Tornado Damage Mitigation: Benefit–Cost Analysis of Enhanced Building Codes in Oklahoma

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ABSTRACT

In April 2014, the city of Moore, Oklahoma, adopted enhanced building codes designed for wind-resistant construction. This action came after Moore suffered three violent tornadoes in 14 yr. Insured loss data and a rigorous approach to estimating how much future damage can be mitigated is used to conduct a benefit–cost analysis of the Moore standards applied to the entire state of Oklahoma. The results show that the new codes easily pass the benefit–cost test for the state of Oklahoma by a factor of 3 to 1. Additionally, a sensitivity analysis is conducted on each of the five input variables to identify the threshold where each variable causes the benefit–cost test to fail. Variables include the estimate of future losses, percent of damage that can be reduced, added cost, residential share of overall losses, and the discount rate.

1. Introduction

In May 2013, the city of Moore, Oklahoma (OK), was struck by a third violent tornado in 14 yr. Insured losses from this storm alone were $1.8 billion (U. S. dollars) with overall damage of $3 billion. (Swiss RE 2014) Tragically, 24 people died including seven children at the Plaza Towers Elementary School. An additional 212 people were injured (Storm Prediction Center 2014). In response to this tragic event, the city enacted a new set of building codes that went into effect in April 2014, which raised the wind load standard to 135 mph from 90 mph (City of Moore 2014; Ramseyer et al. 2014). It was not until the 3 May 1999 tornado, also in Moore, OK, that losses from a single tornado exceeded $1 billion. Population density increases in areas prone to tornadoes makes it more likely that violent tornadoes striking densely populated areas will sustain losses in the billions (Swiss RE 2014). Since 1989, Oklahoma has experienced 1575 tornadoes resulting in almost $32 billion in insured losses[1] (Storm Prediction Center 2014; Hartwig 2014). Two-thirds of that amount is residential[2] [tornado insured loss data provided by the Oklahoma Department of Insurance (K. Dexter 2014, personal communication)]. Cleveland County alone (home to Moore, OK) has had over $10 billion in residential losses since 1989.[3] The estimated cost to meet the new building code is $1 per square foot[4] (Cannon 2014; Hampton 2014; C. Ramseyer 2014, personal communication). If all homes in Cleveland County had been constructed to the new standard, the additional cost

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[1] Oklahoma Department of Insurance and the Insurance Services Office are discussed in full in section 4.

[2] Oklahoma Department of Insurance.

[3] Based on the proportion of damage to Cleveland County contained in the Storm Prediction Center tornado archive.

[4] Moore Association of Home Builders and Chris Ramseyer, professor of civil engineering at the University of Oklahoma, conducted the study to arrive at recommended actions and costs.

would have been less than 2% of the residential, insured losses in Cleveland County.[5] The question addressed here is does the added cost to meet the new standard reduce losses enough to justify the new codes? Further, would the entire state of Oklahoma benefit from the adoption of the enhanced standards?

The remainder of the paper is organized as follows: Section 2 will review literature relevant to tornado mitigation. Section 3 will discuss the changes in the Moore building code. Section 4 will outline the methodology. Section 5 will compare the estimated costs of the new codes statewide with the estimated damage reduction. In section 6, a sensitivity analysis of the results is conducted, and section 7 will conclude the paper.

2. Literature review

Hurricane Andrew struck south Florida in August of 1992. The damage from the storm revealed inadequate construction standards (Fronstin and Holtman 1994) and motivated the state of Florida to adopt one of the most rigorous building codes in the nation (Tsikoudakis 2012). The hurricanes of 2004 and 2005 provided a natural experiment to test the effectiveness of the new codes and showed that homes built under the new codes had better structural performance than older homes [Insurance Institute for Business and Home Safety (IBHS) 2004; Gurley and Masters 2011]. More broadly, it was recognized that enhanced construction standards were a necessary tool in dealing with natural disasters (Iwan et al. 1999; Kunreuther and Michel-Kerjan 2009). Torkian et al. (2014) recently conducted a cost–benefit analysis of various mitigation measures for hurricanes in the state of Florida.

While most of the discussion about mitigation for wind storms focused on hurricanes, tornadoes prompted more interest in reducing casualties (Simmons and Sutter 2011, 2012). But the tornado outbreaks of 2011 caused over $26 billion in insured losses (National Climatic Data Center 2014) and made clear that losses from tornadoes had reached a level that required similar attention given to hurricanes (Simmons et al. 2013). Using tax assessor data and a small sample of insurance claim data from the 3 May 1999 tornado that affected Moore, a benefit–cost analysis was conducted by Sutter et al. (2009). The focus of that study was not building codes but rather voluntary mitigation, and it found that enhanced construction did pass a benefit–cost test for Oklahoma for presumed levels of damage reduction. The current research adds to Sutter et al. (2009) by developing an approach to estimating how much damage can be mitigated and conducting a benefit–cost analysis of the enhanced construction mandated by the new building codes adopted by Moore, OK, but applied to the entire state.

Tornadoes are different from hurricanes and pose a challenge for researchers since wind fields are significantly more complex and spatially variable than those for hurricanes (e.g., Haan et al. 2010). But recent research on the damage paths of tornadoes provides a way to calculate the potential reduction in losses that may be economically viable. A comprehensive report by the Nuclear Regulatory Commission on tornadoes included average wind fields within the damage path for each category of the EF scale (Ramsdell and Rishel 2007). This study was followed by another that examined the 27 April 2011 outbreak and how the damage paths in those tornadoes compared to the averages found in the NRC report (Fricker et al. 2014). Lombardo et al. (2015) provided a similar analysis for the 22 May 2011 Joplin tornado, along with detailed damage statistics for residential construction. This work makes it possible to conduct benefit–cost analysis on wind-resistant construction in areas prone to high tornado risk.

3. Wind-resistant construction

The new Moore, OK, building code (City of Moore 2014) increased the design wind speed to 135 mph (3-s gust at 10 m in open terrain) from 90 mph [American Society of Civil Engineers (ASCE) 2006, 7–05], which required significant changes to the structural details used in the construction of wood frame homes. In general, the vertical load path through the houses and garage are strengthened via enhanced roof sheathing fasteners and fastener schedules, narrower spacing of the roof framing, enhanced connections in the roof framing including the use of hurricane straps, strengthening of gable end walls and wall sheathing, some structural changes to garages, and wind-rated garage doors (Ramseyer et al. 2014). These changes are expected to substantially strengthen residential structures, ensuring that they should stay intact for enhanced Fujita scale category 2 (EF2) wind speeds (while noting that tornadic wind loads are still a topic of current research). However, the roof cover, siding materials, fascia, and gutters may still be expected to fail prior to the new design wind speed because these often fail at EF1 speeds [Wind Science and Engineering Center (WSEC) 2006]. Since shingles in flight have sufficient momentum to

[5] If all homes in Cleveland County (108 000 units) have been constructed to the new standards, the increase in cost would have been $185 million or about 2% of the insured losses in Cleveland County.

break window glass (Masters et al. 2010), one can still expect numerous broken windows in an EF2 tornado. Thus, the Moore, OK, building code will not reduce losses to zero for EF2 wind speeds. However, presuming a well-enforced code, these residential structures should remain intact with all sheathing in place. It should also be noted that the Moore building code is consistent with what is being done based on years of research for hurricane mitigation (e.g., Torkian et al. 2014). For example, the new Moore code is quite similar to the IBHS's "Gold" Fortified Program (Malik et al. 2012).

4. Methodology

a. Estimating future tornado losses in OK

No one knows how many damaging tornadoes will occur in the future or if the path of these storms will come in contact with populated areas. The best that can be done is to collect as much information about the recent past to predict what may happen in future years. In conducting the analysis following the 2011 Joplin tornado, the National Institute of Standards and Technology (NIST) report (Kuligowski et al. 2014) used the Storm Prediction Center (SPC) tornado archive to break out damage by EF-scale categories. The SPC archive provides an estimate of damages per storm (Storm Prediction Center 2014). While the SPC archive provides a reliable comparison of damage across the EF scale or across states, insured losses are a better indicator of the actual cost of tornadoes. Insured losses are normally only available as annual aggregate losses for the nation as a whole. This study uses insured loss data to get the total annual estimate of damage and SPC data to allocate Oklahoma's proportion of that loss, when state data are not available.

The first step is to estimate a current year average loss for the state that can then be used to predict future losses. The Oklahoma Department of Insurance (ODI) provided the authors with insured losses from tornadoes provided to them by the state's insurers for 7 yr, 2007 through 2013. Total reported losses for those 7 yr are \$7.3 billion. The ODI states that reported losses represent 75% of the insurance coverage in the state. Adjusting to get an estimate of the overall total losses brings that amount to \$9.75 billion. A further adjustment for changes in the price level over that 7 yr, urban consumer price index (CPI-U), brings that total to \$10.29 billion. The ODI does not have records prior to 2007. Several large outbreaks occurred in the state prior to 2007 including two violent and costly tornadoes that directly affected Moore, the May 2003 EF4 tornado and the May 1999 EF5 tornado. To estimate losses prior to 2007, national, insured loss data are used from the Insurance Services Office (ISO; Hartwig 2014),[6] which reports that the CPI-adjusted, national losses from tornadoes during the years 1989–2006 are \$161.6 billion. To estimate the portion of those insured losses that occurred in Oklahoma the tornado archive maintained by the SPC is used (Storm Prediction Center 2014). This archive goes back to 1950 and maintains data on the path, intensity, casualties, and damages from tornadoes. The SPC damage data are not as reliable as insured losses paid to victims of these events, but the distribution of SPC damages is a good gauge of what percent of overall national losses occurred in Oklahoma, which according to SPC is 13%,[7] giving insured losses in Oklahoma in the years 1989–2006 of \$21 billion. One final adjustment is necessary before estimating future losses and that is to normalize the losses in prior years to changes that have occurred in population and income. This process is well documented in the literature and provides an estimate of how much loss would occur today if a previous storm were to return based on changes in population and wealth (Bouwer 2011; Brooks and Doswell 2001). Several methods, gross domestic product (GDP), population/income, and housing counts/income, can be used to normalize prior losses to reflect current values. For this study, we normalized losses using GDP. Once that adjustment is made and the ISO and ODI loss data are combined, there is \$31.7 billion in tornado-insured losses for Oklahoma for the 25 yr 1989–2013 or an annual average of \$1.27 billion. The annual average from the ODI data alone is \$1.52 billion and even subtracting the normalization adjustment, the ODI average is \$1.39 billion. The national data used to estimate the losses in Oklahoma for the years 1989–2006 overlaps with the ODI state data and so allows for a check on how they compare with the goal to provide reasonable estimates of future losses. There are 6 yr, 2007–12, where the Oklahoma estimates from national data overlap with the state level recent data. Average losses from the national data applied to Oklahoma for those 6 yr are \$1.05 billion yr^{-1}. Average losses from the ODI data for the same 6 yr are \$1.53 billion. So, for Oklahoma, \$1.27 billion, normalized, in current dollars appears to be a

[6] The Insurance Information Institute reports that tornadoes account for 36% of all category losses. Between 1989 and 2006 overall category losses were \$449 billion. Munich RE reports total category losses between 1993 and 2012 of \$402 billion.

[7] The SPC tornado archive began providing dollar damage amounts in 1996. Using that damage data, and adjusting for changes in the price level across time, the state of Oklahoma accounts for 13% of national damage in the SPC archive between the years 1996 and 2013.

TABLE 1. Tornado damage statistics.

EF scale	Proportion of total track length, A_j	Proportion of total damage, S_j	Proportion of damage for EF-scale level, S_i	Normalized damage rate, R_i^*
EF5	0.009 24	0.23	0.19	1200
EF4	0.0546	0.22	0.18	88
EF3	0.172	0.24	0.17	11
EF2	0.255	0.16	0.12	2.0
EF1	0.364	0.13	0.29	1.3
EF0	0.146	0.01	0.05	0.07

reasonable estimate of annualized loss. This is then used to project future losses over the next 50 yr using an estimate of future price changes of 2%[8] annually that gives the total 50-yr, estimated, insured losses from tornadoes in Oklahoma as $107.4 billion.

b. *Estimating loss reduction with the new codes*

The standard adopted by Moore, OK, should provide adequate protection to decrease the losses from tornadoes rated EF0 through EF2. Over 90% (Storm Prediction Center 2014) of all tornadoes are in that range, although the majority of damage comes from tornadoes rated EF3 and above, as shown in Table 1. Tornadoes do not create uniform wind fields or damage across their path or their life (e.g., Ramsdell and Rishel 2007; Roueche and Prevatt 2013). The rating assigned to a given tornado is based upon the highest level of damage, which should be consistent with worst wind speeds across the entire path. Most of the affected areas do not experience the peak winds of the storm (Ramsdell and Rishel 2007). So, while it may not be practically feasible to construct homes to withstand the peak winds of an EF3 or above tornado, many homes in the path would benefit from enhanced construction as peak winds represent a small portion of the entire path. This section provides an estimate of the portion of tornado damage that could be mitigated with the updated codes adopted in Moore.

Data for this analysis comes from the Storm Prediction Center tornado archive (Storm Prediction Center 2014) but adjusted to mirror the national ISO insured loss data. We then calculate total damage and total pathlength by the EF scale, using these to calculate the proportion of the damage and the proportion of track by the EF scale. These are then used as input to our estimate of the proportion of damage that can be mitigated with the Moore building code, using recently published data from detailed damage surveys.

Table 1 provides the tornado damage statistics used in the current analysis. For example, using the SPC database, the total length of damage from EF5 tornadoes was 0.924% of the total damage track length from all tornadoes in the period. However, these EF5 tornadoes caused 23% of all of the damage (insured losses). In contrast, the EF1 tornadoes represented 36.4% of the total length of all tornado damage tracks, but caused just 13% of the damage. To perform the benefit–cost analysis, we need to determine that proportion of the damage is at various levels, as represented by the EF scale, for each category tornado, since, for example, not all damage in an EF5 rated tornado is at the EF5 level. Table 2 provides the proportion of the total track A_{ij} at each EF-scale damage level "i," for each category of tornado EFj, where $i = 0, 1, 2, \ldots, 5$ and $j = 0, 1, 2, \ldots, 5$, with $\sum_{i=0}^{j} A_{ij} = 1$, as obtained by Ramsdell and Rishel (2007). These values are in reasonable agreement with those found in recent individual tornadoes (e.g., Fricker et al. 2014; Lombardo et al. 2015).

Assuming that the rate of damage per unit area R_i at each level of the EF scale does not depend on the rating of the tornado, the average damage rate (i.e., losses per unit area) for each tornado category j in the EF scale R_j is

$$R_j = \frac{S_j S_\varepsilon}{A_j A_\varepsilon} = \sum_{i=0}^{j} (A_{ij} R_i), \tag{1}$$

where

- A_j = proportion of track in EFj tornadoes relative to the cumulative track of all tornadoes;
- A_ε = cumulative track length for all tornadoes (=53 800 mi);
- R_i = losses per mile of damage track for EFi damage in tornadoes of any category;
- S_j = cumulative proportion of total losses of EFj tornadoes relative to all tornadoes; and
- S_ε = cumulative losses for all tornadoes (=$163B).

Here, we use the track length data as a proxy for the total damaged area since the tornado width data in the SPC database is not variable along the length; that is, only maximum widths are recorded (Ramsdell and Rishel 2007). While R_j represents the damage (loss)

[8] CPI has averaged 2.13% over the last 10 yr.

TABLE 2. Proportion of tornado damage area by EF scale, from Ramsdell and Rishel (2007).

Maximum tornado intensity	Proportion of track area, A_{ij}					
	EF0 ($i = 0$)	EF1 ($i = 1$)	EF2 ($i = 2$)	EF3 ($i = 3$)	EF4 ($i = 4$)	EF5 ($i = 5$)
EF5 ($j = 5$)	0.538	0.223	0.119	0.07	0.033	0.017
EF4 ($j = 4$)	0.543	0.238	0.131	0.056	0.032	
EF3 ($j = 3$)	0.529	0.271	0.133	0.067		
EF2 ($j = 2$)	0.616	0.268	0.116			
EF1 ($j = 1$)	0.772	0.228				
EF0 ($j = 0$)	1					

rate for each category of tornado, the ratio $S_\varepsilon/A_\varepsilon$ (=\$163 billion/53 800 mi = \$3.0 million/mi) represents the average damage rate for all tornadoes regardless of category. Using the data in Tables 1 and 2 with the method of back substitution, the damage (loss) rates per mile of damage track R_i for EFi damage (regardless of the tornado rating, EFj) were obtained. Figure 1 and Table 1 present the normalized damage rate $R_i^* = R_i(A_\varepsilon/S_\varepsilon)$ and $R_j^* = R_j(A_\varepsilon/S_\varepsilon)$.

Figure 1 shows the normalized damage rates for tornadoes of a particular category R_j^* and for damage at a particular level regardless of the tornado category R_i^*. Included in the figure is a damage rate curve that is proportional to the wind speed raised to the third power V^3 and scaled to pass through the normalized EF2 level. From this graph one can see that for tornadoes of EF1, EF2, and EF3 intensities, the overall damage rate is proportional to V^3, while for higher category tornadoes the damage increases in a higher proportion. The upward curvature indicates that the rate of damage for tornadoes is increasing; that is, they become increasingly devastating above EF3.

Figure 1 and Table 1 also provide the normalized damage rates R_i^* for the EFi portion of the tracks. The results indicate that the EF1 and EF2 rates are the same order of magnitude but are about one order of magnitude larger than that for EF0 and about one order of magnitude smaller than for EF3. The damage rate for the EF4 and EF5 damage rates are about two and three orders of magnitude higher than for EF2, respectively. It is noted that the one order of magnitude increase in the damage rate between EF2 and EF3 appears to be consistent with the increase in the loss rates for hurricanes over a similar range of wind speeds (see, e.g., Fig. 8 in Vickery et al. 2006). Using these results, the total loss S_i at each level i of the EF scale can be calculated as

$$S_i = R_i \sum_{j=0}^{5} (A_{ij} A_j). \qquad (2)$$

Table 1 shows that about 46% (=$S_0 + S_1 + S_2$) of all damage is EF0 to EF2 (regardless of the strength of the tornado), while the remainder is split nearly equally between EF3, EF4, and EF5. Thus, even though EF5 tornadoes represent slightly less than 1% of the total track lengths of all tornadoes, and the EF5 portion of track is just less than 2% of the total of EF5 tornado tracks, on average, the EF5 portion of these tracks caused 19% of the damage. This is because the damage rate per unit area is so high, that is, three orders of magnitude higher for EF5 than for EF2.

The damage rates for EF1 and EF2 tornadoes are similar, and examining the R_i^* curve in Fig. 1 suggests that the damage for EF1 tornadoes is disproportionately large. This could be because the design wind speeds in the central regions of the United States are in the EF1 range. In any case, failures clearly begin to accumulate at these wind speeds for residential structures.

The EF scale considers many damage indicators, a key one being residential structures of 1000–5000 ft^2, which

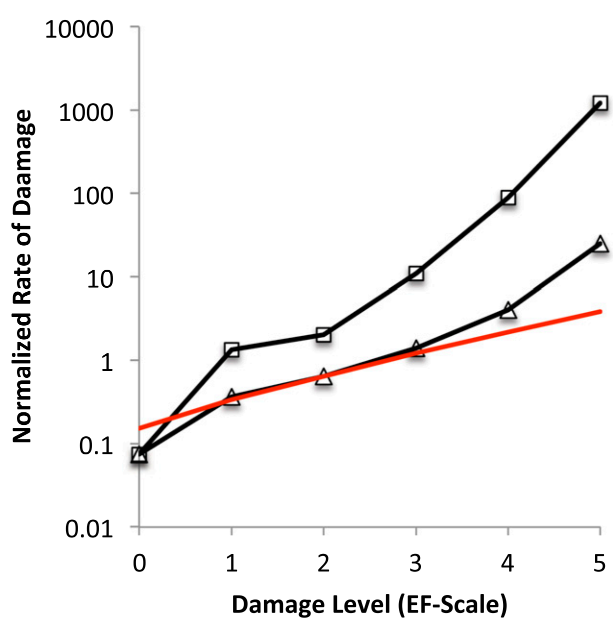

FIG. 1. Normalized damage rates as function of EF scale, where □ is R_i^*, Δ is R_j^*, and the red line is proportional to wind speed to the third power V^3.

TABLE 3. Wind speeds in the EF scale, from WSEC (2006).

EF scale	Wind speeds (mph)
0	65–85
1	86–110
2	111–135
3	136–165
4	166–200
5	>200

is known as the damage indicator (DI)2 [and which is also called FR-12 in WSEC (2006)]. For DI2, there are 10 degrees of damage (DOD), which range from the onset of damage (DOD1) at relatively low wind speeds to complete destruction of an engineered or well-constructed house (DOD10) at high wind speeds. There is a range of wind speeds associated with each DOD (WSEC 2006; Mehta 2013). Table 3 provides the EF-scale wind speeds, while Table 4 provides the DOD for houses (DI2, as determined by WSEC (2006). In particular, EF1 wind speeds are associated with DOD3 (broken glass in windows and doors) and DOD4 (uplift of roof deck and loss of significant roof-covering material, garage doors collapse inward, and failure of porch or carport) for residential structures. DOD6 for this DI (large sections of roof structure removed; most walls remain standing) is in the EF2 range (of 111–135 mph), although inadequate roof fasteners in the vertical load path and internal pressures caused by broken windows or garage doors can reduce these to the EF1 range of wind speeds (e.g., Morrison et al. 2014). Differentiation of the damage levels can be difficult to assess in this range, which may also account for the relatively high levels of EF1 damage when compared to EF2, as shown in Table 1. In the context of the EF scale, the new Moore building code has provisions that deal specifically with portions of DOD4, with DOD5 (entire house shifts off foundation), and with DOD6.

It is not clear from existing research what mitigation will do to the damage rates shown in Fig. 1, although it must lower the damage rates associated with the particular DODs that are targeted by the code changes, just as such code changes have improved building performance in hurricanes (Gurley and Masters 2011). Of the 46% damage that is EF2 or less, about 5% is EF0. Since the Moore building code does not address the type of damage expected at EF0 wind speeds, it is expected that the reductions at this level cannot be eliminated. So, assuming that the EF0 damage remains fixed, this leaves 41% of the overall damage at the EF1 and EF2 levels. The new building code should reduce much of this damage since much of it is in the DOD4/EF1 and DOD6/EF2 range.

Because there is only limited information available relating insurance claims to EF scale, the authors have taken the approach of examining the relative proportions of damage for the DOD levels, particularly for DOD6 and DOD4, and then estimating approximate damage proportions associated with these. Lombardo et al. (2015) identified DOD levels for about 1200 homes in the 22 May 2011 Joplin, Missouri, EF5 tornado. They found, in particular, 269 houses with DOD6, which is damage associated with roof failures. These authors also found 587 houses with DOD1 through DOD4. Thus, significant structural roof failures accounted for about 32% of the houses in the EF2, and below, range. Marshall et al. (2012) examined 7191 houses, also in the Joplin tornado. These authors found more than 5000 houses with EF0 damage, 507 with EF1, and 642 with EF2 damage. Thus, in this analysis, roughly 10% of the

TABLE 4. DOD associated with residential, wood frame houses (DI2), from WSEC (2006).

Degree of damage	Damage description	Expected value (mph)	Lower bound (mph)	Upper bound (mph)
1	Threshold of visible damage	65	53	80
2	Loss of roof-covering material (less than 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% or more); 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 collapsed	170	142	198
10	Destruction of engineered and/or well-constructed residence; slab swept clean	200	165	220

houses had EF2 damage. This range of 10%–30% is consistent with other data, such as Morrison et al. (2014), who found 29% houses with DOD6 for the Vaughan, Ontario, Canada, 2009 EF2 tornadoes.

Since detailed claims data were not available, the authors discussed possible losses at various levels of damage with a professional insurance loss–damage estimator (G. Smith 2014, personal communication) and proportioned the results. In particular, the estimator observed that typical DOD6 roof damage leads to an average cost of rebuilding similar to new construction plus approximately 80% contents loss. Since contents are typically ⅔ of the value of the house, we have taken the approach of estimating the loss to be roughly 1.5 times the cost of new construction (G. Smith 2014, personal communication). Using an approximate value of \$100 ft^{-2}, with a 2000 ft^2 house, leads to approximately \$300 000 of damage per house at DOD6. In contrast, for DOD4, and assuming the sheathing has not failed, one would expect repair costs of \$10 000–\$20 000 for shingles/tiles and broken windows. Thus, the difference in loss is more than a factor of 10 different between DOD4 and DOD6. If one is able to eliminate the DOD6 roof damage, as well as DOD4 roof sheathing damage, as is the intent of the Moore building code, the overall EF2, and less, damage is reduced by about 60% if 10% of the damaged houses in a tornado have structural roof failure (DOD6) and 85% reduction if 30% of the damaged houses have roof failure (DOD6). The better provisions for garage doors in Moore will support the reduction in roof failures (Morrison et al. 2014) but also reduce this portion of DOD4 damage. However, there is currently insufficient information to estimate the reductions for reduced garage door (and sheathing) failures, except as pertains to the roof failures.

One may also expect that the Moore building code would reduce some of the EF3 damage by keeping more of the roofs attached to the walls in severe tornadoes since roof failures lead to subsequent wall collapses, that is, DOD7 (exterior walls collapsed). In addition, much of the damage inflicted by windborne debris is due to roof structural materials penetrating or impacting adjacent structures. Thus, holding the roofs to the walls at the EF2 level should reduce the number of debris impacts that cause other EF2 and EF3 damage. Detailed damage surveys could aid this analysis, but one can assume that some additional EF3 damage will be mitigated. However, we have insufficient information to assess this currently, so we have neglected potential loss reductions at EF3 and greater levels from the analysis. The authors' best estimate then is that between 60% and 85% of the EF1/EF2 damage will be mitigated; an average value of 73% is used for the analysis below. Since 41% of the overall residential damage is in the EF1/EF2 range, one could expect that about 30% of total residential tornado damage costs can be mitigated by adoption of the Moore building code.

5. Benefits versus cost

This analysis is based on the assumption that all homes in Oklahoma are built with the standards adopted by the city of Moore. Based upon engineering recommendations and input from the Moore Association of Home Builders (Cannon 2014; Hampton 2014; Ramseyer et al. 2014; C. Ramseyer 2014, personal communication), the added features will increase the cost of a home by \$1 ft^{-2}. The 2012 American Community Survey for Oklahoma reports that there are 1 671 490 residential homes in the state (Census 2012). The Census reports the median home size for the Midwest to be 2001 ft^2 (Census 2014), while Zillow (2014) shows the median size of all homes for sale in Oklahoma to be 1632. So, if the average sized home is 2000[9] ft^2 that would add \$3.3 billion to the cost of housing in the state. For the new codes to pass the benefit–cost test, losses would need to be reduced by at least that amount over the lifetime of the structure. The structure life used for the benefit–cost analysis is 50 yr.

The benefits come from the reduction in losses caused by tornadic winds. In section 4, an estimate of \$107 billion in future tornado losses for the state of Oklahoma was provided. The Oklahoma Department of Insurance reports that 65% of insured losses are to residential structures (Oklahoma Department of Insurance 2014, personal communication). So focusing on residential alone, \$69.8 billion in losses can be expected over 50 yr. One more adjustment is necessary and that is to discount future losses to provide an appropriate comparison to the current cost of better construction. Using a discount rate of 2.5% (based on the interest rate of the 10-yr U.S. Treasury Note), the present value of future residential losses is \$35.8 billion.[10] In section 4, an estimate was calculated that 30% of overall residential damage could be mitigated with enhanced construction. Using that number against the present value of future residential tornado losses, \$10.7 billion of losses in current dollars can be avoided with the improved codes. The estimates

[9] A Simmons and Sutter study found that the average sized home in Oklahoma County (Oklahoma City) was a little over 1800 ft^2. Also Zillow reports an average home size for the Oklahoma City metro area of 1880 ft^2.

[10] This is found by finding the present value of an annuity with unequal payments. We inflate the current dollar average by 2% each year.

for loss reduction and future losses to residential structures in Oklahoma show that the new Moore codes easily pass the benefit–cost test and should be considered for statewide adoption. It is also worth noting how the result corresponds to the estimate provided by the Multihazard Mitigation Council of FEMA mitigation efforts (MMC 2005). They found that mitigation from the Federal Emergency Management Agency (FEMA) mitigation programs provides \$4 of reduced damage for every \$1 spent on mitigation. These results do not quite reach a 4 to 1 payback but rather a 3.2 to 1 payback on the investment of mitigation provided by the Moore building code.

6. Sensitivity analysis

Five variables are necessary components to the analysis and could differ from the estimates. This section tests the boundaries of each variable that causes the conclusion to change from favorable for the adoption of enhanced construction to unfavorable. The variables are 1) percent of losses that can be reduced, 2) cost of the enhanced construction, 3) future losses, 4) residential share of tornado losses, and 5) the discount rate. The results of the sensitivity analysis are shown in Table 5.

The estimate of losses that can be mitigated is 30%. Holding the other variables constant but changing that input, the percent of losses that must be reduced and still break even with the cost of the mitigation is 10%. Another way to think about this input is to approach it from how much of the EF1 and EF2 damage can be mitigated. The baseline assumption is that 73% of the EF1 and EF2 damage is mitigated. But for a 10% reduction in overall damage, only 24% of the EF1 and EF2 damage needs to be mitigated.

For the cost of enhanced construction, the baseline number is \$1 ft^{-2}, which is the estimate from the city of Moore homebuilders association and the consulting engineers. To force the analysis to fail, based on that input alone, the cost would need to rise above \$3.20 ft^{-2}. The estimate for future tornado losses in Oklahoma is based upon insured losses over a 25-yr period adjusted for inflation plus changes in population and income. That number is then used to get an estimate for the 50-yr tornado losses that can be expected in the state with a modest rise in prices of 2% annually. The 50-yr losses are estimated to be \$107 billion. For the analysis to fail that estimate must drop to \$34 billion. Currently, the residential share of insured losses is 65%. If future storms take paths that cause more damage to commercial structures, the enhanced codes designed for residential structures would not be as cost effective. For this variable to change the analysis, the percent of damage attributed to residential would have to fall to 20%.

TABLE 5. Sensitivity analysis.

Variable	Current value	Threshold value
Percent reduced damage	30%	10%
Additional cost	\$1 ft^{-2}	\$3.20 ft^{-2}
Estimated future losses	\$107.4 billion	\$34 billion
Residential share of loss	65%	20%
Discount rate	2.5%	9%

The final variable is the discount rate. Discount rates are used widely in finance to determine how much people value receiving money now compared to waiting some period of time. This can be measured by how much a bank has to pay an investor to lose access to their funds for a period of time. The application here is an investment made today compared to benefits from that investment that will accrue in the future. A common benchmark for this discount rate is the rate paid on 10-yr U.S. Treasury notes, a good measure of a long-term risk-free rate. This is the approach taken, and at the time of writing this article the rate was 2.5%. But those preferences can change across time. The discount rate causes the conclusion to change when it reaches 9%.

Of the five variables we identify for the sensitivity analysis, the reduction in damage attributable to the enhanced codes and the cost of implementing the new codes form the main contribution of this paper. We now consider a simultaneous change in those two variables that would cause the benefit–cost test to fail. If the cost of construction were to be double the estimate of \$1 ft^{-2}, the benefit–cost test would not fail until the reduction in future damages fell to 18% instead of the 30% we estimate, which is a decrease of 40%. Alternatively, if the actual reduction in damage was 15% instead of 30%, the benefit–cost test would not fail until the cost of construction increased to \$1.62 ft^{-2}.

7. Conclusions

This study was motivated by the action of Moore, OK, in adopting enhanced building codes for residential construction. Oklahoma has suffered significant damage from tornadoes and as population increases in the state, more property and lives are at risk from this deadly hazard. Using data on insured losses for the state as well as an analysis of the amount of damage that can be mitigated, the results indicate that the action of Moore, OK, to enhance their standards is a wise one that will benefit its citizens financially and may even contribute to lower casualties from future tornadoes. Further, there is evidence that the entire state may benefit from following the lead of the city of Moore and should be seriously considered.

The results also provide possible extensions that should be pursued. First, the authors have focused on the reduction of damage in a static model, limited to the reduced damages directly associated with the new codes. But if one house survives the storm, there is less debris that could damage adjacent structures. This nonlinear reduction in damage could be substantial but is beyond the scope of this project. Second, Oklahoma was chosen because of the actions by the city of Moore, but other states suffer significant tornado damage as well. For instance, according to the SPC tornado archive, Alabama has a higher proportion of national damage (15%) than Oklahoma at 13%. Missouri follows close behind Oklahoma at 11%. Third, the study did not consider retrofitting of existing homes. Our model shows a theoretical reduction based on the assumption that all homes in Oklahoma were built to the enhanced codes. Future actual storms will strike homes built to the enhanced codes as well as older, nonenhanced homes. But the proportion of reduced losses to increased cost applies for those homes built to the higher standards. Finally, the role insurers could play in encouraging communities and individuals to build wind-resistant structures was not addressed. For communities that follow Moore's lead, insurers would know which homes were built to the more rigorous standards and could offer incentives. But, without community adoption, if insurers could be guaranteed that a structure meets these standards, it may justify insurance discounts or changes in deductibles that serve as an incentive for individuals to adopt the enhanced standards.

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