Simplified Criteria for the Application of Blast Loads from Accidental Explosions in Plant Design

Sabatino Ditali[a,*], Fulvio Ragno[a], Roberto Fiore[a], Jumriani[b]

[a] Saipem SpA, v.le A. De Gasperi, 16 - 20097 San Donato Milanese (Milan), Italy
[b] PT Saipem Indonesia, Alamanda Tower, Jl. T.B. Simatupang Kav. 23-24, Jakarta, Indonesia
sabatino.ditali@saipem.com

The criteria for the application of accidental design loads - in relation to the required performance to each system of a process plant - need to be established during the design activities. This includes the consideration of blast loads on critical items required for safety, emergency and evacuation purposes, and any equipment whose failure can cause escalation, which shall be designed to resist to accidental explosions.

Based on the typical characteristics of the pressure wave (magnitude, duration, and shape), the force acting on the item of interest needs to be determined for the structural design of supporting structures, process equipment and piping, both in onshore and offshore facilities.

This paper aims to present a guideline, with a set of simplified relations, that can be used for the calculation of the force acting on components subject to accidental explosions, depending on the type of blast loading, and the shape, size and response of the affected object.

The characteristics of the blast load can be calculated with a variable degree of accuracy using explosion models of different sophistication, like CFD (Computational Fluid Dynamic) software.

A key issue in the design activities is establishing a link between the results that such models may provide and the information actually needed by the structural engineer to consistently design a system capable of resisting to the anticipated explosion scenarios.

This is a typical multi-disciplinary field, that challenges the CFD expert, the safety specialist, and the structural engineer to share their experiences, and speak the same language.

1. Introduction

In the petrochemical industry, different types of explosions events – such as Vapour Clouds Explosions (VCE), Pressure Vessels Burst, Condensate Phase Explosion, and Dust Explosions – may determine accidental blast loads on structures and equipment. In each instance, there is a rapid release of energy which is converted into a pressure wave, propagating in the medium in all directions from the source of the explosion.

Particularly relevant to the gas and oil industry are the explosions deriving from the ignition of flammable gas clouds (VCE). A vast amount of experimental evidence lead to identify three main factors governing the intensity of such explosions: congestion (due to process equipment, piping etc.), confinement (due to decks, walls, etc.), and fuel reactivity. These factors influence the fluid-dynamics and thermo-chemistry of the combustion reaction, resulting in a different amplitude and shape of the generated pressure wave. Typical VCE in process plants develop as a deflagration (i.e. a subsonic flame propagation). Highly destructive events like detonations are more unlikely, except in particular conditions of congestion/confinement (e.g. explosions in ducts), or substance reactivity (e.g. ethylene).

2. General Overview

2.1 Peak Side–On Overpressure

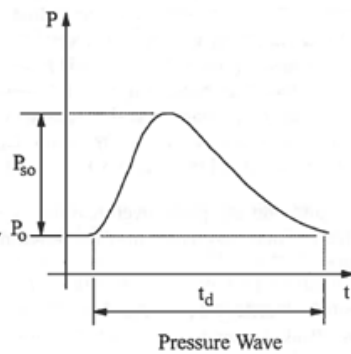Figure 1 shows the typical shape and features of a pressure wave generated by a deflagration.

Figure 1: Deflagration Pressure Wave

The peak side-on overpressure (P_{so}) is the maximum pressure increase above the atmospheric pressure (P_0); the term "side-on" refers to an undisturbed condition of propagation of the blast wave, also called "free-field" overpressure. These overpressures, P_{so} and P_0, are usually expressed in [psi] or [Pa] (with its multiples, kPa and bar, in the following text) depending on the case.

The time (t_d), during which the pressure is greater than the pressure of the surrounding ambient (atmospheric) pressure, is called positive phase duration of incident blast wave and is usually expressed in [s] or [ms]. The subsequent negative phase of the wave, where the pressure falls below the atmospheric, could be important for the design of some items (e.g. explosion-proof doors), but does not significantly affect the response of the structural components.

The impulse (I_0) of the blast (graphically represented by the area below the curve) is defined as:

$$I_0 = \int_0^{t_d} P(t)\, dt \tag{1}$$

and is expressed in units of overpressure and time, such as [psi-ms] or [Pa-s].

The wave profile is often simplified for design purposes into a triangular shape; therefore the impulse equation becomes:

$$I_0 = \frac{1}{2}(P_{SO} \cdot t_d) \quad \text{or} \quad t_d = (2\,I_0)/P_{SO} \tag{2}$$

Positive phase duration (t_d) of deflagrations is typically between 50 ÷ 200 ms. If no detailed results on the time duration are available, and in absence of specific justification, a value of 150 ms is often chosen as representative; however a screening related to the natural frequency of the structure loaded is recommended.

2.2 Peak Reflected Pressure

An object invested by a pressure wave actually experiences a maximum pressure which, due to the reflection phenomena, is greater than the peak side-on overpressure. This is called the reflected pressure (P_r), and can be expressed as:

$$P_r = C_r \cdot P_{SO} \tag{3}$$

The reflection coefficient (C_r), dimensionless, is a function of free-field pressure (P_{so}) and angle of incidence (α) of the wave front relative to the reflecting surface (maximum reflection ratio at 0 degree, i.e. incidence direction normal to the surface). In the low overpressure range (< 1.4 barg), the maximum reflection coefficient is approximately equal to 2 (according to UFC 3-340-02).

2.3 Dynamic Pressure

As the blast waves propagates through the atmosphere, associated air particle movement produces a dynamic pressure $P_{dyn} = (\frac{1}{2} \cdot \rho \cdot u^2)$ which results in a drag load of the same nature of a wind load. This is expressed in [Pa], with particle velocity *(u)* in [m/s] and air density (ρ) in [kg/m^3]. Figure 2 (from UFC 3-340-02), shows the graphical relation between dynamic pressure and incident (side-on) pressure, in U.S. customary units. As a rule-of-thumb, P_{dyn} can be assumed $\frac{1}{3}$ of the side-on overpressure P_{so}. This provides a conservative estimate up to an overpressure of approximately 2 bar (DNV-RP-D101, 2008).

In the low overpressure range (< 1.4 barg), the peak dynamic pressure P_{dyn} [kPa] can also be estimated using the following equation (Newmark, 1956):

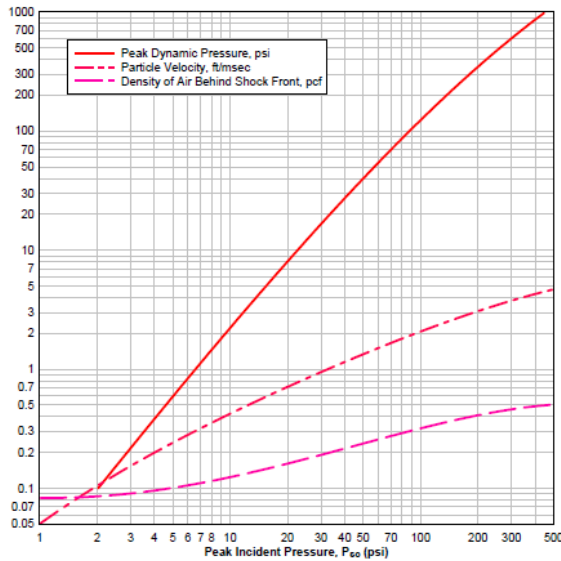$$P_{dyn} \cong 0.0032 \cdot P_{SO}^2 \tag{4}$$

Figure 2: Peak Incident Pressure and Dynamic Pressure parameters

3. Blast Loading

The total force acting on a body hit by a blast wave is the results of several contributions, deriving from the complex interaction of the object with the pressure wave and the motion of the medium particles.

However, the two terms that have the greatest importance in structural design activities are (Olav et al., 2016):

- The static pressure, expressed as **differential pressure** across the object
- The dynamic pressure, expressed as **form drag** past the object

The relative importance of these two terms varies depending on the size and shape of the object. In general, differential pressure is the prevailing factor for the blast design of large structures (e.g. buildings and vessels), while form drag is predominant in determining the force on small objects like pipework, columns, free spanning members, braces, etc..

The following paragraphs provide a guideline to select the most significant parameters for the blast resistant design of typical plant items, and simplified equations for their calculation.

3.1 Small Objects

The design of plant items with a characteristic size smaller than a limit value that is in the range 0.3 ÷ 1 m (FABIG TN-08), is driven by form drag (blast wind). The overpressure applied to the opposite sides of these objects is approximately the same magnitude at any time step, so no net overpressure load is applied to the object, therefore the "small diameter/dimension" objects can be usually designed using the form drag only:

$$F_{bl,small\_obj} = C_D \cdot A \cdot P_{dyn} \tag{5}$$

where (P_{dyn}) is the dynamic pressure introduced in clause 2.3, C_D [-] is the drag coefficient, and (A) is the surface area of the object. Form drag force can be calculated for the defined targets in the CFD explosion studies. Alternatively, it can be estimated using the simplified formulation illustrated in the following section 5.

3.2 Large Objects

The differential pressure becomes the predominant contribution to the blast force acting on objects of characteristic size greater than 2 - 3 m:

$$F_{bl,large\_obj} = F_{DP(max)} \tag{6}$$

CFD analysis may calculate, through the application of the Direct Load Measurement (DLM) method, the differential loads between opposite sides of a large object, along different directions of application of the blast. The accuracy of the DLM method depends on the relative size of the control volumes of the CFD calculation grid with respect to the obstacle size.

An example of this detailed procedure, with reference to the horizontal vessel shown in Figure 3, will consist of the following steps:

1. Locate an adequate array of "sensor points" over the vessel;
2. Record the pressure traces for each sensor;
3. At each time step, average the traces for each side of the vessel to have a single trace for each side;
4. Subtract the averaged (time dependent) traces on opposing sides of the vessel to have a single differential pressure for each direction and time;
5. The maximum among the differential pressures evaluated at the preceding step, is taken as the design pressure difference load;
6. Calculate the net force by multiplying the pressure difference by the relevant obstacle projected area.
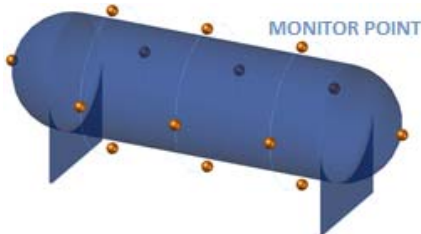

Figure 3 - Monitor points on a (large) pressure vessel

If CFD results are not available, it is possible to apply a simplified method to calculate the pressure difference over large objects, starting from the free-field overpressure (P_{so}) and the positive phase duration (t_d) of the pulse, as illustrated in the following.

Figure 4 shows the profiles (approximated by an isosceles triangular shape) of the reflected pressure acting on the opposite faces of an object of characteristic size D. The symbols have the following meaning:

P_r = maximum reflected pressure on the front-side

P_{SO} = maximum pressure on the rear-side

t_d = positive phase duration of the pressure wave

$\Delta t = D/u_s$ = time required for pressure wave passing across an object of diameter (D) with shock velocity (u_s)

Differential pressure P_{DP} can be calculated, at each time-step, using the equations below (valid for $\Delta t \leq t_d/2$):

$$P_{DP} = \begin{cases} P_r \cdot \left(\dfrac{t}{t_d/2}\right) - P_{SO} \cdot \left(\dfrac{t-\Delta t}{t_d/2}\right) & t \leq t_d/2 \\[3mm] P_r \cdot \left(\dfrac{t_d-t}{t_d/2}\right) - P_{SO} \cdot \left(\dfrac{t-\Delta t}{t_d/2}\right) & t > t_d/2 \end{cases} \tag{7}$$
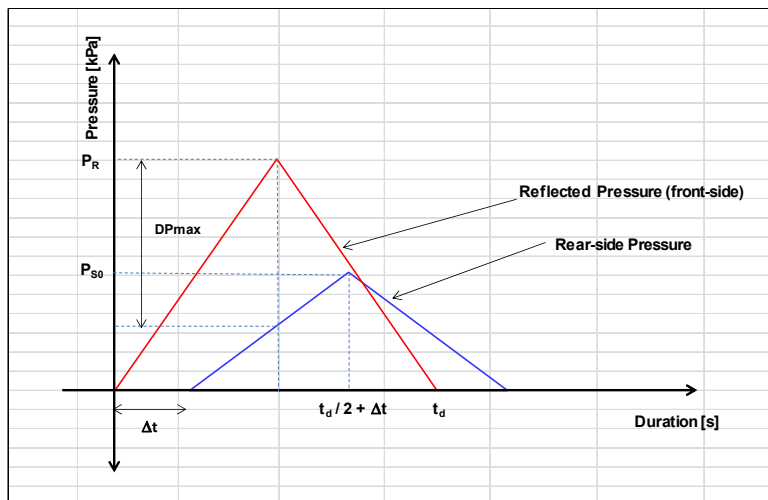

Figure 4 - Estimation of Differential Pressure (P_{DP}) across a Target

When using this approximate method the pressure pulse in the front side of the object will be reflected, while the pressure pulse on the back side will be just attenuated by the distance. In the case the pressure wave hits a non-flat surface, a pressure distribution over the surface shall be applied because the reflection coefficient (C_r) is not uniform; this is typical for circular shapes (i.e. pipes) for which the pressure distribution is sinusoidal and the load can be reduced by a factor of $2/\pi$ (= 0.637).

3.3 Intermediate size Objects

For objects in the intermediate size range (1 ÷ 2 m), both the form drag pressure and the differential pressure contribute to the total force acting on a body.
The following expression can be used to calculate the blast force F [kN]:

$$F_{load}(D) = F_{form,1m} + \left[F_{DP,2m} - F_{form,1m}\right] \cdot \frac{D-1}{2-1}$$ (8)

where:
- $F_{form,1m}$ is the form drag for 1 m size diameter;
- $F_{DP,2m}$ is the maximum differential force for 2 m object size diameter

4. Dynamic Amplification Factor

The Dynamic Amplification Factor (DAF) or Dynamic Load Factor (DLF) is the ratio of the dynamic deflection at any time to the deflection which would have resulted from the static application of the load. The use of the DAF concept in structural analysis allows to estimate stress values or reaction forces for dynamic blast case simply performing a static analysis. The DAF reflects the increase of response to the dynamic load with respect to an equivalent static load, and depends on the duration of the explosion loading (t_d) in relation to the natural period (T_n) of the structure. The ratio (t_d/T_n) determines if the loading can be treated as impulsive (t_d/T_n < 0.4), dynamic ($0.4 \leq t_d/T_n \approx 2$), or quasi-static ($t_d/T_n$ > 2). On this aspect see also other works (Salzano et al., 2012). Figure 5 shows the maximum dynamic load factor (DAF), dimensionless, as a function of the ratio t_d/T_n for three typical load pulses. For deflagrations (approximated by isosceles triangular shape of the pressure pulse in the Figure 5) the maximum DAF of 1.5 is frequently used in practice.
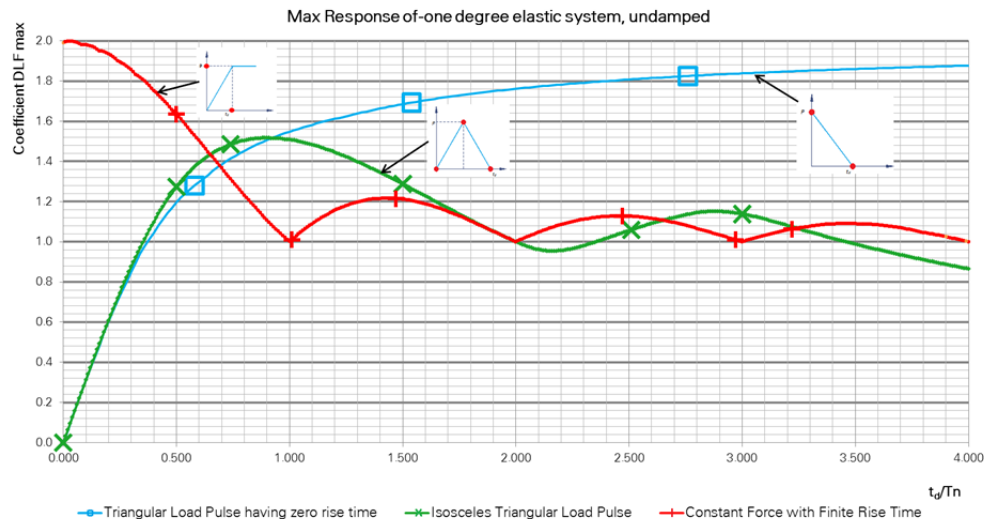

Figure 5: Dynamic Amplification Factors (DAF) for Typical Blast Load Pulses

5. Simplified Formulas for Blast Load

This section, drawing on the material presented in the previous paragraphs, summarizes the simplified relations that can be applied in the blast design of circular/cylindrical shape objects (piping, equipment and structural elements). For other shape - like steel/concrete structures having squared/rectangular or "I" sections - the width is the characteristic dimension and the appropriate C_D shall be used. Drag coefficients (C_D) are recommended in FABIG TN-08 and conservatively are respectively equal to 1.2 for pipes and 2 for box shape. The following relations present, for objects of different diameter, the force F_{blast} [kN] applied per unit of length.

5.1 Small diameter objects (D ≤ 1m)

$$F_{blast} = \left(P_{dyn} \cdot D \cdot DAF \cdot C_D\right)$$ (9)

with:
- $P_{dyn} \approx \frac{1}{3} P_{SO}$, if no detailed calculations, as per clause 2.3 (and expressed in [kPa])
- $DAF = 1.5$, if no detailed calculation, as per clause 4, Figure 5
- $C_D = 1.2$, for circular cylinder shape (i.e. pipe)

5.2 Intermediate diameter objects (1m < D < 2m)

$$F_{blast} = \{(P_{dyn,1m} \cdot C_D) + [P_{DIFF,2m} - (P_{dyn,1m} \cdot C_D)] \cdot [(D-1)/(2-1)]\} \cdot D \cdot DAF \tag{10}$$

with all the parameters defined as per section 3.3, pressures in [kPa] and same C_D, DAF as per section 5.1.

5.3 Large diameter objects (D ≥ 2m)

$$F_{blast} = P_{DIFF,max} \cdot D \cdot DAF \tag{11}$$

Where $P_{DIFF,max}$ can be calculated according to Eq. (7) at the time t = t_d/2:

$$P_{DIFF,max} = \{(C_F \cdot P_r) - P_{SO}\} \cdot [1 - (\Delta t/(t_d/2))] \tag{12}$$

with: - C_F = 2/π = 0.637, shape coefficient for circular shape
- P_R = $C_R P_{SO}$, reflected pressure [kPa]
- C_R = 2.03, reflection coefficient
- t_d = 0.15 s, positive phase duration, and Δt calculated with u_s = 340 m/s (in absence of detailed data)
- DAF = 1.5, if no detailed calculation, as per clause 4, Figure 5

5.4 Example of Application

The application of above Eq. (9), (10) and (11) for various object diameters is summarizes in Table 1 for a side-on free field overpressure of 200 mbar (20 kPa) and with:

- P_{dyn} = 1.28 kPa (applying Eq. [4]);
- u_s = 372 m/s;
- C_r = 2; C_f = 0.637; C_D = 1.2;
- DAF = 1.5;
- t_d = 150 ms

Table 1: Blast Load (kN/m) for side-on overpressure of 200 mbar (20 kPa)

Diameter (m)	P_{dyn} (kPa)	F_{blast} (D ≤ 1m)	F_{blast} (1m<D<2m)	F_{blast} (D≥2m)
0.1	1.28	**0.23**	NA	NA
0.5	1.28	**1.15**	NA	NA
1.0	1.28	**2.30**	NA	NA
1.25	1.28	NA	**5.40**	NA
1.50	1.28	NA	**9.50**	NA
1.80	1.28	NA	**15.76**	NA
2	1.28	NA	NA	**20.74**
3	1.28	NA	NA	**34.34**
4	1.28	NA	NA	**50.08**

6. Conclusions

The estimation of explosion loading onto pipes, equipment and structures represents a task that is often performed in the early phase of the a project, when the results from CFD simulations are not available and low guidance exits on how to perform it without excessive conservativism. This paper presents a simple approach that merges all the types of acting loads (drag, differential) in single, even if approximate, relations that could be applied with judgement starting from the defined blast design (overpressure) values and performance required. These allow to provide a preliminary design and relevant cost-estimate. Given the complexity of the phenomena involved and the multidisciplinary task, the preliminary design will be verified later with more sophisticated methods (CFD and structural) in relation to the criticality of the component under consideration.

References

DNV-RP-D101, 2008, Structural Analysis of Piping Systems, Det Norske Veritas, October 2008.

FABIG TN-8, 2005, Protection of piping systems subject to Fire and Explosion, The SCI, United Kingdom.

Newmark N. M., 1956, An engineering Approach to Blast Resistant Design, University of Illinois, Urbana, USA.

Olav R. Hansen, Malte T. Kjellander, Jan A. Pappas, 2016, Explosion loading on equipment from CFD simulations, Journal of Loss Prevention in the Process Industries, 44, 601-613.

Salzano E., Cozzani V., Kolbe M., 2012, The interaction of accidental explosions with industrial equipment containing hazardous substances, Chemical Engineering Transactions, Vol. 26, 150-164.

UFC 3-340-02, 2008, Structures to Resist the Effects of Accidental Explosions, DoD, USA, 5 December 2008.