DOMINO EFFECT ANALYSIS OF PROCESS EQUIPMENTS USING FRAGILITY CURVE

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ABSTRACT

The European legislation on the control of major accidents hazard (Directive 96/82/EC and the subsequent amendments) requires domino effect assessment. In this context the vulnerability of equipment is important for the correct identification of possible escalation. The explosion domino effect refers to a case where a primary explosion pressure wave would likely to damage equipment in its path. Determining equipment vulnerability when exposed to various explosion overpressure is the primary focus of this paper.

An analytical method is outlined for generating fragility curves for process equipment using the time domain non-linear dynamic analysis. Uncertainties in explosion loadings and equipment are quantified by varying parameters that define them. The uncertainty in each parameter is characterised by several representative values which are selected considering the uncertainty range of that parameter and its engineering implication. The explosion loading is defined by seven magnitude levels which can be linked to various return periods. The state of damage of the structure is defined by five limit states representing various degrees of damage from no damage to the total loss. This allows the statistics of the structural capacity corresponding to each limit state to be determined.

KEY WORDS: Domino effect; escalation; fragility; process equipment; vulnerability; risk; explosion.

1. INTRODUCTION

The explosion domino effect describes the potential for escalation of damage or loss that an installation would sustain as a result of failure of one process equipment due to an explosion event. In Quantitative Risk Assessment a judgement should be made whether an event would stop or escalates beyond its immediate boundaries.

Fragility analysis is emerging as an engineering tool for assessing the domino effect. A fragility curve is a conditional probability that gives the likelihood that an equipment would meet or exceed a certain level of damage for a given explosion event.

The assessment of possible escalation due to domino effect of accidents is required both in quantitative risk analysis and of safety cases; see for example cited references. However, only rather generic threshold criteria are available in the literature to carry out this assessment. A recent literature review highlighted gaps and shortcomings of the existing information (Cozzani & Salzano, 2004a; Cozzani & Salzano, 2004b). A reliable assessment of escalation probability is required for identification of on-site and off-site domino effects.

This paper presents a methodology for assessment of equipment vulnerability under explosion loading for assessment of domino effect in quantitative risk analysis. The method accounts for both probability of events and probability of loss of containment, taking into account statistical variability of material, plate thickness, dynamic parameters and so on.

Fragility curves can be derived using analytical methods or from empirical data obtained from past incidents or even from expert opinion on how much damage an equipment would sustain if subjected to a particular event. Empirical data is severely limited (Lee 1996 and Cozzani et all 2006) and expert opinions are neither reliable nor easy to form leaving analytical methods as the only viable option. Analytical methods are computationally intensive so in the past, highly simplified models and methodologies were used. This induced a great deal of uncertainty in the results limiting their practical use (see references).

The aim of the research effort leading to this paper was to develop, test, and illustrate procedures that can be used by quantitative risk assessors to assign conditional probabilities of failure to equipment as functions of explosion pressure. This paper presents an analytical method for generating explosion fragility curves for process equipment on the basis of non-linear time-domain dynamic analysis (ABAQUS 2006). Uncertainties in explosion loadings and structures are quantified using various parameters that define them. The explosion loading is defined by seven magnitude levels. The damage state of the structure is defined by five limit states representing various degrees of damage. In this study deformation and excessive plastic strains are considered as the major failure mode. A tall cylindrical tank is used to demonstrate the procedure. Although these curves are equipment specific, they can be applied to stocks of similar equipment. Since the dynamic properties of equipment change with size, plate thickness, content, and sail area, perhaps the first fundamental period can be used as a measure of similarity.

Fragility curves are emerging as a useful engineering tool for the domino effect analysis in quantitative risk assessment.

1. FRAGILITY FUNCTIONS

One key element of the assessment methodology is to estimate the damage to the equipment's load bearing system. This is done by estimating the performance of the equipment as a function of explosion intensity. The equipment's performance can be represented in either a damage probability matrix or a fragility curve. A fragility function is a conditional probability with the likelihood that an equipment will meet or exceed a specified level of damage for a given explosion pressure parameter, i.e.

$$Fragility = P[LS \mid EI = y]$$

(1)

Where LS is the limit state, EI is the explosion pressure intensity measure and y is the realisation of the chosen explosion pressure intensity measure. It can be seen that given an explosion of a specific intensity, a prediction of the damage level may be made for each equipment for which a fragility function is defined.

A fragility curve represents the probability that a given equipment's response to various loading conditions exceeds a certain performance limit state, thus, a fragility curve is a conditional probability of a structure meeting or exceeding a given level of damage for a given hazard level. As such, fragility curves are a measure of performance in probabilistic terms.

Actual equipment damage and explosion pressure data are not readily available, thus an analytical description of damage must be used. Since damage states are related to structural capacity and explosion pressure intensity parameters are related to demand on structure, the fragility can be described as the probability that the explosion demand will exceed the structural capacity. This probability of failure is represented by:

$$p_f = P[\mu_d / \mu_c \geq 1]$$

(2)

Where p_f is the probability of exceeding a specific damage-state, μ_d is the structural demand and μ_c is the structural capacity or damage state; both expressed as displacement ductility ratios in this paper.

Assuming a lognormal distribution (Melchers 1996):

$$p_f = \Phi\left[\frac{\ln(\mu_d / \mu_c)}{\sqrt{\beta_d^2 + \beta_c^2}}\right] = \Phi(Z)$$

(3)

Here μ_c is the median value of the equipment load capacity defined for the damage state, β_c is the dispersion or lognormal standard deviation of the structural capacity, μ_d is the explosion demand in terms of a chosen explosion pressure intensity parameter, β_d is the logarithmic standard deviation for the demand and $\Phi(*)$ is the standard normal distribution function.

The first step is to decide on a suite of explosion overpressures that is appropriate and representative of the installation and captures uncertainties inherent in explosion overpressure, such as the intensity and duration. This suite will span across the representative range of overpressure and contain M statistically independent samples. The next step is to determine the critical structural properties of the component (material strengths, mass and support condition). This will be done N times so to produce N statistically different component samples. The explosion overpressure samples will be paired with the component samples to generate $M \times N$ cases for which non-linear dynamic time history analysis should be performed. For each simulation, the peak displacement will be collected as the representative structural response parameter.

Figures 1 shows process equipment that the proposed method can be applied to.

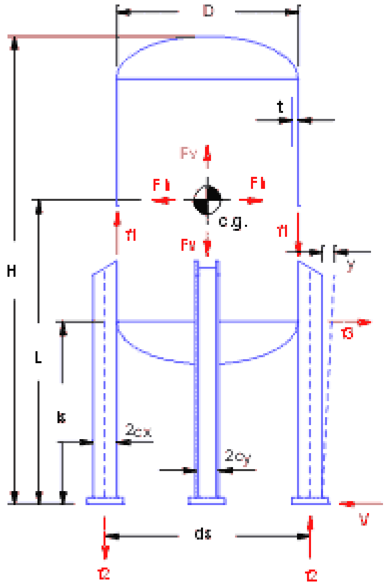

Figure 1 A typical elevated vessel

3. EXPLOSION OVERPRESSURE TIME HISTORY

Much of the difficulty in design explosion pressure specification results from its unavoidable reliance on decisions that must be made with incomplete or uncertain information, since the fabrication starts before the design is finalised. Decisions are thus inevitably subjective. Explosion hazard analysis involves the quantitative estimation of frequency of occurrence of various levels of explosion overpressure at various locations.

A suite of explosion time-histories must be employed. This suite of time-histories must be assembled from explosion studies of the installation. Computational fluid mechanics (CFD) simulations show a lot of scatter since many variables influence the duration. Figure 2 shows a plot of pressure versus duration determined using CFD software. Explosion loading should be defined in terms of variation of pressure with respect to time. Generally, assuming an isosceles triangular pulse gives a good approximation. Two parameters are needed to define the shape; these are pressure and its duration. This triangle has the same positive peak value and area equal to the positive portion of the pulse.

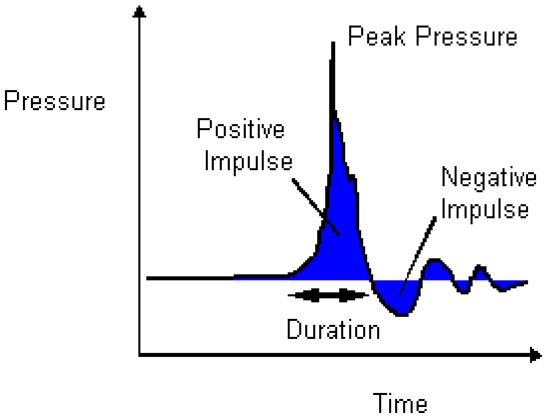

Figure 2: A typical gaseous explosion pulse

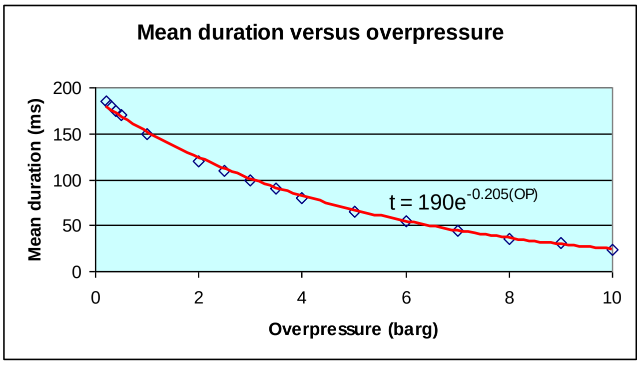

Figure 3: mean value of explosion duration

Figure 3 shows the mean value of duration of explosion loads as a function of the overpressure. This result was obtained from a collection of design explosion for a number of installations. Each design data point is an average made up from a number of CFD simulations. For this work the overpressure was used to group the data. Duration for each pressure level was then averaged and rounded and used for the regression analysis purpose. The scatter for each pressure level is generally higher for high pressure and vice versa. The average coefficient of variation across all pressure was determined to be 0.15. The explosion duration used in this work was mean plus one standard deviation

4. FAILURE MODES

Design for explosion is controlled by deformation or rupture in contrast with normal loads for which limiting the stresses is the primary aim of the design. This is due to the fact that for abnormal loading some level of deformation is allowed, provided it does not lead to collapse or loss of containment.

Deformations should be limited so that it does not lead to loss of containment or escalation. The acceptable transient and permanent deformation is obviously dependent on piping, equipment and instruments attached to the vessel. Generally excessive movement of pipework could break nozzle's connections and would cause leakage.

Rupture of any part of the vessel is not acceptable, since it would lead to major leak and hence loss of containment. The maximum equivalent plastic strains are used to judge rupture. Thus, the resulting strains associated with acceptable displacements should not cause brittle failure or ductile tearing [3]. However, rupture may occur before the allowable displacement is exceeded.

Most vessel do not have Passive Fire Protection (PFP), however, for those vessel which have PFP and if the equipment is required to be in-place after the explosion, then a lower limit of deformation or strain needs to be allowed so to prevent widespread loss of PFP. Such limits should be ascertained by test to check the de-bonding effect of large deformations and strains on a PFP material. Past experience shows that for strains up to 5%, the adhesion of the epoxy-based fire proofing material is not badly affected. For fire proofing which is wrapped around the vessel, larger deformations and strains may be acceptable.

The major mode of failure for this vessel is the lateral displacement. The displacement ductility ratio (Yasseri 2005& 2006) is used as measure of damage in this study.

5. ANALYSIS MODEL

To assess the possibility of escalation during an explosion event, it is imperative to identify explosion vulnerability of process equipment associated with various states of damage. The development of vulnerability information in the form of fragility curves is a widely practised approach when the information is to be developed accounting for the uncertain intensity involved, for example, in estimation of explosion hazard, structural characteristics, pressure-time history, and interaction with the surrounding structure. Detailed modelling has been found to contribute more to accuracy than the sampling technique (see Song and Ellingwood).

Figure 4 shows the equipment used in this study which is a typical process equipment used in the process industry. This equipment was supplied and installed as conforming to data given in Appendix, using the standard industry practice of equipment without consideration for the explosion effect.

The first step is generating a selection of representative samples. One approach is to assign a probability distribution to each of the parameters that collectively define the structure and account for uncertainties. Using a sampling technique such as Importance or Latin Hypercube sampling, these structural parameters can be sampled based on their distribution to create the required number of nominally identical but statistically different structure samples. Not all structural properties need to be treated probabilistically.

In this study the samples are generated by bounding the basic structural parameters such as material strength, equipment mass and damping. The excursion beyond the mean value is set by plus/minus one or two standard deviations. This process generates a large number of samples some of which may be statistically identical. The samples are checked so that the smallest numbers of samples are used whilst still being representative of the reality.

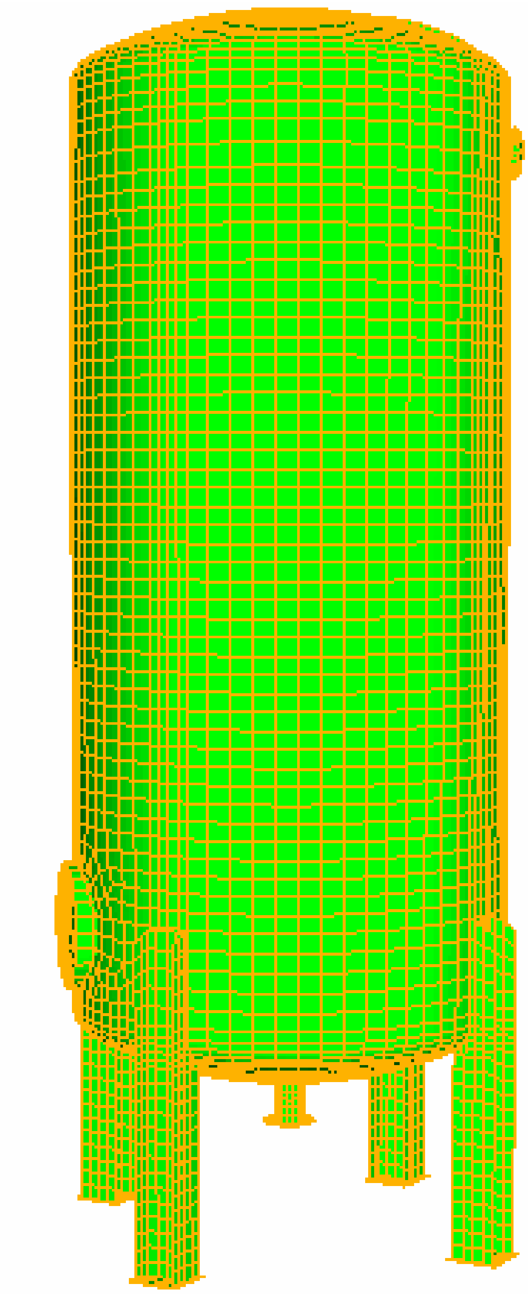

Figure 4: The finite element mesh

The following expressions can be used to determine the true values from the nominal data:

$$\sigma = \sigma_n (1+\varepsilon_n)$$
$$\varepsilon = \ln(1+\varepsilon_n)$$
, subscript n indicates the nominal value. (5)

The tensile strength of mild steels is sensitive to the loading rate. A convenient representation of the dynamic yield stress as a function of the plastic strain rate is given by Cowper and Symond relationship (ABAQUS 2006). Vales of 40.4 and 5 are used for q and D (ISSC Committee V.3 and FABIG Guidance Document, 1993). This is generally adequate for most purposes but in regions where high strain values are anticipated, the equation may no longer be valid and interpretation needs to be carried out with care (Louca, L.A. and J. W. Boh). Transient and final deflections are significantly affected by the strain rate effect. Variability of the strain rate is ignored in this study, but it can be included if desired.

6. PAIRING OF STRUCTURE AND LOAD SAMPLES

In practice four parameters have the greatest impact on the response, namely plate thickness, material strength, welding, holding down bolts, sail area and damping- (damping was included as part of the loading variation). Welding, anchorage and sail area (diameter and height) is fixed for a specific design. Table 1 shows the selected range of these parameters.

Table 1 Structure samples

Sample No.	Mass (kg)	Yield	Plate Thinness (mm)
1	19530	$R-1SD$	9
2	19530	$R-1SD$	10
3	19530	$R-1SD$	11
4	19530	R	9
5	19530	R	10
6	19530	R	11
7	19530	$R+1SD$	9
8	19530	$R+1SD$	10
9	19530	$R+1SD$	11
10	21700	$R-1SD$	9
11	21700	$R-1SD$	10
12	21700	$R-1SD$	11
13	21700	R	9
14	21700	R	10
15	21700	R	11
16	21700	$R+1SD$	9
17	21700	$R+1SD$	10
18	21700	$R+1SD$	11

A combination of the above parameters gives $3\times 3\times 2 = 18$ variations of the original model whose parameters are listed in Table 3.

The criteria used for generating different samples from the basic explosion scenarios have to do with the realistic representation of the explosion on an installation. In this study six levels of explosion were used to envelope all possible explosions on the topside of the installation in question.

At each level of explosion overpressure, the mean value of the impulse duration was determined using the equation given on Figure 6. To represent the uncertainty in the impulse time, plus and minus one standard deviation were also included. Furthermore six levels of structural damping were assumed in this study. By combining the above parameters, we obtain 3x3x2=18 loading samples which are listed in Table 2.

Table 2 Load samples

Sample No.	*OP* **kPa**	t_d **(S)**	ζ **%**
1	OP	0.85t	1
2	OP	t=190EXP(-0.205OP)	1
3	OP	1.15t	1
4	OP	0.85t	2
5	OP	t=190EXP(-0.205OP)	2
6	OP	1.15t	2
7	OP	0.85t	3
8	OP	t=190EXP(-0.205OP)	3
9	OP	1.15t	3
10	OP	0.85t	4
11	OP	t=190EXP(-0.205OP)	4
12	OP	1.15t	4
13	OP	0.85t	5
14	OP	t=190EXP(-0.205OP)	5
15	OP	1.15t	5
16	OP	0.85t	6
17	OP	t=190EXP(-0.205OP)	6
18	OP	1.15t	6

Pairing each of 18 structure samples with the 18 loading samples generates $18^2 = 324$cases at each level of explosion overpressure. From quantified risk assessment it was found that the maximum probable explosion is in the vicinity of 1.2 bar. As a result seven explosion intensities of 20 kPa, 50kPa, 80 kPa, 90 kPa, 100 kPa, 110 kPa and 120 kPa were chosen for this study. Explosion below 30 KPa would not cause much damage to this equipment as it is designed for a seismic site. The 324 structure-load combinations were solved for the explosion time history at all six pressure levels, giving a total of 324x6=1944 cases to be solved. The maximum displacement and deformation at first yield were extracted from each of these analyses.

The next step is to determine the mean ductility ratio for each structure sample for all possible loading levels, i.e.:

$$\mu_i = \sum_{j=1}^{N} \mu_{i,j} \Big/ N \qquad (7)$$

The ductility ratio approximately follows a lognormal distribution (Song and Ellingwood). To show this the mean ductility ratio are plotted on semi log paper. The N computed ductility ratios $\mu_i, \mu_2, ..., \mu_N$, were arranged in increasing order, the m^{th} value is marked on the vertical axis and corresponds to a cumulative probability of $p = m/(N+1)$marked on the horizontal axis. Then the value of standardised normal variable for each p was calculated using the normal distribution table.

The mean ductility ratio for each structure sample was calculated and noted in Table 3. These ductility ratios were ordered in terms of increasing magnitude, and the cumulative frequency of each ratio was determined, (this is equal to the cumulative probability of p). For each p the value for the corresponding standard normally distributed variable is then calculated and noted in Table 4. Samples of (Z_i, μ_i) are plotted on the logarithmic normal distribution graph as shown in Figure 3.

The straight line equation that best fits the samples can be written as

$$y = a\, e^{bx} \qquad (8)$$

Taking logarithms of both sides of this equation results in:

$$\ln y = \ln a + \mathrm{bx} \qquad (9)$$

The standard normal variable becomes:

$$s = \frac{\ln \mu_i - \lambda}{\varsigma} \text{ , or } \ln \mu_i = \lambda + \varsigma s \qquad (10)$$

Equating equations (9) and (10) gives the ordinate intercept of the straight line and its slope, i.e.

$$\lambda = \ln a \, , b = \varsigma \qquad (11)$$

Then the mean value of ductility ratio is:

$$\bar{\mu} = \mu_E = Exp\left(\lambda + 0.5\varsigma^2\right) \qquad (12)$$

The logarithmic standard deviation ς is equal to the second moment reliability index β_d

From Figure 12 it can be seen that they can be approximated by the following straight line.

$$y = 0.8564\, e^{0.5101x} \tag{13}$$

$$\lambda = \ln(0.8564) = 0.975391, \ \varsigma = b = 0.5101 \tag{14}$$

$$\mu_d = e^{\left(0.975391 + 0.5 \times 0.5101^2\right)} = 0.975391$$

$$\text{and } \beta_d = \varsigma = 0.975391 \tag{15}$$

The same process was repeated for the remaining five load levels and the results are shown in table 5 as the mean ductility demand and its dispersion.

Table 3 Mean ductility ratios

Sample No.	Ductility ratio
1	0.421
2	0.459
3	0.496
4	0.516
5	0.618
6	0.689
7	0.731
8	0.764
9	0.809
10	0.867
11	0.900
12	1.020
13	1.099
14	1.160
15	1.260
16	1.440
17	1.738
18	2.021

Table 4 Cumulative frequency, standard variable

Order	$p = m/(N+1)$	Standard normal variable (Z_i)	μ_i
0.421	0.052632	-1.619856	0.482337
0.459	0.105263	-1.252120	0.224838
0.496	0.157895	-1.003148	0.003143
0.516	0.210526	-0.804596	-0.217415
0.618	0.263158	-0.633640	-0.456274
0.689	0.315789	-0.479506	-0.735000
0.731	0.368421	-0.336038	-1.090531
0.764	0.421053	-0.199201	-1.613439
0.809	0.473684	-0.066012	-2.717922
0.867	0.526316	0.066012	-2.717922
0.900	0.578947	0.199201	-1.613439
1.020	0.631579	0.336038	-1.090531
1.099	0.684211	0.479506	-0.735000
1.160	0.736842	0.633640	-0.456274
1.260	0.789474	0.804596	-0.217415
1.440	0.842105	1.003148	0.003143
1.738	0.894737	1.252120	0.224838
2.021	0.947368	1.619856	0.482337

Table 6 defines five damage levels and their mean ductility ratios μ_c are also noted. The corresponding reliability indexes β_c are also given in Table 6.

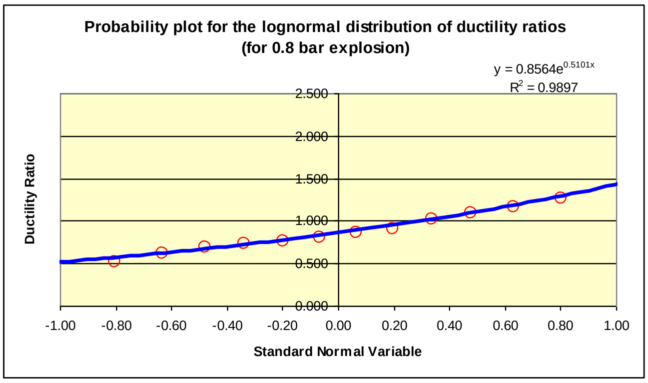

Figure 3 Probability plot of ductility ratio (Data fromTable4)

Equation (3) was then used to determine the probabilities for releasing a certain damage level as a function of the magnitude of applied load with Z_f as the standard Normal distribution defined by equation (4).

Table 7 gives the summary of all results, and Figure 4 is the plot of probability of reaching five predefined limit states for all six level explosion levels. It can be seen that at every damage level, the probability of structure sustaining the corresponding damage increases with increasing overpressure. Also, at a fixed load intensity level, the prescribed level of damage to be tolerated increases.

Table 5 Mean ductility ratio and its dispersion

Load Level (KPa)	μ_d	β_d
20	0.2000	0.4017
50	0.3500	0.4895
80	0.9754	0.5101
90	2.4937	0.5107
100	5.2517	0.5248
110	9.5000	0.5576
120	19.1604	0.6863

For instance the probability that no damage is sustained for 0.8 bar loading level is:

$$p_f = \Phi\left[\frac{\ln(1.0/0.975391)}{\sqrt{0.5101^2 + 0.5^2}}\right] = 0.4860863$$

Table 6 Mean ductility ratio and its dispersion for all damage states

Limit State (LS)	Damage description	μ_c	β_c
LS1	Negligible: Minor repairs , no disrupting	1	0.5
LS2	Light: Repairable damage, some replacement required	2	0.5
LS3	Moderate: serious disruption	4	0.5
LS4	Substantial- beyond repair	6	0.5
LS5	Near collapse	7.5	0.5

Table 7 Fragility data

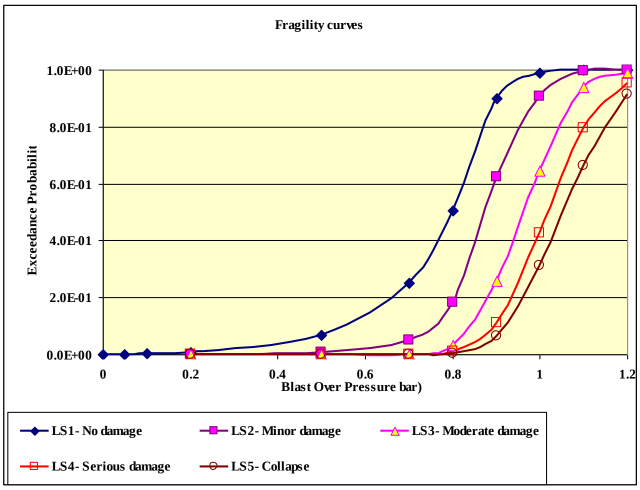

Figure 4 Fragility curves

Table 7 gives the summary of all results, and Figure 4 is the plot of probability of reaching five predefined limit states for all seven explosion levels. It can be seen that at every damage level, the probability of structure sustaining the corresponding damage increases with increasing explosion overpressure. Also, at a fixed load intensity level, the prescribed level of damage to be tolerated increases.

7. CONCLUDING REMARKS

The fragility of a structure or equipment is defined as the conditional probability of its failure for a given level of explosion. These fragility curves can be used to carry out detailed domino effect assessments of essential plant items, and structures that provide protection against explosion induced loss. The fragility curves can be used for Mitigation or elimination of domino effect in the context of ALARP concept.

This approach identifies the load carrying margin for each essential structure and plant item. These margins are reduced to a common basis by considering such factors as the degree of conservatism inherent in the analysis, whether failure of a given plant item would have major consequences for the associated safety function, and so on. The fragility curves relating the probability of plant item failure to explosion demand were estimated. These can be combined with the installation specific explosion hazard curve to give the annual explosion failure frequency for the plant item in question, utilising its adjusted explosion load carrying margin. The risk value associated with the loss of the associated safety function, and hence the value of the averted risk resulting from implementation of a given modification can be estimated. Comparison of the modification costs with the averted risk values can be used as the basis for concluding whether the plant in its current state is ALARP, recognising the limitations imposed by data availability.

Typical process equipment designed using the current industry practice was used for this work. Using non-linear dynamic analyses with ABAQUS, damage data was produced for seven explosion level, and sets of analytical fragility curves were constructed.

These curves can be used for all stock of process equipment with similar characteristics. The first fundamental period can be used as a measure of similarity.

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Table8: Vessel Dimensions and Materials

Vessel Dimensions in SI units (see Figure 1for notations)	
Height, H	4115
Centre of gravity, L	2285
Leg’s clear length, l_s	685
Shell outside diameter, D	1525
Leg pitch diameter, d_s	1525
Shell thickness, t	12.7
Leg weld size, w_s	6
Length of leg to shell weld, l_s	460
Number of legs, n	4
Leg cross Sectional Area, A	4.430 in2, W6x16 (US)
Primary Material	SA-51670 (Yield=240 MPA, UTS=490 MPA)
Allowable Stress used in the Design, S_b	140 MPA (20000 psi)
Corrosion allowance	3.125