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Assessment of the effectiveness of wood pole repair using FRP considering the impact of climate change on decay and hurricane risk

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Abstract

Electric power distribution systems are vulnerable to disruption due to severe weather events, especially hurricanes. Such vulnerability is expected to increase over time due to the impact of climate change on hurricanes and the decay of wood poles that support the distribution lines. This study investigates the effectiveness of using fiber-reinforced polymer (FRP) sleeve to reinforce wood poles subjected to decay and hurricane hazard to restore their lost strength and extend their effective service life. The potential impact of climate change on the pole decay rate and the intensity and frequency of hurricanes is also considered. The optimal FRP repair time based on the structural reliability of the poles is also determined. Three locations with varying climates are chosen to evaluate and compare the results: Miami, Charleston, and New York City. The results show that in all three locations, the application of the FRP sleeve can more than double the service life of the pole depending on the time of the repair. The results also show that climate change significantly increases the vulnerability of the pole. The probability of failure of the pole at the end of the 21st century under RCP8.5 emission scenario in Miami, Charleston, and New York City increase by about 30%, 70%, and 73%, respectively, compared to a no climate change scenario. If climate change is only assumed to affect the decay of the pole, i.e., no change in hurricane hazard intensity, the corresponding increases in failure probability are 5%, 22%, and 20% in Miami, Charleston, and New York City, respectively. This implies that most of the impact of climate change on pole failure risk is due to the increase in hurricane intensity. The impact of climate change on decay is found to be comparatively small. It increases with time as variation in temperature and precipitation becomes more prominent towards the end of the 21st century. The optimization results show that the optimal FRP repair time depends on how the FRP affects the pole's decay rate. If the FRP can significantly slow down the wood decay rate, the optimal time of repair is at the beginning of the pole's life cycle. If the FRP has no impact on the wood decay rate, it is better to repair the pole after significant decay has occurred.

Keywords: Wood poles; FRP repair; Hurricane; Wood decay; Climate change adaptation

1. Introduction

Maintenance is a critical factor in the management of civil infrastructure systems. A good maintenance schedule will save an owner substantially over the life span of a building or system, both economically and in terms of safety. For

electrical utility companies, the maintenance of electric power systems prevents the loss of service and may push lower costs onto the end-user. As such, utility companies develop maintenance plans for various components that are subjected to wear and tear as well as deterioration due to natural causes. An example of such components is the poles supporting overhead networks. Hundreds of millions of poles that are worth billions of dollars are used by utility companies across the U.S. and other countries (Mankowski et al., 2002; Ryan et al., 2014).

Wood poles are most commonly used to support electrical distribution systems in the U.S. due to several factors. Wood

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is readily available in most places across the country or can be acquired relatively cheaply. However, wood is an organic material and is subject to decay and rot, which diminishes its strength over time. Consequently, the NESC (National Electric Safety Code) (IEEE, 2017) recommends that support poles for distribution lines be replaced once they reach two-thirds of their initial strength. Over time, deregulation and downsizing of labor by utility companies make it more difficult to maintain a reliable maintenance schedule, which can quickly identify failing poles (Mankowski et al., 2002). The rate of decay of wood is affected by climatic factors, especially temperature and moisture (Brischke and Rapp, 2008; Teodorescu et al., 2017; Wang et al., 2008). It is, therefore, expected that potential future changes in temperature and precipitation due to climate change will have an impact on wood decay. However, such changes will only affect the rate of decay, not the mechanisms causing the decay. It can be said, therefore, that there is a correlation between climate change and the decay rate and subsequent fragility of wood poles.

Wood poles are also vulnerable to damage due to natural hazards such as tropical cyclones, which are one of the most costly natural disasters in terms of both loss of property and life (Gutowski et al., 2008). There is evidence that the intensity of tropical cyclones has been increasing over the years (Emanuel, 2005; Mann and Emanuel, 2006). The intensity is also predicted to continue increasing in the coming years due to climate change (Knutson et al., 2010; Mudd et al., 2014a, Ouchi et al., 2006; Staid et al., 2014). However, predictions on the potential impact of climate change on tropical cyclones have a large degree of uncertainty because hurricane formation depends on several climatic factors such as sea surface temperature (SST), North Atlantic Oscillation, Southern Oscillation, El Niño effect, vertical wind shear, atmospheric stability, and other factors (Cui and Caracoglia, 2016; Ranson et al., 2014). As such, variability in hurricane activity is a complex convolution of natural and anthropogenic factors. Variability also differs based on the location under evaluation. Global climate models may over or underestimate changes in frequency and intensity of storms in individual basins (Emanuel et al., 2008; Knutson et al., 2010; Ryan et al., 2016).

To reduce the vulnerability of decayed wood poles to hurricanes and climate change, various strategies that involve regular maintenance, repair, or periodic replacement can be employed. Ryan et al. (2016) proposed a framework to study the impact of climate change on wood pole networks considering time-dependent decrease in strength due to decay. An advanced stochastic simulation method was proposed to study the cost-effectiveness of various climate change adaptation measures for wood pole networks (Ryan and Stewart, 2017). In the method of Ryan and Stewart (2017), various adaptation measures based on alterations to design or maintenance practices such as installation of larger poles and more frequent inspections were considered. Another potential strategy is the use of fiber-reinforced polymers (FRP) to repair and strengthen decayed poles. FRP are strands of carbon-fiber reinforcement arranged in parallel and cast into an epoxy

coating and applied to the exterior of structural elements. Carbon-fiber has exceptional tensile capacity, so the application of FRP to the extreme tension fiber of a structural cross-section can increase the bending capacity of the structural element (Grace et al., 1999). The ease of application of FRP makes it an ideal solution to reinforce existing structures. For utility poles, FRP repair can be carried out by simply excavating around the pole and wrapping it with the FRP. As such, service interruption can be avoided (Grace et al., 1999).

Research on the use of FRP products to repair and strengthen building and bridge components is abundant (e.g., Sharif et al. (1994), Najm et al. (2007), Ghobarah and Said (2001), Triantafyllou (1998), and Balsamo et al. (2005)). However, research on the effectiveness of using FRP to repair wood utility poles to improve their structural reliability is scarce. Saafi and Asa (2010) tested the moment capacity of 30-year-old decayed wood poles repaired using FRP. The authors reported that the FRP could restore more than 85% of the initial strength of the poles. Other research in which utility poles were repaired with FRP and tested to determine improvement in strength include Polyzois and Kell (2007), Kell (2001), Chahrour and Soudki (2006), Chahrour and Soudki (2006), and Lopez-Anido et al. (2005). With the use of FRP for wood pole repair gaining popularity, it is essential to investigate the long-term structural performance and lifespan of FRP-repaired poles subjected to hurricanes. It is also crucial to investigate the potential impact of climate change on wood pole decay rate and the possibility of using FRP as a climate change adaptation strategy to reduce the long-term vulnerability of wood poles.

This study aims to i) investigate the changes in the vulnerability of wood poles due to the impact of climate change on wood decay and hurricane hazard, ii) investigate the effectiveness of FRP repair on the long-term structural reliability of wood utility poles, iii) investigate the impact of the time of FRP repair on the service life of the poles, and iv) determine the optimal FRP repair time to minimize the structural reliability of the poles. Three coastal locations are considered to investigate the variation of the results for different geographical conditions: Miami, Florida, Charleston, South Carolina, and New York City, New York. The results of the study will give an insight into the potential increase in the risk of failure of utility poles due to climate change. It will also provide an insight into the effectiveness of using FRP to repair decayed poles to adapt to climate change.

2. Data and methods

2.1. Decay model description

Wooden poles are vulnerable to decay at its base where it contacts the soil. The abundance of moisture and access to oxygen in the soil causes fungal growth and/or the presence of insect infestation from surrounding areas leading to the decrease of the strength of the cross-section. This is especially problematic for utility poles because they are typically cantilevered posts with the largest bending moment reaction at or

close to the ground level. These two factors create a condition where wooden utility poles have a finite service life.

The decay model developed by Wang et al. (2008) is adopted in this work. The model, based on a study of Australian wood samples, incorporates several physical parameters that include wood specie, chemical treatment, wood type (sap/core/heartwood), and climate parameters (mean annual temperature and rainfall). The decay rate, $r_{\text{un}'\text{stake}}$, for an untreated test stake is defined as:

$$r_{\text{un}'\text{stake}} = k_{\text{wood}} k_{\text{climate}} \quad (1)$$

where k_{wood} is a function of the durability class of the species and varies across the section of the wood. k_{climate} is a function of the annual rainfall and mean temperature. A detailed description of the decay model is provided in Wang et al. (2008).

2.2. Climate data

Climate has a profound effect on the decay rate of wood. As seen in the decay model parameters, two climatic factors are key to determining a time-based decay model, average temperature, and annual rainfall. The climate model data used here comes from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble (Maurer et al., 2007). CMIP5 provides precipitation and temperature data statistically downscaled to finer resolutions using the monthly bias-correction and spatial disaggregation (BCSD) method. Two Representative Concentration Pathways (RCP) are chosen to study the potential impact of climate change on decay and hurricane hazard RCP4.5 RCP8.5. RCP4.5 is chosen to represent a medium emission scenario, while RCP8.5 represents a high emission scenario. Seventy-one and 70 outputs from different Global Climate Models (GCMs) are available for RCP4.5 and RCP8.5, respectively. All the outputs in 1950–2099 are used to account for uncertainties in the models, as discussed in subsequent sections.

2.3. Pole failure risk

Wood poles supporting power lines can fail due to two causes: hurricane wind (Type 1 failure) and excessive decay (Type 2 failure). Failure caused by hurricane wind depends on the intensity of the wind load as well as the capacity of the pole, which is affected by time-dependent deterioration. Poles that fail due to hurricanes cannot be repaired using FRP and are, therefore, replaced with new poles. Type 2 failure occurs when the strength of the pole falls below a threshold due to excessive decay. The threshold considered here is the NESC recommended threshold, as discussed earlier, which is the point at which the strength of a pole falls below two-third of the initial strength. The methods to evaluate the two failure modes are discussed below. Poles that undergo Type 2 failure are repaired using the FRP method described above.

2.3.1. Type 1: Failure due to hurricane wind

The probability of failure of a pole due to hurricane wind is computed by convolving the fragility of the poles and the hazard probability, as shown in Eq. (2).

$$P_{\text{fl}}(t) = \int F_{\text{D}}(V, t) f_{\text{v}}(V, t) dV \quad (2)$$

where $P_{\text{fl}}(t)$ is the probability of pole failure due to hurricane wind, $F_{\text{D}}(V, t)$ is the time-dependent fragility of the poles, and $f_{\text{v}}(V, t)$ is the time-dependent hazard function. Hence, the impact of wood decay and hurricane hazard are considered in calculating $P_{\text{fl}}(t)$. A method for the time-dependent fragility analysis of poles has been developed and is detailed in Salman and Li (2016a).

Because of the unpredictability of hurricane wind speeds throughout the service life of a pole, wind must be modeled as a random variable with a time-sensitive probability distribution. As such, hurricane simulation is typically employed to model hurricane hazard. The hurricane simulation model developed by Xu and Brown (2008) is adapted. The required parameters for the hurricane simulation in Florida and South Carolina are taken from Huang et al. (2001) and Xu and Brown (2008). The parameters for New York City are found by fitting probability distributions to histograms of the parameters from Lin et al. (2010). A summary of the simulation parameters is given in Table A1. The radial wind field model developed by Holland (1980) is used to calculate the gradient wind speed at locations of interest. The gradient wind speed is converted to a surface and then 3-s gust wind speed using factors of 0.8 and 1.287, respectively (Vickery et al., 2009; Xu and Brown, 2008). The rise in central pressure of the hurricane after landfall is modeled using the approach developed by Vickery and Twisdale (1995). Wind speed decay after landfall is accounted for using the models developed by Kaplan and Demaria (1995) and Kaplan and Demaria (2001). The radius to maximum wind is modeled using the equation from FEMA (2011). The simulation is carried out for 200,000 hurricane seasons. More details of the simulation procedure can be found in Salman and Li (2016b).

At the moment, climate models seem inconsistent on the projection of changes to hurricane frequency due to climate change (Knutson et al., 2010; Landsea et al., 2010), but most models project an increase in intensity (Emanuel, 2005; Knutson et al., 2008; Oouchi et al., 2006; Staid et al., 2014; Stewart et al., 2014; Webster et al., 2005). While the increase in global intensity is projected to be between 2% and 11% (Knutson et al., 2010) under the status-quo assumptions, changes in the global intensity and frequency may be significantly different from the changes observed in individual tropical cyclone basins. For this study, only the northern Atlantic basin is considered as this is the area that feeds storms affecting eastern U.S. Webster et al. (2005) have shown that for most areas, the annual frequency and duration of hurricanes is not statistically significant from zero, while the North

Atlantic basin shows an increase in frequency with a 99% significance confidence level. However, the majority of literature concerning hurricane frequency with respect to climate change is still inconclusive, as summarized by Knutson et al. (2010). This is because the relation between anthropogenic forcing and hurricane activities is not well understood. Hence, there is no unified method of modeling climate change impact on hurricanes, and there is no consensus in the published literature on even the direction of the change. Based on a review of the literature, the range of change in frequency and intensity in the Atlantic Basin and the U.S. east coast under RCP8.5 are -25% to $+55\%$ and $0-25\%$, respectively. The corresponding values for frequency and intensity for RCP4.5 are -62% to $+58\%$ and -10% to $+12\%$, respectively.

From the studies mentioned above, this work assumes that the rise of intensity of hurricanes for the eastern U.S. will increase linearly by 10% and 20% by the end of the 21st century for the RCP4.5 and RCP8.5 scenarios, respectively (Mudd et al., 2014b). Due to the large amount of discrepancy for the projected increase or decrease in frequency, no change is assumed between now and 2099.

2.3.2. Type 2: Failure due to excessive decay

Type 2 failure is evaluated as the probability that the strength of a pole at the time of inspection is less than two-thirds of the initial strength as given by Eq. (3). Here, the strength of the pole at the time of inspection is evaluated using the decay model discussed earlier. The strength at any time, t , is then a function of the decay rate, which in turn is a function of climatic parameters (temperature and precipitation). The temperature and precipitation in any given year are modeled as normally distributed random variables with mean and standard deviation determined from all the outputs of the CMIP5 global climate models.

$$P_{f2}(t) = P \left[M_n(t) < \frac{2}{3} M_{n0} \right] \quad (3)$$

where $P_{f2}(t)$ is the probability that pole strength is less than two-thirds of the initial strength at any time t , $M_n(t)$ is the strength of the pole at time t , and M_{n0} is the initial strength of the pole obtained from ANSI-O5.1 (ANSI, 2002).

The NESC requires utility companies to regularly inspect and maintain the poles supporting power lines (IEEE, 2017). To comply with the NESC requirement, utility companies typically carry out periodic inspections to identify poles that need maintenance. Considering the vast number of poles in distribution systems, it is neither practical nor economically feasible to inspect all the poles in a system frequently. Utility companies typically inspect a small percentage of the poles in their network every year. The number of years it takes to finish inspecting all the poles and start over is the length of the inspection cycle. For example, Florida Power and Light inspects 1/8 of its pole population every year as part of an eight-year pole inspection cycle plan. In a survey of 261 North American utilities, Mankowski et al. (2002) reported that the average inspection cycle for distribution poles is about eight

years. In this study, it is assumed that the poles are inspected on an 8-year cycle.

2.4. FRP repair planning

The NESC recommends the replacement of wood poles once they reach two-thirds of their initial strength due to decay. Rather than replacing the poles outright, it is possible to reinforce the base of the poles with FRP to restore some of the lost strength. The repair is beneficial if the cost of applying the repair can overcome the costs of replacing the poles when adjusted for labor, materials, and interruption to network performance.

Saafi and Asa (2010) developed a remediation technique using a wet lay-up FRP sleeve applied at the ground line extending three-pole diameters in length and tested on southern pine class 4 poles. Intact poles of the same age were used to compare the effects of the FRP repair. After the application of the FRP to poles below the 67% initial strength threshold, 85% of the initial strength had been restored. As mentioned by Saafi and Asa (2010) the FRP jacket may reduce the rate of decay from the outer layers of wood by limiting the moisture and oxygen coming into contact with the pole. While Saafi and Asa (2010) assumed that the strength of the FRP jacket will deteriorate with time, there is no data on the extent to which the FRP will be weakened. Hence, it is assumed here the FRP strength does not deteriorate with time. If information on the deterioration of the FRP becomes available, it can easily be incorporated in the time-dependent reliability of the poles. There is, however, strong evidence that the repair of structural components using FRP can significantly decrease the strength deterioration of the component (Debaiky et al., 2002; Masoud and Soudki, 2006; Pantazopoulou et al., 2001). Hence, it is assumed in this study that the decay rate of the pole will be halved after the application of the FRP. A sensitivity analysis is carried out to determine the effects of this assumption on the results, which will be discussed in section 3.6.

The FRP wrap had been determined by Saafi and Asa (2010) based on experimental data to increase the capacity by about 30% of the initial strength of the pole. To account for uncertainty in the strength added by the FRP repair, a uniform distribution is assumed with the added strength ranging from 20% to 40% of the initial strength. It is acknowledged that the level of improvement in strength due to repair by FRP will depend on factors such as the type of FRP used and how it is installed, among others. Hence, we assumed that the FRP and installation method from Saafi and Asa (2010) are used.

The planning of the FRP repair can be carried out in two ways. The first approach is the threshold-based maintenance planning approach in which the FRP is applied, when the decay of the pole reaches a certain threshold. In such approach, the empirical decay model discussed earlier can be used to determine the time at which the strength will fall below a certain threshold (the NESC threshold for example). The FRP repair can then be planned. In the absence of a decay

model, periodic inspection can be carried out to determine whether the threshold for repair is reached.

The second approach for the repair planning is through optimization. In this approach, the repair is planned to optimize a specific parameter over the lifespan of the pole. In such a case, the time of the repair will depend on the objective of the optimization. For example, the objective of the optimization can be to maximize the structural reliability of the pole, i.e., minimize the probability of failure. Another objective, which is more common in maintenance planning for structures and infrastructure, is to minimize the maintenance cost over the lifecycle or within a specific timeframe. A multi-objective optimization can also be considered. In such a case, trade-off among the various objectives is required. As this study is focused on the structural performance of the poles considering decay over time, the FRP repair planning here will be carried out through optimization considering structural reliability over a specific period as the objective. The optimization problem over a planning period T can be formulated as:

Given : Pole configuration; decay model; $P_H = T$
 Find : $t = t_{FRP}$
 To minimize : $P_{f1}(T, t_{FRP})$ or $P_{f2}(T, t_{FRP})$
 Subject to : Integer t_{FRP} in $[0, T)$ years

Where P_H is the planning horizon, t_{FRP} is the time of the FRP repair, P_{f1} is the probability of Type 1 failure, P_{f2} is the probability of Type 2 failure. Recall that Type 1 failure considers both decay and hurricane hazard while Type 2 failure is based on only decay. In locations with hurricane risk, Type 1 failure can be used for the optimization. In locations with no hurricane risk, Type 2 failure can be used. The optimization problem here is complex and cannot be expressed by a closed-form expression containing the decision variable. Hence, the optimization problem can be solved using either numerical exhaustive search method or heuristic algorithms such as particle swarm optimization and genetic algorithm. In this case, the decision variable (optimal repair time or year) is discrete and the solution space is bounded within $[0, T)$ (e.g., 2010 to 2100). Therefore, a numerical exhaustive search is feasible for the current problem. A MATLAB algorithm is developed to solve the optimization problem exhaustively.

3. Case study and results

3.1. Pole description

The most common species of wood used for utility distribution is southern pine (Mankowski et al., 2002). As such, a southern pine pole is considered. The decay rate described earlier is a function of the pole durability class, which is based on the average expected service life of the pole. Treated poles sampled in Florida have shown evidence of poles working up to 50 years (KEMA, 2006). Hence, in this study, a durability class 1 is assumed based on the classification employed in the decay model adapted (Wang et al., 2008). Similarly, despite southern pine being defined as a softwood, the decay rate of

sapwood behaves as if it were a hardwood. This study assumes that the FRP sleeve is meant to be applied to treated poles in the field, with the treatment applied to the sapwood. The time lag for decay to begin has a high degree of uncertainty, so for this study, the average decay rate across all three locations for heartwood was used to estimate the number of years before decay begins and rounded to the nearest year. The estimated time lag is approximately five years. This approach is considered as the effect of the time lag on the overall life extension of a pole is insignificant and the decay rate for all locations is very small in the early years.

ANSI-O5.1 (ANSI, 2002) gives a minimum circumference for poles to be used for each class. A Class 4 southern pine pole is chosen, which has a minimum circumference of 63.5–105.4 cm depending on the length of the pole of 6.1–21.3 m. For the purpose of calculating the moment capacity at the ground line, where the maximum stress occurs, a pole length of 13.7 m is used, which is typical for distribution lines. This yields a minimum circumference at 1.8 m from the butt of the pole to be 89 cm or a diameter of 28.3 cm. The pole is assumed to support 3 ACSR conductors with a diameter of 18.3 mm located 0.3 m from the tip. It also supports one AAC neutral with a diameter of 11.8 mm at 1.5 m from the tip. The span between the poles for wind pressure calculation is assumed to be 46 m (Short, 2005).

Sapwood decays at a different rate compared to heartwood. The thickness of sapwood in southern pine varies and has a higher prevalence in timber with a faster growth rate. The thickness of the sapwood can be described using the diameter of the outside bark using Eq. (4) (Schultz, 1997).

$$T_{\text{sap}} = 0.36d_{\text{bark}} - 0.224 \quad (4)$$

where d_{bark} is the outside bark diameter at breast height (in cm) in 27-year-old southern yellow pine trees as demonstrated by Schultz (1997). The assumed exterior diameter is based on the ANSI-O5.1 (ANSI, 2002) classification of class 4 poles. For the analysis, d_{bark} is approximated to be 27 cm based on statistical data of loblolly pine (Schultz, 1997) and height of class 4 poles. This data is then assumed to be similar for other species of southern yellow pine trees, which are commonly used in the U.S. for wood construction and electrical poles.

The decay model described in Wang et al. (2008) mentions various methods of decay direction (external vs. internal). Decay may progress from both the center progressing outwards or from the pole surface and progress inward. For this study, the decay pattern is only modelled progressing from the surface inward.

3.2. Case study locations

Three locations have been selected to analyze the impact of climate change on hurricanes and the decay rate, and thus the lifecycle, of wood poles. Miami, Florida, Charleston, South Carolina, and New York City, New York, are selected to give a wide breadth of climates. Miami has a tropical monsoon climate, which lends itself to being hot and humid year-round.

Because of its location between the Gulf of Mexico and the Atlantic Ocean, it is the most likely city in the U.S. to be affected by tropical storms and hurricanes. Charleston has a milder subtropical climate with hot summers and mild winters. Charleston still has above average humidity and is prone to tropical cyclones that follow the east coast. However, historically, there have been no Category 5 storms to hit Charleston, but a few Category 4 events have occurred. New York City has a much colder continental climate meaning it has hot summers and cold winters (Peel et al., 2007). The hurricane risk in New York City is lower than that of Charleston. The average projected temperature and precipitation from the CMIP5 for the three locations are shown in Fig. A1. Using the projected data, the mean decay rate of heartwood and sapwood are calculated and shown in Fig. 1. As temperature and precipitation increase due to climate change, so does the decay rate of the poles. It is noted that the decay rate is affected by local environmental conditions where the higher temperature and precipitation in Miami accelerate the deterioration process. To illustrate the effects of climate change, Climate data from 1950 to 1970 is used for the no climate change scenario plot.

3.3. Impact of FRP repair time on strength

The period of interest is 2010–2099. FRP repair can be carried out at any time while the pole is in service. One repair scenario will be applying the FRP wrap when the pole's strength reaches two-third of its initial value, which is the NESC threshold for repair or replacement. Fig. 2 shows a plot of the variation of pole strength with time. The time it takes for the strength to reach the NESC threshold is defined as the service life of the pole. For illustration purposes, the added strength due to FRP repair is assumed to be 30% of the initial pole strength. From the analysis, the average service life of the pole in Miami is around 27 years with no climate change effect. The average service life in Miami for both RCP4.5 and RCP8.5 is the same as the no climate change scenario. This is because the difference between the two in terms of changes in decay rate only becomes apparent later in the 21st century, as seen in Fig. 1. Even towards the end of the 21st century, the increase in decay rate due to climate change does not have a significant impact on the change in diameter of the poles and the strength, as seen in Fig. 2. For example, the service life of the pole in Miami only decreased from 62 years for the no climate change scenario to 59 years for the RCP8.5 scenario.

The application of the FRP adds about 35 years to the service life of the pole in Miami with no climate change and 33 and 32 years for RCP4.5 and RCP8.5, respectively. The FRP adds about 49, 44, and 42 years to the service life in Charleston with no climate change, RCP4.5, and RCP8.5, respectively. The corresponding additions are greater than 52, 51, and 49 years in New York City. The variation in the service life in the three locations is due to the varying climates in the regions with poles in Miami having the highest decay rate due to its tropical monsoon climate.

Note that the sudden change in the slope of the lines after about 70 years is due to the transition from the decay of the

sapwood to the heartwood. Because the k_{wood} factor in Eq. (1) is lower for the heartwood, the transition leads to a decrease in decay rate, which resulted in a decrease in strength loss seen in Fig. 2.

As mentioned previously, the CMIP5 provides 71 and 70 outputs from different Global Climate Models (GCMs) for RCP4.5 and RCP8.5, respectively. The results shown in Fig. 2 are based on the ensemble means of the 71 and 70 outputs. In Fig. 3, the change in strength with time for the individual GCM outputs is plotted. The plots in Fig. 3 give an indication of the model uncertainty from the GCMs. The model uncertainty is associated with the fact that different GCMs provide different outputs for a given radiative forcing depending on the simplifications and assumptions used in the models (Bastidas-Arteaga and Stewart, 2015). It can be seen from Fig. 3 that the variation in the results considering all the GCM outputs is small. In subsequent analyses, the temperature and precipitation are modeled in a Monte Carlo simulation as normally distributed random variables with mean and standard deviation determined at each time from all the GCM outputs, as mentioned earlier.

The FRP can also be installed at any time before the strength of the pole reaches the NESC threshold. In Fig. 4, the time of repair is varied along the pole's service life to determine if there is an optimal time of repair. The figure shows the relation between the service life of the pole and FRP repair age. For Fig. 4, the added strength by the FRP is assumed to be 30% of the initial strength of the pole for illustration purposes. From the results, it is apparent that there is a positive correlation between earlier repair time and extended pole life. This is most likely due to the assumption that the presence of the FRP reduces the amount of moisture and fungal contact with the underlying pole, which produces a slower decay rate than merely treating the poles. The only exception to this trend is for Miami, in which there is an uptick of service life for FRP installation at the NESC threshold (27 years) compared to installation at 20 years. This is most likely due to the projections that precipitation is not expected to drastically increase in the RCP4.5 and RCP8.5 conditions in Miami with the RCP8.5 scenario actually projecting that precipitation will decrease (Fig. A1). In all cases, the service life could not be accurately estimated past the 90-year mark as the CMIP5 data only extends through the end of the 21st century. Hence, in cases where the service life extends beyond the end of the 21st century after FRP repair, the service life is not estimated. Consequently, only two points of the New York City results are plotted. The service life of the poles for repair at 10 and 20 years extends beyond the 90-year mark.

3.4. Type 1 failure risk results

Figure 5 illustrates the change in the probability of Type 1 failure (due to hurricane winds) for each of the three zones studied for three repair scenarios: no FRP, FRP installation at 16 years, and FRP installation at 32 years. To determine the failure probabilities here and in subsequent sections, the gain

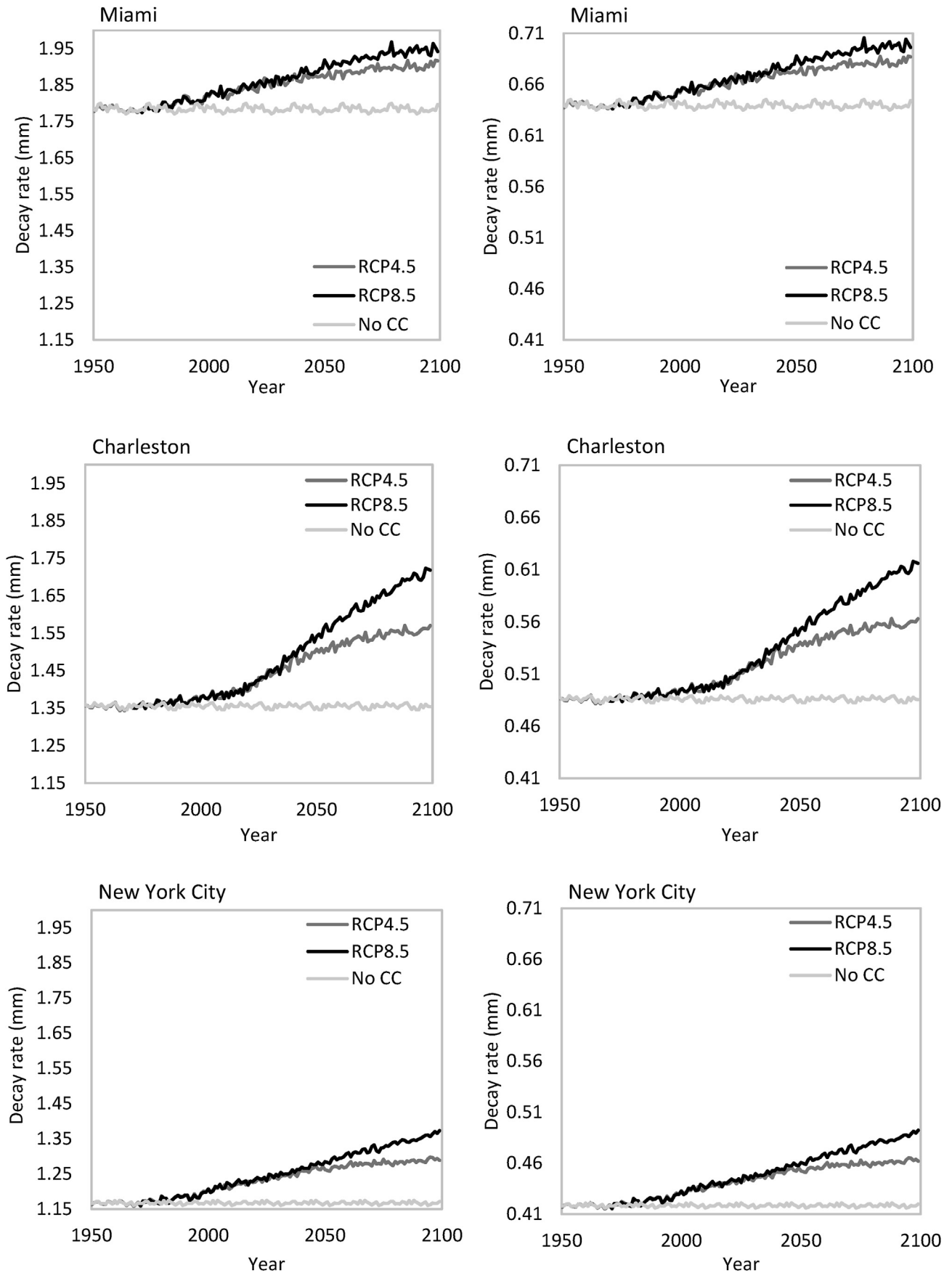


Fig. 1. Mean decay rate, left: sapwood, right: heartwood in 1950–2099 (No CC is no climate change scenario).

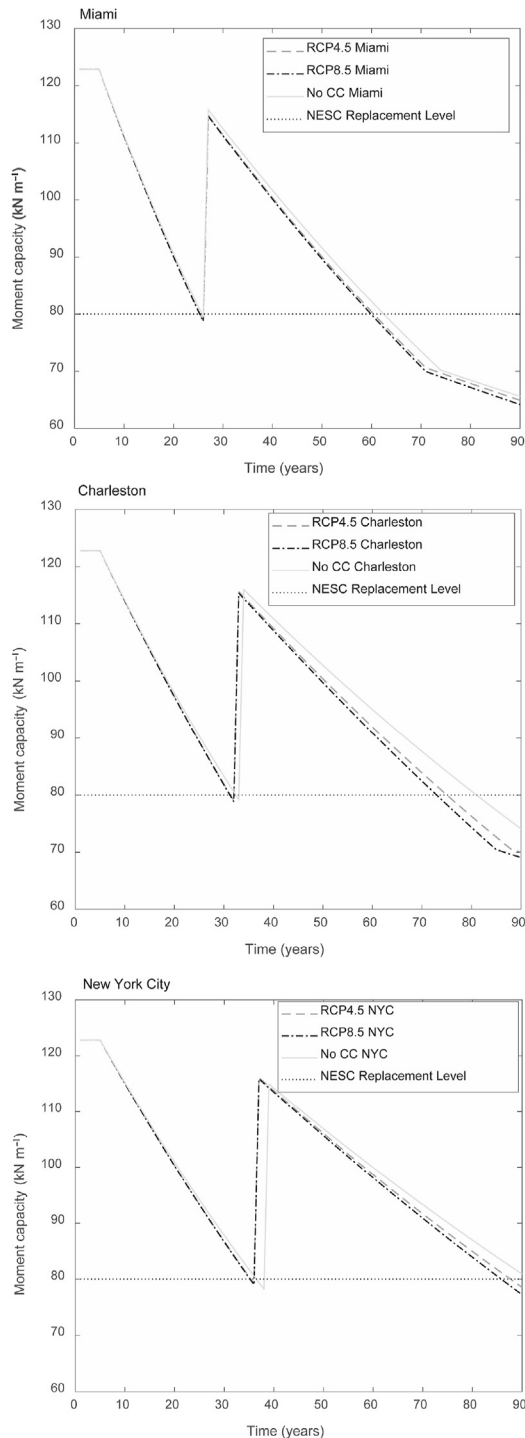


Fig. 2. Average strength plot with FRP repair at NESC strength threshold (No CC is no climate change scenario).

in strength due to FRP repair is assumed as random as described in Section 2.4. The figure illustrates that the effectiveness of FRP repair is not only time-dependent but location or climate-dependent as well. This is most readily apparent in the New York City cases in which the difference between applying the FRP coat at 16 or 32 years do not differ greatly. However, the decision to apply the FRP sleeve reduces the probability of failure in New York City from about 4% in 2099

in the no-FRP and no climate change scenario to less than 1% for both scenarios in which FRP sleeve is used as evidenced in Fig. 5.

The results in Fig. 5 demonstrate that climate change dramatically increases the probability of failure, subsequently lowering the lifespan of wooden poles. RCP4.5 and RCP8.5 scenarios increased the failure probabilities in Miami at the end of the 21st century by about 15% and 30%, respectively, compared to the no climate change scenario. The corresponding increases are 23% and 70% in Charleston, and 25% and 73% in New York City. The comparatively lower increase in Miami is due to a decrease in precipitation towards the end of the 21st century for the RCP8.5 scenario and little increase in precipitation for the RCP4.5 scenario, as seen in Fig. A1.

While the decision to implement the FRP repair always improves the lifespan of wooden utility poles, as seen in Fig. 5, the optimal time of repair is dependent on the location. In most cases, there was a positive relationship between early repair and extension of effective service life. The exception to this being applying FRP at the time of replacement for Miami. This again is most likely due to the predicted decrease in precipitation in Miami. It is seen that the application of the FRP sleeve is effective in mitigating the probability of failure of the poles due to the RCP4.5 and RCP8.5 scenarios.

Note that the parameters used in the time-dependent fragility analysis to obtain the annual probabilities of failure are summarized in Table A2.

3.5. Type 2 failure risk results

As mentioned in Section 2.4.2, Type 2 failure is defined by passive decay eroding the available strength of electrical poles to an unacceptable state as defined by the NESC. Fig. 6 illustrates the probability of Type 2 failure for each location over the service life of the pole. The analysis assumes that all poles were installed, and subsequently began their decay process, in 2010 and modeled using climate parameters based on the CMIP5 scenarios mentioned previously through the end of 2099.

It can be seen from the left column in Fig. 6 that climate change has little impact on Type 2 failure probability. This is because the increase in decay rate due to climate change is not large enough to have a significant impact on the decrease in diameter and, subsequently, the strength of the pole. This is evident from Fig. 2, where it is seen that climate change has little impact on the strength of the pole over time. For example, the pole used in the case study has a diameter of about 283 mm. The average decay rate of the sapwood in Miami increased gradually from about 1.83 mm per year in 2010 to about 1.94 mm per year in 2099 under RCP8.5, as seen from Fig. 1. The corresponding increase for the heartwood is from about 0.65 to about 0.7 mm per year. This resulted in a negligible impact on the failure probabilities of the pole. Note that Figs. 1 and 2 are plotted using average annual temperature and precipitation, while in Figs. 5 and 6, the temperature and precipitation are sampled from a normal

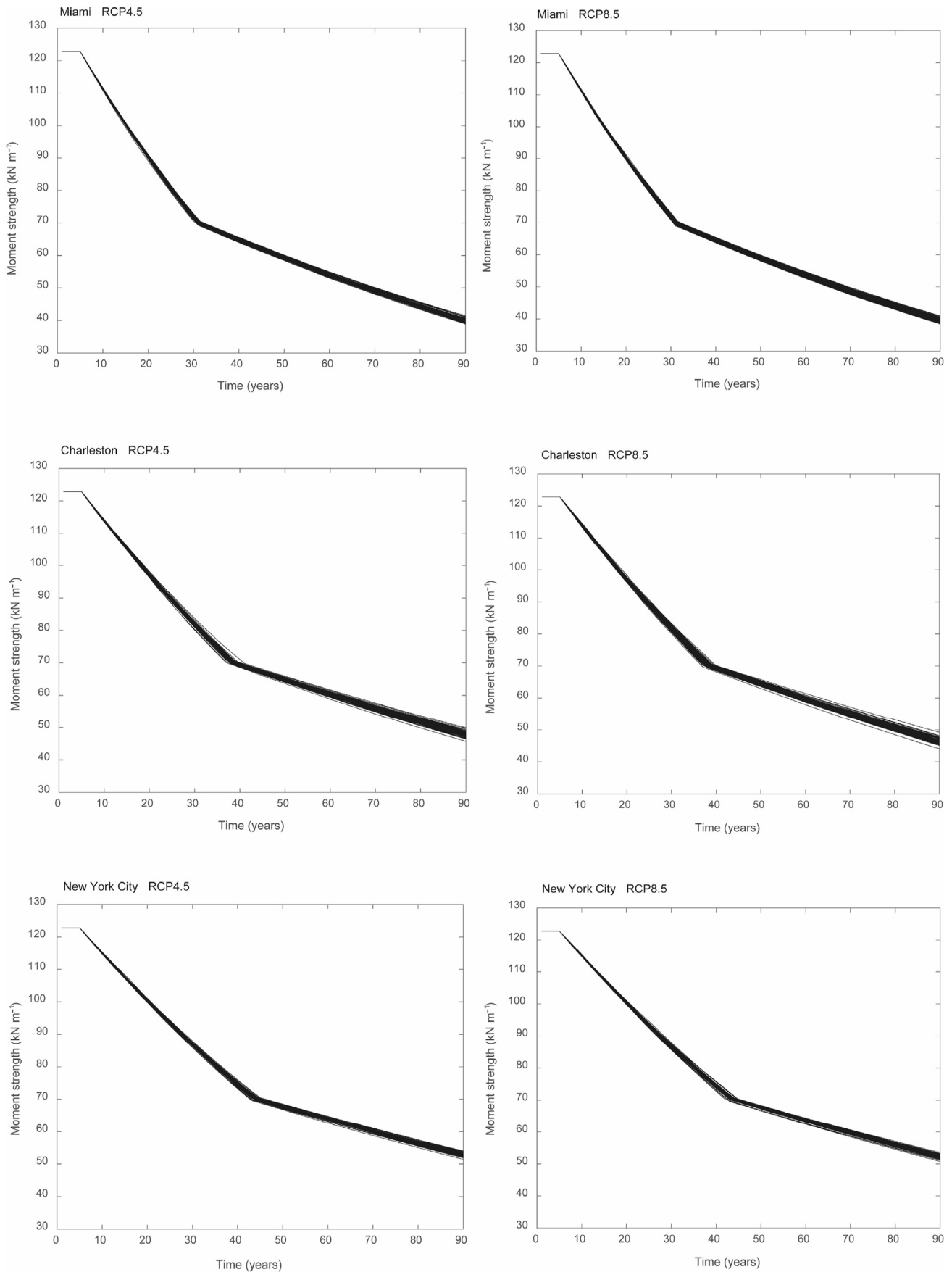


Fig. 3. Strength plots of all CMIP5 outputs with no FRP repair.

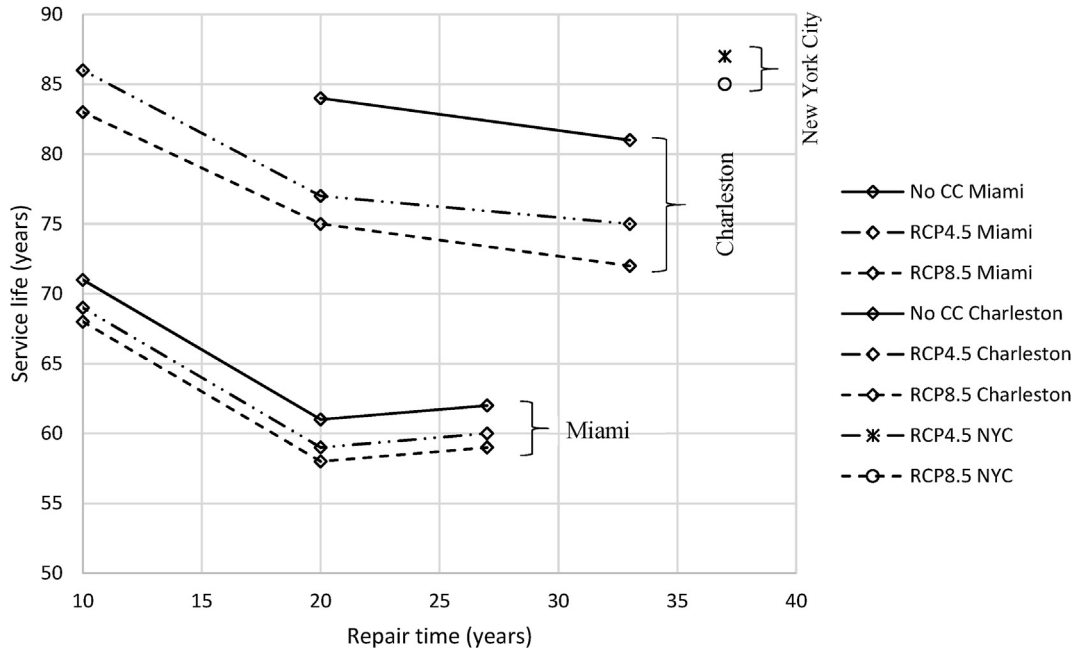


Fig. 4. Estimated average service life for different repair times (No CC is no climate change scenario).

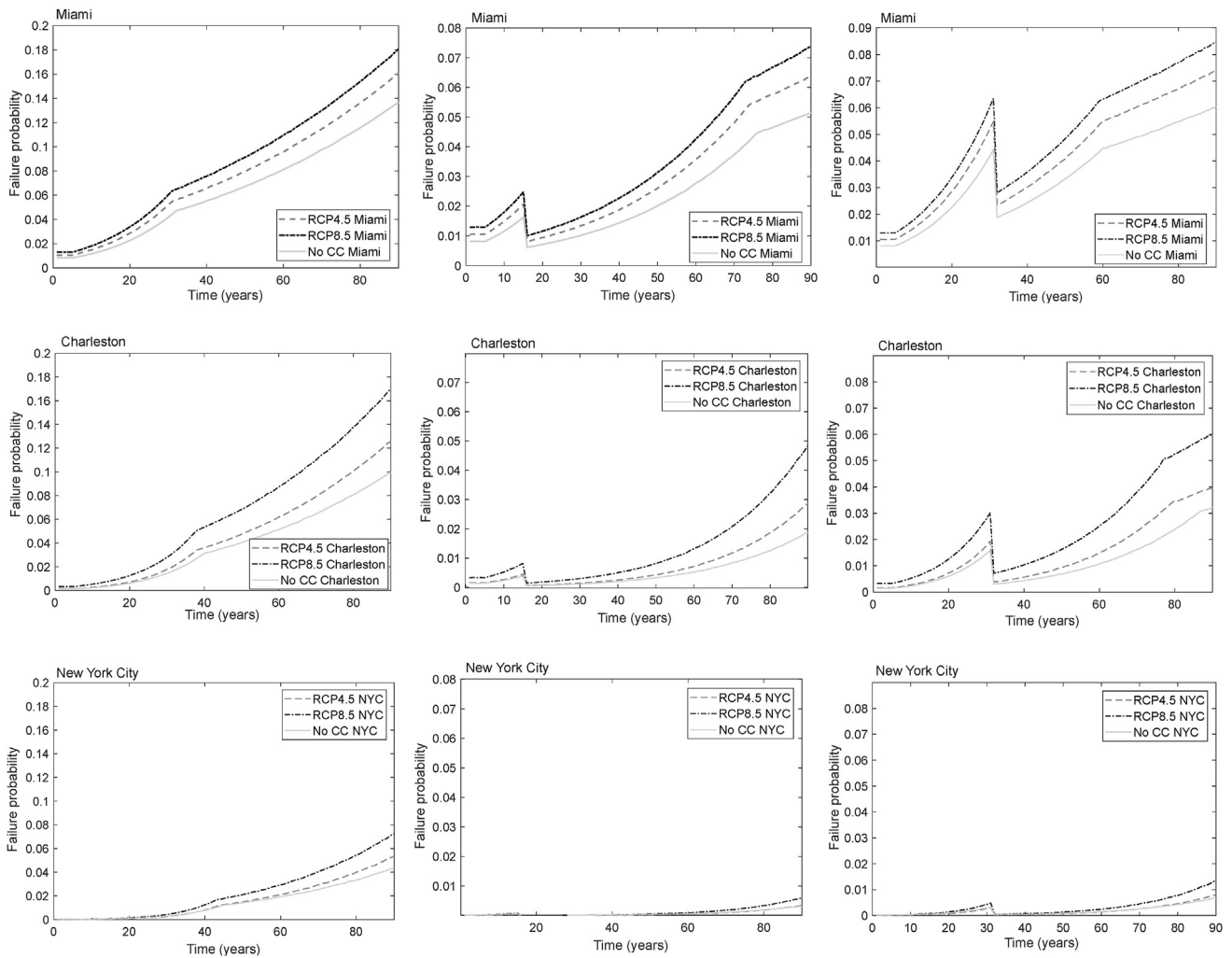


Fig. 5. Type 1 failure probabilities with no FRP (left), FRP installation at 16 years (middle), and installation at 32 years (right) (No CC is no climate change scenario).

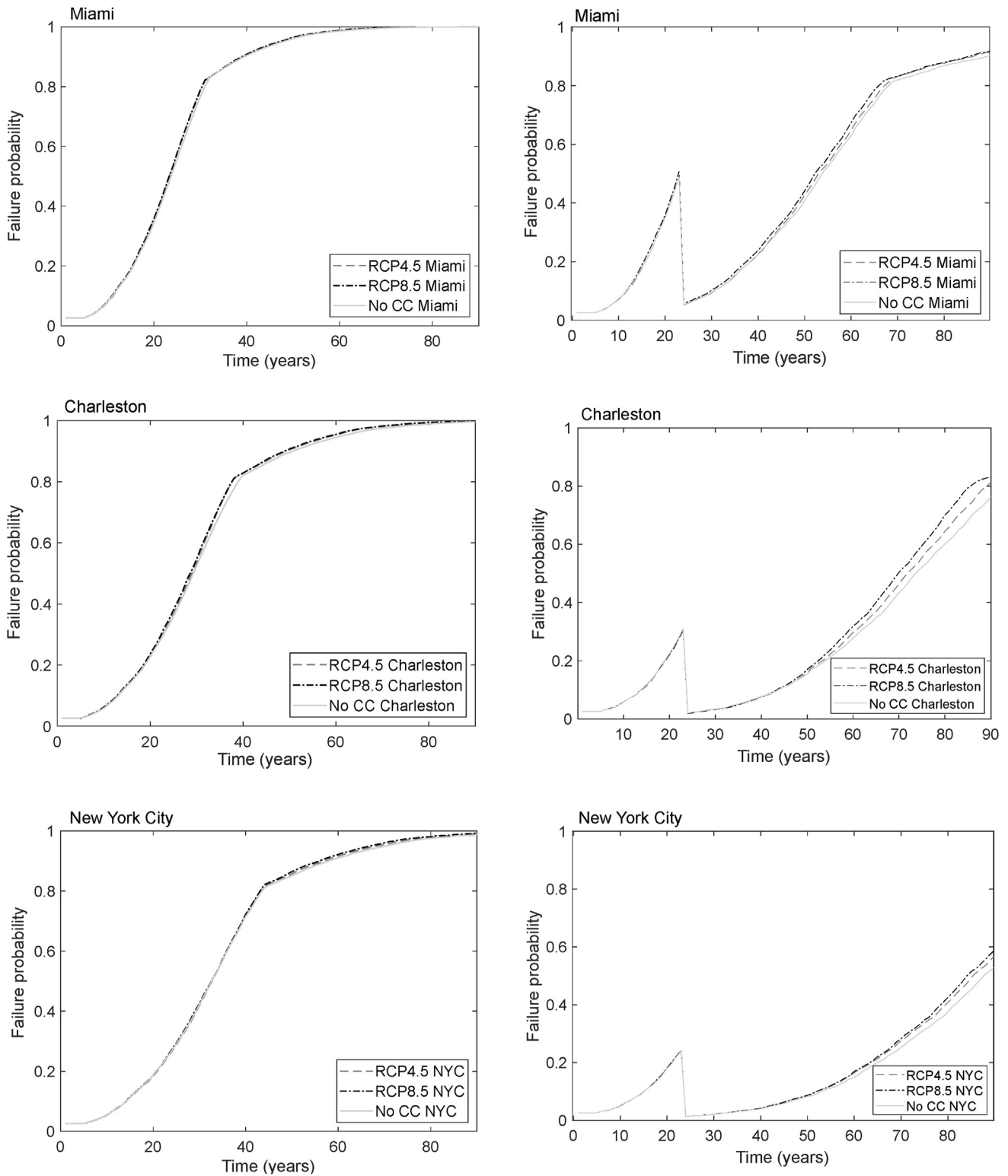


Fig. 6. Type 2 failure probabilities with no FRP (left) and with FRP installed at 24 years (right) (No CC is no climate change scenario).

distribution each year based on the outputs from various GCMs in the CMIP5 records.

Comparing the results with no FRP and with FRP, the cases with FRP repair show a higher impact of climate change on failure probability (comparing the two figures for Charleston,

for example). This is because the application of the FRP causes decay towards the end of the 21st century to occur in the sapwood, which has a higher decay rate compared to the heartwood. In the case with no FRP, however, the sapwood will decay completely by the middle of the century, and the

decay will attack the heartwood, which has a much lower decay rate, as seen in Fig. 1. This transition will significantly decrease the decay rate despite climate change resulting in little impact of climate change on the failure probability by the end of the 21st century.

When comparing the results from Fig. 6 to that of Fig. 5, the largest discrepancy is that the spread of the results in Fig. 6 is significantly lower. The reason is that for the Type 1 failure probability, the limit state function is a convolution of the failure probability given a wind speed with the probability of the wind speed occurring. The combined impact of climate change on both decay and hurricane hazard in Fig. 5 resulted in a much higher impact on Type 1 failure probabilities. This is further discussed in the subsequent sensitivity analysis section.

Note that the initial strength of the class 4 southern pine pole selected for the case study is 55.2 MPa and is lognormally distributed with a coefficient of variation of 20%, according to ANSI-O5.1 (ANSI, 2002). Because of the large coefficient of variation, the probability that the strength of a new pole is less than two-third of 55.2 MPa is about 2%. That is why the failure probabilities in Fig. 6 for new poles is about 2%.

3.6. Sensitivity analysis

As mentioned previously, studies have been done to predict the magnitude of changes to tropical cyclone intensity and frequency through the end of the 21st century (Emanuel, 2005; Knutson et al., 2008; Mudd et al., 2014b; Oouchi et al., 2006; Webster et al., 2005). Based on these results, a linear increase in intensity of 10% by the year 2099 for the RCP4.5 scenario and 20% for the RCP8.5 scenario with no change in frequency was assumed. To investigate the sensitivity of Type 1 failure (due to hurricane wind) to only changes in decay rate due to climate change, the failure probabilities are evaluated assuming that there is no increase in the intensity of hurricanes. Only the impact of climate change on decay rate is considered. The results are shown in Fig. 7. Comparing Fig. 7 to Fig. 5 exemplifies the impact that an increase in storm intensity has on the failure probabilities. When only taking into account the impact of climate change on decay for the two RCP scenarios (Fig. 7), the increase in the probability of failure without FRP by the end of 2099 under RCP8.5 scenario range from about 5% in Miami to about 22% and 20% in Charleston and New York City compared to a no climate change scenario. Adding increases in the probability of more intense wind events (Fig. 5), however, yields an increase in failure probabilities of the baseline no-FRP case of about 30%, 70%, and 73% in Miami, Charleston, and New York City, respectively.

As previously mentioned, Saafi and Asa (2010) assumed that after the application of an FRP sleeve, the rate of decay of the poles is roughly half of the decay rate prior to the installation of the sleeve. To investigate the impact of the

assumption on the results, a sensitivity analysis is carried out assuming the FRP has no effect on the decay rate of the poles. The results are shown in Fig. 8 for Type 2 failure. The assumption has a significant impact on the results. In New York City for example, the probabilities increased from around 0.55 to more than 0.9. The results illustrate an additional advantage of the FRP repair. Not only does it restore the strength of the poles, but it can slow down the decay rate and, consequently, extend the service life of the poles. Note that while the extent to which the FRP slows down the decay is unknown in this case, there is significant evidence that the repair of structural components using FRP can significantly decrease the strength deterioration of the component as mentioned previously (Debaiky et al., 2002; Masoud and Soudki, 2006; Pantazopoulou et al., 2001).

3.7. FRP repair optimization results

The objective of the optimization is to find the FRP repair time that will minimize the failure probability over the considered period (2010–2099). Fig. 9 shows the FRP repair optimization results, where the maximum failure probability variation over the considered period for different repair times is plotted. Note that only Type 1 failure probability is considered because the case study locations have hurricane risk. Recall that Type 1 failure includes the effects of both wood decay and hurricane hazard. For locations without hurricane hazard, the optimization can be carried out in a similar manner using Type 2 failure probability. The plots on the left side of Fig. 9 show the results based on the previously stated assumption that the application of the FRP will slow down the wood's decay rate by half. The results show that the optimal FRP installation time is at the beginning of the pole's life cycle, i.e., at the end of the decay lag period. This is because of the assumption of the significant decrease in the decay rate of the wood after FRP installation. Early FRP installation leads to slow decay throughout the considered period, which significantly decreases the failure probability. The plots in Fig. 5 confirm this trend.

The results on the right side of Fig. 9 show the optimal repair time if the FRP installation has no effect on the decay rate of the wood. In this case, the optimal repair time is not at the beginning of the pole's life cycle. Rather, it is more than halfway through the life cycle in all cases. The results show that it is better to allow the pole to decay significantly before the repair is carried out. The optimal repair times in Miami, Charleston, and New York City with no climate change are 58, 59, and 59 years, respectively. While climate change has an impact on the failure probabilities, as seen earlier, it does not affect the optimal FRP repair time. In Miami, the optimal repair times are 58, 57, and 59 years, for no climate change, RCP4.5, and RCP8.5, respectively. The corresponding repair times are 59, 58, and 60 years in Charleston; and 59, 59, and 60 years in New York City.

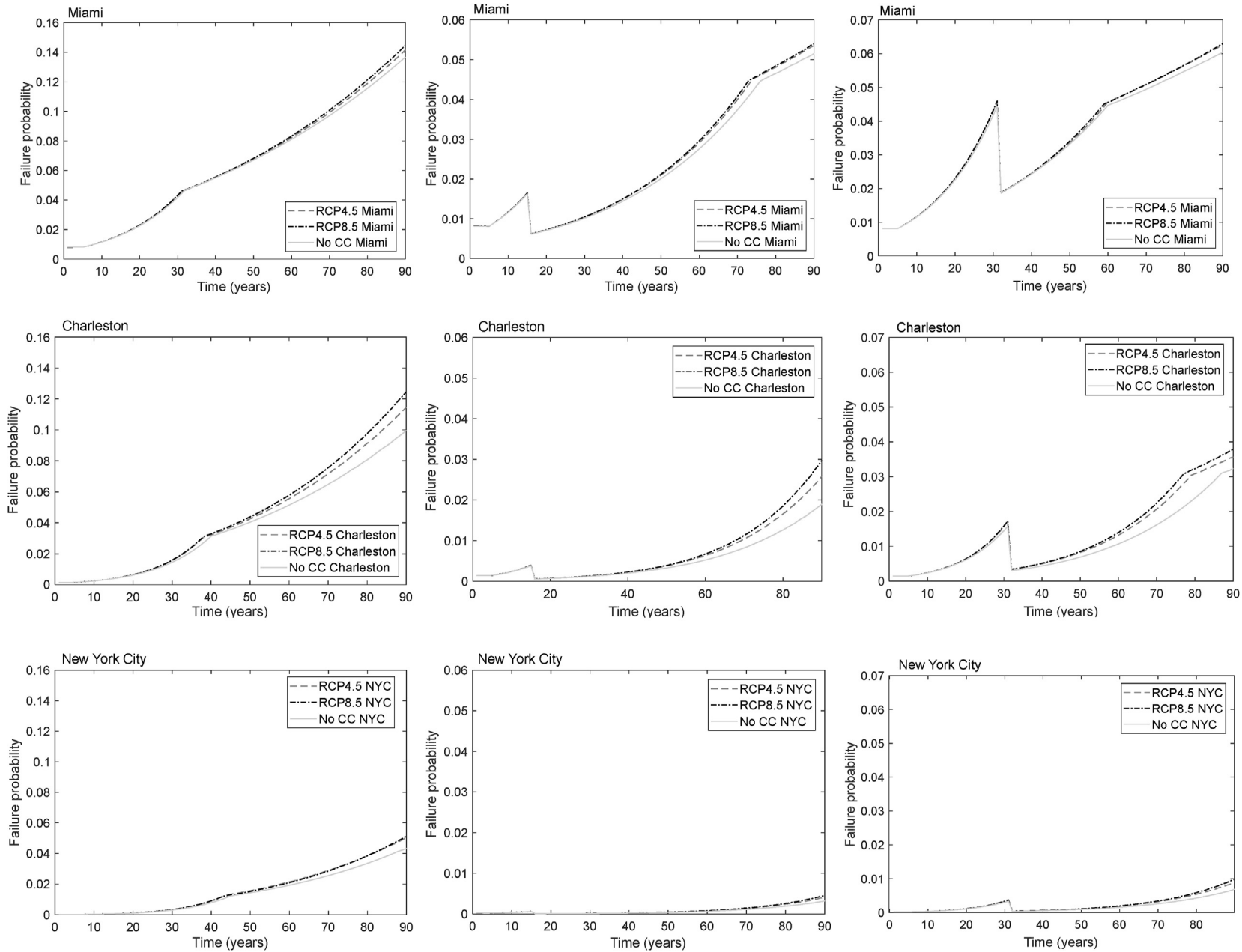


Fig. 7. Type 1 failure probabilities with no FRP (left), FRP installation at 16 years (middle), and installation at 32 years (right) without hurricane intensity increase (No CC is no climate change scenario).

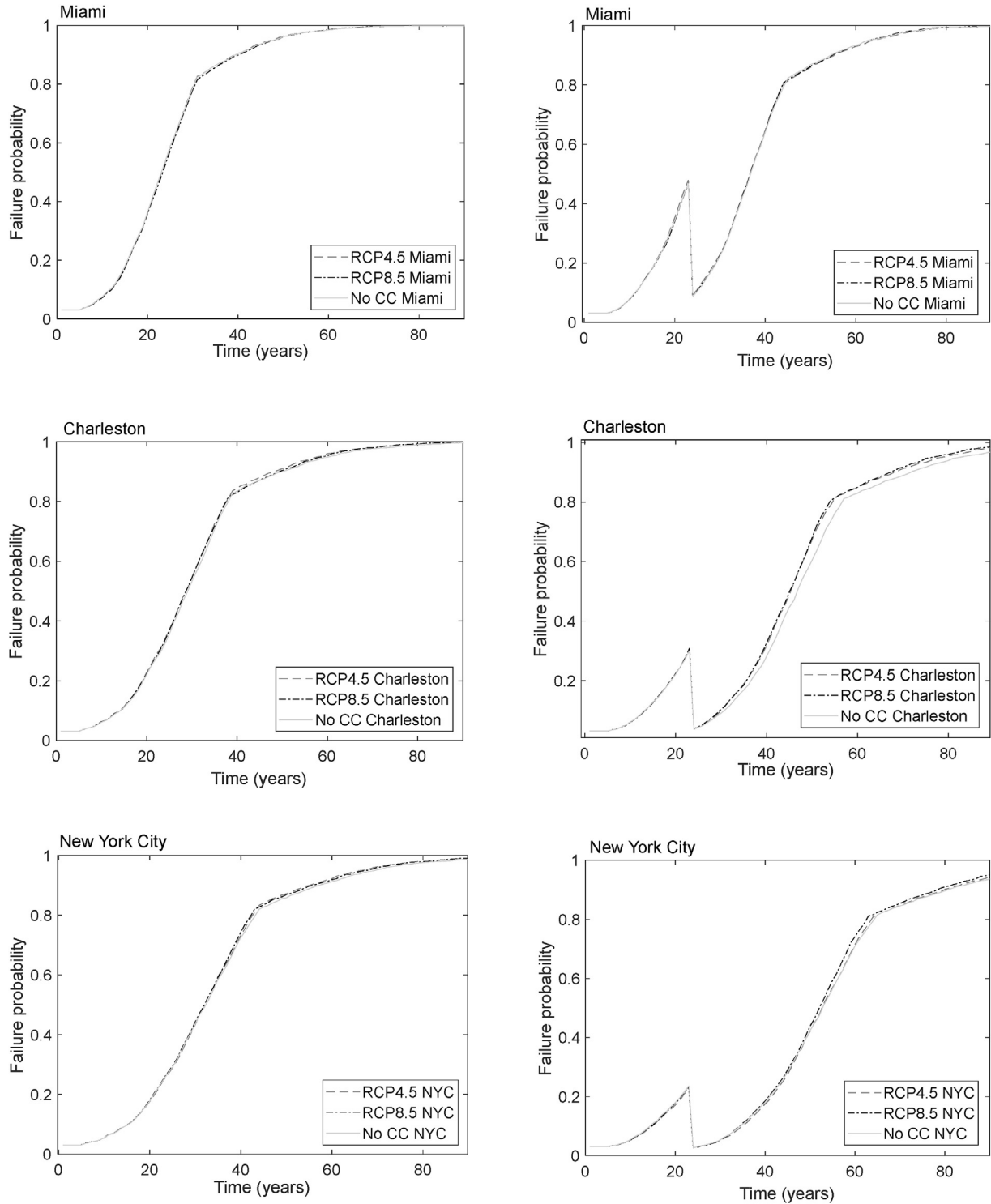


Fig. 8. Type 2 failure probabilities with FRP installed at 24 years, assuming a decrease in wood decay rate after FRP repair (left), assuming no change in wood decay rate after FRP repair (right) (No CC is no climate change scenario).

Even though the decay rates in the three considered locations vary, the results on the right of Fig. 9 show that the optimal repair time is independent of location. This is because the optimization is based on the maximum failure probability over the considered period. Hence, the optimal repair year depends on the point at which the failure

probability at the end of the 21st century and the year of the repair will be minimized. In other words, the optimization is about finding a balance point to keep the failure probability from becoming too large over the 90-year period. Hence, the magnitude of the failure probability does not influence the optimal repair time.

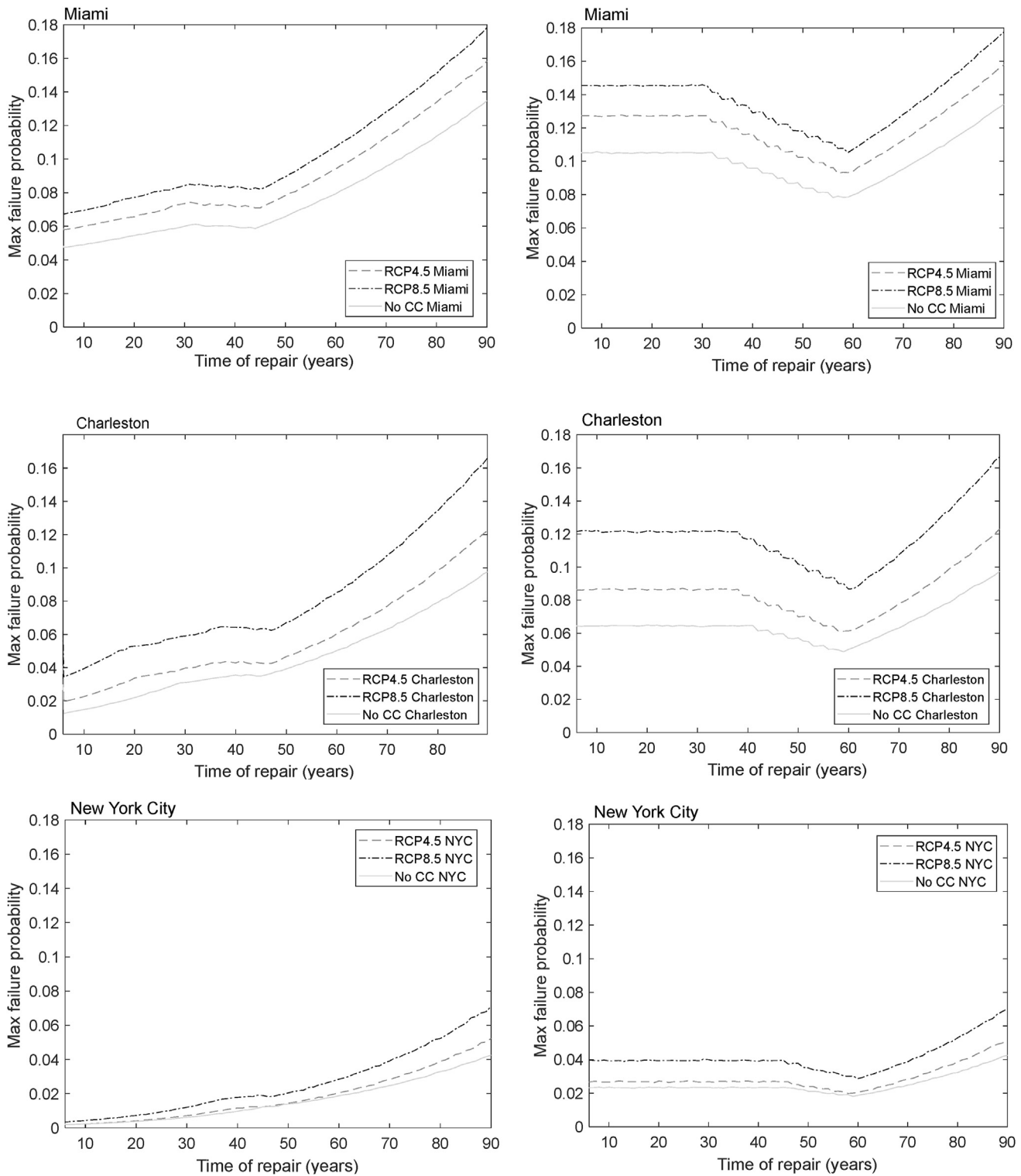


Fig. 9. FRP repair optimization results for type 1 failure probabilities, assuming a decrease in wood decay rate after FRP repair (left), and assuming no change in wood decay rate after FRP repair (right) (No CC is no climate change scenario).

4. Conclusions

This study investigates the effectiveness of using fiber-reinforced polymer (FRP) sleeve to reinforce wood poles subjected to decay to restore their lost strength and extend

their useful service life. The potential impact of climate change on the pole decay rate and the intensity and frequency of hurricanes is also considered. Additionally, the optimal FRP repair time based on structural reliability consideration is determined. Poles located in Miami, Charleston, and New

York City, are considered in a case study. The results of the case study show that FRP is highly effective in extending the pole's service life. Repair using FRP extended the service life in Miami, Charleston, and New York City by about 35, 49, and >52 years. The higher increase in service life in Charleston and New York City is because of lower pole decay rates relative to Miami. The results also show that the effect of climate change is highly related to the location under investigation. In Miami, where precipitation was projected to decrease over time, the increase in failure probability at the end of the 21st century due to decay and hurricane hazard under RCP4.5 and RCP8.5 emission scenarios was 15% and 30%, respectively. In Charleston and New York City, however, where both temperature and precipitation were projected to increase over time, the corresponding increases are 23% and 70%, and 25% and 73%, respectively. It is also concluded from the results that while the incremental change in climate conditions does not significantly impact the rate of decay of poles, the increased intensity of storms over time does have a significant impact on the structural reliability of the poles over time. This conclusion is true for all three locations considered.

Based on the optimization results, it can be concluded that the optimal FRP repair time depends on the impact of the FRP on the decay rate of the wood. If the FRP can significantly decrease the decay rate, the optimal repair time is at the beginning of the pole's life cycle. However, if the FRP has no impact on the decay rate, then it is better to repair the pole after significant decay. Hence, more experimental data is required to characterize the kinetics of the decay rate after repair. In addition, the durability of the bonding between the timber and the FRP as well as the durability of the FRP should be considered in the future. It should also be noted that the outcome of the optimization could change when cost is included.

In general, the results show that the application of an FRP reinforcement sleeve is effective in decreasing the risk due to both deterioration and wind loading. While reinforcement of wooden electrical distribution poles has been common practice, typically, reinforcement is in the form of metal plates or splints to shore up the ground-level cross-section. The major benefit of using an FRP solution is that it can simultaneously protect and strengthen poles from multiple threats. While steel sheets may increase the cross-sectional moment capacity, the plates are typically not installed around the entire circumference of the pole, which still allows for fungal and moisture attacks to the section. Additionally, the effectiveness of steel plates has a high degree of uncertainty as it is difficult to predict how well the plates are attached or bonded to the poles.

It should be noted, however, that the results of the case study are based on a specific decay model, locations, and climate change scenarios. The decay model adopted in this study uses yearly averaged data. Consequently, the effects of extreme daily or seasonal conditions that could significantly increase the decay rate are not captured. More precise predictions will require a more advanced decay model able to account for daily or seasonal data. However, the method proposed in this study is general and can be used with any data

for the sake of wood pole asset management by utility companies.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.accre.2020.10.001>.

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