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A fuzzy set analysis to estimate loss intensity following blast wave interaction with process equipment

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Abstract

Blast waves are able to produce structural damage to process equipment even at great distances from the source point of an explosion. A loss of containment may follow and, if hazardous substances are released, relevant secondary scenarios may be triggered, resulting in domino effects.

The present study was focused on the assessment of the expected structural damage and of the associated intensity of loss of containment of process vessels loaded by blast waves. Hence, a knowledge-based fuzzy set analysis was used to assess the expected overall probability of occurrence of different damage states defined for several categories of process equipment items. The fuzzy approach was also used to obtain specific threshold values for the escalation sequences (domino effects), taking into account the hazard due to the expected secondary scenarios caused by the loss of containment following blast wave impact.

Keywords: Domino effects; Explosion; Threshold values; Quantitative risk analysis; Probit analysis; Fuzzy set analysis

1. Introduction

Blast waves are able to produce structural damages to process equipment even at great distance from the source point of the explosion (Lees, 1996). Loss of containment (LOC) may follow the structural damage, possibly triggering relevant secondary scenarios (domino effects).

Although several studies were dedicated to the detailed analysis of blast wave damage to process equipment, only few simplified models are available for the assessment of equipment damage by blast waves in the framework of quantitative risk analysis and, in particular, of domino effect (Bagster & Pitblado, 1991; Eisenberg, Lynch, & Breeding, 1975; Khan & Abbasi, 2001). Previous studies carried out by the current authors were dedicated to the definition of simplified models and of threshold values for structural damage following blast wave interaction with process equipment (Cozzani & Salzano, 2004a; Cozzani & Salzano, 2004b; Cozzani & Salzano, 2004c). In particular, a probabilistic model for structural damage was developed for several categories of process equipment, relating the damage probability to incident (or side-on) static overpressure. However, these studies were not specifically addressed to the estimation of damage extension and of the associated LOC intensity that may follow blast wave impact.

Nevertheless, an assessment of the LOC intensity from the damaged item is of fundamental importance to evaluate the possibility and the relevance of escalation sequences that may lead to domino accidental scenarios. As a matter of fact, the severity of the secondary event is mainly influenced by the LOC intensity. Thus, the credibility of an escalation leading to a domino accident is highly dependent on the LOC intensity following structural damage. In spite of this, to the author's knowledge, no engineering correlation is given to estimate the LOC intensity after the damage caused by a blast wave.

The present study, was focused on the assessment of the expected LOC intensity caused by blast wave impact.

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The starting point of the analysis were the models for damage probability derived from blast wave data analysis for different equipment categories (Cozzani & Salzano, 2004a). A knowledge-based fuzzy set analysis of damage data for the available process equipment blast wave was undertaken in order to relate the intensity of the blast wave impacting on the target equipment—in terms of peak incident (side-on) overpressure—to the probability of occurrence of limit states defining either the structural (mechanical) damage level or the LOC intensity level. The original fuzzy methodology proposed by Hong and Lee (1996) was used to build an expert system, in order to evaluated the expected frequencies of secondary accidental events due to different LOC intensities and to obtain threshold values for escalation sequences leading to domino accidents.

2. Structural damage caused by blast waves

When blast waves impact on equipment items, structural damages and loss of containment are possible. The effects of an explosion on nearby equipment are dependent on a number of different factors influencing the interaction, such as the explosion type and energy, but also on geometrical factors as the directionality of the blast wave and the congestion of the area. Details on blast wave propagation, its characterization and idealization in the far field can be found elsewhere (Baker, Cox, Westine, Kulesz, & Strehlow, 1983).

In the analysis of escalation phenomena, the LOC caused by a primary explosion is usually of concern when it takes place at a significant distance from the origin of the primary event, i.e. in the far-field. This allows us to limit the present analysis to the few explosive phenomena which are able to produce long-distance destructive blast waves, as solid explosives (point-source explosions), gas or vapour cloud explosions, some types of mechanical explosions and BLEVEs. These different categories of explosions may result in blast waves characterized by different shape, time duration and maximum peak pressure. It must be remarked that several uncertainties may affect the characterization of the explosion source, due to the difficulties in the description of accidental events: e.g. gas dispersion to form a flammable cloud is often influenced by the wind and by the atmospheric turbulence, thus requiring in general the introduction of worst case options in the analysis. In this framework, it is well known that the typical duration of explosive phenomena ranges from very few milliseconds in the case of solid explosives to hundreds of milliseconds or even more in the case of low Mach number deflagrations (unconfined vapour cloud explosion). With respect to the interaction of the blast wave with the process equipment items, there is not a detailed understanding of the effect of the loads experienced by complex structures in the wide range of transient blast waves. As a conclusion, even the assessment of structural damage caused by an over-simplified worst case analysis of the explosion source requires a complex and time consuming deterministic structural analysis, usually carried out by analytical methods or by the use of expensive and time consuming finite element codes. In the context of quantitative risk analysis (QRA), the use of such tools is unfeasible due to the excessive resources required, unless very specific problems need to be addressed, as for instance blast wall design on offshore structures. Therefore, in the more general framework of QRA, engineering correlations based on empirical observations are needed, in particular to address the analysis of possible escalation phenomena following the blast wave. To this aim, an extended review of blast wave damage data on target vessels (atmospheric, pressurized, elongated and auxiliary equipment) was performed in a previous study (Cozzani & Salzano, 2004a).

All available historical and analytical damage data for these classes of equipment are reported in the literature in terms of peak ‘side-on’ pressure, which corresponds to the maximum incident static overpressure. This simplification may be accepted if risk analysis rather than design objectives are pursued. Indeed, the use of incident static peak pressure as the only parameter to characterize the blast wave effect is acceptable only in the quasi-static regime (i.e. when the total duration of the dynamic load due to the blast wave is higher than natural period of the equipment), or, with some conservative approximation, in the impulsive and dynamic regime. On the other hand, it must be remarked that the use of pressure-impulse diagram for damage estimation is inhibited by the almost complete lack of data for large-scale process equipment, even if a qualitative criterion is available: a longer duration of the loading impulse leads to an increase in the energy transferred, and to a lower overpressure required to produce damage to process equipment (Schneider, 1997).

Therefore, in the mainframe of the development of simplified approaches to the quantitative assessment of damage probability, models based on probit functions for structural damage due to peak overpressure were obtained for the four equipment categories cited previously (Cozzani & Salzano, 2004a). These models assume a linear dependence of the probit value, Pr, with respect to the natural logarithm of the dose. As discussed above, due to the available damage data, the dose was defined as the peak static overpressure ΔP° expressed in Pa:

$$\mathrm{Pr} = a + b\ln\left(\Delta P^{\circ}\right) \quad (1)$$

where a and b are the model coefficients, summarized in Table 1. The probit value, Pr, is correlated to the probability of occurrence of the event (the damage of equipment) by an integral function (Finney, 1971). Fig. 1 shows the values of damage probability with respect to peak static overpressure obtained from this approach. The figure points out the importance of a separate analysis of structural damage