Value of Information on the Risk/Benefit of Infrastructure under Strong Winds in Mexico

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ABSTRACT: The occurrence of hurricanes has produced many fatalities and damages in Mexico (1) and new efforts for preparation and risk mitigation are being conducted In this work, several cost-effective strategies to reduce the expected number of fatalities and losses, given the site exposure to wind hazard and given the consequences level of the structures failure, are recommended. The strategies are based on risk and reliability concepts and tools, like the expected life-cycle cost (which includes the initial and expected future costs in the structure life-cycle) associated to proposed scenarios with different levels of epistemic uncertainty. As a means to compare the structure failure probability with an allowable safety measure, the acceptable failure probability of structures is obtained for several consequences costs.

1. INTRODUCTION

The topic of information value was treated in early works by Von Neumann and Morgenstern, (1944). Some theoretical developments come from Computer Sciences like by Howard (1966) and from the Nuclear Industry like by Koerner, Wilson, Romanek, Rocco, Sharp and Gilbert (1998). Since then a wide range of fields became interested as the Risk Management like in Yakota and Thompson (2004) and Bayesian Statistics like in Rosenblueth (1982). Civil Engineering is not an exception on developing applications of the theme, like the one about how to deal with flaw information like by Tang (1973), and the various revivals of the aspects of risk based optimization, especially when new information is generated by the health monitoring techniques, like in the works of Frangopol, D., Strauss, A., and Bergmeister, K. (2009), Straub (2011), Pozzi M, Der Kiureghian A. (2012) and Thöns S, Faber MH (2013), among others.

Infrastructure maintenance offices with limited resources present ideal conditions to justify an assessment of information value to set the planning and money allocation for intervention and protection investment in a country or region.

In particular, Wind Engineering by Simiu and Scanlan (1996) and Holmes (2007) provides a significant opportunity to confirm the value of new information to reduce the uncertainty on the design parameters and improve the protection of valuable infrastructure. In this paper the value of reliability is made explicit through the quantifications of gains derived by improving the infrastructure knowledge.

Modern codes consider reliability-based specifications as propose by Cornell (1969) and Esteva (1969) and the expected life-cycle cost for engineering decision making like in CFE (2008a) and CFE (2008b). Someway, the new wave of performance-based design criteria overlaps part of the objectives of the information value ideas.

The occurrence of hurricanes has produced many fatalities and damages in Mexico as shown by Lopez, et al. (2008) and a series of new efforts to mitigate these consequences are being conducted throughout the use of the risk/benefit ratio, expected lifecycle cost and structural reliability concepts and tools like by Ellingwood and Tekie, (1999).

In particular, for electrical substations and power transmission towers, the effect of epistemic uncertainty on the estimation of structures failure probability has been measured as, for example, Alam and Santhakumar (1996) and the cost of reliability has been sketched through the relationship between the cost and reliability of alternative designs and through the acceptable failure probability as a function of the cost of failure consequences like by Lopez, et al. (2009). The benefits are expressed in terms of epistemic uncertainty reduction, with the consequent reduction on failure probability and the derived widening of safe and profitable operational conditions of the infrastructure as done by Ang and De Leon (2005).

In this paper, the cost of reliability is appraised through the cost estimation of several designs for the same facility, either an electrical substation or a bridge, both under a strong winds environment that governs the design. Also, it is shown that, if the epistemic uncertainty on wind velocity is reduced (with a corresponding cost ΔC), the expected benefits derived from the increased confidence on the infrastructure safety, are significant and offset by far the cost ΔC and the margin difference becomes increases as the infrastructure importance grows like by Ellingwood (2007).

2. PROPOSED FORMULATION

Several risk and reliability studies are performed to explore the effect of new information on the design wind velocity for important and vulnerable infrastructure facility under strong winds in Mexico. Structural vulnerability is assessed for scenario maximum wind velocities for infrastructures located at sites where typically strong winds occur along the year, especially within the hurricane season in the Atlantic coast. The occurrence probabilities are obtained for the maximum wind velocity at these sites.

The unconditional (total) infrastructure annual failure probability P_f is calculated as in Ang and Tang (2007) by the convolution of the conditional annual failure probability (vulnerability) $P(F|W_v)$ over the occurrence probability (hazard) of the scenario (prescribed) maximum wind velocities $P(W_v)$.

$$P_f = \int P\left(\left\langle F \middle| W_v \right\rangle\right) P(W_v)\, dW_v \qquad (1)$$

Although the infrastructure vulnerability may be improved (for future designs), through a sound structural design, here it will be considered that the wind hazard model is the component to be enhanced through the incorporation of new information about the maximum wind velocity on the zone.

From extremes theory as done by Ang and Tang (1990), a possible distribution for maximum wind velocity is Gumbel:

$$F_V(v) = \exp\{-\exp[-\varphi(v-u)]\} \qquad (2)$$

Where v is the maximum wind velocity and φ and u are the distribution parameters. The scenario maximum wind velocities are taken as the mean values and the corresponding coefficients of variation are taken from the maximum wind velocities at the site. By doing this, the mean value becomes a random variable and, as a consequence, the infrastructure failure probability becomes also a random variable.

For sites where records are not available or are scarce, qualitative information can be incorporated through Bayesian updating as done by Straub (2011).

Beta distribution functions are fitted to the unconditional annual failure probabilities and the unconditional annual failure probability is estimated for specific sites in Mexico.

With the unconditional infrastructure annual failure probability, the expected life-cycle cost $E(C_L)$ (Eq. 3) may be calculated for both conditions: with and without new information and for several levels of failure consequences as in Ang and De Leon (2005).

$$E(C_L) = C_i + E(C_D) \qquad (3)$$

The consequences involve not just the initial cost C_i but also the expected losses due to the infrastructure failure $E(C_D)$.

The failure probability of a structural component is defined as the probability of the event when the load C exceeds the resistance R as done by Ang and Tang (1990). Taking C and R as statistically independent and lognormally distributed random variables, the failure probability is expressed as:

$$P_f = P(C > R) = P(\frac{C}{R} > 1) \qquad (4)$$

If the safety factor θ is expressed as θ = R/C, the Cornell's reliability index, β, and its relationship with the failure probability, P_f, are expressed:

$$\beta = \frac{\ln(\breve{R}/\breve{C})}{\sqrt{CV_R^2 + CV_C^2}} \qquad (5)$$

$$P_f = \emptyset(-\beta) = 1 - \emptyset(\beta) \qquad (6)$$

where $\breve{R}$ and $\breve{C}$ are the medians of the resistance and the load, while CV_R and CV_C are the coefficients of variation of the same variables, respectively. The median of X is:

$$\breve{X} = \frac{\mu_x}{\sqrt{1+CV_x^2}} \qquad (7)$$

Where μ_x is the mean value and CV the coefficient of variation of X.

3. CASE OF ELECTRICAL SUBSTATION

A typical electrical substation, known as double-switch, capable of 400Kv, (see Fig. 1), was analyzed and 2 design levels were considered: maximum wind speeds of 160 and 200 Kph. The structural complex consists of five frames made out of beams and columns, two frames 1, two frames 3 and one frame 2. The frames were analyzed by using STAAD (2008) and the limit state was the exceedance of either the axial, shear or bending capacity whatever occurs first in the critical substation member. From preliminary analyses it was found that the critical member is the corner column of the substation. Given that the columns are composed by 4 steel angles, the limit state of a single angle failure involves a conservative definition and allows for an additional safety margin before occurs the substation collapse. The fragility curve, conditional failure probabilities under given maximum wind velocities, is shown in Fig. 2.

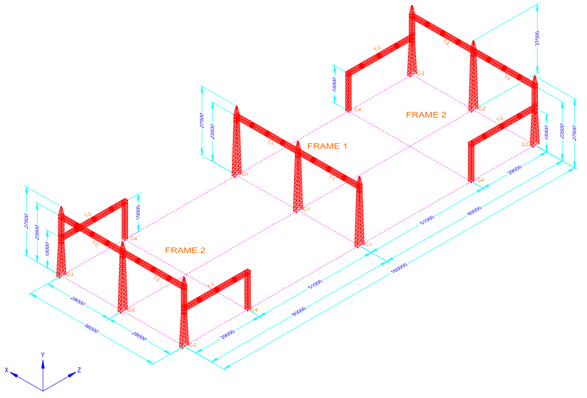

Fig. 1 Typical substation of 400 Kv

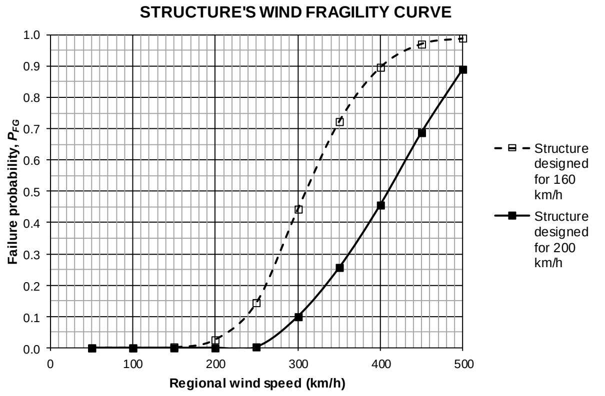

Fig. 2 Substation fragility curves for 2 designs

From the fit of recorded (previous to the hurricane Wilma in 2005) annual maximum wind velocities at Cozumel, Mexico: φ= 0.05 and u = 6.636 and v is in m/s. With these data, the substation annual failure probability is: $7X10^{-6}$ for the design under 160 Kph and $1.2X10^{-12}$ for the design under 200 Kph. These results would make people think that the substation has a very high safety margin. Damage evidences at Cancun, near Cozumel (because of Wilma in 2005), are taken to infer higher maximum velocities and the new information is taken, in a simplified way, as follows: five strong hurricanes (with maximum velocities over 220 Kph) from 1980 to 2007: Allen, Gilbert, Emily, Wilma and

Dean are added to the previous database and the exceedance probability for 220 Kph is estimated as 0.2. This is obtained by dividing the time period (27 years) over the number of hurricanes (5) and by grossly estimating a relative frequency of 0.2 for the velocity of 220 Kph.

By fitting the Gumbel distribution to the new relative frequencies distribution (Table 1), the new maximum wind velocities model has the parameters: φ= 0.04 and u = 37.5 The standard deviation was reduced from 8.18 to 5.26 Kph and the coefficient of variation is 0.22.

Table 1 New relative frequencies of maximum wind velocities for Cozumel

v	fr
140	0.05
160	0.3
180	0.25
200	0.2
220	0.2

4. ACCEPTABLE INFRASTRUCTURE FAILURE PROBABILITY

The expected life-cycle cost (ELCC) of the substation may be expressed:

$$E[C_L] = C_i + E[C_D] \tag{8}$$

And the initial cost (Lind and Davenport, 1972):

$$C_i = C_1 - C_2 \ln(P_f) \tag{9}$$

C_1 and C_2 are constants which depend on the structural type and P_f is the annual probability of exceeding the limit state. In addition,

$$E[C_D] = PVF_1[C_D]P_f + PVF_2[C_{DR}]P_f \tag{10}$$

where C_D is the cost of damage/failure consequences including fatalities, injuries, loss of revenues, and the repair/reconstruction costs, C_{DR} the deferred revenues due to service interruption, PVF_1 is the present worth factor required to update future costs to present value and PVF_2 the present worth factor to update the deferred revenues after a time translation due to the duration of repair/reconstruction works (Sthal, 1986; Watts and Chapman, 2008; Campos, 2011).

$$PVF_1 = [1 - \exp(-rT)]/r \tag{11}$$

$$PVF_2 = [PVF_1 - T\exp(-rT)][1 - \exp(-r\Delta T)]/r \tag{12}$$

where r is the net annual discount rate, T the structure nominal operating life and ΔT the reconstruction period. From the minimization of the expected life-cycle cost as in Sutter, et al. (2009)

$$\partial E[C_L]/\partial P_f = 0 \tag{13}$$

the annual acceptable failure probability is obtained through:

$$P_f = C_2 /[PVF_1(C_D) + PVF_2(C_{DR})] \tag{14}$$

By assessing Eq. (14) for typical data in Mexico, C_2 = 1 million USD, C_{DR} = 500 million USD, r = 0.08, for Mexico, T = 200 and ΔT = 2 years. See Fig. 4.

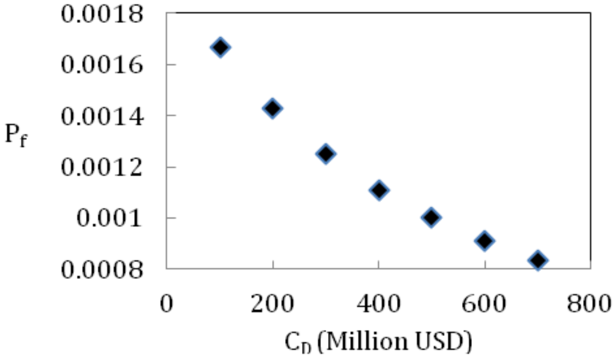

Fig.4 Acceptable failure probability for substation according to the cost of failure consequences

With the wind velocity occurrence distribution, and with the conditional failure probabilities for the considered substation (Fig. 5), it is calculated that the unconditional annual reliability index is 4.3 for the design under 160 Kph, which are well above the acceptable values. However, with the more realistic wind velocity occurrence distribution, the annual reliability index becomes1.62, which is below the acceptable value. Table 2 shows the parameters of the beta distribution fitted for the unconditional annual failure probability of the substation and the percentiles 80 and 90 of the failure probability.

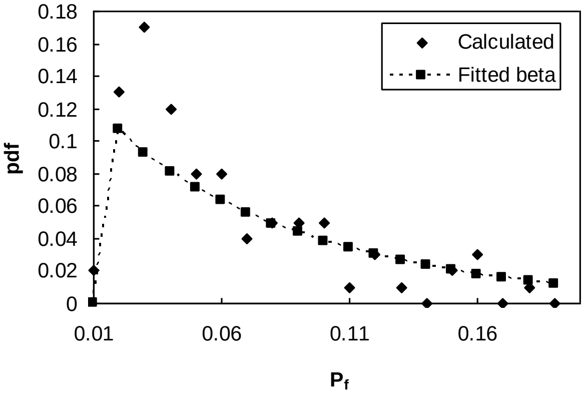

Fig. 5 Unconditional failure probability for substation

The parameters of the velocity distribution are: φ = 0.24 and u = 37.55.

Table 2 Beta parameters and percentiles for Minatitlan

α	β	80%	90%
0.0936	11.7	0.12	0.18

With the new maximum wind distribution, the annual reliability index for the substation designed under 160 Kph, is 2.12 which is well below the acceptable value. However, for the design under 200 Kph the annual reliability index is 3.05 which is just above the 3.02 corresponding to the acceptable value. If the substation design is kept as for the design wind velocity of 160 Kph, the substation would be exposed to have severe damages when the strong winds occur. Also, a comparison of expected annual life-cycle costs were calculated under 2 scenarios: with or without additional recording and monitoring works to update the maximum wind velocities. The cost of these works was considered to be 0.1 million USD. See Fig. 6.

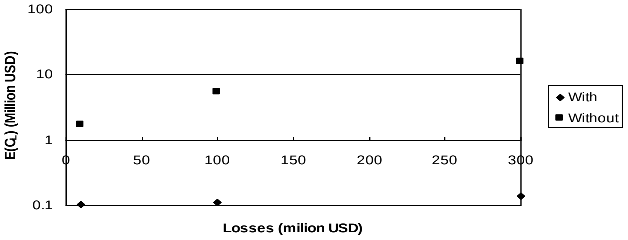

Fig. 6 ELCC with and without new information

For Minatitlan, the maximum wind velocity distribution is:

$$F_V(v) = \exp\left[-\left(\frac{w-v}{w-u}\right)^k\right] \tag{15}$$

where k = 12.95, u = 12.08 and w = 49.

The convolution of substation vulnerabilities, for a substation design under 120 Kph produces the unconditional annual failure probability, for Minatitlan. The above calculations show that there is a room for risk-based and cost-effective design recommendations in Mexico. In addition, the cost of reliability is shown (Fig. 7) by estimating the annual failure probability of five alternative designs of substations for wind velocities of 40, 80, 120, 160 and 200 Kph. The alternative designs represent 2 under designs (63 and 83% of the original substation cost), the original design and 2 over designs (65 and 91%).

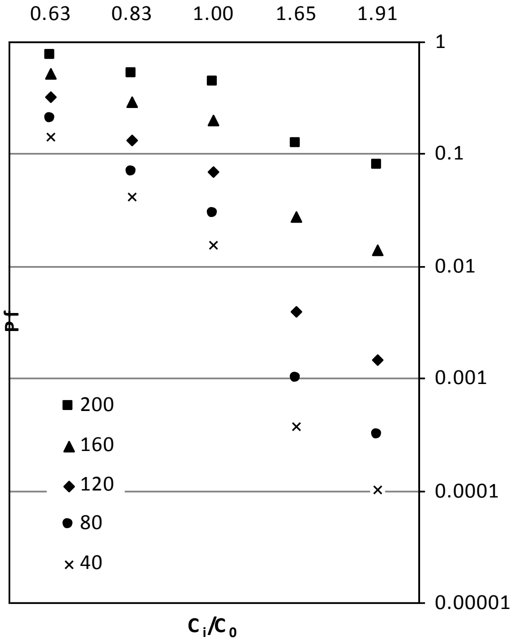

Figure 7 Variation of P_f for relative initial cost for several alternative designs in Kph

5. CASE OF TAMPICO BRIDGE

Tampico bridge (Fig. 8) is located in a strong

Fig. 8 Tampico bridge

winds area, at the shoreline of the Mexican Gulf, where the maximum wind velocities have reached 250 Kph. The bridge is a cable stayed reinforced concrete box girder supported by reinforced concrete piers. The cross section has a trapezoidal supported by reinforced concrete piers and piles. The limit state considered for the reliability analysis is the event where the pair (bending moment, axial force) on the critical pile is located out of the safe zone of the interaction diagram shown in Fig. 9 like in De Leon, Ang (2006).

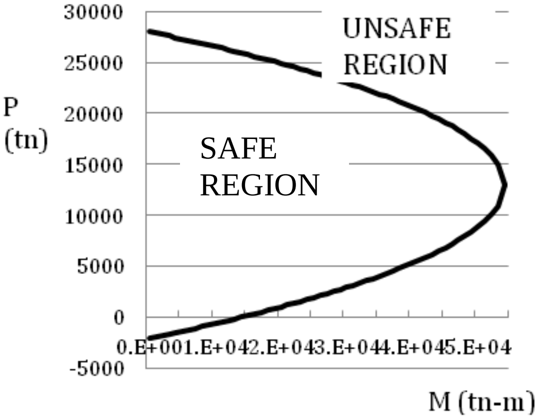

Fig. 9 Resistant moment-axial force interaction diagram for the critical pile of Tampico bridge

Recorded wind velocities, from a scarce and discontinuous data base up to 2003, allowed for the determination of an extreme distribution curve (Sanchez, 2003):

$$F_V(v) = \exp[-(\beta / v)^{\gamma}] \qquad (16)$$

with parameters β = 45 and γ = 3.5

With these data the bridge reliability has been calculated to be 4.95 as done by De Leon and Ang, (2006).

However, if additional evidence of stronger winds is considered, and the original maximum wind velocity distribution with probabilities is updated, the modified distribution is obtained. By doing that, new parameters are found for the maximum wind velocities distribution: β = 60 and γ = 2.3 which change the demand distribution of wind forces on the bridge. A new reliability analysis reveals that the bridge reliability index is 4.02 instead of 4.95. See Table 3 for a sample of the simulation process to estimate the bridge reliability. The Indicator I serves to limit the maximum wind velocities to less than 300 kph. PR_1 and PR_2 are the two resistant axial load given the resisting moment. The random number

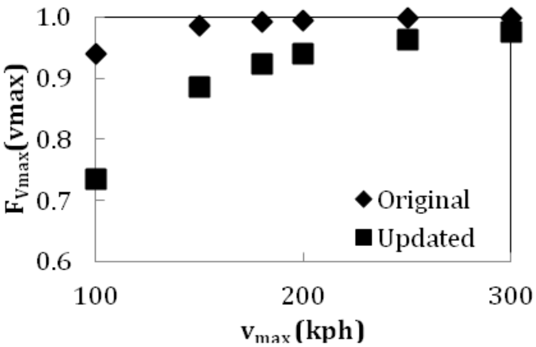

Fig. 10 Original and modified distributions for maximum wind velocity of Tampico bridge

Table 3 Sample of simulation for original wind velocity distribution

RN	V (kph)	P	M	I	PR_1	PR_2
0.94	204	14265	22735	1	24413	1586
0.51	71	14263	2875	1	27595	1595
0.98	350	14269	60619	0	0.000	0.000
0.23	51	14263	1018	1	27857	-1857
0.25	52	14263	1141	1	27840	-1840
0.37	60	14263	1837	1	27742	-1742
0.76	105	14263	6586	1	27055	-1055
0.00	29	14263	548	1	28075	-2075
0.58	78	14263	3541	1	27499	1499
0.91	175	14264	17340	1	25359	640

RN has uniform distribution. If the acting load lies outside the safe area the trial is counted as a failure and the failure probability is estimated as the ratio between the number of failures and the total of trials. In this case they were 10,000.
It has been estimated that the expected damage cost is about 50 times the bridge initial cost.

The acceptable annual reliability index has been obtained for the bridge (Fig. 11).

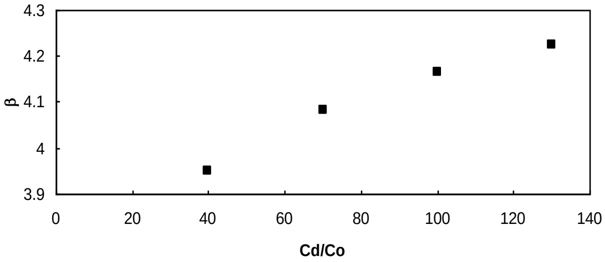

Fig. 11 Acceptable annual reliability index as a function of the ratio between expected damage cost C_d and initial cost C_o.

Therefore, the acceptable annual reliability is 4. It is observed that, from the resulting original and updated annual reliability indices, the original wind velocity distribution may mislead to the wrong interpretation that the bridge does not need any intervention. However, with the new information, it becomes clear that a preventivefollow-up is required.

6. CONCLUSIONS AND RECOMMENDATIONS

Economic parameters were obtained to characterize the cost of reliability and the risk/benefit ratio for an electrical substation and a bridge under strong winds in Mexico. It is shown that the benefits of doing research to update the modeling of the maximum wind velocity, offset the costs of the works to obtain additional data, especially when the cost of damage/failure consequences is high. The value of this information becomes especially important in cases where the original information (like records) is scarce, discontinuous and not completely reliable. Future research may complete structural substation and bridge types and other sites with different wind hazard to set the basis for a reliability-based code for optimal design of infrastructure under wind hazard in Mexico.

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