in elevation of between 100 and 150 feet.

Roofing gravel from the Witherspoon building was transported 50 feet across Weatherford Street, impacting upon the windows of 933 Weatherford.

4.3 Glazing performance

As the tornado passed the warehouse district and toppled several buildings in downtown Fort Worth, it accumulated large amounts of debris, as seen Figure 4. The debris fractured windows in most buildings within approximately three city blocks on either side of the tornado's path. The most extensive breakage to result from debris impacts occurred on building façades which faced the approaching tornado.

After breakage of the windward windows, high winds pressurized the buildings. Windows on leeward sides of the buildings fractured due to increased loadings resulting from internal pressurization, impact from windborne debris generated inside the building, and windborne debris impacting the outside as the tornado passed and wind directions changed. Typically, fewer windows were fractured on building sides facing away from the approaching tornado.

Buildings that underwent the most damage had monolithic glazing of various types, annealed, heat strengthened, and fully tempered. While heat strengthened and fully tempered window glass has much higher strength than annealed in resisting uniform wind loading, it has little, if any, additional resistance than does annealed glass to resist fracture resulting from debris impact. Any monolithic glass type, like that which glazed the most severely damaged buildings, when fractured in a windstorm will vacate its fenestration. The fractured spandrel lites on the Mallick Tower and the Cash America International Building, heat strengthened glass, attest to the above statements. Once one

or more large openings exist, i.e., once the building envelope is violated, wind and rain enter the building and increase damage significantly.

Several glazing possibilities exist that will reduce the probability of breaching the building envelope in a windstorm. At a first level, glazing with sealed insulating glass (IG) provides one level of protection for short duration windstorms. Insulating glass consists of two plies of glass around a sealed air space. The outer lite of the IG serves as a sacrificial ply and protects the interior lite. As long as the interior lite does not fracture, the IG unit will maintain closure of the building envelope, keeping wind and rain out of the building. Under a long duration, severe windstorm, repeated impacts can fracture the interior lite of the IG unit and open the building envelope. While increasing protection minimally, IG units made with two lites of monolithic glass offer only a marginal increase in protection against windborne debris impact. Insulating glass, as its name implies, provides additional benefits to any building it glazes with respect to energy savings.

At a next level, glazing with laminated glass (LG) provides a high level of protection in maintaining closure of the building envelope in a severe windstorm. Laminated glass consists of two plies of glass bonded together by an elastomeric interlayer. Laminated annealed glass, when fractured, will tend to remain in the frame. If secured to the frame with glazing tape or structural silicone sealant, LG provides a very high level of protection. For even more protection, IG fabricated using LG in one or both lites provides the most protection available using standard glazing products.

Unfortunately, any of these options cost more than monolithic glass. In addition, given another severe windstorm, they will fracture and require replacement. They provide their benefit simply by maintaining closure of the building envelope following fracture, thus greatly reducing losses from internal damage. Whether or not the risk of another severe windstorm occurring justifies the cost of using a more secure glazing type is a matter for the building owner to decide.

5. Conclusions

In the early evening of March 28, 2000, a tornado rated between F1 and F2 traveled through the western outskirts of inner city Fort Worth, crossed the Trinity River, and wreaked havoc on the downtown. Numerous buildings were damaged, accommodation complexes evacuated, and electricity supply cut-off. Many areas of downtown Fort Worth were closed for over a week as repair crews removed broken glass from high-rise buildings.

The 6:30 PM timing of the event was fortuitous given that many of the office workers and shoppers had left the inner city for the day. Only one death can be attributed to actual structural failure, the case of a brick wall collapsing on a person who sought shelter behind it.

Best estimates of lower bound wind speeds range from 80-100 mph in standard terrain at 10m height. It was estimated that the wind speeds were not significantly greater than this, due to the relatively few buildings that suffered total collapse. Indeed, in terms of Fujita scale rating, only a few houses of good domestic construction received F2 damage. The engineered buildings that did suffer total structural failure have been assessed as having structural deficiencies, rather than excessive wind speed leading to the failure.

Several low-rise buildings in the industrial area just to the west of the Trinity River suffered complete collapse and became significant sources of debris. This debris started a chain of destruction of the cladding and contents of the largely glass-clad buildings that lay in the path of the tornado on its way through the downtown. As the debris impacted on subsequent buildings, more material was launched into the flow field, feeding the destructive power of a tornado that was rather mild in terms of wind speeds.

The two major sources of debris were a tilt-up concrete wall panel of a candy factory and a large warehouse. The collapse of the former was attributed to the failure of the roof truss to top plate connection, which left 24-foot high concrete wall panels unsupported, which consequently fell. For the latter, large overhanging roofs to loading bays were not designed to resist significant uplift forces and subsequent pullout of base plate connections lead to a progressive collapse of the structural steel frame. In each case, roofing material was launched into the flow field and traveling in the order of one mile and reaching elevations in excess of one hundred feet.

Breach of windward walls through debris impact in several buildings lead to internal pressurization and subsequent failure of roofing and side-corner windows. This occurred on both low-rise and high-rise buildings. For the low-rise buildings, in one case an outer brick veneer wall was blown out; while on another, the complete roof system, deck and trusses, was removed on a leading corner. In the case of the thirty-five story, completely glass-clad building, over half of all windows were broken, with many corner windows broken, despite the buildings' chamfers. Despite the glass breakage of this building, the internal partition wall, which formed a corridor around the lift core, remained intact and became a pressure barrier.

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7. Acknowledgements

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Appendix A – Photographs

Figure A1. Looking east over Sweet Shop Factory to downtown area.

Figure A2. Looking east over Johns Manville warehouse to downtown area.

Figure A3. Northeast corner of Sweet Shop Factory.

Figure A4. Debris from Johns Manville warehouse in Harrold Street.

Figure A5. Northwest face of Cash America International building.

Figure A6. Southwest and southeast faces of Cash America International building, showing internal debris piled up at the south corner.

Figure A7. Southwest and northeast faces of Cash America building, showing wind damage in corner regions.

Figure A8. Southeast face of Cash America building showing uplift failure of entrance canopy.

Figure A9. EIFS wall construction failure on northwest face of Education Employees Credit Union.

Figure A10. West face of Trinity Terrace.

Figure A11. Calvary Temple Church steeple failure and impact markings on brickwork.

Figure A12. Western side of Calvary Temple Church with Mallick tower beyond.

Figure A13. Sweet Shop roof debris on Fournier Street, just south of W 7th Street.

Figure A14. Air-conditioning equipment from the roof of Calvary Temple Church in W 5th Street.

Figure A15. Southwest face of 933 W Weatherford showing failure of roof corner.

Figure A16. Inside office in 933 W Weatherford.

Figure A17. Failure of roofing and corner structure 933 W Weatherford.

Figure A18. West face of Mallick Tower.

Figure A19. Debris impact Point in vision glass on Mallick Tower.

Figure A20. Impact facture on outer lite of insulating glass unit on the ground floor of INSpire Insurance Building, southwest façade.

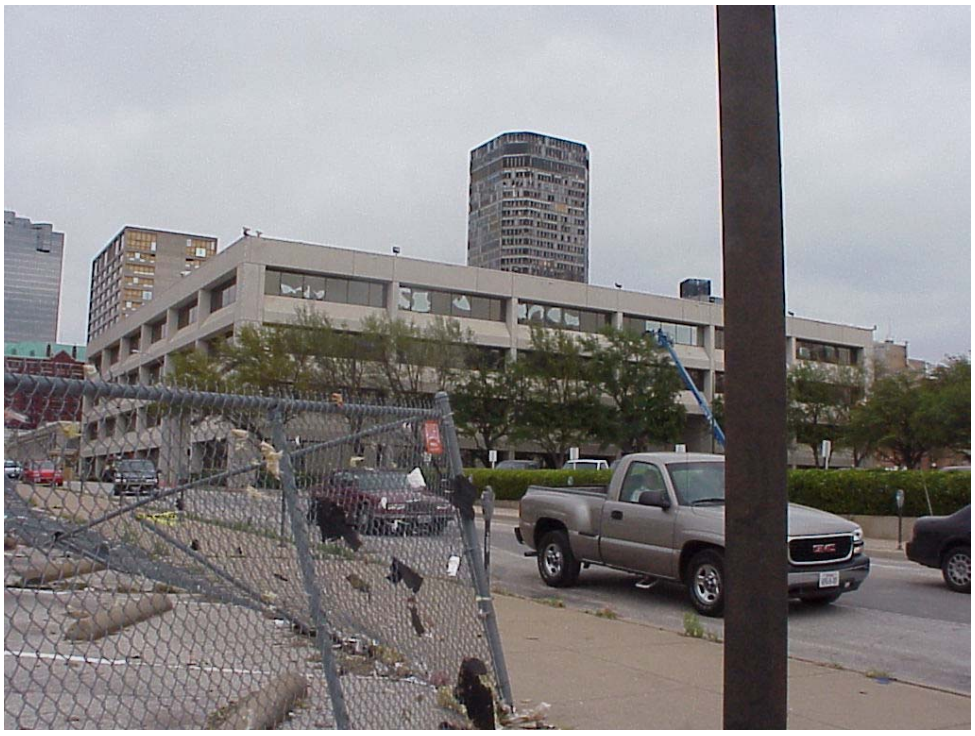

Figure A21. Looking east from Florence and 2nd, INSpire Insurance and Bank One beyond.

Figure A22. Broken outer lites of insulating glass units on ground floor of INSpire Insurance Building, southwest façade.

Figure A23. Bent GI gate on 2nd Street adjacent to Hunter Plaza, bent towards north.

Figure A.24 Window breakage at Hunter Plaza, south facing interior of U-shaped plan.

Figure A25. Looking southeast down Taylor, Outlet Mall to left, Library to right and west corner of Bank One in background.

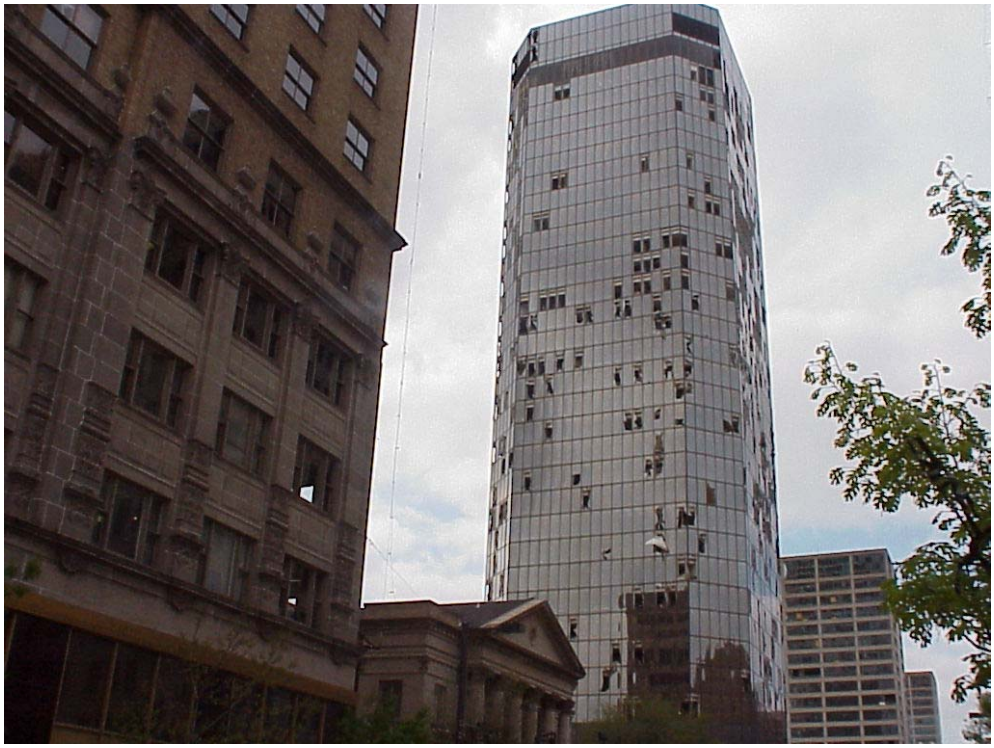

Figure A26. Southeast face of Bank One building.

Figure A27. Inside top floor restaurant of Bank One looking southwest.

Figure A28. Southwest face of UPR Tower from Bank One

Appendix B – Wind speed calculations

Calculating the wind speed to cause plastic moments in GI pipe fences
Fort Worth Tornado

Location	fence on Florence & 2nd Sts				gate on 2nd St				fence on Stayton St			
	US	Metric			US	Metric			US	Metric		
post diameter	1.875	47.63	mm		2.375	60.33	mm		2.375	60.33	mm	
post wall thickness	0.13	3.18	mm		0.19	4.76	mm		0.13	3.18	mm	
post height	6	1828.71	mm		12.5	3809.81	mm		10	3047.85	mm	
post spacing	12	3657.42	mm		5.3333	1625.51	mm		10	3047.85	mm	
top rail diameter	0	0	mm		2.375	60.33	mm		1.625	41.28	mm	
wire diameter	0.125	3.175	mm		0.125	3.18	mm		0.125	3.18	mm	
wire spacing	2	50.8	mm		2	50.8	mm		2.375	60.33	mm	
C_D	1.2	1.2			1.2	1.2			1.2	1.2		
air density		1.2	kg/m^3			1.2	kg/m^3			1.2	kg/m^3	
drag on post		0.0627	V^2	N		0.1655	V^2	N		0.1324	V^2	N
drag on top rail		0.0000	V^2	N		0.0588	V^2	N		0.0755	V^2	N
drag on wire		0.6020	V^2	N		0.5574	V^2	N		0.7040	V^2	N
base moment for post		0.0573	V^2	Nm		0.3152	V^2	Nm		0.2017	V^2	Nm
base moment for top rail		0.0000	V^2	Nm		0.2242	V^2	Nm		0.2301	V^2	Nm
base moment for wire		0.5504	V^2	Nm		1.0617	V^2	Nm		1.0729	V^2	Nm
total base moment		0.6077	V^2	Nm		1.6011	V^2	Nm		1.5047	V^2	Nm
yield stress	55,000	379.5	MPa		55,000	379.5	MPa		55,000	379.5	MPa	
Plastic modulus		1682.98	mm^3			3999.75	mm^3			2739.18	mm^3	
MP		638.69	Nm			1517.90	Nm			1039.52	Nm	
	mph	m/s			mph	m/s			mph	m/s		
Velocity @ 2-3 m	73	32			69	31			59	26		
$K_z^{1/2}$ Exposure B case 1	0.8367											
$K_z^{1/2}$ Exposure B case 2	0.7550											
Velocity @ 10m, Exposure C, 1	87	39			82	37			70	31		
Velocity @ 10m, Exposure C, 2	96	43			91	41			78	35		

Appendix C. Summary of other inner city tornadoes

A brief summary of tornadoes that have impacted downtown areas is presented in the following table. Data sources included the NCDC storm database and the archives of Texas Tech's Institute for Disaster Research.

Date & time	City	Tornado Category	Damage swath characteristics	Type of damage
11 May 1970 ~ 9:30pm	Lubbock, TX	F5 (F4*)	~ 8 miles long ~ 4000yds wide	Plastic deformation of frame and subsequent damage to brick cladding of 23-story high rise building. Extensive window glass damage to 15-story building. Extensive cladding and structural frame damage to numerous low-rise buildings including factories and warehouses.
3 April 1974 ~4:30pm	Xenia, OH	F5	~ 31 miles long ~ 1600yds wide	Extensive damage to 6–story buildings including wall collapse and severe cladding damage. 85% of city destroyed.
13 May 1980 ~ 3:00pm	Kalamazoo, MI	F3 (F2*)	~ 11 miles long ~ 1350yds wide	Extensive window damage to 9-story building from roof gravel. Collapse of 6-story load bearing masonry brick wall.
12 May, 1997 ~ 1:50pm	Miami, FL	F1	~ 8 miles long ~ 150yds wide	Window damage to downtown buildings
16 April 1998 ~3:40pm	Nashville, TN	F3	~15 miles long ~1300yds wide	Many windows broken in downtown, including those in at least 2 tall towers. Downtown closed for 1 working day & a weekend.
11 August 1999 ~12:00am	Salt Lake City. UT	F2	~4 miles long ~150yds wide	Many window failures in downtown, including Wyndham Hotel and Delta Center Sporting Complex. Building

* reassessed Fujita rating by TTU Institute for Disaster Research