# Implementation of the Joplin Tornado Recommendations: A Paradigm Shift in Designing for Tornadoes

May 5, 2016

SDR Meeting

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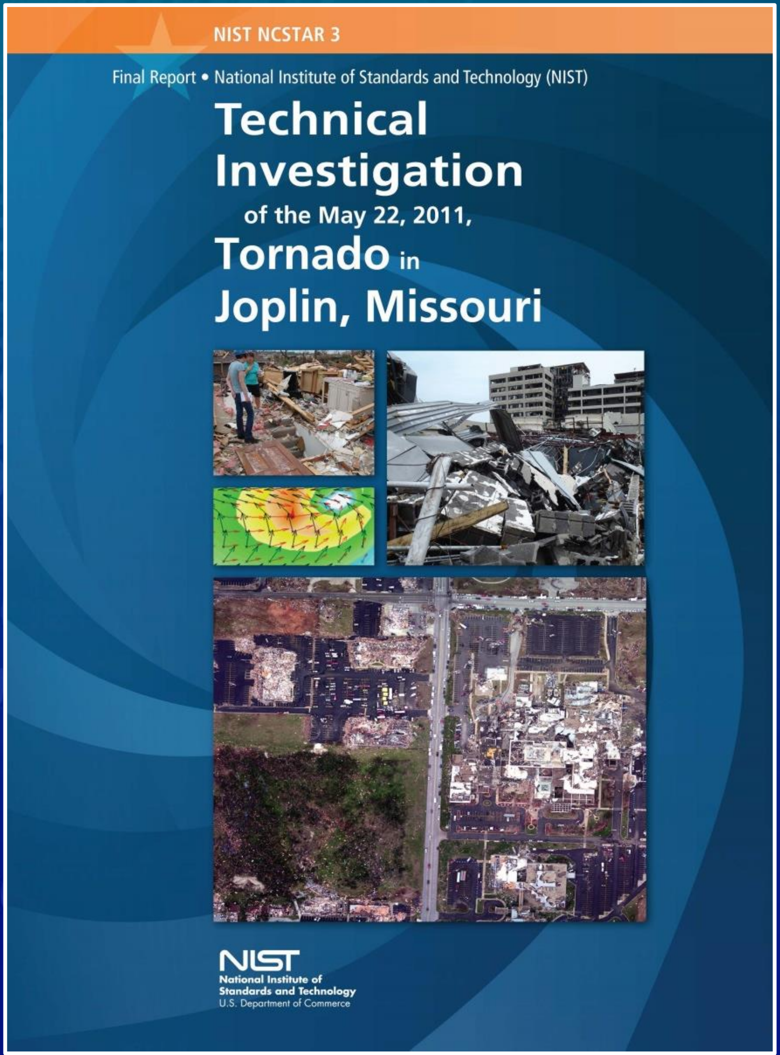
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

# Final Report

**March 2014**




The first study to include storm characteristics, building performance, emergency communication and human behavior - and assessment of the impact of each on injury or death.

- **47 findings**
- **16 recommendations for improving:**
  - Tornado hazard characterization
  - How buildings and shelters are designed and constructed in tornado–prone regions
  - Emergency communications that warn of threats from tornadoes.

available from www.nist.gov/el/disasterstudies

| R # | JOPLIN TORNADO INVESTIGATION RECOMMENDATION SUMMARY | LEAD |
|---|---|---|
| 1 | Development and deployment of technology to measure tornado wind fields | NOAA |
| 2 | Archival of tornado event data | NWS |
| 3 | Development of tornado hazard maps | NIST |
| 4 | Improvement of EF Scale; means for continued improvement; adoption by NWS | NWS |
| 5 | Development of performance-based standards for tornado-resistant design | ASCE |
| 6 | Development of performance-based tornado design methodologies | NIST, FEMA |
| 7 | a) Development of tornado shelter standard for existing buildings;<br>b) Installation of tornado shelters in more buildings in tornado-prone regions | ICC |
| 8 | Development of guidelines for public tornado sheltering strategies | FEMA |
| 9 | Development of guidelines for selection of best available refuge areas | FEMA |
| 10 | Prohibition of aggregate coverings or ballast in tornado-prone regions | ICC |
| 11 | Development of requirements for enclosures of egress systems in critical facilities | ICC, NFPA |
| 12 | a) Development of tornado vulnerability assessment guidelines for critical facilities;<br>b) Performance of vulnerability assessments by critical facilities in tornado-prone | FEMA |
| 13 | Development of codes, standards, and guidance for emergency communications;<br>Development of joint plan by emergency mgrs/media/NWS for consistent alerts | NFPA |
| 14 | Deployment of “push” technologies for transmission of emergency information | FEMA |
| 15 | Research to identify factors to enhance public perception of personal risk | NSF, NIST |
| 16 | Develop technology for real-time, spatially-resolved tornado threat information | NOAA |

| R # | RECOMMENDATION IMPLEMENTATION (red – in progress, black – in planning) | LEAD |
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# Context – Building Codes and Standards

National model building codes, standards, and practices seek to achieve life safety for the hazards considered in design.

Tornado hazards are not currently considered in the design of buildings, except for safety–related structures in nuclear power plants, storm shelters, and safe rooms.

# Why Don't We Design for Tornadoes?

**High death toll. Total fatalities by hazard, 1950-2011:**

**5,600 tornado** 3,102 hurricane 459 earthquake

- **High frequency of occurrence, potential high cumulative economic loss**
- **In the US, Annual aggregate losses from severe thunderstorms including tornadoes have, on average, accounted for more than half of all catastrophe losses since 1990. (Lloyds, 2013)**
- **Yet we design for hurricane and earthquake hazards, but not for tornadoes!**

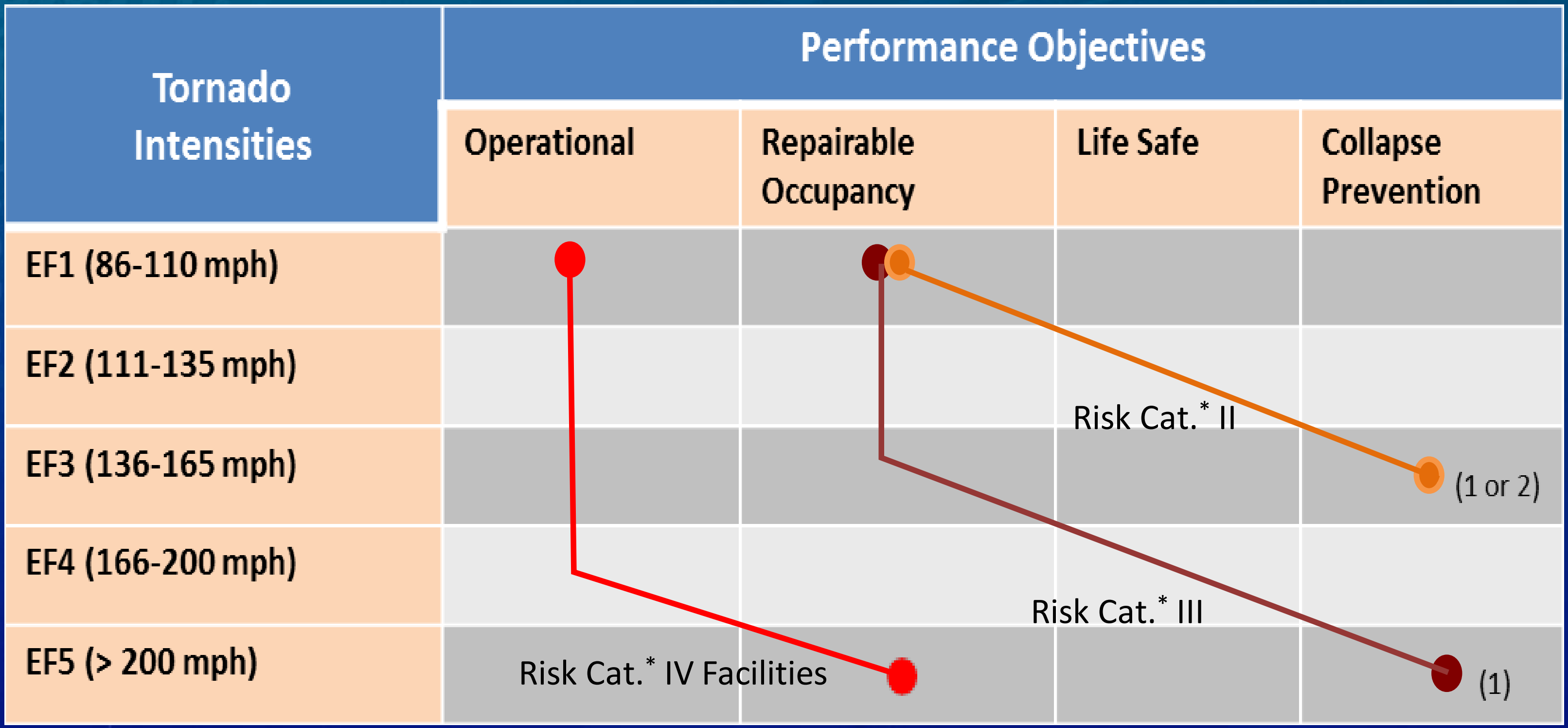
In 2011, 1,600+ tornadoes caused over $25B damage

# Development of Performance-Based Standard for Tornado-Resistant Design

**Recommendation 5 (ASCE):** NIST recommends that nationally accepted performance–based standards for the tornado–resistant design of buildings and infrastructure be developed in model codes and adopted in local regulations to ensure the resiliency of communities to tornado hazards. The standards should encompass tornado hazard characterization, performance objectives, and evaluation tools. The standards shall require that critical buildings and infrastructure such as hospitals and emergency operations centers are designed so as to remain operational in the event of a tornado.

- **Target Standard : ASCE 7-22**

# Tornado-Resistant Design
# Example Performance Objectives




(1) Hardened area, shelter–in–place.
(2) Public shelter.
* Based on ASCE 7–10.

# Implementation of Performance-Based Design (PBD)

Continued working with ASCE Technical Committee on PBD for Extreme Winds (ad-hoc)

- Committee is creating a PBD framework for extreme wind hazards, including tornadoes, intended for inclusion in ASCE 7-22.
- Developing performance objectives and building performance levels for different wind hazards and risk categories of buildings
  - hurricanes, tornadoes, other windstorms
  - structural, cladding, and other building systems

# Implementation of Performance-Based Design (cont'd)

Additional requirements to implement PBD for tornadoes

- New tornado hazard maps (R3)
- New tornado wind load design methods (R6)
  - variation of wind speed with height and terrain
  - pressure coefficients
  - atmospheric pressure change (APC)
  - missiles

To create more accurate tornado hazard maps in the future

- Better tornado wind / climate data needed (R4 / R2)

# Improving Tornado Wind Speed & Climate Data

**Recommendation 4 (NWS):** NIST recommends that new damage indicators (DIs) be developed for the Enhanced Fujita tornado intensity scale to better distinguish between the most intense tornado events. Methodologies used in the development of new DIs and associated degrees of damage (DODs) should be, to the extent possible, scientific in nature and quantifiable. As new information becomes available, a committee comprised of public and private entities should be formed with the ability to propose, accept, and implement changes to the EF Scale. The improved EF Scale should be adopted by NWS.

**Recommendation 2 (NWS):** NIST recommends that information gathered and generated from tornado events (such as the Joplin tornado) should be stored in publicly available and easily accessible databases to aid in the improvement of tornado hazard characterization.

# Background – Estimating Wind Speed from Damage using the EF Scale

- Degree of Damage (DoD) assigned to a Damage Indicator (DI) (e.g. house, school)

- Estimated wind speed associated with each DoD

2. ONE-AND TWO-FAMILY RESIDENCES (FR12)
(1000 – 5000 sq. ft.)

Typical Construction

- Asphalt shingles, tile, slate or metal roof covering
- Flat, gable, hip, mansard or mono-sloped roof or combinations thereof
- Plywood/OSB or wood plank roof deck
- Prefabricated wood trusses or wood joist and rafter construction
- Brick veneer, wood panels, stucco, EIFS, vinyl or metal siding
- Wood or metal stud walls, concrete blocks or insulating-concrete panels
- Attached single or double garage

| DOD* | Damage description | EXP | LB | UB |
|---|---|---|---|---|
| 1 | Threshold of visible damage | 65 | 53 | 80 |
| 2 | Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding | 79 | 63 | 97 |
| 3 | Broken glass in doors and windows | 96 | 79 | 114 |
| 4 | Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport | 97 | 81 | 116 |
| 5 | Entire house shifts off foundation | 121 | 103 | 141 |
| 6 | Large sections of roof structure removed; most walls remain standing | 122 | 104 | 142 |
| 7 | Exterior walls collapsed | 132 | 113 | 153 |
| 8 | Most walls collapsed, except small interior rooms | 152 | 127 | 178 |
| 9 | All walls | 170 | 142 | 198 |
| 10 | Destruction of engineered and/or well constructed residence; slab swept clean | 200 | 165 | 220 |

* DOD is degree of damage

Source: NOAA. http://www.spc.noaa.gov/efscale/2.html

# Background - Rating Tornadoes: The Enhanced Fujita (EF) Scale

- EF Number is then assigned to a tornado based on estimated wind speed
- Wind speed ranges associated with EF Numbers

| EF Number | Wind Speed (mph) |
|---|---|
| 0 | 65-85 |
| 1 | 86-110 |
| 2 | 111-135 |
| 3 | 136-165 |
| 4 | 166-200 |
| 5 | 200+ |

- Typical damage state with EF-scale rating:

EF1


EF3


EF5

# ASCE Standard on Wind Speed Estimation in Tornadoes

- Standards committee co-chaired by NWS and NIST staff
  - 93 members
  - mainly meteorologists, wind engineers, structural engineers
- Scope of new standard includes wind speed estimation by
  - EF Scale
  - Radar and In-situ Measurements
  - Forensic Engineering
  - Treefall Patterns
  - Remote Sensing
- Scope also includes requirements for data and metadata
- Intended for adoption by NWS

# ASCE Standard on Wind Speed Estimation in Tornadoes (cont'd)

Source: NOAA

## EF Scale Improvements

- Better guidance for existing DIs to provide more consistent wind speed estimates
- Development of new engineering-based DIs

## Example- Jersey Barriers

- New DI based on wind tunnel tests to determine speeds required for overturning

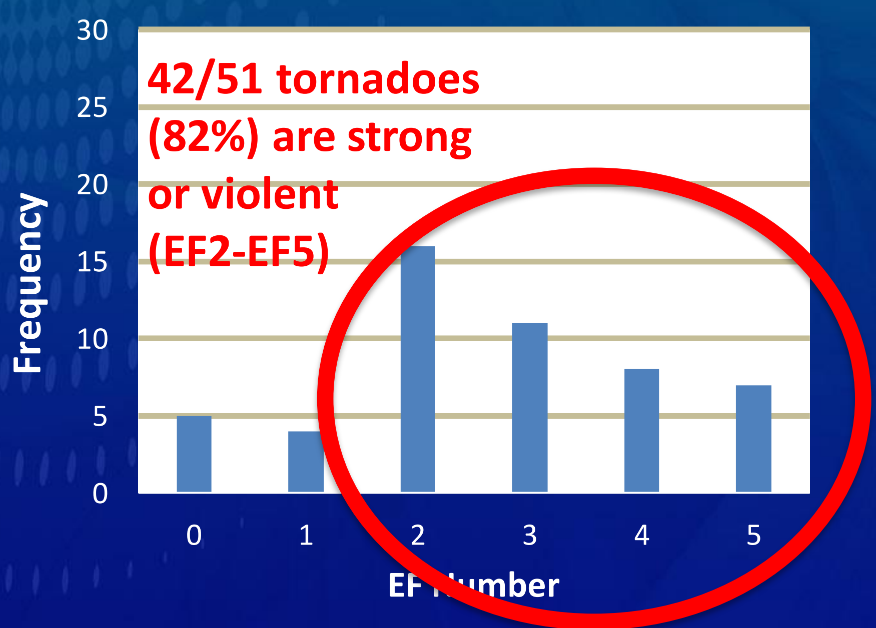


**Key Limitation** – EF Scale is damage based. The tornado has to hit something in order to get an estimated wind speed.

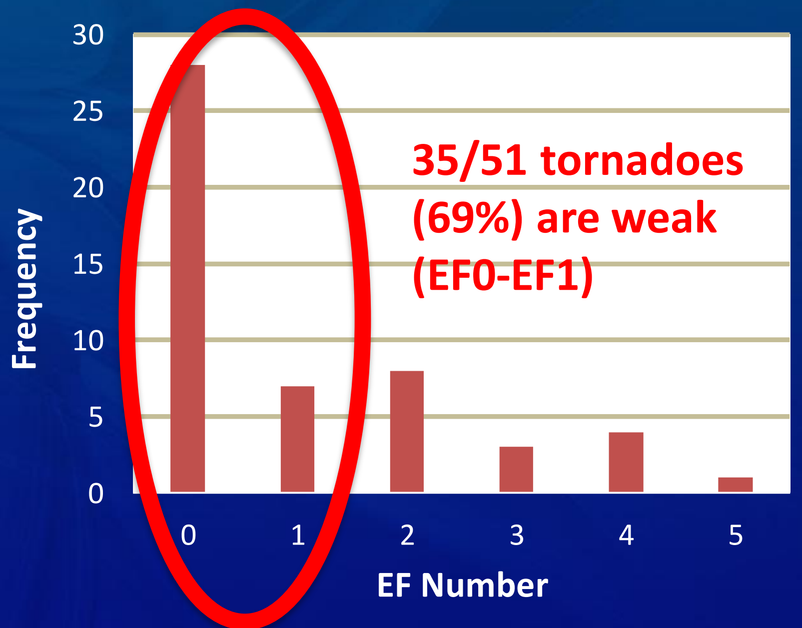
# Comparison of Tornado Wind Speeds Estimated by Mobile Radar and Damage

Sample Size = 51 Tornadoes*

**EF Numbers from Mobile Radar Measurements**
Observations below 500 m AGL (above ground level)




**EF Numbers for the Same 51 Tornadoes Reported in NOAA OneTor Database**
From ground surveys of damage using EF Scale




**Mobile radar indicates much stronger winds than implied by damage**

*Data Source: A Mobile Radar Based Climatology of Supercell Tornado Structures and Dynamics, by Alexander, Curtis R., Ph.D., The University of Oklahoma, 2010.

# Tornado Hazard Maps

**Recommendation 3 (NIST):** NIST recommends that tornado hazard maps for use in the engineering design of buildings and infrastructure be developed considering spatially based estimates of the tornado hazard instead of point–based estimates.

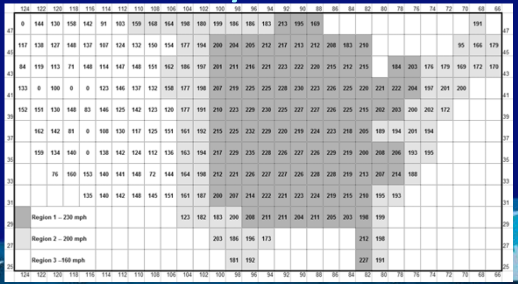
- Existing tornado hazard maps do not account for biases and increased risk of strike on large spatial systems
- Contracted with ARA to develop *Tornado Hazard Maps for Building Design.* Presently 1.5 years into a four-year effort
- Progress to date:
  1. Reviewed the state-of-knowledge on tornado climatology, biases in tornado databases, and tornado risk assessment
  2. Conducted data analysis and sensitivity studies of factors affecting tornado data to inform tornado hazard maps development plan
  3. Quantified tornado risk metrics for pilot municipality (Joplin) and sensitivity analysis to guide prioritization of maps development
  4. Held stakeholder workshop to update key private sector, academic, and governmental stakeholders on progress of the tornado hazard maps development effort (September 2015)

ICC, FEMA 361


ANSI/ANS 2.3 (2011)
for Safety-Related Structures and
Components of Nuclear Power Plants


* 3-second gust at 33 ft

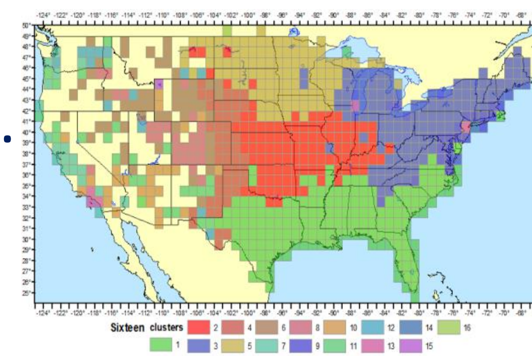
NUREG/CR-4461



# TORNADO RISK MAPS FOR BUILDING DESIGN
# NIST IDIQ CONTRACT SB1431-12-CQ-0014
# Overview

EF DOD 4: Mean 97 mph

**Applied Research Associates, Inc.**
**8537 Six Forks Rd, Suite 600**
**Raleigh, NC 27615**




APPLIED RESEARCH ASSOCIATES, INC.®
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# Tornado Hazard Modeling Process Overview

**Approach**

1. **Build on existing modeling and analysis tools**
2. **Probabilistic modeling, bias corrections**
3. **Develop engineering-damage-to-windspeed probabilistic models**
4. **Develop integrated tornado climatological model**
5. **Develop regional variations and iterate**
5. **Finalize PBD metrics and building/system spatial parameters**
6. **Produce regional tornado windspeed hazard curves and associated metrics**
7. **Develop tornado spatial variations/ smoothing for maps**

## Data

### Databases
- NWS
  - SPC
  - DAT
  - Storm Data
- HAZUS
- Census
- NLCD
- HUD
- •
- •
- •

### Literature
- Individual Event Data
- Damage Maps
- Radar
- Models

### Tornado Events
- Individual Historic
- New Data
- Field Surveys
  - Damage Model
  - Damage Indicators
  - Tornado Rating, PW, PL
- Validation

## Modeling/Analytics

### Components
- Reporting Trend
- Reporting Eras
- Population Bias
- F, EF Ratings
- Path Variable
- PLIV
- Region Dependencies
- Land Use-Land Cover
- Random Encounter
- Bias Corrections
- Correlations

### Tornado Windfield
- Single Cell Vortex
- Probabilistic Parameters
  - Intensity
  - RMW
  - Translation Speed ($V_t$)
  - Vertical Profile
  - Core Slope
  - $V_r/V_\sigma$ (Inflow)
  - Vz (Continuity)
  - Path Width, Path Length
- Scalable

### Windspeed -to-Damage
- TORDAM
- Tornado Strike Simulations
- 3D Str. Load Model
- Probabilistic load/ Resistance
- Failure Mode Sequence
- WBD Loads
- Internal Pressure
- Progressive Failure
- Damage States

## Climatology & Mapping

### Tornado Climatology
- Occurrence Rates
- Tornado Days
- Point Probability
- Path Direction
- Elevation
- Land Fraction
- •
- •
- •

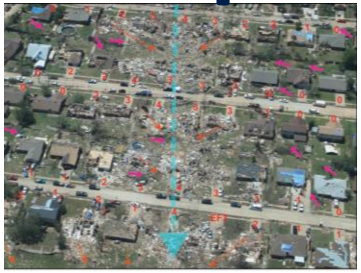
### Geospatial Analysis
- Variables
- Cluster Analysis
- Statistical Significance

### Regionalization
- Hazard Model
- Risk Metrics
  - Windspeed Exceedance Frequencies
  - Spatial Characteristics of Building Systems
  - WEF ~ $10^{-3}$ to $10^{-8}$ per year
  - Other Tornado Effects ?

### Tornado Hazard Maps
- Spatial Smoothing for Contours
- Supporting Tables/Data

# Damage vs.Windspeeds

- Tornado Intensity Ratings (max windspeed) are based on observed damage.
  - Fujita (F) Scale adopted in 1977, EF in 2007
  - The windspeeds associated with the damage scales are based on subjective estimates
  - There are significant uncertainties associated with damage intensity classification and potential biases in the windspeed estimation
  - Damage based classifications produce 2 major biases in the database: under-classifications from random encounters with DI and the use of default EF0 classifications for unknown
  - The tornado climatology development needs to be based on engineering estimates of windspeeds, validated as much as possible
- A significant task of this project is to develop engineering- based, probabilistic damage-to-windspeed relationships for the NIST/ASCE tornado windspeed maps.

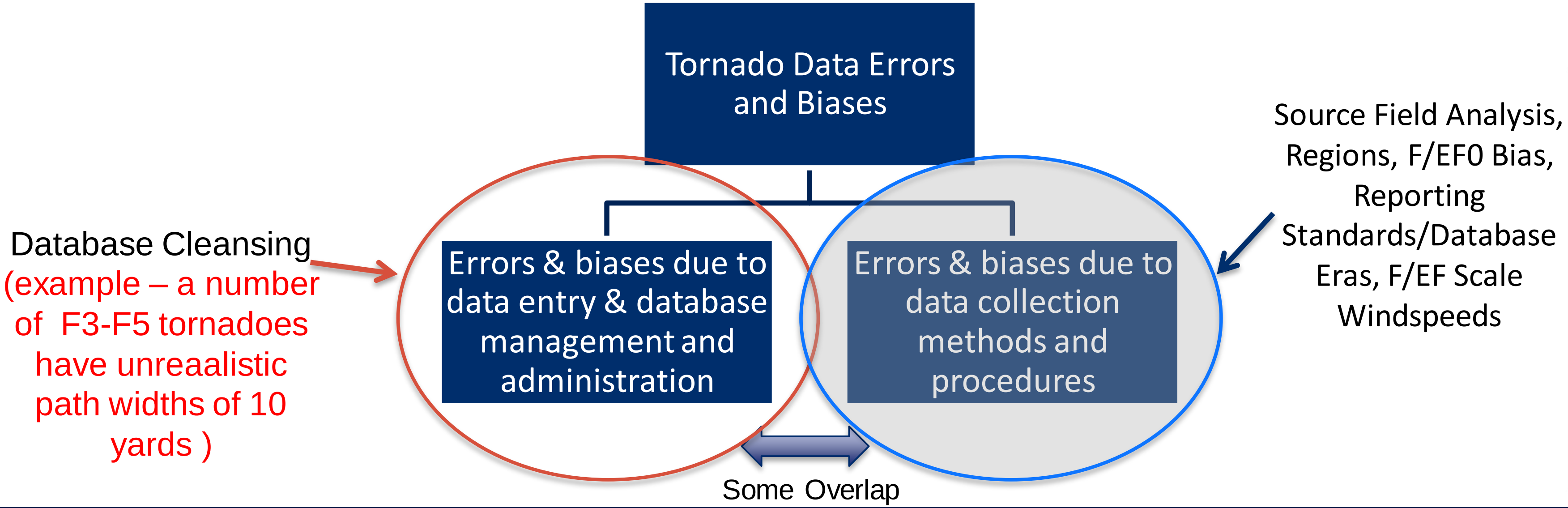


EF DOD 4: Mean 97 mph

Hurricane Andrew: 155-165 mph

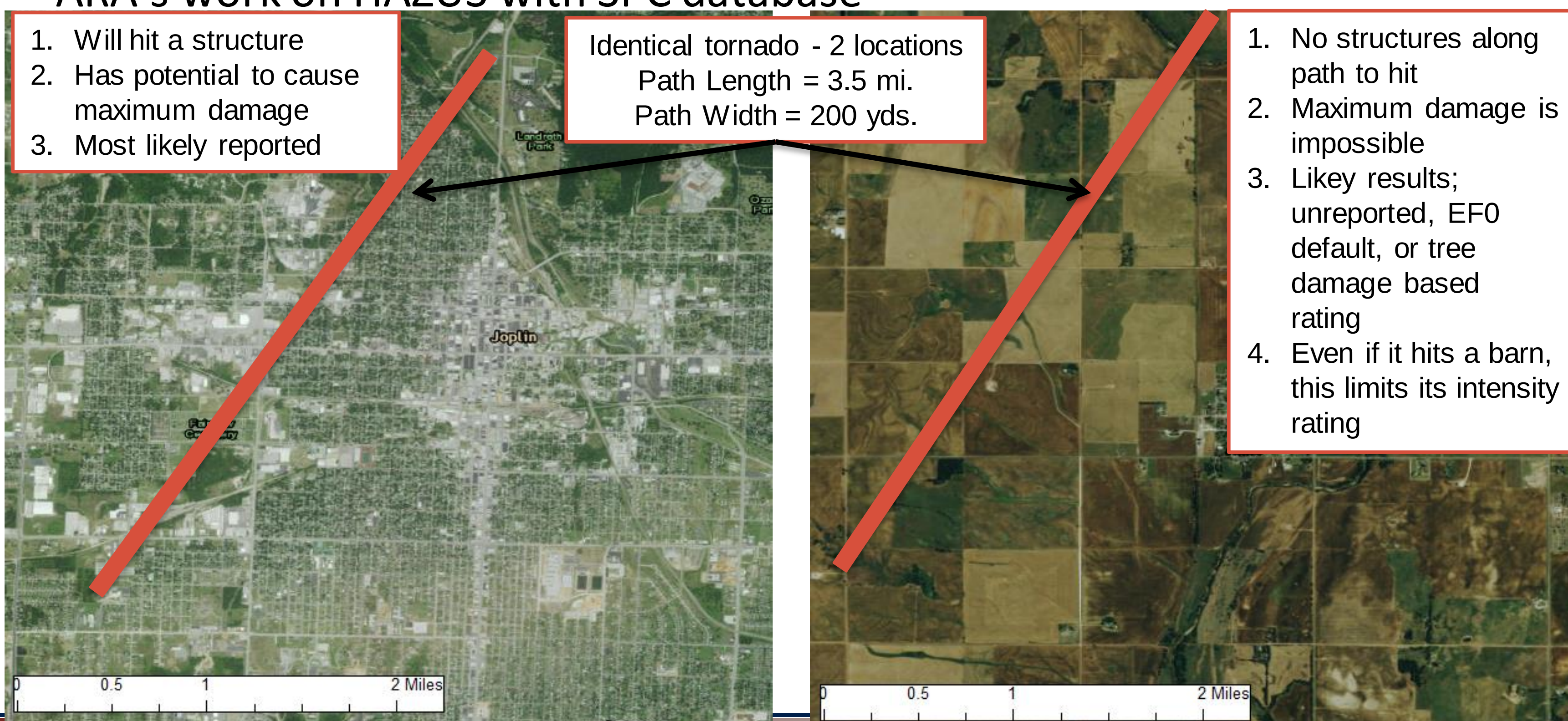
# Database Cleansing

- Identify and understand errors and biases within the SPC database that are due to data entry and database maintenance
  - E.g. discrepancies, zero values, missing values, default values etc.
- Model and correct for these errors with approaches consistent with available level of effort
- Approach can be considered to include both component and system level analysis/modeling



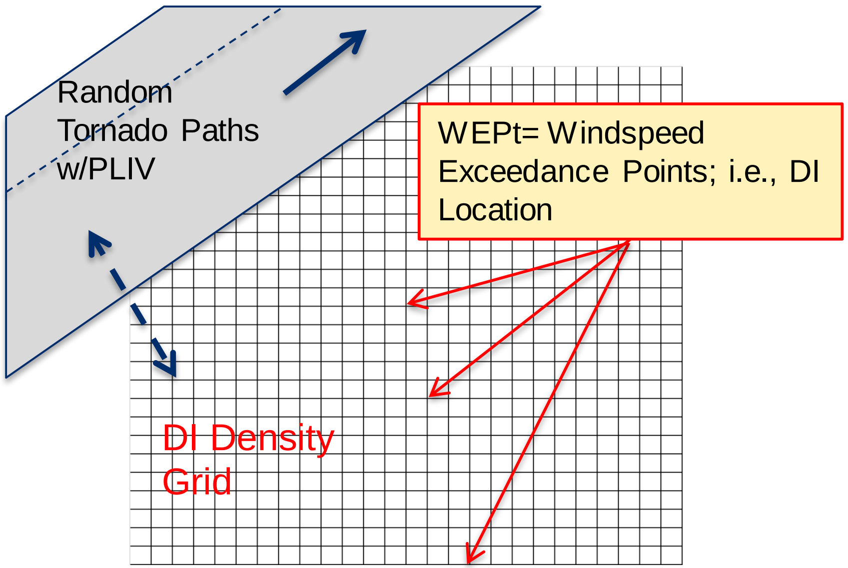
# Population (Bldg. Den.) Bias in Tornado Data

- Tornadoes are classified by damage
  - Tornadoes that produced no damage are not reported or are under-rated
- Our analysis approach is use a modeling approach with validation based on reported events vs building density
- Initial work underway using 2000 census and building information data from ARA's work on HAZUS with SPC database



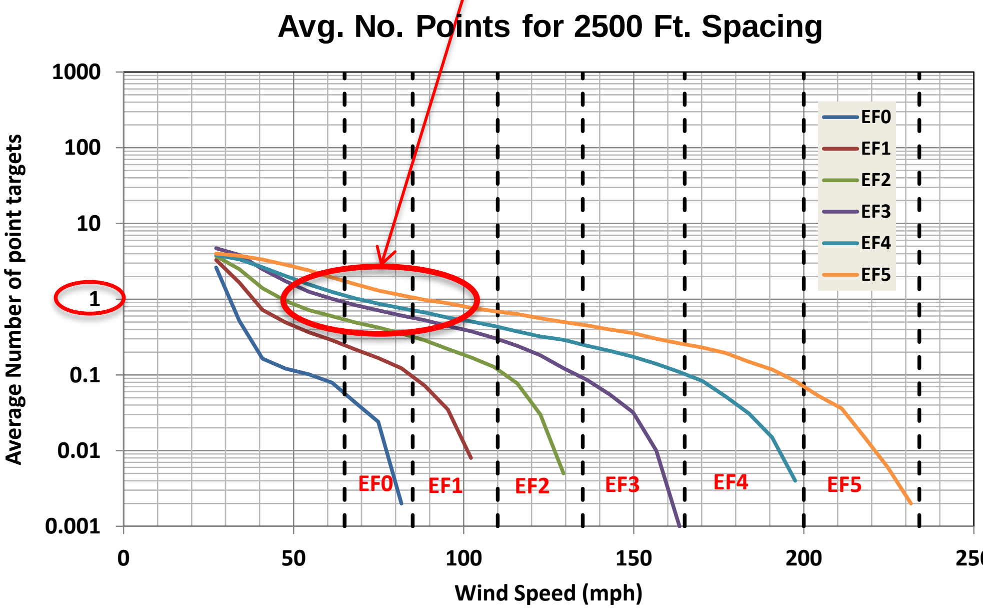
# Modeling Approach for Quantification of Pop. Density Bias

## 1. Tornado- BD Simulations




## 2. Results for 2500 ft. BD Spacing

- Low EF Damage will Dominate the Ratings or NO DAMAGE will occur.



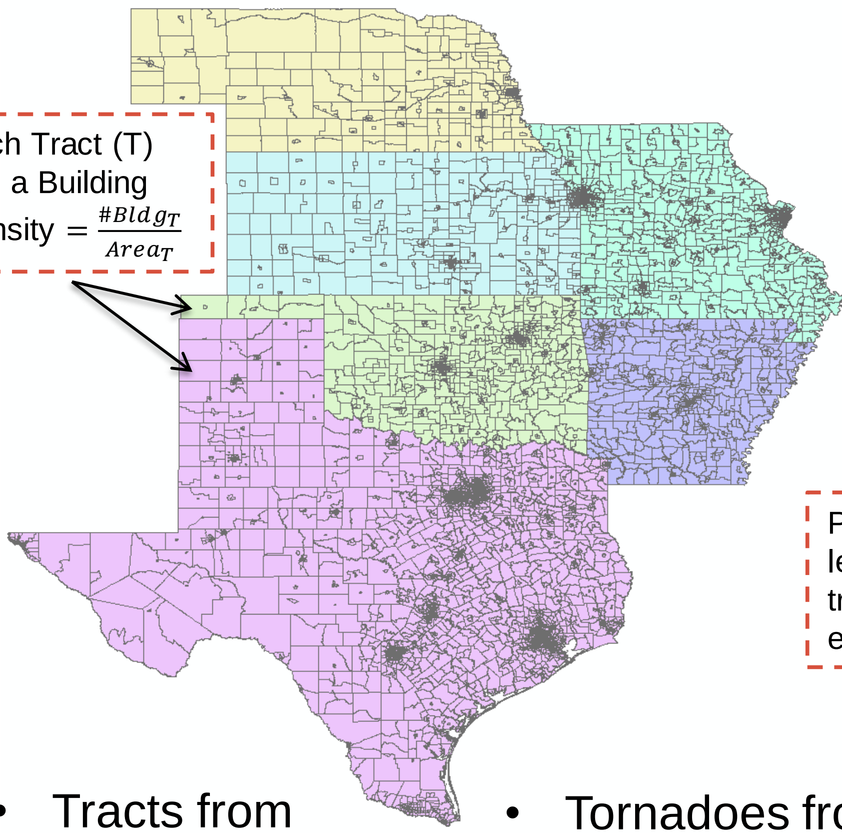

## 3. Results for 500 ft. Spacing

- Many EF0 will produce no damage
- Some EF1 will produce no damage
- Higher intensities have a good chance of being under-classified by 1-2 EF scales.

# Analysis Method for Initial Empirical Quantification of Building Density Bias

## Analysis Region Census Tracts

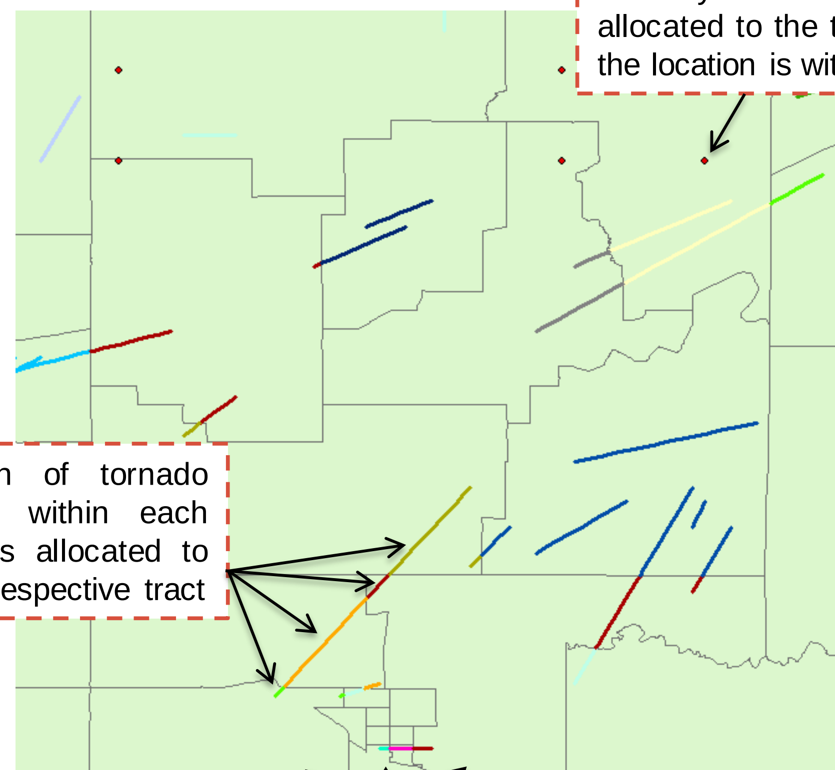
Each Tract (T) has a Building Density $= \frac{\#Bldg_T}{Area_T}$



- Tracts from 2000 Census

## Allocation of Tornadoes to Census Tracts

Entire length of tor. w/ only 1 location allocated to the tract the location is within

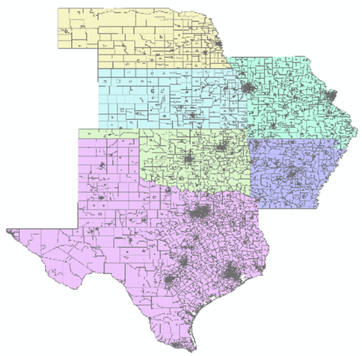


Portion of tornado length within each tract is allocated to each respective tract

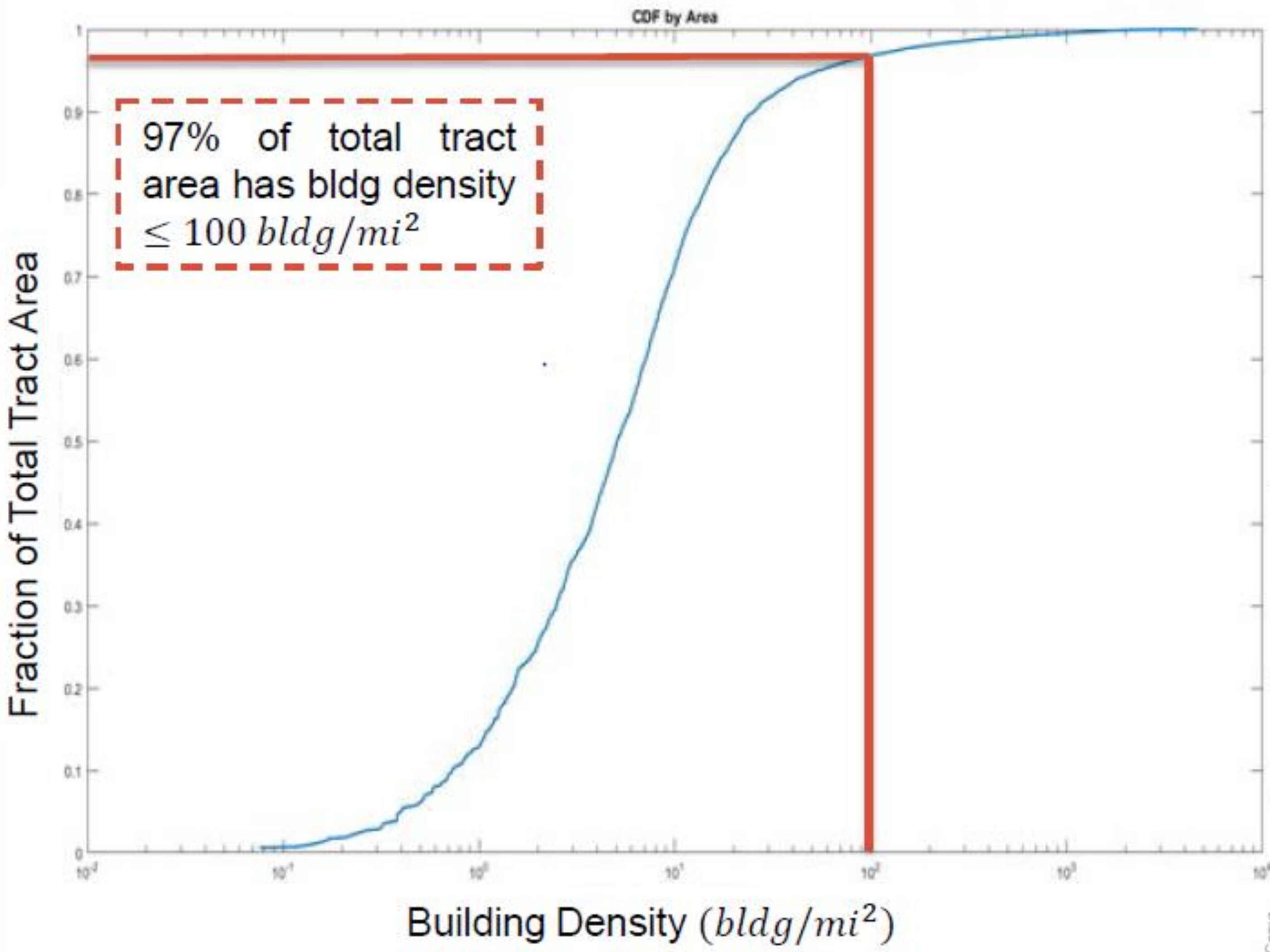
Tracts

- Tornadoes from 1995-2005

# Building Density - Midwest Test Region

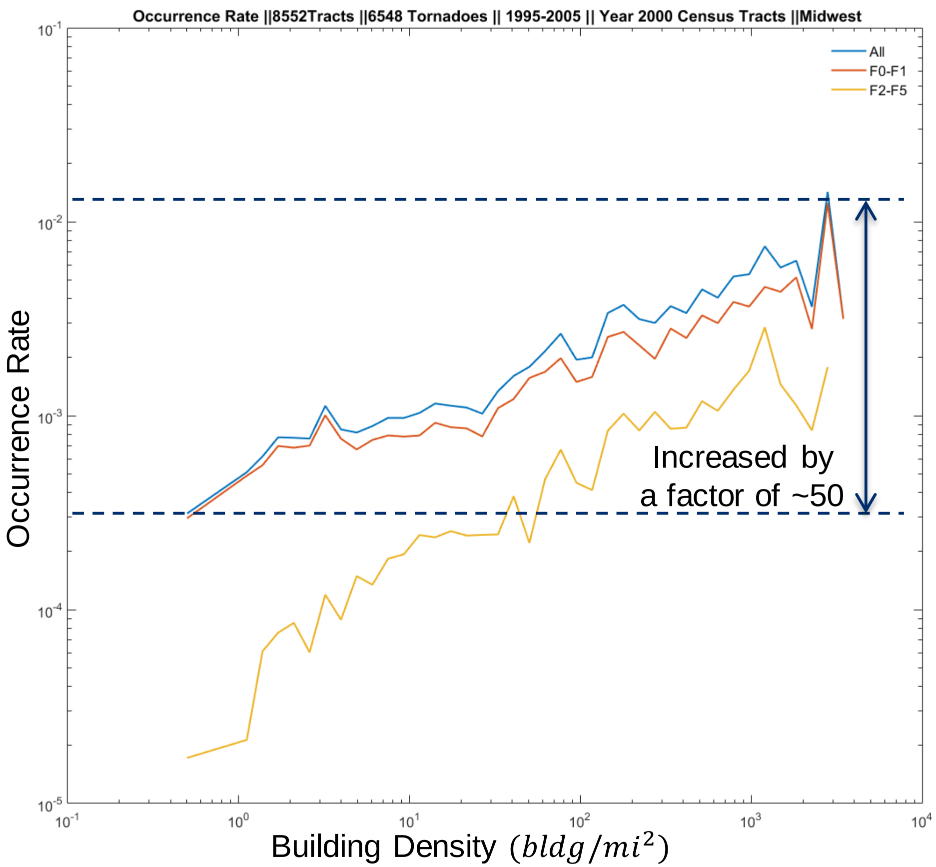


Tracts from 2000 Census

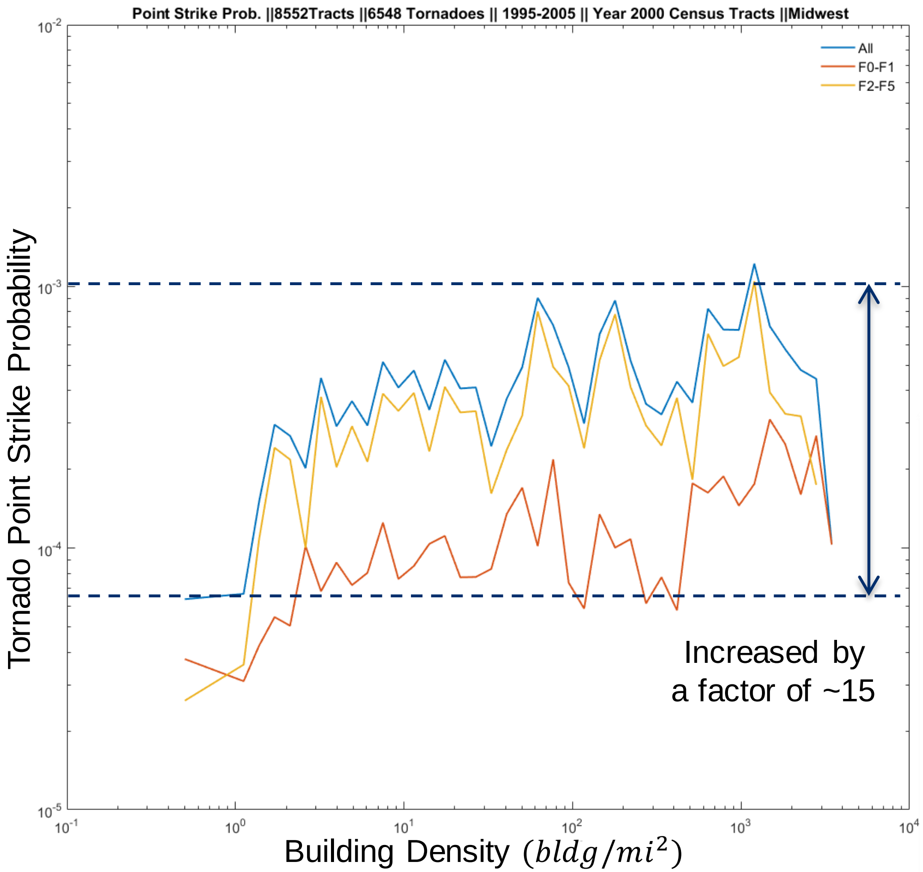


# Tornado Occurrence Rate & Point Probability Increase with Building Density

## Tornado Occurrence Rate vs. Building Density (BD)




## Tornado Point Strike Probability vs. Building Density

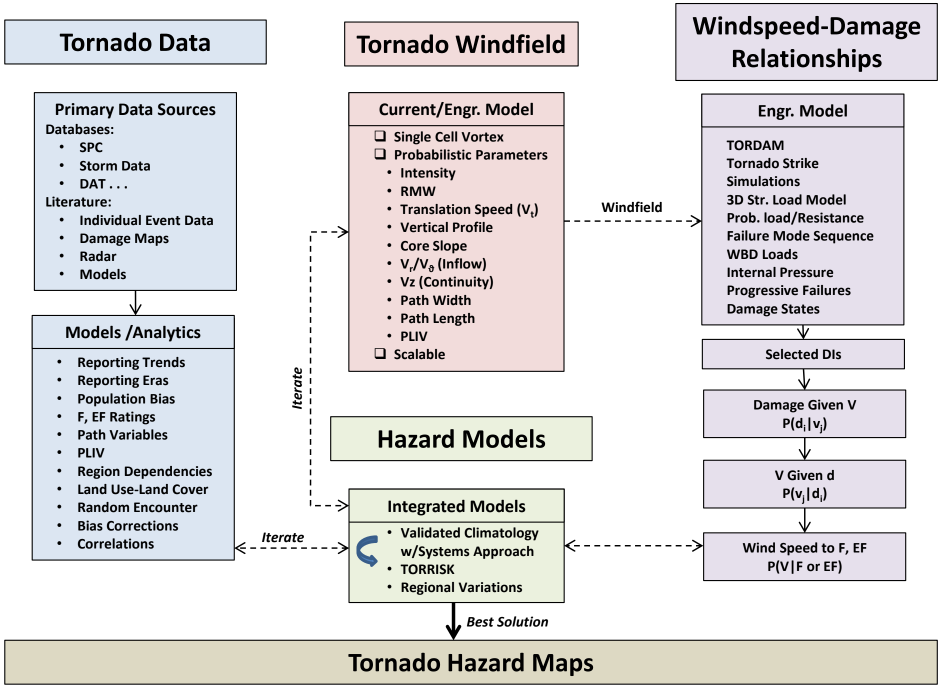



*Significant BD bias in the database is noted even for the relatively modern period of 1995 - 2005*

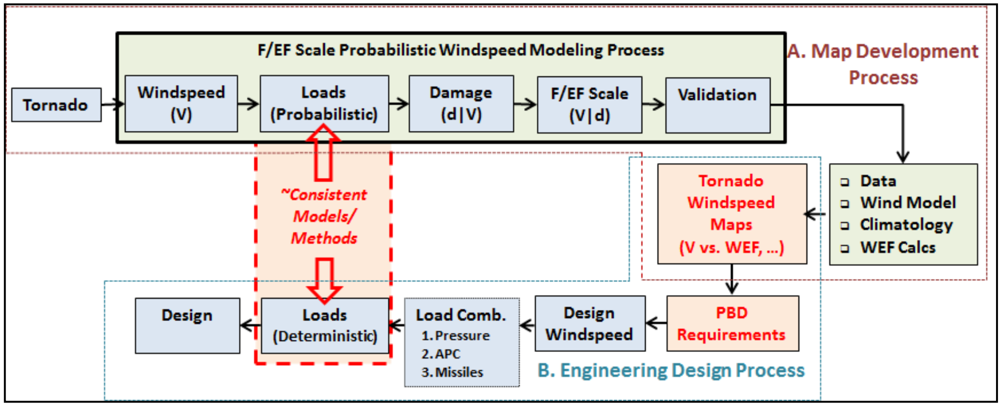
# Project Summary

- Tornado hazard analysis is a complicated, iterative process, with many components.
- There are many biases/ limitations of the raw, damage-based tornado datasets.
- Our approach includes both component and "system" analysis methods.
- A consistent 3D modeling approach is being used for tornado hazard and damage-to-windspeed calculations.
- New field work is needed to support and validate tornado hazard and damage to windspeed modeling.

## Integrated System Framework

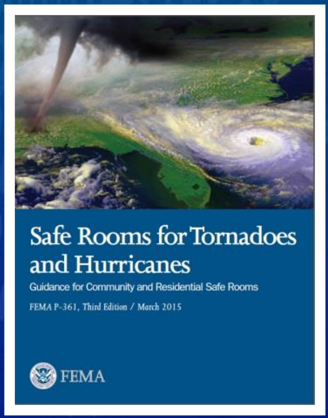



## Windspeed Map- PBD Framework

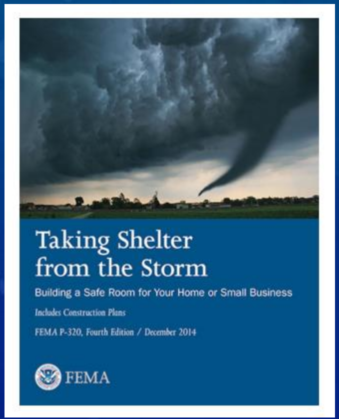


# Sheltering Guidance

**Recommendation 8 (FEMA):** NIST recommends the development and implementation of uniform national guidelines that enable communities to create safe and effective public sheltering strategies. The guidelines should address planning for siting, designing, installing, and operating public tornado shelters within the community.



Source: FEMA.



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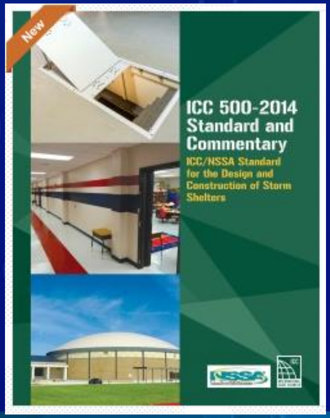

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- NIST developed significant new guidance material that was incorporated into two FEMA Safe Room publications (FEMA P-320, 4th ed., and FEMA P-361, 3rd ed.)
- NIST led development of *Chapter 3: Structural Design Criteria* in the ICC 500 Commentary
- Proposed shelter safety requirements and guidance for new **NFPA 1616 Standard for Mass Evacuation and Sheltering**

# Code Changes, Shelters

**Recommendation 7 (ICC):** NIST recommends that: (a) a tornado shelter standard specific for existing buildings be developed and referenced in model building codes; and (b) tornado shelters be installed in new and existing multi–family residential buildings, mercantile buildings, schools and buildings with assembly occupancies located in tornado hazard areas identified in the performance–based standards required by Recommendation 5.

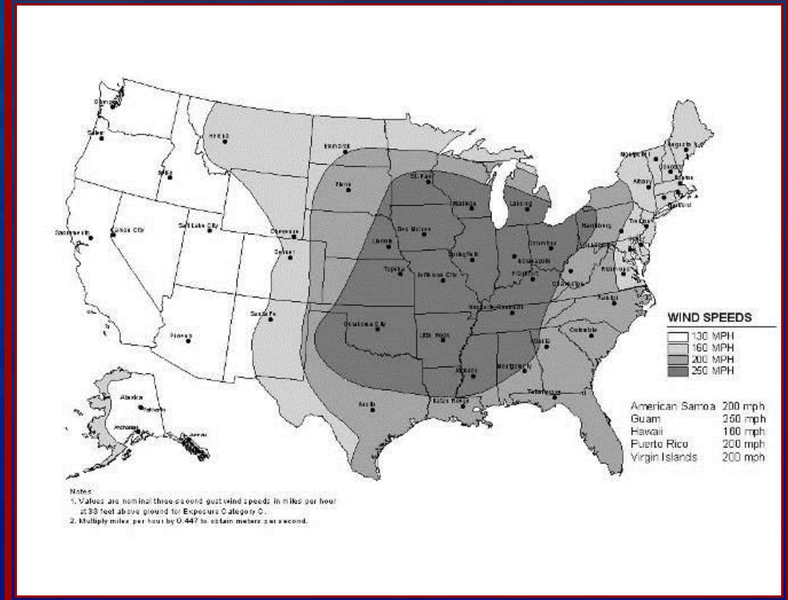
## 7(b): NIST-developed code changes were approved for the 2018 IBC and IEBC

- Developed in coordination with the Building Code Advisory Committee (BCAC) and FEMA
- Expand requirements for incorporation of ICC 500 storm shelters at both new and existing schools, including assembly spaces associated with schools

# Code Changes, Shelters (cont'd)

- **Parallel requirements for**
  - New buildings on existing school campuses (IBC)
  - Additions to buildings on existing school campuses (IEBC)
- **Require ICC 500 shelters large enough to protect the population of the school, provided the new construction is of sufficient size**
- **Applies to**
  - Group E occupancies
  - Indoor assembly spaces associated with the Group E occupancy, e.g., theaters, auditoriums, gymnasiums w/bleachers

New IBC/IEBC shelter requirements apply in the 250 mph tornado wind speed zone (dark grey)



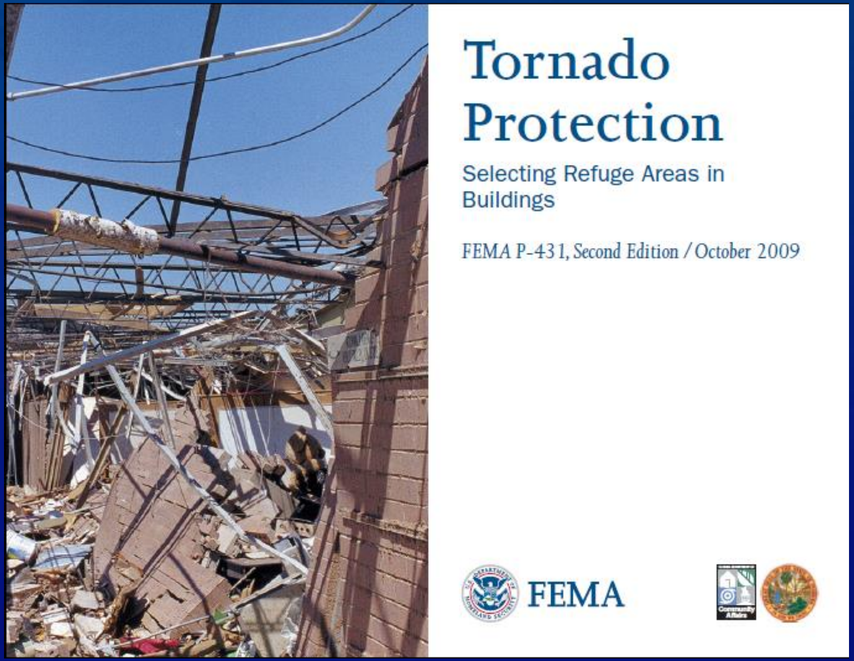
# Guidance – Best Available Refuge Areas

**Recommendation 9 (FEMA):** NIST recommends that uniform guidelines be developed and implemented nationwide for conducting assessment of tornado risk to buildings and designating best available tornado refuge areas as an interim measure within buildings until permanent measures fully consistent with Recommendations 5 and 7 are implemented.

**Working with FEMA to update**

***FEMA P-431 Tornado Protection: Selecting Refuge Area in Buildings***

- Current version deals almost exclusively with schools
- The revised version will
  - have a new, engineering–based selection methodology
  - cover a much broader array of building occupancies and types
- Phase I of project completed 4/30/16




Source: FEMA.

# Summary of Standards, Code, and Guidance Development

Work in progress
Completed

- **Existing Standards**
  - ASCE/SEI 7-22, Minimum Design Loads for Buildings and Structures
  - ICC 500-2019, Standard for Design and Construction of Storm Shelters
- **New Standards**
  - ASCE/SEI Standard for Estimation of Wind Speeds in Tornadoes
  - NFPA 1616, Standard for Mass Evacuation and Sheltering
- **Building Codes**
  - 2018 International Building Code (IBC)
  - 2018 International Existing Building Code (IEBC)
- **Guidelines**
  - FEMA P-431, Tornado Protection: Selection Refuge Areas in Buildings
  - FEMA P-320, Taking Shelter from the Storm: Building a Safe Room for Your Home or Small Business, 4th ed. (December 2014)
  - FEMA P-361, Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms, 3rd ed. (March 2015)
  - ICC 500-2014 Commentary on the Standard for Design and Construction of Storm Shelters (January 2016)

# Paradigm Shift

**Engineers, architects, building owners and operators, governments, and society are beginning to understand that ignoring tornado hazards is not an appropriate response.**

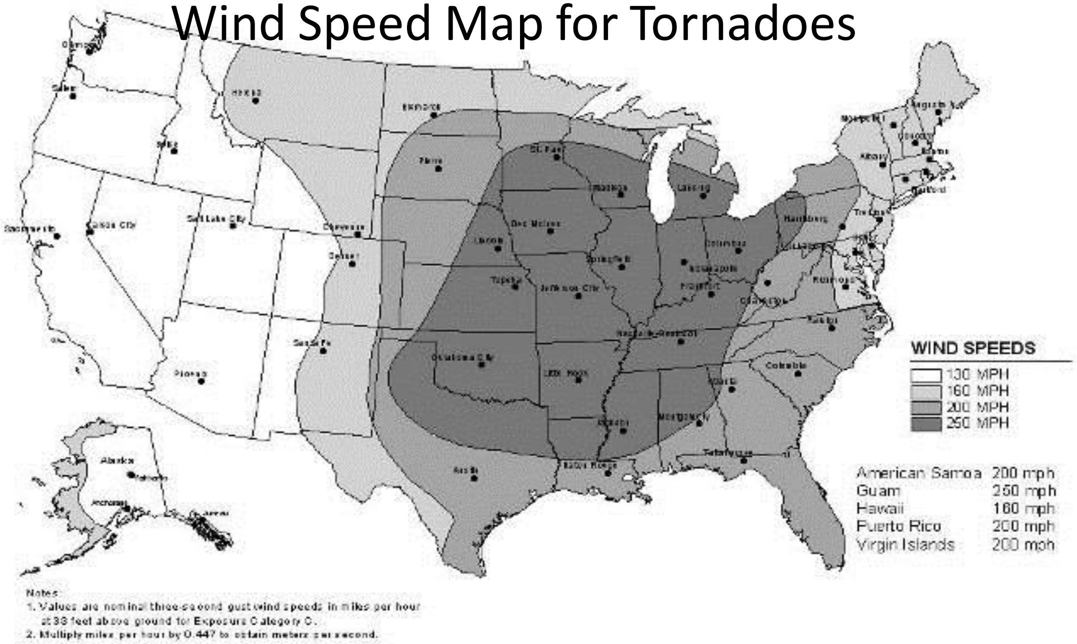
**While the probability for a tornado strike on any individual building is low, the probability of a tornado impacting a community is orders of magnitude larger.**

# Changes are Already Occurring

**The 2015 IBC requires ICC 500 storm shelters in schools and critical emergency operations facilities (911 call centers, emergency operations centers, fire, police, ambulance and rescue stations) in areas having tornado design speeds of 250 mph.**

These code provisions were successfully introduced by FEMA, following their MAT report on the Spring 2011 Tornadoes.

ICC 500-2014 Shelter Design
Wind Speed Map for Tornadoes



# Changes are Already Occurring (cont'd)

The State of Alabama began requiring ICC 500 shelters on school campuses in 2010, following the Enterprise tornado that killed 8 students.

Two years later Alabama expanded the requirements to include college campuses.

Illinois passed legislation in 2014 requiring ICC 500 shelters at new schools.

Many shelters at schools are now being designed to also accommodate nearby residents, and be available to the community 24/7, including features such as

- remote unlocking on tornado watch, warning, or siren activation
- volunteer shelter manager programs
- accommodation of area residents even during the school day

# Changes are Already Occurring (cont'd)

**The city of Moore Oklahoma recently adopted new building code provisions intended to be equivalent to 135 mph design wind speed for residential construction**

**Some hospitals and other facilities are beginning to explicitly consider tornado hazards during the design process**

**- e.g., the rebuilt St. John's Regional Medical Center**

**Not just structural engineering…**

**Area communities are developing regional standards for tornado sirens, in the absence of national standards.**

# Implementation of the Joplin Tornado Recommendations: A Paradigm Shift in Designing for Tornadoes

May 5, 2016

SDR Meeting

## *QUESTIONS?*

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