Hazard and safety probes for LNG tanks

Josef Rötzer, Hamish Douglas, Helmut MaurerDywidag International, Munich

The behaviour of liquefied natural gas storage tanks under blast wave conditions and the results of dynamic load factor analysis

The investigation of containments for the storage of liquefied natural gas has to be extended to their behaviour under blast wave conditions, dependent on the risk prevailing on the site.

As in the case of earthquakes (See *LNG journal* July/August 2005), the investigation of the blast load case must consider the complete tank structure.

The impact load case is usually a local load. The available formulae have been developed on the basis of a large number of national investigational and experimental programmes, mostly in connection with national nuclear programmes.

There are two types of explosion: that caused by the detonation of, for example explosives and that caused by the ignition of a gas cloud or bursting of a pressure vessel or pipeline.

The former is referred to as detonation, the latter a deflagration. The propagation speed and the pressure of the deflagration wave are lower than that of a detonation. For the design of LNG/LPG plants, the blast waves to be considered are normally those resulting from gas-cloud explosions.

Description of shape

The intensity and development of a blast wave (overpressure-time-relationship) generated in a gas cloud explosion is a function of the volume of the cloud, the reactivity of the gas-air mixture, the degree of confinement of the cloud and the intensity of the source of ignition.

Depending on the above parameters a pressure wave will be formed propagating from the source of ignition.

During a short time immediately after the travelling pressure or blast wave encountered the front of an object, the wave will be reflected causing a peak reflected overpressure. At the rear side of the structure, the blast pressure is less than the travelling peak overpressure.

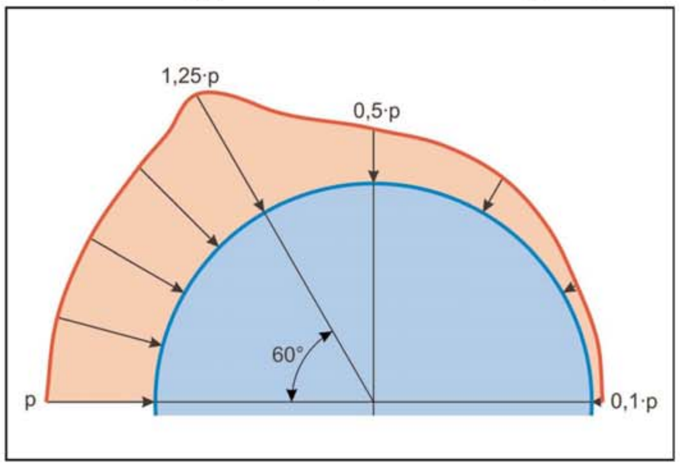

Figure 1: Shape of a blast loading [1]

For spherical or cylindrical structures, the resulting overpressure-time relationship for the structure is a triangular shape.

The accompanying pressure distribution on the structure depends on the angle between the wave front and the surface of the object. Figure 1 shows a typical pressure distribution on a cylindrical wall [1].

Dynamic enhancement

The quotient of impulse duration td and the natural vibration duration T determines the impulsive loading behaviour.

The Dynamic Load Factor (DLF) characterizes the dynamic behaviour of the system. It shows the response of a single-degree-of-freedom-system (SDF) to the exciting pulse.

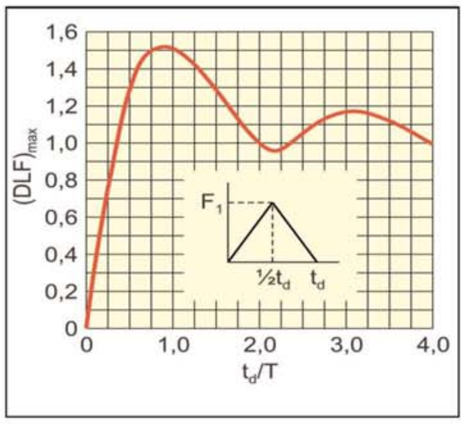

Figure 2: Dynamic Load Factor DLF for triangular loads [2]

In the range of td/T values less than 0.3, it leads to a reduction of the equivalent static load. In the range of td/T values higher than 0.3, it leads to an enhancement of the equivalent static load, with a maximum enhancement factor of approximately 1.70.

Effect on structure

For the determination of the displacements and stresses of the structure under blast loadings, a variety of approaches can be applied, ranging from the simple linear single-degree-of-freedom-system to advanced non-linear finite element models.

With the well-known dynamic load factor method, the maximum forces and displacements in a containment exposed to quasi-static-loading can be analysed using the classical shell theory.

In the FIP note /3/ is reported that for an actual project the maximum of the axial and tangential membrane forces of a shell structure calculated by such a simplified calculation method deviate no more than 12 percent from the values obtained with a full dynamic FE-analysis; and the maximum radial fix-end bending moments was 25 percent higher under the quasi-static-load.

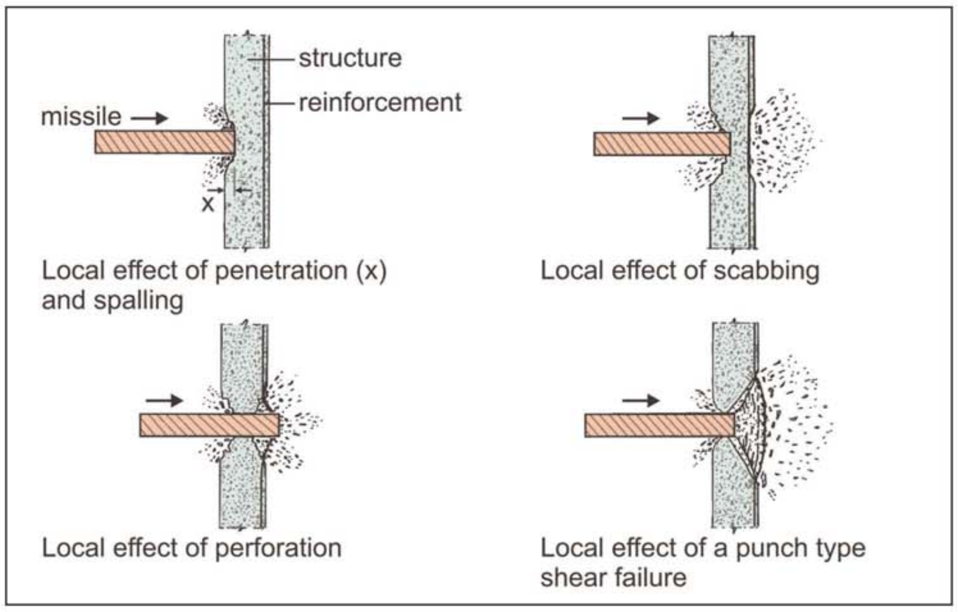

Figure 3: General local failure mechanism under Impact

In conclusion, the dynamic load factor method provides reasonable results and the use of a full dynamic analysis is not essential for the investigation of a cylindrical structure under blast loading.

Impact on concrete structures

GENERAL FAILURE MECHANISM: The scenario impact examines the load-

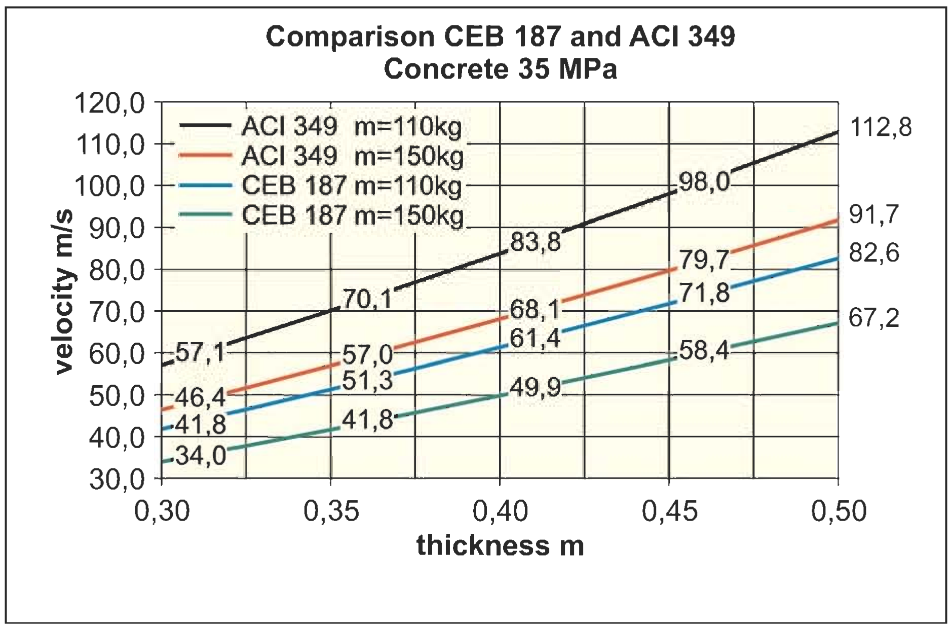

Figure 4: Resulting critical projectile speed for a concrete strength of 35 MPa

structure-behaviour under the effect of a flying object, e.g. a valve, at a collision with the outer tank concrete structure. Impact loads are in principal local loads, whereas the blast wave impinges on and affects the complete structure.

When a structure is subjected to an impact, in general, two different phenomena are of interest.

i) local damage, which includes spalling, penetration, perforation, scabbing and punching shear
ii) global response of the structure and reactive forces including bending and shear

The deformation mechanism of the impacting projectile can be characterized as hard or soft impact.

At soft impact, the projectile undergoes a large deformation. The kinetic energy is absorbed by plastic deformation of the projectile. A calculation with decoupling of load and structure is possible.

In a first step, the impact force-time-relation is derived. In a second step, the result can be taken as action force and applied to every structure or system.

Hard impact denotes the situation where the flying body has no deformation capacity and the total kinetic energy must be absorbed by the target. A separate calculation of the impact load is not possible as the response of the structure influences the loading.

AVAILABLE EMPIRICAL FORMULAE: Bangash [4] gives a comprehensive overview of the formulae applicable for impact on concrete and steel for non-deformable (hard impact) and deformable missiles (soft impact).

The data covers a 40-year period, starting with the empirical investigations of the Army Corps of Engineers (ACE) in 1946 and the National Defence Research Committee (NDCR) which led to the Petry formula in 1982 and others.

Barr [5] gives recommendations for hard missiles impacting on flat reinforced concrete targets, concrete slabs with steel plates and for a multitude of other scenarios.

The characteristic feature of Barr is that the validity of the formulae is defined for a range of values for each relevant parameter and for the different stages penetration, scabbing, cracking and spalling.

The work is based on extensive studies carried out by the United Kingdom Atomic Energy Authority UKAEA, the Central Electricity Generating Board CEGB, and by the National Nuclear Corp. NNC, as well as on work carried out by the French CEA and EdF, by GRS in Germany, and by a variety of laboratories in the US.

PREFERRED EMPIRICAL FORMULAE:

CEB 187 formula:

On the basis of more than 200 impact experiments using hard missiles the CEA-EDF formula of French Atomic Energy (CEA) and Electricité de France was developed further.

The resulting formula of Barr [5] describes the velocity corresponding to the missile kinetic energy required just to perforate the target. This formula was also used in the CEB 187, Concrete Structures under Impact and Impulsive Loading [6] for consistency.

$V_c = 1.3\ r^{1/6}\ fcy^{1/2}\ [pe2/pm]^{2/3}\ (r+0.3)^{1/2}$ [1]

The input variables in this formula are:

V_c [m/s] = critical projectile speed
r [kg/m^3]= concrete density
f_{cy} [Pa] = characteristic compressive strength of concrete measured at cylinders
p [m] = projectile perimeter
e [m] = concrete thickness
m [kg] = projectile mass
r [%] = reinforcement quantity

The range of variables in the experiments is also the boundaries for application.

$45 < Vc < 300$ [m/s]
velocity of the projectile
$15 < fcy < 37$ [MPa]
concrete strength
$0 < r < 0.75$ [%]
ewef reinforcement, each way each face
$0.2 < p/p/e < 3$ [m/s]
specific perimeter
$150 < m/p2/e < 1000$ [kg/m^3] specific mass of missile

ACI 349 formula

The ACI 376 [7] is currently under preparation and the formula proposed there is still under discussion. The formula in ACI 376 is taken from ACI 349, Code Requirements for Nuclear Safety Related Concrete Structures [8] and probably will be modified. In ACI 349 no limits for the applicability are given.

$v2 = 1.89\ fc\ w1/3\ [dh2/M]4/3$ [2]

The input variables in this formula are:

v [m/s] = critical projectile speed
d [m] = projectile diameter
M [kg] = projectile mass
w [kg/m3]= concrete density
fc [Pa] = characteristic compressive strength of concrete measured at cylinders
h [m] = concrete thickness

EVALUATION OF THE FORMULAE

BS 7777, part 1 [9] defines an impacting valve with 50kg mass, travelling at 45m/s. Most specifications for LNG tanks require a mass of 110kg and a missile diameter of 4" (0.104 m).

Masses of 110kg and 150kg are taken as input values for calculations to compare the results of the CEB 187 formula (equation 1) with the values of the ACI 349 formula (equation 2). The resulting graphs are shown in Figure 4. CEB 187 requires a 20 percent to 25 percent enhanced thickness in comparison with ACI 349.

Conclusion

The dynamic load factor method provides reasonable results and the use of a full dynamic analysis is not an obligation for the investigation of a cylindrical structure under blast loading.

Consideration of two formulae currently in use for missile impact shows that for common masses and velocities, the load case flying valve impact does not govern the thickness of the dome structure.

Often the conditions of the case stability of the total system during erection and operation or fire determine the thickness of the roof. ■

Notes:

[1] STUVO-Rapport 70. Betonconstructies Voor de Opslag van Tot Vloeistof Gekoelde Gassen (Cryogene opslag). 1983

/2/ Biggs. J.M.: Introduction to Structural Dynamics. New-York: McGraw-Hill Book Company, 1964.

/3/ Breugel. K. van.: FIP notes 1992/3: Structures and protective systems for prevention and containment of industrial catastrophes: design principles and examples (Part 1).

/4/ Bangash. M.Y.H.: Impact and Explosion. Blackwell Scientific Publications. Oxford 1993.

/5/ Barr. P.: Guidelines for the Design and Assessment of Concrete Structures subjected to Impact - 1987 Edition. SRD R 439. United Kingdom Atomic Energy Authority. Safety and Reliability Directorate.

/6/ CEB Committee Euro-International de Beton. Bulletin d`Information No 187. Concrete Structures under Impact and impulsive Loading. Synthesis Report. 1988.

/7/ ACI 376: Draft 2005. Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases (RLG). November 2005.

/8/ ACI 349: 1988. Code Requirements for Nuclear Safety Related Concrete Structures. 2001.

/9/ BS 7777: Flat-bottomed. vertical. cylindrical storage tanks for low temperature services: Part 1: Guide to the general provisions applying for design. construction. installation and operation. BSI Standards. 1993.