Impacts of Climate Change on the Assessment of Long-Term Structural Reliability

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Abstract: Global climate change has triggered studies across various science and engineering fields. This study demonstrates the need to account for climate change in assessing structural reliability. Civil engineering infrastructure is generally expected to function and serve over decades, and it should be able to withstand the various environmental changes that will occur in its lifetime. The authors study the impacts of climate change on the long-term resistance and loading of infrastructure by using global climate projections through the end of this century. The individual effects on resistance and loading are studied and then aggregated to estimate the projected net structural reliability. These results are compared with those of the case with no climate change to investigate relative effects. Global mean changes in natural hazard events are used to account for changes in loading patterns. The effect on resistance is studied by using time-dependent structural aging through a proposed degradation function accounting for different modes of degradation, including temperature effects, carbonation, corrosion, and fatigue. Global means are used in this study with results that can be applied to the conditions at specific locations for reliability assessment of particular structures. The authors show that seemingly small changes in climate have significant impacts on long-term structural reliability. **DOI: 10.1061/AJRUA6.0000906.**

Introduction

Global climate change is one of the most important concerns that we face in the coming years. The effects of climate change are multidimensional, ranging from natural ecosystems to the built environment, with social, health, safety, and economic impacts. Therefore, the study of the effects of global climate change is relevant in many science and engineering disciplines, including civil engineering. Civil engineering infrastructure is required to withstand and resist any weather-based environmental activity. Furthermore, civil engineering infrastructure is designed to function over many decades. There exists a direct connection between the changes in short-term weather patterns and long-term climate fluctuations with the state of infrastructure. Therefore, it becomes necessary to study the effects of climate change on long-term structural reliability.

Climate change models provide projections of global and regional changes for different environmental parameters and natural hazards. In considering civil infrastructure reliability, environmental factors such as concentration of carbon dioxide and temperature may affect the rate of corrosion, whereas temperature also induces thermal loads, effectively reducing the available resistance of infrastructure components. In addition, the change in the frequency, intensity, and extent of natural hazards including hurricanes, tornados, snow, and precipitation affects the design load on the structure. Although a relatively small short-term change may not be significant, the changes in long-term reliability need to be studied to address sustained incremental changes.

In this paper, the authors study the impacts of climate change by quantifying the individual effects of changes in different environmental factors on the resistance and loading of a structure. The probabilistic assessment of individual variation in both the resistance and load functions at an instant of time allows for the approximation of structural reliability at that time. Performing similar calculations over longer timescales enables the estimation of the time-dependent variation of reliability over a given duration. As infrastructure components are expected to function over long service lifetimes, it becomes important to assess the change in reliability over the duration of the design life while accounting for the changes in the surroundings and environment during the period. The results presented are valid in relative terms compared with those of the case without considering such effects.

This study uses climate change projections to investigate their impacts on civil infrastructure. The effects of a rise in temperature are threefold on the structure with a decrease in modulus of elasticity, induced thermal loads, and increased rate of corrosion. The increase in the level of carbon dioxide promotes carbonation and a decrease in the strength of concrete and masonry. The increase in environmental loads depends on the increase in both the extremes and frequencies of natural events. Such changes vary from region to region. This study uses global means to investigate the need to incorporate climate change in the assessment of structural reliability.

Background

There are several extensive climate change models in the literature. However, the Intergovernmental Panel on Climate Change (IPCC) reports provide the most widely accepted projections of long-term climate patterns. This study uses the mean global climate projections from the IPCC fourth assessment report (Meehl et al. 2007). These models estimate the change of a quantity projected over a certain number of years. In this study, the authors assume that the change occurs linearly within the period of interest. This is in accordance with the fact that the global carbon dioxide level

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has historically increased approximately linearly. Although temperature changes appear to be correlated logarithmically to the carbon dioxide level, the difference between a linear or logarithmic assumption is negligibly small for a change of a few degrees in temperature over several years.

Studies on time-dependent structural reliability include Li et al. (2015), who studied structural reliability under nonstationary loads. They proposed a methodology to model the time-dependent resistance function, subtracting the dead loads to obtain the resultant available resistance, and finding the probability of nonstationary loads exceeding the resistance at any instant. Thus, time-dependent probability of failure of the structure can be estimated by using the distribution of extremes of the expected live loads or environmental loads. Whereas Li et al. (2015) analyzed the effect of nonstationary environmental loads and aging, this study aims to specifically investigate the impact of climate change variables on long-term structural reliability.

Peng et al. (2010) studied the effect of increased carbon dioxide emissions on the carbonation of concrete structures and structural reliability over time. They used predictive carbonation depth models to estimate reliability by accounting for levels of carbon dioxide, corrosion mechanisms, material strength, structural dimensions, and the ambient structural environment. The results show that the probability of corrosion initiation can be as high as 4.6 times the nonaffected case. Stewart et al. (2011) also studied the impact of a rise in carbon dioxide levels on concrete infrastructure. They similarly used extended carbonation depth, corrosion initiation, and reliability models on carbonation to estimate the structural reliability. An increase in damage caused by carbonation of up to 400% by 2100 was found. Compared with the previous work in carbonation, this study comprehensively investigates the effects of climate change on reliability, including impacts on all degradation mechanisms and loadings on a structure. Climate change effects on a failure mechanism are correlated to strength, and a fractional change in strength is then assessed rather than using failure mechanism models. The aim is to investigate a need to include climate change in assessing long-term structural reliability. In addition, the previously used models for carbonation require extensive knowledge of the structure and environment. The generalized methodology presented in this paper is not limited to a structure but can be used across infrastructures in a region.

The following climate-dependent modes of degradation are considered in this study. The modulus of elasticity of any structural material decreases with an increase in temperature. The decrease tends to be linear at lower temperatures and exponential at higher temperatures. Therefore, for the temperature ranges considered within the scope of this study, the decrease in modulus of elasticity with increasing temperature is assumed to be linear. The increase in temperature also induces thermal loads. Depending on the end-fixity conditions, a maximum thermal stress of $E\alpha\Delta T$ is generated, where E is the modulus of elasticity, α is the coefficient of thermal expansion, and ΔT is the change in temperature. Temperature also affects the rate of corrosion of an element. Corrosion depends on several environmental factors including moisture content, temperature, and exposure to various chemical agents, with the rate of the chemical reaction increasing with an increase in temperature. The Arrhenius equation for reaction rates suggests that the rate of a chemical reaction increases exponentially with temperature. Although long-term corrosion of civil engineering materials generally does not follow a strict exponential trend because of a simultaneous dependency on several other factors, it is reasonable to assume an exponential variation for the temperature ranges considered in this study.

Concrete is the most widely used construction material, followed by steel and masonry. The strength of reinforced concrete and masonry is significantly affected by carbonation. Carbonation reduces the material strength and leads to the corrosion of steel reinforcement. Chi et al. (2002) studied the effect of carbonation on the mechanical properties of concrete. They found the strength of concrete to be inversely proportional to the depth of carbonation. A study by Sagüés et al. (1997) shows that the depth of carbonation is directly proportional to the square root of the concentration of atmospheric carbon dioxide. Therefore, it is assumed that the long-term strength is negatively correlated to the square root of the atmospheric carbon dioxide concentration. The modes of degradation as applied to a demonstrative concrete structure, as well as example steel and wood structures, are considered in this study.

Methodology

Modeling of Structural Resistance and Loads

Following Li et al. (2015), the structural resistance is assumed to decrease with time such that $R(t) = R_0 G(t)$, where $R(t)$ is the structural resistance at time t, R_0 is the initial resistance, and $G(t)$ is the degradation function. $G(t)$ is a stochastic function, and it is generally modeled by using simple polynomial functions as proposed in Enright and Frangopol (1998), Melchers (2003), and Ellingwood (2005) and used in Li et al. (2015), in which reliability is assessed by using simplistic polynomial models, i.e., linear, squared, and square-root functions of time t. However, on the basis of the mechanical properties of the modes of degradation considered and to understand the effect of these different factors on the resistance function, the authors propose a model for the degradation function given as

$$G(t) = 1 - at - b\sqrt{t} - \exp\left(\frac{c}{t}\right) \quad (1)$$

The terms in this formulation account for the variations in resistance caused by different degradation factors. Specifically, the square-root term accounts for carbonation, the exponential term accounts for accelerated corrosion caused by temperature, and the linear term accounts for other mechanisms of degradation, including fatigue. Carbonation primarily affects concrete and masonry. Carbonation and corrosion are not independent for these structures. Carbonation acidifies the aggregate, reducing the strength of the composite while allowing increased penetration of moisture and oxygen to the reinforcement. In this study, however, carbonation is related to the acidification of the composite, and temperature is attributed to the corrosion rate. The variation in carbon dioxide and temperature levels are correlated but treated separately in the degradation function as each factor, acidification and corrosion, affects a structure differently. In the context of climate change, increased fatigue can be caused by more severe freeze-thaw cycles or heat events. The linear term could be replaced by any other simplistic polynomial function based on the dominant degradation mode. For simplicity and assuming fatigue to be dominant compared with other strength-reducing factors, it is assumed to be linear in this study.

The degradation function is applicable to other types of structures through proper choice of the parameters. A steel or wood structure, for example, will not be sensitive to carbonation. The dominant modes of degradation for a steel structure are corrosion and fatigue. Similarly, a wood structure is highly sensitive to moisture content and temperature. Almost all mechanical properties of wood decrease with increases in temperature or moisture content.

Most studies on properties of wood linearly relate the logarithm of a mechanical property of wood to moisture content and temperature as in Gerhards (1982). Therefore, the same degradation function is applicable to steel and wood structures with the exclusion of the square-root term.

The selection of parameters has a significant impact on results. In general, the parameters of the degradation function are estimated and can be updated through periodic inspections or observations of the structure. The parameters a, b, and c are estimated by assuming that each term is driven solely by the attributed degrading mechanism, such that fatigue only affects a, carbonation b, and corrosion c. Therefore, an attributional quantification of the fraction of the total degradation caused by each degradation mechanism helps in estimating these parameters. Such fractional attribution of the degradation among several damaging mechanisms depends on the type of structure, its usage, and its location. For example, the degradation of a steel structure will be dominated by corrosion whereas concrete may be dominated by carbonation, and a coastal structure is more prone to corrosion whereas a bridge deck is prone to fatigue. The results for a demonstrative example presented in this study assume that 10% of the degradation is caused by carbonation, and corrosion and fatigue each contribute 45% of the degradation for a concrete structure. These values are selected because a concrete structure is most affected by corrosion and fatigue in the long run. Carbonation catalyzes corrosion and also acidifies the composite. As this study treats corrosion and acidification separately, the effect of corrosion and fatigue on the overall strength is given a higher weight compared with the carbonation-induced acidification. The results for the example steel and wood structures are also given with varying parameter selection values for the degradation function. In addition, the results of a sensitivity analysis are provided to investigate the effect of changes in parameters on the results presented. The attribution of fractions of degradation to specific mechanisms for different structures can be adjusted according to the periodic observations and degradation quantification for any structure of interest. The periodic observations of a structure and tests using nondestructive evaluation (NDE) techniques can help estimate the extent of a specific degradation mode, e.g., extent of corrosion in reinforced concrete or amount of moisture in wood. These observations should be used to update the parameters selected for the degradation function to change the weights of the dominant modes of degradation for a structure over time.

The environmental load events considered in this study are assumed to be Poisson processes with time-dependent mean occurrence rate $\lambda(t)$ and mean load intensity $\mu_s(t)$, where the subscript s denotes structural loads. The changing mean rate and mean intensity parameters model the increasing frequency and severity of climate-dependent natural hazards including hurricanes, tornados, and rain and snow events.

Reliability Analysis

The probability of failure P_f of the structure at any instant is given as

$$P_f(t) = P[R(t) < S(t)] = \int_0^\infty F_{R,t}(s) f_{S,t}(s) ds \tag{2}$$

where $R(t)$ = resistance function; $S(t)$ = load effect; and F and f = cumulative distribution function (CDF) and probability distribution function (PDF), respectively. R and S are assumed to be statistically independent.

The hazard function $h(t)$, defined as the probability of failure of the structure in the time interval from t to $t + dt$ given that the structure has survived up to time t, is expressed as

$$h(t) = \frac{P(t_f \leq t + dt | t_f \rangle t)}{dt} = \frac{P(t < t_f \leq t + dt)}{P(t < t_f) dt} \tag{3}$$

where t_f = time of failure. The numerator of Eq. (3) can be expressed as

$$P(t < t_f \leq t + dt) = \lambda(t) dt \cdot P[R(t + dt) < S(t + dt)] \cdot P(t < t_f) \tag{4}$$

Hence, the hazard function becomes

$$h(t) = \lambda(t) \cdot P[R(t + dt) < S(t + dt)] \tag{5}$$

Ignoring the randomness in the estimation of the parameters a, b, and c and assuming dt is infinitesimally small so that no uncertainty is induced in the estimation of $G(t + dt)$ given $G(t)$, $G(t + dt)$ and hence $R(t + dt)$ are deterministic such that

$$\begin{aligned} P[R(t + dt) < S(t + dt)] &= 1 - P[S(t + dt) < R(t + dt)] \\ &= 1 - F_S[R(t + dt)] \end{aligned} \tag{6}$$

The hazard function is then written as

$$h(t) = \lambda(t) \cdot \{1 - F_S[R(t)]\} \tag{7}$$

The hazard function is also related to the structural reliability $L(t)$ as proposed by Ellingwood and Mori (1993)

$$h(t) = -\frac{d}{dt} \ln[L(t)] \tag{8}$$

Therefore, the structural reliability and probability of failure are expressed as

$$L(t) = \exp\left(-\int_0^\tau \lambda(t) \cdot \{1 - F_S[R(t)]\} dt\right) \tag{9}$$

$$P_f(t) = 1 - L(t) \tag{10}$$

Climate Change Projections

The IPCC report (Meehl et al. 2007) presents a number of different models to project the change in the physical climate-related parameters of interest. The average global temperature increase is projected between 1.79 and 3.13°C for 2000–2100 as estimated by different models. In this study, a temperature increase of 2.65°C in 100 years is used, a value proposed by one of the projection models and lying within the range of the projection. Similarly, different models project the increase in the concentration of carbon dioxide to be 2 to 2.5 times from 2000 to 2100. Hence, this study uses an estimated 100% increase in 100 years for the carbon dioxide levels.

The change in the intensity of the extremes of natural events directly affects the environmental loads on the structure. For example, the maximum surface wind speed of hurricanes and cyclones are expected to increase by 6–14% by the end of the century, precipitation extremes are projected to increase by 4–5%, increased wave heights and a rise in sea levels are expected, and there is an increased possibility of more intense extratropical storms and snow events. Such changes in the extremes of these events increase the environmental loads on structures during significant load event occurrences. Increases in hazard extreme intensity of 5, 10, and 15% over 100 years are used in this study.

Application and Results

To estimate the parameters of the degradation function, this study assumes that the resistance at the end of 40 years is 80% of the initial resistance. This assumption is in accordance with Li et al. (2015) to facilitate the comparison of our results with those of the previous study. Although the value of reduction in structural strength would vary by type of structure and location, the aim of this study is to compare the probabilities of failure at a particular instant with and without including the effects of climate change. Thus, $G(40) = 0.8 = 1 - a \cdot 40 - b\sqrt{40} - \exp(c/40)$. For this application, the authors assume that 10% of the degradation of the structure is caused by carbonation, whereas corrosion and fatigue each contribute to 45% of the degradation. The three unknown parameters may therefore be calculated by equating the fraction of total decrease to individual terms. This results in values for a, b, and c of $0.09/40$, $0.02/\sqrt{40}$, and $\ln(0.09) \cdot 40$, respectively.

The demonstrative percentages for attributional causes of degradation would vary depending on several factors, including the type of structure, location, exposure, and loading. To study the sensitivity of the degradation function to the choices of the values of the three parameters, a local sensitivity analysis is performed. A normalized sensitivity coefficient φ_i for a particular independent variable X_i for the degradation function G is calculated as

$$\varphi_i = \frac{\partial G}{\partial X_i} \cdot \frac{X_i}{G} \tag{11}$$

where $X_i = a, b$, or c = parameters of degradation function. Under the current assumptions and $t = 40$ years, the absolute values for φ are $\varphi_a = 0.112$; $\varphi_b = 0.025$; and $\varphi_c = 0.271$. These values represent the sensitivity of the model to different assumed parameters and quantify how the degradation function is expected to change with changes in estimates of the parameters. From the results, the function is most sensitive to the parameter c, followed by a and then b. The parameters b and c are the climate-dependent factors in the degradation function, with the model being more sensitive to c than to b.

The design equation $0.9R_n = 1.4D_n + 1.7L_n$ specified in ACI 318 (ACI 1989) and as used in Li et al. (2015) is used to estimate nominal dead load, where the subscript n denotes nominal or code-specified values. Although this code has since been superseded by newer codes, it was chosen to facilitate comparison with other studies that do not consider climate change factors. For simplicity and to be consistent with Li et al. (2015), it is assumed that $D_n = L_n$ and $R_n = R_0$. The dead load is assumed to be stationary and constant such that it can be directly subtracted from the resistance function to estimate the reliability of the remaining effective resistance against the environmental load. The reliability hence becomes

$$L(t) = \exp\left(-\int_0^\tau \lambda(t) \cdot \{1 - F_S[R_0 \cdot G(t) - D_n]\} dt\right) \tag{12}$$

The environmental load is assumed to be Poisson distributed with a mean rate of occurrence of $1/\text{year}$. This models an extreme environmental load such as a hurricane. The occurrence of such loads can be estimated as Poisson events although their effect on a structure is not necessarily Poisson. In this equation, the effect is also estimated to be Poisson because of an estimate of a simultaneous reaction of a structure to the load and negligible residual effects compared to the service life of the structure. The case for two dependent or simultaneously occurring environmental load events can be similarly analyzed by using the joint rate of occurrence and joint mean intensity.

The mean of the extreme load is assumed to be $\mu_S = 0.6L_n$ (which will subsequently be varied in this study to reflect increasing intensity of extreme hazard events with climate change), with a coefficient of variation of 0.3, and it is assumed to follow a Type I distribution as in Li et al. (2015). This choice of the mean of the extreme load makes the design equation the critical design equation at the mean. In general, the critical design equation depends on load combinations and type of dominant hazards in the area.

With the selected parameters, first, the impact of climate change on the resistance is studied without varying the properties of environmental loads. The effect of changes in each parameter is studied separately and then aggregated to analyze the combined effect. The modulus of elasticity decreases with elevated temperatures and is directly proportional to the structural resistance. The change in resistance is normalized to the fractional change in the modulus of elasticity. This is accounted for in the reliability as

$$L(t) = \exp\left[-\int_0^\tau \lambda(t) \cdot \left(1 - F_S\left\{R_0\left[G(t) - \frac{\Delta E}{E} \cdot \Delta T(t)\right] - D_n\right\}\right) dt\right] \tag{13}$$

where ΔE = change in modulus of elasticity per °C at lower temperatures; E = design modulus of elasticity; and ΔT = change in temperature with time. ΔE is taken to be 17 MPa/°C, E 31 GPa (typical for concrete) from Naus (2005), and ΔT 2.65°C in 100 years, assuming temperature change to be linear in time.

Elevated temperatures also increase thermal loads in the structure. Assuming end conditions such that temperature increases cause corresponding full thermal stresses, the degradation function decreases by an amount equal to $\alpha \Delta T$. Though this assumption may not be valid for the case of expansion and construction joints, given the value of the coefficient of expansion for structural materials and the projected change in temperature, the effects are small for the assumption to be valid. This is reflected in a corresponding change in structural reliability as

$$L(t) = \exp\left[-\int_0^\tau \lambda(t) \cdot \left(1 - F_S\left\{R_0[G(t) - \alpha\Delta T(t)] - D_n \frac{\Delta E}{E} . \Delta T(t)\right\}\right) dt\right] \tag{14}$$

where α = assumed as 10×10^{-6} (approximate median for concrete).

Reduction in strength caused by carbonation is captured in coefficient b in the degradation function. The IPCC report suggests an increase of 2 to 2.5 times in the carbon dioxide levels in 100 years, and historically the levels of carbon dioxide have increased linearly. This study uses the lower projected estimate of 100% linear increase in 100 years for carbon dioxide levels, and the coefficient b correspondingly increases by the same amount. Similarly, the accelerated corrosion caused by an increase in temperature affects c. Assuming that the rate of corrosion increases by 2%/°C from Pijanowski and Mahmud (1969) and Qi et al. (2014), c changes by the same amount linearly with temperature, which is consistent with the exponential effect of temperature particularly at low temperatures with an increase of 2.65°C in 100 years.

With the impact of the choice of parameters on the results, a sensitivity analysis of the calculated reliability or probability of failure to the choice of parameters for the degradation function can be

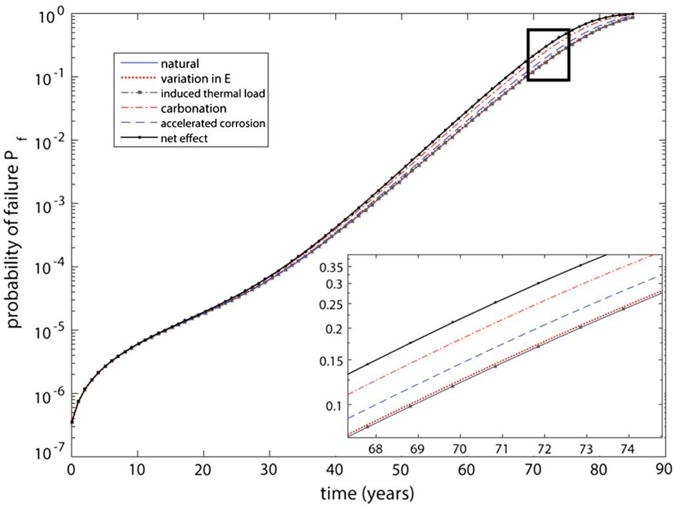

Fig. 1. Probability of failure versus time, with changes in resistance caused by environmental factors

performed similar to Eq. (11), changing G to L or P_f. The analysis at $t = 40$ years results in the sensitivity indices of $\varphi_a = 7.47 \times 10^{-4}$; $\varphi_b = 1.78 \times 10^{-4}$; and $\varphi_c = 1.63 \times 10^{-3}$ for P_f. As these are sensitivity magnitudes, the results are the same for L. This shows the effect of changes in parameters on the failure probability results presented. The parameters b and c correspond to the climate-dependent parameters, and the probability of failure P_f is more sensitive to c than to b, which is consistent with the sensitivity analysis of the degradation function, G.

Accounting for these climate-dependent factors affecting the resistance, Fig. 1 shows the effect of individual factors on structural reliability over time. These are compared with the probability of failure calculated without incorporation of increased degradation caused by climate change, indicated as "natural" on the plot. The combined effect of all environmental factors, indicated as "net effect" on the plot, is also shown. The climate projections in the IPCC report are for 100 years from 2000 to 2100. Therefore, the structural reliability plots are plotted for 85 years, until the year 2100.

From Fig. 1, the effect of induced thermal loads is negligible compared to the probability of failure without consideration of any climate effects. The difference in reliability is on the order of 0.6% between the two cases, resulting in overlapping lines on the plot. The effect of change in modulus of elasticity is slightly larger than for thermal loads although also negligible in the considered period. Carbonation and accelerated corrosion are found to have larger effects. The order of change depends on the fraction of degradation attributed to each factor. For the assumptions of this study, carbonation has the largest effect. As described previously, the fractional attribution to each degradation mechanism can be adjusted according to the type and location for any structure of interest. From the net effect line in Fig. 1, it can be observed that the net probability of failure accounting for the climate change effects on resistance is nearly double that of the natural degradation line after 40 years, with a greater increase in probability of failure as time increases. The degradation of the structure is accelerated under climate projections through 2100, showing the importance of accounting for climate change in structural reliability assessment.

As discussed in the "Methodology" section, the degradation for steel and wood can be similarly modeled by using the same degradation function but ignoring the carbonation term. Fig. 2 shows the change in reliability for steel and wood caused by environment-induced changes in material properties. Fig. 2(a) is the probability of failure of an example steel structure. It is generated by neglecting the carbonation term and attributing equal degradation weights of 50% each to fatigue and corrosion because both factors are dominant factors for the degradation of steel. Fig. 2(b) is similarly generated for wood. The dominant degradation mechanisms for wood are fatigue, biochemical attacks, and moisture-temperature effects. All of these factors have an effect on the mechanical properties of wood. By assigning equal weights to the four factors and attributing fatigue, biochemical attacks, and moisture to the linear term in the degradation function, 25% of the degradation is attributed to temperature. Hence, the exponential term accounts for a quarter of total degradation, and the square-root term is neglected. As per Gerhards (1982), at lower temperatures of 0–50°C, a change of 10°C in environmental temperature decreases the strength parameters by 2–3%, and the effect on the natural logarithm of the mechanical property is directly related to a linear change in temperature. Therefore, the plot is generated by using a change of 2% and the exponential

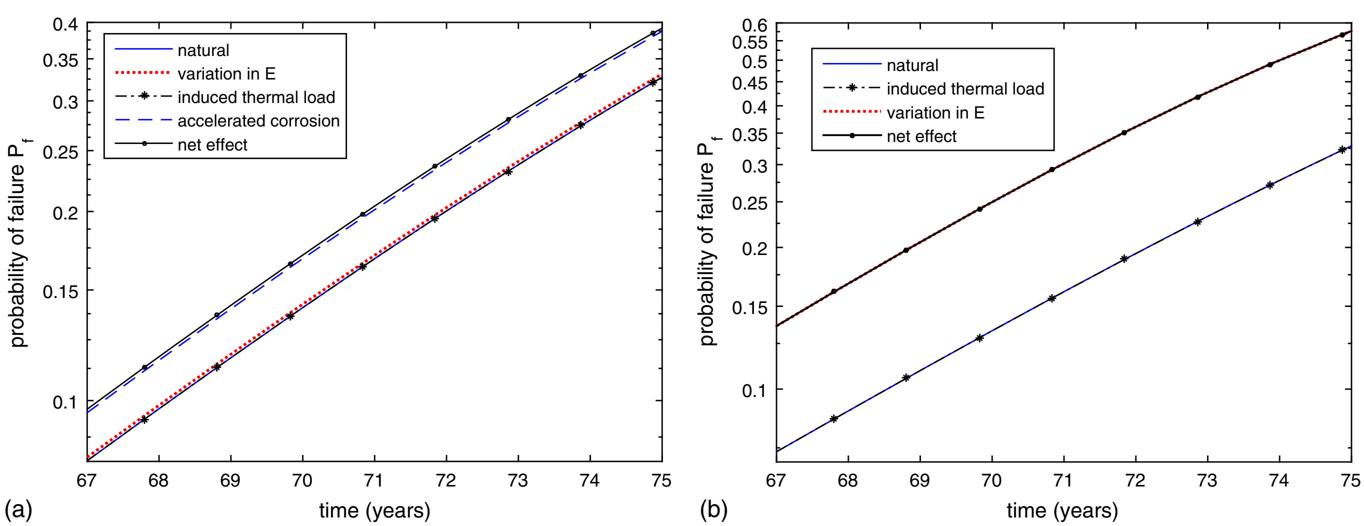

Fig. 2. Probability of failure of example: (a) steel; (b) wood structures with change in resistance caused by environmental factors

relationship with temperature. Also, although moisture content and temperature affect the properties of wood simultaneously, the effect of moisture is not considered separately because projection of moisture content levels is difficult and specific to time and region. Moreover, the exponential term for wood correlates the strength property, which is modulus of elasticity in the studied case, to temperature. Therefore, the temperature term is sufficient, and the fractional modulus of elasticity term in Eqs. (12) and (13) is not considered separately to avoid double counting the environmental effects on resistance.

From Fig. 2(a), despite equal weights for corrosion and fatigue in the degradation function, corrosion has the greatest effect on decreasing the reliability of the steel structure over time. Fig. 2(b) shows the increase in probability of failure for the wood structure because of variation in modulus of elasticity. The effect of induced thermal loads is negligible in both cases.

Then, the authors study the effect of changes in the extremes of environmental loads. As previously discussed, the frequency of natural hazards and the intensity of the extremes of these events are expected to increase. The effects of extreme loads may not be directly proportional to the increase in intensity. Therefore, different load effect scenarios are considered, which will depend on the region, loading event, and structure. The IPCC provides projections of increases in maximum wind speed, precipitation extremes, and snow events. The projections also estimate an increase in the number of severe events. However, no clear consensus exists on quantifying the increase in number of occurrences. Therefore, in this study, the authors assume that the mean rate of occurrence remains the same, whereas the intensity of extremes changes. Any resulting increase in probability of failure will thus be a conservative estimate of decreasing reliability. Further increases in failure probability are expected if increases in the mean rates of natural hazard event occurrences are included. The projections of change in number and intensity of events vary by site and hazard. Region-specific studies for particular hazards, such as hurricanes for the eastern United States in Mudd et al. (2014), can be used to provide estimates of the impact of climate change on reliability for a structure at a specific site under a specific hazard. The increase in the severity of environmental events depends on the region being studied. In this paper, however, rather than restricting the analysis to a specific region, the effect on reliability caused by a 5, 10, and 15% increase in the intensity of extremes in 100 years is studied. The coefficient of variation is assumed to remain constant, whereas the mean changes with time such that it increases by the given percentage in 100 years. Fig. 3 shows the effect on reliability of changes in the intensity of extremes of significant environmental load events over time. For comparison, reliability without (indicated as "natural at existing environmental load") and with (indicated as "net at existing environmental load") decreased resistance because of climate change factors are shown.

Fig. 3 shows the impact of an increase in the mean intensities of environmental load events on the reliability of structures. The probability of failure is increased at each instant. The failure probability increases by as large as 3.5 times compared with that of the original curve.

Finally, with increasing natural hazards, the authors study the variation in reliability in the presence of two different environmental load events. The first load events are modeled with the same characteristics as in the preceding. The second process models more frequent, lower intensity events, with an assumed rate of occurrence of 10/year, mean $\mu_{S2} = 0.4L_n$, coefficient of variation = 0.4, and following a Type 1 distribution. The mean for the first load event increases linearly in time corresponding to the specified increase in intensity in 100 years, whereas the increase in the mean intensity of the extreme of the second event is assumed to be exponential to vary the fraction of change corresponding to each event. The probability of occurrence of the extremes of both loads simultaneously is assumed to be negligibly small with independence between the two load events, so the two Poisson processes can be merged directly. Fig. 4 shows the reliability over time under the action of two load events.

In Fig. 4, the lowest probability of failure curve provides the failure probability of the structure when the mean intensity of the extremes of the two environmental loads remains constant over time, but the resistance of the structure changes with the varying environmental conditions. The remaining lines show the reliability for the corresponding percentage changes in the mean intensities in 100 years. In Fig. 4, the reliability decreases with the increase in load intensities. There is an increase in probability of failure at each time step, with the failure probability increasing by as large

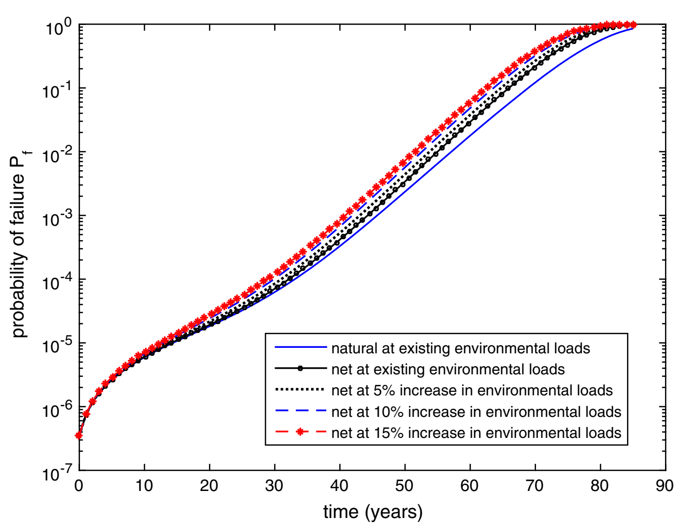

Fig. 3. Probability of failure versus time, with increase in the extremes of loads, corresponding to an increase of 5, 10, and 15% increase in the mean in 100 years

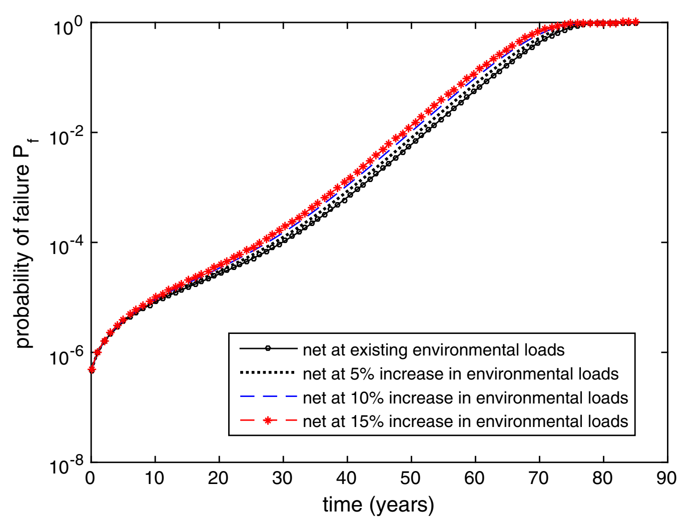

Fig. 4. Probability of failure versus time, in which two different significant load events act on the structure

as 2.5 times compared with that of the case without accounting for increased environmental loads.

Conclusion

This study focuses on the need to incorporate climate change in the assessment of long-term structural reliability. Generally, the service life of civil infrastructure spans across decades, and in many cases, structures are used past their design service lives. When looking over these longer time horizons, it becomes important to account for changes in environmental patterns to accurately assess the future reliability of a structure. The authors use global mean projections for estimated changes in environmental factors to investigate their impact on structural reliability. This study shows the significant relative effect of changing climate patterns on the long-term performance of civil infrastructure.

Climate change affects both the resistance of a structure and the loadings on the structure. The resistance is most affected by carbonation and accelerated corrosion attributed to an increase in temperature. Although a general structure with assumed structural parameters is used in the application of this study, given the attribution of different degradation mechanisms to different factors in the resistance function, the effect on the resistance of coastal structures would likely be even greater compared with that of inland structures. The authors also show the importance of accounting for changes in the extremes of live load events in reliability studies. The effect on reliability of increases in event intensity depending on the type of hazard and projected hazard levels is significant. With the combined effect of climate change on the resistance and loading, the probability of failure based on global mean projections increases by two to four times. The increase may be even higher, depending on the type and location of a structure. The projections and impacts are estimated at lower values. Therefore, the estimates of increases in failure probability are conservative.

Although global means are used in this study, the extensive regional projection data available can be used to assess the long-term reliability of a particular structure. It may be useful to account for extended hazard models based on expected service life and usage of the structure instead of code-specified hazard intensities. A general methodology is presented in this paper. Location-specific assessment should account for the projected increase in the extremes of the relevant natural hazards in the area, including hurricane and nonhurricane winds, precipitation, snow, and wave heights. Structures under more than one type of dominant hazard would have a multiplicative effect on the reliability and would be more prone to damage and failure. The results shown are therefore conservative in underestimating the impact of climate change on decreasing structural reliability, and estimates may change in the case of joint load occurrences. On the basis of the type and usage of a structure, other modes of degradation can be included, which may be affected by the variations in environmental parameters caused by climate change.

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