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Blast Damage Consideratons for Horizontal Pressure Vessel and Potential for Domino Effects

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Process equipment containing hazardous or flammable materials in petrochemical facilities can be subjected to significant blast loads from accidental Vapour Cloud Explosions (VCE). Storage tanks are of particular importance, since these can potentially contain significant amounts of such materials. Calculating the response (damage) of particular types of tank and associated equipment under explosion blast loads can be complicated and expensive. Moreover, determining if the predicted damage has any potential for releasing the contents of the tank can be challenging and involve complex calculations. Simplifications can be made to model certain types of equipment such as bullet tanks in order to obtain qualitative estimates of damage based on empirical data, analytical approximations, and observed damage from industrial explosions. The simplified models can be used to assess the potential for damage in terms of the peak pressure (P) and impulse (i) which is the integral of pressure-time function. These parameters can be used to define any blast load. Therefore, the damage estimate is not only dependent on the equivalent static pressure, but takes the blast duration into account.

Pressure-impulse (P-i) curves can be used to graphically define the magnitude of any potential explosions as pressure-impulse combinations that cause specific damage levels. Using P-i curves developed for increasing damage levels, qualitative damage levels can be defined as the area bound in a pressure-impulse diagram between two curves. Calculated VCE blast loads can be plotted on the P-i diagram to perform qualitative blast assessment of the equipment damage. Furthermore, the tank (or other equipment) model can be used to produce damage contours on a plant plot plan that can be used as an aid in new plant facility siting.

1. Introduction

Accidental VCE in chemical processing plants can have devastating consequences on buildings and other infrastructure and can cause serious injuries and render large areas inoperative. Furthermore, the damage to equipment used to process and store hydrocarbons and other flammable materials could result in releases of liquids and vapours that could potentially trigger additional explosions.

The types of equipment are numerous as are the hazardous materials involved in petrochemical processes. One type of equipment susceptible to blast is pressurized storage tanks commonly used in such facilities. These tanks can be subjected to severe blast loads resulting from accidental Vapour Cloud Explosions (VCE), since they are often located near potential sources of explosions. Calculating the response (damage) of a particular type of tank and associated equipment under specific explosion blast loads can be complicated. Moreover, determining if the predicted damage has any potential for releasing the contents of the tank can be challenging and involve complicated calculations. Simplified

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methodologies described in this paper can be used to effectively model certain damage modes conducive to such releases.

2. Potential Damage Modes

Horizontal storage tanks such as “bullet” tanks are typically designed for internal pressure and are significantly robust. These tanks may resist significant blast loading without sustaining damage that would compromise the integrity of the shell. The overall capacity of a tank to resist blast loads, can be much higher than that of conventional buildings, as illustrated in Figure 1 where a relatively intact tank was located near a building destroyed by an explosion overpressure. Approximate blast resistance values of cylindrical storage tanks indicate higher than 50 kPa (7.3 psi) resistance based on displacement and failure of connecting piping [ASCE]. However, associated impulse values are not provided. Moreover, the resistance is not specific to tank size, mass, or support conditions.

Figure 1 Comparative Blast Damage of Building and Bullet Tank

Since damage to the tank components can potentially lead to accidental release scenarios conducive to subsequent VCEs more detailed analyses are warranted. Moreover, if the material in the storage tank is toxic, the secondary release could produce toxic cloud which can be significantly larger than the flammable cloud and potentially cause more fatalities than the primary explosion itself. Such modes of damage can occur at significantly lower blast pressures, but nonetheless be of critical importance and should be considered in their design and siting. A few examples of such damage can be failures of couplings, nozzles, or valves caused by excessive shifting of the tank during an explosion. This paper examines the lateral behavior (sliding, tipping, or other) of tanks loaded by a uniform overpressure with an instantaneous rise time and relatively short duration (1 s or less). In general, the most common forms of lateral displacements that could compromise the integrity of the tank are sliding along the long dimension of the concrete supports as shown in Figure 2 or along the short dimension as shown in a Figure 3.

Figure 2 Tank Sliding in Long Dimension

Figure 3 Tank Sliding in Short Dimension

3. Simplified Analysis Methodology

3.1 Blast Load Modelling

In general blast loading of structures is a well understood topic and is treated extensively in the literature [UFC 3-340]. The simplified blast modelling assumes that the pressure is instantaneously applied and to decay linearly to the atmospheric pressure over time t (duration of the blast). Integrating the pressure function over the duration yields the impulse of the blast. Therefore, a blast load (illustrated in Figure 4) can be defined by its pressure and impulse values.

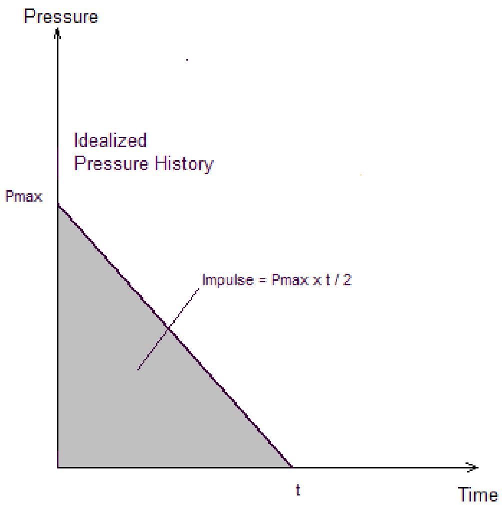

Figure 4 Idealized Blast Pressure Function

The pressure wave from the blast will impinge on the side of the tank facing the explosion and will quickly wrap around the body of the tank loading the top and bottom with nearly equal intensity and finally the back side, as illustrated in Figure 5. The difference in the horizontal components of the blast load is fundamentally that the front face of the tank will "reflect" the pressure wave causing the pressure to increase in intensity. The enhancement to the incident pressure is known as "reflection factor" C_r and can be approximated from the equation given in the ASCE.

$$C_r = (2 + 0.05 \cdot P_{so}) \tag{1}$$

Where P_{so} is the incident pressure in psi

The net impulse on the front side of the tank will be reduced by "clearing effects" which result when the loaded area has one or more relatively small dimensions that allow the blast to reach the edges of the loaded area in a very short time. The back side pressure can be considered to have a finite rise time, as the pressure is not applied uniformly over time. The lag time between the front and back loads can be approximated by using the distance between the front and the back as one half of the tank diameter and the shock front velocity [ASCE]

$$U = 1130 \cdot (1 + 0.058 \cdot P_{so})^{\frac{1}{2}} \tag{2}$$

Where U is the shock front velocity and has the units ft/s.

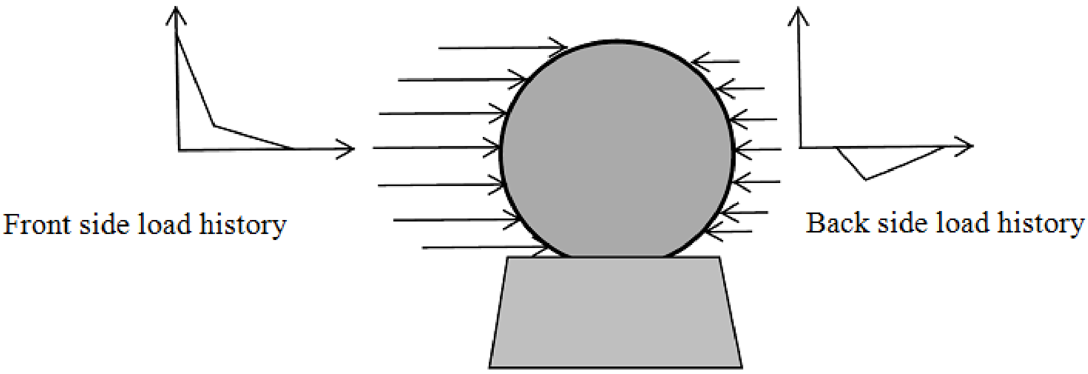

Figure 5 Simplified Horizontal Blast Loading on Tank

4. Dynamic Analysis

The response (sliding) of the tank in the horizontal direction relative to its support can be estimated using simplified dynamic analyses based on the strength of the connections, friction between the steel and concrete, and the dimensions of the support. The Single-Degree-of-Freedom methodology can be effectively used to calculate deflections in the direction of interest only accounting for the strength and stiffness of the support and the overall mass of the system when loaded by a horizontal blast. The equation of motion for such a system is [BIGGS].

$$F(t) = k(x) + C \cdot \left(\frac{dx}{dt}\right) + M \cdot \left(\frac{d^2x}{dt^2}\right) \tag{3}$$

Where

x = horizontal deflection, length

K = stiffness, typically expressed as pressure/length

F(t) = load function in the horizontal direction, typically pressure vs. time

M = Mass of system

In many cases, horizontal tanks are supported on concrete saddles anchored with steel rods embedded in the concrete. Typically, the anchors are not more than 25 mm (typically up to a fraction of an inch) in diameter, as shown in Figure 6. Therefore, the total available capacity of the connections to resist lateral shifting is limited. However, this force can usually be considered as constant once the peak value of the anchor is developed and before the "ultimate" capacity is attained when the anchor ruptures. After the anchors rupture, the resisting force will be the friction between the steel tank and the concrete support. The idealized resistance function of a typical anchor is shown in Figure 7 [WA-RD271.1].

Figure 6 Anchor Failure by Rupture

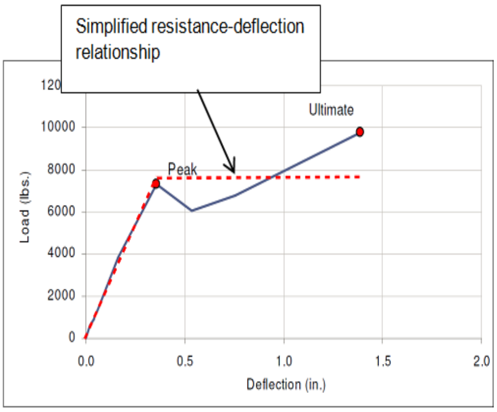

Figure 7 Idealized Anchor Resistance-deflection Function

The equation of motion can be solved numerically using a spread sheet or other similar method that allows the following
Consider the loading function as a variable of time (including front load and back load)

1. Account for post-yielding behaviour of the tank connections and for subsequent resistance to sliding caused by friction, as represented in **Error! Reference source not found.**
2. Consider mass variations in the contents of the tank

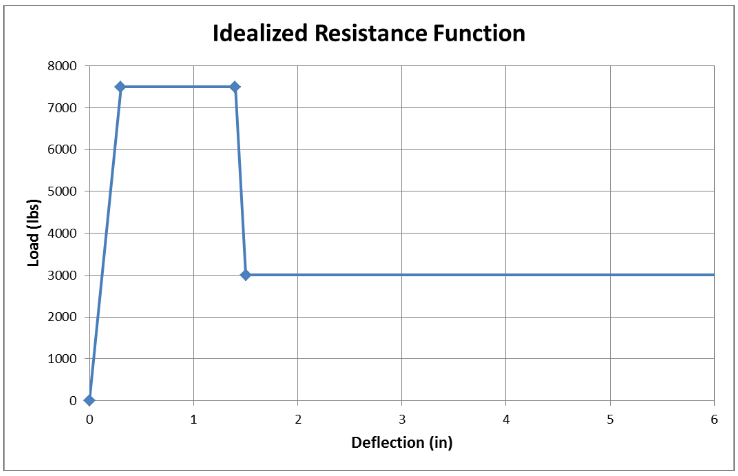

Figure 8 Idealized Combined Resistance-Deflection Function for Tank Sliding

Figure 9 Tank Sliding

5. Pressure-Impulse Diagrams

Since a specific component deflection (or damage) can be caused by blast loads with different pressure and duration, the pressure-impulse (P-i) combinations can be analytically determined and used to construct P-i curves, such as the one shown in Figure 10 to represent all of these potential loads. A graphical blast assessment can then be performed by comparing the pressure and impulse of a particular blast to the P-i curve particular to a deflection such as the one shown in Figure 10.
The P-i curves corresponding to specific deflections of interest can be used to bind the blast loads (pressure-impulse points) that can potentially cause the specific levels of response. Any point representing a blast load that plots above and to the right of a given curve would result in greater damage than the curve represents. An example of a P-i diagram developed to assess the potential of a tank to sliding is shown in Figure 11. The curves are based on a hypothetical example based on a 9091 kg (20,000 lb.) tank with a 1220 mm (48 in) diameter and 7620 mm (25 ft.) length. The resistance function is the one shown in .

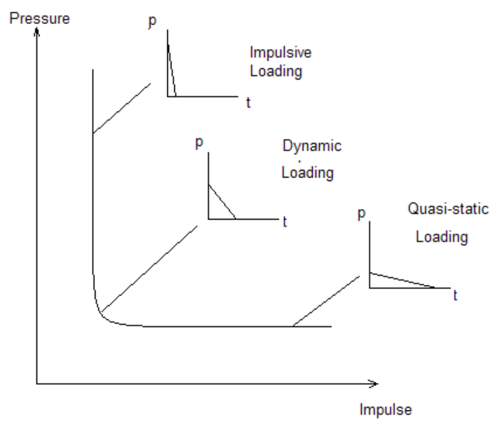

Figure 10 Pressure-Impulse Curve (Example)

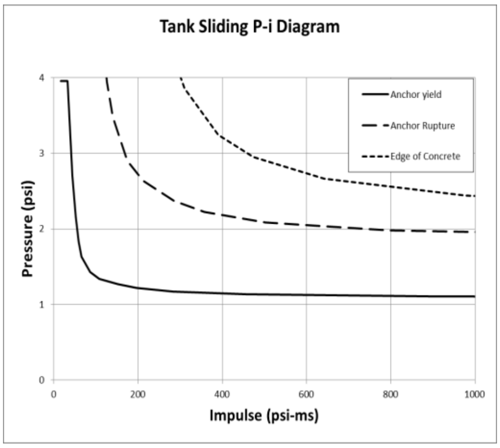

Figure 11 P- i Curves for a Hypothetical Tank

6. Conclusions

The body of storage tanks can have significant capacity to resist blast loads from accidental industrial explosions. However, the contents of the tank can be released from damage to other components such as nozzles and flanges at the connections of pipes. Simplified analyses can be used to determine the total lateral displacement of the tank under the applied blast loads. The amount of deflection that the tank can sustain without damaging critical components will determine the maximum allowable blast loading the tank can withstand without catastrophic release of the hazardous contents.

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