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An assessment of reliability of a blast wall using limited statistical information on blast loading

Keywords

reliability, blast wall, explosion, blast loading, sacrificial cladding, small-size sample

Abstract

A design of a blast wall is considered. Methods of structural reliability analysis and quantitative risk assessment are applied to the design. The basic idea of this design is to apply a probability of failure of cladding components as a criterion of damage to the cladding. This probability is used as an estimate of the proportion of cladding components destroyed by an explosion. The cladding failure probability is estimated by quantifying and propagating uncertainties related to a mechanical model of cladding and elements of the statistical sample containing records of blast loading. It is demonstrated how to estimate the cladding failure probability when the size of this sample is small from the standpoint of classical statistics. The case study included in the paper considers a design of a cladding for a blast wall to be deployed for protecting a fuel tank against an explosion of a railroad tank car.

1. Introduction

A blast wall is a physical barrier separating a vulnerable object from a potential explosion which produces a blast loading capable to damage the object [13]. Blast walls are normally deployed to provide structural protection against military weapons or improvised explosive devices. However, blast walls are in principle suitable to mitigate the level of blast loading generated by accidental explosions occurring in industrial facilities and during a transportation of hazardous goods. Such blast loading is sometimes accompanied by impact of projectiles and spread thermal radiation.

Blast wall can be relatively lightweight and weak and still offer some degree of protection because a high level of deformation can absorb a significant amount of the blast wave energy. The cost of rigid, non-destructible walls is often prohibitive and a significant mitigation of blast can be achieved using relatively lightweight frangible or sacrificial walls [3], [13]. The energy of blast loading can be absorbed by lightweight systems used as sacrificial cladding (SC). They can be mounted on the front of a non-sacrificial structure to be protected or serve as a component of a blast wall [4]–[6], [16].

The present study describes how to design in a probabilistic way an SC of a blast wall deployed to protect vulnerable object against an accidental explosion. The basic idea is that a cladding failure probability may serve as a measure of explosive damage to the SC. It is shown how to estimate this probability by an approach which combines methods of structural analysis (SRA) and quantitative risk assessment (QRA). The estimation is based on a separate treatment of stochastic (aleatory) and epistemic (state-of-knowledge) uncertainties related to a mechanical model of SC. The proposed estimation procedure allows also the data on blast loading to be uncertain in the epistemic sense. The study is aimed at increasing safety of industrial facilities and parts transportation infrastructure where accidental explosions can cause major accidents.

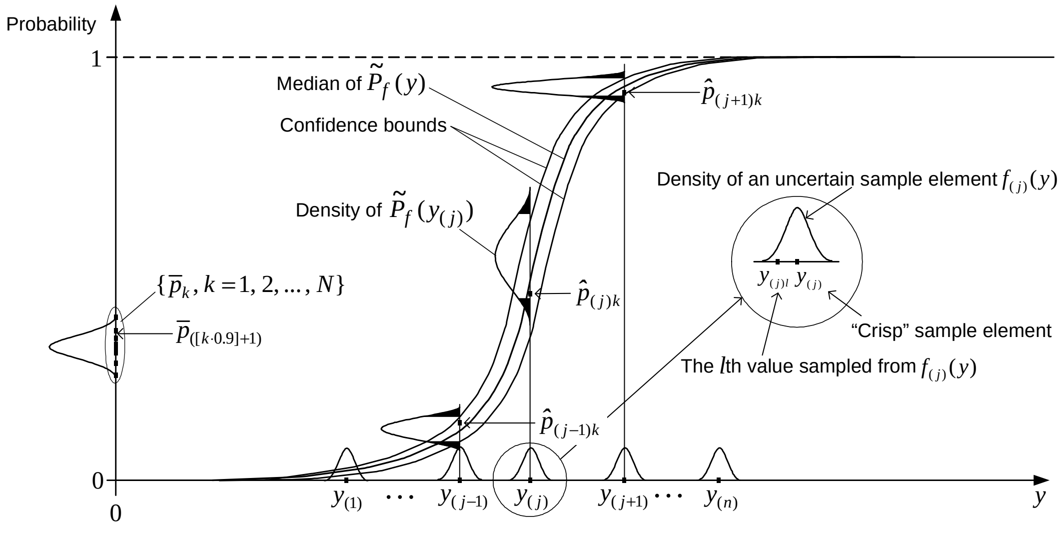

Figure 1. A schematic illustration of the epistemic uncertainty in the value of the fragility function $\tilde{P}_f(\boldsymbol{y})$

2. Failure probability of sacrificial cladding as a measure of damage degree

In the case where all individual components of SC are nominally identical or a continuous SC can be discretised notionally into nominally identical components, a different number of them will fail (will be "sacrificed") at different intensities of reflected blast wave. Characteristics of a pressure history of this wave can be represented by a n_y-dimensional vector $\boldsymbol{y}$ with the components $y_1, y_2, y_3, \ldots, y_{n_y}$ expressing overpressure, positive duration, impulse, etc. ($n_y \geq 1$). Then the relative number of the failed components and so the degree of damage to SC can be estimated by a conditional probability of failure of an individual component:

$$P_f(\boldsymbol{y}) = P(\cup_i D_i \mid \boldsymbol{y}) \qquad (1)$$

where D_i is the random event of damage to an SC component related to the failure mode i (the ith damage event, in brief). The function $P_f(\boldsymbol{y})$ is known in SRA and QRA as a fragility function and its arguments $\boldsymbol{y}$ are called the demand variables (e.g., [15]).

If the blast wave characteristics are uncertain and represented by a random vector $\boldsymbol{Y}$, the unconditional probability of SC component failure, P_f, can be expressed as a mean value of the fragility function $P_f(\cdot)$ with a random arguments $\boldsymbol{Y}$, namely,

$$P_f = \int_{\boldsymbol{y}} P_f(\boldsymbol{y})\, f_{\boldsymbol{Y}}(\boldsymbol{y})\, \mathrm{d}\,\boldsymbol{y} = E_{\boldsymbol{Y}}(P_f(\boldsymbol{Y})) \qquad (2)$$

where $f_{\boldsymbol{Y}}(\boldsymbol{y})$ is the joint probability density function of $\boldsymbol{Y}$. (2) is a standard definition of a failure probability widely used in SRA. The problem of estimating P_f for blast loading generated by an accidental explosion is that statistical data for fitting the model $f_{\boldsymbol{Y}}(\boldsymbol{y})$ will typically be unavailable. However, P_f can be estimated with a small-size sample consisting of observations $\boldsymbol{y}_j$ of $\boldsymbol{Y}$ obtained by experiment [17]. Let this sample be

$$\boldsymbol{y} = \{\boldsymbol{y}_1, \boldsymbol{y}_2, \ldots, \boldsymbol{y}_j, \ldots, \boldsymbol{y}_n\} \qquad (3)$$

Elements of $\mathbf{y}$ can be transformed into fragility function values $P_f(\boldsymbol{y}_j)$ and a new, artificial sample $\{P_f(\boldsymbol{y}_1), P_f(\boldsymbol{y}_2), \ldots, P_f(\boldsymbol{y}_j), \ldots, P_f(\boldsymbol{y}_n)\}$ formed. The latter sample can be used to compute a bootstrap confidence interval $]0, \overline{P}_f[$ for P_f. The closer is the upper limit $\overline{P}_f$ to unity, the larger number of SC components should be expected to be lost in case of an explosion. Consequently, $\overline{P}_f$ can be used as a conservative measure of the damage to a blast wall.

The interval estimate $]0, \overline{P}_f[$ comes from the classical, Fisherian statistics. If necessary, the sample $\mathbf{y}$ can be used to estimate P_f in a Bayesian format, namely, by a conservative percentile of a posterior distribution obtained by applying $\mathbf{y}$ [7], [18].

The form of the sample $\mathbf{y}$ assumes that there are no uncertainties in the data $\boldsymbol{y}_j$. This assumption may not be correct in a number of cases. For example, if the blast wave characteristics are not directly recorded in experiment but are obtained by means of a mathematical modelling, the elements of $\mathbf{y}$ can be uncertain (fuzzy). Uncertainty in an individual element of $\mathbf{y}$, say, the element j can be quantified by an epistemic probability distribution with the density $f_j(\boldsymbol{y})$ [9]. A one-dimensional visualisation of a crisp and uncertain data points $\boldsymbol{y}_j$ and $f_j(\boldsymbol{y})$ is shown in

Figure 1. The interval estimation of P_f is possible also with the uncertain, as shown in the next section.

3. Dealing with uncertainties in the mechanical model of sacrificial cladding

In the case where the damage event(s) D_i are backed by the model(s) m_i, the fragility function $P_f(\boldsymbol{y})$ can be expressed as

$$P_f(\boldsymbol{y}) = P(\bigcup_i (m_i(\boldsymbol{Z}, \boldsymbol{y} \mid \boldsymbol{\theta}) \leq 0)) \qquad (4)$$

where $\boldsymbol{Z}$ is the vector of random input variables; $\boldsymbol{\theta}$ is the vector of parameters of the model of $m_i(\cdot)$. The random safety margin $m_i(\boldsymbol{Z}, \boldsymbol{y} \mid \boldsymbol{\theta})$ is a standard function of SRA, in which the vector $\boldsymbol{Z}$ and so the function m_i express the stochastic uncertainty (e.g., [11]). The uncertainty modelling prevailing in QRA requires to consider an epistemic uncertainty related to the parameter vector $\boldsymbol{\theta}$ (e.g., [1]). This uncertainty can be expressed by a random vector $\boldsymbol{\Theta}$ with a joint density $\pi(\boldsymbol{\theta})$. One or more components of $\boldsymbol{\Theta}$ can be used to express uncertainty in the accuracy of the model $m_i(\cdot)$. One can interpret the epistemic density $\pi(\boldsymbol{\theta})$ of the as a prior distribution which can be updated, at least in theory, given a new data. Then the posterior density will have the form $\pi(\boldsymbol{\theta} \mid \text{data})$.

With the random parameter vector $\boldsymbol{\Theta}$, the fragility function $P(D_i \mid \boldsymbol{y})$ becomes an epistemic random variable defined as

$$\tilde{P}_f(\boldsymbol{y}) = P_f(\boldsymbol{y} \mid \boldsymbol{\Theta}) = P(\bigcup_i (m_i(\boldsymbol{Z}, \boldsymbol{y} \mid \boldsymbol{\Theta}) \leq 0)) \qquad (5)$$

An illustration of the random fragility function $\tilde{P}_f(\boldsymbol{y})$ is shown in *Figure 2*. This illustration assumes that the vector $\boldsymbol{y}$ has only one component, for instance, the positive overpressure of the reflected blast wave.

The typical approach to dealing with epistemic uncertainties in fragility functions is establishing confidence bounds around the point estimates of fragility curve or median fragilities (e.g., [15]). Most authors consider the confidence bounds the final result of analysis. However, a further propagation of the epistemic uncertainty quantified by $\boldsymbol{\Theta}$ is necessary to estimate the failure probability P_f. In case where the explosion demand $\boldsymbol{y}$ is represented by the small-size sample $\mathbf{y}$, the estimation of P_f can be expressed as an estimation of a mean of fragility function values with uncertain (fuzzy) data $\tilde{P}_f(\boldsymbol{y}_j)$ (j = 1, 2, … , n). Such data can be used for updating a Bayesian prior distribution expressing epistemic uncertainty in P_f [18]. However, if a development of a prior for P_f is problematic or there is no interest in the Bayesian estimation of P_f, the failure probability can be estimated by a Fisherian confidence interval computed by means of a simulation-based procedure explained in the remainder of the present section.

An estimate of P_f can be obtained by computing estimates of the fragility function values $P_f(\boldsymbol{y}_j \mid \boldsymbol{\theta}_k)$ for all n elements $\boldsymbol{y}_j$ of the sample $\mathbf{y}$ and the values $\boldsymbol{\theta}_k$ of the parameter vector $\boldsymbol{\Theta}$ generated from $\pi(\boldsymbol{\theta})$ or $\pi(\boldsymbol{\theta} \mid \text{data})$ (k = 1, 2, … , N). This will require to estimate the fragility function $n \times N$ times. The kth loop of the estimation of P_f should start from sampling the value $\boldsymbol{\theta}_k$. For each $\boldsymbol{\theta}_k$, the estimates $\hat{p}_{jk}$ of $P_f(\boldsymbol{y}_j \mid \boldsymbol{\theta}_k)$ should be computed for all elements of $\mathbf{y}$ and grouped into the sample $\hat{\boldsymbol{p}}_k = \{\hat{p}_{jk}, j = 1, 2, ..., n\}$. An illustration of three elements of $\hat{\boldsymbol{p}}_k$ is given in *Figure 2*. The sample $\hat{\boldsymbol{p}}_k$ can be used to calculate a one-sided bootstrap confidence interval $]0, \overline{p}_k[$ for P_f. A repetition of this process N times will yield a sample consisting of N upper limits of the confidence interval, namely, $\{ \overline{p}_k$, k = 1, 2, … , N }. This sample will express the epistemic uncertainty related to the upper limit of this interval (see the abscissa axis in *Figure 2*). A conservative percentile of this sample, say, $\overline{p}_{([N \cdot 0.9]+1)}$ can be used as the final result of the conservative estimation of the failure probability P_f.

In the case of the uncertain data expressed by the densities $f_j(\boldsymbol{y})$, the procedure of the estimation of P_f can be applied in a similar way, with the difference that some number N_l of the samples $\mathbf{y}_l = \{\boldsymbol{y}_{1l}, \boldsymbol{y}_{2l}, \dots, \boldsymbol{y}_{jl}, \dots, \boldsymbol{y}_{nl}\}$ will have to be sampled from the distributions $f_j(\boldsymbol{y})$ (j = 1, 2, … , n). A one-dimensional illustration of the sample element $\boldsymbol{y}_{jl}$ is given in *Figure 1*. The procedure shown in Fig. 4 should be applied to each $\mathbf{y}_l$. A repetition of this process N_l times will yield a sample of confidence interval limits, $\{ \overline{p}_k$, k = 1, 2, … , $N \times N_l\}$. A percentile of this sample, say, $\overline{p}_{([N \cdot N_l \cdot 0.9]+1)}$ may serve as a conservative estimate of P_f. Clearly, the estimates $\overline{p}_{([N \cdot N_l \cdot 0.9]+1)}$ will tend to be more conservative than $\overline{p}_{([N \cdot 0.9]+1)}$, because the variability of the limits $\overline{p}_k$ will be larger in the former case than in the latter.

4. Case study

The estimation of the SC failure probability P_f will be illustrated for a blast wall intended to protect against a railway tank car explosion known as boiling-liquid expanding vapour explosion (BLEVE). The tank car is used for a transportation of liquefied propane. Mechanical effects of BLEVE occur as blast and projectiles [19]. The present case study will consider the blast loading only whereas the protection against projectiles will be addressed in brief at the end of this section.

The object to be protected by the blast wall is a diesel fuel tank (”target”) located 63 m form external railway tracks (*Figure 2*). The worst case scenario will be considered, according to which the angle of incidence of the blast wave will be equal to 90 degrees (*Figure 3*). The fuel tank is surrounded by a protective embankment used to stabilise the blast wall. The wall is to be built from non-sacrificial posts and SC consisting of profiled steel sections (*Figure 4*).

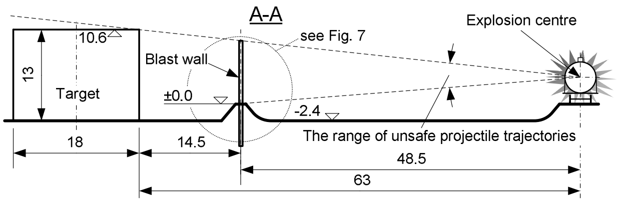

Figure 2. The elevation of the accident situation (see *Figure 3*)

The elements $\boldsymbol{y}_j = (y_{1j}, y_{2j})$ of the sample **y** will consist of overpressure y_{1j} and positive phase duration y_{2j} of the reflected blast wave, respectively. Experiments which could yield **y** are very expensive. Therefore, **y** was obtained by calculation and not by a direct recording $\boldsymbol{y}_j$. The real-world statistical sample used in this case study was compiled from 30 data pairs (x_{1j}, x_{2j}), where x_{1j} and x_{2j} is weight and pressure of liquefied propane in the tank car j, respectively (*Table 1*, Cols. 2 and 3). The pairs (x_{1j}, x_{2j}) were used to calculate the mass of trinitrotoluene (TNT) which could cause an explosion with an energy equivalent to the energy of BLEVE (*Table 1*, Col. 4) [19]. The TNT mass and the explosion stand-off equal to 48.5 m were used to calculate y_{1j} and y_{2j} by applying a standard empirical model developed for TNT [10] (*Table 1*, Cols. 5 and 6).

Two random damage events D_1 and D_2 related to the maximum dynamic response of profiled sections and backed by the respective safety margins m_1 and m_2 expressed by (6) will be considered. The fragility function $P_f(\boldsymbol{y})$ will have the form $P(D_1 \cup D_2 \mid \boldsymbol{y})$. The safety margins expressed as functions of random variables present in the mechanical model of profiled sections have the form

$$m_1(\boldsymbol{Z}, \boldsymbol{y} \mid \boldsymbol{\Theta}) = p_R(\boldsymbol{Z} \mid \boldsymbol{\Theta}) - y_1 \qquad (6a)$$

$$m_2(\boldsymbol{Z}, \boldsymbol{y} \mid \boldsymbol{\Theta}) =$$

$$= u_{pl,\max}(\mathrm{Z}, \mathrm{y} \mid \Theta) - u_{pl,dyn}(\mathrm{Z}, \mathrm{y} \mid \Theta) \qquad (6b)$$

where $\boldsymbol{Z} = (Z_1, Z_2, Z_3, Z_4)$ and $\boldsymbol{\Theta} = (\Theta_1, \Theta_2, \ldots, \Theta_5)$ are the vectors used to model aleatory and epistemic uncertainties, respectively (*Table 2*); $p_R(\cdot)$, $u_{pl,max}(\cdot)$ and $u_{pl,dyn}(\cdot)$ are deterministic functions used to compute quantities given in (6).

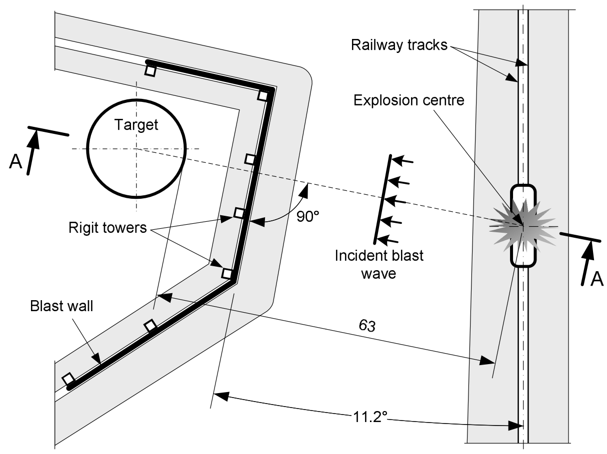

Figure 3. The plan of the potential accident site

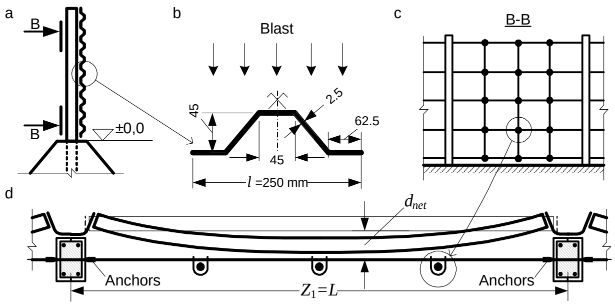

Figure 4. Details of the blast wall: (a) vertical section; (b) profiled steel section; (c) view from the back showing a safety net; (d) plan

Probability distributions of the components of $\boldsymbol{Z}$ and $\boldsymbol{\Theta}$ were chosen partly on the basis of information on natural variability of the quantities used in the analysis and partly on the basis of subjective reasoning. Cross-sectional dimensions of profiled sections are considered to be fixed (deterministic) quantities (*Figure 4b*).

Table 1. Characteristics of the reflected blast wave y_{1j} and y_{2j}

j	x_{1j}, kg	x_{2j},kPa	TNT, kg	y_{1j}, kPa	y_{2j}, ms
1	2	3	4	5	6
1	60939	2575	83.29	13.51	35.45
2	57566	2462	90.30	14.04	35.69
3	57419	2395	77.14	13.04	35.22
4	59472	2602	99.41	14.69	35.97
5	54108	2453	73.21	12.72	35.07
6	56751	2312	66.63	12.18	34.80
7	61307	2615	71.69	12.60	35.01
8	59950	2264	89.97	14.01	35.67
9	55176	2572	74.78	12.85	35.13
10	58094	2531	73.30	12.73	35.07
11	57839	2446	83.50	13.53	35.45
12	58116	2270	52.10	13.42	35.40
13	57777	2424	83.45	13.52	35.45
14	60724	2457	79.33	13.21	35.30
15	56333	2411	77.83	13.09	35.25
16	55878	2193	71.71	12.60	35.01
17	59339	1922	64.05	11.96	34.69
18	52549	2301	64.18	11.97	34.70
19	59697	2364	82.32	13.44	35.41
20	59215	2406	74.52	12.83	35.12
21	60088	2492	86.58	13.76	35.56
22	55379	2581	78.12	13.11	35.26
23	58567	2502	71.68	12.60	35.01
24	53204	2613	73.93	12.78	35.10
25	57594	2204	81.13	13.35	35.37
26	58586	2355	70.36	12.49	34.95
27	53499	2461	78.41	13.14	35.27
28	51802	2508	79.44	13.22	35.31
29	57106	2351	68.00	12.30	34.86
30	55286	2471	83.16	13.50	35.44

The probability distributions of the aleatory random variables Z_1 to Z_3 can be easily specified from information on random properties of steel structures (e.g., [14]). The natural period of elastic vibration, Z_4, is considered to be an aleatory quantity because it can be measured experimentally. We assumed the nominal value of this period, 3.4 ms, given by Louca *et al.* [12] to be a mean value of a normal distribution of Z_4. The probability distributions of the epistemic variables grouped into the vector $\boldsymbol{\Theta}$ were used to express uncertainty related to parameters of the models $p_R(\cdot)$, $u_{pl,max}(\cdot)$ and $u_{pl,dyn}(\cdot)$. These distributions quantify the doubts expressed by Louca *et al.* [12] and Juocevičius and Vaidogas [8] about quantities represented by $\boldsymbol{\Theta}$.

The functions on the right-hand side of (6) are based on a mechanical model of profiled sections proposed by Louca *et al.* [12]. The dynamic pressure capacity is given by

$$p_R(\boldsymbol{Z} \mid \boldsymbol{\Theta}) = \frac{8Z_2\Theta_1 w_{el}}{l_E^2(Z_1,\Theta_3)l}\Theta_4\Theta_5 \quad (7)$$

where $l_E(\cdot)$ is the effective span; w_{el} is the deterministic elastic section modulus depending on the cross-sectional dimensions; l is the cross-sectional width (*Figure 4b*).

The maximum plastic dynamic deflection capacity is given by

$$u_{pl,\boldsymbol{max}}(\boldsymbol{Z},\boldsymbol{y} \mid \boldsymbol{\Theta}) = \frac{5}{48}\cdot\frac{Z_2\Theta_1 l_E^2(Z_1,\Theta_3)}{0.5Z_3 h}\times$$
$$\times\frac{\Theta_4\Theta_5}{\Theta_3}\mu(Z_1,Z_2,Z_4,y_1,y_2 \mid \Theta_1,\Theta_3,\Theta_4,\Theta_5) \quad (8)$$

where $\mu(\cdot)$ is the function used to compute the ductility ratio and given by

$$\mu(\boldsymbol{Z},\boldsymbol{Y} \mid \boldsymbol{\Theta}) =$$
$$= \Theta_2\varphi\left(\frac{y_2}{Z_4},\frac{p_R(Z_1,Z_2 \mid \Theta_1,\Theta_3,\Theta_4,\Theta_5)}{p_r(y_1)}\right) \quad (9)$$

where $\varphi(\cdot,\cdot)$ is the function fitted to the graphs developed by in the book [2] and used for retrieving values of $\mu(\cdot)$.

The dynamic plastic deflection due to the blast load is computed using the following expression

$$u_{pl,dyn}(\boldsymbol{Z},\boldsymbol{y} \mid \boldsymbol{\Theta}) = \frac{p_r(y_1)l_E^4(Z_1,\Theta_1)}{384Z_3}\cdot\delta(y_2) \quad (10)$$

where $\delta(y_2)$ is the dynamic loading factor computed by

$$\delta(y_2) = \max_t\left(\begin{matrix}1-\cos(2\pi t/Z_4)+\\ +\dfrac{\sin(2\pi t/Z_4)}{2\pi y_2/Z_4}-\dfrac{t}{y_2}\end{matrix}\middle| 0 \le t \le y_2\right) \quad (11)$$

In the present case study, the ranges of the sample components y_{1j} and y_{2j} are [11.6 kPa, 14.4 kPa] and [23.0 ms, 25.8 ms], respectively.

Figure 5 shows a histogram of the sample $\{\overline{p}_k, k = 1, 2, \ldots, 500\}$ obtained by generating 500 values $\boldsymbol{\theta}_k$ and applying the procedure described above (N = 500). Exceeding the maximum dynamic plastic deflection (the event D_2) was a dominating failure mode and this failure determined the confidence limits $\overline{p}_k$. The 90th percentile of the above sample, $\overline{p}_{([N\cdot 0.9]+1)}$, is equal to 0.263. This value is a conservative estimate of the SC failure probability P_f. It means that less than 26.3% of

Table 2. Aleatory and epistemic random variables used in the analysis of the blast wall shown in *Figure 4*

Description and notation (notation used this study ≡ notation from the original text by Louca *et al.* [16])	Mean/coeff. of variation	Probability distribution
Aleatory random quantities (components of $\boldsymbol{Z}$)		
Span (spacing of posts) $Z_1 \equiv L$ (m) (see *Figure 4d*)	2.0/0.005*	Lognormal
Static yield strength of profiled section steel, $Z_2 \equiv p_y$ (MPa)	554/0.11*	Lognormal
Modulus of elasticity of profiled section steel, $Z_3 \equiv E$ (GPa)	200/0.06*	Normal
Natural period of elastic vibration of profiled sections, $Z_4 \equiv T$ (ms)	3.4/0.05	Normal
Epistemic random quantities (components of $\boldsymbol{\Theta}$)		
Enhancement factor for steel strength, $\Theta_1 \equiv \gamma$, the uncertainty in Θ_1 was modelled by the expression $1 + \Delta\times\xi^{**}$ ($\Delta = 0.12$)	1.012/0.011	Beta, $\xi \sim \mathrm{Be}(1, 9)$
The factor of uncertainty related to the model of ductility ratio μ, Θ_2	1/0.04	Normal N(1, 0.04)
Reduction factor for stiffness of profiled sheet, $\Theta_3 \equiv f_K$; the uncertainty in Θ_3 was modelled by the expression $1 - \Delta\times\xi^{***}$ ($\Delta = 0.3$); the mode of Θ_3 is equal to 0.85	0.85/0.05	Beta, $\xi \sim \mathrm{Be}(3, 6)$
Reduction factor for transverse stress effect, $\Theta_4 \equiv f_C$	0.99/0.085	Beta Be(70, 1)
Reduction factor for flattering of cross-section, $\Theta_5 \equiv f_F$; the uncertainty in Θ_5 was modelled by the expression $1 - \Delta\times\xi^{***}$ ($\Delta = 0.2$); the mode of Θ_5 is equal to 0.952	0.933/0.038 2	Beta, $\xi \sim \mathrm{Be}(2, 4)$
* Spaethe [14]; ** This linear transformation is used to obtain a Beta distribution defined on the interval]1, 1.12[which covers potential values of the strength enhancement factor [8]; *** This linear transformation is used to obtain a Beta distribution defined on the interval [Δ, 1]		

profiled sections will be destroyed ("sacrificied") in case of an explosion. This percentage can be changed as needed by redesigning SC, say, choosing a different profiled section.

A BLEVE produces high-energy projectiles generated by a rupture of tank car vessel [19]. It is highly probable that the blast wall under study will have to sustain an impact by some of them. Therefore, the height of the wall will be governed by unsafe trajectories of potential projectiles (*Figure 2*). The profiled sections will not be able to stop larger projectiles and, in our opinion, a safety net should be added behind the cladding (*Figure 4c* and *d*). The net can be designed to sustain not only primary projectiles from vessel rupture but also profiled sections which will fail under blast loading and/or projectile impact. The space between cladding and safety net, δ_{net}, should allow to reach the maximum dynamic plastic deflection of the profiled sections, $u_{pl,max}$ (*Figure 4d*). As this deflection is a random quantity, the value of δ_{net} can be chosen by reducing the probability $P(u_{pl,\boldsymbol{max}}(\boldsymbol{Z}, \boldsymbol{y} \mid \boldsymbol{\Theta}) \geq \delta_{max})$ to some small and tolerable value.

The horizontal cables of the net can span over several posts. Cable ends can be anchored in rigid towers distributed along the barrier (*Figure 3*). Additional anchors can be added where the cables cross the posts (*Figure 4d*). This will add extra stability to the posts and so the cladding. However, a detailed design of safety net, posts, and towers was beyond the scope of this case study.

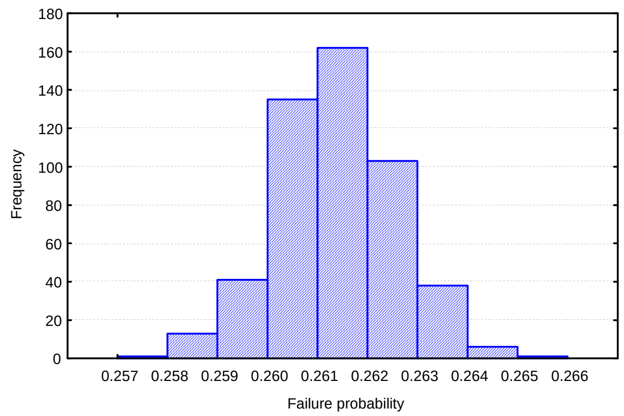

Figure 5. Histogram of the sample $\{\ \overline{p}_k,\ k = 1, 2, \ldots, 500\}$

6. Conclusions

The design of sacrificial cladding (SC) for blast walls deployed as protection against accidental explosions has been considered. Such a design may face considerable uncertainties related to potential blast loading. The behaviour of SC components subjected to blast loading may also be uncertain to a large degree. A consistent quantification and propagation of these uncertainties is possible by combining methods of structural reliability analysis and quantitative risk assessment. An application of these methods to an analysis of SC components can yield an estimate of probability of their failure under blast loading. This probability can be used as a measure of explosive damage to SC provided that the SC consists of nominally identical components. A component failure probability will be proportional to the relative number of the components which may fail (be "sacrificed") in case of an explosion.

An estimation of the SC failure probability will require to specify a probabilistic model of blast wave characteristics. Such model can be difficult to obtain as post-mortem data on accidental explosions are rarely available in the amount allowing to compile a statistical sample for fitting the model. However, the SC failure probability can be estimated without such model. A sample of blast loading characteristics recorded in experiment or estimated by explosion simulation can be directly applied to the probability estimation. The size of this sample can be small from the standpoint of the classical statistics. Such estimation can be carried out by a simulation-based propagation of stochastic and epistemic uncertainties through a fragility function developed for an SC component. The estimate will have the form of a one-sided confidence interval of the failure probability. The upper limit of this interval can be used for making decisions concerning the degree of the damage to SC which may be caused by an explosion.

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