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Extension of the Performance-Based Hurricane Engineering (PBHE) Framework to Account for Climate Change and Structural Aging Effects

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ABSTRACT: The US Gulf and Atlantic coasts are frequently affected by severe tropical storms, locally known as hurricanes, which produce significant economic and life losses every year. The effects of climate change and structural aging are expected to further exacerbate the hurricane risk in this region. Wooden single-family houses are particularly vulnerable to hurricane wind and windborne debris actions. This paper extends the performance-based hurricane engineering (BPHE) framework to account for the nonstationarity of both hazard (induced by climate change) and vulnerability (induced by structural aging). In particular, existing structural aging models and a predictive model for hurricane wind speed distributions under changing climate conditions are combined to derive a multi-layer Monte Carlo simulation approach for probabilistic damage, loss, and cost-benefit analysis. The effects of different nonstationarity assumptions (i.e., climate change only, structural aging only, and climate change in conjunction with structural aging) are investigated, and their implications are discussed. The proposed methodology is demonstrated through the hurricane loss analysis of a wooden single-family house located in Pinellas Park, FL. For this application example, both climate change effects and structural aging effects are significant when considered independently. The combined effects of climate change and structural aging can increase the expected total losses during a 50-year design service life by as much as 96% when compared to the case with no climate change and no structural aging.

1. INTRODUCTION

The Gulf and Atlantic coasts of the United States are frequently affected by hurricanes, which produce economic losses that are usually of the order of several billion dollars, as well as significant life losses. Climate change is expected to exacerbate these losses due to the predicted increase in sea water temperature and sea water level (Emanuel 2005; Stocker et al. 2013; Cui and Caracoglia 2016; Pant and Cha 2018; Esmaeili and Barbato 2021, 2022). In addition, the strength of structural components can degrade over the lifetime of a structure via a process called structural aging, which can be produced by environmental stressors and repeated loading (Berdahl et al. 2008; Bisadi and Padgett 2015; Li et al. 2015; Alhawamdeh and Shao 2021).

Previous studies by the author have developed the performance-based hurricane engineering (PBHE) framework (Barbato et al. 2013a) and then extended it to account for the effects of climate change on the loss analysis of wooden single-family homes (Esmaeili and Barbato 2022). The effects of climate change were assessed via a predictive model for wind speed distributions based the projection scenarios from the fifth assessment report (AR5) by intergovernmental panel on climate change (IPCC) (Stocker et al. 2013) and historical statistics of intensity measures used to describe hurricanes (Esmaeili and Barbato 2021). However, the combined effects of nonstationary hazard induced by climate change and nonstationary vulnerability produced by structural aging have not yet been investigated. In particular, the existing PBHE framework even in its extended version cannot accommodate both sources of nonstationarity.

This study proposes a new extension of the PBHE framework that can account for both hazard and vulnerability nonstationarity, thus enabling the consideration of both climate change and structural aging effects. The newly extended framework is applied to the loss analysis of light-frame wooden single-family houses, which are common in the US Gulf and Atlantic coasts. Existing aging models that are appropriate for wooden structures are reviewed and selected for this application. Finally, the expected losses obtained considering the combined effects of climate change and structural aging are compared with those obtained by considering no climate change or structural aging, climate change only, and structural aging only effects.

2. NEW EXTENDED PBHE FRAMEWORK

The extended PBHE framework presented in this study is based on the PBHE framework developed by Barbato et al. (2013a) and its extension by Esmaeili and Barbato (2022). The performance of a target structure is described by a decision variable (DV), which depends on damage measures (DM), engineering demand parameters (EDP), intensity measures (IM), structural parameters (SP), interaction parameters (IP), and a vector of climatological parameters (C). The probabilistic description of the selected DV is given by:

$$
\begin{aligned}
G\left(DV_{t,\tau}\right) = & \int\int\int\int\int\int G\left(DV_{t,\tau} \middle| DM_\tau\right) \\
& \cdot f\left(DM_\tau \middle| EDP, C_t\right) \cdot f\left(EDP \middle| IM, IP, SP_\tau\right) \\
& \cdot f\left(IP \middle| IM, SP_\tau\right) \cdot f\left(IM \mid C_t\right) \cdot f\left(SP_\tau \mid C_t\right) \\
& \cdot f\left(C_t\right) \cdot \mathrm{d}DM_\tau \cdot \mathrm{d}EDP \cdot \mathrm{d}IM \cdot \mathrm{d}IP \cdot \mathrm{d}SP_\tau \cdot \mathrm{d}C_t
\end{aligned} \quad (1)
$$

where a subscript t denotes explicit dependence on the global time scale (i.e., calendar year); a subscript τ denotes explicit dependence on the structural time scale (i.e., age of the structure); $G(\bullet)$ = complementary cumulative distribution function (CDF); $G(\bullet|\bullet)$ = conditional complementary CDF; $f(\bullet)$ = probability density function (PDF); and $f(\bullet|\bullet)$ = conditional probability density function. The climatological parameters, C_t, depend explicitly on the global time scale to account for the effects of climate change. In this study, the solution of Eq. (1) is obtained using a multilayer Monte Carlo simulation approach (Barbato et al. 2013a; b; Unnikrishnan and Barbato 2015, 2016, 2017).

3. AGING MODELS

The modeling of structural aging is highly dependent on the structural materials and the stressors that can produce deterioration of structural components. For light-frame wooden single-family homes, the main deterioration mechanisms are associated with wood components, roof covers, and nailed connections.

3.1. Aging Models for Wooden Components

Degradation of wooden components can be identified as the irreversible changes in the mechanical, physical, and chemical properties of the material due to applied environmental and biological stressors (Kránitz et al. 2016). Aging by itself does not affect most of the mechanical properties of wood (e.g., compressive strength, Young's modulus, shear strength) for periods shorten than a century, although, some wood species might become more brittle (Kránitz et al. 2016). In order for degradation to take place, biological stressors controlled by temperature and relative humidity need to affect the wood. Stirling et al. (2017) performed a detailed literature review on organisms that can affect western red cedar wood, and identified a list of fungi that can be particularly damaging for wood products. Droin et al. (1988) developed a model for kinetics of moisture adsorption of wood, which is critical in determining the severity of biological stressors on wooden components. Witomski et al. (2016) investigated the changes in the strength of Scots pine wood due to mass loss caused by brown rot and white rot fungi, and observed that the bending strength could decrease by 50% in correspondence to 7% and 20% of decayed wooden mass due to brown rot and white rot, respectively.

In this work, the biological mass loss of wood caused by fungi is modelled following the empirical mass loss decay model proposed by Viitanen et al. (2010), which considers the effects of relative humidity, *RH*, air temperature in °C, *T*, and age of the wood in hours, τ_w . In this model, decay process is described by an activation parameter, $\alpha(\tau_w)$, which assumes values between zero (before any weathering of the wood) and 1 (when mass loss is initiated). Both activation and mass loss processes occur only when $RH \geq 95\%$ and $T \geq 0$°C. The mass loss percentage, $ML(\tau_w)$, is given by:

$$ML(\tau_w) = \sum_{i=1}^{n} \left[\left. \frac{\mathrm{d}ML(RH,T)}{\mathrm{d}\tau} \right|_i \cdot \Delta\tau_{w,i} \right] \quad (2)$$

where $\left. \frac{\mathrm{d}ML(RH,T)}{\mathrm{d}\tau} \right|_i = 0$ when $\alpha(\tau_w) < 1$, and $\left. \frac{\mathrm{d}ML(RH,T)}{\mathrm{d}\tau} \right|_i$ is a positive linear function of *RH* and *T* when $\alpha(\tau_w) = 1$. The wooden mass loss produces a relative reduction in the modulus of rupture (MOR), $R_{MOR}(\tau_w)$, which can be modeled as a random variable defined between zero and 1 by using the experimental data reported by Curling et al. (2002) for southern pine wood affected by brown rot.

3.2. Aging Models for Roof Covers

The model for the strength loss of shingles is derived by using the data in Dixon et al. (2014), which reported the percentage of fully or partially unsealed shingles observed in field inspections of roofs as a function of the roof shingle age. The ratio of unsealed field shingles is given by:

$$R_{shingle}(\tau_s) = \begin{cases} 0 & \tau_s \leq 6\text{y} \\ 0.0 < 0.0257 \cdot \tau_s \\ -0.1542 + \varepsilon_{shingle} \leq 1.0 & \tau_s > 6\text{y} \end{cases} \quad (3)$$

where $\varepsilon_{shingle}$ is a random variable assumed to follow a normal distribution with zero mean and standard deviation equal to 0.2, and τ_s denotes the age (in years) of the shingles. The non-stationary uplift strength of roof shingles is modeled as:

$$F_{shingle}(\tau_s) = F_{shingle,0} \cdot \left[1 - R_{shingle}(\tau_s) \cdot R_{unsealing} \right] \quad (4)$$

in which $F_{shingle,0}$ represents the random variable describing the uplift strength of the shingles for the as-built structure, and $R_{unsealing}$ is random variable used to describe the relative portion of unsealing for all roof shingles.

3.3. Aging Models for Nailed Connections

The strength of nailed connections generally degrades due to a combination of repeated loading/unloading cycles, mass loss of the connected wood members, and metal rusting effects. In this study, the metal rusting effects are neglected based on a preliminary analysis of the rust formation on the nail perimeter using the corrosion model proposed by Zelinka (2013).

The pull-out strength degradation due to wooden mass loss is modeled using the data presented in Takanashi et al. (2017), which reported the reduction in withdrawal strength for joints with nails in radial and tangential joints as a function of *ML*. The withdrawal strength reduction due to wood decay, $R_{nail,w}(\tau_w)$, is assumed equal to 1 (i.e., full strength loss) for $ML > 40\%$, whereas for $ML \leq 40\%$ is given by:

$$R_{nail,w}(\tau_w) = 1 - 0.0313 \cdot \tau_w + \varepsilon_{R_{nail,w}} \quad (5)$$

where $\varepsilon_{R_{nail,w}}$ is the regression error, which is assumed to follow a normal distribution with mean equal to zero and standard deviation equal to 0.218.

The separation strength of the roof sheathing, $F_{rs}(\tau_w)$, and of the wall sheathing subject to pressure action, $F_{pws}(\tau_w)$, are assumed to be proportional to the residual withdrawal strength of the nails and are given by:

$$F_{rs}\left(\tau_w\right) = F_{rs,0} \cdot \left[1 - R_{nail,w}\left(\tau_w\right) \cdot R_{rs,rot}\right] \quad (6)$$

$$F_{pws}\left(\tau_w\right) = F_{pws,0} \cdot \left[1 - R_{nail,w}\left(\tau_w\right) \cdot R_{ws,rot}\right] \quad (7)$$

respectively, in which $F_{rs,0}$ and $F_{pws,0}$ represent the random variables describing the separation strength of the roof sheathing and of the wall sheathing subject to pressure action for the as-built structure, respectively, and $R_{rs,rot}$ and $R_{ws,rot}$ a random variable used to describe the relative portion of roof and wall sheathing, respectively, affected by rot.

The fatigue load effects on the nail pull-out strength are modelled according to Alhawamdeh and Shao (2021) as:

$$R_{nail,f} = A \cdot N_f^B \quad (8)$$

in which $R_{nail,f}$ denotes the fatigue load normalized by the static capacity (also known as load reduction factor), N_f is the number of constant amplitude cycles to failure, and A and B are regression constants that depend on the connection configuration, the nail material, and the wood material. For the case of Douglas Fir wood with no adhesive, A and B assume the values of 2.484 and -0.140, respectively. In addition, the Miner's linear cumulative damage model is used to correct for non-constant amplitude effects (Miner 1945).

4. SIMULATION PROCEDURE

The simulation procedure used in this study to account for the effects of structural aging consists of three steps: (1) simulating weather data based on future climatological conditions, (2) estimating the decay in strength of the different structural components, and (3) estimating hurricane wind losses for the aged structure.

4.1. Simulating Weather Data

Weather data simulation is needed to produce future time series of T and RH for any given location of interest, which are then used as input for the adopted aging models. These aging models require hourly temperature, T_h, and hourly relative humidity, RH_h. In this study, the probability distributions of the hourly temperature and relative humidity are obtained from the probability distributions of the deviations between the corresponding yearly, monthly, daily, and hourly quantities, which are obtained from historical data and are assumed to be stationary. For example, the time series of the hourly temperature in a given future year is obtained by: (1) sampling the projected change in the yearly temperature, ΔT_y, following the procedure described in Esmaeili and Barbato (2021); (2) sampling the monthly deviations, ΔT_m, for each month in a year; (3) sampling the daily deviations, ΔT_d, for each day in a given month; and (4) finally sampling the hourly deviations, ΔT_h, for each hour in any given day. A similar approach is followed also for simulating the time series for RH_h. Figure 1 shows the comparison of one year of historical data for T_h and RH_h in Pinellas Park, FL, with the corresponding samples obtained using the proposed random sampling procedure.

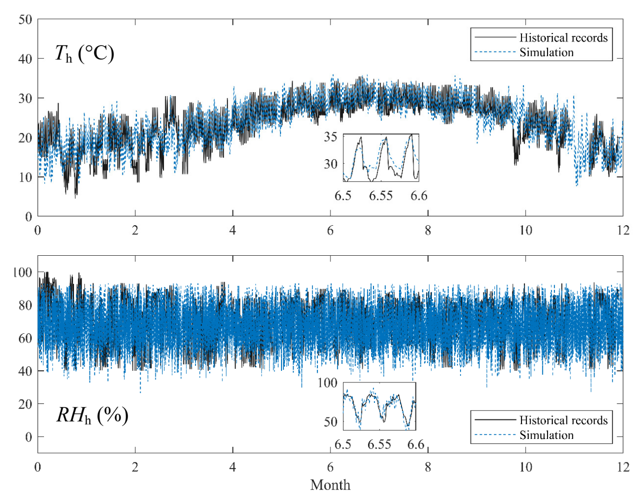

Figure 1: Comparison of historical records and sample realizations for 1-year period of temperature and relative humidity in Pinellas Park, FL.

4.2. Simulating Strength Decay

The strength degradation of the different components described by the models given in Eqs. (2) through (7) is obtained by using as input the sample time series of T_h and RH_h. The strength degradation of the nailed connections is obtained using Eq. (8), in which the applied load can be modeled as a function of the yearly peak wind speed. The yearly peek wind speed is sampled using the model proposed in Esmaeili and Barbato (2021). The number of load cycles is estimated based on the duration of sustained peak wind speed. This study uses a simplifying assumption that the duration of sustained peak wind speed for hurricanes can be modeled as a normally-distributed random variable with a mean equal to 2 hours and a standard deviation of 30 minutes. It is observed here that strength decay is a process with memory, i.e., irreversible unless repairs are performed. Therefore, when considering structural aging, while weather time series can be sampled independently for different years, the degradation effects need to be simulated for the entire design service life of a structure under consideration.

4.3. Loss Estimation

The total losses over the design service life of a structure are estimated using a multi-layer Monte Carlo simulation approach described elsewhere (Barbato et al. 2013a; Unnikrishnan and Barbato 2016, 2017; Esmaeili and Barbato 2022). The hazards considered in this study are wind and windborne debris, which are sampled using the predictive model proposed in Esmaeili and Barbato (2021). It is noted here that, when accounting for structural aging, due to the memory of the degradation process, a single sample needs to span the entire time period under investigation (typically the design service life of the structure of interest). By contrast, when both climate change and structural aging are neglected, as in the original PBHE framework (Barbato et al. 2013a), or when only climate change effects are considered, as in the first extension of the PBHE framework (Esmaeili and Barbato 2022), the sampling process of the hurricane losses in any given year can be performed independently from the sampling of any different year, as the considered processes are memoryless.

5. CASE STUDY

The case study presented in this paper is a single-family wooden structure located in Pinellas Park, FL. The annual frequency at the site is equal to 0.514 hurricanes per year. The house is considered as part of an existing residential development, as shown in Figure 2, where the considered building is identified by a red circle.

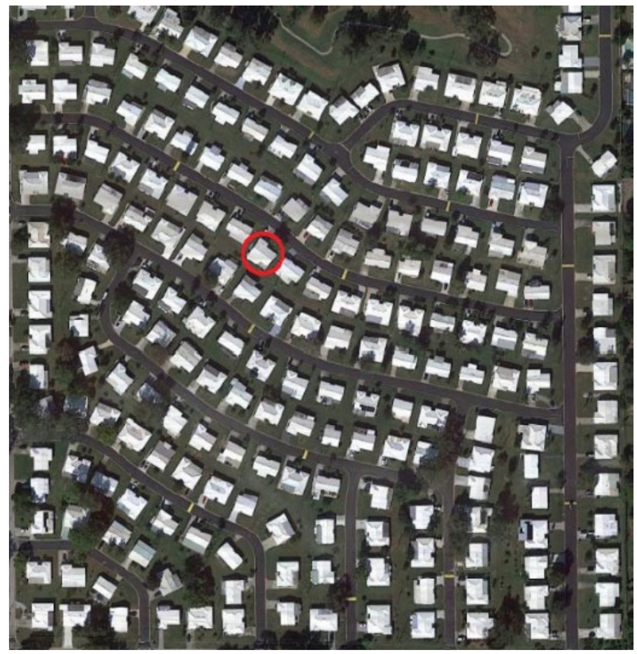

Figure 2: Overview of the residential development with considered building identified by a red circle.

The house has plan dimensions equal to 40ft (12.19m) by 60 ft (18.28m), with wall of height equal to 10ft (3.05m) and a gable roof with a 5/12 slope. The unfolded view of the structures is shown in Figure 3. The construction year for this house is assumed to be 2015, and the loss analysis is performed for an assumed 50-year design service life, i.e., for the period 2015-2065.

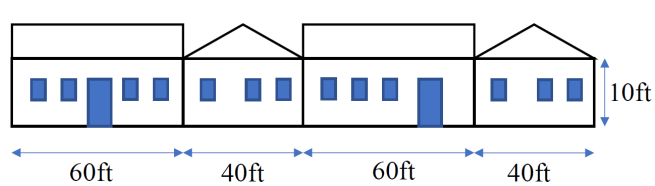

Figure 3: Unfolded view of the considered house.

5.1. Modeling Assumptions

The following limit states are considered: (1) separation of the roof cover (shingles), (2) separation of the roof sheathing (corresponding to a 6d C6/12 nailing pattern), (3) pressure failure of windows, (4) impact failure of windows (assumed unprotected), (5) pressure failure of doors, (6) tension failure of roof-to-wall connections, (7) uplift failure of wooden walls, (8) lateral failure of wooden walls, (9) pressure failure of the wall sheathing, and (10) impact failure of the wall sheathing. The complete statistical descriptions of the capacities corresponding to these limit states and of the costs associated with the repair of the associated damage are reported elsewhere (Unnikrishnan and Barbato 2016; Esmaeili and Barbato 2022). The strength degradation is also function of the exposure level for wood components prone to mass loss. In this application example, high exposure is assumed, which corresponds to assuming $R_{ws,rot} = 0.30$ and $R_{rs,rot} = 0.50$ in Eqs. (6) and (7).

A constant discount rate equal to 3% is assumed for all loss analyses. At the beginning of the sampling procedure, the values of the strengths corresponding to the different limit states considered in this study are sampled together with 50 years of hurricane events according to the model presented in Esmaeili and Barbato (2021). To assess the effects of climate change, the following representative concentration pathways (RCP) from the IPCC AR5 (Stocker et al. 2013) are considered: RCP 2.6 (carbon emission decline starting in 2020), RCP 4.5 (carbon emission decline starting in 2040), RCP 6.0 (carbon emission decline starting in 2080), and RCP 8.5 (no carbon emission decline during the 21st century). When a structural component is damaged during the 50-year sample, it is assumed that the component is immediately replaced and the cost of replacement is immediately added to the losses. If structural aging is considered, the strength reduction and the damage index representing the fatigue effects are modeled as non-decreasing (i.e., the probability distributions at a given year are conditional to the current value being higher than the value in preceding years). However, when an aged component is damaged and replaced, it is assumed that the aging of the new component restarts from the beginning.

5.2. Analysis Results

The expected losses associated with the considered structure and different modeling assumptions are presented in Table 1. All analysis results are based on 100,000 samples obtained using the procedure described in this paper.

Table 1: Analysis results in terms of expected total losses for the considered structure.

Assumptions	**No aging**	**Aging**
No climate change	$52,738	$69,957
RCP 2.6	$60,650	$85,623
RCP 4.5	$65,460	$92,844
RCP 6.0	$59,678	$83,998
RCP 8.5	$72,831	$103,360

The results reported in Table 1 indicate that the effects of the nonstationarity individually induced by climate change and structural aging are substantial. The expected total losses suffered by the reference structure when considering only climate change effects (i.e., no structural aging) increase between 15.0% (RCP 2.6) and 38.1% (RCP 8.5) when compared to the baseline case corresponding to no climate change and no aging during the 2015-2065 period. The effects of structural aging alone (i.e., when neglecting climate change effects) produce a 32.7% increase of expected total losses when compared to the baseline case.

It is also observed that the combined effects of climate change and structural aging are highly nonlinear, as they produce increases in the expected total losses that are significantly higher than the sum of the individual effects. In fact, when both climate change and structural aging are included in the analysis, the expected total losses increase between 62.4% (RCP 2.6) and 96.0% (RCP 8.5). It is concluded that, for the application example considered, considering the effects of both climate change and structural aging is crucial to estimate expected total losses. These estimates are needed for guiding optimal design and retrofit decisions.

6. CONCLUSIONS

In this study, the performance-based hurricane engineering (PBHE) framework is extended to account for both hazard nonstationarity induced by climate change and vulnerability nonstationarity caused by structural aging. Existing degradation models for different structural components of wooden single-family homes are used in conjunction with a new sampling technique to generate temperature and relative humidity time series for future years. The proposed methodology is applied to the loss analysis of a light-frame wooden single-family house located in in Pinellas Park, FL, during a 50-year design service life of the structure corresponding to the 2015-2065 period. The model for nonstationarity of hurricane wind hazard under climate change scenario is adopted from a previous study by Esmaeili and Barbato (2021a), where climate change scenarios were based on the fifth Assessment Report of the Intergovernmental Panel on Climate Change. In order to account for the uncertainties for the future climatological conditions, a multi-layer Monte Carlo simulation approach is utilized. Four different cases are investigated: (1) no climate change and no structural aging; (2) climate change and no structural aging; (3) no climate change and structural aging; (4) climate change and structural aging. It is found that the effects of both climate change and structural aging are significant when considered independently. In addition, their interaction can substantially and nonlinearly increase the expected total losses for the considered structure, with increases as high as 96% for RCP 8.5 and high exposure when compared to the case in which both climate change and structural aging are neglected. It is concluded that both climate change and structural aging effects, as well as their interaction, need to be considered when performing a hurricane-induced loss analysis of light-frame wooden houses. Further research is needed to assess the effects of climate change and structural aging in locations prone to coastal flooding. In this study, several assumptions need to be further investigated, e.g., the assumed models for repair time, discount rate, fatigue effects, and exposure level to wood mass loss should be improved by future studies.

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