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An economic analysis of wind resistant construction

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ABSTRACT

Reinforced construction and strengthened building codes have been demonstrated to reduce expected damage from hurricanes in a cost effective manner. We examine whether reinforced construction (e.g. anchor bolts, hurricane clips, directional nailing) can provide efficient mitigation of property damage from tornadoes, using a case study of homes damaged in the May 3 1999 Oklahoma City Tornado. We find that if a package of wind resistant construction measures that cost no more than $500 could reduce insured losses by 30%, wind resistant construction could have a positive net present value in the most tornado prone states. A 30% reduction in wind damage is in line with estimates of damage reduction for construction in hurricane winds. The expected property damage reduction falls off rapidly in less tornado prone states.

1. Introduction

Severe weather imposes a heavy toll on both persons and property in US. Between 1997 and 2006, extreme weather produced an average of 649 fatalities and $33 billion in property damage annually in the US[1] Wind hazards contribute substantially to this total, with tornadoes, hurricanes and wind produce 35% of these fatalities, while tornadoes produce about $1 billion in property damage annually. While much has been done to protect people from weather hazards, many observers argue that US has not done enough to mitigate hazards and build sustainable communities. Mileti (1999, pp. 135–136) concludes, "[in fact, individuals, organizations, business, and governments tend not to adopt or implement on any large scale the mix of sustainable mitigation precautions that would enable them to avoid long-term losses from hazards]". To help correct this perceived deficiency, the Federal Emergency Management Agency (FEMA) in 1995 established a Mitigation Directorate to implement a National Mitigation Strategy.

All measures which can reduce the costs of hazards, however, are not efficient. Efficiency involves minimizing the sum of damage costs plus costs incurred to reduce damage from hazards. Despite the concern expressed by Mileti and others that the US does not invest enough in hazard mitigation, full scale risk analysis, or economic benefit cost analysis, has rarely been applied to confirm specific instances where efficient mitigation opportunities have been missed: "Many land use planning and development management applications use information generated from hazard identification or vulnerability assessment rather than full-scale risk analysis" (Deyle et al., 1998, p. 122).

We perform a benefit-cost analysis of one proposed mitigation measure, strengthened construction for homes in tornado prone regions. Tornadoes are known as nature's most violent storms and can cause massive destruction. The May 3, 1999 F5 tornado which struck the Oklahoma City metropolitan area caused $1 billion in damage while nationally tornadoes caused over $1.3 billion in property damage in 2003. Strengthened construction may do little to reduce the devastation from the strongest tornadoes, those rated F5 on the Fujita damage scale, but very few tornadoes are this powerful. Only 63 of nearly 50,000 tornadoes in the US between 1950 and 2006 were rated F5, while about 75% of tornadoes were rated F0 or F1 with estimated winds less than 112 mph. The International Code Council's Committee on Hurricane resistant Construction includes building standards for wind guest in excess of 110 mph, so the winds for these tornadoes are not out of line with recommended high wind building practices.[2]

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[1] See "67 Year List of Severe Weather Fatalities" available at www.weather.gov/os/hazstats/images/67-years.pdf.

[2] The Fujita Scale of tornado damage takes on integer values from 0 to 5. Estimated wind speeds are F0, 40–72 mph; F1, 73–112 mph; F2, 113–157 mph; F3, 158–206 mph; F4, 207–260 mph; and F5, 261–318 mph (Tornado Project n.d.). The Enhanced Fujita scale now in use by the National Weather Service maintains the existing 0–5 rating but offers revised estimates of the wind speeds causing the various levels of damage. The upper range for an EF1 tornado is unchanged; see www.wind.ttu.edu/EFScale.pdf. All the tornado statistics in this paper unless otherwise noted are based on the authors' calculations from the Storm Prediction Center's tornado archive (SPC n. d.).

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Further, many homes on the periphery of the path of an F5 tornado receive only F0 or F1 damage. Thus strengthened construction could readily reduce property damage from tornadoes.

Strengthened construction as a means of reducing damage from tornadoes is hardly a new idea. An insurance industry study in the aftermath of the deadly 1925 Tri-State Tornado noted, “Over 60 percent of damage was caused by straight blowing winds. … Much of this damage could have been avoided without great increase in construction cost” (quoted in Felknor, 1992, p. 110). Recently the Institute for Business and Home Safety has emphasized reinforced construction in tornado prone regions as a component of their *Fortified … for safer living* program, and Ridley et al. (2003) note that one Oklahoma City home builder has marketed tornado safety construction with success in the aftermath of the May 3, 1999 tornadoes.

In this study, we examine the potential economic value of strengthened construction to reduce damage from tornadoes. We do so by estimating the expected annual tornado damage, using historical tornado records, as well as damage estimates based on a case study from the May 3, 1999 Oklahoma City F5 tornado. Since sufficiently reliable engineering estimates of damage reduction with mitigation in tornadic winds are incomplete or unavailable, we calculate the damage reduction necessary for a zero net present value as our criteria for efficiency. Our results suggest that wind resistant construction may be efficient even when valuing only tornado damage avoided. We perform a variety of sensitivity tests to illustrate the dependence of our results on various parameters. In the most tornado prone states, mitigation would have to reduce damage by 25–30% to have a positive net present value based on insurance payments in the May 3 tornado and a $500 added cost of construction. Generally tornado damage has been considered too infrequent to include as a design criteria in building codes (Crandell, 2002). Our case study suggests that tornado damage *may* be significant enough to merit consideration, at least in the most tornado prone states. The potential for strengthened construction to provide safety benefits by reducing fatalities and injuries in tornadoes could modestly contribute to the expected benefits of strengthened construction.

The remainder of this study proceeds as follows. Section 2 describes the framework employed to calculate the net present value of wind resistant construction. Section 3 discusses the derivation of the sources of the empirical components of our model. Section 4 presents the calculation of cost effectiveness along with sensitivity analysis. Section 5 offers a brief conclusion.

2. A benefit-cost model for wind resistant construction

We develop in this section a framework for calculating the net expected present value of wind resistant construction, which requires some notation. Consider a representative home of value V. Damage to the home will depend on the strength of the tornado when it strikes the home. Let d_j be the damage to the home, measured as a percentage of the home's initial value, if it suffers damage from a tornado with an F-scale rating of j, $j = 0,1,\ldots,5$. Let c_j be damage to contents from a tornado with a rating of j on the F-scale, again measured as a percentage of the home's initial value. Let r_j be the damage reduction with wind resistant construction when a home is struck by a tornado rated j on the F-scale. To illustrate, suppose an F1 tornado would produce on average damage equal to 40% of the value of the structure with normal construction, but damage equal to only 10% of value on homes with wind resistant construction. Then $d_1 = 0.40$, while $r_1 = 0.75$, so 3/4 of the damage could be avoided in this case. Note that d_j and c_j when calculated from insurance payments can exceed 1.0. Let π_j $j = 0, 1, 2, 3, 4, 5$ be the annual probability that the home will suffer tornado damage with a rating of j on the Fujita scale.

We will restrict our analysis to wind mitigation measures in new construction. Therefore, the benefits and costs of reinforced construction do not occur at the same time; the cost must be incurred upfront when the structure is built, while the benefits occur over the life of the structure and must be discounted. Let C be the cost of tornado resistant construction, the increase in cost due to addition of wind resistant features. Let i be the real interest rate for discounting. Let T be the useful life of the reinforced structure. We calculate the value to society of wind resistant construction, and thus include benefits over the full life of the structure without regard to how long initial residents plan to live in the structure. Alternatively, if the resale market for housing effectively captures the present value of future losses avoided by better construction, the direct social benefits and private benefits will be the same. Note that T is the typical life of a structure and not it's potential useful life and must take into account homes that are torn down or retired from use before the end of their potential life.

The net present value (NPV) of tornado resistant construction is

$$\mathrm{NPV} = \sum_{t=0}^{T-1}\left[\sum_{j=0}^{5}\pi_j^*(d_j^* + c_j)^* r_j\right]V/(1+i)^t - C. \tag{1}$$

If we substitute $\delta = \Sigma 1/(1{+}i)^t$, the net present value of wind resistant construction equals zero if

$$\sum_{j=0}^{5}\pi_j r_j(d_j + c_j) = \frac{C}{\delta V}. \tag{2}$$

We make one set of calculations based on values of d_j and c_j for each F-scale category. Another set of calculations ignores F-scale distinctions and considers only an overall probability of a tornado, π, and average damage to all homes, d and c. In this case the net present value of strengthened construction equals zero if

$$\pi \cdot r(d + c) = \frac{C}{\delta V}. \tag{3}$$

The reduction in damage required for net present value to equal zero can then be written

$$r = \frac{C}{\delta V \pi(d + c)}. \tag{4}$$

We will use (1), (2) and (4) in our calculations. We now discuss our estimates of the components of this valuation model.

3. Sources of our estimates

We estimate annual tornado probabilities using the Storm Prediction Center's (SPC, n.d.) national tornado archive for 1950–2003. The archive lists a number of storm characteristics, including its rating on the Fujita scale of tornado damage, year, state, and estimated area of the tornado damage path. To determine the overall annual probability of a tornado in a state, we took the total damage path area of all tornado segments in the state over the period, divided by 54 to yield the mean annual amount of tornado damage in the state, divided by land area in 2000. For example, the area of tornado damage paths in Mississippi was 1089 mi^2 over the period, while state land area is 46,907 mi^2. The probability of tornado damage for any home site in the state over the period was 0.0232, or 4.30×10^{-4} per year, the highest in the nation. This annual probability corresponds to a return period of 2300 years. Table 1 presents the estimates for each of the 48 contiguous states, ranked from highest to lowest

Table 1
Annual probability of tornado by state.

Rank	State	Probability
1	Mississippi	0.000430
2	Arkansas	0.000426
3	Oklahoma	0.000411
4	Kansas	0.000349
5	Iowa	0.000346
6	Indiana	0.000315
7	Alabama	0.000268
8	Wisconsin	0.000249
9	Illinois	0.000245
10	Tennessee	0.000239
11	Nebraska	0.000232
12	Georgia	0.000227
13	Louisiana	0.000189
14	Michigan	0.000175
15	Missouri	0.000173
16	Ohio	0.000172
17	North Carolina	0.000163
18	South Carolina	0.000144
19	Pennsylvania	0.000141
20	Minnesota	0.000136
21	Texas	0.000135
22	Kentucky	0.000123
23	Massachusetts	0.000113
24	Rhode Island	0.000106
25	South Dakota	0.0000929
26	New Jersey	0.0000806
27	Delaware	0.0000781
28	Maryland	0.0000767
29	Florida	0.0000679
30	Connecticut	0.0000658
31	Virginia	0.0000435
32	New York	0.0000432
33	North Dakota	0.0000346
34	Colorado	0.0000190
35	Wyoming	0.0000167
36	New Hampshire	0.0000156
37	Vermont	0.0000147
38	West Virginia	0.00000727
39	Montana	0.00000659
40	Maine	0.00000430
41	New Mexico	0.00000414
42	Utah	0.00000280
43	Oregon	0.00000173
44	California	0.00000173
45	Washington	0.00000156
46	Arizona	0.00000156
47	Idaho	0.00000123
48	Nevada	0.00000051

Based on authors' calculations from the Storm Prediction Center tornado archive, tornadoes in the US 1950–2003.

probabilities. All 48 states experienced tornadoes during this period, but the probability varies greatly as Nevada has the lowest probability at 5.10×10^{-7}, or a mean return time of almost two million years. Our use of a probability calculated using average damage over the entire 54 year period assumes that the incidence of tornado damage has remained constant over time.

To determine the probability of damage from tornadoes of different Fujita scale strengths, the π_j's, we tallied the total area of tornadoes of each category in the state over the period 1950–2003, divided by 54 to produce an annual amount of damage, and then divided by land area in 2000. Note that since the number of tornadoes of some types in some states is quite small, observed damage per year even over a span of 54 years may deviate substantially from the unobserved true mean.

The estimates of tornado probabilities in Table 1 assume an equal probability of a tornado across the state, which is highly unlikely. An alternative method employed by Schaefer et al. (1986) maps tornado paths on a 1° longitude and 1° latitude grid to produce a smooth estimate of tornado probabilities at locations within a state. Employing all tornadoes in the SPC archive for 1950–2000, Schaefer et al. (2002) estimate that the highest annual probability within the contiguous US is 6×10^{-4}, in Central Oklahoma, which exceeds our estimate of 4.11×10^{-4} for the state as a whole.

The incompleteness of tornado records could also affect our estimates of tornado probabilities. Not all tornadoes have been observed and recorded in the archives. Tornadoes occurring in sparsely populated rural areas are less likely to be seen and documented. The record of recent tornadoes may be more complete since the ease of reporting and documenting tornadoes has increased over time with affordable technological advances (cell phones, video cameras, satellite imagery) and due to the popularity of storm chasing. Consequently the area of tornado damage reported in the SPC archive likely underestimates the true amount of tornado damage. To examine the possibility of error in the records, we calculated the annual tornado rate (tornadoes per 10,000 mi^2 land area per year) for each county in Kansas, Oklahoma and Texas, three states at the heart of Tornado Alley. Comparison with the average county population density from 1950 through 2000 indicates a significant potential bias in the tornado archive.[3] We ranked the counties in these states according to average population density over this period. The tornado rate for the top decile of counties ranked by average population density (exceeding 85.7 persons per mi^2) was 11.7 per year per 10,000 mi^2 land area, compared to 1.56 per year per 10,000 mi^2 for the least populated decile of counties (below 3.53 persons per mi^2). The difference was significant for both tornadoes rated F3 or stronger (0.952 per 10,000 mi^2 vs. 0.0714) and for tornadoes rated F2 or weaker (10.7 vs. 1.49). The tornado rate in the most populous counties of these states, 11.7, is approximately equal to double the overall rate for these states of 5.92, which suggests that the true tornado rate may be as much as twice that calculated on recorded tornadoes. In sensitivity analysis then we will calculate the net present value of strengthened construction with a tornado probability twice as large as the probability for Oklahoma based on the actual tornado area over 1950–2003.

Our estimate of tornado damage to non-reinforced homes uses data from the May 3rd 1999 Oklahoma City F5 tornado. A team from Texas Tech University surveyed homes in the path and assessed the damage as F0, F1, F2, F3, F4 or F5 (Marshall, 2002). Although the tornado was rated F5 on the Fujita scale, by convention the rating of a storm refers to its highest rating at any point along its path, so not all homes struck by the tornado received damage rated F5. Data on the dollar value of damage is taken from two sources, the reduction in appraised value for property taxation and insurance payments for structure and contents.[4] The damage survey was comprehensive rather than based on a representative sample, as Crandell and Kochkin (2005) recommend. Our interest is in the relationship between the dollar value of damage and the F-scale damage assessment for individual homes, not in the relationship between home characteristics, proximity to the tornado vortex, and damage level. Consequently the lack of a statistically representative sample should not excessively hamper our analysis here.

Tax Assessor records and damage ratings were available for 761 homes along the Oklahoma County portion of the tornado path. Note that the tornado was at F4 intensity at this portion of its

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[3] Average population density is the mean of county population in the six decennial censuses between 1950 and 2000 divided by land area in 2000.

[4] The Oklahoma County Tax Assessor's office provided the assessed value of homes and the Oklahoma Insurance Commission provided the insurance payments.

Table 2
Tornado losses by F-scale rating of damage.

F-Scale	Tax assessor losses			Insurance payments		
	Number of homes	Mean value	Mean loss (%)	Number of homes	Structure (%)	Contents (%)
F0	249	$63,086	61.90	22	133.8	43.66
F1	83	$65,434	79.69	5	144.9	35.22
F2	136	$67,053	80.75	12	168.3	96.88
F3	214	$66,920	81.99	30	161.2	82.23
F4	79	$64,013	82.51	10	161.4	77.78
All	761	$65,225	75.00	79	153.3	69.96

storm path, so we have homes with damage ratings from F0 to F4 but no F5 damage. We matched insurance payments to the addresses of 79 of the homes. The mean of the assessed values of the 761 homes in 1998 was $65,225 with a range from $17,900 to $115,450. The mean assessed values of the homes subject to each category of damage ranged from $63,086 for F0 damage to $67,053 for F2 damage. The small differences in mean assessed value allow us to compare loss ratios across categories without differences in value confounding the results.

Table 2 presents the number of homes, mean assessed loss, insurance payment for the structure, and insurance payment for contents for each F-scale damage category, with all losses expressed as a percentage of the assessed value of the home in 1998. Two interesting results emerge. First, insured losses for a structure can indeed exceed the assessed value of a home. Overall for all homes in our sample assessed loss is 79.2% of assessed value, while insurance payments for the structure and contents are 153.3% and 70.0% of assessed value. Loss based on assessed value is approximately equal for F1 and stronger damage, between 80% and 85%, while insurance payments level off at F2 at around 160% for structure and 80–95% for contents. Why the insurance payment for structure exceeds the value by such a large amount is puzzling. Although assessed values for property taxes can be below market value, Oklahoma County uses a regression model to assess value based on the market value of recently sold homes. Insurance often pays for replacement value, so perhaps escalating construction costs explain this. Second, a home receiving damage assessed as F0 or F1 can sustain substantial losses. Assessed loss is 62% of value for F0 tornado damage and 80% for F1 damage. Yet the wind speeds of an F0 tornado are estimated to be in the range of 40–72 mph and the damage done is described as "some damage to chimneys; breaks off branches of trees" (Tornado Project, n.d.). Clearly damage for these homes is higher than seems possible for these wind speeds. We will make calculations based on both assessed damage and insurance payments for our NPV calculations.

Our dataset also contains the year built and area in square feet for each home. We estimated an econometric model of our three loss measures with dummy variables representing the F-scale of rated damage, year built and square feet as control variables. Square feet and year built were individual and jointly insignificant, and the regression analysis offered no real refinement of the relationship between F-scale damage and loss, so we perform calculations based on the simple breakdown of loss by F-scale category as reported in Table 2.[5]

We lack a precise estimate of the loss reduction possible with strengthened construction. Engineers have estimated the effect of strengthened construction on damage from hurricane winds. This analysis involves subjecting sample homes to hurricane force winds in wind tunnels, field examination of damage in the aftermath of hurricanes, and analysis of insurance payments.[6] Potential losses due to hurricane force winds depend on numerous factors, including the type and shape of roof, elevation of the structure, and nearby structures and terrain. Maintaining the integrity of the outer building envelope is one crucial factor since a breach of the envelope leads to pressure on the roof and loss of the roof leads to substantial contents damage and collapse of walls (Cook, 1994, p. 77; Applied Research Associates, 2001, pp. 1–4). Tornadic winds generate different loads and stresses on buildings than hurricane winds, and damage may depend on direction changes and duration of tornadic winds (Wurman and Alexander, 2005). Thus loss reduction estimates for hurricane winds cannot be applied to tornadoes. In addition, even should we wish to apply estimates from hurricane studies to tornadic winds, we would require detailed information on the composition of the housing stock in tornado prone regions, e.g., the shape of roofs and quotes and various types of construction. We do not possess such an inventory.

Instead of using an estimate of the loss reduction possible with strengthened construction in tornadoes, we calculate the loss reduction required for mitigation to break even. We calculate this value in two ways. First, we assume that the same percentage loss reduction holds for each type of tornado and use the annual probability of a tornado, or $r_0 = r_1 = \cdots = r_5 = r$ and the state value π from Table 2. This approach has one main drawback and one main advantage. Strengthened construction is not expected to be effective against tornadoes rated F4 or F5 on the Fujita scale. Although an above ground safe room can be designed to withstand the strongest tornado, such rooms cost thousands of dollars and are intended to protect residents, not the entire structure (FEMA, 1999). Thus the probability of any tornado will overestimate potential benefits. On the other hand, a tornado's rating on the F-scale is its maximum intensity, so many homes in the path of an F4 or F5 tornado receive only F0 or F1 damage. Consequently excluding the areas of F4 or F5 tornadoes entirely from calculation of the probability of a tornado will underestimate benefits. Second, we assume that mitigation produces the same loss reduction in percentage terms for homes subject to different damage levels, but limit the F-scale levels against which mitigation reduces losses. Thus we in turn assume strengthened construction reduces losses only from F0 tornadoes, then F0 and F1 tornadoes, up to reducing losses from all except F5 tornadoes. We use the damage areas of tornadoes of each F-scale in the state to calculate the probabilities π_0 through π_5 for each state.

We assume a useful life of 50 years for the strengthened structure, $T = 50$, which seems to be a reasonable estimate of the expected useful life of a home built today. As of the 2000 Census, the median year built for housing units nationally was 1971. Only

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[5] See also De Silva et al. (2006) who estimate models of home value over time for the homes struck by the tornado in this sample and a matched sample of nearly undamaged homes.

[6] For details on the procedure see Applied Risk Associates (2002a b, 2003).

Table 3
Minimum damage loss reduction required for cost effectiveness.

Case	Description	Real discount rate	
		3%	6%
1	Baseline (Oklahoma tornado probability)	0.315	0.499
2	High value home ($V = \$115{,}450$)	0.178	0.282
3	Low value home ($V = \$17{,}900$)	1.15	1.82
4	Low cost ($C = \$300$)	0.189	0.300
5	High cost ($C = \$700$)	0.441	0.699
6	Mississippi tornado probability	0.301	0.477
7	Arkansas tornado probability	0.304	0.482
8	Texas tornado probability	0.958	1.52
9	High tornado probability (Oklahoma*2)	0.157	0.250
10	Baseline, assessed loss	0.938	1.49

22.3% of the nearly 116 million US housing units were built before 1950, and only 15.0% built before 1940. We calculate present value using real discount rates of 3% and 6%.

We consider a package of four mitigation measures: use of anchor bolts to attach the walls of the structure to the foundation, tornado straps to attach the roof to the walls, directional nailing of the roof, and oriented strand board (OSB) plywood for walls. One Oklahoma home builder who has been using these construction techniques since 1999 estimates that their extra cost is around $500. An engineering study of improved building codes in South Carolina estimated the increased cost of extra nailing and hurricane straps at under $100 each for most structures (Applied Research Associates, 2002b), which seems consistent with the $500 total. So we use $500 as a baseline case but also let the cost vary between $300 and $700 in sensitivity analysis.

4. Calculations of cost effectiveness

We now calculate the percentage loss reduction required for the net present value of strengthened construction to equal zero. The net present value is positive if r exceeds this threshold. Strengthened construction is less likely to be efficient the higher the threshold and definitely is not efficient if the threshold exceeds one. The value for r for $\text{NPV} = 0$ provides insight on the likely efficiency of wind resistant construction, not a definitive answer.

Table 3 presents the critical values for r for several cases using the overall tornado probability in the state and ignoring F-scale distinctions. We illustrate the calculations using the baseline case listed first in Table 3. The baseline case uses the annual probability of a tornado in Oklahoma, $\pi = 0.000411$, the mean assessed value of a home in our sample, $V = \$65{,}225$, a cost of strengthened construction of $C = \$500$, and the mean values of insurance payment for structure and contents relative to assessed value, $d = 1.533$ and $c = 0.6996$. Substitution of these values into Eq. (4) above yields a critical value of r of 0.315 for a 3% discount rate and 0.499 for a 6% discount rate. Thus for the average home in our Oklahoma sample, strengthened construction must reduce structure and contents loss by 30% or 50% to pass a cost benefit test. Since the costs of strengthened construction must be incurred upfront but reduced losses result over the life of the strengthened home, a higher discount rate implies mitigation must reduce a higher proportion of loss to be efficient.

The remainder of the cases in Table 3 explore the effect of changing V, C and π. Cases 2 and 3 consider a high and low value home, with assessed values of $115,450 and $17,900, the maximum and minimum values in our dataset. These cases assume that the cost of strengthened construction is the same as the baseline for these other homes.[7] In the 3% discount rate case the required proportion of loss for mitigation to break even falls from about 31% to 18% for the high valued home and exceeds 100% for the low valued home. Cases 4 and 5 show the effect of varying the additional cost of strengthened construction to $300 and $700 respectively. This variation in cost has a greater impact on loss reduction than the observed range in assessed values. We next consider the impact of the annual tornado probability on the calculations. Cases 6, 7 and 8 consider the tornado probability in Mississippi and Arkansas, which have the highest annual tornado probabilities in the US, and Texas, which recorded the most tornadoes over the period. The annual tornado probability in Mississippi and Arkansas is only slightly higher than Oklahoma's, and the higher probability lowers the required loss reduction by about one percentage point with a 3% discount rate and two percentage points for a 6% discount rate. In Texas the required loss reduction is 96% with a 3% discount rate and exceeds 100% with a 6% discount rate. Thus even for a state in "Tornado Alley" strengthened construction cannot be cost effective.[8] Case 9 considers an annual tornado probability equal to twice that of Oklahoma, which is plausible given the incompleteness of tornado records and the potential for an unequal probability across a state. In this case the required percentage of loss avoided is half that of the baseline case, 16% for a 3% discount rate and 25% for a 6% discount rate. Case 10 considers a loss equal to only that of the loss in the mean assessed value, 0.750 from Table 2, with the baseline house from Case 1. The minimum loss reduction in this case naturally is much higher, 94% for Oklahoma with a 3% discount rate and 149% with a 6% discount rate. Thus damage must exceed the assessed value of homes in our sample for strengthened construction to possibly be cost effective. A loss reduction of 15% is definitely consistent with engineering estimates of loss reduction possible with strengthened construction for hurricanes (Applied Research Associates, 2001, pp. 6-1–6-10). Building to the 2000 International Residential Code in Texas has been estimated to reduce losses from a future hurricane by 40% (Applied Research Associates, 2003, pp. 4–5).

Although we cannot know the value of r with precision, we know that the reduction in loss cannot exceed 100%. Thus the annual tornado probability for which the loss reduction must be 100% for the NPV to equal zero provides a bound for potential efficient mitigation. This probability is given by $\pi = C/[V^*(d+c)^*]$, and equals 0.000129 for a 3% discount rate and 0.000205 for a 6% discount rate. To provide insight as to where strengthened construction might be cost effective, we calculated the cutoff values of r for each state using the tornado probabilities in Table 1 and the baseline Case 1 from Table 3. Table 4 displays the results with states grouped by the value of r required for $\text{NPV} = 0$. Five states total have a break even value of r under 0.40 (Kansas and Iowa in addition to Mississippi, Arkansas and Oklahoma), and comprise the states where construction is most likely to be cost effective. Seven states have values in the range of 0.4–0.6, five in the range of 0.6–0.8, and four in the 0.8–1.0 range. Strengthened construction cannot be cost effective in the remaining 27 states, and our assumptions would need to be wildly off the mark for construction to be even close to cost effective in the 18 states with values over 2.0, at least when only tornado damage is included in the benefits. Not surprisingly strengthened construction for

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[7] As examination of (4) reveals, if the cost of strengthened construction varies proportionally with the value of the home, say strengthened construction always costs 2% of value, then changing V will not affect the value of r for which $\text{NPV} = 0$.

[8] Note that the annual tornado probability is not equal across the state, so strengthened construction may well be cost effective in parts of the state, and we have not considered mitigation against hurricane winds.

Table 4
Comparison of minimum cost reduction for cost effectiveness across states.

Minimum value of r	States
Under 0.40	Mississippi, Arkansas, Oklahoma, Kansas, Iowa
0.40–0.59	Indiana, Alabama, Wisconsin, Illinois, Tennessee, Nebraska, Georgia
0.60–0.79	Louisiana, Michigan, Missouri, Ohio, North Carolina
0.80–0.99	South Carolina, Pennsylvania, Minnesota, Texas
1.0–2.0	Kentucky, Massachusetts, Rhode Island, South Dakota, New Jersey, Delaware, Maryland, Florida, Connecticut
Over 2.0	Virginia, New York, North Dakota, Colorado, Wyoming, New Hampshire, Vermont, West Virginia, Montana, Maine, New Mexico, Vermont, California, Oregon, Washington, Arizona, Idaho, Nevada

Values are calculated using the baseline case home (#1) from Table 3 and the state specific tornado probabilities in Table 1.

tornadoes could only be economically viable in some parts of the country.[9]

We now break down tornado damage by F-scale to illustrate how this affects the minimum damage reduction required for wind resistant construction to be cost effective. Clearly the measures under consideration here would not be sufficient to prevent destruction of a home by an F5 tornado, so including the probability of *any* tornado clearly overstates expected benefits. To explore the sensitivity of the results in Table 3 to inclusion of strong or violent tornadoes, we calculated the minimum damage reduction required for a zero NPV in (2) assuming first that strengthened construction can prevent damage only from F0 tornadoes, then can prevent damage from F0 and F1 tornadoes, and add F-scale categories one at a time until we exclude only F5 tornadoes.

Table 5 presents the minimum damage reduction based on tornadoes over the period 1950–2003 for Mississippi, Arkansas, Oklahoma and Texas. The calculations employ the baseline Case 1 and the results in Panel A apply the insured loss as a percentage of home value for the overall sample, $d = 1.533$ and $c = .6996$, to each F-scale level. Thus Panel A shows exclusively the effect of adjusting the probabilities by F-scale, the π_j's. Wind resistant construction will not pay for itself in any of these states if only damage from F0 and F1 tornadoes can be prevented, since r is 2.0 or higher in each state. Although tornadoes rated F0 or F1 on the Fujita scale account for about 75% of tornadoes, these weak tornadoes have shorter damage paths and consequently compromise only 17.5% of tornado damage area, an insufficient amount for mitigation to pay for itself.[10] Of course a substantial portion of the damage from stronger tornadoes would be classified F0 or F1, but protection against only weak tornadoes is unlikely to be efficient in any state. By contrast, omission of the damage areas from F5 tornadoes has very little effect on the minimum r required for reinforced construction to pay off. Arkansas did not experience an F5 tornado over this period, and so its minimum r is the same as in Table 3, while the largest difference is two hundredths for Oklahoma, which had the most F5 damage of any state in this period.[11] The ranking of the states at the different F-scale levels indicates the relative rate of tornadoes of different strengths in each state. Oklahoma and Texas have the smallest minimum r's when only F0 tornadoes are included, while Arkansas has the lowest values when tornadoes up to F3 and F4 are included.

Panel B of Table 5 makes these calculations using the values of insured losses for structure and contents by F-scale level from Table 2 instead of the mean for all F-scale categories. Since insured losses are lower (although still substantial) for F0 and F1 tornadoes, the minimum r values for a zero NPV are higher here than in Panel A. When insured losses jump at F2, the minimum r's in Panel B become less than the corresponding values in Panel A. This is due both to the higher loss level and the larger percentage of damage done by F2, F3 and F4 tornadoes. As Panel B reveals, the minimum loss required for $\text{NPV} = 0$ is lower for tornadoes up to F4 than in Panel A for Mississippi and Arkansas.

We have considered a reduction in tornado property damage as the exclusive benefit from strengthened construction. But strengthened construction could also protect residents from tornadoes and reduce damage from straight-line and hurricane winds. The cost effectiveness of strengthened construction and stricter building codes with respect to hurricanes has already been examined, and so we do not address this possible benefit. Indeed, our analysis applies only to homes which do not also face hurricane risk. Thunderstorm winds can equal those of an F0 or F1 tornado, but trying to quantify this benefit is beyond the scope of this paper. We can offer a perspective on the value of possible life saving effects of strengthened construction, using Oklahoma as an example. Oklahoma experienced 265 tornado fatalities between 1950 and 2007, or 4.57 fatalities per year. Between 1985 and 2006, 31.9% of tornado fatalities occurred in what the National Weather Service characterizes as permanent homes, or 1.46 permanent home fatalities per year. The 2000 Census reported 1.08 million single family homes in Oklahoma, so 1.35×10^{-6} tornado fatalities per home per year. To compare life savings with damage reduction, lives must be valued. The Environmental Protection Agency (EPA, 1997) used a value for $4.8 million for lives saved by the Clean Air Act, based on a meta-analysis of published economic studies on the value of a "statistical life," and we will apply this figure here. Adjusting for inflation gives a value $7.6 million in 2007 dollars. The value of tornado fatalities expected to occur in a single family home in Oklahoma is $10.27 per year, or $272 over the 50 year life of the home with a 3% real discount rate. For comparison, the annual value of expected tornado damage for the mean valued home in our sample is $59.86 based on insurance payments and $20.11 based on assessed value. Thus potential life savings will be smaller than property damage. Estimating the proportion of single family home tornado fatalities that might be avoided with strengthened construction is beyond the scope of this paper. But fatalities per tornado escalate rapidly with F-scale rating, from 0.00105 for F0 to 3.17 for F4 and 16.4 for F5. And avoiding the total destruction of a home is important in preventing tornado fatalities (Simmons and Sutter, 2008). If strengthened construction could reduce fatalities by 36%, the value over the life of a home would be $100, or 20% of the assumed cost of strengthened construction.[12]

5. Conclusion

Tornadoes have been presumed too infrequent to include as a design criteria for building codes (Crandell, 2002). Our case study of damage from the May 3, 1999 Oklahoma City F5 tornado suggests that strengthened construction for homes in tornado

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[9] Only 12 states have an annual tornado probability high enough for their cutoff value of r to be less than 1.0 with a 6% real discount rate.

[10] Authors' calculation from the Storm Prediction Center archive. A total of 1843 tornadoes with 112.9 mi^2. of damage area were not classified on the F-scale in the archive and are omitted in these calculations.

[11] These calculations omit tornadoes unclassified on the F-scale, but in each state the number of unclassified tornadoes was small.

[12] A full analysis of safety benefits would also need to consider injuries prevented with strengthened construction. If strengthened construction did produce safety benefits, the benefit of in-home tornado shelters and safe rooms would be reduced.

Table 5
Minimum damage loss reduction for cost effectiveness, F-scale probability based.

State tornado probability	F-scale for which reinforced construction reduces damage (inclusive)				
	F0	F1	F2	F3	F4
5A: Mean insured payment for all F-scale categories					
Mississippi	22.6	2.18	0.695	0.400	0.313
Arkansas	45.3	2.58	0.641	0.347	0.304
Oklahoma	14.2	2.05	0.677	0.437	0.315
Texas	16.9	4.32	1.88	1.27	0.970
5B: mean insured payment for each F-scale category					
Mississippi	28.5	2.67	0.651	0.371	0.291
Arkansas	57.1	2.58	0.585	0.318	0.279
Oklahoma	17.9	2.52	0.636	0.407	0.313
Texas	21.2	5.31	1.84	1.22	0.923

prone states may be cost effective. If a package of construction measures with an added cost of $500 can reduce tornado damage by 30%, wind resistant construction could have a positive net present value. This figure is similar to damage reductions estimated for wind load designs in hurricane prone regions. Our estimate is based on insurance payments for structure and contents damage, which averaged over 220% of the assessed value of the home for property tax purposes; the level of damage was much lower and the damage reduction much greater when damage was based on the loss in appraised value of the home. Our analysis identifies several factors such as a lower cost of strengthened construction, costs which increase less than proportionally with home value, or areas of particularly high tornado risk which could reduce the damage reduction based on insurance payments required for a positive net present value below 20%.

Our results suggest that wind resistant construction may be an efficient mitigation measure, at least in some places, particularly within the inclusion of reduced tornado casualties and straight-line wind damage. All calculations in this analysis use a risk neutral weight on loss reductions and use tornado damage as the sole source of wind damage. The inclusion of a weighting function that incorporates risk aversion or loss aversion would further support wind resistant construction. Wind resistant construction can be efficient when considering only tornado damage if it can reduce damage by 30%, at least in some cases in the tornado prone states like Mississippi, Arkansas and Oklahoma. But the potential economic viability of wind resistant construction disappears even in states with lower tornado risk. Further research would be required to better estimate the reduction in tornado loss possible with strengthened construction as well as possible life saving benefits. Specifically more refined estimates of tornado probabilities or home designs particularly vulnerable to tornado wind damage could help identify opportunities to efficiently apply wind resistant building techniques.

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