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HINDCASTING VALIDATION OF A RESILIENCE COMPUTATIONAL ENVIRONMENT ARCHITECTURE: COMMUNITY LEVEL DAMAGE ASSESSMENT FOLLOWING THE 2011 JOPLIN, MISSOURI TORNADO

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Resilience 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. To comprehensively assess community resilience, all sectors, including physical infrastructure (buildings, bridges, electric power network, etc.) and the socio-economics should be considered. For this purpose, the Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, USA, developed an Interdependent Networked Community Resilience (IN-CORE) computational environment. The developed computational environment is capable of simulating effects of different natural hazards including tornadoes, earthquakes, tsunamis, etc., on physical and socio-economics sectors of a community, accounting for interdependencies between the different 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 United States, which was hit by an EF-5 tornado on May 22nd, 2011, is modeled in IN-CORE computational environment. This tornado was the costliest and deadliest single tornado in the U.S. over the last half century. Using the IN-CORE computational environment, a detailed topological dataset of the community and the actual tornado path, the damage caused by the tornado to the physical infrastructure of the city of Joplin was estimated. The results were compared with post-disaster dataset to validate this computational environment.

Keywords: Community Damage Assessment, Resilience, Tornado Fragilities, Joplin Tornado.

1 Introduction

Community resilience to natural hazards may be improved by using risk-informed decision-making tools. The Center for Risk-Based Community Resilience Planning, headquartered at Colorado State University in Fort Collins, Colorado, U.S.A., developed an Interdependent Networked Community Resilience (IN-CORE) computational environment. The developed computational environment can be used by community decision-makers to estimate the effects of different natural hazards including tornadoes on the physical and socio-economic sectors of a community, accounting for certain interdependencies between the sectors. Although, tornadoes are common natural hazards in the U.S. with small footprints, they may result in high casualty rates and billions of dollars in economic losses. Numerical simulations are valuable and the associated models need to be verified/validated. To verify damage assessment of a community subjected to tornadoes, damages caused to a community by a real tornado were estimated in this study. On May 22nd, 2011, an EF-5 tornado (rated based on the Enhanced Fujita tornado intensity scale) cut more than a 6-mile path of destruction through the city of Joplin, MO. With more than 360 km/hr wind speed, the 1.1-km-wide tornado, caused 161 fatalities, approximately 1,371 injuries and more than US$2.8 billion in losses, making it the deadliest and costliest single tornado in the country since 1947. It should be noted that Doppler radar, and thus early warning for tornadoes, did not exist in 1947 as it did in 2011. NIST (2014) investigations, estimated that 553 non–residential buildings and around 7,400 residential structures were damaged by this tornado event. The non-residential buildings that were severely damaged included, one of the two major regional hospitals, and 10 of the 20 local public schools, several parochial schools, 28 churches, 2 fire stations, and both large and small commercial businesses (NIST, 2014). In this study, using IN-CORE, a detailed topological dataset of the community as well as the estimated tornado path, the damage caused by the tornado to the buildings of the city of Joplin was estimated. In addition to the actual event, idealized tornado scenarios (rectangles with different EF regions) can be generated in IN-CORE. In this study, the building damage assessments of the city of Joplin for three idealized tornado scenarios were performed and the results were compared to the damage assessed following the event.

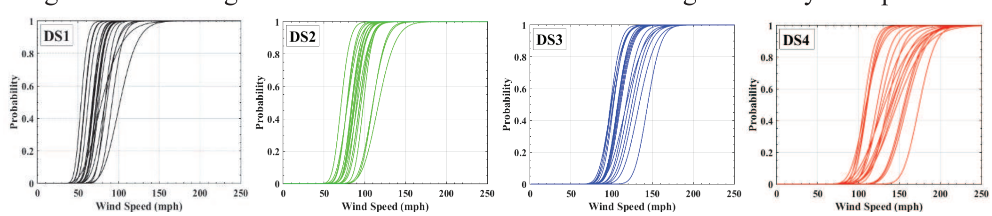
2 2011 Joplin Tornado Buildings Damage Assessment

To assess the building damages in this study Performance-Based Engineering (PBE) approaches were used, which provide performance metrics outputs that can be used to inform decision makers for risk mitigation strategies and enhance community resilience. PBE methodologies have been developed for different natural hazards including earthquakes (e.g. Deierlein et al., 2003), wind (e.g. Ciampoli et al., 2011) and tsunamis (e.g. Attary et al., 2017a). To assess the damage caused by tornadoes to individual buildings, geocoded data of the actual event EF rating was used as an estimate of the wind speed at the location for each building. Since the estimated wind speed in each EF region represent a range of wind speeds, the wind speed for each building was selected randomly (considering a uniform distribution) from the specific wind speed range for each EF region. Performing Monte Carlo simulations, the statistical damage prediction for each building in Joplin was obtained. To estimate the damage caused by the tornado to buildings, tornado fragility functions were used in this study as an alternative to structural analysis. Fragility functions provide the probability of a structure to 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. In this study, GIS data of all buildings in Joplin before the disaster were gathered and used to assign tornado fragilities to each building, performing community damage assessment. To reduce the number of required fragilities, buildings in the community were categorized into a portfolio of 19 representative archetype buildings. Table 1 shows the details of these 19 building types. In this study, fragility functions for residential buildings (T1-T5) and big-box stores (T15 and T16) were adopted from Masoomi et al. (2017) 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. (2017).

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

Build. 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

Figure 1a through 1d shows the fragility curves of these 19 building types for each damage state which spans the entire range of wind speeds that are typically associate with a tornado. Using random wind speed based on the EF region and building fragility parameters, the probability of exceeding the four damage states was calculated for each building in the city of Joplin.



(a) (b) (c) (d)

Figure 1. Fragility curves for the four damage states of (a) Slight, (b) Moderate, (c) Extensive and (d) Complete for the 19 archetype buildings

3 Interdependent Networked Community Resilience Modeling Environment (IN-CORE)

As mentioned previously, the Center for Risk-Based Community Resilience Planning, developed a computational environment known as Interdependent Networked Community Resilience Modeling Environment (IN-CORE). The purpose of developing this computational environment is to build a research tool for resilience researchers, as well 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. IN-CORE has the capability of computing the proposed resilience measures at the user-desired community level. The implementation in this paper is developed on the first version of IN-CORE, which is an open source (scheduled for full release in 2019) 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. For tornado damage assessments, the software, 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 (see Attary et al, 2017b for more details). 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 & 19.8% as EF0 (Figure 2).

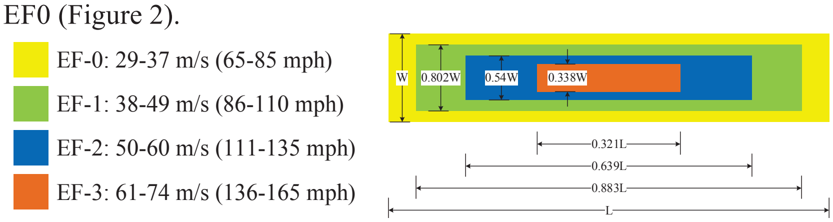


Figure 2. Sample idealized path model for an EF 3 tornado

In this study, the building damage assessment of the city of Joplin for three idealized tornado scenarios (numbers 2-4 below) were 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. 3a).

2-An EF5 tornado with mean length, width and angle based on the historical data (Fig. 3b), which represent the average values for length, width, and length based on all EF5 tornadoes documented between 1973-2013.

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

4-1000 EF5 tornadoes with width modeled as a random variable based on the historical data of (2) and start and end points (Fig. 3d).

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 were 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 are shown in Figure 4, 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. In other words, light blue dots are unlikely to reach DS4, whereas dark blue have a significant probability of reaching DS4. Table 2, 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 2, 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 a randomization allowing for better risk and resilience planning.

Table 2. 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

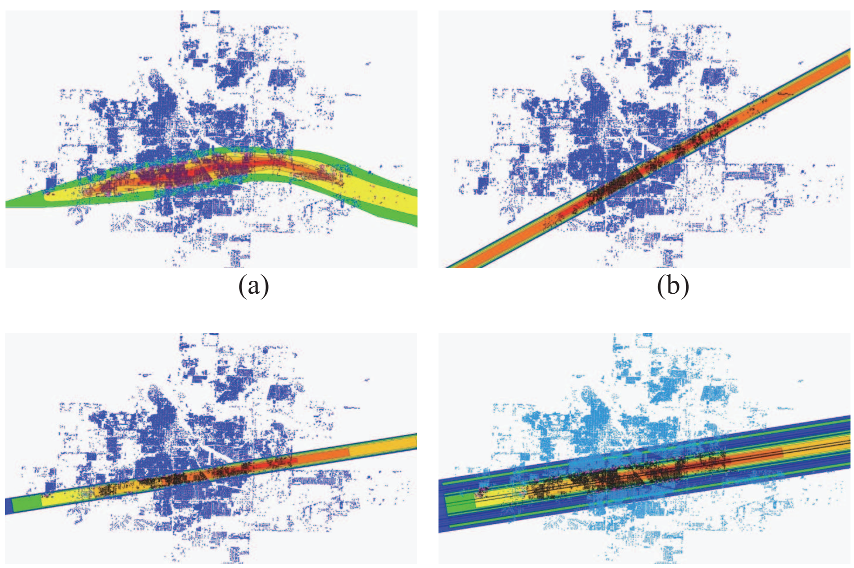

(a) (b)
(c) (d)

Figure 4. Probability of reaching damage state complete for the four tornado scenarios

In order to validate the analysis results some quantitative measures were compared with post-disaster data. For example, it was reported by NIST (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 (see Attary et al, 2017b, for more details). Simulations of the other physical infrastructure sectors of the community such as electric power network (e.g., Attary et al., 2017c) as well as socio-economic sectors/attributes considering their interdependencies will be discussed in forthcoming publications by the authors.

4 Closure

Risk-informed decision-making tools, capable of performing community damage assessments for different scenarios and hazards may be used by community leaders and decision makers to enhance the post-disaster resilience of communities. The Interdependent Networked Community Resilience (IN-CORE) computational environment is capable of performing risk assessment of communities subjected to different hazards such as tornadoes, earthquakes, tsunamis, etc. including damage, loss, and functionality and recovery assessments. 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. 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 were calculated. Good accuracy in damage estimation was observe d for IN-CORE and recovery modeling validation is underway.

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