EXTERNAL HAZARD EFFECTS ON STEEL AND CONCRETE RLG TANKS

External hazards play a significant role in the selection of the tank containment system and materials of construction

> **THE STORAGE** tank system and tank material selection are based on both safety and economic considerations to provide a safe storage solution for both the owner and public while being economically feasible.

External hazards play a significant role in the selection of the tank containment system and materials of construction. The various external hazards which can affect a tank system and may require consideration in the facility risk assessment are listed in the industry standards covering refrigerated liquefied gas (RLG) storage tank systems [Ref 1, 2]. However, the major external hazards such as external fire, external explosion and projectile impact should always be included in the facility risk assessment performed by the facility owner. The risk assessment determine credibility of these hazards and magnitude of external loads and effects these hazards apply to tank systems. While the storage system's outer tank is often constructed of pre-stressed concrete to mitigate these external hazards, in some cases an outer steel tank may be adequate.

This article will examine the resistance of steel and concrete tanks subjected to these three external hazards. In addition, other factors besides just the outer component materials may impact the tank storage concept selection. Those factors will also be examined.

EXTERNAL FIRES

Effects of any external fire on the tank structure can be characterized by two parameters: thermal radiation intensity and fire duration.

Certain fire conditions, for example a fire on a relief vent system, may apply a high intensity thermal radiation on the tank but only for a short duration. Other fire conditions, for example a fire in a distant process unit, may apply low intensity radiation but for a long duration.

Outer tanks made from concrete are typically able to withstand short duration high intensity fires or low intensity long duration fires due to significant thermal mass of concrete and natural resistance of concrete to heat.

Steel tanks are also able to resist significant thermal radiation without any mitigation but only for a relatively short time period. The obvious concern for steel structures is a reduction in steel strength with increase in temperature. However, it may take a considerable time for even relatively high thermal radiation before the steel tank temperature reaches this critical level. For example, it can be demonstrated that for 15 kW/m^2 radiation it takes up to 100 minutes for the temperature of a steel tank painted white to reach the critical level. However, it still appears prudent to provide a fire mitigation system for any steel tank where an external fire is considered a credible event in the facility risk assessment.

A different design condition is one where the fire has both high radiation intensity and long duration. An example of such a condition is an adjacent tank fire, which even with proper tank separation distances may impose thermal radiation intensities of 32 kW/m^2 or more for many hours while the entire content of the adjacent tank is completely burned. Even when the tank is constructed with prestressed concrete, the external wall and roof will be subjected to temperatures that reduce the effectiveness of the concrete wall prestress system. Analysis indicates that up to a 75% reduction in horizontal prestress can occur for a concrete wall with internal bonded tendons exposed to 32 Kw/m^2 radiation for 48 hrs. For vertical tendons, which are typically located further from the wall outer surface, the vertical prestress force reduction can be as high as 33%. The reduction in prestress is due to relaxation and softening of prestressing steel at elevated temperature as well as tendon tension losses due to the difference in coefficients of thermal expansion for prestressing steel and surrounding concrete. Furthermore, the temperature of the concrete wall inside surface keeps increasing even after the fire is over. The hot wall core keeps radiating heat toward the insulated inside surface. Analysis indicates that the concrete wall inside surface temperature can exceed 220°C well after the exposure to the fire has ended. Therefore, wall vapor barrier and insulation in contact with the inside wall surface should not deteriorate while expose to such temperature.

It can be demonstrated that a typical concrete tank with an internal bonded post-tensioning system, functioning only as a primary vapor container and secondary liquid container, retains its structural integrity despite significant loss of prestress. However, if a concrete tank is the main structural component of the system, designed to resist all operating loads including liquid product hydrostatic pressure (e.g. a membrane tank), such reduction in prestress may result in loss of the ability to carry those loads, and, thus, result in product release. Appropriate mitigation measures should be considered to ensure that the temperature of the prestressing system is kept within the reasonable limits for outer concrete tanks that carry product hydrostatic pressure during normal operation.

In addition, special considerations are necessary for concrete tanks which are post-tensioned horizontally with external wire wrapping covered with a relatively thin shotcrete cover rather than with bonded internal tendons. The external post tensioning systems which are relatively close to the outer tank surface will be exposed to much higher temperature in the case of external fire.

Table 1 summarizes response of steel and concrete tanks for various external fire conditions.

> ‘There is a common misconception that concrete tanks are always required to resist external hazards’

EXTERNAL EXPLOSION

There are two types of explosions: detonation and deflagration. Detonation type explosions are characterized by a shock wave with an essentially instantaneous rise of peak overpressure. Detonations are produced by military or industrial grade explosives. Deflagration type explosions are characterized by rapid but gradual increase in overpressure at subsonic speed. Deflagrations are produced by ignition of vapor clouds. Explosion loads are generally defined by the peak free field overpressure, the positive pressure pulse duration and the shape of the pressure versus time curve.

Industry publications [Ref. 3, 4, 5] provide good guidance on calculating external overpressure applied to the tank structure due to explosions. The dynamic response of the structure can be determined either with a pseudo-static method or with a transient dynamic analysis. The pseudo-static method applies the blast overpressure with an assumed distribution pattern around the tank wall and roof following the blast pressure-time curve and examining the dynamic response of the structure. This method is specified for example in [Ref 6]. The other option is to use commercially available computer software specifically designed to perform transient dynamic analysis. It allows accurate determination of the structure’s response to external explosion loads. The transient time-history of the explosion overpressure pulse and its effect on the tank structure can then be used to determine the maximum internal forces and displacement for the tank components during the event. As an example of a 3-D transient dynamic analysis, the tank deformed shape at various time steps determined using LS-DYNA FEA software is shown in Figure 1. The tank analysed was a 87m diameter concrete tank subject to an external explosion of 200 millisecond total pulse duration and a 30 kPa free field overpressure (shock type wave).

Table 1

FIRE TYPE	CONDITION	STEEL TANK	CONCRETE TANK
HIGH INTENSITY/ SHORT DURATION OR LOW INTENSITY/ LONG DURATION FIRE	Short duration/low intensity	No mitigation required	No mitigation required
	High intensity or significant duration	Mitigation	No mitigation required
HIGH INTENSITY / LONG DURATION	No Liquid Product Load	Mitigation	No mitigation required
	Liquid Product Load Apply	Mitigation	Prestress system temperature shall stay low – likely needs mitigation

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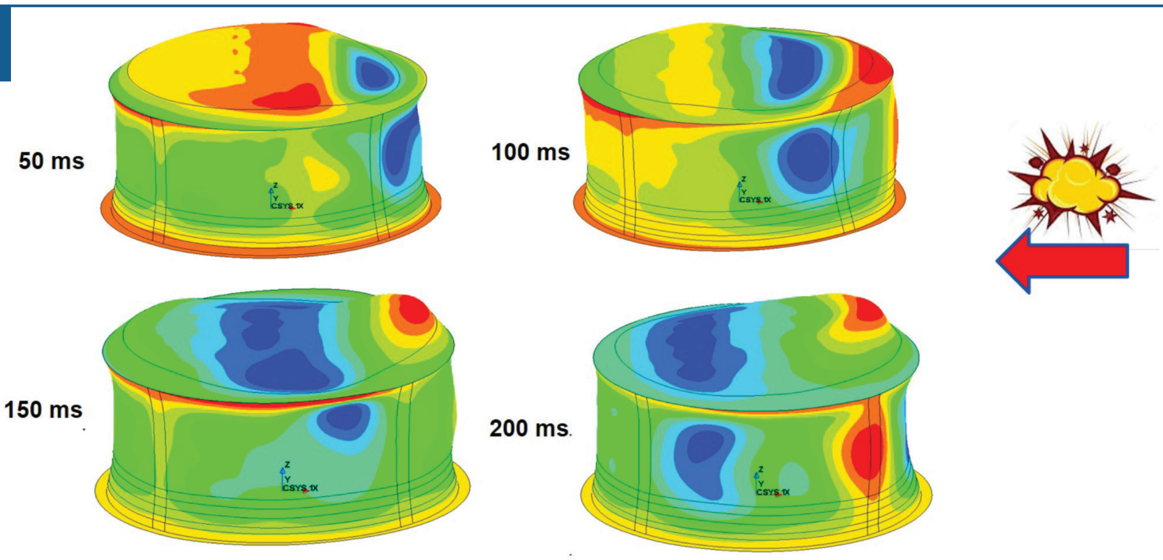

While the literature provides good guidance for the process of applying an external overpressure to a structure, the guidance on how to evaluate structural resistance and to choose appropriate acceptance criteria for steel and concrete tanks subject to external explosion is limited. The best guidance is provided in [Ref. 3], which is specific for petrochemical facilities.

Table 5.B.1.A of [Ref. 3] provides classification for structures in a facility depending on the acceptable damage level. Further Table 5.B.1.B provides classification for response by individual structural components.

Considering that RLG tanks typically store large volumes of flammable, combustible and toxic product, failure of either the entire tank or its individual component could significantly affect public safety. Therefore, RLG tanks are considered to be low allowable damage level structures and RLG tank components belong to the low response limit category.

Tables 5.B.2 and 5.B.3 provide acceptance criteria for the low damage level steel and concrete structures. Steel tank components, such as wall and roof plates, structural stiffeners and roof framing, shall follow the low response limit criteria in Table 5.B.2 of [Ref. 3]. In addition, the stresses in roof plate fillet welds shall be within the fillet weld stress limits and the roof deflections shall be acceptable considering the attached roof platforms and piping.

Concrete tank components shall follow the low response limit criteria in Table 5.B.3 of [Ref. 3] for both reinforced and prestressed concrete structures. In addition, the concrete structures shall meet ULS and SLS criteria specified in the standards addressing concrete RLG tanks [Ref 10]. The deflections of concrete roof shall also be kept to acceptable limits considering the platforms and piping. Furthermore, both the maximum and minimum internal pressures and the hydrostatic liquid load, when the outer tank in service is subjected to this load (e.g. single wall and membrane tanks), should be included in the evaluation. The analysis indicates that tension at dynamic rebounding combined with tension due to internal operating loading may govern the concrete structure design for external explosion.

A peak free field overpressure of 70 mbar or less does not generally govern the design of steel tanks. It can be demonstrated that a short duration peak free field overpressure up to 250 mbar can be successfully accommodated by a properly designed steel tank. Concrete tanks not subjected to product hydrostatic loads can accommodate peak free field overpressures of 300 mbar or more without significantly influencing the design of the concreter tank.

Generally, the acceptance criteria are established to maintain product and vapor containment to allow safe shut down of the tank. If the owner wishes to limit damages to the tank to only minor repairs, the criteria should be tightened. For example:

- Steel tanks local plastic strains should not result in a global permanent set.
- The stresses in concrete tank components should be limited. The stresses in reinforcing steel should not exceed 90% of the yield and compressive stresses in concrete 75% of concrete compressive strength to ensure that permanent damages are limited.

PROJECTILE IMPACT

Impact due to wind-borne projectiles is often considered in the risk assessment. Industry [Ref. 9] provides guidance for typical wind-borne projectiles to be considered for the design. Other projectile shapes and sizes are also often considered in risk assessments and project requirements.

Perforation is the main concern for projectiles impacting steel tanks. Typically, empirical formulas developed by Ballistic Research Laboratory (BRL) [Ref. 7] are used to evaluate perforation resistance of steel plates subjected to projectile impact. A factor of safety of at least 1.25 shall be applied over the calculated thickness required to resist perforation. It should be noted that BRL formula was developed assuming no stresses exist in the impacted target. If significant tensile stresses in the steel tank is expected due to hydrostatic loads (for example a single wall tank or an outer container of a membrane tank system) BRL formula may not be valid and special analysis may be required.

Three following concerns shall be addressed for projectiles impacting concrete tanks:

- perforation
- penetration
- scabbing.

While many empirical formulae exist for projectile impact resistance of concrete structures, the equations in CEB Bulletin 187 [Ref. 8] are based on numerous testing performed in several European countries and consider many parameters including a wide range of projectile shapes, projectile velocity, concrete strength, percentage of reinforcement, and other parameters. As such, CEB Bulletin 187 has been found to be the most useful and appropriate for the evaluation of concrete structures.

Perforation should be addressed for all concrete tanks. Due to the empirical nature of the equations, CEB Bulletin 187

Table 2

PROJECTILE DESCRIPTION	PROJECTILE MASS	PROJECTILE VELOCITY	REQUIRED THICKNESS TO RESIST PERFORATION	
			STEEL TK	CONCRETE TK
	kg	m/s	mm	mm
25mm DIA Steel ball	0.067	56	0.9	29
150 Nominal DIA Pipe Sch 40	130	47	16.0	434
300 Nominal DIA Pipe Sch 40	340	47	15.7	506
100NB Valve (impact area based on Nominal pipe DIA)	50	45	11.7	316
350mm DIA Utility Pole	510	55	24.0	678
100x300 Wood Plank (3.5m long)	50	83	15.5	383

recommends that the concrete thickness required for perforation resistance shall be at least 15% greater than the calculated value. An additional 20% should be applied on the top of this value to comply with the tank industry standards [Ref. 10].

As an illustration Table 2 shows required thicknesses to prevent perforation from various often specified wind-borne rigid projectiles calculated using empirical equations discussed above for steel and concrete tank walls not subject to hydrostatic product load:

Note that the required calculated thicknesses may vary depending on the shape of the projectile impacting area and angle of impact. Impact by large projectile (automobile, small airplane, etc.) will require special analysis taking into account both tank response and projectile stiffness.

Concrete walls subject to hydrostatic product load during normal operation shall be also checked for projectile penetration. The purpose is to ensure that the projectile, while not completely perforating the wall, does not damage prestressing system, which is the main load carrying component. For example, NFPA 59A [Ref. 11] requires that a membrane tank outer concrete container wall, which is subjected to hydrostatic load during normal operation, be designed for any one tendon completely ineffective if the penetration depth exceeds the distance to the tendon from the tank outside surface.

Concrete scabbing is breakage of concrete on the side of the concrete wall opposite to the side being impacted. [Ref 11] requires that scabbing be checked for tanks without an internal steel liner to ensure that any non-metallic vapor barriers and wall insulation are not getting damaged at impact.

SUMMARY

External hazards are important components of the risk assessment. External hazards often are not given the attention that they deserve.

There is a common misconception that concrete tanks are always required to resist external hazards. However, analyses indicate that properly designed steel tank can successfully resist significant external explosions and impacts from many typically specified wind-borne projectiles. Steel tanks can also resist a significant short duration fire without mitigation. However, they may require heat mitigation measures when exposure time to fire is significant. Therefore, steel tanks can provide safe and economical solution for RLG storage even if significant external hazards are identified by the risk assessment.

Concrete tanks can handle significant thermal radiation without mitigation and may provide higher resistance to external explosions and projectile perforation than steel tanks. However, not all concrete tanks perform equally well under all hazards. The resistance provided by concrete tank to external hazards is very much dependent on whether the tank is subject to high loads during normal operation. When functioning only as a secondary container, concrete tanks can resist significant external loads without compromising overall containment. However, when the concrete wall service as the main load resisting component, much more attention is required as a reduction of the prestressing system capacity may result in the loss of product containment. Prestress and load carrying capabilities must be maintained for all expected external hazards. Such tanks may not be suitable for sites where the risk assessment identifies high level external hazards unless additional mitigation measures are provided.

For more information:
This article was written by Alex Cooperman, McDermott International's storage business, CB&I Storage Solutions. Cooperman will be speaking in more detail about this subject at the Cryogenic Storage Tanks Conference in Munich on 22-23rd October.

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01 Figure 1: Tank Deformed Shape at Various Transient Analysis Time Steps (deformations exaggerated 100 times for visualisation purposes)