Design Criteria for Temporary Structures in Uncertain Extreme Natural Hazard Load Environments

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Abstract: In design of temporary structures, designers often face the question:"What is an appropriate design load level for the structure, given that future loads are uncertain?" This is especially the case in situations where the structure is subject to potential natural hazards such as hurricanes, with potentials for extreme wind pressures. The uncertainty in predicting loads may result in inadequate designs causing severe losses to contractors and erectors. A proper design with considerations for the uncertainties inherent in natural-hazard loads, along with information on extreme load events during construction, will minimize potential losses and enhance the system reliability. In this paper, a three-stage decision-based programming model is introduced to determine design loads resulting from probable extreme hazard events for temporary structures such as hurricanes. This model evaluates the expected cost of implementing a contingency plan against extreme wind loads when meteorological data indicate potentials for occurrence of hurricane events exist. An example of a steel structure under construction is presented to illustrate the proposed methodology. In this example, the significance of having a contingency plan, to safeguard against hurricanes, is presented and shown to improve the profitability of the project, and to impact the decision-making process at the time of bidding.

Keywords: temporary structure; wind load; uncertainty; optimization.

1. Introduction

Hurricanes are frequent events in the southern and southeastern regions of the United States. In many such events, the potential for landfalls exists with severe property damage and losses. The annual frequency of occurrence in the eastern US is estimated to be 2.1 hurricanes per year (Miller, 1999). Hurricanes are classified based on the Saffir–Simpson Scale, which is driven by the hurricane's wind speed (Li, 2011). Klotzbach et al. (2009) classify hurricanes into three categories; (1) Tropical storm, (2) Hurricane, and (3) Intense hurricane. A hurricane has categories 1 or 2 and an intense hurricane has categories 3, 4, or 5 on the Saffir–Simpson Scale.

Forecasting of hurricane losses provides a basis for estimating the adequate catastrophe cover such as insurance premiums and reinsurance. The premium is usually evaluated as the expected annual loss (EAL) for each category of structures in a certain region; while the probable maximum loss (PML) dictates if reinsurance is required or not. The forecasted loss can also be represented by the exceedance probability curve (EP-curve). Such a curve describes the probability of exceeding a certain loss value given the occurrence of a hurricane. Understanding the risk of an upcoming hurricane during construction may help contractors determine the cost associated with the construction process and recovery, if any.

Three principles govern the risk of a temporary structure or a structure during construction to hurricanes or extreme wind events. These are (1) hazard; (2) vulnerability; and (3) exposure. The hazard component identifies the frequency and severity of the hurricane by generating the distribution of hurricane wind speed at the desired location. The vulnerability and exposure components take these expected wind speed values along with specific information pertaining to the susceptibility of the structure to the hazard to evaluate the loss or damage generated at the different levels of the probability of hurricane occurrences. This information on hazard, exposure, and vulnerability can be used in evaluating the insurance losses following hurricane events. This is often done by producing an exceedance probability curve for a given structure or structure type (Hamid, 2007). However, these models are mainly applicable to permanent structures that represent the major stock of buildings in the insurance inventory. Besides, extending these models to temporary structures may not be an attractive option for some contractors since they often require a large computational and knowledge base. Nevertheless, in some projects where the profitability is highly dependent on whether a hurricane occurs or not during the construction period, the use of models similar to those in permanent structures may be justified. In such cases, this could affect the decision of the contractor when participating in the bid process.

Extreme events such as hurricanes or earthquakes may need a robust planning process to account for their possibilities to attain a reliable and economic design. A recourse decision after observing of uncertainties may be possible, which represents an opportunity for contractors to reach a more optimal design. Stochastic optimization provides one of the tools for optimizing the design while considering the effect of uncertainties. Stochastic optimizations have been used in many fields such as constructing models for solving capacity allocation under uncertainty (Chen et al., 2015; Chen et al., 2002; Andreatta et al., 2011), air traffic flow management (Triki et al.,2005), and in applications for disaster management (Barbarosoğlu et al., 2004; Bozorgi et al., 2013; Noyan et al., 2012).

In stochastic programming, several design parameters are defined as random variables, with data sampling methods used to determine their probability distributions. However, enumeration of all possible scenarios, in a data-sampling scheme, is sometimes unattainable because of lack of basic information upon which a scenario can be modeled. Before starting the scenario generation, the stochastic optimization problem should be properly defined. The information needed for proper definition includes (1) the number of stages that decisions are required; (2) the time between stages; (3) type of information that will be available at the time that a decision should be made; and (4) time needed for taking a response action (for example, the forecasting system for hurricanes will require 3-4 days for taking actions).

In this study, the effect of unpredictable actions such as hurricanes on a temporary bracings design plan for structures under construction or erection is discussed. An example of a steel structure under construction is given to illustrate the proposed methodology.

2. Proposed Hurricane Catastrophe Model

Estimating the loss generated from hurricanes for temporary structures has its peculiarities. For instance, the estimated loss could be affected by (1) the dynamic nature of temporary structures such as the change in the resistance as a function of the construction sequence; (2) the construction period and the fact that it may not completely fall within the hurricane season; (3) parties involved – since, in contrast to permanent structures where only the owner and the insurer share the risk, temporary structure failures may be shared by several parties (e.g., the contractor, subcontractor, erector, owner and the insurance company, depending on the contract's nature); (4) potential for the alteration of the original design after forecasting a hurricane; and (5) major components (such as cranes, scaffold and falseworks), their installation demands and usage. To clarify the latter item, it is noted that each time one of these components is erected, it is treated as a new system under a new wind load effect (triggered by the locality) and with different usage, configurations, and users (Shapiro, 2004).

2.1 ESTIMATED LOSS

Using the Poisson distribution to model hurricane events with an average occurrence rate λ, and considering the cumulative distribution function of losses given the occurrence of a hurricane as $F(l)$, then the exceedance probability (EP) of a given loss, l , can be evaluated using the following series of computation

$$EP = \Sigma P(l|X=i)P(X=i) \quad (1)$$

The summation considers the fact that theoretically during a given year, any number of events would be possible. $P(X=i)$ is from Poisson distribution and indicates the probability that there will be i events in T=1 year. In general, for i events (and assuming events are statistically independent of one another),

$$P(l|X=i) = 1-(1-p)^i \quad (2)$$

Where $p = 1 - F(l)$, in which $p,$ and $F(l)$ are the exceedance probability and the cumulative distribution function of the loss for i=1, respectively. Using this relation in the equation for EP and substituting for $P(X=i)$ from the Poisson equation, it can be shown that the resulting series has a limit, according to the Maclaurin series for the exponential function, in the following form (noting that T= 1 year).

$$EP(l, T = 1year) = 1 - e^{-\lambda(1-F(l))} \quad (3)$$

The uncertainties in loss estimations of temporary structures can be considered to be a product of two components – namely, the uncertainty in the wind speed distribution and uncertainty in the construction sequence when the hurricane hits. These uncertainties are related to the wait-and-see phase (before uncertainties about the wind speed are realized, typically at the bidding phase) since it cannot be known unless the hurricane makes landfall. However, at the beginning of the project, the design wind speed for each construction sequence is known and belong to the here-and-now phase (see Fig.1). Considering these uncertainties, Eqs. 1,2 and 3 can be adjusted such that they become valid for temporary structure as follows:

$$EP(l, t = 1year) = 1 - \sum_{s_i} \sum_{n=0}^{\infty} F^n(l|s_i) \frac{(\lambda)^n}{n!} e^{-\lambda} P(s_i)$$

$$EP(l, t = 1year) = 1 - \sum_{s_i} P(s_i) e^{-\lambda(1-F(l|s_i))} \quad (4)$$

Where $P(s_i)$ represents the probability of being in construction sequence i, $F(l|s_i)$ is the cumulative density function of loss given erection sequence s_i, and n is the number of events per year.

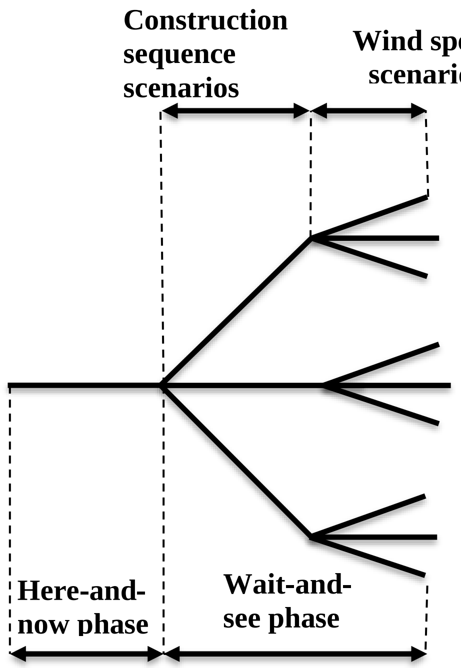

Figure 1: Scenario tree

The information needed to estimate the loss is (1) the probability of being in a certain erection sequence; (2) the mean frequency of occurrence of hurricanes and the wind speed probability distribution under such an event in the region; and (3) the distribution of losses given a certain wind speed distribution and an erection sequence.

If the construction period does not cover the full hurricane season (between July 1 and October 31), Eq.4 can be adjusted by reducing the mean frequency of occurrence based on the length of time when the construction falls within the hurricane season. Alternatively, a new mean frequency of occurrence of a hurricane for months of construction may be derived from hurricane wind data.

Dividing the construction into sequences requires identifying the stopping points of each phase of construction. For example, if an erector could put up the entire structure in a day, the construction could be thought of as one sequence. However, often the erection takes a longer time requiring the erector to decide upon stages of construction or a stopping point where the construction could be thought of as a separate structure with its design wind speed. Identifying the stopping points does not follow any set of rules. For example, the erector may decide on dividing the construction into sequences based on the time taken to finish each stage (say for instance, if erecting two bays and two tiers can be finished per day). Then, the stages of construction could easily be identified. It is noted that, the probability of being in a certain construction sequence could be evaluated as the portion of time spent in that sequence, or from past performances of the contractor in similar situations.

2.1.1 Optimization of the design of temporary bracings

In structures under construction, the number of temporary bracings needed to ensure stability depends on the uncertain demand (e.g., wind load). Thus, the design of these bracings requires forecasting wind loads to provide the necessary capacity and resiliency. In the following paragraph, a stochastic formulation for optimizing the expected cost of construction during the hurricane season is presented.

2.1.1.1 Model Formulation The problem that faces the contractor can be summarized as follows:

– At the beginning of the project, the erector needs to decide on a certain design wind speed, x_1. This is the decision stage and can also be denoted as [here-and-now] decision that implies a cost $A(x_1)$.

– After forecasting a hurricane, the erector may decide on the installation of additional temporary bracings x_2. This new decision is made after forecasting and implies an additional cost $B(x_1, x_2, \xi_1, \xi_2)$ that depends on the initially decided design wind speed x_1, decided alterations x_2, stage of construction ξ_1, and the forecasted wind (or hurricane) ξ_2.

– Depending on the stage of construction ξ_1 and the forecasted wind (or hurricane) ξ_2 the demand is $d(\xi_1, \xi_2)$.

– Since the installation of temporary bracings was based on the forecasting of an incoming hurricane and not the actual wind speed, an additional cost of failure, $D(x_1, x_2, \xi_1, \xi_2)$ may apply that depends on the amount of alterations in the design wind speed (i.e., after the installation of additional temporary bracings) and the actual demand $d(\xi_1, \xi_2)$.

– Consequently, the total cost for each [here-and-now] option $C(x_1, x_2, \xi_1, \xi_2) = A(x_1) + B(x_1, x_2, \xi_1, \xi_2) + D(x_1, x_2, \xi_1, \xi_2)$ is a random variable. Therefore, choosing an optimal [here-and-now] decision (i.e., design wind speed at the beginning of the construction) is a choice among distributions, not numbers.

With the above assumptions, the problem is formulated in a three-stage expected cost stochastic programming formulation (Birge, and Louveaux, Francois, 2011; Wallace and Ziemba, 2005) as follows assuming a linear variation of cost with the decision variables:

$$\min \mathbb{E}_{\xi_1,\xi_2}[c_0(\xi_1)x_1(\xi_1) + c_1(\xi_1)x_2(x_1,\xi_1,\xi_2) + c_2(\xi_1)w(\xi_1,\xi_2,x_1,x_2)] \tag{5}$$

$s.t$

$$x_1 + x_2(x_1,\xi_1,\xi_2) \geq k(\xi_1,\xi_2) \tag{6}$$

$$x_2(x_1,\xi_1,\xi_2) \leq \big(e - \Pi(\xi_1,\xi_2)\big)M \tag{7}$$

$$x_1(\xi_1), x_2(\xi_1, x_1) \geq 0 \tag{8}$$

Where:

$x_1(\xi_1)$ is the first stage decision (i.e., initially decided design wind speed) that must be made before the future is realized. This first stage decision could be allowed to vary with the construction sequence ξ_1.

$x_2(x_1, \xi_1, \xi_2)$ is the second stage decision (i.e., amount of alteration in design wind speed) that could adapt to the additional information available at the end of the first stage that is a function of the construction sequence ξ_1, first stage decision x_1, and information about a forecasted hurricane ξ_2.

$w(\xi_1, \xi_2, x_1, x_2)$ is a measure of the deficiency of meeting the demand that is a function of the construction sequence ξ_1, first stage decision x_1, second stage decision x_2, and information about a forecasted hurricane ξ_2.

$c_0(\xi_1)$ = cost coefficient that converts first stage design variable x_1 to monetary value. To consider the dynamic nature of construction where the cost of temporary bracings does not apply until the start of the new construction sequence, this coefficient is assumed to be a function of the construction sequence ξ_1.

$c_1(\xi_1)$ = cost coefficient that converts second stage design variable x_2 to the monetary value that is a function of the construction sequence.

$c_2(\xi_1)$ = cost coefficient that converts the deficiency of meeting the actual demand that is a function of the construction sequence.

$k(\xi_1, \xi_2)$ = the forecasted demand at the second stage (i.e., after forecasting a hurricane) that is a function of construction sequence and forecasted wind speed.

e is a vector of ones (i.e., $e_s = 1$ for all construction sequence, s)

$\Pi(\xi_1, \xi_2)$ is equal to 1, if the contractor cannot fulfill the required design wind speed at a certain construction sequence in the time limit of response (generally the response time for a hurricane is between 3 to 4 days) and $\Pi(\xi_1, \xi_2)$=0 if he can install the additional temporary bracings in the time limit for response. This value is assumed to be dependent on the construction sequence, and forecasted wind speed.

M is a large positive constant (e.g., 1×10^9). There is only one restriction on M, i.e., M should guarantee that some feasible x_2 always exists, such that the time constraint for taking a response action can be met.

Expression (5) describes the erector's objective in making a decision that is considered optimal on average by minimizing the expected value $\mathbb{E}_{\xi_1,\xi_2}[.]$. Note that the variable $x_2(x_1, \xi_1, \xi_2)$ defines a policy or rule to be followed, if a certain uncertainty is detected. For example, if a hurricane was forecasted, x_2 takes some value depending on the information available at that time about the stage of construction, and the wind speed distribution.

The condition denoted by Expression (6) represents a minimum capacity that will need to be considered for the structure at different construction sequences, once a hurricane is forecasted. The parameter $k(\xi_1, \xi_2)$ is equated to x_1, if the contractor is willing to accept the failure of the structure at all or some stages of construction. The condition denoted by Expression (7) considers the ability of the contractor to put the necessary temporary bracings within the appropriate time. This condition indicates that if time limitation exists, the original design wind speed at that particular construction sequence in response to the forecasted hurricane cannot be altered.

For practical purposes, the above formulation is approximated by a scenario tree (see Fig. 1). Using the generated scenarios, the formulation in (5–8) could be rewritten as follows:

$$\min_{x_1 \geq x_1^l} c_0 x_1 + \sum_{i_1 \in \Omega_1} p_{i_2} \, \mathrm{Q}_1(\mathrm{x}, \xi) \qquad (9)$$

Where:

$$Q_1(x,\xi) = \sum_{i_1 \in \Omega_1} p_{i_1|i_2} \left\{ \begin{array}{c} \min\left[c_1({\xi_1}^{i_1}) x_2(x_1, {\xi_1}^{i_1}, {\xi_2}^{i_2}) + c_2({\xi_1}^{i_1}) w({\xi_1}^{i_1}, {\xi_2}^{i_2}, x_1, x_2) \right] \\ s.t \\ x_1 + x_2(x_1, {\xi_1}^{i_1}, {\xi_2}^{i_2}) \geq k({\xi_1}^{i_1}, {\xi_2}^{i_2}) \\ x_2(x_1, {\xi_1}^{i_1}, {\xi_2}^{i_2},) \leq \left(e - \Pi({\xi_1}^{i_1}, {\xi_2}^{i_2})\right) M \\ x_2(x_1, {\xi_1}^{i_1}, {\xi_2}^{i_2},) \geq 0 \end{array} \right\}$$

i_1 *and* i_2 are the scenario generated of the construction sequence, and wind speed, respectively.

p_{i_1} and p_{i_2} are the probability of being in the construction sequence i_1, and the probability of realizing a wind speed i_2, respectively.

${\xi_1}^{i_1}$ is a realization of a construction sequence such that $i_1 \in \Omega_1$, where Ω_1 is the space construction sequence scenarios.

${\xi_2}^{i_2}$ is a realization of a wind speed forecast such that $i_2 \in \Omega_2$, where Ω_2 is the space of wind speed scenarios.

x_1^l is the lower bound of first stage design wind speed that could be based on the daily expected wind speed.

$p_{i_1|i_2}$ is the conditional probability of realizing construction sequence i_1 at realized wind speed i_2.

Example. Steel frame under construction during the hurricane season.

Situation:
The contractor needs to decide on a design wind speed value before starting the construction. The construction falls in the hurricane season. Of course, the contractor does not know whether or not a hurricane will hit during the construction period. Therefore, the contractor wants to quantify the risk of construction to identify the need for catastrophe risk transfer measures and to quantify the feasibility of the project.

In this example, the construction is decomposed into 16 construction sequences as shown in Fig. 2. The sequences start with the first-floor bays then followed by the tier on the second floor. For example, SEQ12 represents the first sequence at the second tier. The construction sequence starts by constructing an initial braced box then going outward. The cost is assumed to be a function of the design wind speed multiplied by a cost coefficient that converts the design wind speed into a monetary value. The contractor or erector may consider modeling the cost as a function of the return period, this modeling choice is also acceptable.

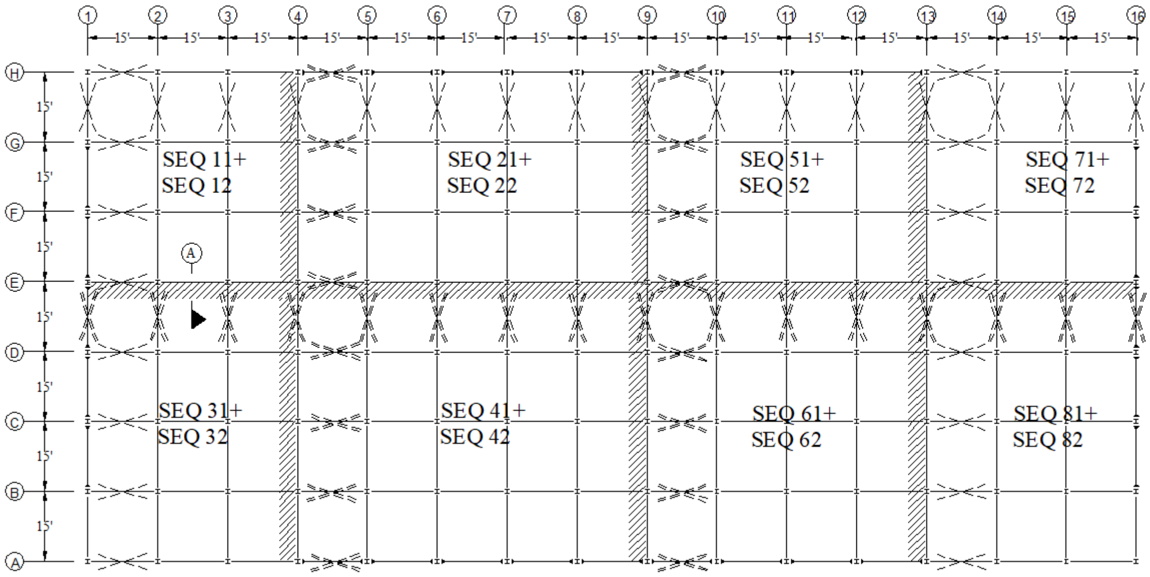

Figure 2. The sequencing plan of construction

The process the contractor would follow is:

– Decide on the current design wind speed.

– Add additional temporary bracings if a hurricane was forecasted, this additional quantity is a function of the initial design wind speed and the predefined estimate of required hurricane design wind speed.

Economic information:

– The cost coefficient of initial temporary bracings, $c_0 = 100$

– The cost coefficient of the additional temporary bracings needed once a hurricane is forecasted can be higher than the initial unit cost if the surge in the prices once a hurricane is forecasted is considered. In this example, we use $c_1 = 150$

– The cost of failure if the demand was not met varies with the construction sequence is also needed,
– The cost of failure of each sequence is assumed to be equal to 10,000.

For simplicity in the optimization, $w(\xi_1, \xi_2, x_1, x_2) = \max\,[d(\xi_2) - (x_1 + x_2), 0]$. This condition implies that the cost of failure only applies if the demand $d(\xi_2)$ was higher than the new altered design wind speed of the sequence. The probability of being in any construction sequence is assumed to be equally likely (see Fig. 3). An alternative model may consider the number of bays constructed in each sequence relative to the total number of bays or the plan area of the sequence to the total plan area as a measure of the probability of being in that particular construction sequence.

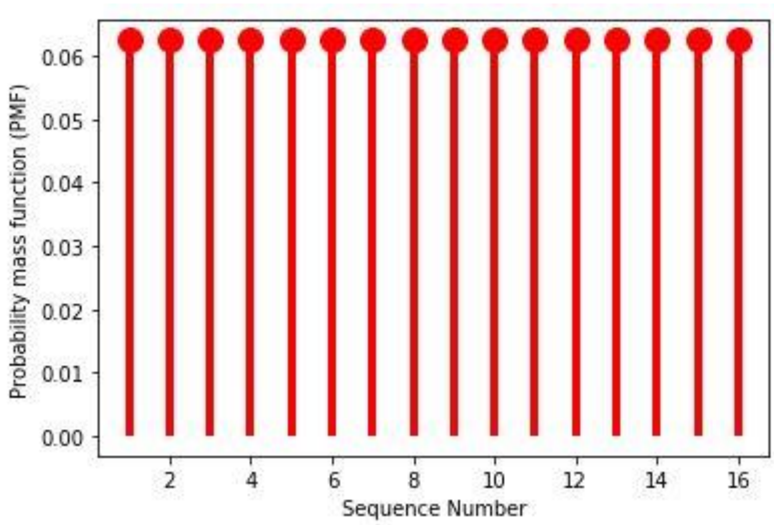

Figure 3: Uniform distribution for the probability of being in a particular construction sequence

The conditional probability is evaluated assuming independence between wind speed and construction sequence, that is $p_{i1|i2} = p_{i1}$. However, if construction is to be partially conducted in the hurricane season, it may be necessary to consider the interdependence between the wind speed and the construction sequence, because the forecasting of the hurricane may delay or alter a particular construction sequence.

Our construction is assumed to be located in Miami-Dade County (in the State of Florida, in US), where the associated hurricane probabilities are as follows (Klotzbach et al., 2009):

– Probability of tropical storms bringing a wind speed that exceed 40 mph = 33.2%

– Probability of hurricanes bringing a wind gust that exceed 75 mph to the county =11.7%

– Probability of intense hurricanes bringing a wind gust that exceeds 115 mph to the county =4.5%.

The above probabilities are equivalent to the probability of forecasting a certain event that requires a response plan. A distribution model based on these probabilities is shown in Fig. 4. This probability distribution is constructed based on the assumption that wind speeds are equally likely to occur within the aforementioned ranges. For example, wind speed in the range between 115 mph to 300 mph is equally likely with a probability density function of $4.5/(300 - 115)$. However, hurricanes cannot be predicted very accurately; and several past hurricanes (e.g., hurricane Katrina) surprised observers with their change in intensity or their inaccurate forecast (Hayden, 2006; Hayden 2019). To account for imperfect forecasting, the probabilities of the wind speed scenarios were taken to be equivalent to the probability of an inaccurate forecast that is assumed to follow a normal distribution centered around the forecasted value ξ_2 and with a standard deviation of 20 mph (Hayden, 2006; Hayden 2019) (i.e., $i_2 \sim N(\xi_2, 50)$). The normal distribution was chosen because the reported data indicates that the shift in hurricane intensity could lead to either a more intense or less intense hurricane than what has been forecasted. For example, a category 5 (wind speed in the range of 155-250 mph) hurricane may end up as a category 3 hurricane (wind speed in the range of 110-130 mph) (Hayden, 2006; Hayden 2019).

Cost coefficients could be evaluated by calculating the increase in cost per one mph increase in design wind speed. The parameter c_2 represents the cost of failure per deficiency in satisfying one mph of wind speed. For example, in SEQ82, $c_2 = 8{,}500$ means that there is a potential loss of \$8,500 if the demand was higher than the design wind speed by 1 mph. However, this failure cost is limited to the cost of the construction sequence (i.e., as seen in Fig. 5, beyond certain wind speed (within Category 5), the failure cost is considered independent of the wind speed). Table 1. summarizes the information needed for each construction sequence.

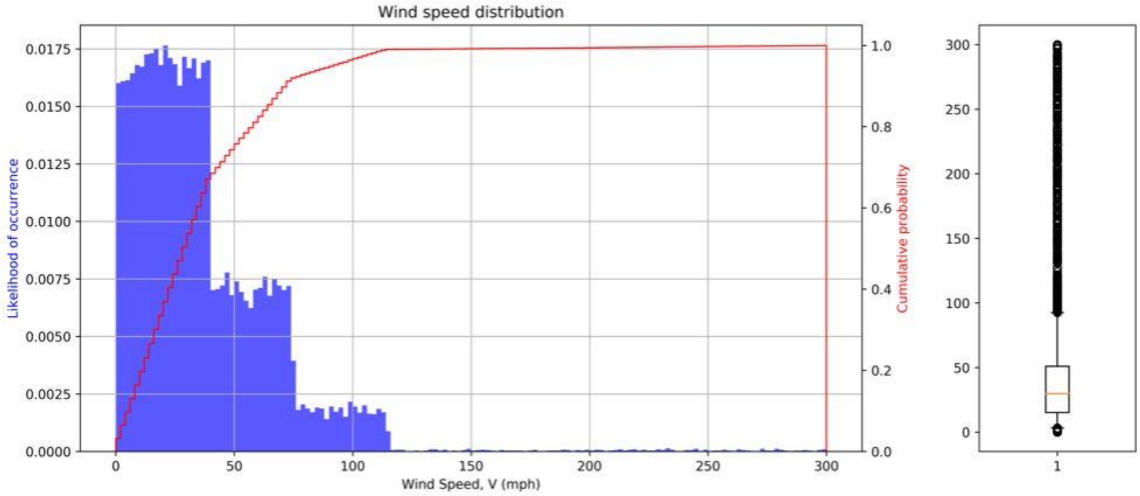

Figure 4: Distribution of 100,000 random samples of wind speed.

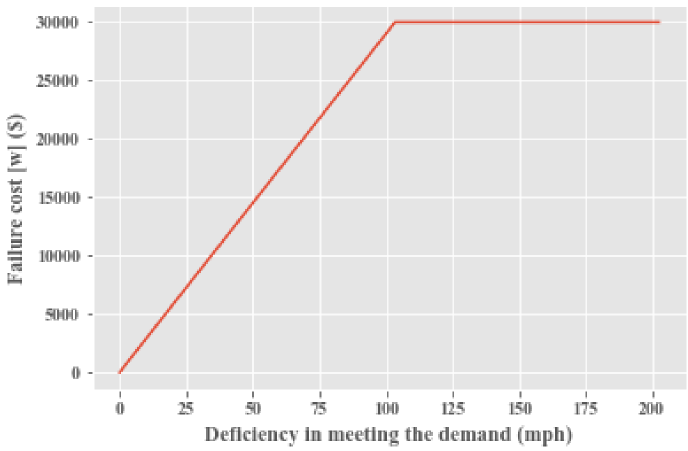

Figure 5. Failure cost as a function of the deficiency in meeting the realized wind speed

Table 1: Defined parameters for the optimization problem

Sequence ID	p_{i1}	$c_0(\$/mph)$	$c_1(\$/mph)$	$c_2(\$/mph)$
SEQ11	1/16	10	15	100
SEQ12	1/16	11	16	150
SEQ21	1/16	12	17	200
SEQ22	1/16	13	18	250
SEQ31	1/16	14	19	300
SEQ32	1/16	15	20	350
SEQ41	1/16	16	21	400
SEQ42	1/16	17	22	450
SEQ51	1/16	18	23	500
SEQ52	1/16	19	24	550
SEQ61	1/16	20	25	600
SEQ62	1/16	21	26	650
SEQ71	1/16	22	27	700
SEQ72	1/16	23	28	750
SEQ81	1/16	24	29	800
SEQ82	1/16	25	30	850

If a multiplicative relationship between cost and design wind speed cannot be properly prescribed, various scenario generation in the optimization problem can be considered to include different alternative design wind speeds and their associated costs. Accordingly, the optimization is performed to arrive at the best alternative by assuming no time limitation at any construction sequence and a relatively reasonable wind speed forecast. With this scheme, we also accept that the failure of the structure will occur if the cost estimation was in favor of the failure.

Optimization result

Assigning a lower bound at the first stage based on expected daily wind equal to 40 mph, the optimization model yields an expected cost of temporary bracings = \$11,200. It is noted that the optimization model finds that the lower bound of the first stage wind speed (i.e., 40 mph) is the optimum decision at all stages. This result is understandable because of the low failure cost and the use of a "neutral" risk measure (i.e., the expectation). If the failure cost is greater or a more conservative risk measure is used, a change in the decision is expected.

3. Concluding Remarks

Temporary structures may be more vulnerable to a higher wind speed than the permanent ones due to their lower stability, lower resistance and the high drag coefficient that is especially prevalent in temporary structures with lattice elements. To account for the higher wind effects, which are often expected in hurricanes, temporary bracings are usually installed until the structure can resist the applied loads.

For the construction period that falls into the hurricane season, it is sometimes necessary to account for hurricane loads in the second stage after the forecasting of a hurricane. However, the cost of a contingency plan should be evaluated to ensure that the risk on the contractor and erector is not excessive. This study presents a three-stage stochastic optimization formulation that can help in choosing the appropriate design wind load, given that the wind load is uncertain. The formulation presented can also be used in evaluating the expected cost of the contingency plan against hurricane wind loads. This optimization model can be refined by considering measures of risk other than those expected if the contractor feels that a more conservative decision-making process is required. Some measures of risk that can be used are (1) conditional value at risk (C-VAR); (2) value at risk (VAR); (3) chance constraints; and (4) worst-case scenario optimization, which seems only reasonable in highly sensitive applications such as in the case of nuclear power plant temporary works.

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