CrossMark

ORIGINAL PAPER

Hindcasting community-level building damage for the 2011 Joplin EF5 tornado

Navid Attary[1] (ID) **· John W. van de Lindt[1] · Hussam Mahmoud[1] ·
Steve Smith[2] · Christopher M. Navarro[3] · Yong Wook Kim[3] ·
Jong Sung Lee[3]**

Abstract Resiliency of communities prone to natural hazards can be enhanced through the use of risk-informed decision-making tools. These tools can provide community decision makers key information, thereby providing them the ability to consider an array of mitigation and/or recovery strategies. The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, developed an Interdependent Networked Community Resilience (IN-CORE) computational environment. The purpose of developing this computational environment is to build a decision-support system, for professional risk planners and emergency responders, but even more focused on allowing researchers to explore community resilience science. The eventual

✉ Navid Attary
  attary.navid@gmail.com

  John W. van de Lindt
  jwv@engr.colostate.edu

  Hussam Mahmoud
  Hussam.Mahmoud@colostate.edu

  Steve Smith
  smith-st@mssu.edu

  Christopher M. Navarro
  cmnavarr@illinois.edu

  Yong Wook Kim
  ywkim@illinois.edu

  Jong Sung Lee
  jonglee1@illinois.edu

[1] Department of Civil and Environmental Engineering, Center of Excellence for Risk-Based Community Resilience Planning, Colorado State University, Fort Collins, CO 80523, USA

[2] Geography/Social Science Department, Missouri Southern State University, Joplin, MO 64801, USA

[3] National Center for Supercomputing Applications (NCSA), University of Illinois at Urbana-Champaign, Champaign 61801, USA

goal was being to integrate a broad range of scientific, engineering and observational data to produce a detailed assessment of the potential impact of natural and man-made hazards for risk mitigation, planning and recovery purposes. The developing computational environment will be capable of simulating the effects from different natural hazards on the physical and socioeconomic sectors of a community, accounting for interdependencies between the sectors. However, in order to validate this computational tool, hindcasting of a real event was deemed necessary. Therefore, in this study, the community of Joplin, Missouri in the USA, which was hit by an EF-5 tornado on May 22, 2011, is modeled in the IN-CORE v1.0 computational environment. An explanation of the algorithm used within IN-CORE is also provided. This tornado was the costliest and deadliest single tornado in the USA in the last half century. Using IN-CORE, by uploading a detailed topological dataset of the community and the estimated tornado path combined with recently developed physics-based tornado fragilities, the damage caused by the tornado to all buildings in the city of Joplin was estimated. The results were compared with the damage reported from field studies following the event. This damage assessment was done using three hypothetical idealized tornado scenarios, and results show very good correlation with observed damage which will provide useful information to decision makers for community resilience planning.

Keywords Joplin tornado · Community damage assessment · Tornado fragilities · Resolution

1 Introduction

Tornadoes occur regularly in the USA with geographically small strike areas but can result in high casualty rates and billions of dollars in economic loss. The resilience (ability to absorb impacts and recover rapidly from hazards) of communities to tornadoes can be enhanced through the use of risk-informed decision-making tools. The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, developed a beta version of the Interdependent Networked Community Resilience (IN-CORE) computational environment. The developed computational environment is capable of simulating the effects of different natural hazards including tornadoes on the physical and socioeconomic sectors of a community, accounting for select interdependencies between the sectors. In this study, the beta version of IN-CORE was used to assess the damage caused by tornadoes to buildings in Joplin, Missouri. One of the important aspects of IN-CORE is the use of physics-based (developed by numerical simulations rather than being empirically derived) models. Although numerical simulations are valuable, these models need to be verified. In order to verify damage assessment of a community subjected to tornadoes, damages caused by the EF-5 tornado [rated based on the Enhanced Fujita tornado intensity scale (McDonald and Mehta 2006)] which struck the city of Joplin Missouri, USA, on May 22, 2011, were estimated in this study. The 2011 Joplin tornado resulted in 161 fatalities, approximately 1371 injuries and more than $2.8 billion in damages, making it the deadliest and costliest single tornado in the country since 1947 (FEMA 2011). It is worth mentioning that in 1947, Doppler radars did not exist and the ability to warn those in the path of tornados was essentially nonexistent. The Joplin tornado was one of the estimated 1691 tornadoes that occurred in the USA in 2011 (NWS 2011), but due to the severity of the damaged caused by this tornado, it was widely studied by researchers (e.g., Coulbourne and Miller 2012; Prevatt et al. 2012a, b; Lombardo et al.

2015; Roueche et al. 2016) and is utilized in this study to validate the IN-CORE tornado damage predictive models. Figure 1 shows the tornado path with red cross-hatching closest to the centerline representing the wind speed within the vortex that was estimated to have EF5 wind speeds [> 320 km/h (> 200 mph)], reducing to yellow for EF4 wind speeds and as the cross-hatched areas move laterally outward from the tornado path eventually reaching EF1 rating as light blue.

Several organizations including the National Institute of Standards and Technology (NIST), the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers (ASCE) assessed the damage caused by this tornado in Joplin, MO. The majority of the tornado fatalities (84%) occurred inside buildings, further underscoring the need for buildings damage assessment of the community. Simulations of the other physical infrastructure sectors of the community such as electric power network (e.g., Attary et al. 2018) as well as socioeconomics considering their interdependencies will be discussed in forthcoming publications by a host of other authors. Kuligowski et al. (2014) investigations estimated that 553 non–residential buildings and approximately 7400 residential structures were damaged by the tornado. About 43%, or 3181, of these residential buildings were considered destroyed, i.e., structures with a damage classification of extensive or complete (Kuligowski et al. 2014). The non-residential buildings that were severely damaged included one of the two major regional hospitals serving the city of Joplin and the surrounding area, and 10 of the 20 local public schools, several parochial schools, 28 churches, 2 fire stations and both large and small commercial businesses (Kuligowski et al. 2014). In this study, using IN-CORE a detailed topological dataset of the community and the estimated tornado path, the damage caused by the tornado to the buildings of the city of Joplin was estimated. Idealized tornado scenarios (Standohar-Alfano and van de Lindt 2014) can be generated in IN-CORE. These tornado paths are modeled in an idealized form with rectangular regions making up the different EF ratings based on the relative percentage of length and width assigned to that particular EF-rated area. In this study, the building damage assessments of the city of Joplin for three idealized tornado scenarios were performed and results were compared to the damage assessed following the event.
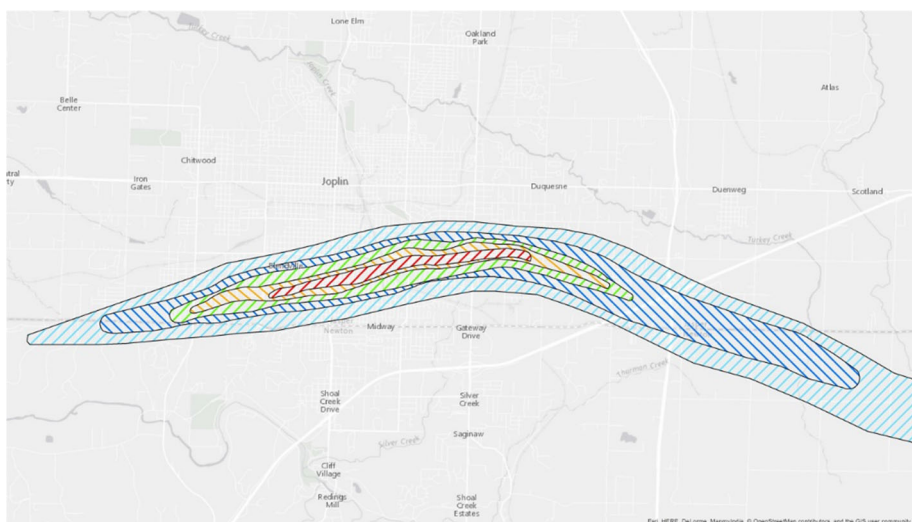

Fig. 1 2011 Joplin tornado estimated path with EF zones (Adapted from NWS 2011)

2 Joplin tornado buildings damage assessment

The building damage assessments presented herein are based on Performance-Based Engineering (PBE) approaches, which provide performance metrics outputs that can be used to inform decision makers for risk mitigation (Porter 2003) and to enhance community resilience. PBE methodologies have been developed for different natural hazards including earthquakes (e.g., Deierlein et al. 2003), fire (e.g., Hamilton 2011), wind (e.g., Ciampoli et al. 2011) and tsunamis (e.g., Attary et al. 2017). Typically, PBE frameworks are based on the total probability theorem which would disaggregate the problem into different analysis phases that include hazard analysis, structural analysis, damage analysis and loss analysis (Porter 2003). These phases must be carried out in sequence, resulting in an estimation of the frequency for which different levels of decision variables would be exceeded. To assess the damage caused by tornadoes to individual building, the estimated wind speed (the hazard intensity measure) at the location of the structure should be estimated. Geocoded data of the actual event EF rating (see Fig. 1) can be used as an estimate of the wind speed at the location for each building. Since the estimated wind speed in each EF region represents a range of wind speed, the wind speed for each building was selected randomly (with a uniform distribution) from the specific wind speed range for each EF zone. Repeating this process and performing Monte Carlo simulation, the statistical damage prediction for each building in Joplin can be obtained. To estimate the damage caused by the tornado to buildings, tornado fragility functions were used in this study. Fragility functions (see, e.g., Ellingwood et al. 2004 for fragility development details) provide the probability that a structure will reach or exceed a specified level of damage as a function of a given intensity measure (wind speed for the case of tornadoes) of the hazard and is often given in the form of a cumulative lognormal distribution. Using tornado fragilities and wind speed at the location of the structure, the probability of reaching different damage states, namely slight, moderate, extensive and complete, can be calculated for each building in the community. This process is performed for all the buildings in a community to estimate the total structural damage spatially throughout the community. In this study, geocoded details (GIS data) of all buildings in the city of Joplin at the time of the disaster (May 2011) was gathered. By assigning tornado fragilities to each building, community damage assessment is possible. However, currently, physics-based tornado fragilities are just being developed and many do not yet exist in the literature. Therefore, the buildings in the community should be categorized to reduce the number of required fragility functions. There is clearly a need for sensitivity analysis to determine how many building types must be modeled for basic community resilience assessment and subsequent risk-informed decision. This is beyond the scope of the present paper, but the 19 archetype buildings proposed by Memari et al. (2018) are utilized herein to represent the Joplin community, and Table 1 shows the details of these 19 building types. As can be seen from the table, since the overarching goal is to assess the resiliency of a community, considering physical and socioeconomic sectors, the selected building archetypes consider the occupancy of each building in addition to other characteristics such as building material, area, roof type.

Using the detailed data of the buildings from the city of Joplin, all buildings were categorized into the aforementioned 19 archetypes. For example, five typical wood residential buildings (see Standohar-Alfano and van de Lindt 2014 for details) were used to represent all the residential buildings in the city of Joplin. Each of the residential buildings of the city was then assigned to one of these five archetype buildings based on their

Table 1 Types of buildings assumed to exist in the city of Joplin

Building type	Building description
T1	Res. wood bldg.—small rectangular plan—gable roof—1 story
T2	Res. wood bldg.—small square plan—gable roof—2 stories
T3	Res. wood bldg.—medium rectangular plan—gable roof—1 story
T4	Res. wood bldg.—medium rectangular plan—hip roof—2 stories
T5	Res. wood bldg.—large rectangular plan—gable roof—2 stories
T6	Business and retail building (strip mall)
T7	Light industrial building
T8	Heavy industrial building
T9	Elementary/middle school (unreinforced masonry)
T10	High school (reinforced masonry)
T11	Fire/police station
T12	Hospital
T13	Community center/Church
T14	Government building
T15	Large big-box
T16	Small big-box
T17	Mobile home
T18	Shopping center
T19	Office building

characteristics such as area, roof type, number of stories. Figure 2 shows different building types (different colors in the figure) assigned to all of the buildings of the city. For example, residential buildings are shown in red and heavy industrial buildings are shown in yellow in Fig. 2.
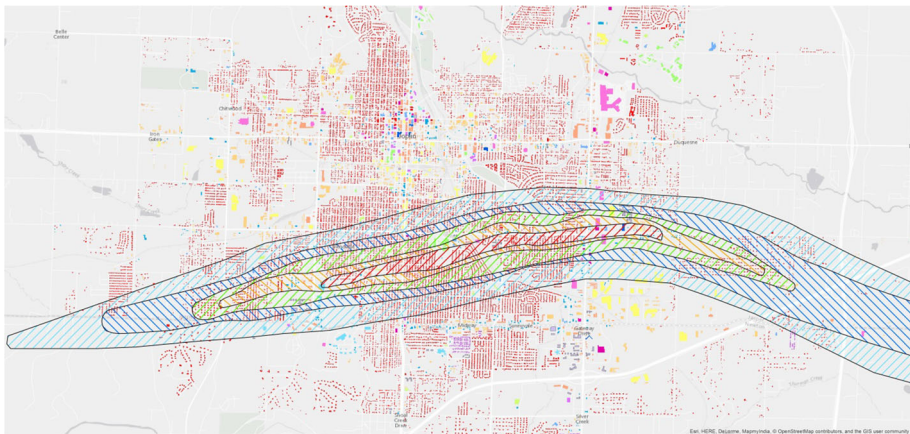

Fig. 2 19 archetype buildings in the city of Joplin and the estimated tornado path and EF zones (Adapted from NWS 2011)

Existing fragility functions in the literature were used in this study for these 19 archetype buildings to estimate the damage caused by the Joplin tornado to buildings. In particular, fragility functions for residential buildings (T1–T5) and big-box stores (T15 and T16) were adopted from Masoomi et al. (2018) and Koliou et al. (2017), respectively, while school buildings (T9 and T10) were modified and adopted, from Masoomi and van de Lindt (2016), and the remaining 10 buildings were adopted from Memari et al. (2018). Table 2 provides fragility parameters used for the 19 building archetypes. It should be noted that one of the purposes of this study is to verify physics-based tornado fragilities, and it is noted that empirical fragilities for the Joplin tornado exist in the literature (e.g., Roueche et al. 2016, 2017).

As shown in Fig. 3a–d, the fragility curves of these 19 building types for each damage state span the entire range of wind speeds that we typically associate with a tornado. Thus, it is proposed herein that these building types are therefore sufficient to reasonably assess a community, working on the assumption that the correct archetype (fragility) is assigned to a building with that level of resistance or performance. Perhaps as more tornado physics-based fragilities become available, a detailed sensitivity analysis can be performed to assess the number of archetypes needed for this purpose. Using the wind speed and building fragility parameters, the probability of exceeding the four damage states, namely

Table 2 Fragility parameters of the 19 archetypes buildings used in this study (Masoomi et al. 2018; Koliou et al. 2017; Masoomi and van de Lindt 2016; Memari et al. 2018)

| Building type	Lognormal distribution for damage state (mph)								References
	Slight		Moderate		Extensive		Complete		
	λ	ξ	λ	ξ	λ	ξ	λ	ξ	
T1	4.52	0.11	4.70	0.11	4.77	0.11	4.81	0.12	Masoomi et al. (2018)
T2	4.62	0.17	4.76	0.14	4.80	0.12	4.91	0.12	Masoomi et al. (2018)
T3	4.31	0.10	4.44	0.10	4.63	0.10	4.70	0.10	Masoomi et al. (2018)
T4	4.42	0.15	4.51	0.13	4.60	0.12	4.69	0.14	Masoomi et al. (2018)
T5	4.45	0.13	4.54	0.11	4.67	0.10	4.71	0.10	Masoomi et al. (2018)
T6	4.22	0.11	4.43	0.11	4.70	0.11	4.88	0.21	Memari et al. (2018)
T7	4.29	0.11	4.50	0.10	4.59	0.10	4.67	0.10	Memari et al. (2018)
T8	4.21	0.12	4.37	0.14	4.77	0.15	4.94	0.19	Memari et al. (2018)
T9	4.29	0.12	4.56	0.11	4.69	0.11	4.93	0.16	Masoomi and van de Lindt (2016)
T10	4.33	0.12	4.54	0.11	4.70	0.11	5.07	0.12	Masoomi and van de Lindt (2016)
T11	4.37	0.25	4.70	0.12	4.85	0.12	4.99	0.19	Memari et al. (2018)
T12	4.42	0.10	4.59	0.09	4.97	0.09	5.16	0.09	Memari et al. (2018)
T13	4.06	0.12	4.46	0.11	4.68	0.11	4.95	0.17	Memari et al. (2018)
T14	4.07	0.12	4.36	0.11	4.62	0.11	4.84	0.13	Memari et al. (2018)
T15	4.14	0.12	4.37	0.12	4.83	0.12	5.06	0.12	Koliou et al. (2017)
T16	3.99	0.12	4.27	0.12	4.90	0.12	5.05	0.12	Koliou et al. (2017)
T17	4.28	0.12	4.47	0.12	4.60	0.11	4.70	0.12	Memari et al. (2018)
T18	4.24	0.12	4.44	0.12	4.68	0.10	4.86	0.17	Memari et al. (2018)
T19	4.23	0.12	4.48	0.12	4.71	0.11	4.97	0.17	Memari et al. (2018)
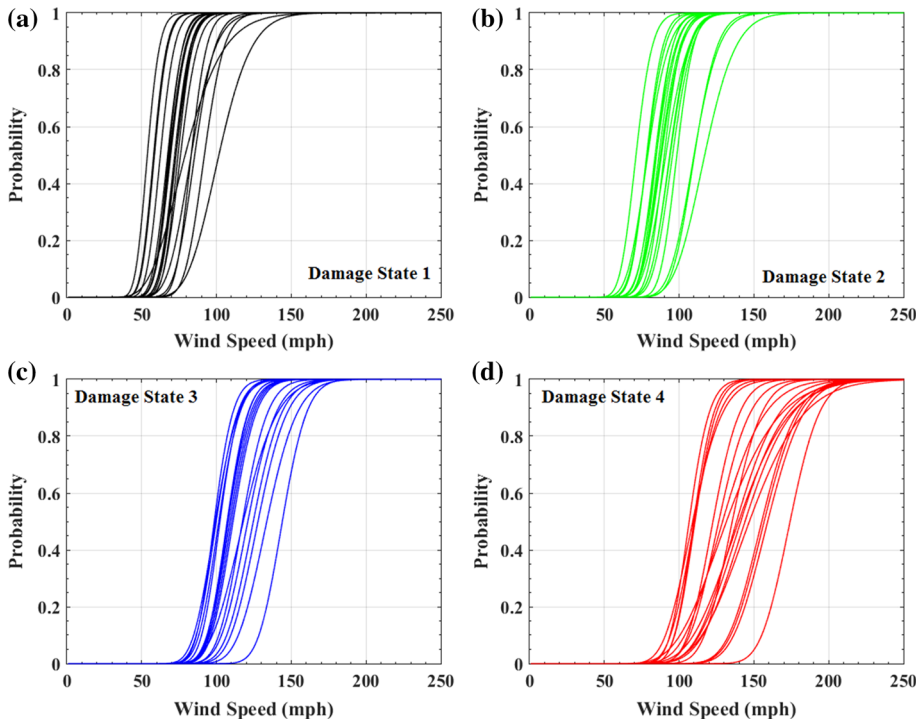
Fig. 3 Fragility curves for the four damage states of **a** slight, **b** moderate, **c** extensive, **d** complete for the 19 archetype buildings

slight, moderate, extensive and complete, was calculated for each building in the city of Joplin.

2.1 Community-level building damage assessment and validation

As mentioned earlier, using the estimated EF zones and geocoded details of the buildings, the range of wind speed and fragility parameters for each building was determined. Using Monte Carlo simulation with 10,000 iterations and randomly selecting the wind speed, with uniform distribution, within each iteration from within the associated EF region wind speed range, the probability of buildings reaching each damage state was determined. Figures 4, 5, 6 and 7 show the probability of each building being located in each of the four damage states. For example, in Fig. 4, the buildings at the center of the tornado path are predicted to be in or exceed a slight damage state almost 100% of the time, in line with intuition for such a high wind speed. As one moves laterally outward from the tornado path centerline, these probabilities become lower, although not significantly since this is just for damage state 1, i.e., slight damage, which is the state, many buildings are expected to be in, due to the tornado.

By inspecting Fig. 4 through Fig. 7, and as expected, overall the number of buildings with higher probabilities is reduced as the damage state goes from slight (Fig. 4) to moderate (Fig. 5), extensive (Fig. 6) and complete (Fig. 7). In order to validate the analysis results, both qualitative and quantitative measures were compared with post-
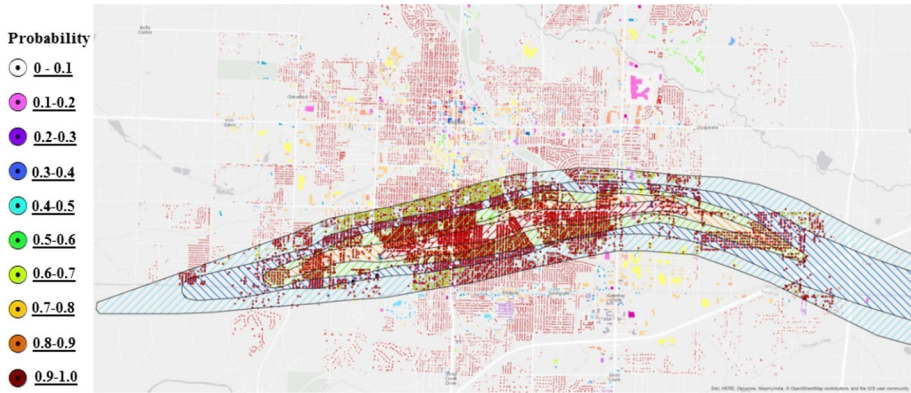
Fig. 4 Probability of reaching damage state slight for the buildings of Joplin community
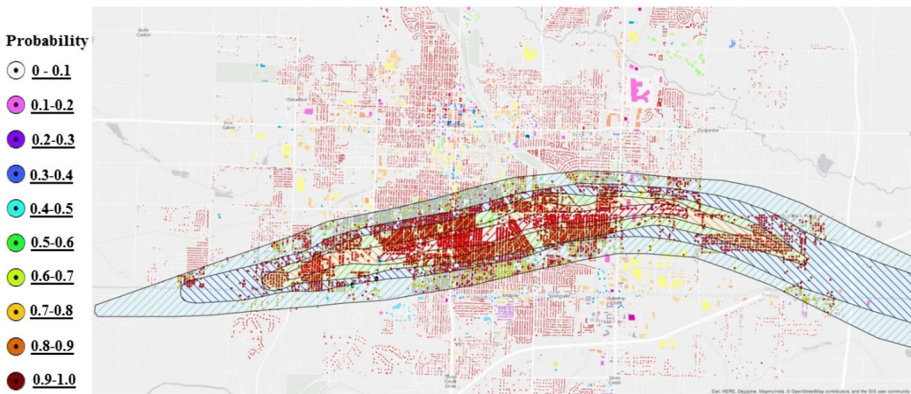

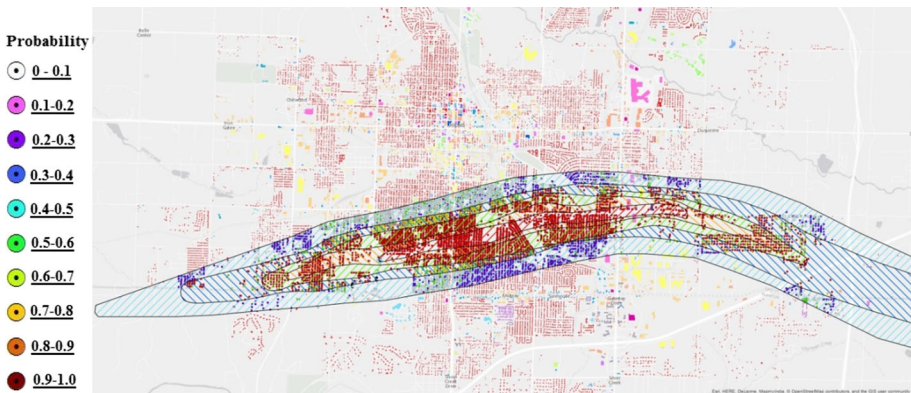**Fig. 5** Probability of reaching damage state moderate for the buildings of Joplin community

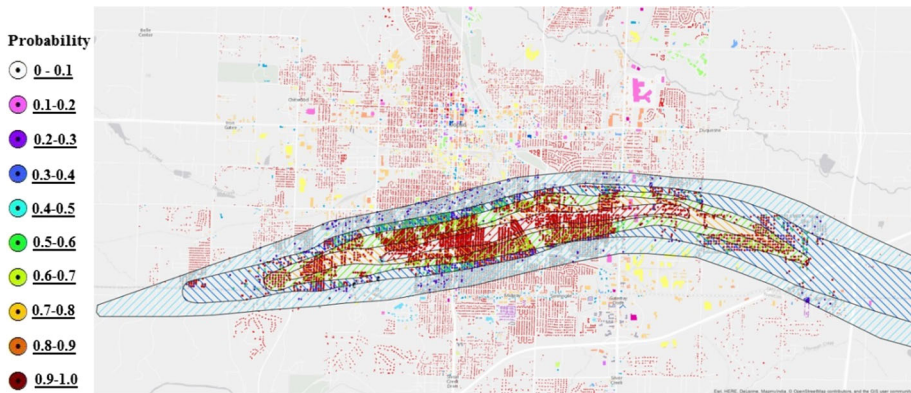**Fig. 6** Probability of reaching damage state extensive for the buildings of Joplin community

Fig. 7 Probability of reaching damage state complete for the buildings of Joplin community

disaster data. For example, it was reported by Kuligowski et al. (2014) that a total of 7411 residential buildings had some level of damage with 3181 experiencing severe damage. Simulation results showed that 7156 residential buildings would have more than 95% probability of reaching slight (DS1) damage state. In addition, 3633 residential buildings would have more than a 95% probability of reaching damage state extensive, which is consistent with the actual reported results. Alternatively, the results may be compared with aerial images captured after the event. Figure 8a through Fig. 8f shows the simulation results for the probability of reaching damage state *complete* (DS4) over these aerial images and in most cases the predicted probability is arguably reasonable based on the aerial view of the damage to the buildings. For example, in Fig. 8b probabilities of complete damage in the EF3 region of the tornado are predicted to be 70–90% and some houses are destroyed while a few remain somewhat intact. This type of logic may be used within each of the figures, keeping in mind that it is probabilistic so 100% definitive conclusions are not necessarily possible, nor needed.

2.2 Sensitivity of community-level analysis to input resolution

One of the major challenges when performing community-level analysis is the resolution that should be used to describe data from the community and the subsequent analysis using that resolution. The data collected in this study and the analysis are at the maximum resolution possible (at the individual building level) for community analysis; thus, the effect of using lower resolutions on the results can be explored for future analyses. In this study grid lines with five different sizes, 15.24 × 15.24 m (50 × 50 ft), 30.48 × 30.48 m (100 × 100 ft), 60.96 × 60.96 m (200 × 200 ft), 152.4 × 152.4 m (500 × 500 ft) and 304.8 × 304.8 m (1000 × 1000 ft) were overlaid on the building inventory. Then, one of the 19 types of the building was assigned to each cell. To determine the type that should be assigned to each cell, two methods were used. In the first method, the number of buildings for each building type within each cell was calculated and the type of building representing the majority within each cell was assigned to the cell (i.e., assigned based on statistical mode). In addition, the total number of buildings in each cell was calculated and assigned to the cell. In the second method, again the total number of buildings in each cell was assigned to the cell but the type that was selected to represent all buildings within the cell was randomly selected as one building types identified as being contained within the cell,
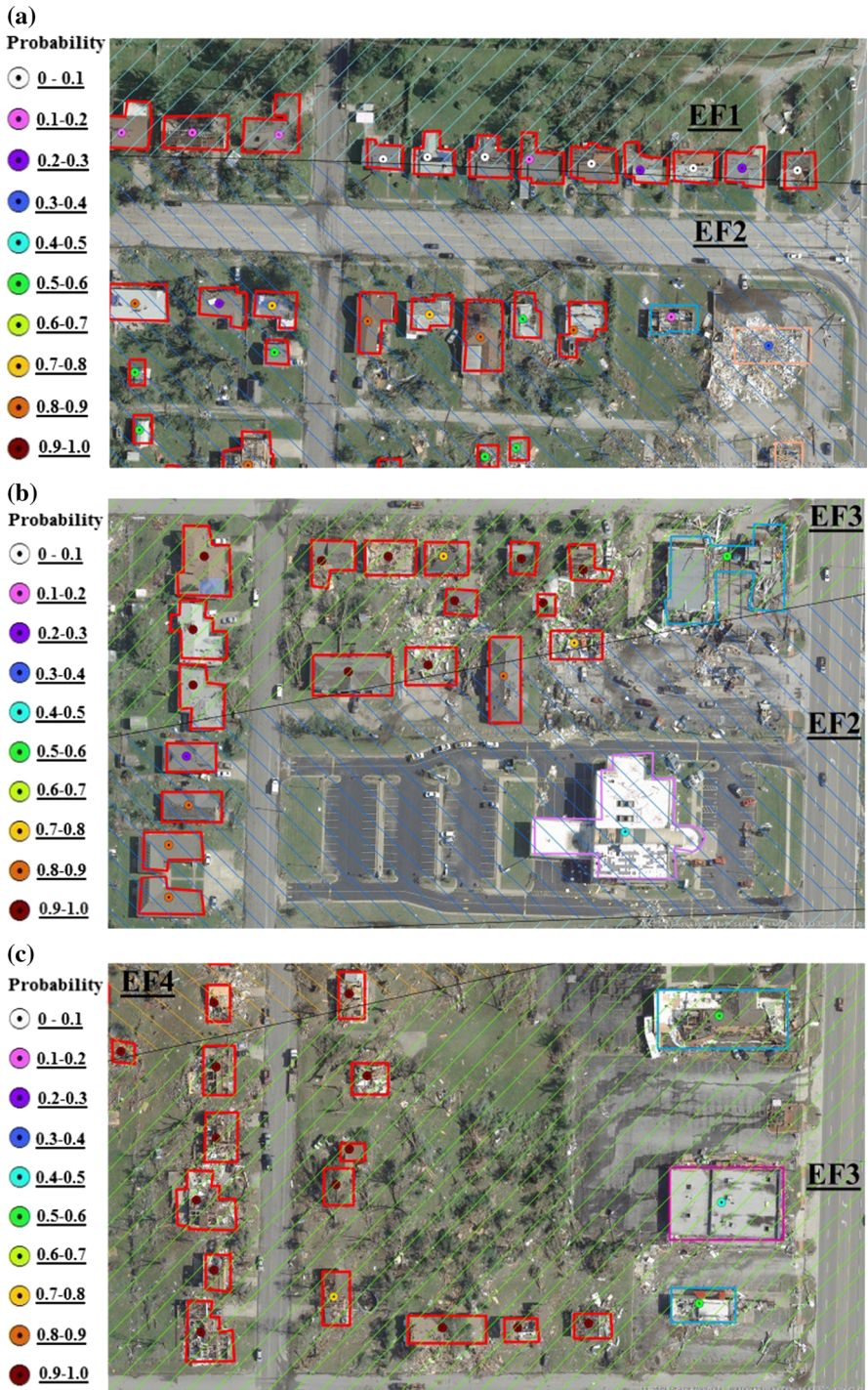
Fig. 8 Probability of reaching damage state complete overlaid on aerial images after the event. (Base image adopted from Missouri Spatial Data Information Service 2016)
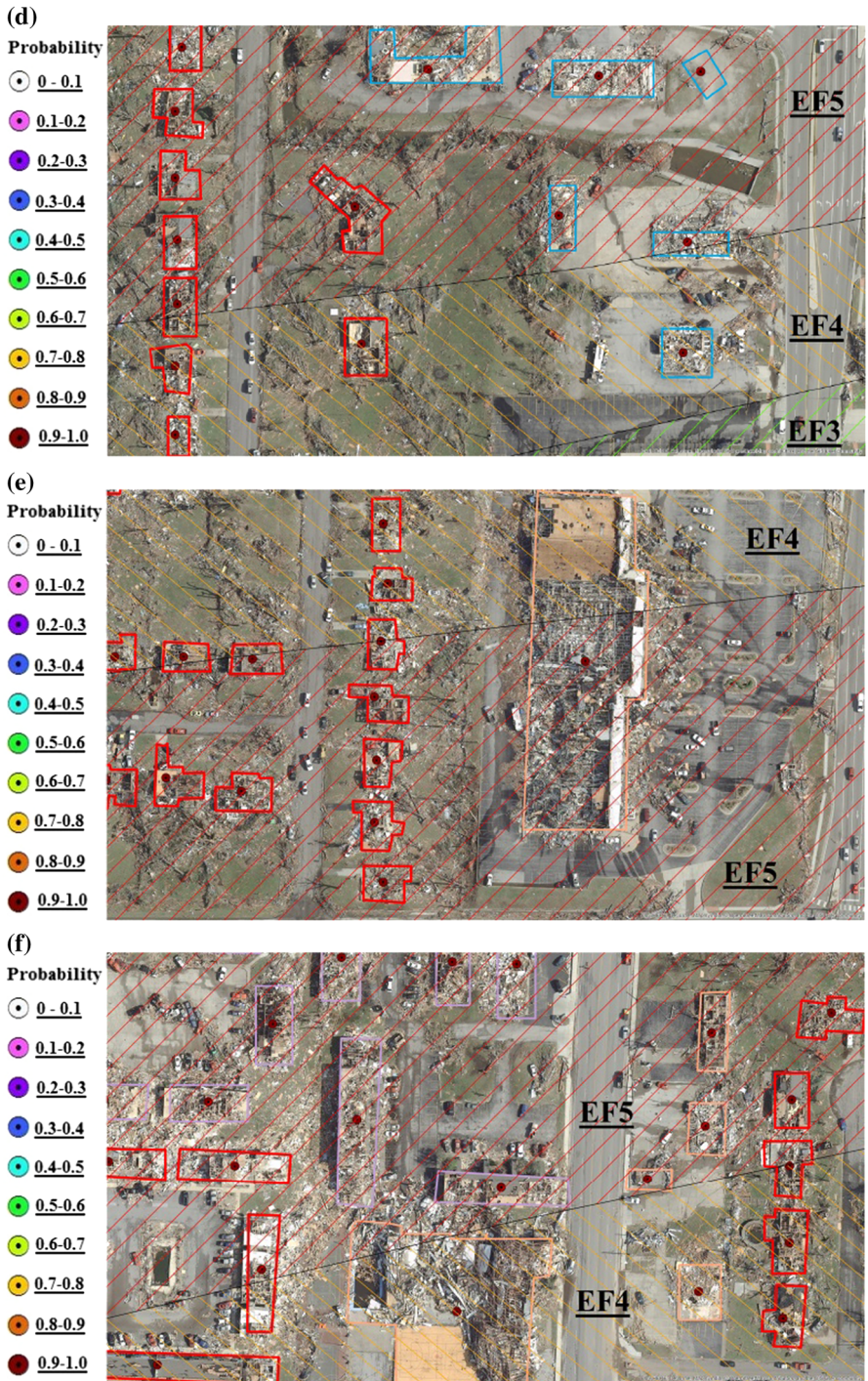
(d)

(e)

(f)

Fig. 8 continued

mimicking the case that an analyst would select one building from a small spatial region to represent that region (i.e., cell). It is important to mention that the buildings may not be fully contained within one cell and the grid lines might intersect buildings, resulting in double counting one building as being contained within more than one cell. Therefore, in this study, to avoid considering a building in more than one cell, the center point of the footprint of the buildings was used for the analysis instead of the original footprints of the buildings. Figure 9 shows the process for the five assumed gridline sizes for one specific region of the city of Joplin. (Cell type was assigned based on statistical mode value.)

Figure 10 shows these five sizes of gridlines overlaid on top of the entire city of Joplin. (The type is assigned to the cells based on the statistical mode method described earlier.)
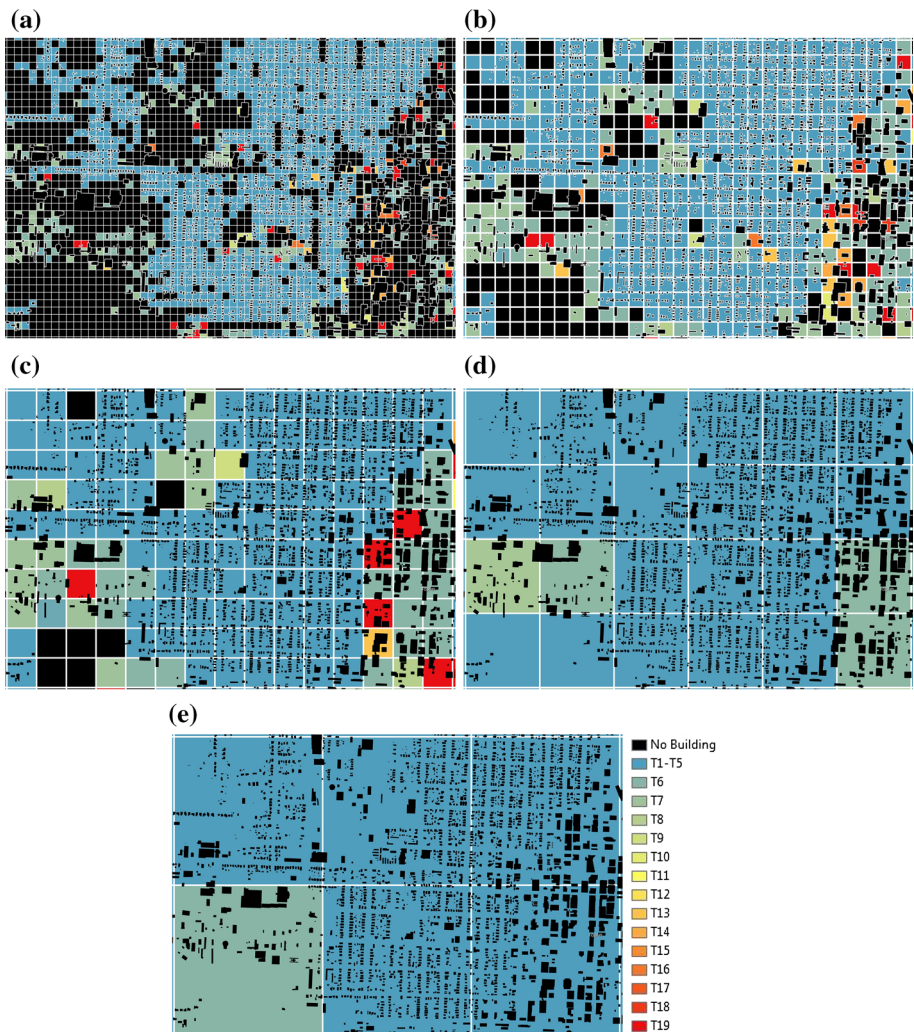

Fig. 9 Different sizes of gridlines overlaid on building inventory for a small region in Joplin and the assigned building type (by color), **a** 15.24 × 15.24 m (50 × 50 ft), **b** 30.48 × 30.48 m (100 × 100 ft), **c** 60.96 × 60.96 m (200 × 200 ft), **d** 152.4 × 152.4 m (500 × 500 ft), **e** 304.8 × 304.8 m (1000 × 1000 ft)

(a)   **(b)**

(c)   **(d)**
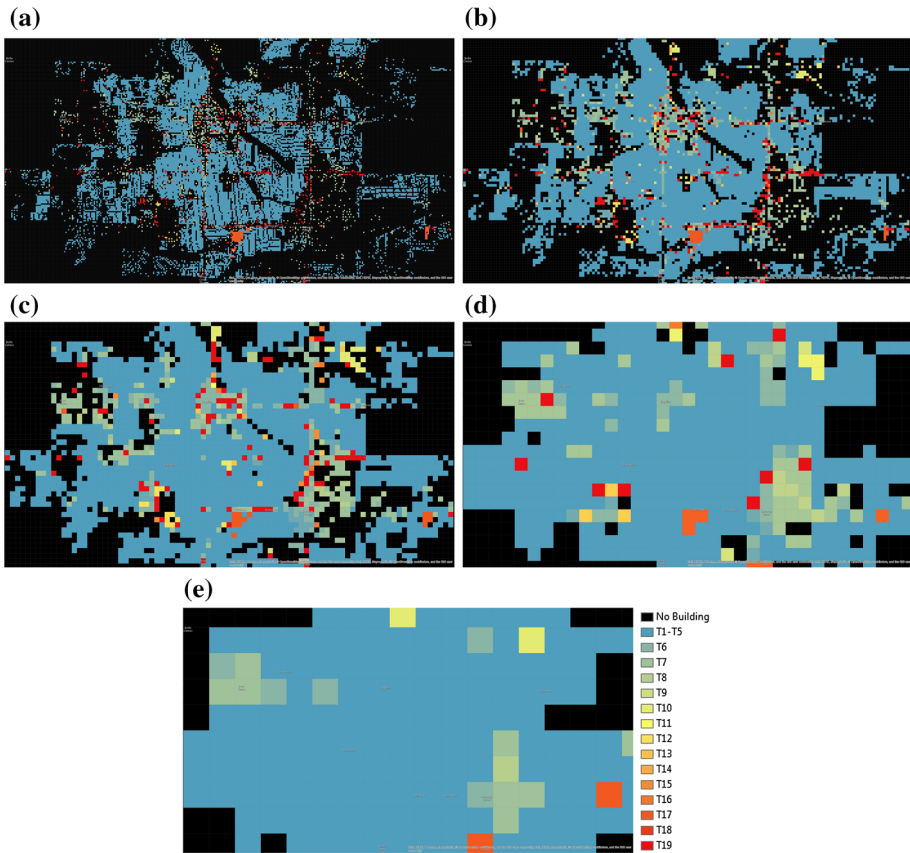

(e)

Fig. 10 Different sizes of gridlines overlaid on building inventory of the entire city of Joplin and the assigned building type (by color), **a** 15.24 × 15.24 m (50 × 50 ft), **b** 30.48 × 30.48 m (100 × 100 ft), **c** 60.96 × 60.96 m (200 × 200 ft), **d** 152.4 × 152.4 m (500 × 500 ft), **e** 304.8 × 304.8 m (1000 × 1000 ft)

As clear from Figs. 9 and 10, by decreasing the resolution, many types of buildings would disappear from the map and not be considered in the analysis.

Similarly, using the actual path for the tornado identified in NWS (2011), the EF region that each cell was located in could be determined. By performing the analysis discussed earlier for individual buildings for these five cases, the probability of reaching each damage state for each cell can be calculated. Using the number of buildings inside each cell, the total number of buildings from each archetype was then calculated. Table 3 shows the results of the analysis indicating the total number of each building archetype having more than a 50% probability of reaching DS4 for each of the five resolutions and for the two methods described earlier (statistical mode and random selection). It can be seen in Table 3 that for the low-resolution analysis, many of the building types are not considered which would likely result in major analysis errors for community analysis, particularly for analysis that includes socioeconomic sectors. It can also be observed from the results in Table 3 that low-resolution analysis can over-/underpredict the number of buildings from each type. As expected, by increasing the resolution for the number of buildings the

Table 3 Total number of each building archetype having more than 50% probability of reaching DS4 for the two cases of selecting the type based on statistical mode and random selection

Type	1000 × 1000 ft	500 × 500 ft	200 × 200 ft	100 × 100 ft	50 × 50 ft	Actual event
Statistical mode scenario [P(DS4) > 50%]						
T1–T5	9510	7167	5597	5040	4781	4621
T6	0	4	35	94	107	116
T7	74	103	98	99	104	102
T8	0	0	1	4	4	4
T9	0	0	0	5	6	6
T10	0	0	5	4	4	5
T11	0	0	0	0	0	0
T12	0	18	8	9	10	10
T13	0	0	4	9	9	9
T14	0	0	0	0	1	1
T15	0	0	1	3	3	3
T16	0	0	0	1	1	1
T17	111	0	0	0	0	0
T18	0	0	0	1	1	1
T19	0	48	88	125	130	137
Random selection scenario [P(DS4) > 50%]						
T1–T5	1927	3041	4449	4735	4720	4621
T6	800	909	306	212	140	116
T7	705	393	190	114	102	102
T8	106	125	18	7	4	4
T9	643	283	64	8	6	6
T10	0	0	5	4	4	5
T11	0	0	0	0	0	0
T12	0	0	21	12	10	10
T13	731	529	106	19	9	9
T14	0	0	0	3	1	1
T15	285	77	16	3	3	3
T16	0	0	0	1	1	1
T17	0	0	3	0	0	0
T18	0	0	6	1	1	1
T19	3498	1549	359	188	149	137

damage predictions for each archetype converge to the building level analysis. As an example, Fig. 11 shows this convergence for the residential buildings for the two methods.

3 Interdependent Networked Community Resilience (IN-CORE v1.0) modeling environment

As mentioned previously, the Center for Risk-Based Community Resilience Planning developed a computational environment known as IN-CORE. The purpose of developing this computational environment is to build a research tool for resilience researchers, as well
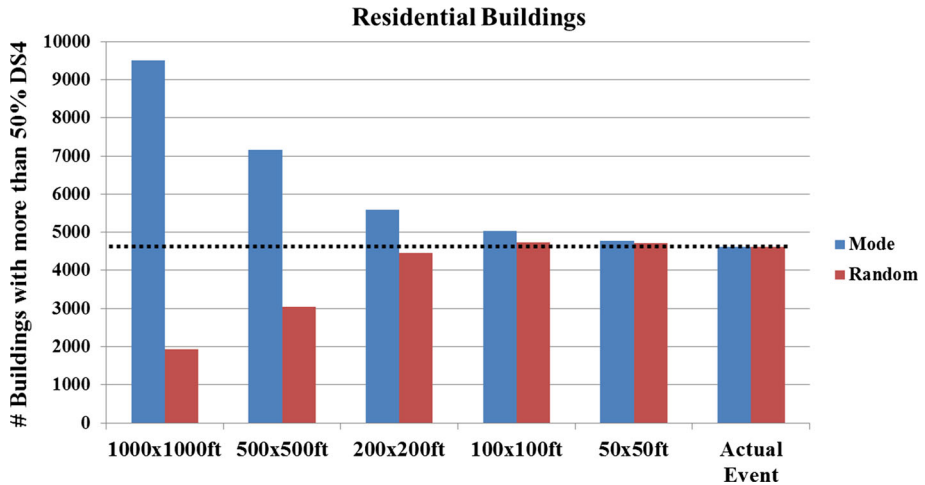
Fig. 11 Number of residential buildings with more than 50% probability of reaching DS4 for two methods (statistical mode and random selection) with five different resolutions

as eventually provide a robust risk-informed platform for decision support. IN-CORE integrates a broad range of scientific, engineering and observational data to produce a detailed assessment of the potential impact of hazards for risk mitigation, planning and recovery purposes.

The Interdependent Networked Community Resilience (IN-CORE) modeling environment has the capability of computing the proposed resiliency measures at the user-desired community level. The implementation in this paper is developed on the first version of IN-CORE, which is based on Ergo (ergo.ncsa.illinois.edu) (previously referred to as MAE-Viz)—an open-source multi-hazard assessment, response and planning tool for performing risk-based community resilience planning. IN-CORE v1.0 is a Java application with a plug-in based architecture that allows researchers to extend IN-CORE's capabilities through the addition of new science/features. These features can be connected with the existing 40 + analyses to produce new scientific results. The core technologies of the Ergo framework include Eclipse Rich Client Platform (RCP), Geotools, Visualization Toolkit, JFreeChart, KTable and Jasper reports. These technologies make up the core of Ergo and provide capabilities such as data management, visualization, analysis as shown in Fig. 12.

The Eclipse RCP framework allows IN-CORE to be extensible via the Open Services Gateway Initiative (OSGi) specification, which describes a modular system and a service platform for the Java programming language that allows applications to be extended by adding new bundles that add or enhance capabilities of the platform. Eclipse builds on this through the concept of extensions to contribute functionality to a certain type of application programming interface (API) defined by a plug-in through an extension point. A plug-in defines a contract or API with the definition of an extension point. This allows other plug-ins (bundles) to add contributions (extensions) to the extension point (see Fig. 13). It is through this mechanism that a new extension point for Tornado models was defined for IN-CORE and several concrete implementations (extensions) described previously were added to the system. Additionally, future models can use this extension point to add new modeling techniques.
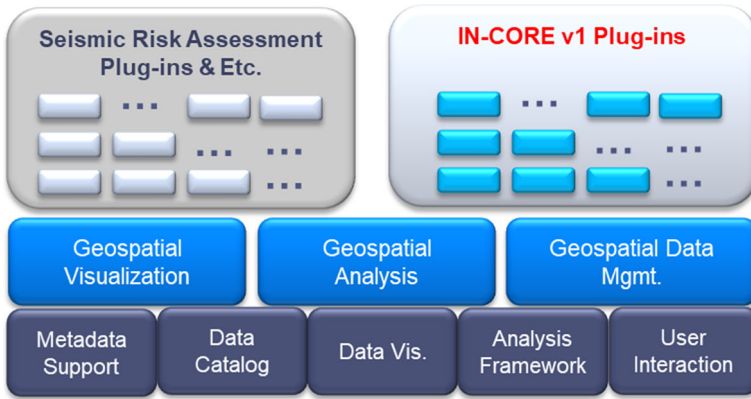
Fig. 12 IN-CORE architecture

In a similar way, a new analysis was added to IN-CORE through the analysis extension point "edu.illinois.ncsa.ergo.core.analysis.newAnalyses" to allow users to create scenario tornado events. This analysis allows users to select a tornado model (e.g., mean width, random width) and specify any required inputs. The output of the analysis was defined as a new data type, tornado hazard, defined through the "gisSchemas" extension point "edu.illinois.ncsa.gis.gisSchemas" and captures a shapefile representing the EF bounding boxes and in the case of a tornado model, an xml file, representing model parameters. This new data type defines what type of data the dataset contains so current and future analyses requiring a tornado hazard know this data type can be used in any analysis input field requiring tornado hazard. Each analysis description is an Extensible Markup Language (XML) file that defines the valid data types for each analysis input, so IN-CORE can determine which analyses can be connected in a workflow to generate required data or if a
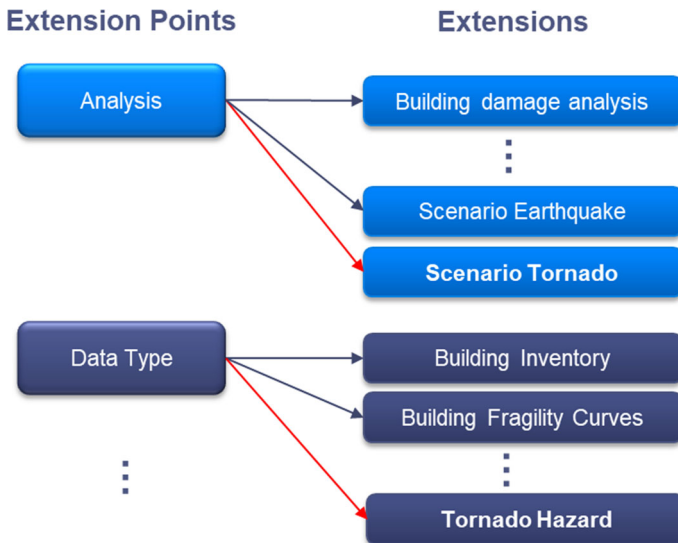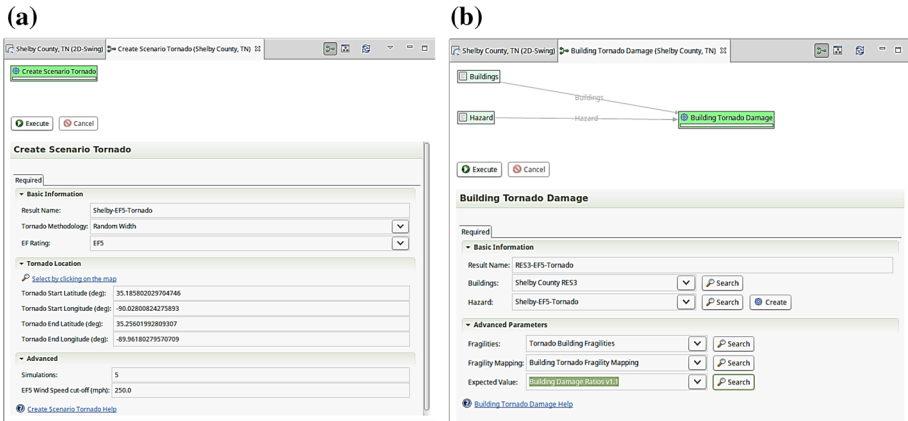

Fig. 13 Extensibility of IN-CORE

(a)   **(b)**

Fig. 14 **a** Scenario tornado analysis, **b** building damage analysis chained with scenario tornado analysis

dataset is already created from a previous execution, which datasets can be selected as input. This new data type not only supports modeled tornadoes but also can be used to import real tornado events where the EF boundaries are defined by a shapefile dataset. When an analysis uses a tornado hazard dataset to obtain values for a given location, the default implementation in IN-CORE uses a uniform random distribution to calculate the wind speed within an EF box. For comparison, the linear interpolation method is also implemented. The user interface to configure the scenario tornado is constructed automatically from the analysis description file based on the widgets defined in the description and is shown in Fig. 14. Figure 14a shows the user interface for scenario tornado analysis. Users can define various parameters such as start point and end point of the tornado, EF rating. Figure 14b shows the chaining of the scenario tornado analysis and building damage analysis. As mentioned previously, IN-CORE allows users to chain analyses based on the data types defined in the analysis description. After chaining the analyses, IN-CORE generates the scenario tornado and passes the resulting tornado hazard to the building damage analysis to compute building damage.

In this study, IN-CORE was used to model the Joplin community and to assess the damage caused by the 2011 tornado. However, one benefit of this simulation tool is its ability to assess the community for different scenarios. Hypothetical tornado scenarios may be modeled in an idealized form with rectangular EF regions divided into different EF ratings based on the relative percentage of length and width assigned to that particular EF-rated area. The values selected for the length and width of each EF zone are computed based on existing tornado statistics performed, as introduced by Standohar-Alfano and van de Lindt (2014). For example, for an EF3 tornado, 32.1% of the length is classified as EF3, 31.8% as EF2, 24.4% as EF1 and 11.7% as EF0. Similarly, 33.8% of the width is classified as EF3, 20.2% as EF2, 26.2% as EF1 and 19.8% as EF0 (Fig. 15).

In this study, the building damage assessment of the city of Joplin for three idealized tornado scenarios (numbers 2–4 below) was performed and results were compared with the actual event simulations. The considered tornado scenarios are as follows:

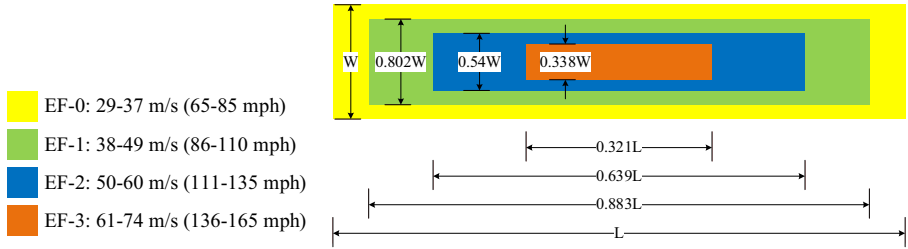1- An EF5 tornado with actual path that occurred in 2011 (Fig. 16a).

EF-0: 29-37 m/s (65-85 mph)
EF-1: 38-49 m/s (86-110 mph)
EF-2: 50-60 m/s (111-135 mph)
EF-3: 61-74 m/s (136-165 mph)

Fig. 15 Sample idealized path model for an EF 3 tornado
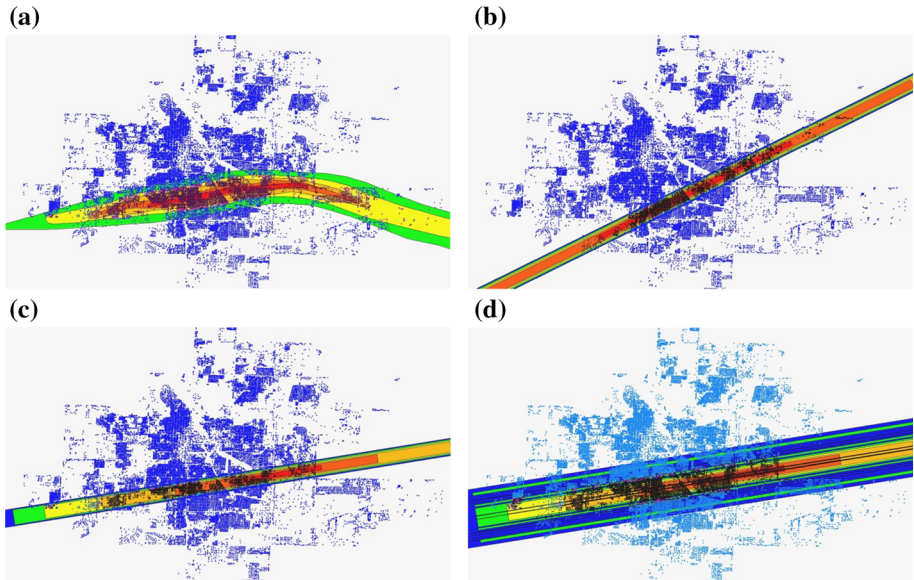

Fig. 16 Probability of reaching damage state complete for the four tornado scenarios

2- An EF5 tornado with mean length, width and angle based on the historical data (Fig. 16b). This is the averages for length, width and length based on all EF5 tornadoes documented between 1973 and 2013.

3- An EF5 tornado with mean width based on historical data and start and end points (Fig. 16c).

4- 1000 EF5 tornadoes with width modeled as a random variable based on the historical data of (2) and start and end points (Fig. 16d).

In IN-CORE, the user can select the location of the idealized tornado. In this study, the criteria for selecting the locations of the tornadoes for scenarios 2–4 are based on matching the location of the center point of the EF5 region of the tornado, with a similar point for scenario 1. For scenarios 3 and 4, the start and end points were chosen in a way that the EF2 regions were approximately the same length as the EF2 region of the actual tornado path. The EF regions were automatically generated by IN-CORE based on the aspect ratios explained earlier. The damage assessment resulting for the four tornado scenarios is shown in Fig. 16, in which the buildings are shown with dots (associated with the centroids of

their footprints), and the darker the dots, the higher the probability of reaching damage state complete (DS4) a building. Table 3 shows the percentage of buildings from each archetype (see Table 1) in the city of Joplin with more than a 50% probability of reaching damage state complete (DS4) for the four assumed tornado scenarios. As can be seen from Table 4, these percentages for scenario 1 and 4 are relatively close. This implies that by using a large number of tornado scenarios, it is possible to estimate the damage to the buildings within a community and replicate the damage caused by real tornadoes that might hit the community. Although there is clearly some biased introduced by knowing the path, one could argue that decision makers would have a better understanding of the needs and possible damages to the community with such as randomization allowing for better risk and resilience planning.

4 Summary and conclusion

Communities around the world are subjected to different hazards such as earthquakes, hurricanes and tornadoes. The use of risk-informed decision-making tools, capable of performing community damage assessments for different scenarios, by community leaders and decision makers, can enhance resiliency of communities. The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, developed an Interdependent Networked Community Resilience (IN-CORE) computational environment. IN-CORE is capable of performing risk assessment of communities subjected to different hazards such as tornadoes, earthquakes, tsunamis, including damage, loss and some functionality and recovery assessments. Different physical infrastructures such as buildings, bridges, electric power and water networks as well as socioeconomic infrastructures and their interdependencies may be modeled in this computational environment. To verify such a computational tool, communities subjected to actual hazards should be simulated, comparing the results with real event post-disaster data. For this purpose, the city of Joplin Missouri and particularly the 2011 tornado that passed through the city was simulated in IN-CORE to assess the tornado building damage capabilities of the model. For this study, geocoded details of the buildings of the community before the event were used to categorize each of the more than 40,000 buildings in the city. Using existing fragilities from the literature for the suite of 19 archetype buildings, combined with estimated wind speeds, the probability of reaching four damage states, namely slight, moderate, extensive and complete, was calculated for each building. Comparing the results with post-disaster data of the actual event showed that although there were many uncertainties involved in this assessment, the results are quite promising, underscoring that this tool can be used to assess damage to communities subjected to tornadoes. The resolution selected for community-level analysis plays an important role in the obtained results of this type of analysis. Choosing five different resolutions for performing the community building damage analysis with grid sizes ranging from 15.2 (50) to 304.8 m (1000 ft) showed that by choosing the grid size greater than 200 ft the results would substantially deviate from reality and therefore it is not recommended for detailed community-level analysis. In addition, three idealized tornado scenarios were utilized in this study and the results of the damage by building archetype for one of the idealized scenarios (with 1000 random tornadoes) was shown to be closest to the results of the actual tornado scenario, suggesting that such an analysis is able to capture the damage caused by real events and has the potential to be used for city/community and disaster planning

Table 4 Percentage of buildings of each building type with more than 50% probability of reaching damage state complete for the four assumed tornado scenarios

Scenario	Res.	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19
1	18.25	19.29	10.06	3.87	15.38	10.00	12.50	41.46	17.05	14.29	18.18	13.33	0.00	10.00	22.08
2	8.38	8.29	4.15	0.00	2.56	0.00	0.00	39.02	5.68	3.57	18.18	0.00	0.00	0.00	9.26
3	8.66	12.36	3.32	2.58	15.38	10.00	0.00	34.15	7.95	0.00	13.64	3.33	0.00	10.00	12.54
4	19.41	21.06	7.88	2.58	17.95	10.00	12.50	48.78	15.91	17.86	18.18	13.33	0.00	10.00	23.36

purposes. Forthcoming papers by the authors will provide the results for other sectors of the city of Joplin such as the electric power network and socioeconomic sectors, as well as recovery modeling, and continue to validate the IN-CORE platform.

References

Attary N, Unnikrishnan VU, van de Lindt JW, Cox DT, Barbosa AR (2017) Performance-based tsunami engineering methodology for risk assessment of structures. Eng Struct. https://doi.org/10.1016/j.engstruct.2017.03.071

Attary N, van de Lindt JW, Mahmoud H, Smith S (2018) Hindcasting community level damage For The Joplin MO 2011 EF5 Tornado: buildings-electric power network. J Nat Hazards Rev (under review)

Ciampoli M, Petrini F, Augusti G (2011) Performance-based wind engineering: towards a general procedure. Struct Saf 33:367–378

Coulbourne WL, Miller J (2012) Performance of school buildings in the Joplin, MO, Tornado. In: Structures congress 2012. ASCE, pp 989–998

Deierlein G, Krawinkler H, Cornell C (2003) A framework for performance-based earthquake engineering. In: Pacific conference on earthquake engineering, Citeseer, pp 1–8

Ellingwood BR, Rosowsky DV, Li Y, Kim JH (2004) Fragility assessment of light-frame wood construction subjected to wind and earthquake hazards. J Struct Eng 130(12):1921–1930

FEMA (2011) The response to the 2011 Joplin, Missouri, Tornado lessons learned study. Federal Emergency Management Agency, Washington, DC

Hamilton SR (2011) Performance-based fire engineering for steel framed structures: a probabilistic methodology. Stanford University, Stanford

Koliou M, Masoomi H, van de Lindt JW (2017) Performance assessment of tilt-up big-box buildings subjected to extreme hazards: tornadoes and earthquakes. J Perform Const Facil 31:04017060

Kuligowski ED, Lombardo FT, Phan LT, Levitan ML, Jorgensen DP (2014) Final Report, National Institute of Standards and Technology (NIST) technical investigation of the May 22, 2011, Tornado in Joplin, Missouri. National Construction Safety Team Act Reports (NIST NCSTAR)-3

Lombardo FT, Roueche DB, Prevatt DO (2015) Comparison of two methods of near-surface wind speed estimation in the 22 May, 2011 Joplin, Missouri Tornado. J Wind Eng Ind Aerodyn 138:87–97

Masoomi H, van de Lindt JW (2016) Tornado fragility and risk assessment of an archetype masonry school building. Eng Struct 128:26–43

Masoomi H, Ameri MR, van de Lindt JW (2018) Wind performance enhancement strategies for wood-frame buildings. J Perform Const Facil. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001172

McDonald JR, Mehta KC (2006) A recommendation for an Enhanced Fujita scale (EF-Scale). Wind Science and Engineering Center, Texas Tech University

Memari M, Attary N, Masoomi H, Mahmoud H, van de Lindt JW, Pilkington S, Ameri MR (2018) Minimal building fragility portfolio for damage assessment of communities subjected to tornadoes. J Struct Eng. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002047

Missouri Spatial Data Information Service (2016). http://msdis.missouri.edu/webservices/imagery/index.html

NWS (National Weather Service) (2011) NWS central region service assessment Joplin, Missouri, Tornado—May 22, 2011. Silver Spring, MD

Porter KA (2003). An overview of PEER's performance-based earthquake engineering methodology. In: Proceedings of 9th international conference on applications of statistics and probability in civil engineering

Prevatt DO, Roueche DB, Van De Lindt JW, Pei S, Dao T, Coulbourne W, Graettinger AJ, Gupta R, Grau D (2012a) Building damage observations and EF classifications from the Tuscaloosa, AL, and Joplin, MO, tornadoes. In: Structures congress 2012, pp 999–1010

Prevatt DO, van de Lindt JW, Back EW, Graettinger AJ, Pei S, Coulbourne W, Gupta R, James D, Agdas D (2012b) Making the case for improved structural design: Tornado outbreaks of 2011. Leadersh Manag Eng 12(4):254–270

Roueche DB, Lombardo FT, Prevatt DO (2016) Development of empirically-based fragilities of residential damage in the 2011 Joplin, Missouri, tornado. In: Geotechnical and structural engineering congress 2016, pp 1283–1294

Roueche DB, Lombardo FT, Prevatt DO (2017) Empirical approach to evaluating the Tornado fragility of residential structures. J Struct Eng 143(9):04017123

Standohar-Alfano CD, van de Lindt JW (2014) Tornado risk analysis for residential wood-frame roof damage across the United States. J Struct Eng 142(1):04015099