



# Generalized Cost-Effectiveness of Residential Wind Mitigation Strategies for Wood-Frame, Single Family House in the USA

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Wind is one of the deadliest and most expensive hazards in the United States. Wind hazards cause significant damage to buildings and economic losses to homeowners. Economic losses average approximately \$3.8 billion annually from hurricane winds and are not decreasing, even despite enhanced construction practices to reduce wind damage. Thus, the effectiveness of mitigation strategies should be evaluated in order to lower the cost incurred by this hazard. Several studies have suggested building code improvements to mitigate the wind hazard, this additional comprehensive research provides selecting economically beneficial mitigation strategies to consider in building code revisions. In a step toward addressing this need, the current study was conducted to determine the cost effectiveness of mitigation strategies for new and retrofit construction of a wood-framed, single-family, residential building case study. Net benefit, defined as the difference between the life-cycle wind loss before and after implementation of the mitigation strategy, was calculated for 15 wind mitigation strategies and their combinations, with new and retrofit construction costs ranging between \$1,200 to \$12,000 and a decision-making time horizon ranging between 5 and 30 years. Payback periods, defined as the number of years to recover the investment, were calculated for each mitigation strategy. Results were summarized by cost effectiveness for all ASCE 7 wind speed contour intervals. The results of this study serve as a starting point for further refinement of the economic justification needed to properly evaluate potential building code changes.

**Keywords:** wind hazard, cost effectiveness, net benefit, payback period, wood frame residential, mitigation, Hazus-MH, resilient construction

## INTRODUCTION

Wind is one of the deadliest and most expensive hazards in the United States (Emanuel et al., 2006). From 2010 to 2020, the continental U.S. experienced average property damage of \$3.8 billion per year from tropical storms and hurricanes (National Weather Service, 2020). Furthermore, the frequency and magnitude of wind hazard events has increased in recent decades (National Science Board (U.S.)

and National Science Foundation (U.S.), 2007; Rosenzweig and Solecki, 2014). For instance, 2020 is known as one of the most active Atlantic-Caribbean-Gulf of Mexico tropical cyclone seasons, with multiple tropical storm and hurricane events in the Gulf Coast and southeastern United States (National Oceanic and Atmospheric Administration, 2020). Therefore, a future change in building codes regarding wind design speed contours is probable.

Hurricane risk assessment strategies for building structures are focused on both storm surge and wind induced risk (Unnikrishnan and Barbato, 2016a; Unnikrishnan and Barbato, 2017; Baradaranshoraka et al., 2017), but it is challenging to isolate the most effective mitigation approach under various scenarios of new and retrofit modeled structures. In recent years, several studies analyzed the cost effectiveness of various mitigation approaches for various structure models. Among these, Performance-Based Hurricane Engineering framework was frequently used to assess risk and cost-effectiveness of mitigation measures of residential structures subjected to hurricane hazard (Barbato et al., 2011; Barbato et al., 2013; Unnikrishnan and Barbato, 2015; Unnikrishnan and Barbato, 2016a; Unnikrishnan and Barbato, 2016b; Unnikrishnan and Barbato, 2017). Although in recent years, it is a common practice to consider multi-hazard criteria for hazard mitigation planning and cost calculation, especially in the coastal region where flood and wind are the two most common hazards, it is also important to calculate the losses from the wind hazard individually and then to evaluate the cost effectiveness of the mitigation plan. This is because flood events are more severe but less frequent, while wind events are the most commonly occurring atmospheric phenomena causing damage to structure even when there is no flood or storm surge. While the increasing elevation of buildings may reduce the chances of losses from flood events, it concurrently increases the chance of losses from the force of wind, which increases with elevation. Hamid et al. (2010) used a probabilistic model to assess risk to insured residential property associated with hurricane wind. Pinelli et al. (2004) estimated expected annual damage induced by hurricane winds on various building types for possible damage states.

In the United States, the building code requirements for hazard mitigation are disparate in each state. For instance, the State of Florida has one of the most comprehensive building codes for hurricane hazards (FBC, 2020). To decrease the unprecedented challenge for residences located in hurricane and wind-prone communities, improvements in the building codes in the areas with outdated or non-comprehensive building codes and/or construction to higher standards are recommended (Stevenson et al., 2020). Proven, existing construction practices can reduce the cost and damage from wind hazards (Gurley and Masters, 2011; Simmons et al., 2020). However, improving the building resiliency through such mitigation actions is usually associated with a higher investment cost that needs to be evaluated by benefit-cost analysis (Torkian et al., 2014). According to Qin and Stewart. (2020a), mitigation activities are associated with the effectiveness of mitigation strategies, and they should be evaluated in order to reduce the cost incurred by hazards. Although the building codes

and some guidelines, such as Federal Emergency Management Agency (FEMA) publications, show the minimum design requirement and suggest mitigation strategies for improving building resiliency to natural hazards, they tend to overlook the cost-effectiveness of mitigation strategies. Several studies have suggested building code improvements to mitigate the wind hazard [Applied Research Associates, Inc. (ARA), 2008; Pinelli et al., 2009], this additional comprehensive research provides selecting economically beneficial mitigation strategies to consider in building code revisions.

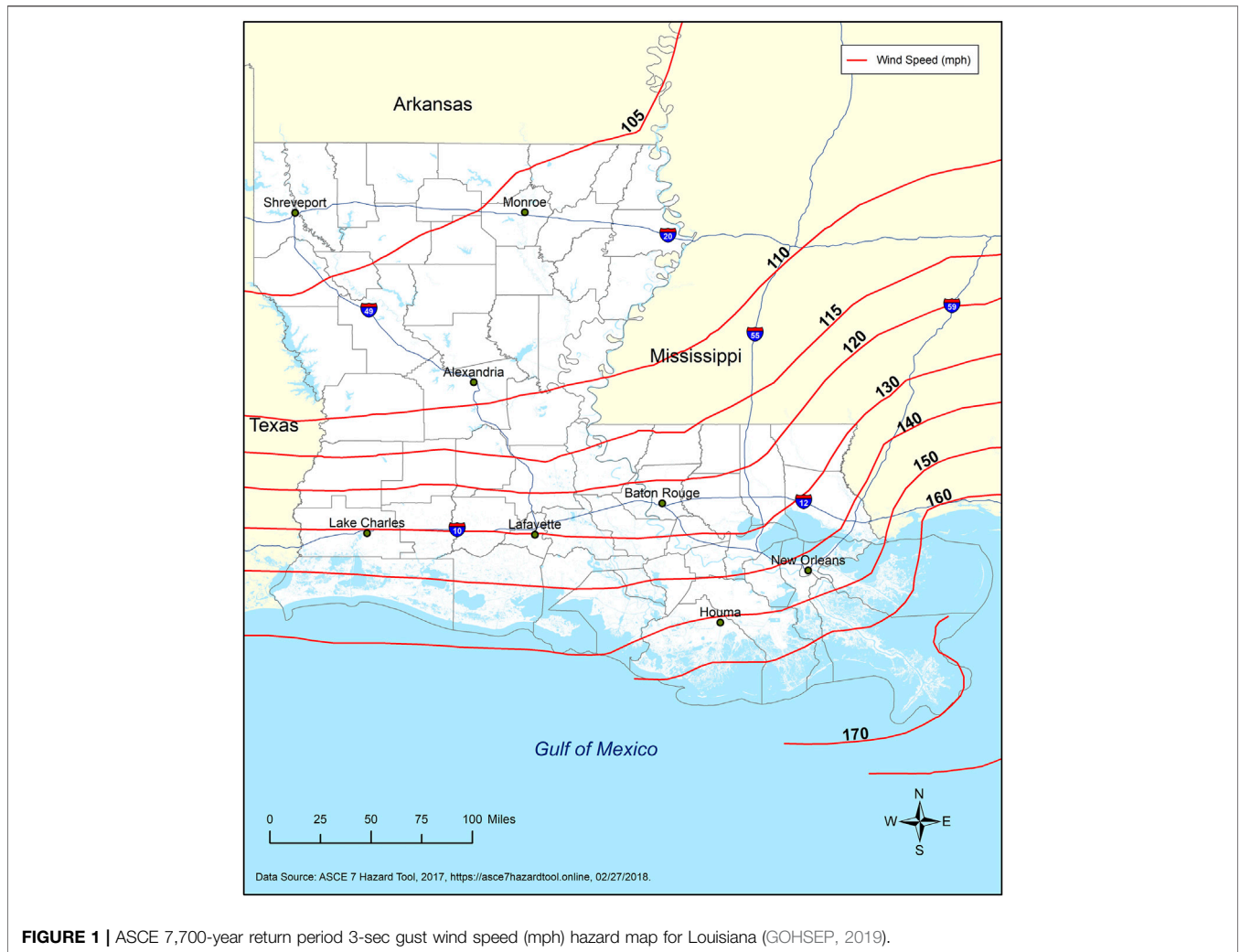
The net benefit of mitigation strategies can be calculated using factors such as cost of mitigation-avoided loss, particular location of the building within the wind contours, building life-cycle or time horizon, and the payback period—the time in years required to recover the initial investment (Orooji and Friedland, 2017; Qin and Stewart, 2020b; Orooji and Friedland, 2021a). Net benefit analyses continually show that the mitigation is cost-effective; however, the homeowners or decision-makers are also interested in knowing the payback period of investment in mitigation to make better decisions on selecting mitigation strategies (De Nocker et al., 2006; Chiu et al., 2013; Noshadravan et al., 2017; Noori et al., 2018).

In this research, we aim to provide detailed and informative guidance for decision-makers and other stakeholders to improve their understanding of the effectiveness of mitigation strategies which can enhance community resilience against wind hazards and form a basis for building code revisions. To achieve this goal, a methodology is provided to first calculate the payback period of each mitigation option based on the location of the building within the wind contours. Then, based on the net benefit and cost-effectiveness results of proposed mitigation options, a generalized recommendation list is provided for use by decision-makers and stakeholders.

To achieve the research objectives, a wood-framed, single-family, residential building case study is used to calculate the cost-effectiveness of mitigation strategies that are available in Hazus loss functions in each mitigation scenario. Net benefit as an indicator for cost-effectiveness is defined as the difference between the life-cycle wind loss before and after implementing the mitigation strategy. Net benefit is calculated for 15 wind mitigation strategies, with new and retrofit construction costs ranging between \$1,200 to \$12,000 and a decision-making time horizon ranging between 5 and 30 years. Payback periods are calculated for each mitigation strategy, and results are summarized by cost-effectiveness for all American Society of Civil Engineers (ASCE) 7–16 wind speed contour intervals (ASCE, 2017).

## METHODOLOGY

This research contributes to the literature by providing a methodology and results that can serve as a starting point for further refinement of the economic justification needed to properly evaluate potential building code changes to make building communities more resilient against the wind hazard. Also, it provides a system to rank the mitigation strategies based on the cost savings and payback period of the mitigation investment.



**FIGURE 1 |** ASCE 7,700-year return period 3-sec gust wind speed (mph) hazard map for Louisiana (GOHSEP, 2019).

### Wind Hazard Characteristics

The International Code Council (ICC) model building codes (e.g., International Building Code) reference ASCE 7, an engineering standard used to determine loads on structures. The 700-years return interval for a 3-s wind gust at 33 feet above the ground level (basic wind speed) forms the basis for ASCE 7 Risk Category (RC) II building design. RC II buildings are those that pose a moderate risk to human lives and include single-family homes. The 700-years wind speed is defined as the wind speed that has an annual exceedance probability (AEP) of 1/700, or 0.143%. In 50 years, there is approximately a 7% probability of this level of wind speed being equaled or exceeded. **Figure 1** provides the ASCE. (2017) RC II 3-s gust wind contour lines for the state of Louisiana, which range from 47 m/s (110 mph) to 80 m/s (180 mph).

The probability density function of a two-parameter Weibull distribution ( $f(v)$ , **Eq. (1)**) is commonly used to describe the occurrence of annual extreme wind speeds (e.g., Vickery et al., 2000; e.g., Li and Ellingwood, 2006). The Weibull distribution has the flexibility of accounting for extreme wind based on its two parameters and is straightforward to use (Drobinski et al., 2015). In the two-parametric Weibull distribution,  $u$  and  $a$  parameters

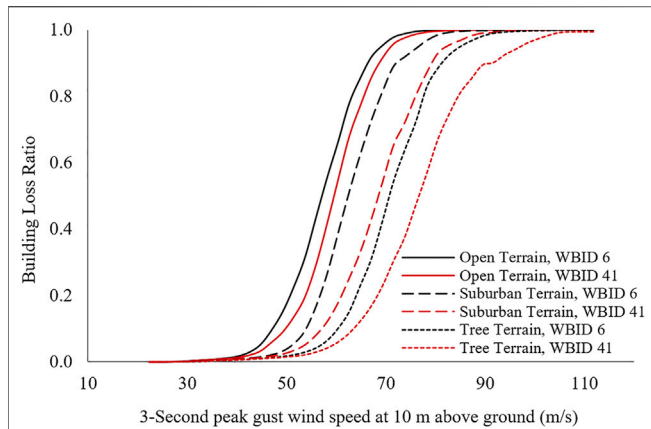
represent shape and scale, respectively. These two parameters correspond to specific sites and minimization of the squared error of the inverse cumulative Weibull distribution (**Eq. 2**) of wind speed data corresponding to 25-, 50-, 100-, 300-, 700-, and 1700-years return periods obtained from the Applied Technology Council Wind Speed website (<http://windspeed.atcouncil.org/>) at the locations of the 700-years return period, 3-s gust wind speed contours specified in ASCE 7.

$$f(v) = \frac{dF(v)}{dv} = \frac{a}{u} (v/u)^{a-1} \exp[-(v/u)^a] \tag{1}$$

$$F^{-1}(P) = v = u \left[ -\ln \frac{1}{R} \right]^{a-1} \tag{2}$$

### Wind Loss Functions

Building loss functions,  $L(v)$ , as shown in Hazus-MH database (FEMA, 2012; FEMA, 2018), define economic building loss as a function of attributes such as building structure type, wind speed, and the classifications of terrain (Vickery et al., 2006). In this research, to generalize the effectiveness of wind mitigation,



**FIGURE 2 |** Building-loss functions, expressed as the ratio of repair or replacement cost to building value, for multiple terrain classifications for an unmitigated (ID 6) and partially mitigated (ID 41) building extracted from the Hazus database.

Hazus-MH loss functions, which are publicly available and applicable to a variety of building configurations in the United States, were used. Also, it should be noted that although the loss functions term is used here to compromise with the definitions in Hazus-MH, in some studies they may call them vulnerability curves or damage functions.

Hazus-MH is a computer-based, multi-hazard model developed by FEMA used to estimate direct losses for building, contents, and loss of use. Multiple Hazus models are implemented within a geographic information system (GIS) platform to analyze wind, flood, and earthquake hazards. Economic losses as a function of wind speed (i.e., loss functions) for five terrain classifications are embedded within the Hazus-MH Hurricane Model. Each loss function is associated with a unique building configuration, called the wind building identity (WBID). Hazus-MH loss functions are widely used for loss studies and are applicable nationally (Jain et al., 2005). **Figure 2** shows an example of the loss ratio of damage to the building value, as a function of wind speed for multiple classifications of terrain (e.g., open, suburban, trees) for

unmitigated (WBID 6) and partially mitigated (WBID 41) buildings.

This study utilizes the Hazus wind loss functions, which are extracted from the Hazus-MH version 3.2 database, rather than the Hazus software itself. Building loss functions  $L_b(v)$  are defined as the ratio of the estimated repair or replacement cost to the total building value. The repair cost is assumed to be equal to an average construction cost for a new building in the location of the case study. This cost is obtained using RSMMeans square foot costs databook (Gordian, 2013). However, removing the damaged components of buildings may increase the repair cost which is not considered in this study. Content loss functions  $L_c(v)$  is defined as the ratio of content loss to content value, where the content value is estimated as 50 percent of the building value (FEMA, 2012). Loss of use functions  $L_u(v)$  represents the number of days needed to repair a damaged building. These days are then converted into a value expressed in terms of building value.

### Residential Building Characteristics

The residential building data used in this study were obtained from the databases underlying the Hazus-MH Hurricane Model. In the Hazus database, wood-frame, single-family houses are characterized using a combination of “building options” i) within five “mitigation categories” (n): 1) roof shape, 2) roof-to-wall (RTW) connection type, 3) presence of secondary water-resistant (SWR) barrier, 4) roof deck attachment (RDA) nailing pattern, and 5) shutter and garage door types.

A wood-frame, single-family, one-story residential building is characterized using one of the building options in each mitigation category, and each of the 15 mitigation strategies has two or more building options. Given these options, Hazus classifies single-family, one-story homes into 160 unique WBIDs based on the combination of building options ( $i|n$ ) within the five mitigation categories ( $n$ ). A numerical coding system to describe each building WBID in the Hazus database was developed by Orooji and Friedland. (2017), shown in **Eq. (3)**, where  $\beta_n$  is the coefficient for mitigation category  $n$ . Values of  $i|n$  and  $\beta_n$  are provided in **Table 1**. The building options shown by underlined text in **Table 1** are standard building options expected in an unmitigated building. All other options provide additional resistance to wind hazards.

**TABLE 1 |** Descriptions and numerical coding for one-story, single-family, residential building WBID calculation (adapted from Orooji and Friedland 2017).

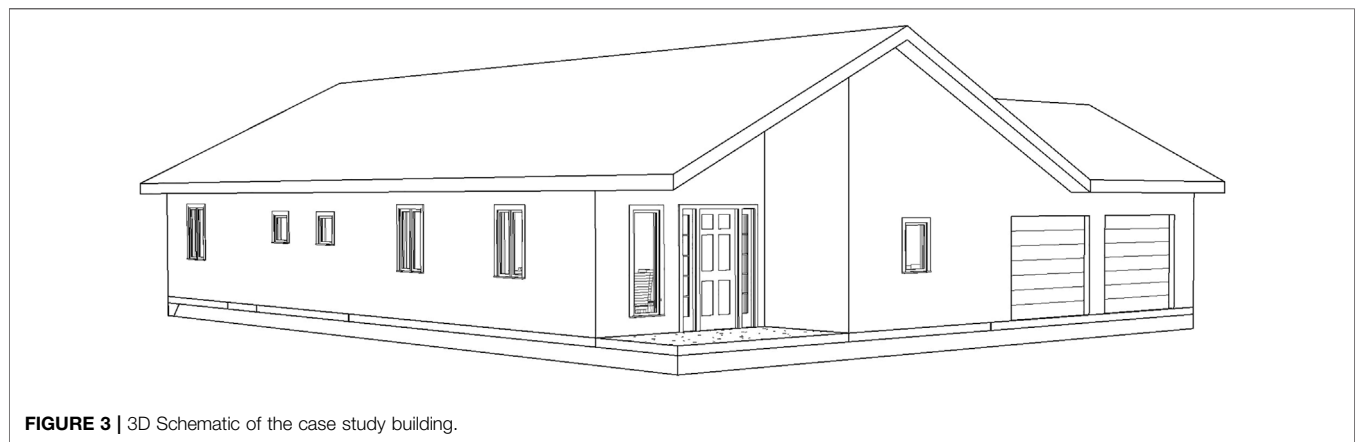
Mitigation category, $n$	1	2	3	4	5
Description	Roof shape	SWR	RDA nailing pattern	RTW connection	Shutter and garage door types
WBID. coefficient $\beta_n$	80	40	10	5	1
Building options and numeric coding, $i n$	Gable = 0 Hip = 1	No = 0 yes = 1 —	<u>6</u> days @ 152 mm/305 mm = <u>0</u> 6 days/8 days @ 152 mm/152 mm = 1 8 days @ 152 mm/305 mm = 2	Strap = 0 Toe-nail = 1	no shutters, no garage door = 0 shutters, no garage door = 1 no shutters, standard garage door = 2 shutters, SFBC garage door = 3 no shutters, weak garage door = 4

Underlining denotes standard building options that correspond to unmitigated buildings. SWR, secondary water-resistant barrier; RDA, roof deck attachment nailing pattern; RTW, roof-to-wall connection type.

**TABLE 2** | WBIDs corresponding to unmitigated buildings and mitigated buildings for each mitigation strategy, *m*.

<i>m</i> #	Description	WBID																	
0	Unmitigated	6	8	10	86	88	90	—	—	—	—	—	—	—	—	—	—	—	—
1	SWR	46	48	50	126	128	130	—	—	—	—	—	—	—	—	—	—	—	—
2	RDA	16	18	20	26	28	30	36	38	40	96	98	100	106	108	110	116	118	120
3	RTW	1	3	5	81	83	85	—	—	—	—	—	—	—	—	—	—	—	—
4	Shutter	7	9	87	89	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5	SWR + RDA	56	58	60	66	68	70	76	78	80	136	138	140	146	148	150	156	158	160
6	SWR + RTW	41	43	45	121	123	125	—	—	—	—	—	—	—	—	—	—	—	—
7	SWR + Shutter	47	49	127	129	—	—	—	—	—	—	—	—	—	—	—	—	—	—
8	RTW + RDA	11	13	15	21	23	25	31	33	35	91	93	95	101	103	105	111	113	115
9	RDA + Shutter	17	19	27	29	37	39	97	99	107	109	117	119	—	—	—	—	—	—
10	RTW + Shutter	2	4	82	84	—	—	—	—	—	—	—	—	—	—	—	—	—	—
11	RTW + RDA + SWR	51	53	55	61	63	65	71	73	75	131	133	135	141	143	145	151	153	155
12	RDA + SWR + Shutter	57	59	67	69	77	79	137	139	147	149	157	159	—	—	—	—	—	—
13	SWR + RTW + Shutter	42	44	122	124	—	—	—	—	—	—	—	—	—	—	—	—	—	—
14	RDA + RTW + Shutter	12	14	22	24	32	34	92	94	102	104	112	114	—	—	—	—	—	—
15	RTW + RDA + SWR + Shutter	52	54	62	64	72	74	132	134	142	144	152	154	—	—	—	—	—	—

SWR, secondary water-resistant barrier; RDA, roof deck attachment nailing pattern; RTW, roof-to-wall connection type.



**FIGURE 3** | 3D Schematic of the case study building.

$$WBID = \left( \sum_{n=1}^5 \beta_n \times i | n \right) + 1 \tag{3}$$

Based on the building options, WBIDs were categorized as “unmitigated” or “mitigated” using **Table 1**. WBIDs 6, 8, 10, 86, 88, and 90 do not have any mitigation options; therefore, **Table 2** categorized them as unmitigated buildings. All other buildings are considered to have at least one mitigation option. The 15 mitigation strategies with their corresponding WBIDs were defined in **Table 2**, where “SWR,” “RDA,” “RTW,” and “Shutter” referred to the implementation of mitigated building options for mitigation categories 2, 3, 4, and 5, respectively. Unmitigated building options are used for another category.

### Residential Wind Mitigation Cost

The one-story residential case study building utilized for this study was developed by Orooji and Friedland. (2021b), which assumes a floor area of 206m<sup>2</sup> (2,213 SF) and an unmitigated construction cost of \$258,487 located in a light suburban community in Louisiana (Latitude: 29.35, Longitude: 90.24).

**Figure 3** shows a 3D schematic of the case study building. Each mitigation strategy considered will result in additional new or retrofit construction cost, using the assumptions in **Table 3**, which were adapted from Orooji and Friedland. (2017) who obtained cost data from a local builder’s supply, “big box” stores, and published component-level housing cost data included in RSMean (Gordian, 2013).

### Average Annual Loss

Average annual loss (*AAL*) is the average expected loss per year calculated over a long period of time. It is calculated as the integral of the loss exceedance curve (**Eq. 4**). *AAL* can be expressed in two ways, first as a percentage of building value where the loss function is a function of building value, and second as absolute currency where the loss function is manifested in terms of currency. In this paper, *AAL* refers to an average annual loss in general, and *AAL*<sub>%</sub> and *AAL*<sub>\$</sub> refer to relative and absolute *AAL*, respectively.

$$AAL = \int_0^{\infty} v(P)dP \tag{4}$$

**TABLE 3 |** New and retrofit construction cost for each mitigation strategy in a one-story residential building (adapted from Orooji and Friedland 2017).

Mitigation options	New construction cost	Retrofit cost
SWR	\$1,200 (\$450 material and \$750 installation)	\$11,120 [\$1,200 for taping and \$9,920 for removing roof shingles and installing new roof shingles (\$3.2 per square foot)]
RDA 1	\$850 (adding nails and labor installation rate of \$0.25 per square foot)	\$10,770 [\$850 for adding nails and labor installation rate of \$0.25 per square foot and \$9,920 for removing roof shingles and installing new roof shingles (\$3.2 per square foot)]
RDA 2	\$200 (adding nails and labor installation rate of \$0.25 per square foot)	\$10,120 [\$200 for adding nails and labor installation rate of \$0.25 per square foot and \$9,920 for removing roof shingles and installing new roof shingles (\$3.2 per square foot)]
RDA 3	\$850 (adding nails and labor installation rate of \$0.25 per square foot)	\$10,770 [\$850 for adding nails and labor installation rate of \$0.25 per square foot and \$9,920 for removing roof shingles and installing new roof shingles (\$3.2 per square foot)]
RTW	\$1,500 (\$250 material cost for 180 straps, and \$1,250 for installation)	\$1,700 (\$250 material cost for 180 straps, and \$1,450 for installation, considering that the top 4 inches of drywall needs to be removed and reinstalled)
Shutter	\$3,128 (shutter cost and installation)	\$3,128 (shutter cost and installation)
Shutter + SFBC garage door	\$4,328 (\$3,128 shutter cost and installation + garage door reinforcement \$600 per single opening)	\$4,328 (\$3,128 shutter cost and installation + garage door reinforcement \$600 per single opening)

SWR, secondary water-resistant barrier; RDA, roof deck attachment nailing pattern; RTW, roof-to-wall connection type.

In the Hazus-MH Hurricane Model repository, direct economic loss functions are presented as a function of wind speed at 2.24 m/s (5 mph) intervals instead of continuous curves. Therefore, Monte Carlo simulation was used to estimate AALs for each type of direct economic loss function (Eqs 5–7).

$AAL_{b,\%}$ ,  $AAL_{c,\%}$ , and  $AAL_{u,\%}$  represent the average annual loss of building, content, and loss-of-use, respectively;  $S$  is the number of simulations; and  $Rand_s$  is a random number between zero and one generated for each simulation  $s$  representing the non-exceedance probability.  $F^{-1}(Rand_s)$  is the inverse of the cumulative Weibull distribution and returns the maximum annual wind speed for each simulation, and  $L_b$  [ $F^{-1}(Rands)$ ],  $L_c$  [ $F^{-1}(Rands)$ ], and  $L_u$  [ $F^{-1}(Rands)$ ] returns the building, content, and loss-of-use economic losses, respectively, as a proportion of building value corresponding to the maximum wind speed for simulation years.

$$AAL_{b,\%} = \frac{1}{S} \sum_{s=1}^S L_b [F^{-1}(Rand_s)] \tag{5}$$

$$AAL_{c,\%} = \frac{1}{S} \sum_{s=1}^S L_c [F^{-1}(Rand_s)] \tag{6}$$

$$AAL_{use,\%} = \frac{1}{S} \sum_{s=1}^S L_{use} [F^{-1}(Rand_s)] \tag{7}$$

Total average annual loss  $AAL_T$  as a proportion of building value,  $AAL_{T,\%}$  is the summation AAL of the building, content, and loss-of-use expressed as a ratio of building value (Eq. (8)). The absolute value of average annual loss in monetary terms,  $AAL_{T,\$}$ , is calculated by Eq. (9) where  $BV$  is a building value.

$$AAL_{T,\%} = AAL_{b,\%} + AAL_{c,\%} + AAL_{u,\%} \tag{8}$$

$$AAL_{T,\$} = AAL_{T,\%} \times BV \tag{9}$$

$AAL_{T,\%}$  data presented in this study were obtained from research conducted by (Orooji, 2015), who estimated by

WBID by summing the average of 50,000 Monte Carlo simulations for each type of loss (building, content, loss of use).

### Net Benefit and Payback Period

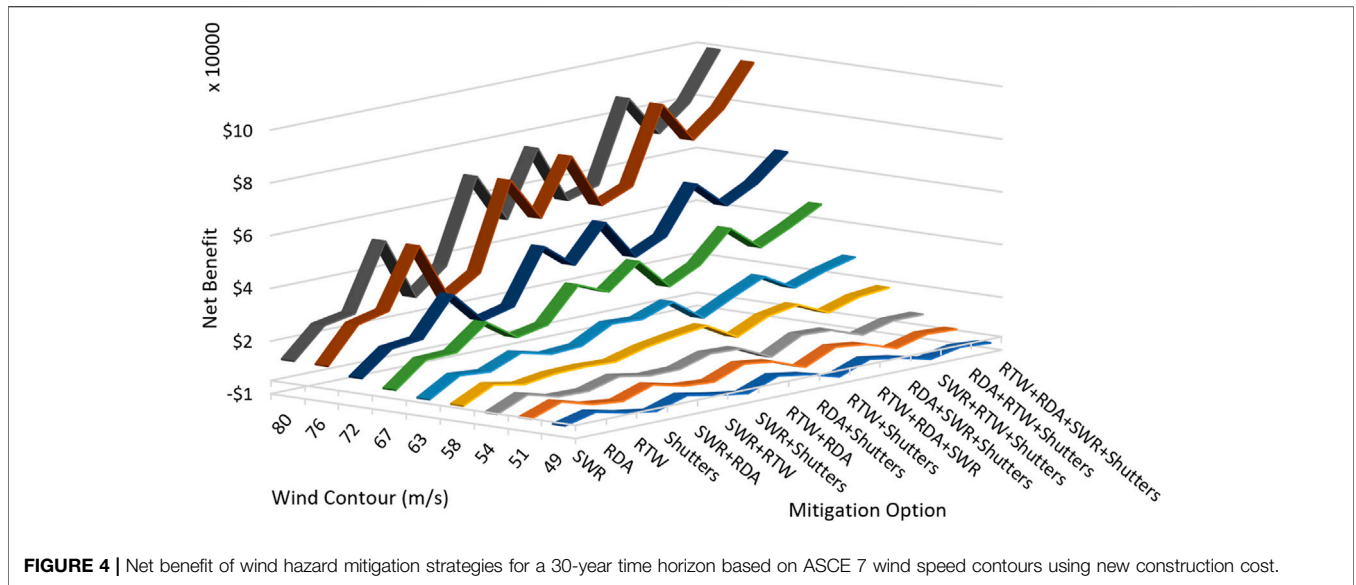
The life-cycle wind loss ( $L_K$ ) of these WBIDs is calculated using Eq. (10), considering an adjusted discount rate ( $R_{AD}$ ) of 4%, where  $K$  represents the decision-making time horizon (years) and  $B$  is the building cost.  $R_{AD}$  shows the relationship between inflation and discount rates. The cost of the material and installation, which depends on the type of construction (retrofit or new),  $C_m$ , is also included in the life-cycle wind loss calculation.

$$L_K = c_m + B \times AAL_{T,\%} \times \sum_{k=1}^K \frac{1}{(1 + R_{AD})^{k-1}} \tag{10}$$

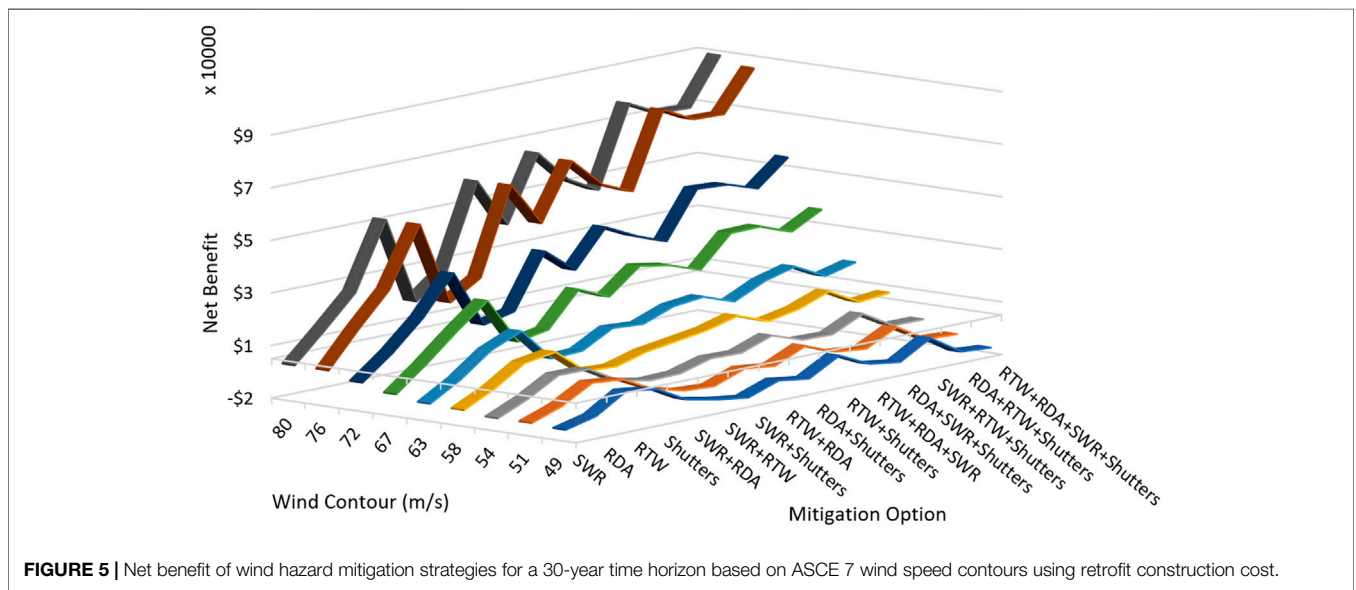
The life-cycle wind loss for mitigation strategy  $m$  ( $\overline{L_{K,m}}$ ) considering a  $K$  year life-cycle is calculated by averaging the WBID. The life-cycle wind loss ( $L_{K,w}$ ) for each mitigation strategy ( $m$ ) is listed in Table 2; (Eq. 11). The number of WBIDs in each mitigation strategy is represented by  $q$  and the value ranges from  $w_1$  to  $w_q$ . For example,  $m = 0$  in Table 2 signifies the generalized class of unmitigated buildings, and the mean life-cycle wind loss ( $\overline{L_{K,0}}$ ) is calculated by averaging the life-cycle wind loss of WBIDs 6, 8, 10, 86, 88, and 90.

$$\overline{L_{K,m}} = \left[ \frac{\sum_{w=w_1}^{w_q} L_{K,w}}{q} \right]_m \tag{11}$$

The cost effectiveness of a mitigation strategy within a particular wind contour indicates a positive net benefit ( $NB$ ) after implementing the mitigation strategy. Each mitigation strategy is analyzed by comparing the life-cycle wind loss before and after the implementation of the mitigation strategy. In other words, the net benefit of mitigation strategy  $m$  is the difference between the mean life-cycle wind loss of the



**FIGURE 4 |** Net benefit of wind hazard mitigation strategies for a 30-year time horizon based on ASCE 7 wind speed contours using new construction cost.



**FIGURE 5 |** Net benefit of wind hazard mitigation strategies for a 30-year time horizon based on ASCE 7 wind speed contours using retrofit construction cost.

unmitigated buildings ( $\overline{L_{K,0}}$ ) and the mean life-cycle wind loss after implementing the mitigation strategy  $m$  ( $\overline{L_{K,m}}$ ) (Eq. 12). To evaluate the cost effectiveness of mitigation scenario  $m$ , the net benefit/cost ratio ( $NBCR_m$ ), which is defined as the ratio of the net benefit of scenario  $m$  to the initial cost of the mitigation scenario ( $C_m$ ) is calculated (Eq. 13).

$$NB_m = \overline{L_{K,0}} - \overline{L_{K,m}} \tag{12}$$

$$NBCR_m = \frac{NB_m}{C_m} \tag{13}$$

To represent the variability of the calculated net benefit, a one-sample  $t$ -test is calculated to determine the 95% confidence

interval for the mean life-cycle wind loss across wind contours for each mitigation strategy ( $m = 0-15$ ).

Payback period is the time required for the net benefit to become zero. If zero net benefit occurs between any two decision-making time horizons, the payback period is calculated by linear interpolation.

## RESULTS

Net benefits can be positive or negative and are calculated for a building without insurance for wind hazard. Positive values occur

**TABLE 4 |** Payback period (in years) of mitigation strategies by wind contour, m/s (mph), for new construction (NC) and retrofit construction (RC).

m#	Description	49 (110)		51 (115)		53 (120)		58 (130)		62 (140)		67 (150)		71 (160)		75 (170)		80 (180)	
		NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC
1	SWR	>30	>30	>30	>30	>30	>30	11.9	>30	9.4	>30	5.3	>30	<5	>30	<5	>30	<5	>30
2	RDA	<5	>30	<5	>30	<5	>30	<5	>30	<5	>30	<5	20.1	<5	16.4	<5	7.6	<5	8.3
3	RTW	>30	>30	16.7	19.9	10.1	11.9	<5	5.7	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
4	Shutters	>30	>30	>30	>30	18.0	18.0	7.9	7.9	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
5	SWR + RDA	14.7	>30	7.4	>30	5.7	>30	<5	>30	<5	>30	<5	18.8	<5	13.3	<5	9.3	<5	9.9
6	SWR + RTW	>30	>30	23.6	>30	1.57	>30	6.4	>30	<5	>30	<5	16.3	<5	11.9	<5	7.6	<5	7.4
7	SWR + Shutters	>30	>30	>30	>30	15.7	>30	7.3	>30	<5	17.3	<5	9.3	<5	6.5	<5	<5	<5	<5
8	RTW + RDA	14.1	>30	7.1	>30	5.1	>30	<5	27.3	<5	17	<5	10.1	<5	7.4	<5	<5	<5	<5
9	RDA + Shutters	>30	>30	15.0	>30	9.3	>30	5.1	23.0	<5	13.7	<5	8	<5	5.6	<5	<5	<5	<5
10	RTW + Shutters	>30	>30	>30	>30	29.4	>30	10.3	10.8	6.5	6.8	<5	<5	<5	<5	<5	<5	<5	<5
11	RTW + RDA + SWR	23.9	>30	11.1	>30	7.4	>30	<5	26.5	<5	16	<5	9.5	<5	7	<5	<5	<5	<5
12	RDA + SWR + Shutters	>30	>30	18.9	>30	11.2	>30	5.9	21.8	<5	12.7	<5	7.3	<5	5.1	<5	<5	<5	<5
13	SWR + RTW + Shutters	>30	>30	>30	>30	22.8	23.9	9.6	10.0	6.0	6.1	<5	<5	<5	<5	<5	<5	<5	<5
14	RDA + RTW + Shutters	>30	>30	23.5	>30	13.3	>30	7.0	26.4	<5	14.8	<5	8.3	<5	6	<5	<5	<5	<5
15	RTW + RDA + SWR + Shutters	>30	>30	27.4	>30	14.6	>30	7.5	24.1	<5	13.5	<5	7.5	<5	5.1	<5	<5	<5	<5

SWR, secondary water-resistant barrier; RDA, roof deck attachment nailing pattern; RTW, roof-to-wall connection type.

**TABLE 5 |** Mitigation recommendation (mitigation strategy number) by wind contour, m/s (mph), for new construction (NC) and retrofit construction (RC) based on the highest net benefit (NB) and the highest net benefit cost ratio (NBCR).

Mitigation recommendation criteria	49 (110)		51 (115)		53 (120)		58 (130)		62 (140)		67 (150)		71 (160)		75 (170)		80 (180)			
	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC		
Highest NB	2	N	8	3	11	3	12	13	15	13	15	15	15	15	15	15	15	15	15	
Highest NBCR	2	N	2	N	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3

N, none of the mitigation strategies is recommended.

**TABLE 6 |** Mitigation recommendation by wind contour, m/s (mph), for new construction (NC) and retrofit construction (RC), for a 30-year time horizon.

	49 (110)		51 (115)		53 (120)		58 (130)		62 (140)		67 (150)		71 (160)		75 (170)		80 (180)		
	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	NC	RC	
SWR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
RDA	-	-	-	-	-	-	-	-	-	-	□	-	□	-	□	□	□	□	□
RTW	-	-	-	-	-	-	-	-	-	-	□	□	□	□	□	□	□	□	□
Shutters	-	-	-	-	-	-	-	-	-	□	□	□	□	□	✓	✓	✓	✓	✓
SWR + RDA	-	-	-	-	-	-	-	-	-	-	□	-	□	-	□	□	□	□	□
SWR + RTW	-	-	-	-	-	-	-	-	-	-	□	-	□	□	□	□	□	□	□
SWR + Shutters	-	-	-	-	-	-	-	-	-	□	-	□	□	✓	□	✓	✓	✓	✓
RTW + RDA	-	-	-	-	-	-	-	□	-	□	-	✓	□	□	✓	□	✓	✓	□
RDA + Shutters	-	-	-	-	-	-	-	□	-	□	-	□	□	✓	□	✓	✓	✓	✓
RTW + Shutters	-	-	-	-	-	-	-	-	-	□	□	□	□	□	✓	✓	✓	✓	✓
RTW + RDA + SWR	-	-	-	-	-	-	-	□	-	□	-	□	□	□	✓	✓	✓	✓	✓
RDA + SWR + Shutters	-	-	-	-	-	-	-	□	-	□	□	□	□	✓	✓	✓	✓	✓	✓
SWR + RTW + Shutters	-	-	-	-	-	-	-	-	-	□	□	□	□	✓	✓	✓	✓	✓	✓
RDA + RTW + Shutters	-	-	-	-	-	-	-	□	-	□	-	□	□	✓	□	✓	✓	✓	✓
RTW + RDA + SWR + Shutters	-	-	-	-	-	-	-	□	-	□	□	✓	□	✓	✓	✓	✓	✓	✓

SWR, secondary water-resistant barrier; RDA, roof deck attachment nailing pattern; RTW, roof-to-wall connection type.

“✓” denotes that the mitigation strategy has more than \$40,000 net benefit for the corresponding wind contour.

“□” denotes that the mitigation strategy has between \$25,000 and \$40,000 net benefit for the corresponding wind contour.

“○” denotes that the mitigation strategy has between \$10,000 and \$25,000 net benefit for the corresponding wind contour.

“-” denotes that the mitigation strategy has less than \$10,000 net benefit for the corresponding wind contour.

when the accumulated avoided losses exceed the new or retrofit implementation construction cost. Positive values represent mitigation strategies that are, on average, cost effective during

the time period considered. On the other hand, negative values occur when the reduction in AAL is not sufficient to recoup the new or retrofit construction costs within the given time horizon.



**TABLE 7** | Percent decreases in the average annual total loss due to mitigation parameters (minimum/average/maximum)—residential buildings (FEMA, 2012).

Mitigation strategy	Decrease in average annual building loss (%)		
	Minimum	Average	Maximum
Install shutters	17	33	46
Upgrade roof	3	16	49
Add secondary water resistance	3	12	35
Install shutters and upgrade roof	46	59	71
Install shutters, upgrade roof, and add secondary water resistance	51	68	85
Upgrade roof and add secondary water resistance	4	19	57

Negative values represent mitigation strategies that are, on average, cost ineffective during that time period.

**Figure 4** shows the average net benefit of the 15 evaluated wind hazard mitigation strategies for a 30-years time horizon on ASCE 7 wind speed contours for a newly constructed building on terrain ID 2 (0.15 m, light suburban). The highest net benefit occurs for the mitigation option that includes all the mitigation strategies, RTW + RDA + SWR + Shutter, inside the 62 m/s (140 mph) wind contour. But the same is not the case for wind speeds below 62 m/s (140 mph). The RDA mitigation strategy gives a higher positive result for wind speeds below 62 m/s (140 mph).

The net benefit of wind hazard mitigation strategies for a 30-years time horizon on ASCE 7 wind speed contours, based on the retrofit cost, is shown in **Figure 5**. The mitigation option that includes all the mitigation strategies, RTW + RDA + SWR + Shutter, has the highest net benefit inside the 67 m/s (150 mph) wind contour. Below 67 m/s (150 mph) the net benefit is higher for SWR + RTW + Shutter combination, and below 53 m/s (120 mph) winds RTW has a higher net benefit.

Whether a mitigation strategy is cost effective or not is highly dependable on the payback period. Here, the period is assumed to be 30 years. If a mitigation strategy gives positive values below the 30-years time horizon, the cost of mitigation strategy and the loss are redeemed within 30 years of the building life. If not, the mitigation strategy is considered cost ineffective within the 30-years time horizon. **Table 4** presents the payback period of mitigation strategies inside each wind contour for new and retrofit construction.

It is noteworthy that adding secondary water resistance and changing the nail pattern requires replacement of roof cover and maybe more economical if applied upon roof replacement. In addition, replacing toe-nail roof-wall connections with rated strap connections requires removal and reinstallation of the top 4 inches of drywall and maybe more economical if applied during drywall replacement (Orooji and Friedland, 2017). These retrofit adjustments can significantly reduce the payback period, similar to that of new construction for the mitigation strategies of SWR, RDA, RTW, and their combinations. **Table 5** provides mitigation strategies for each wind speed contour for the case study based on the highest net benefit and NBCR.

## DISCUSSION

In this study, the mitigation strategies are analyzed based on net benefit value and payback period. The payback period calculated in this study has some values that are outside the time frame

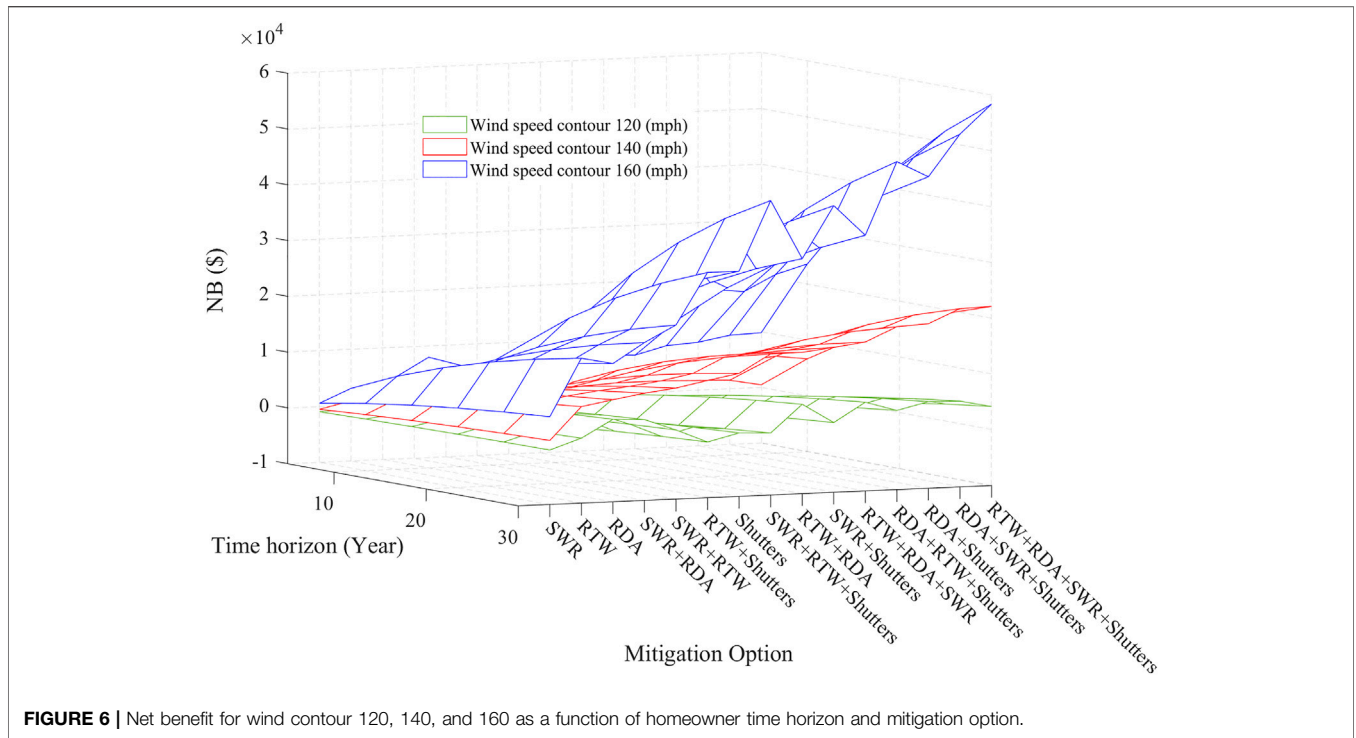
assumed for this study. Those values are not extrapolated to find the exact payback period outside the range, but instead they are denoted as “out of the range” values of >30 or <5 years.

The results show that all 15 mitigation strategies are cost effective within the 58 m/s (130 mph)–80 m/s (180 mph) wind contours, and all mitigation strategies except SWR only are cost effective inside the 53 m/s (120 mph) wind contour. Moreover, all mitigation strategies except SWR, Shutters, SWR + Shutters, RTW + Shutters, and SWR + RTW + Shutters are cost effective inside the 51 m/s (115 mph) wind contour. RDA, SWR + RDA, RTW + RDA, and RTW + RDA + SWR mitigation strategies are cost effective inside the 49 m/s (110 mph) wind contour. For retrofit construction, utilization of only SWR is not cost effective inside any wind contours shown. All other strategies are cost effective within the 67 m/s (150 mph)–80 m/s (180 mph) wind contours. Also, inside the 49 m/s (110 mph) wind contour, no mitigation strategy is cost effective, showing that the mitigation strategy is cost effective outside the 49 m/s (110 mph) wind contour only when installed during construction. Inside the 51 m/s (115 mph) wind contour, only RTW provides a cost-effective return on investment in 30 years.

**Table 5** shows mitigation recommendations in each wind contour based on the highest NB and NBCR. The most frequent strategy with the highest NB is strategy no. 15 (RTW + RDA + SWR + Shutters) with all mitigation practices together and the most frequent strategies with the highest NBCR are strategies no. 2 (RDA) and 3 (RTW).

**Table 6** shows the recommended mitigation strategies in each wind contour based on the net benefit for a 30-years time horizon for new and retrofit construction. The recommendations are categorized into four groups. First, highly recommended mitigations are mitigation strategies with more than \$40,000 in net benefit. The second and third groups are the mitigation strategies that have between \$25,000 to \$40,000 and \$10,000 to \$25,000 in net benefit after 30 years. The fourth category includes the mitigations that have less than \$10,000 in net benefit after 30 years and are denoted by “-”. To validate the results, the percentage decreases in the average annual total loss by mitigation strategy reported by Hazus were presented in **Table 7**.

Under unprecedented hazard scenarios, increases in wind intensity may damage even the residences that have applied the recommended mitigation plan. The recommended mitigation strategies, which are effective for the 30-years payback period, exhibit cost-effectiveness for only ASCE 7 wind speed contour intervals, which is a basic wind speed followed as a standard in engineering building codes. Extra caution should be taken to avoid risks due to intensified wind, which may become more common in



**FIGURE 6 |** Net benefit for wind contour 120, 140, and 160 as a function of homeowner time horizon and mitigation option.

the future under climate change scenarios. **Figure 6** implies that for each of the 15 mitigation strategies, the net benefits have large gaps among the contour surface along the y- and z-axes, for all five mitigation categories over a 30-years time horizon. Thus, one should apply the best judgment for receiving risk-free net benefit based on the location of the building within the existing wind contour and the probability of experiencing a more intense wind over the relevant time horizon.

According to FEMA. (2012),  $AAL_T$  can be reduced only by implementing six of the 15 mitigation strategies, i.e., by 1) installing shutters, 2) upgrading roof, 3) adding SWR, 4) installing shutters and upgrading roof, 5) installing shutters, upgrading roof, and adding SWR, and 6) upgrading roof and adding SWR. For each of these mitigation strategies, one can decrease the AAL by 12–68 percent, on average. For example, upgrading the roof of a residential building can reduce the  $AAL_T$  by 3–49 percent, while installing shutters, upgrading roof, and adding SWR can reduce the average annual total loss by 51–85 percent. These six mitigation strategies make a huge contribution to reducing the AAL; therefore, one should consider these mitigation strategies for either new construction or retrofit.

### ADDITIONAL ASSUMPTIONS, LIMITATIONS, AND FUTURE WORK

This study is based on loss functions extracted from the Hazus-MH version 3.2 database. Hence, the calculated net benefit depends on the accuracy of the Hazus-MH loss functions. The latest version of Hazus-MH (version 4) can be utilized in future work to calculate the net benefit. Also, wind directionality was not

considered in this study, since in Hazus, wind direction is an attribute for engineered building types, and it is not an attribute for wood-frame single-family homes.

The nature of our analysis focuses on using the mitigation techniques presented in Hazus. However, the practicality of some of the mitigation strategies for existing buildings (e.g., RTW), needs further investigation. For example, strengthening a component can lead to overload of an unretrofitted, component. In future work, FORTIFIED Roof™ (<https://fortifiedhome.org/roof/>) by Insurance Institute for Business & Home Safety (IBHS) can be considered as one of the mitigation strategies that have a combination of all mitigation practices for the roof component of a building.

The AALs are calculated for ASCE 7 Risk Category II wind contours. The life cycle cost analysis includes AAL and does not account for homeowner’s insurance. Because insurance premiums are a significant life-cycle cost, these will be included in future work. Moreover, for new construction, for which the cost of wind mitigation is typically amortized into a monthly mortgage payment, the homeowner may realize significant savings on the insurance that reduce the overall cost of ownership and shorten or eliminate the payback period. Inclusion of policy payments requires a different analysis that simulates individual events and apportion loss to the homeowner or the insurance carrier.

Although hurricane is a multi-hazard (e.g., surge/flooding, rain, debris), in this study, authors only considered the wind effect of hurricane on building to isolate the impact of wind mitigation options with regards to the wind hazard.

The repair or replacement cost in this paper is adopted from RSMMeans cost of new construction but the actual repair cost can be higher due to the cost of removing the damaged components.

Also, the costs are always prone to change as the prices for material and labor change daily. Therefore, the numbers are used in this research solely to explain the methodology and changing them can affect the recommended mitigation strategies based on the net benefit cost ratio. In future studies, more comprehensive cost studies can improve the accuracy of results.

The literature on the impacts of climate change on extreme winds is conflicting, and since there is still debate about the future of thunderstorm activity, it should come as no surprise that there remains a general lack of consensus regarding the impact of global climatic change on tornado frequency and/or intensity. Forecasts are difficult to make, even with the most advanced general circulation models (GCMs), in part because of the vast difference in scale between model output and the local nature of the weather conditions that create tornadoes. Furthermore, an incomplete understanding of the physics involved in tornadic development complicates projections. Therefore, in this study, the impact of climate change is not considered.

For future work, sensitivity analysis will be performed to evaluate the analysis by changing the cost of the building value and understanding the impact of fluctuating material cost. Since this analysis depends on the building value of a one-story, single-family, residential wood-framed building, future work should consider varied unit costs of the building. If the results replicate the same trend in the net benefit and payback period values, the confidence of the results will be improved. Also, the sensitivity analysis can be performed on the selection of other ranges of discount rates. The other factors that vary over time are new and retrofit cost and adjusted discount rate. These factors should also be considered in the sensitivity analysis by varying one factor at a time while holding all others constant. Finally, the impact potential climate change effects will be considered in future work to support longer time horizons for building mitigation avoided loss analysis.

## SUMMARY AND CONCLUSION

This research presents the generalized cost effectiveness of residential wind mitigation strategies for wood-frame, single-family housing in the United States. Results show that significant opportunities exist to improve economic resilience to wind hazards. Implementing cost effective wind mitigations pays off the initial or retrofit cost within the building life while improving the overall performance of buildings. Building codes have minimum standards for mitigation strategies in wind-prone areas. Enhancing the building codes based on this and future analysis will result in better building performance against wind hazards and benefit citizens and communities financially through decreased public assistance. Important contributions of the study are as follows:

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- cost effectiveness of mitigation strategies inside different wind contours for new and retrofit construction, considering a wood-framed, single-family residential building
- net benefit of the mitigation strategy for a combination of 15 wind mitigation strategies, with new and retrofit construction costs ranging between \$1,200 and \$12,000 and a decision-making time horizon ranging between 5 and 30 years
- payback periods for each mitigation strategy and results summarized by net benefit for all ASCE 7 wind speed contour intervals
- enhanced economic benefits of implementing mitigation strategies during building construction rather than as a retrofit

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

RS initiated the research, data analysis, and manuscript preparation. FO improved the methodology and contribute to the analysis. CF provided original ideas and supervised this research and advice on the overall project methodology. CM, AT, and NB assisted in running the analysis. FO, CF, AT, CM, RS, NB, and RR contributed the organizing the research, formulation, and selection, and evaluation of the case study as well as writing of the manuscript. All authors contributed to the article and approved the submitted version.

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