Journal of Loss Prevention in the Process Industries 40 (2016) 17–28

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Ballistic experiments on the mechanism of protective layer against domino effect caused by projectiles

Dongliang Sun [a, *], Juncheng Jiang [b], Mingguang Zhang [b], Zhirong Wang [b]

[a] State Environmental Protection Key Laboratory of Environmental Risk Assessment and Control on Chemical Process, School of Resources and Environmental Engineering, East China University of Science and Technology, Shanghai 200237, China

[b] Jiangsu Key Laboratory of Urban and Industrial Safety, Jiangsu Key Laboratory of Hazardous Chemicals Safety and Control, College of Safety Science and Engineering, Nanjing Tech University, Nanjing 210009, Jiangsu, China

A R T I C L E I N F O

Article history:
Received 8 December 2011
Received in revised form
20 November 2015
Accepted 23 November 2015
Available online 2 December 2015

Keywords:
Ballistic experiment
Domino effect
Influential mechanism
Projectiles
Protective layer

A B S T R A C T

The mechanism of protective layer against the domino effect caused by high velocity and low mass projectiles was investigated using ballistic experiments, under various values of thickness, surface density, fabric structure, and impact velocity. The results showed that unit absorption energy generally decreased and then increased with thickness and surface density. The critical value of thickness existed, the highest absorption was demonstrated in UD composite, and the back convex reached the maximum when impact velocity reached the ballistic limitation. Stretching fracture of fiber was the major way of energy absorption. Finally, four layers were designed for the protective layer.

1. Introduction

In chemical industries, equipment explosion may generate fragments which can be projected over long distances, damaging other nearby equipment, and may cause severe consequences. This is known as the domino effect, a well-known cause of major accidents (Antonioni et al., 2009; Cozzani et al., 2006a,b; Nguyen et al., 2009). Fragment projection in explosive accidents is an important origin for the domino effect on a chemical process vessel (Pietersen, 1988). Generally speaking, when an explosion occurs, the containers are ruptured by internal pressure and fragments from the ruptured vessel propagate randomly in any direction. The fragments may then fall to the ground or collide with other equipment nearby. When a fragment impacts on a given target vessel, the impacted vessel may be penetrated or perforated, causing a secondary explosion. These subsequent explosions themselves cause fragments, and multiple events may spread throughout the facility.

Each cycle of the domino effect includes three considerations: the source, fragment trajectories, and the target:

- the source: fragment generation from the original explosion;
- fragment trajectories: fragment projection;
- the target: fragment impact on a target vessel, which may penetrate or perforate it, creating secondary incident(s).

Accidental explosion can produce fragments and debris which may fly over large distance, as discussed above. Here, it is worth noting that the characteristics of explosion phenomenon in industrial environment are completely different from the fragmentation of warhead or more in general cased explosives. Indeed, the produced fragment from accidental explosion are always within the "moderate velocity" regime i.e. in the sub ordnance range (up to approximately 500 m/s), at least in the far field, and that fragments have non-perforating shape as in military bullets. The projectiles from the fragmentation of warhead or cased explosives are always with high velocity and low mass. Besides, there is very little nonmilitary investigation into larger scale impact situations such as those that may be encountered following an explosion of a piece of machinery, i.e. thick plates struck by flat faced, non-perforating projectiles (Salzano and Basco, 2015).

For fragments from accidental explosion, significant prior research has been undertaken to investigate the three considerations above, and the dominant effects may be summarized as

* Corresponding author. East China University of Science and Technology, Mail Box 563, No. 130 Meilong Road, Xuhui District, Shanghai 200237, China.
E-mail address: dongliangsun@ecust.edu.cn (D. Sun).

http://dx.doi.org/10.1016/j.jlp.2015.11.020
0950-4230/

follows in Tables 1–3:

It is shown in Tables 1–3 that the mechanism of fragment generation from accidental explosion, projection, impact, and damage to equipment has been explored by many researchers. The dominant effects may be roughly summarized as follows (four stages):

- Probabilistic models have been developed for fragment generation, including the number of fragments, shape and size, mass, initial velocity at departure, initial (horizontal and vertical) departure angles, aerodynamic lift and drag coefficients, and the degree of filling of the source vessel).
- Trajectory equations of the fragments, probabilistic models of fragment impact, and a simplified plastic model for assessing the rupture probability with high reliability have been proposed, and the ground distributions of fragments, impact, and damage probabilities assessed. The effects of various factors were also evaluated.
- Specific probabilistic models of the number of fragments from horizontal cylindrical and spherical vessel explosions have been derived. The effects of various parameters on the ground distributions of fragments, the probability of impact onto the target, and the rupture probability of the impacted target have been explored.
- The mechanisms of the domino effect caused by fragments have been explored and various explanatory models developed.

At present, all the achievements above focus on the fragments from accidental explosion with moderate or low velocity and high mass. Actually, high velocity and low mass projectiles (e.g. from the fragmentation of warhead or more in general cased explosives) and their security issues (e.g. against domino effect) have seldom been explored. Based on the former research, the passive measure (protective layer) was considered, to analyze the reduction effects on the domino effect. Material for protective layer against the projectiles should be firstly considered to research the influential mechanism of protective layer on the domino effect caused by projectiles. The effect of projectiles on the target is mainly mechanical shock, and the projectiles penetrate the material, leading to fragmentation and destruction. Therefore, the dynamic strength and impact toughness of material should be focused on for the material of bulletproof protection layer. Based on the research ideas on bullet-proof material performance, UHMWPE (Ultra-high Molecular Weight Polyether) fiber composite was adopted to carry out the impact performance testing. UHMWPE fiber composite has become an important part of lightweight bulletproof equipment, owing to its lower density, larger fracture energy, the highest total impact energy absorption ratio in high performance fibers, larger strength and modulus compared to the metal and ceramic plate's material. UHMWPE fiber composite is the best material to make bulletproof armor, lightweight bulletproof helmet, radar shield and aerospace structural components due to the better impact toughness, the highest total impact energy absorption ratio in advanced composite. The development of the composite materials is promoted by the excellent properties of UHMWPE fiber and abundant and cheap raw material resources, which shows great application potential in the field of application of bullet impact and shock (Abrate, 1991; Cantwell and Morton, 1991; Richardson and Wisheart, 1996; Shyr and Pan, 2003). UHMWPE fiber composite is made of UHMWPE fiber and LLDPE (Linear Low Density Polyethylene) resin, and the fabric structure of UHMWPE fiber includes UD (Unidirection) cloth, plain weave fabric and thin layer of three orthogonal to the fabric.

To meet the need of preventing the domino effect, and fill the blank on the control mechanism of the domino effect caused by projectiles with high velocity and low mass at home and abroad, UHMWPE fiber composite above was chosen as the protective layer, to mold a number of samples with different values of thickness,

Table 1
Summarized flow of dominant effects of significant prior research on the source (fragment generation from accidental explosion).

Year	Author	Reference	Dominant effects of significant prior research on the source (fragment generation)
1971	Westin	(Westin, 1971)	Ruptured tank cars involved in accidents were summarized.
1980	Tulacz & Smith	(Tulacz and Smith, 1980)	Missiles generated by pressure component failure and its application to gas-cooled nuclear plant design were assessed.
1985	Holden and Reeves	(Holden and Reeves, 1985)	Random variables (fragments number, shape, mass, initial velocity at departure, and initial departure angles, etc.) were discussed.
1986, 1988	Holden	(Holden, 1986, 1988)	Random variables (fragments number, shape, mass, initial velocity at departure, and initial departure angles, etc.) were researched.
1994	CCPS	(CCPS, 1994)	Guidelines for evaluating the characteristics of vapor cloud explosions, flash fires, and BLEVEs were developed.
1996	Lees	(Lees, 1996)	Hazard identification, assessment, and control for loss prevention in process industries were derived.
1998	Baum	(Baum, 1998)	Rocket missiles generated by failure of a high pressure liquid storage vessel was investigated.
2006	Cozzani et al.	(Cozzani et al., 2006a,b)	Shape, range of drag factor and mass range of a representative set of fragment geometries defined on the basis of past accident data were obtained.
2007	Abbasi & Abbasi	(Abbasi and Abbasi, 2007)	The mechanism of the boiling liquid expanding vapor explosion (BLEVE) was explored.
2009	Mébarki et al.	(Mébarki et al., 2009a, 2009b)	Probabilistic distributions of the source terms were developed.
2009	Gubinelli & Cozzani	(Gubinelli and Cozzani, 2009a, 2009b)	The reference fragmentation patterns of the vessels were identified, and the fragment number and drag factors were assessed.
2012	Abdolhamidzadeh et al.	(Abdolhamidzadeh et al., 2012)	The roots, triggers, and other aspects of a domino accident were investigated.
2012	Sun et al.	(Sun et al., 2012)	More specific and accurate probabilistic models of the number of fragments from a horizontal cylindrical vessel explosion were developed by collecting and analyzing data from past accidents leading to fragment projection, and a more reasonable probability density function for the number of fragments from a spherical vessel explosion was proposed.