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THE EFFECTS OF EXTREME WINDS ON ATMOSPHERIC STORAGE TANKS

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The impact of hurricanes, tornados, severe storms, or more in general extreme winds can damage the equipment of industrial plants, leading to the loss of containment of hazardous material from the damaged structures, which in turn can pollute or evolve to catastrophic scenarios involving fires or explosions. This type of accidents is known as Natech (Natural hazard triggering technological accident).
Among natural events, extreme winds can affect atmospheric storage tanks, due to their intrinsic structural vulnerability combined with their capacity to store large quantities of hazardous material, often flammable.
In this work, the authors have evaluated the vulnerability (and the fragility) function for storage tanks impacted by extreme wind loads for the aims of industrial risk assessment., taking into account either the structural damage or the loss of containment. Monte Carlo simulations method estimates the uncertainty associated with the random behavior of the parameters of the model. A case study for a vertical storage tank shows that non-negligible risk occurs for filling level higher than 15%.
The study offers guidance on how to include the wind-related phenomena as entry parameters for industrial risk assessment in geographical areas prone to strong winds.

Keywords: Atmospheric storage tank, Extreme winds, Wind load, Natech, Monte Carlo simulation, Fragility.

1. Introduction

In recent decades, extreme natural phenomena such as earthquakes, floods, hurricanes or tsunamis have caused serious consequences, thousands of human losses, incalculable economic losses and irreparable damage to public infrastructures and private assets. Similarly, industrial facilities and industrial parks have suffered devastating effects from these events. In this case, the economic losses related to the business interruption and to the restoration are relevant. Furthermore, the unwanted and uncontrollable release of hazardous material from damaged equipment is an additional risk to the population, to the environment and to assets. These types of accidents are Natech events (Natural hazard triggering Technological accidents) [1, 2].
Among natural events, extreme winds may affect the integrity of an industrial installation. Hurricanes Katrina and Rita, which occurred in 2005 in the Gulf of Mexico, are major examples. The two events caused extensive damages to onshore and offshore installations, leading to the spill of different hazmat throughout the entire area, causing great environmental damage and incalculable economic losses [3-4].
Due to their design and purpose, atmospheric storage tanks are vulnerable to Natech events, including earthquakes [5], tsunamis [6[, volcanic effects [7], flooding [8] and extreme winds [9-12]. This work deals with the development of fragility curves for atmospheric storage tanks with respect to wind load. To this aim, the model has started with standard assessment for the vulnerability of the analyzed industrial equipment with respect to the wind load and wind debris. Hence, fragility curves for either structural or Natech failure-related risks have been assessed. To this aim, Monte Carlo simulations have been performed. Finally, an application case has been tested for a specific atmospheric tank.

The results can provide the input necessary to develop and implement pro-active safety procedures, and more generally for existing risk assessment tools for Natech events, following sound but simplified approaches typically adopted for other natural events such as earthquake or flooding [8, 13-15].

2. The model

When a hurricane, storm or tornado impacts atmospheric storage tanks, these can clearly suffer different types of damage and more specifically: i) the shell buckling of the tank [11,12]; ii) the total or partial overturning of the tank due to wind effects [11]; and iii) damage caused by the debris or flying object [16]. These three failure mode are the basis for the model and are described in details in the following paragraphs.

2.1 Shell buckling

The API-620 and API-650 [17-18], govern the design of atmospheric storage tanks against external wind loads. This includes shell buckling. It occurs when the pressure exerted by the wind load q_{eq} at any point along the tank shell exceeds the tank resistance pressure P_r, which is the sum of the tank critical pressure P_{cr}, i.e. the maximum resistance pressure of the tank material, and the pressure exerted by the fluid contained in the tank, the fluid pressure P_f (Figure 1).

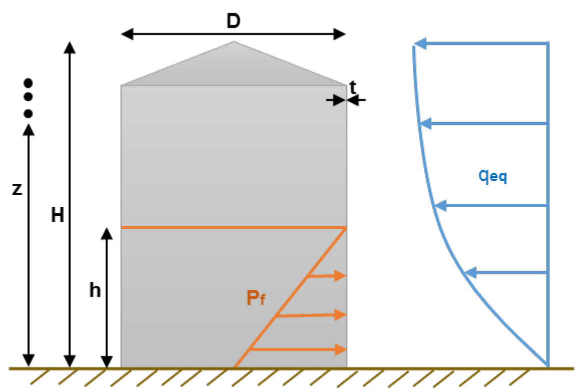

Figure 1. Representation of the wind load and forces acting on an atmospheric vertical storage tank.

The critical pressure P_{cr} can be estimated from the mechanical properties of the tank as [19]:

$$P_{cr} = \frac{2 \cdot E \cdot t}{D}\left(\frac{1}{(n^2-1)\left(1+\left(\frac{2 \cdot n \cdot H}{\pi \cdot D}\right)^2\right)} + \frac{t^2}{3 \cdot D^2 \cdot (1-\nu^2)}\left(n^2 - 1 + \frac{2 \cdot n^2 - 1 - \nu}{1+\left(\frac{2 \cdot n \cdot H}{\pi \cdot D}\right)}\right)\right) \quad (1)$$

where E is the elasticity module, t is the thickness of the shell, D is the diameter of the tank, n is a parameter which is included to minimize the critical pressure, H is the height of the tank, and ν is the Poisson's coefficient. Besides, the fluid pressure P_f is a function of the density of the stored fluid ρ_f, the gravity constant g and the filling level h:

$$P_f = \rho_f \cdot g \cdot h \quad (2)$$

The distribution of the pressure acting along the diameter of the shell simulates the wind load. According to API-650 and EN 1993-1-6 [20], the wind pressure varies both along the

circumference and in height. However, given the typical dimension of the tanks, the pressure along the height can be assumed constant.
Maraveas et al. [21] have recently presented a model to estimate the wind pressure p on the circumference of a tank, following the classical equation:

$$p = C_p \cdot q \cdot G_s \tag{3}$$

where C_p is the wind pressure coefficient, G is a gust factor, and q is the velocity pressure, which is evaluated as:

$$q = 0.613 \cdot K_z \cdot K_{zt} \cdot K_d \cdot V^2 \quad \left[\frac{N}{m^2}\right] \tag{4}$$

where K_z is the velocity pressure exposure coefficient, K_{zt} is the topographic factor (1.0 for all structures except those on isolated hills or escarpments), K_d is the wind directionality factor (0.95 for round tanks), V is the wind speed (3-second gust at 10 m over open terrain). Each of these factors are defined in the ASCE-7 standard [22].
The wind pressure coefficient C_p can be calculated on the basis of the Fourier series decomposition as [23]:

$$C_p(\theta) = \sum_{i=0}^{m} a_i \, cos(i\theta) \tag{5}$$

where θ is the longitude measured from windward, and a_i are the Fourier Coefficients, which are reported by several studies for thin-wall equipment [24-26].
It should be noted that Eq. 5) applies to fixed roof tanks only. If open-roof tanks are considered, a negative coefficient of wind pressure must be included to take into account the internal pressure, i.e. the pressure exerted on the internal side of the tank wall. The following expression calculates the pressure coefficient for tanks with open roof [23]:

$$C_p(\theta) = \begin{cases} -0.8 + \sum_{i=0}^{m} a_i \cdot cos(i\theta) & H/D \geq 2 \\ -0.5 + \sum_{i=0}^{m} a_i \cdot cos(i\theta) & H/D \leq 1 \end{cases} \tag{6}$$

Quite clearly, the distribution of the wind pressure p exerted over the shell varies with height and with the radial coordinate ($0 < \theta° < 360$). Nevertheless, the adoption of an equivalent uniform external pressure q_{eq} over the entire surface of the tank shell, facilitates tank design against shell buckling (Eq. 7):

$$q_{eq} = k_w \cdot p_{max} \tag{7}$$

where p_{max} is the maximum value of the non-uniform wind pressure, and:

$$k_w = 0.46 \cdot \left(1 + 0.1\sqrt{\frac{C_\theta}{\omega \cdot t}\frac{D}{2}}\right) \tag{8}$$

where ω is a length parameter for the tank shell, and C_θ is an external pressure buckling factor.
Eventually, the relationship between the wind load (q_{eq}) and the resistance pressure of the tank (P_r), determines if the equipment will suffer damage by buckling or deformation of its shell:

$$\begin{cases} if\ q_{eq} - P_r \geq 0 \ \rightarrow Damage\ (buckling) \\ if\ q_{eq} - P_r < 0 \ \rightarrow No\ Damage\ (no\ buckling) \end{cases} \tag{9}$$

2.2. Tank Overturning

Extreme winds can overturn atmospheric tanks [11]. This study evaluates the damage caused by overturning for storage tanks without anchorage to the ground. Figure 2 shows the overturning of a tank from the impact of a wind load.

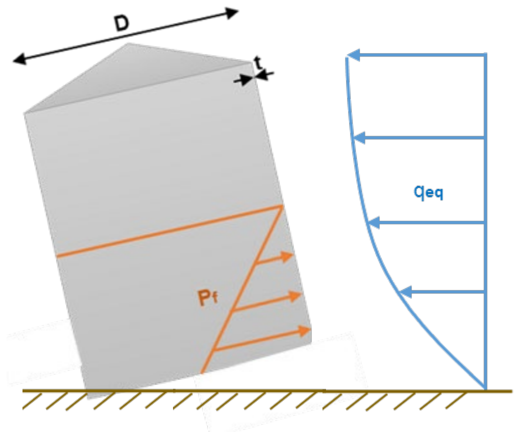

Figure 2. Representation of the overturning of a vertical storage tank by a wind load.

The API 650 gives stability criteria for un-anchored vertical storage tanks subjected to strong winds. In this work, we have used the following criteria for overturning:

$$0.6M_w + M_{Pi} < \frac{M_{DL}}{1.5} + M_{DL} \quad (10)$$

$$M_w + F_p(M_{Pi}) < \frac{(M_{DL}+M_F)}{2} + M_{DLR} \quad (11)$$

where M_w is the overturning moment about the shell-to-bottom joint from horizontal plus vertical wind pressure; M_{Pi} is the moment about the shell-to-bottom joint from design internal pressure; M_{DL} is the moment about the shell-to-bottom joint from the nominal weight of the shell and roof structure supported by the shell that is not attached to roof plate; M_{DLR} is the moment about the shell-to-bottom joint from the nominal weight of the roof plate plus any attached structural; F_p is the pressure combination factor; and M_F moment about the shell-to-bottom joint from liquid weight. If both conditions (Eq. 10 and 11) are not satisfied, the tank overturns.

2.3. Debris or flying projectiles

Debris or flying projectiles transported by strong winds may have the potential to damage storage tanks [27]. Following Lin [28] , the determining factor for estimating whether an object can buckle or penetrate a storage tank will be the impact force F_i, which can be calculated from the physical properties of the object and the impact velocity:

$$F_i = \frac{1}{2} \cdot \rho_a \cdot u_0^2 \cdot A \cdot C_F \quad (12)$$

where ρ_a is the air density; A is the reference area of the debris; C_F is an aerodynamic force coefficient; and, u_0 is the impact velocity. Eq. 12) applies to those debris that are not attached to the ground, so that when the aerodynamic force of the debris exceeds the gravitational force ($F_i > m_p \cdot g$), the wind can move and lift the object. Following classic dynamic, the following expression computes the speed at which a debris starts its flight. Since:

$$m_p \cdot g = A \cdot l \cdot \rho_p \cdot g \tag{13}$$

It is:

$$u_o^2 = \frac{2 \cdot l \cdot \rho_p \cdot g \cdot I}{\rho_a \cdot C_F} \tag{14}$$

where l is a dimensional characteristic of the debris, and ρ_p is the density of the debris. Finally, once the impact has caused damage, it is important to calculate what is the depth of penetration l_p due to the impact. Nguyen et al. [29] have proposed a model based on the physical and mechanical characteristics of a debris and the target, given the angle of incidence α. The proposed correlations are:

$$l_p = \frac{\left(-d_p \cdot cos(\alpha) + \sqrt{\left(d_p \cdot cos(\alpha)\right)^2 + \frac{4}{\pi} \cdot tan(\alpha) \cdot \left(\frac{E_C}{f_u \cdot \varepsilon_u}\right)^{\frac{2}{3}}}\right)}{2 \cdot tan(\alpha)} \qquad \alpha \neq 0 \tag{15}$$

$$l_p = \left(\frac{E_c}{f_u \cdot \varepsilon_u}\right)^{\frac{2}{3}} \cdot \frac{1}{\pi \cdot d_p} \qquad \alpha = 0 \tag{16}$$

where d_p is the equivalent diameter of the section of the fragment impacting the target, E_c is the kinetic energy $\left(E_c = (m_p \cdot u_0^2)/2\right)$, and f_u and ε_u are the ultimate strength and ultimate strain of the constitutive material of the target, respectively.
Eventually, the debris can perforate the tank shell if l_p > t (tank thickness), provided $F_i > m_p \cdot g$.
.

3. Fragility assessment

A fragility function is a mathematical function that expresses the probability of exceeding some unwanted event (i.e. the damage) based on some measure of the environmental excitation (solicitation) [30]. When atmospheric storage tanks are considered, in the light of Natech risk assessment, the vulnerability of an industrial system should be however defined in terms of expected degree of loss of content from any element or group of elements under risk, given the natural event magnitude or intensity [31].
In order to derive the fragility curves, it is mandatory to characterize both the tank and natural hazard, as in the following section.

3.1. Storage tank characterization

As mentioned above, the sizing of a tank is based on the API-650 standard, which structurally defines the three main components: the shell, the roof and its base. The information required for each of the components of the tank are:

i) Shell: diameter, height (based on tank course levels), thickness (for each ring) and material.
ii) Roof: type of roof (roof or conical), roof thickness, support for fixed roof, floating roof, type of floating roof seal.
iii) Base: anchor/unanchored to the ground, number of anchor bolts and their diameter, thickness of the bottom plate and concrete ring.

3.2. Wind Hazard Characterization

The wind speed characterizes the wind load and establishes the category of the hurricane affecting the storage tank. Table 1 shows the hurricane categories according to the Saffir/Simpson scale, based on the wind speed (one minute maximum sustained winds at 10 m, over open water) [32]. The table includes the description of the consequences for the civilian buildings, for the sake of comparison.

Table 1. Characterization of wind hazard based on the Saffir/Simpson scale *[32]*.

Wind Load	**Hurricane Category**	**Pressure at Center of the Eye (kPa)**	**Wind Speed (km/h)**	**Consequences**
Low Load	1	98.0	33-43	No damage to buildings. Damages basically in mobile house, bushes and trees.
Medium Load	2	96.5-97.9	43-49	Damage to roofs, doors and windows. Significant damage to vegetation, mobile homes, etc.
High Load	3	94.5-96.4	49-58	Small buildings damaged structurally. Destruction of mobile homes.
	4	92-94.4	58-69	Severe damage to lower parts of buildings near exposed coasts. Mobile homes destroyed completely.
Very High Load	5	<92.0	>69	All buildings damaged, small buildings destroyed.

For each range of wind speeds in Table 1, the model developed above can calculate the distribution of the pressures, the non-uniform wind pressure p and the equivalent uniform pressure q_{eq}.

3.3. Fragility Curve assessment

A Monte Carlo simulations method has been adopted for the evaluation of the fragility curves of storage tanks impacted by a wind load, and estimates the uncertainty associated with the random behavior of the parameters of the model. Figure 3 summarizes the adopted iterative process, which includes the treatment of the uncertainty of the parameters.

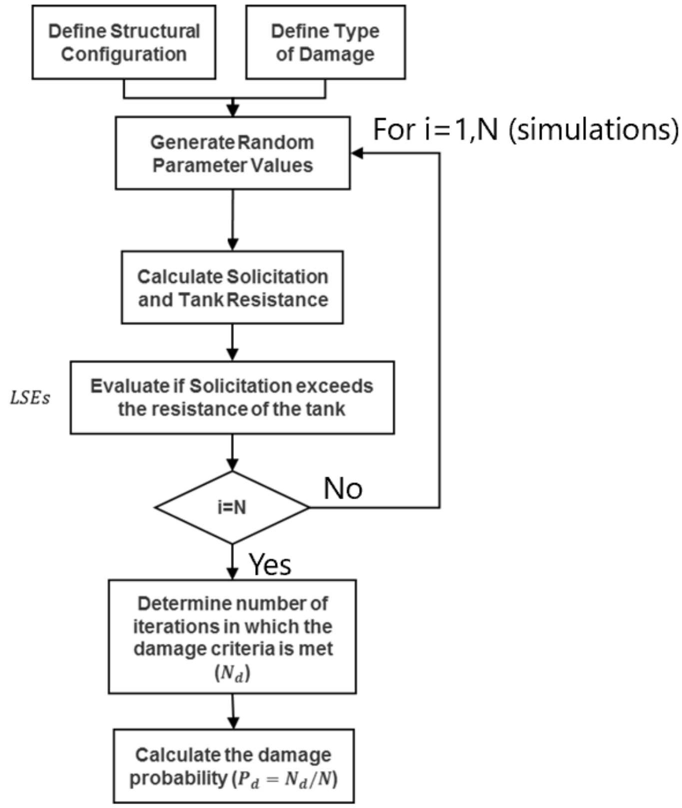

Figure 3. Methodology to estimate damage probability of a storage tank integrating the uncertainty within a purely probabilistic framework.

In the methodology reported in Figure 3, for a given type of tank, subjected to either buckling, overturning, or debris impact, it is necessary to select a type of probability distribution functions for each of the random parameters in the models. Table 2 summarizes the types of distribution that were included in this study, with means and coefficients of variations for each random variable. The variability of physical parameters (such as densities) was estimated from the variation in temperature and pressure conditions to which each element of a tank is subjected. All parameters of the model may be estimated from the values reported in the international standards API-650 and ASME-7.

Table 2. Parameters with uncertainty for Monte Carlo simulation as in Figure 3.

Parameter	Unit	Type of distribution	Mean (μ)	Coefficient of variation (CV)
ρ_a	Kg/m^3	Normal Uniform Lognormal Exponential Weibull Gamma	Air density of the affected area	9.6%
ρ_p			Debris density	10.2%
ρ_f			Density of the stored fluid at 1 bar and 25°C	9.1%
K_z	-		1.26	11.9%
K_{zt}	-		1.00	5%
K_d	-		0.95	8.2%

With this information, for each of the N simulations or iterations, the method generates the values of the random parameters in each of the models. With the parameters and variables of both the natural hazard and the storage tank defined, it is possible to evaluate if the solicitation S exceeds the resistance R of the storage tank. The following equation sets the calculation of the damage probability of a storage tank impacted by a natural event:

$$p_d = \frac{\sum_{i=1}^{N_{sim}} g(i)}{N_{sim}} \tag{17}$$

where $g(i)$ is defined as Limit State Equation (LSE):

$$g(i) = \begin{cases} 1 \; if \; R - S \leq 0 \\ 0 \; if \; R - S > 0 \end{cases} \tag{18}$$

where both R and S have to be defined with respect to the corresponding criteria for buckling, overturning, and debris impact, as described in the previous section.
Based on the above, the Monte Carlo simulations yield the damage probabilities for a given structural configuration of a tank and different wind intensities.

3.4. Natech scenario

Both intensity and frequency of occurrence characterize natural hazards. The frequency of occurrence of a natural hazard can be estimated from the return period t_r (years) [33]:

$$f = \frac{1}{t_r} \tag{19}$$

The return period values are available in the literature and databases for specific regions or areas in the world (see e.g. [34]). The frequency of the final accidental scenario f_e, that is, the Natech event, is determined by combining the frequency of the natural hazard, the probability of damage p_d and the probability of failure p_f:

$$f_e = f \cdot p_d \cdot p_f \tag{20}$$

It is important to establish the difference between damage and failure. Damage relates to an affectation or malformation suffered by the tank. However, it does not mean that the tank is losing any containment. On the contrary, a failure is associated with a crack or opening caused by a defect or breach in the tank, by which the stored material will escape. In addition, if the tank collapses totally, the total release of the stored fluid will be instantaneous. That is, in a few seconds the totality of the stored material will be lost. Consequently, a dependence exists between the damage probability and the failure probability, where the damage of the equipment must first occur for its subsequent failure, as originally proposed in the earlier works of Salzano et al. [5,14,15].
The probability of failure of a component of the storage tank after the tank has suffered a damage, results from a historical data analysis from several databases that collect information related to industrial accidents caused by different natural events (ARIA, FACTS, MHIDAS, MARS and ICHEME). Since a significantly high wind load or wind speed is needed to damage a tank, the probabilities of failure were determined for high and very high wind loads (according to Table 1), which correspond to hurricanes class 3, 4 and 5. The Table 3 summarizes the values obtained for each of the types of failure associated with a high wind load.

Table 3. Failure probabilities calculated for different types of failure on storage tanks.

Failure Probabilities		
Failure Mode	**High Wind Load**	**Very High Wind Load**
Collapse of the structure	0.08	0.10
Total connection failure	0.11	0.13
Partial connections failure	0.23	0.17
Shell rupture	0.32	0.40
Failure of the tanks roof	0.26	0.20

4. Case Study

In order to show the application of the model, the authors performed a fragility assessment for a vertical storage tank, which works at atmospheric conditions. The guidelines presented in section 3.1 governed the characterization of the tank. Table 4 shows the characteristics of tank TK-101.

Table 4. Characterization of a storage tank (TK-101) according to API-650.

Parameter	Unit	Value
Diameter	*m*	33.52
Height	*m*	14.11
Steel Grade	-	235
Thickness	*mm*	6.35-18.5
Stored fluid	-	Gasoline
Filling degree	*(%)*	3; 5; 8; 10
Typo of Roof	-	Dome
Roof Thickness	*m*	0.00635
Dome Radius	*m*	28.82
Bottom plate thickness	*mm*	14
Anchorage	-	None
Floating Roof	-	None

MATLAB R2016a program [35], estimated the probability of damage of a storage tank under the impact of a wind load or impact by a projectile dragged by the wind. The name of the program is Natech Tank Analyzer (Natanks) for the assessment of fragility for storage tanks during Natech events. Natanks encapsulates the methodology presented above, in which the characterizations of the storage tank, and the natural hazard (extreme wind) are combined into a probabilistic approach to obtain the fragility curve of the equipment associated with the Natech event (See Figures 4, 5).

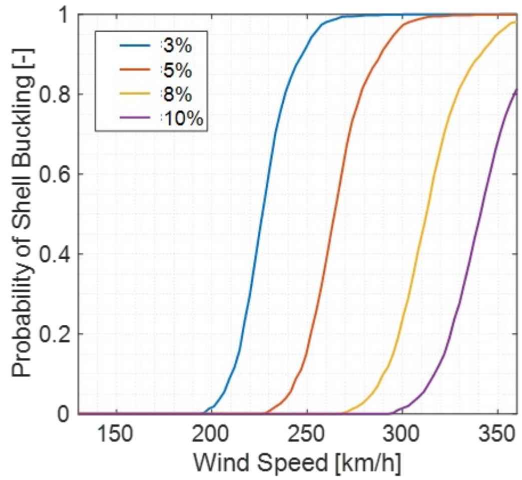

Figure 4. Probability of damage by Shell buckling of the TK-101 impacted by a wind load and four different filling levels h.

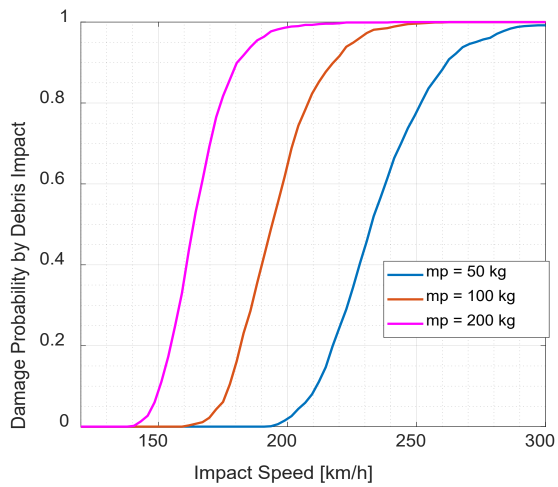

Figure 5. Probability of damage debris impact for three different debris masses mp; filling level = 10%.

From the fragility curves for a vertical storage tank with a dome roof, it is evident that as the wind speed increases the probability of buckling damage also increases. The figure presents four curves which correspond to different filling levels. Quite clearly, the curve moves to the right with higher filling level, thus indicating that the tank will have a factor of additional resistance thanks to the stored fluid and a higher wind speed will be required to damage the tank.

Figure 5 shows the damage probability by debris impact, for different debris masses (m_p). The debris is a rectangular steel plate, as shown previously. Table 6 shows the results of the TK-101 impacted by a very high wind load (hurricane category 5) with wind speed of 260 km/h, with a return period of 500 years.

Table 6. Accidental scenario considered for the event tree.

Information for Risk Assessment	Unit	Value
Hurricane category 5	km/h	260
Return period of natural hazard (t_r)	y	500
Asset at risk	-	Storage Tank TK-101
Filling level	%	5
Damage: Shell Buckling		
Damage probability (p_d)	%	45.7
Failure: Shell Rupture		
Failure probability (p_f)	%	40.0
Probable penetration depth (h_p)	m	0.011
Frequency of final accidental scenario (f_e)	y^{-1}	$3.66 \cdot 10^{-4}$

Several authors agree that high wind loads present little risk to vertical atmospheric storage tanks, unless their filling level is below 15%. Other authors claim that the damage may occur only in the upper part of the structure [23,36]. The present study verifies the aforementioned. According to API-650, a storage tank is designed to resist a maximum wind speed of 190 *km/h*.

Given that there is a probability of loss of containment due to the failure of the equipment, one of the final consequences of the event is the loss of the storage tank operability and its consequent reconstruction. Additionally, if the shell rupture occurs in the upper part of the equipment, the scenario of a flammable material cloud is possible, and gasoline can escape due to the failure of the equipment. If the tank has a filling level of 5% with gasoline, approximately 626.55 m^3 of the highly volatile material will be released to the environment.

Natech events are accidents with low probability of occurrence but with serious consequences. Taking into account all the above information, the frequency of the occurrence of the Natech event on the storage tank is evaluated at approximately $3.66 \cdot 10^{-4}\ y^{-1}$, which is a fairly acceptable value considering the serious consequences mentioned.

5. Conclusions

The present work focuses on analyzing the structural consequences of the impact of an extreme wind load on a vertical storage tank, aiming at the qualitative and quantitative assessment of Natech scenarios through the definition of specific fragility curves for the loss of containment from atmospheric storage tanks with respect to the wind intensity.

A case study for a vertical storage tank, which works at atmospheric conditions, illustrates the methodology and shows how its results can facilitate the decision process regarding the need to reinforce the system, so that the occurrence value of the Natech event is less than the order of 10^{-5}, the value recommended in this study. Future works will be devoted to other tank designs, which include proper girder design and different layout for the storage farm taking into account wind direction and shadow effect.

The study allows the wind-related phenomena to be considered as entry parameters for industrial risk assessment.

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