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A probabilistic framework for hurricane damage assessment considering non-stationarity and correlation in hurricane actions

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ABSTRACT

The intensity and/or frequency of hurricane storms may change due to the impact of potential climate change. This paper presents a probabilistic framework to assess the hurricane damage to residential constructions considering the non-stationarity and correlation in hurricane actions. The framework includes a non-stationary Poisson process of hurricane occurrence, a failure rate function of hurricane damage, and explicit formulas for evaluating the mean and variance of annual hurricane damage. The framework is illustrated using a case study of Miami-Dade County, Florida, where the current probabilistic models of hurricane intensity and occurrence rate were estimated by examining hurricane history in this area. The impacts of time-variant hurricane intensity and time-variant hurricane frequency on building damage are assessed individually using the developed framework. The paper also investigates the effects of correlation in hurricane wind speeds on hurricane damage.

1. Introduction

Civil infrastructures are subjected to natural hazards such as hurricanes and earthquakes. In coastal areas, wind hazard can cause extensive economic losses, social disruption, and fatalities. For example, hurricane Katrina of 2005 caused more than US $100 billion in losses and resulted in about 2000 fatalities with the greatest coastal flood height ever recorded in the US [17]. Moreover, the coastal areas have a steady increase in population and wealth in the past decades [24], suggesting that the potential of even larger human and economic losses exists in future. In recent years, there has been growing evidence that global climate change may affect both the frequency and severity of the extreme events from natural hazard [7,3]. Knutson et al. [12] estimated that in the 21st century, hurricane speeds may increase by as much as 20% around the world; Australian Greenhouse Office [1] reported that peak wind speed will increase by 2–5% by the year 2030 and 5–10% by 2070. The IPCC (Intergovernmental Panel on Climate Change) also indicated that hurricane intensity and frequency may be affected by the increase of sea surface temperature [5]. The public and regulatory authorities are increasingly concerned with the potential impact of climate change on the safety of civil infrastructures.

A critical part of life-cycle risk assessment for built environment is the probabilistic modeling of extreme structural loads due to natural hazards such as hurricanes. Most existing hurricane damage assessments assume that the wind actions are stationary with time [15,24]. This assumption, however, is questionable if the impacts of climate change are to be considered. To assess the life-cycle risk of civil infrastructures in the context of global climate change, the non-stationarity in hurricane actions must be taken into account. The implications of non-stationarity in wind loads due to climate change have been considered in only a few studies. Bjarnadottir et al. [4] conducted a study on the impact and adaptation assessment of climate change on hurricane damages using the non-stationary storm wind field model. The possible increase in storm intensity was considered by changing the maximum annual wind speed. Similar work has also been by Li and Stewart [16], in which the Extreme Type I distribution was utilized to model the distribution of wind speed. These researches focused only on the effect of time-variant storm intensity; none of them considered the possible change in storm frequency. Li et al. [14] was among the first attempts to assess time-dependent structural reliability by considering the time-varying load intensity and frequency simultaneously. Two extreme cases of serial correlation in load intensities, i.e., statistically independent and fully correlated, were compared. However, the paper did not

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consider the more general cases of serial correlation in wind load intensities. Thus, the effect of serial correlation in stochastic load process on structural reliability has not been fully studied yet [13].

This paper proposes a probabilistic framework for hurricane damage assessment to residential constructions, accounting for the potential effects of time-variant hurricane intensity, time-variant hurricane frequency and correlation in hurricane wind speeds as a result of climate change. The framework includes a non-stationary Poisson process of hurricane occurrence, a failure rate function of hurricane damage, and explicit formulas for evaluating the mean and variance of annual hurricane damage. To evaluate the effects on hurricane damage of correlation in hurricane wind speeds, a Monte Carlo simulation-based approach is used, employing Nataf transformation to generate correlated wind speed series. The conventional Nataf transformation is modified to handle correlated random variables with large coefficient of variation (COV) of more than 0.5. The framework is demonstrated through a case study of Miami-Dade County, Florida. The "current" probabilistic characteristics of the hurricane actions in this region are obtained by examining historical hurricane records. The effects of non-stationarity and correlation in wind speeds on hurricane damage are then investigated using the developed framework.

2. Stochastic models for wind action

2.1. Hurricane data

Miami-Dade County, Florida was chosen in this paper to illustrate the potential impact of climate change on hurricane damage to residential constructions. The historical hurricanes obtained from the US National Hurricane Center's Database (http://coast.noaa.gov/hurricanes/) were used to estimate the "current" characteristics of hurricanes affecting this region. The considered Miami-Dade region is shown in Fig. 1, which is a circle with a radius of 45 km, consistent with the area of this County of 6296 km^2. In total, there were 27 hurricanes occurring from 1901 to 2010, which directly strike the Miami-Dade region. The tracks of these hurricanes are shown in Fig. 1.

Fig. 2 shows the time series and monthly distribution of the 27 hurricanes over the 110-year period. There were 86 years in which no hurricane occurred in a given year, and 3 years in each of which 2 hurricanes stroke the County. The average annual number of hurricanes in this region is 0.245. Miami-Dade's hurricane season runs from the beginning of June through the end of November (except that there was one hurricane occurring in February, 1952). The most active months are August, September and October. These 3 hurricane-active months account for 74% of all Miami-Dade's hurricanes.

Fig. 3 shows the time series and the histogram of the maximum sustained surface wind speeds (1-min average at 10 m height) of these 27 historic hurricanes. From Fig. 3, it can be seen that the 4 Major hurricanes which had a wind speed greater than 51 m/s occurred mainly in September. From these limited data, there appears to be no obvious long-term trend in the maximum wind speed, although other researches [20] showed an upward trend in the mean and upper quantile of the maximum wind speeds of Florida hurricanes. Based on the 27 historical hurricane records, the mean and the standard deviation of the hurricane wind speed (1-min sustained) are 31.8 m/s and 16.2 m/s, respectively.

2.2. Stationary hurricane wind process

The hurricane hazard is expressed by climatologists in terms of wind speed probability for a standard averaging time (1-min or 10-min), exposure (open terrain) and elevation (10 m). Unless noted otherwise, the wind speeds cited in this paper refer to 1-min sustained wind speeds. A number of wind field models have been developed and used for wind speed simulation and risk analysis in the last three decades [22,25,15,4]. These wind field models were developed using similar approaches: (1) determine statistically the distributions of key site-specific storm parameters including rate of occurrence, central pressure, heading, radius of storm, and crossing position along the coast, etc., (2) sample the storm parameters, and (3) record the wind speed when the storm passes the site.

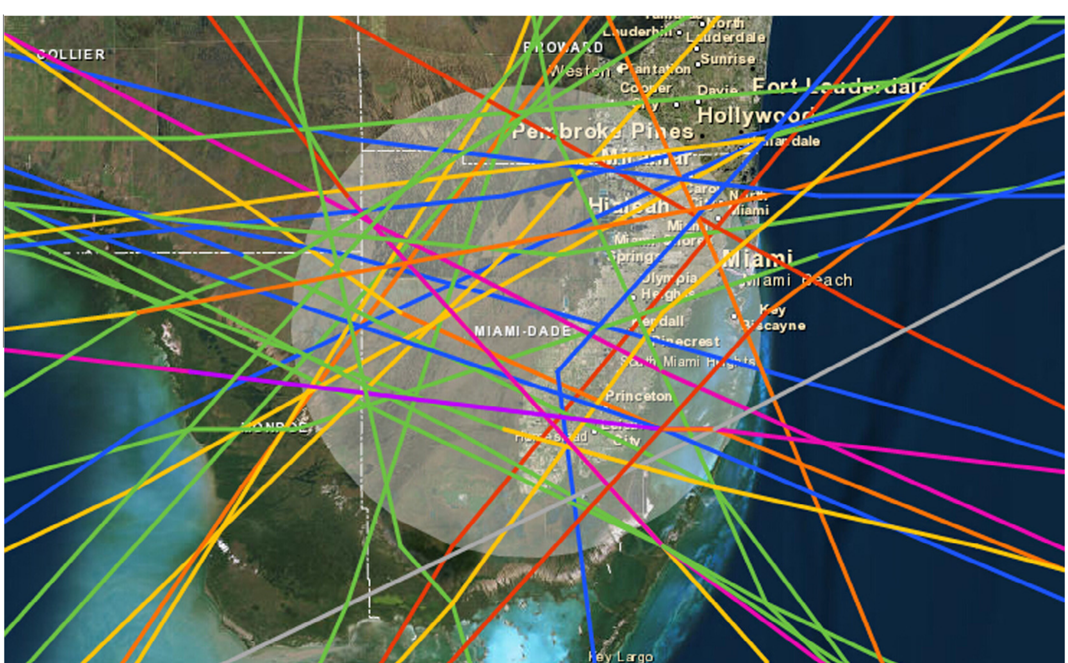

Fig. 1. Miami-Dade County, Florida and the tracks of hurricanes from 1901 to 2010 (figure reproduced from US National Hurricane Center website).