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The Effects of Extreme Winds on Industrial Equipment

Oscar J. Ramírez Olivar[a], Santiago Zuluaga Mayorga[a], Felipe Muñoz Giraldo[a], Mauricio Sánchez-Silva[a], Ernesto Salzano[b,]*

[a]Department of Chemical Engineering, Universidad de los Andes, Carrera 1E #19A-40, Bogotá (CO)
[b]Department of Civil, Chemical, Environmental and Materials, Università di Bologna, Via Terracini 28, 40131 Bologna (IT)
ernesto.salzano@unibo.it

Climatic variation is becoming increasingly relevant in the assessment of risk due to natural hazards, which may have severe impact on chemical and petrochemical industries. These kinds of accidents are now defined as Natech events (Natural Hazard Triggering Technological Accidents).
Among the industrial equipment, atmospheric storage tanks are particularly vulnerable to weather phenomena and particularly to strong winds, hurricanes, typhoons and tornadoes. The failure of the tank shell may indeed result in the release of large amount of hazardous substances rather than the pure structural damage of the shell. In this article, a review and an evaluation of hazard for extreme winds are presented. Hence the vulnerability of vertical storage tanks when subjected to extreme loads is evaluated by considering several failure states such as shell buckling and overturning. Debris hazard will be also evaluated.

1. Introduction

In recent decades, climatic variability has presented substantial changes over the entire planet that affect directly and significantly temperature and precipitation patterns. These changes in the Earth's climate have influenced the increase and severity of natural events of a meteorological nature such as hurricanes, tornadoes and storms (Banholzer, et al., 2014). These natural events in extreme conditions have the potential to affect the functioning of a society generating serious human, economic and structural losses.
Extreme wind loads present some hazards not only in urban but also industrial areas. Indeed, the impact of wind or the impact of debris drag by the wind over process equipment or a storage area may damage the structure of vulnerable process equipment thus leading to the loss of containment (LOC) of hazardous material (hazmat) and eventually triggering severe, additional accidental scenarios such as fires, explosions or toxic dispersions. These types of accidents are known as NaTech events (Natural Hazard Triggering Technological Accidents) (Krausmann et al., 2017). Despite the large number of analysis for strong winds, Natech risks related to strong wind are rarely analysed in the open literature.
Among industrial equipment, atmospheric storage tanks are particularly vulnerable to Natech, either from the structural point of view, or because they have the capacity to store large quantities of hazardous materials. From this, several studies have been carried out with the objective of estimating the fragility or probability of damage of storage tank farms impacted by the wind load (Uematsu & Uchiyama, 1985; Portela & Godoy, 2005; Zhao & Lin, 2014). This paper presents a review and evaluation of the hazards present in an event with extreme winds. Hence, a fragility analysis is carried out for vertical storage tanks subjected to extreme wind loads.

2. Types of damage by wind loads.

Natural hazards such as hurricanes, typhoons and tornadoes have the potential to cause serious consequences for the territory in its path. Each of these events has a classification regarding its severity and intensity. Table 1 and 2 present the classification for hurricanes and tornadoes according to the wind speed and its consequences in different structures respectively (Allaby, 2007).

Table 1. Wind load Classification Based on wind speed for Hurricanes.

Wind Load	Hurricane Category	Pressure at Center (Pa)	Wind Speed (km/h)	Consequences
Low Load	1	98000	119-153	No damage buildings. Damages basically in mobile house, bushes and trees.
Medium Load	2	96500-97900	154.4-177	Damage to roofs, doors and windows. Significant damage to vegetation, mobile homes, etc.
	3	94500-96400	178.5-209	Small buildings damaged structurally. Destruction of mobile homes.
High Load	4	92000-94400	210.8-249.4	Severe damage to lower parts of buildings near exposed coasts. Mobile homes destroyed completely.
Very High Load	5	<92000	210.8-249.4	All buildings damaged, small buildings destroyed.

Sundararajan establishes that statistical analyzes and probabilistic methods are fundamental for any evaluation of structural performance against the effects of extreme winds, given that the wind climate is a random process and it must be described through statistical terms (Sundararajan, 1995). In addition, the wind to have a natural behavior, and the models that describe their behavior have uncertainty in some of its parameters, which must be treated to obtain more accurately results. Figure 1 presents a structural reliability analysis and risk assessment for wind loads proposed by the same author.

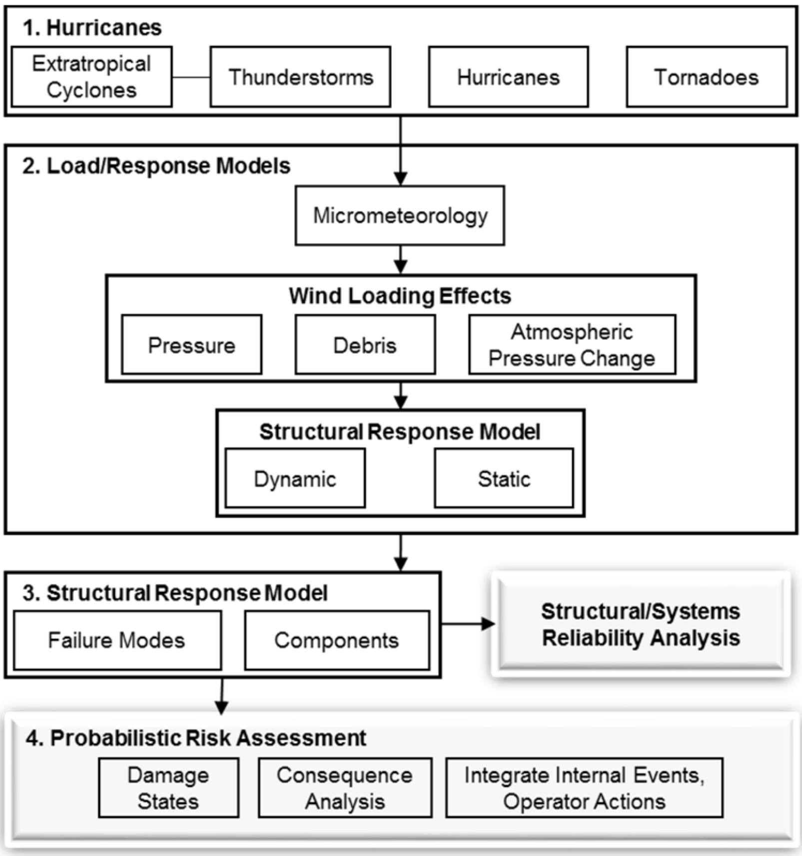

Figure 1: Structural reliability analysis and facility risk assessment for extreme wind effects (Sundararajan, 1995).

Considering that this information is defined for urban structures in general, different authors have developed studies in which determine the probability of different types of damage for storage tanks by the impact of a wind load generated by this type of natural hazards. Below some studies are presented for three types of damage, shell buckling, tank overturn and damage by impact of a debris.

Table 2. Wind load Classification Based on wind speed for Tornadoes

Wind Load	Hurricane Category	Wind Speed (km/h)	Consequences
Weak	F-0	64-116	Slight damage: Some damage to chimneys, branches broken off trees.
	F-1	116-180	Moderate damage: Mobile homes pushed off foundations or overturned, vehicles pushed off the roads.
Strong	F-2	182-253	Considerable damage: Mobile houses destroyed. Light debris projectiles generated. Detached roofs of buildings.
	F-3	254-331	Severe damage: Small buildings walls torn off. Heavy vehicles pushed off the roads.
Violent	F-4	333-418	Devastating damage: Well-constructed houses levelled. Cars thrown and large missiles generated.
	F-5	420-512	Incredible damage: Total destruction of structures and very large projectiles generated.

2.1 Buckling of tanks under wind loads

Wind buckling is one of the most common damage caused by the impact of a wind load, some authors have presented the most representative examples in recent decades, which show different storage tanks buckled by the passage of a hurricane or tornado (Flores & Godoy, 1991; Godoy, 2007).

Figure 2: Buckling of a tank in the island of Guam, under a hurricane, 2002 (LEF - Learning from Engineering Failures, s.f.).

In order to determine what is the wind load necessary to damage a storage tank, several experimental studies have been carried out in which a representative structure of the equipment is subjected to high wind loads, wind tunnel (Burgos, et al., 2014; Uematsu, et al., 2015). Zhao and Lin present a mathematical model for buckling calculating of a storage tank against a wind load, the model is based on the mechanical properties of the tank and the wind speed (Zhao & Lin, 2014). Eq(1) allows me the definition of the non-uniform pressure of wind load:

$$p = C_p q_z \quad (1)$$

where p is the non-uniform wind load or wind pressure, C_p is the wind pressure coefficient and q_z is the velocity pressure.

$$C_p(\theta) = \sum_{i=0}^{m} a_i \cos(i\theta) \quad (2)$$

where θ is the longitude measured from windward, and a_i is the Fourier coefficient. Eq(3) defines the uniform pressure, with which it will be compared with the resistance pressure of the storage tank.

$$q_{eq} = k_w p_{max} \quad (3)$$

$$k_w = 0.46\left(1 + 0.1\sqrt{\frac{C_\theta}{\omega}\frac{r}{t}}\right) \quad (4)$$

From the model presented by Zhao and Lin, a failure criterion is established, where if the wind load q_{eq} is greater than the resistance pressure P_r of the storage tank, the tank will be damage by buckling ($q_{eq} > P_r$).

2.2 Overturning of tanks under wind loads

The overturning of a storage tank is another type of damage that a tank can suffer due to the impact of an extreme wind load. According to some authors, this is one of the least likely types of damage to occur, and when it occurs the storage tank must be empty or partially empty. However, the API-650 standard (American Petroleum Institute, 2007) establishes some stability criteria (overturning stability) with which a storage tank that is under high wind loads can be designed.

Figure 3: Overturning of a tank hit by hurricane Katrina, 2005 (LEF - Learning from Engineering Failures, 2012).

In section 5.11 of the API-650 standard, stability criteria are presented for vertical storage tanks that do not have anchorage in the tank bottom. These stability criteria are determined from the mechanical properties of the tank and the impact force of the wind load. Additionally, it mentions that the tank can also be subject to sliding due to wind and proposes an additional friction factor for the overturning force. Also, in section 5.12, the standard presents the stability criteria for storage tanks that have anchorage in the tank bottom.

2.3 Damage by debris impact dragged by a wind load.

The debris produced by an explosion or dragged by an extreme wind load may damage any type of structure, because the impact has the ability to buckle and penetrate a storage tank roof or shell. For the case of explosions, some studies have developed a simplified model that compares the resistance of a tank by the impact of a shock wave or object (fragment or debris), based on Johnson's number (Salzano and Basco, 2015).

Figure 4: Storage tank damaged by landslide debris, 2014 (GNS Science, 2014).

For the case of debris dragged by the wind, Lin proposes a methodology to simulate the trajectories of objects dragged by the wind and risk calculation by their impact on structures. This methodology can also be applied to storage tanks (Ning Lin, 2005). Eq 5) determines the force (F) of impact of an object based on wind speed.

$$F_f = \frac{1}{2}\rho_a U^2 A C_F \tag{5}$$

where ρ_a is the air density, U is the wind speed, C_F is an aerodynamic force coefficient and A is the reference debris area for C_F. Eq. 5), applies to debris that are free and unattached to the ground, so when the aerodynamic force of an object exceeds its gravitational force ($F_f > mgI$), the object can be dragged by the wind.

$$U^2 = \frac{2h\rho_m gI}{\rho_a C_F} \tag{6}$$

Eq. 6) can be used to estimate the wind speed at which the debris starts its flight as $mg = Ah\rho_m g$, where ρ_m is the debris density, h is the debris characteristic dimension and g is the gravitational constant. Eq. 5 and 6) can be used to determine the wind speed at which objects on the ground, free or attached, become aerial debris.

Lin (2005) also proposes an expression to estimate the joint probability P_d, that is, the probability of generation of a debris ($P(G)$), the probability of impact on the structure once the debris has been generated ($P(I)$) and the probability to damage the structure ($P(F_f > F_r)$:

$$P_d = P(G) \cdot P(I) \cdot P(F_f > F_r) \tag{7}$$

where F_r is the resistance force or the storage tank.

3. Storage tank damage probability for wind loads

The damage probability of a storage tank against a wind load was determined by Monte Carlo simulations in order to treat the uncertainty associated with the natural behavior of the wind. The models used are those presented above for the buckling of the tanks shell and the damage by impact of debris. The tank on which the probabilistic study is carried out, is a gasoline storage tank located in the Gulf of Mexico, an area affected in recent decades by strong hurricanes.

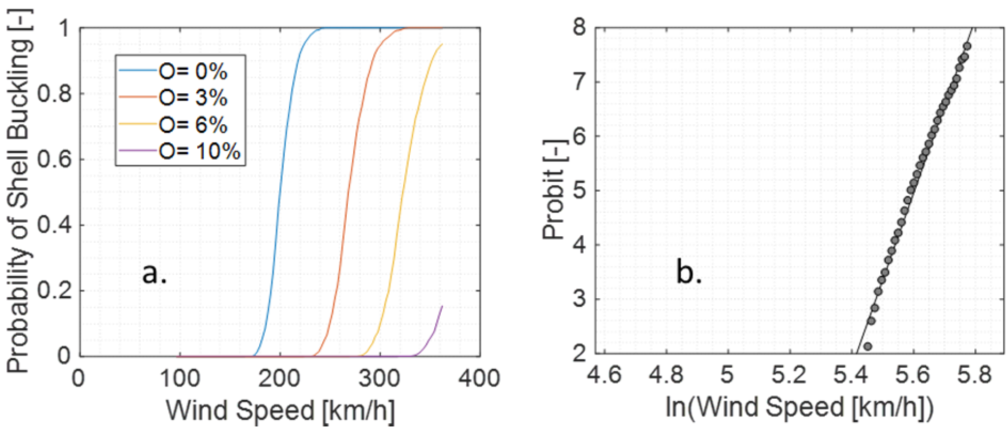

Figure 5: a). Damage Probability due to shell buckling impacted by a wind load at three different filling levels. b). Damage Probability due shell buckling (O=3%) impacted by a wind load represented by a Probit function.

Figure 5a and 5b show the probability of damage due to buckling of the tank shell by the impact of the wind at different speeds. The curves of Figure 5a are at different filling levels (O). Quite clearly, the curve moves to the right for much filled tanks. That indicates that a higher wind speed is needed to damage the tank shell, which is consistent since the liquid stored inside the tank provides an additional internal resistance factor against the external wind load.

Figure 6 shows the probability of damage by the impact of a debris at different impact speeds and different debris weights. As the weight of the debris decreases the curve moves to the right, which indicates that for debris of smaller weights you need a higher impact speed to cause damage to the structure of the tank. This is consistent, since the impact force is directly proportional to the debris weight.

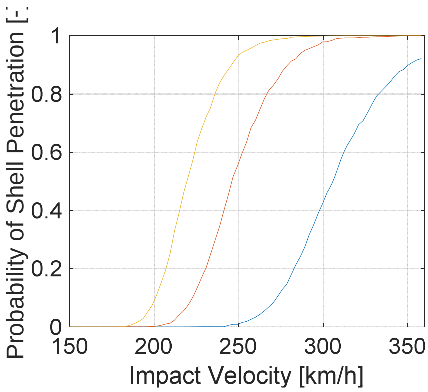

Figure 6: Damage Probability by debris impact at different debris weights (---: 150kg, ---: 100kg, ---: 75kg).

4. Conclusions

The focus of this work is to analyse and evaluate natural hazards (such hurricanes, tornedos) and its effect on vertical storage tanks in order to estimate the occurrence of a NaTech event. Since storage tanks have the capacity to store large amounts of hazardous material, it is important to evaluate the conditions on which a tank could fail, taking into account different types of damage. The estimation of the damage probability by the impact of a natural hazard is significantly important, bearing in mind that this is one of the input parameters to the standard risk analysis.

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