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The Interaction of accidental Explosions with Industrial Equipment containing hazardous Substances

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Domino effects are likely in the case of industrial explosions. This paper describes some results for typical equipment containing hazardous materials loaded by pressure waves produced by different explosion sources.

1. Introduction

An explosion may be defined as the rapid release of energy in the atmosphere, with the consequent generation of a destructive pressure wave. Whatever the physical or chemical reason for the origin of the destructive phenomenon, any pressure wave generated by the explosion may be characterised by the maximum pressure observed on a pressure-time plot at any location within the physical domain, defined as peak pressure (or peak overpressure if relative to the atmospheric pressure, P_k), by the impulse (I_{exp}), i.e. the area under the pressure-time curve, by a total duration t_{exp}, and by the drag force (P_d), which represents the pressure correlated to the explosion wind.

Ruling out detonation of condensed-phase explosives and nuclear explosion, drag forces may be usually considered as negligible for accidental explosions. Furthermore, positive phase values of pressure history are often only considered, thus disregarding the decay and the rarefaction phases of the pressure waves.

When project engineers are dealing with large-scale industrial explosions, e.g. in early-design phase, a triangular shape (either rectangular or isoscele) is typically considered. Hence, peak overpressure and total duration are the only needed parameters for the analysis of the interaction of explosion with any target as buildings, blast walls or even industrial equipment, whatever the level of complexity of the analysis. However, accidental explosions are typically dynamic in nature and very complex pictures are typically observed. Furthermore, other complex phenomena as the reflection of pressure wave either on the ground or on the loaded equipment, flow separation, effects due to the geometry and the relative position of the loaded equipment and pressure wave may affect the level of the observed structural damage. Besides, geometric characteristics of the target equipment, design pressure, and natural period of the structure greatly affect the damage experienced by the equipment, too.

As a conclusion, the effect of accidental explosion on complex equipment is hardly predictable by a deterministic approach, and even the assessment of the resistance of a simple, flat blast wall to an idealized triangular blast wave is a matter of debate (Czujko, 2001; Louca and Boh, 2004).

This paper gives some insights for typical equipment containing hazardous materials loaded by pressure waves produced by different explosion sources, aiming at giving simplified tool for the

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analysis of domino effects (or knock-on effects), i.e. for the analysis of the escalation of a primary explosion in a large-scale complex industrial system.

2. The interaction of pressure waves with industrial equipment

The Single Degree of Freedom Method (SDOF) is widely used in the process industry for predicting structural response of object (equipment, buildings, structures) to blast loads. It is a simple approach which idealizes the actual structure into a spring mass model and is very useful in routine design procedures in order to obtain accurate results for relatively simple structures subjected to limited ductility. A more refined alternative is the Multi-Degree of Freedom (MDOF) system, which may have a large number of modal periods. Details can be found in classical textbook as Biggs (1964). In the last years computational codes based on Finite Element Analysis (FEA) as LS-DYNA (2003), a commercial version of the public domain U.S. Department of Energy code DYNA3D (Whirley and Englemann, 1993), are commonly used for detailed structural analyses.

When risk assessment or domino effect analyses are concern, the cost of detailed structural analysis may be however too high and strong simplification is needed. To this aim, Pressure-Impulse (P-I) diagrams (or Iso-damage plot), based on SDOF idealisation, are generally produced for any defined damage or failure defined in terms of maximum displacement (Baker et al., 1983). Typical applications of P–I diagrams are however based on empirical results and related to houses, small office buildings, light-framed industrial buildings, or human response to pressure waves (Schneider, 1998). Furthermore, these plots are difficult to find in the literature for knock-on effects, which include the analysis of the loss of containment rather than the purely mechanical structural damage of equipment (Cozzani and Salzano, 2004).

In any case, P-I diagrams (and MDOF) generally based on the response of a structure to pressure loads as characterized by the load ratio between the duration of pressure load τ_d and the fundamental natural period T of the structure.

The fundamental natural period of a structure is the longest natural period at which the member will respond to any load, either seismic wave or explosion or any other impulse. As the overpressure interaction with any object is usually represented as a uniform load, this is the predominant mode of response in most explosion situations. Depending on the value of the load ratio, three response regimes (or realms) are typically defined, denoted respectively as impulsive, dynamic and quasi-static (or static). Conventionally, the range for fully dynamic response is defined as e.g. in the IGN guideline (Bowerman et al., 1992):

$$\begin{aligned} \frac{\tau_d}{T} &< 0.4 && \textit{Impulsive} \\ 0.4 \le \frac{\tau_d}{T} &\approx 2.0 && \textit{Dynamic} \\ \frac{\tau_d}{T} &> 2.0 && \textit{Quasi Static} \end{aligned} \tag{1}$$

Actually, this classification is too sharp. A more recent classification was given by Czujko (2001), who proposed the following sketch for the loading regime:

$$\begin{aligned} \frac{\tau_d}{T} &<< 1.0 && \textit{Impulsive} \\ \frac{\tau_d}{T} &\approx 1.0 && \textit{Dynamic} \\ \frac{\tau_d}{T} &\ge 2.0 && \textit{Quasi Static} \\ \frac{\tau_d}{T} &> 5.0 && \textit{Static} \end{aligned} \tag{2}$$

Similarly, NORSOK (2000) has considered different dynamic boundaries, reducing the corresponding values given by IGNs (Bowerman et al., 1992) as it follows:

$$\begin{aligned}
&\frac{\tau_d}{T} < 0.3 && \textit{Impulsive} \\
0.3 \le &\frac{\tau_d}{T} \le 3.0 && \textit{Dynamic} \\
3.0 < &\frac{\tau_d}{T} \le 6.0 && \textit{Quasi Static} \\
&\frac{\tau_d}{T} > 6.0 && \textit{Static}
\end{aligned} \qquad (3)$$

The four regimes here cited reflect the behaviour of any object when experiencing an external load as a pressure wave.

In general, when static or quasi-static regimes are of concern, the interaction is only dependant on the overall static pressure exerting on the object surface. When the realm is impulsive, much higher peak loads can be tolerated than the static capacity of the target (UKOAA, 2003). This aspect is essential in risk assessment, land use planning or domino effects analysis of a large number of scenarios, where the use of structural analysis of single equipment is too heavy, the intensity and direction of the pressure waves are not well defined and the complexity of equipment does not allow simple analysis. Indeed, the evaluation of the ability of any primary explosion to trigger secondary, catastrophic scenarios (domino effects), is reliable and conservative if using only the minimum static (side-on) overpressure parameter in the pressure-impulse diagram (on this aspect, see also Schneider, 1997; Whitney et al., 1992) . On the other side, this concept does not apply comfortably to design phase, where the conservative options may too expensive.

Finally, for intermediate regimes as the dynamic realm, no simplified analyses are possible. A typical approximation regards the use of the Dynamic Amplification Factor (DAF), which is defined as the ratio of maximum dynamic displacement over static displacement. The DAF transforms a dynamic peak load into a static load with the same effect on the structure. For long explosion times and in case of an idealized triangle-shaped shock wave load, the value of DAF approaches its boundary limit of 2, which means that the same damage is produced by a corresponding half the value of static pressure.

3. Results and discussion

Let consider some typical industrial equipment which may be the target of explosion wave in the view of domino effects, as e.g. horizontal and a vertical atmospheric (low pressure) storage tanks of different volume, containing fuel oil (either empty or half full), and pressurized horizontal cylinder containing propane gas only (Table 1). For these equipment, explosion loading realm can be characterized by the results obtained by Finite Element Analysis (FEA) model of equipment. In the following, an explicit-based, large deformation, dynamic FEA code LS-DYNA (2003) is used for the study. LS-DYNA is a commercial version of the public domain U.S. Department of Energy code DYNA3D (Whirley and Englemann, 1993). The explicit formulation is ideally suited for analyzing the dynamic response of structures subjected to impulsive loading. It has a robust suite of constitutive material models and contact surface algorithms. The strain rate effects follow recommendations in TM 5-855-1 (1998). The finite element is deleted from the calculation at that point in time after reaching its specified rupture criterion (i.e., ultimate effective plastic strain).

The geometrical model was discretised by using a variable-size mesh ranging from about 1 cm to 3 cm. A single shell element represents the wall and roof of the equipments. Due to the expected high-pressure loading that led to high strain rates and the possibility of plastic deformations, an isotropic, piecewise linear, elastic-plastic with failure material model (MAT 24, LS-DYNA) was used for the steel components. The steel material has an elastic modulus of 199,948 MPa, Poisson's ratio of 0.30, unit weight of 7850 kg/m^3 and a nominal rupture strain of 0.29.

For the equipment and fill level reported in Table 1, Table 2 reports the natural period for ten vibrational modes, as calculated by LS-Dyna.

Table 1. Sketch of industrial equipment analysed. V = vertical; H = horizontal.

N	Equipment	Fill	Vol (m^3)	Radius (m)	Wall thickness (m)	Roof thickness (m)
1	Atmospheric V	Empty	250	6.6	0.005	0.005
2	Pressurised H	Gas filled	100	2.8	0.018	0.018
3	Atmospheric V	Empty	30,000	44	0.021 - 0.006	0.006
4	Atmospheric V	Half	30,000	44	0.021 - 0.006	0.006

Table 2. Natural period (ms) for ten vibrational modes, for equipment reported in Table 1.

N	1 (T)	2	3	4	5	6	7	8	9	10
1	82.37	82.37	82.25	82.19	76.17	76.13	74.22	74.22	67.23	67.23
2	530.70	121.96	87.80	83.65	68.17	53.92	47.09	40.06	38.91	35.22
3	492.51	453.64	342.71	341.85	335.82	314.85	302.46	277.52	269.81	263.16
4	711.69	492.10	469.15	453.14	427.50	391.05	387.19	373.32	369.81	349.65

The data for equipment 3 and 4 are greater than the data produced by Liu and Schubert (2004), which give an average natural period of about 150 ms for either horizontal or vertical natural mode shapes, whereas smaller tanks are comparable.

Now, let consider triangular blast waves with total duration of: a) 200 ms, thus reproducing long-duration vapour cloud explosion; b) 100 ms, i.e. a shorter VCE; c) 10 ms, i.e. a short-duration explosion which is characteristic of BLEVE explosion, confined, partially confined and small scale explosion; c) 1 ms, that representing strong solid and other point-source explosions.

For these durations, Table 3 reports the ratio of explosion duration over response time in order to identify the realm.

Table 3. Time ratios τ_d/T for first vibrational mode for the equipment reported in Table 1, by varying explosion duration.

N	Equipment/Modes	t_d = 200 ms	t_d = 100 ms	t_d = 10 ms	t_d = 1 ms
1	Atmospheric (empty) V	2.43	0.38	0.41	0.28
2	Pressurised (filled) H	1.21	0.19	0.20	0.14
3	Atmospheric (empty) V	0.12	0.02	0.02	0.01
4	Atmospheric (filled) V	0.01	0.00	0.00	0.00

Results reported in Table 3 show clearly that empty large scale atmospheric vessels have very low values for the time ratios with respect to partially or fully filled equipment, which indeed are the only of our interest if domino effects are of concern (Salzano and Cozzani, 2005). However, the differences are relatively negligible if the large uncertainties in accidental explosion are taken into account. Hence, data for empty vessel, which are more common, may be used for reference.

Both empty and non-empty vessels are characterised by dynamic or impulsive realms unless very long-duration explosion as VCEs are considered, for which static realm can be seen If following the scheme of Czujko (2001). Either the quasi-static or the static regime are never reached if following NORSOK definition. Impulsive regime characterise very short-duration explosions, whatever the equipment or fill level or the scale of equipment.

If considering the assumption given above, these data clarify that static pressure alone is always suitable for the definition of domino effects criteria but however conservatively.

Regarding the atmospheric tanks, the work done worldwide for seismic analysis can be applied, as the liquid content can add further load on the tank structure. To this aim, the work of Malhotra et al. (2000) defines two other natural period related to the impulsive (T_{imp}) and convective (T_{conv}) responses of tank due to liquid movement (sloshing, overturning, due to liquid), as it follows:

$$T_{imp} = C_i H \left(\frac{\rho r}{hE} \right)^{0.5} \tag{4}$$

$$T_{conv} = C_c r^{0.5} \tag{5}$$

where C_i (a-dimensional) and C_c (with dimension of m $s^{0.5}$) are constants which depend on the ratio of height H over the radius r of the liquid level, H is the total tank height, ρ is the density of liquid, E is modulus of elasticity of the material, and h is the average thickness of shell. For steel materials, the values of C_i and C_c as reported by the authors. The two effects (impulsive and convective) may produce damage to tanks. For a steel tank with radius r of 10 m and total height of 9.6 m, filled with water to a height H of 8 m (H/r = 0.8), the calculated values are T_{imp} = 0.123 s and T_{conv} = 4.96 s. If considering both effects conjunctly, the interaction may be considered essentially static or quasi-static unless very short duration explosions are considered.

The work of Leal and Santiago (2004), can be usefully adopted for sphere by varying filling level. For a 14.5 m diameter sphere, natural periods of 2.90 s and 4.44 s were respectively calculated fpr filling level of 25 % and 75 %, thus demonstrating that impulsive realm applies for any type of explosion.

The work of Roy and Antaki (2001) may be of help for pipelines, even if they refer to detonation. Their results have been adopted for the compilation of the Table 4, which again reports the time ratios for several tubes and pipelines of different diameter and materials. Same conclusions as in the equipment analysed in previous Tables can be seen. Unless very short impulsive explosions, the realm is static or quasi static for VCE only and dynamic for the most of accidental explosions.

Table 4. Time ratios τ_d/T for tubes of different diameter and materials, for the fundamental vibrational mode, by varying explosion duration.

Equipment	Diameter	τ_d/T			
Tube		t_d = 200 ms	t_d = 100 ms	t_d = 10 ms	t_d = 1 ms
Threaded Pipe	3/8"	2.032	1.016	0.102	0.010
Threaded Pipe	1"	7.418	3.709	0.371	0.037
Conduit	2"	13.894	6.947	0.695	0.069
Conduit	3/4"	4.706	2.353	0.235	0.024
PVC	1"	5.842	2.921	0.292	0.029
PVC	3/4"	1.652	0.826	0.083	0.008

Finally, typical values for the natural period for some element or equipment which may be of interest in the framework of industrial systems (e.g. as barriers for the escalation) are also reported in the following Table for the sake of completeness.

Table 5. Time ratios τ_d/T for some typical industrial element and equipment (Fabig, 1999).

Equipment	Natural period (ms)	τ_d/T			
		τ_d =200 ms	τ_d =100 ms	τ_d =10 ms	τ_d =1 ms
Concrete walls	> 10	20	10	1	0.1
Brick wall	> 20	10	5	0.5	0.05
Blast wall	35 (unstiffened)	5.75	2.85	0.28	0.03
Blast wall	31 (stiffened)	6.45	3.23	0.32	0.03

Also in this case, the value of fundamental natural period allows the prediction on the realm, which is impulsive for short-duration explosion, and dynamic if the total duration of pressure loading is higher than 100 ms.

4. Conclusions

The conclusions of this analysis is that the impulsive realms, which may be evaluated with good approximation by one-degree of freedom methodologies (e.g. the value of incident static pressure), may be adopted for very short duration explosion (<< 10 ms), however conservatively, on the safe side.

Pressurised equipment (cylinder, spheres) are under impulsive regime even for longer duration (up to 100 ms). When duration of explosions is larger than 100 ms, pipelines, blast wall, brick walls and the effect of liquid movement for large scale equipment (sloshing, overturning) may be evaluated under the static or quasi-static realms. For explosion duration between 1 ms and 100 ms the analysis should be addressed under dynamic realm for all equipment, for which higher value of static pressure should be considered, under conservative assumption, for the same damage level.

This work is preliminary in the sense that all structural elements, as e.g. saddle for pressurised equipment, should be considered for a proper domino effects analysis.

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