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Analysis of the Behaviour of the Floating Roof in a Cylindrical Storage Tank Subjected to Seismic Excitation for the Mitigation of Fire Risk

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Natural Hazard triggering Technological Disasters (NaTech) are accidents resulting from natural hazards, such as earthquakes, interacting with industrial risks. Seismic damage to the equipment of industrial plants can lead to major accidents such as explosions, fires or hazardous releases. In this framework, the cylindrical liquid storage tank with floating roof is a common equipment vulnerable to earthquakes. In particular, rim seal fires can be initiated by damage to the sealing system. Impact between metallic parts, such as the bumper bars and the tank shell, may be the cause.
The aim of this work is to investigate the horizontal dynamic behaviour of the floating roof of a tank under seismic excitation in order to assess and mitigate the associated risk of major accidents. For this purpose, a simplified model has been developed, considering the bumper bars rigid and partially deformable.
Finally, some fragility curves have been realized to estimate the probability of occurrence of a given maximum contact force as a parameter of structural damage and possible ignition of fire.

1. Introduction

Seismic events in the past have shown that industrial plants are vulnerable to earthquakes. Their vulnerability results from the complexity of the layout: they are characterized by many connections, equipment, and components which, combined with the complexity of their operations, make them highly susceptible to seismic excitation. This implies the possibility of accidental chains forming, with a possible domino effect, which can cause explosions, fires and releases of dangerous substances treated by the industrial processes. In cases where natural disasters interact with industrial risk, this is referred to as NaTech events (Natural Hazard triggering Technological Disasters). Among the NaTech events, the earthquake is one of the most significant, it simultaneously affects the entire plant, and it can cause simultaneous damages to equipment (Krausmann et al., 2016; Young et al., 2004).In terms of safety, in Italy industrial plants that operate with hazardous substances are called “major hazard industrial plants” and are subject to Italian standard D.Lgs. 105/2015, transposition of Directive 2012/18/EC – Seveso III.
One of the typical equipment in major hazard industrial plants is the cylindrical liquid storage tanks with floating roof (Paolacci et al., 2009b). Seismic damages to the floating roof and non-structural elements can cause hazardous substance releases, fires and explosions.
As a part of major accidents, rim seal fire is the most common type of fire in a tank with a floating roof. This occurs when the sealing system is damaged, loses its integrity and allows the leakage of vapors that can be ignited (Moshashaei et al., 2017). These vapors can be ignited by sparks from impact between bumper bars and tank wall, two metallic parts. In fact, the bumpers, which certainly limit the horizontal displacements of the roof and prevent damage to the sealing system, can also cause some issues. The punctual and repeated impact of the bars against the tank wall can generate high contact forces. In addition to producing sparks due to the contact between two metallic materials, the impact can also cause damage to the tank. Evaluation of the contact force is therefore useful for local checks of the tank section.

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In this framework, the horizontal dynamics of the roof with the sealing system and with the bumper bars is of particular interest for the earthquake NaTech risk assessment of atmospheric tanks with floating roofs.
Prediction of the horizontal dynamic response of the floating roof of a tank subject to seismic excitation at the base allows the assessment, the monitoring and the mitigation of the seismic risk, especially related to fires and explosions. Indeed, some proposals for monitoring have already been made in (Marino et al., 2017), so models that describe the horizontal dynamics of the roof would be used to estimate some risk thresholds for the activation of early warning systems. In addition, some efforts have already been made in the field of passive seismic protection of industrial components (Paolacci et al., 2009a), and in particular of the floating roof by Zahedin Labaf et al. in (Zahedin Labaf et al., 2022), in which a hybrid control system is proposed, where a base isolation system is equipped with a tuned mass damper inerter.
In this study, the horizontal dynamics of the floating roof with sealing system and bumper bars is the subject of interest. In particular, in the field of impact dynamics, in (Andreaus et al., 2017b) and (Andreaus et al., 2017a) the use of collision buffers is proposed for the attenuation of structural pounding in case of earthquakes.
The main objective is to investigate the dynamics of the impact of the roof bumper against the tank shell in order to provide more information for the risk assessment related to the damage of the sealing system. By the assumption of decoupling between the vertical and horizontal motion of the roof, a simplified and reduced model with finite element method is realized.
Several fragility curves have been realized, considering first a hard impact, and subsequently a soft impact, as a possible measure of risk mitigation. The probability of exceeding the limit state data can be used by risk analysts in the event tree analysis and fault tree analysis (Salimbeni et al., 2022).

2. Cylindrical liquid storage tanks with floating roof

2.1 Floating roof

Tanks with floating roof are used for the storage of volatile products. The roof floats on the surface of the product and, by sliding vertically along the shell, ensures that most of the vapor remains contained under the roof.
The roof is a circular steel structure with floating caissons that allow it to float above the product stored. Generally, the diameter of the floating roof is about 400 mm smaller than the inside diameter of the tank. The space between the outer edge of the roof and the inside of the tank shell is closed by a flexible sealing system. Also, some elements are required for the functionality of the tank, such as flexible piping systems, edge vents, rain drainage system, roof supports, guide pipe, stilling pipe and floating roof sealing system.

2.2 Sealing systems and limiting bumper bars

The rim seal must be sufficiently flexible to adapt to possible construction irregularities, to limit the possibility of impact between steel parts, and to recenter the roof during the operation phases. In addition, it allows the roof to move vertically during the normal operation of the tank.
The floating roofs are equipped with the primary and secondary seal: the secondary one is mounted above the primary seal with the aim of minimizing vapor and odor losses. In practical use, different types of sealing rim are currently employed. For primary seal, several solutions are available, including metal shoes, non-metallic tubular or fabric seals. The working range of sealing systems, as stated by the manufacturers, is usually 205±100 mm. The sealing systems are also installed with initial compression. The initial compression ensures adherence to the tank wall to prevent the seal from being stretched. Horizontal displacements of the floating roof greater than 205+100 mm will result in excessive compression on one side of the seal and possible separation from the other side of the seal.
The seal allows variations of 100 mm in the rim space: excessive deformation of the seal is prevented by limiting bumper bars mounted on the lower edge of the outer rim of the roof. The bars are made of steel.

3. Modelling

3.1 Basic assumptions

The constituent elements of a tank with floating roof are as follows: the walls and bottom of the tank, the fluid, the floating roof, the sealing system, the bumper bars. A comprehensive model for assessing the seismic response of tank with floating roof should include all the elements listed above. In order to study the only horizontal dynamics of the floating roof, the vertical motion of the roof can be decoupled from the horizontal one. This hypothesis is based on the following assumptions:
- the hypothesis of small vertical displacements of the roof is true;
- there is no tangential action of the fluid transmitted to the floating roof.

By introducing the decoupling hypothesis, it's possible to move from the comprehensive model to a simplified model where only the horizontal dynamics is relevant.

Furthermore, since the stiffness in the roof plane is much greater than the radial stiffness of the sealing system, the roof can be considered as a rigid body. The simplified model is also reduced in the number of the degrees of freedom.
The proposed model is simplified and reduced. In particular, it considers only 1 degree of freedom of the floating roof- the horizontal displacement in the direction of application of the seismic action- and the degrees of freedom of the bumpers, related to their deformation at the impact.
The dynamic parameters that characterize the horizontal response of the roof are m, the mass of the roof, k_S and c_S , stiffness and damping coefficient of the sealing system (or damping factor ξ_S), k_B and c_B , stiffness and damping coefficient of the bumper bars, G_0 the initial gap.
The bumper bars are initially considered rigid. A hard impact is a contact that occurs in an infinitely small time between non-deformable collision bodies. Any loss of energy during the impact is represented by a constant value of the coefficient of restitution, defined as the ratio between the post and pre-impact speeds. The coefficient of restitution assumes values between 0 (fully plastic contact) and 1 (fully elastic contact). Without considering any source of energy loss (c_B=0) and assuming that the collision bodies are rigid, the impact is elastic and hard.
Then, the possibility of using partially deformable bumper bars is investigated. By using deformable bumper bars, it is possible to limit the contact forces generated by the impact. In soft impact the deformation of collision bodies is considered. The phenomenon of contact can be simulated by a simple model represented by a linear spring element, which assumes a linear relationship between the contact force and the overclosure, without taking into account (c_B=0) the energy loss during the impact. In this case, the impact is elastic soft.
In the case of partially deformable bumper bars, where the deformable part will be made of non-metallic material, it must be considered that the working range of the sealing systems is 200±100 mm. Therefore, the deformation of the bumpers must be such as to ensure that the displacements of the roof are always within this range.

3.2 Finite element model

Using the finite element software Abaqus/Explicit, a simplified and reduced model of the tank with floating roof shown in the Fig. 1 is developed. The material properties and dimensions of the tank are reported in Tab. 1. The case study is taken from the tank in (Paolacci et al., 2009a).

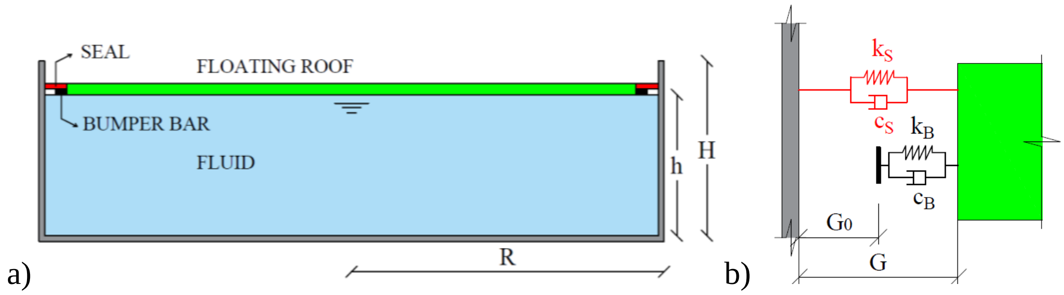

Figure 1: Tank with floating roof: a) a complete model; b) a detail of the simplified and reduced model

The tank is treated as a rigid body (Discrete Rigid Surface); therefore, it has not been assigned any type of material. The roof is modeled as an equivalent shell, with distributed mass and stiffness, like that of Matsui in (Matsui, 2007). The sealing system is modelled as an annular shell part: the seal is tied to the outer rim of the roof and to the inner wall tank. The sealing system is discretized using membrane elements with significantly lower in-plane stiffness than the radial stiffness of the roof. The roof can therefore be considered as a rigid body. A stiffness values k_S is assigned to the sealing system, in terms of the Young's modulus of the material E_S. The damping of the sealing system is fixed at 1% in terms of damping factor ξ_S .
The limiting bumper bars are continuously modeled by assigning a contact interaction between the outer edge of the roof and the inner wall of the tank. A thickness property is assigned to the contact, reducing the nominal gap. At first, the bumper bars realize a hard impact by assigning a frictionless tangential behavior and a "hard contact" normal behavior. Later, the contact behavior in the normal direction is assigned as a bilinear pressure-overclosure relationship, defining $\lambda = \frac{k_B}{k_S}$ the ratio between the stiffness of the seal and the stiffness of the bumpers, three different values for λ are investigated, (λ =10,100,1000), keeping ξ_S = 0.01.
The fluid is not modeled, due to the decoupling hypothesis.

Table 1: Geometrical and mechanical properties of the case study.

Tank's radius R [m]	27.43
Tank's height H [m]	15.60
Fluid's height h [m]	13.60
Density of the roof γ [kg/m^3]	380.00
Thickness of the roof t [m]	0.25
Young's modulus of the roof material E_r [Pa]	2.10×10^{11}
Poisson's coefficient of the roof material ν [-]	0.3
Young's modulus of the seal material E_S [Pa]	1.00×10^{4}
Damping factor of the seal ξ_S [-]	0.01
Nominal gap G [m]	0.20
Real gap G_0 [m]	0.10
Linear stiffness of the bumper k_B [N/m]	various
Damping coefficient of the bumper c_B [Ns/m]	0.00

4. Seismic fragility analysis

The fragility function represents the probability that the seismic demand (EDP - Engineering Demand Parameter) on a building exceeds the limit state (LS) as an undesirable condition for a specific intensity measure (IM) (Lallemant et al., 2015).

4.1 Probabilistic seismic demand model

The probabilistic seismic demand model establishes the relationship between the EDP and IM of the earthquake. To define this relationship, several analytical methods can be used. The Cloud Method is one of the most commonly used, because it has the advantage over other methods of using ground motion without the need for scaling.

Under the assumption of a lognormal probability distribution for demand EDP, the median demand D_m is related to IM by a power law of the type

$$D_m = a(IM)^b \tag{1}$$

where a and b are the coefficients obtained by linear regression of of D and IM on the bi-logarithmic plane

$$ln(D_m) = b \cdot ln(IM) + ln(a) \tag{2}$$

The probability model of seismic demand has the form

$$P[D \geq LS|IM] = 1 - \Phi\left(\frac{ln(LS) - ln(D_m)}{\sqrt{{\beta_{D|IM}}^2 + {\beta_{LS}}^2}}\right) \tag{3}$$

where Φ is the standard cumulative normal distribution function, $\beta_{D|IM} = \sqrt{\frac{\sum_{i=1}^{N}(ln(D_i) - ln(D_m))}{N-2}}$ is the conditional logarithmic standard deviation depending on the variability of the data set, N is the number of ground motions, D_i $(i = 1, \ldots, N)$ is the i-th computed value of the demand, β_{LS} is the uncertainty related to the selected limit state (in this work place equal to 0).

4.2 Selection of ground motions

A set of 20 accelerograms was chosen to investigate the behavior of the floating roof. In particular, 6 long duration earthquakes, 8 near fault earthquakes and 7 standard records were selected to cover a proper range of PGA.

4.3 Fragility curves

First, the effect of the stiffness of the sealing system k_S on the number of impacts I was studied.

Considering G_0 = 100 mm and hard impact, the results (Fig. 2b) clearly show that as the period of oscillation of the system decreases or as the stiffness of the sealing system increases, the probability of an impact reduces for the same PGA. This is evident not only from the trend of the fragility curves, but also from the data cloud in Fig. 2a. For the case where the sealing system is more rigid, T = 0.75 s, it is observed that many points of the cloud are located around the value 0 of $ln(I)$.

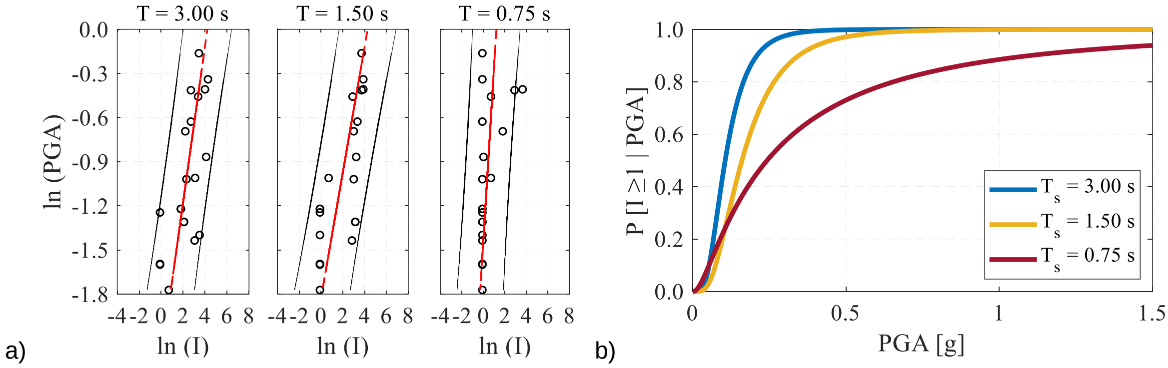

Figure 2: Results by varying k_S, with G_0 = 100 mm and considering hard impact: a) linear fit demand model of number of impacts with PGA; b) seismic fragility curves of number of impacts.

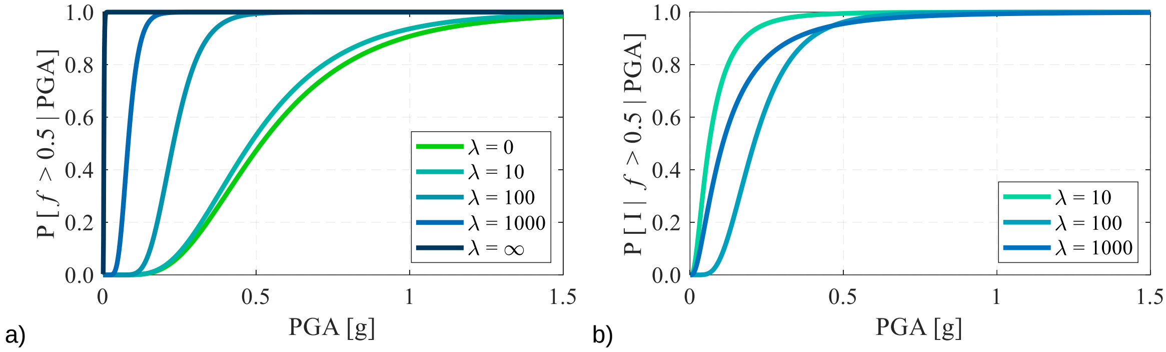

Figure 3: Results by varying k_S, with G_0 = 70 mm and considering soft impact; a) force ratio f; b) number of impacts I with f > 0.5.

Therefore, by acting on the stiffness of the sealing system, it is possible to limit floating roof displacements and thus the probability of roof-mantle impact.

Considering the partially deformable stop system, with G_0 = 70 mm, the role of the stiffness of the bumper k_B was studied for the most flexible case of the sealing system.

Defining f as the ratio between the maximum contact force recorded in the soft impact and the maximum contact force in the rigid case, with G_0 = 70 mm, fragility curves show the probability that this ratio is greater than 0.5.

Two limit cases have been added: the case of a rigid impact, for which the probability that f > 0.5 is always 1, and the case of an impact so deformable that it is as if the bumper was not present, which corresponds to the case of a hard impact with G_0 = 100 mm.

Not only is the magnitude of the contacting forces interesting, but also how often contacting with high forces occurs. Therefore, the probability of multiple impacts with f > 0.5 was investigated.

From Fig. 3a it seems that the consideration of the partial deformability of the bumper is not convenient, since for the case λ = 10 with G_0 = 70 mm it tends to the case of rigid stop with G_0 = 100 mm. Instead, as can be seen in Fig. 3b, the probability of more than one collision with f > 0.5 is higher in the case of λ=10. This indicates that the proposal to insert a partially deformable bumper layer can be effective, assuming an adequate stiffness design.

The introduction of deformable bumpers may also include the addition of dampers, the effect of which was not investigated in this study, to control the horizontal oscillations of the floating roof.

5. Conclusions

In this work, the possibility of an impact between the roof and the shell as a cause of the initiation of a fire has been investigated. The results are presented in the form of fragility curves. The fragility curves are used in a risk analysis to estimate the frequency of occurrence of an incidental event.

Specifically, the influence on the maximum contact forces and the number of impacts with the highest contact forces of two parameters- the stiffness of the sealing system and the stiffness of the bumper- was investigated.

By increasing the stiffness of the sealing system, the probability of one or more impacts occurring is reduced, while a proper design of the bumper stiffness is required. In fact, by introducing a deformable bumper, an increase in the deformability of the bumper corresponds to a decrease in the probability of impacts with contact forces greater than 50% of those that would be obtained with a hard impact, but the probability of more than one impact with significant contact forces grows.

The results, which are presented in relative terms, can also be used to perform structural checks by defining damage states for the tank shell.

The preliminary nature of this work certainly requires further studies on the optimal design of stiffness parameters compatible with operating conditions and also the role of dissipation, but it represents an example of a fire risk mitigation system in tanks with floating roof.

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References

Andreaus U., Baragatti P., De Angelis M., Perno S., 2017a, A Preliminary Experimental Study about Two-Sided Impacting SDOF Oscillator under Harmonic Excitation. Journal of Computational and Nonlinear Dynamics, 12.

Andreaus U., Baragatti P., De Angelis M., Perno S., 2017b, Shaking table tests and numerical investigation of two-sided damping constraint for end-stop impact protection. Nonlinear Dynamics, 90, 2387–2421.

Krausmann E., Cruz A. M., Salzano E., 2016, Natech risk assessment and management: reducing the risk of natural-hazard impact on hazardous installations.

Lallemant D., Kiremidjian A. S., Burton H., 2015, Statistical procedures for developing earthquake damage fragility curves. Earthquake Engineering & Structural Dynamics.

Marino A., Ciucci M., Paolacci F., 2017, Smart technologies for integrated natural risk management: Innovative methodologies and remote sensing. American Society of Mechanical Engineers, Pressure Vessels and Piping Division PVP.

Matsui T., 2007, Sloshing in a cylindrical liquid storage tank with a floating roof under seismic excitation. Journal of Pressure Vessel Technology, Transactions of the ASME, 129(4), 557–566.

Moshashaei P., Alizadeh S. S., Khazini L., Asghari-Jafarabadi M., 2017, Investigate the Causes of Fires and Explosions at External Floating Roof Tanks: A Comprehensive Literature Review. Journal of Failure Analysis and Prevention, 17(5), 1044–1052.

Paolacci F., Giannini R., De Angelis M., Ciucci M., 2009a, Experimental investigation on the seismic behaviour of base-isolated steel storage tank. 11th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures, Guangzhou, China.

Paolacci F., Giannini R., De Angelis M., Ciucci, M., 2009b, Seismic vulnerability of major-hazard industrial plants and applicability of innovative seismic protection systems for its reduction. 11th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures, Guangzhou, China, Nov. 17-21.

Salimbeni M., De Angelis M., Ciucci M., 2022, Earthquake NaTech Risk Assessment in Major-Hazard Industrial Plants, a Case Study: Cylindrical Liquid Storage Tank with Floating Roof. Chemical Engineering Transactions, 91, 193–198.

Young S., Balluz L., Malilay J., 2004, Natural and technologic hazardous material releases during and after natural disasters: A review. Science of the Total Environment, 322, 3–20.

Zahedin Labaf D., De Angelis M., Basili M., 2022, Multi-objective optimal design and seismic assessment of an inerter-based hybrid control system for storage tanks. Bulletin of Earthquake Engineering.