Fire Safety Journal 92 (2017) 177–187

Contents lists available at ScienceDirect

Fire Safety Journal

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

An innovative framework for determining the damage probability of equipment exposed to fire

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ARTICLE INFO

Keywords:
Domino effect
Damage probability of equipment
Heat radiation
Structural reliability method
Kolmogorov backward equation

ABSTRACT

When considering a quantitative risk assessment of domino effects in chemical process facilities, the Damage Probability of equipment exposed to Fire (DPF) is a key element. In this paper, an innovative framework is proposed to determine the DPF, and the approach is demonstrated using a vertical plate. Being different from the current Probit model, structural reliability methods are applied to a pre-established lumped temperature model to obtain the DPF. Moreover, the static and dynamic DPF are distinguished, where the static one is obtained through the first-order reliability method and response surface method with an innovation in the pre-analysis of stable state to derive the limit state equation, while the dynamic one is obtained solving the Kolmogorov backward equation using the finite difference method based on stochastic diffusion process and first passage failure theories. The vertical plate demonstration shows the feasibility and availability of the proposed framework. A more practical case study with a horizontal LPG tank is also discussed to validate the suggested approach.

1. Introduction

Domino accidents in chemical and process industries have been drawing attention for several decades, and many catastrophes strengthened their importance [1]. A lot of research and papers have been made in the field. It can be witnessed by the recent encompassing volume on this topic by Reniers and Cozzani [2]. Therein, quantitative risk assessment is a widely used technique whose key components include the damage probabilities of equipment exposed to heat radiation, blast wave overpressure and/or blast fragments [3–5]. In this paper, the damage probability of equipment exposed to heat radiation from fire (DPF) is focused upon.

Industrial fire scenarios may cause a severe heat load on various equipment and result in a bucking, cracking or rupture of containment. The mechanism might be a decreased tensile strength of the material of the shell wall, an increased internal pressure, a generated high local thermal stress, or the melting of the nonmetallic parts. These issues are usually and specifically settled via experiments [6,7] or cumbersome finite element modeling [8,9]. On the positive side, both the experiment and finite element modeling are reliable and accurate. However, they may be too heavy to integrate into a technical framework for quantitative risk assessment of domino effect.

To determine the DPF, a square of the ratio of two distances was used earlier [10]: one is the maximum distance at which the source fire could damage the target unit based on a heat radiation threshold, and the other is the spatial distance between the source and target unit. Reviewing this ratio method, the interpretation of the derived DPF is ambiguous, and the uncertainty source is unclear. In Khan and Abbasi's work [3], though the combination of build-up high pressure and material failure of pressure vessels was considered specifically, the determination of DPF still used the ratio method. Currently, the Probit model, linking the DPF with time to failure of equipment (*ttf*), is widely used [4,5]. The Probit parameters are obtained by applying a lognormal probability density function to the estimated time for an effective mitigation (*tte*). The *ttf* is calculated using a fitted relation to heat radiation intensity and equipment volume [11]. Essentially, the Probit model is a binary-class regression that the coefficients are just determined by *tte* and absolutely irrelevant to *ttf*.

In this paper, structural reliability methods are introduced [12]. The static DPF, which is independent of time, is firstly researched using the first-order reliability method (FORM) and response surface method (RSM) [13] coupling with an innovation in the pre-analysis of stable state (PASS) of the lumped temperature model (LTM) to derive the limit state equation (LSE). The dynamic DPF that depends on time is obtained by solving the Kolmogorov backward equation (KBE) using the finite

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http://dx.doi.org/10.1016/j.firesaf.2017.05.015
Received 29 September 2016; Received in revised form 17 March 2017; Accepted 22 May 2017

Acronyms

DPF	Damage probability of equipment exposed to fire
FDM	Finite difference method
FORM	First-order reliability method
FPF	First passage failure
KBE	Kolmogorov backward equation
LSE	Limit state equation
LTM	Lumped temperature model
MFPT	Mean first passage time
PASS	Pre-analysis of stable state
RSM	Response surface method
RTI	Rising time interval
SDE	Stochastic differential equation
SDP	Stochastic diffusion process
tte	Estimated time for an effective mitigation
ttf	Time to failure of equipment

difference method (FDM) based on stochastic diffusion process (SDP) and first passage failure (FPF) theories [14,15]. The static and dynamic DPF offer complementary perspectives to state the same problem. To display the landscape of the proposed framework and approach clearly, a vertical plate is used to make a demonstration. A more practical case study with a horizontal LPG tank is also discussed. Though the research is carried out within a quantitative risk assessment of domino effect in mind, inherently safer design of target equipment and layout optimization of plants or clusters could also be elaborated.

In the following, Section 2 briefly introduces some preliminary theories and methods. The framework of the approach and its demonstration using a vertical plate to guide the application and interpretation are presented in Section 3.The practical case study of a horizontal LPG tank is discussed in Section 4. Finally, some conclusions are made in Section 5.

2. Preliminary theories and methods

2.1. The Probit method and model

According to Cozzani et al.'s theory and method [4,11], the Probit model is essentially an empirical binary-class regression which is the following:

$$\Phi^{-1}(DPF) = k_1 + k_2\ln(ttf) \tag{1}$$

where $\Phi^{-1}(\cdot)$ is the inverse of standard normal cumulative distribution function, and k_1 and k_2 are regression coefficients.

The basic assumption is that the target equipment exposed to fire is absolutely safe as long as *ttf* is greater than *tte*. Thus two special values of *tte* are taken instead of *ttf* to calculate k_1 and k_2. Statistics show that an effective mitigation could start in less than 5 min only in 10% of cases, and less than 20 min in 90% cases [11]. In Eq. (1), 5 min corresponds to the inverse value of 3.71, while 20 min corresponds to the inverse value of 6.27. Then k_1 and k_2 are calculated as 9.25 and −1.85, respectively.

As for the *ttf*, it is determined by fitting two sets of numerically simulated data, and the fitting relation is as follows [4].

$$\begin{cases} \ln(ttf) = -1.13\ln I - 2.67\times 10^{-5}V + 9.9, & \text{Atmospheric} \\ \ln(ttf) = -0.95\ln I + 8.845V^{0.032}, & \text{Pressurized} \end{cases} \tag{2}$$

where I is the heat radiation intensity of fire and V is the equipment volume.

2.2. Structural reliability and first-order reliability method (FORM)

By definition, the performance of components or systems can be described using a performance function $g(\boldsymbol{X})$, where $\boldsymbol{X} = [X_1,\cdots,X_i,\cdots,X_n]^{\mathrm{T}}$ is a vector of basic random variables. $g(\boldsymbol{X})$ is usually explicitly or implicitly derived from LSE. Failure corresponds to $g(\boldsymbol{X})$ taking non-positive values. Thus the failure probability P_{f} can be calculated integrating the joint probability density function of $\boldsymbol{X}$, $f_{\boldsymbol{X}}(\boldsymbol{x})$, over the failure domain

$$P_{\mathrm{f}} = \int\limits_{g(\boldsymbol{x})\le 0} f_{\boldsymbol{X}}(\boldsymbol{x})\mathrm{d}\boldsymbol{x} \tag{3}$$

In general cases, there is no analytical solution to Eq. (3), and the integral is potentially high-dimensional. For this reason, various structural reliability methods are developed including FORM. The key idea of FORM is to approximate $g(\boldsymbol{X})$ using a first-order Taylor expansion and the expansion point, which is also called design point, is chosen on the failure or limit state surface. A detailed FORM procedure is the following [13]:

(i) Assign the initial design point $\boldsymbol{x}^*$ with the mean $\boldsymbol{\mu_X}$;

(ii) Calculate the sensitivity coefficient $\cos\theta_{X_i}$

$$\cos\theta_{\mathrm{X_i}} = -\frac{\frac{\partial g(\boldsymbol{x}^*)}{\partial \mathrm{X_i}}\sigma_{\mathrm{X_i}}}{\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}}\left[\frac{\partial g(\boldsymbol{x}^*)}{\partial \mathrm{X_i}}\right]^2\sigma_{\mathrm{X_i}}^2}} \tag{4}$$

where σ_{X_i} is the standard deviation of X_i.

(iii) Calculate the reliability index β

$$\beta = \frac{g(\boldsymbol{x}^*) + \sum_{\mathrm{i}=1}^{\mathrm{n}}\frac{\partial g(\boldsymbol{x}^*)}{\partial \mathrm{X_i}}\left(\mu_{\mathrm{X_i}} - \mathrm{x_i^*}\right)}{\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}}\left[\frac{\partial g(\boldsymbol{x}^*)}{\partial \mathrm{X_i}}\right]^2\sigma_{\mathrm{X_i}}^2}} \tag{5}$$

(iv) Calculate the new design point $\boldsymbol{x}^*$

$$\mathrm{x_i^*} = \mu_{\mathrm{X_i}} + \beta\sigma_{\mathrm{X_i}}\cos\theta_{\mathrm{X_i}} \tag{6}$$

(v) Repeat steps from (ii) to (iv) until the difference of $||\mathbf{x}||$ is less than 10^{-6};

(vi) Calculate P_{f}

$$\mathrm{P_f} = 1 - \Phi(\beta) \tag{7}$$

where $\Phi(\cdot)$ is the standard normal cumulative distribution function.

In this paper, if $\boldsymbol{X}$ is characterized with a non-normal distribution and is not mutually independent, the JC method and orthogonal transformation method are suggested [13].

2.3. Response surface method (RSM)

FORM is feasible if $g(\boldsymbol{X})$ is explicit. On the contrary, if $g(\boldsymbol{X})$ is implicit, a combination of RSM and FORM is available. The key idea of RSM is to approximate $g(\boldsymbol{X})$ using a response surface function, where a second-degree polynomial is always widely used [13].