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Research Article

A Stepwise Risk Assessment for Explosion Events considering Probability Distribution of Explosion Load Parameters

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The potential risk of explosion always exists in offshore topside facilities that deal with flammable materials. Thus, explosion risk analysis taking into account possible scenarios should be performed during the design process to reduce probability of such terrible accidents. There are several technical documents for explosion risk analysis. The analysis usually includes performance criteria, risk acceptance range, and corresponding explosion design load taking into account explosion pressure. However, this standard procedure is not sufficient to assess the potential risk of explosion, since it is usually based solely on the severity of overpressure. Therefore, more in-depth analysis is required to understand the potential risk taking explosion wave profiles into account. In the present paper, a stepwise analysis of gas explosion risk elements has been performed. Quantitative and qualitative analyses of explosion risk have been performed based on the framework of typical explosion risk analysis methods. In addition, both the probability distribution of explosion load parameters taking into account overpressure and its impulse and their correlation have been investigated extensively.

1. Introduction

As a result of increasing energy demand, the offshore oil and gas industry is using the advanced technologies to explore more remote, deeper, and harsh environments [1–6]. Thus, hazard for accidental loads and the related engineering problems are increasing and both the risk management for such an issue and technical design method for getting a resistance against the potential incidents are becoming more challenging [7]. Speaking of a floating production storage and offloading (FPSO) facility, it is a representative multi-functional structural system in the offshore industry. This type of structure does not require much external support and allows for the transformation of gaseous material into a readily transportable form using gas processing and liquefaction installation as well as a storage system. To dispose all systems on each module properly, the topside area of floating, production, storage, and offloading (FPSO) ships becomes highly congested. Moreover, a large amount of flammable gas and combustible substances is produced during operation. Such an environment not only increases the risk of explosion but also aggravates the level of damage or structural failure caused by the explosion. Thus, an explosion on the FPSO topside platform could cause serious engineering problems leading to devastating effects. Workers as well as all structural components would be exposed to risk. Moreover, oil leakage due to hull failure could also cause terrible pollution to the ocean environment and marine ecosystem. To prevent such accidents, FPSO facilities should be designed based on reasonable explosion risk assessment (ERA) of hazardous scenarios and consequences. ERAs are extremely helpful in making risk-informed decisions to reduce terrible accidents. It is carried out during the design process as part of safety studies and is performed to reduce the acceptance level for explosion hazard as much as possible and to provide the dimensioning explosion pressure for structural response of safety critical installations like the vessel, piping system, and equipment. Indeed, a technical document is usually issued based on the safety discipline so as to provide design inputs. It includes the related performance criteria and corresponding explosion design loads considering the effect of overpressure and drag pressure [8, 9]. However, this standard is not enough to establish the explosion risk criteria. More detailed qualitative analysis and specific quantitative assessment associated with explosion incident should be required. A lot of researchers and experts have analysed the gas explosion risk in several offshore facilities for mitigating or preventing gas explosion and reflecting that result to design a process as safety function [10–12]. In these studies, quantitative risk assessment based on its frequency and consequence output has been accomplished. A detailed 3D model was used for reflecting the geometrical characteristics of actual industrial facilities, and some technical method like event tree analysis (ETA) had been applied for risk calculation. On the other hand, some researchers have attempted to develop the technical methodology for explosion risk analysis in the step of prediction for explosion impact. Gupta and Chan [13] proposed an explosion risk analysis (ERA) methodology using time-varying release rates in the dispersion simulation. This research is aimed at improving the accuracy of dispersion analysis results which can directly have influence on the predicted explosion impact, and it also proposed some methods for effective ERA study in terms of time domain. Das and Weinberg [14] have studied the method for improving the estimation of a flammable mass of gas cloud. This research presented the correlation model with respect to vapour cloud explosion in the quantitative risk assessment (QRA) study. The research for developing numerical models and methodologies using computational fluid dynamics (CFD) techniques has been also performed by many other researchers [15–17]. Although a number of research topics associated with ERA for offshore facilities have been explored, there are still several open issues. In the present work, a practical method to assess the explosion design load taking into account peak pressure and duration time, in both positive and negative pressure stages, has been presented using probability distribution function with correlation analysis and compared with conventional industrial practices. This study can benefit the safety management of offshore operations and act as a guideline for ERA models.

2. Explosion Risk Assessment (ERA)

To perform the explosion risk assessment, several steps are required considering explosion cause, affecting parameter, and its probabilities as well as consequence according to each risk elements in terms of personnel or environment. These analyses could be divided into two categories, qualitative and quantitative analyses. As for the qualitative analysis, risk information is expressed in words, namely, it concentrates on the description of a certain event, frequency, and consequence associated with explosion risk rather than the numerical analysis of its output.

In quantitative risk analysis, however, each risk is quantified. It is required to calculate each risk output considering specific scenarios, and then this result is compared with risk acceptance criteria. Both of them are important to manage facilities safely from any severe accidents. This study, however, has more focused on the quantitative perspective in evaluating explosion risk elements. In particular, the explosion pressure wave profile has been investigated thoroughly. This is because it is totally dependent on explosion properties and it can also directly influence the structural stability. Under some worst scenarios like more congested and confined geometrical conditions or much more flammable gas leak rates, higher explosion pressure would be generated in spite of similar explosion magnitude. Therefore, detailed analysis for each element included in explosion pressure profiles should be required to quantify the explosion risk level more clearly. A general risk assessment model for explosion incident has been described in Figure 1. At first, it is essential to define the explosion event. This means that the boundary condition should be marked clearly including interfaces with other systems. Besides, all the activities that could be occurring within the target and may directly have influence on the potential risk should be listed. The next step is to identify the risk elements, which is the most important step in the entire risk assessment, since the establishment of the risk elements directly affects what kind of data would be analysed. Subsequent consequence and frequency analyses are performed as per identified risk elements, and through the result of those analyses, the risk level could be obtained. Once the risk is estimated based on the previous analysis, the next step is to evaluate whether that risk level is tolerable or not. If the risk level is evaluated as tolerable, then it is managed by safety design discipline. Otherwise, risk reduction measures would be required. This research also follows this procedure, but the key interest is the dashed area in Figure 1. In this part, most of previous researches paid more attention to the potential impact on the environment, equipment asset, and people by explosion incident rather than its immediate cause. This study, however, has been more focused on the cause to bring about the devastating result rather than how many/much people, equipment, and surrounding environment would be damaged under the explosion incident.

2.1. Explosion Event Definition. The explosion event considered in this study is a gas explosion on the process area of a floating production storage and offloading (FPSO) topside. In general, the FPSO topside area is built with modules which could be divided into several parts according to operational tasks, and there are many kinds of equipment and installation systems for oil processing, gas compression, and treatment [18]. Thus, many flammable gaseous materials could be produced during the operation, leading to a potential risk for ignition and explosion. Once explosion occurred, the explosion wave propagates into the air and then surrounding structural members would be exposed to the wave pressure. This wave load directly influences the structural failure [19]. The impact exerted on the structure under explosion depends on several factors such as the type of explosive material, released energy, and ignition location. Considering these conditions, a variety of explosion events could be defined [20, 21].

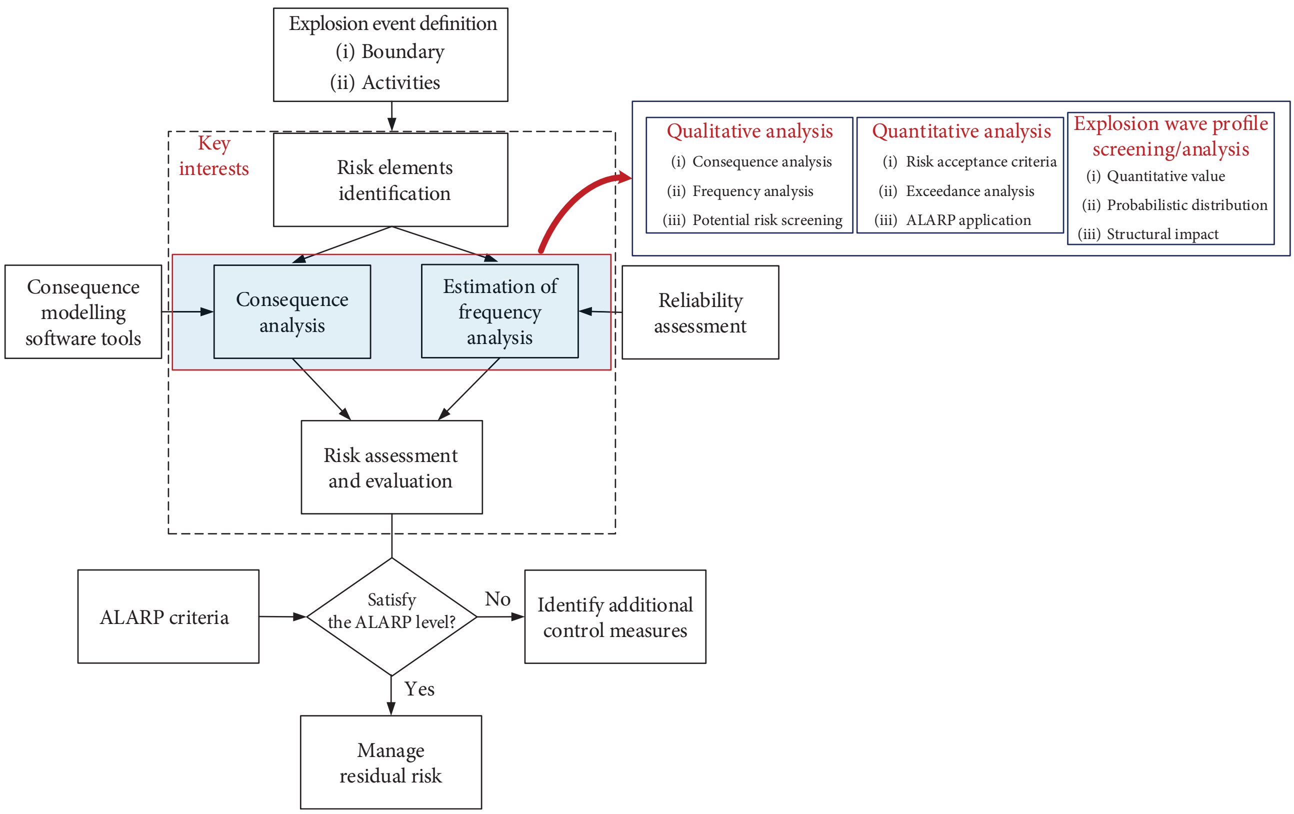


Figure 1: The flowchart of the explosion risk assessment model.

2.2. Identifying Risk Elements

2.2.1. Qualitative Risk Assessment. To define the qualitative risk level of the FPSO topside area, safety function as well as risk screening should be considered simultaneously, since the FPSO topside is a very heavily complicated structure due to many other substructure and operation systems [22]. Safety function means the design and operation method or maintenance philosophies against explosion incident. As for the general method for screening of potential risk, it could be divided into two parts, consequence and likelihood. The purpose of risk screening is to identify which area is considered to be at low risk from explosion incident and not requiring the additional action for more specific structural assessment [23]. Table 1 shows the list of risk screening processes considering safety function and maintenance doctrine. Consequence and likelihood have been categorized based on the risk level, and the influence of safety installation according to each risk level has been also investigated. Besides, the potential explosion risk has been classified using the risk matrix as described in Table 2. The high- and low-risk facilities can be identified based on the given matrix. For the low-risk area, we can see that there is a little number of equipment set and piping rack, which would result in low congestion and confinement compared to those for the relatively higher-risk area. Therefore, such an area could be free from the high level of intervention for the safety control, and then it can facilitate more focusing on the relatively high-risk area. Figure 2 shows the explosion pressure contour of the case in which the ignition occurred at the centre of the module. From this figure, we can discriminate which area should be requiring more focus in a potential explosion incident. Besides, the obstacle and equipment set had a crucial effect on the transport of explosion waves. It is obvious that the higher level of explosion pressure occurred in the highly congested area, especially the vicinity of the blast wall, while an explosion wave can get out if the empty space or gap between other equipment exists along the wave route, so a weak pressure has been measured in the less-congested area.

2.2.2. Quantitative Risk Assessment: As Low as Reasonably Practicable (ALARP) Application. In quantitative risk assessment, ALARP principle has been applied as risk acceptance criterion. ALARP is a principle of quantitative risk expressing that potential risk should be reduced to a certain level which is as low as reasonably practicable. However, the concept of ALARP should not be only understood as simply as a quantitative measure for the risk, since it also means a practical judgment of the balance between potential risk and benefit in terms of design. The ALARP application could be divided into three regions: the negligible (acceptable) region, ALARP (tolerable) region, and unacceptable region. The most important key in determining whether the risk could be considered as ALARP is the establishment of a reasonably practicable range. In terms of ALARP, the risk level should be sufficiently low and does not exceed the described acceptance criteria. If the

Table 1: Risk screening index considering safety function.

(I) Risk level		Description for consequence severity
A	Low	(i) No loss of production and damage to equipment (ii) Negligible
B	Moderate	(i) Safety installation can cover most of the area (ii) Minor damage to equipment and/or facility
C	Major	(i) Safety installation can cover some parts only, requiring significant preventive action (ii) Serious loss of production
D	Critical	(i) Urgent remedial action required
(II) Risk level		**Description for likelihood or frequency**
1	Almost certain	(i) Expected to occur in most circumstances (ii) Safety installation for only human living areas.
2	Likely	(i) Will probably occur in most circumstances (ii) Safety installation covers the critical potential area of the FPSO structure
3	Possible	(i) Must occur at some time (ii) Safety installation covers most of the area of the FPSO structure
4	Unlikely	(i) May occur at some time (ii) Requiring a medium level of maintenance and intervention
5	Rare	(i) May occur, but only under exceptional circumstances (ii) Requiring a high level of maintenance and intervention

Table 2: Risk matrix diagram for potential risk screening.

Likelihood or frequency		Consequence severity			
		Low (A)	Moderate (B)	Major (C)	Critical (D)
Almost certain	1	High	Extreme	Extreme	Extreme
Likely	2	Moderate	High	Extreme	Extreme
Possible	3	Low	High	Extreme	Extreme
Unlikely	4	Low	Moderate	High	Extreme
Rare	5	Low	Moderate	High	High

risk level is over the ALARP region, it is unacceptable. Figure 3 shows the ALARP application to the overpressure versus the frequency exceedance curve. For determining the ALARP region in explosion incident, the exceedance frequency of overpressure has been considered. In this curve, the risk level could be regarded as the ALARP region if it occurred in the range from 10^{-5} to 10^{-4} per year. Based on this range, we can also get a reasonably practicable range for overpressure and it is often regarded as design strength of offshore structures. If the design strength is similar with the predicted explosion load in the unaccepted zone, risk reduction measures would be certainly required during the design stage.

In the ERA, however, the drawback of this approach is to be based solely on the overpressure as the measure of potential risk. Although the overpressure is usually regarded as a dominant factor influencing the structural mechanical damage, many researchers have revealed some other factors which can influence structural stability from the explosion wave profile [24, 25]. That is why the more in-depth analysis is required to understand the potential risk of mechanical damage under the explosion wave.

3. Risk Screening Indicator from Explosion Wave

3.1. Risk Elements of Explosion Wave. The explosion wave is produced in an explosion event and can directly influence structural members even at farther distances. As mentioned above, explosive ignition generates blast waves; moreover, in the more congested area, overpressure and wave reflection could be enhanced [26]. To quantify explosion wave properties, therefore, extensive analysis for the explosion wave measured reflecting detailed geometrical condition should be required. Although a lot of studies related to explosion load has been performed, they were mostly focused on peak overpressure [26–29]. In present study, however, three factors have been used as risk elements of the explosion wave profile. They are duration, impulse, and overpressure in each phase. A large amount of explosion wave data have been analysed based on these factors. Figure 4 shows the definition of a monitoring method for measuring the explosion pressure data used in this study. A thousand of monitoring points and monitoring panels has been distributed on the targeted area. Once ignition occurred at a certain point, explosion wave propagates through the monitoring points and panels, so that pressure-time history at each position could be recorded. The pressure-time history information is a general type for analysing the consequence of an explosive incident. By using it as loading condition in the structural analysis, the mechanical behaviour and damage pattern of the target could be investigated. However, the main objective of this study is to assess the influence of each risk element required in ERA, i.e., the accuracy of structural analysis or technical method is distinct from the present task. The first mission, therefore, is to extract the risk elements in the explosion pressure profile. For extracting them, idealizing the explosion wave profile is required since the original explosion wave

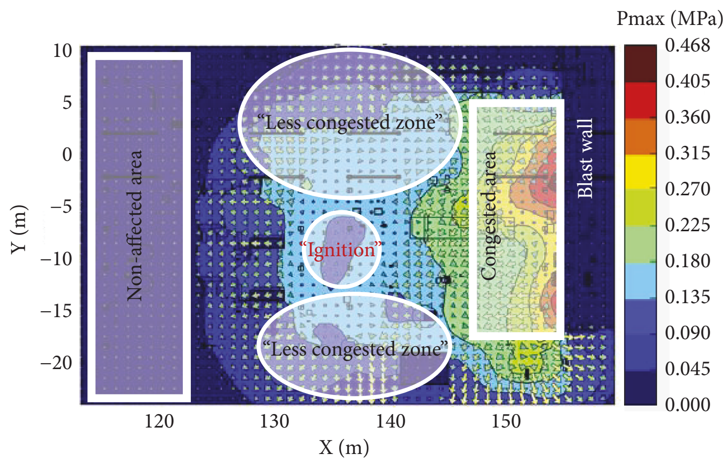


FIGURE 2: Explosion pressure contour according to wave propagation [18].

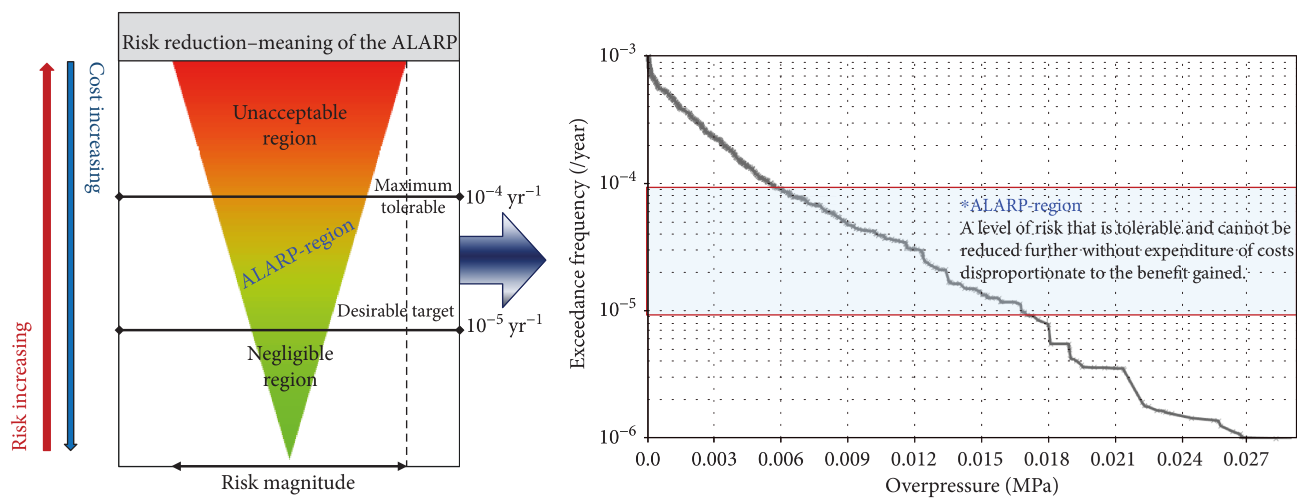


FIGURE 3: The application of the ALARP principle; the overpressure versus exceedance frequency.

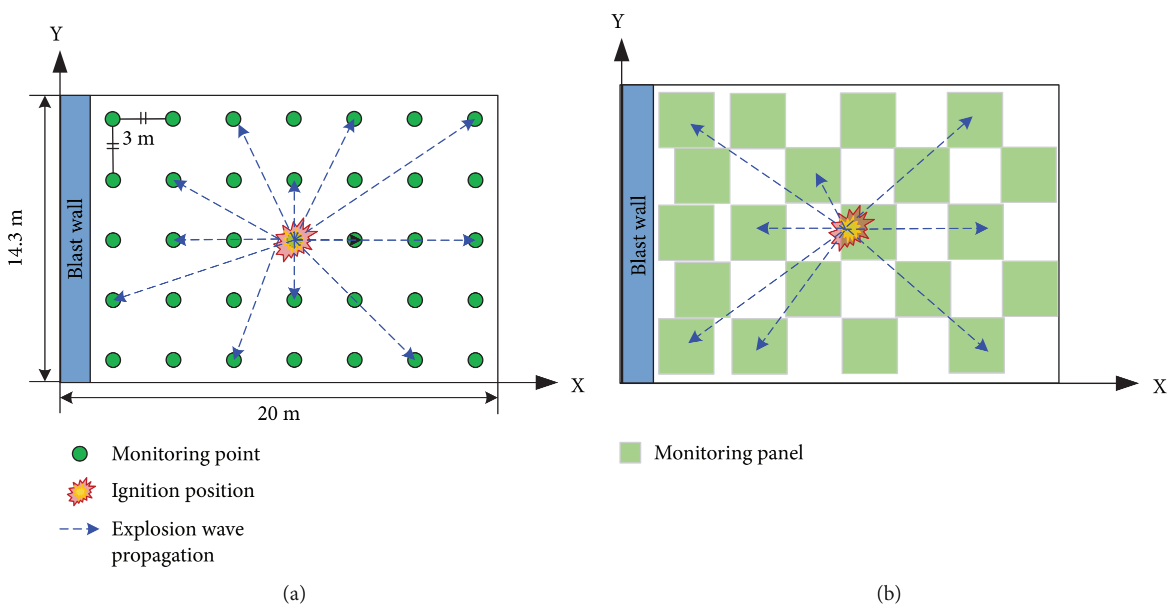


FIGURE 4: Definition of monitoring tools on the deck. (a) Monitoring point; (b) monitoring panel.

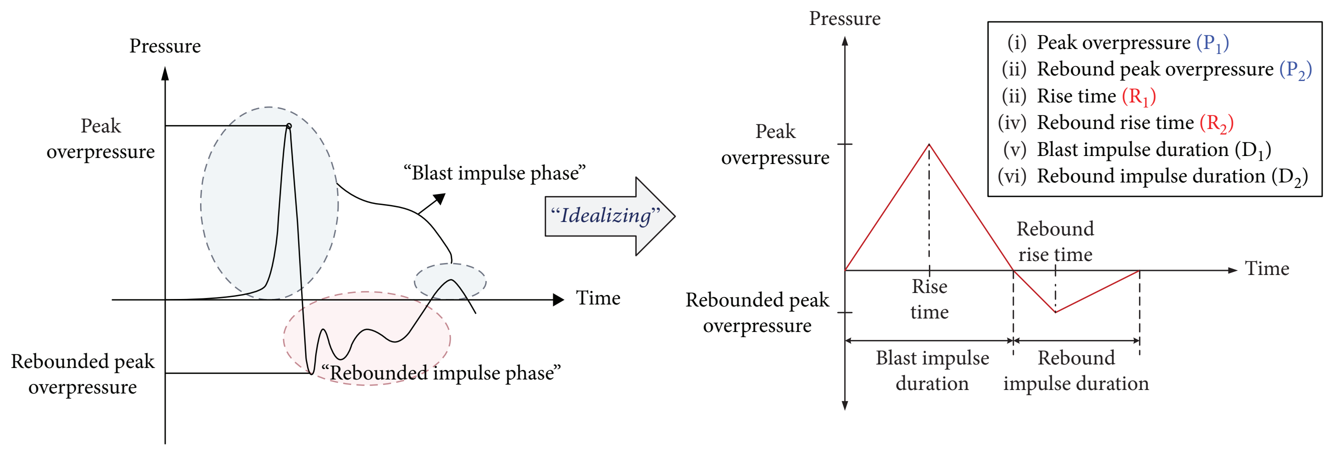


Figure 5: Idealized explosion wave profile and the definition of its risk elements.

profile has a complicated shape due to the transition of the pressure phase or pressure oscillation state. An original curve without idealizing cannot be made to the standardization form due to its irregular shapes. That is why the idealizing curve is needed. The method for idealizing is to apply the equivalent impulse with the original curve [30]. Through this method, the shape of the curve is changed as a triangular wave form which could be compared clearly. Figure 5 shows both the original explosion wave profile and idealized wave curve. As described in the box, selected risk elements in this curve are peak overpressure, rebound peak overpressure, rise time, and duration in each pressure phase. A huge amount of data set has been reproduced based on these variables, and then consequence analysis has been carried out.

3.2. Consequence Analysis of Risk Elements in Explosion Wave. In this chapter, consequence analysis for reproduced explosion wave profiles has been carried out in order to investigate the numerical distribution of each risk factor. Firstly, peak pressure in both the positive and negative pressure phases has been analysed since they greatly influence the structural response. Second, impulse has been investigated separately divided by the positive and negative pressure phases. The negative pressure phase is often disregarded due to its less proportion, but it takes up a relatively large portion when the ignition occurred in congested area, like the FPSO module. That is why the negative phase should be also focused on. Lastly, time factor has been considered in two categories, rise time and rebound rise time. This is because the explosion pressure is changed extremely during this section. Thus, most deformation usually occurred within the rising time [20]. In addition, it is also important to investigate how explosion pressure and impulse vary when similar charges are exploded in order to check the higher risk area and any other parameter which could influence the magnitude of explosion pressure. Figure 6 shows the results for average peak pressure and impulse in both pressure phases. All explosion conditions including gas cloud size and position and grid size are the same, but the ignition position is different. P1 and I1 mean the overpressure and impulse in the positive pressure phase, and the counterparts (P2 and I2) represent those things in the negative pressure phase. As for the result about average overpressure, the separation module areas had the relatively higher P1 values compared to the compression area. In addition, adjacent modules from the blast wall such as modules 1, 3, 4, and 6 had more severe overpressure, but independent modules from the blast wall like modules 2 and 5 showed relatively lower values. In addition, in the comparison for the adjacent module from the blast wall, modules 3 and 6 showed higher values of overpressure rather than modules 1 and 4, since there are much more explosion hazard materials. From the turret, hydrocarbons flow to the oil separation module and gas-processing facilities, so that the higher risk of oil and gas fire, explosion, high radiation heat loads are involved in this area. That is why modules 3 and 6 have the higher level of overpressure than other modules in each group. However, in the case of negative peak pressure (P2), there is no clear relationship between the level of peak pressure and the module's characteristics. When it comes to the average impulse, it is clear that the highest level of impulse has been measured in modules 3 and 6 in each group, but modules 2 and 5 had a higher value than modules 1 and 4, unlike the previous result. The other remarkable thing is that the distribution of pressure and impulse shows the different pattern. The positive peak pressure is much higher than negative peak pressure, but on the contrary, the impulse of the negative phase is bigger than positive phase's impulse in all modules. This means that longer time is required to recover from the peak value to the atmospheric pressure in the case of the negative pressure. The specific results for each module were summarized in Table 3.

4. Probabilistic Analyses

4.1. Probability Distribution of Explosion Pressure Parameters. The explosion incident is a quite complex phenomenon, since several variables having the uncertainties should be

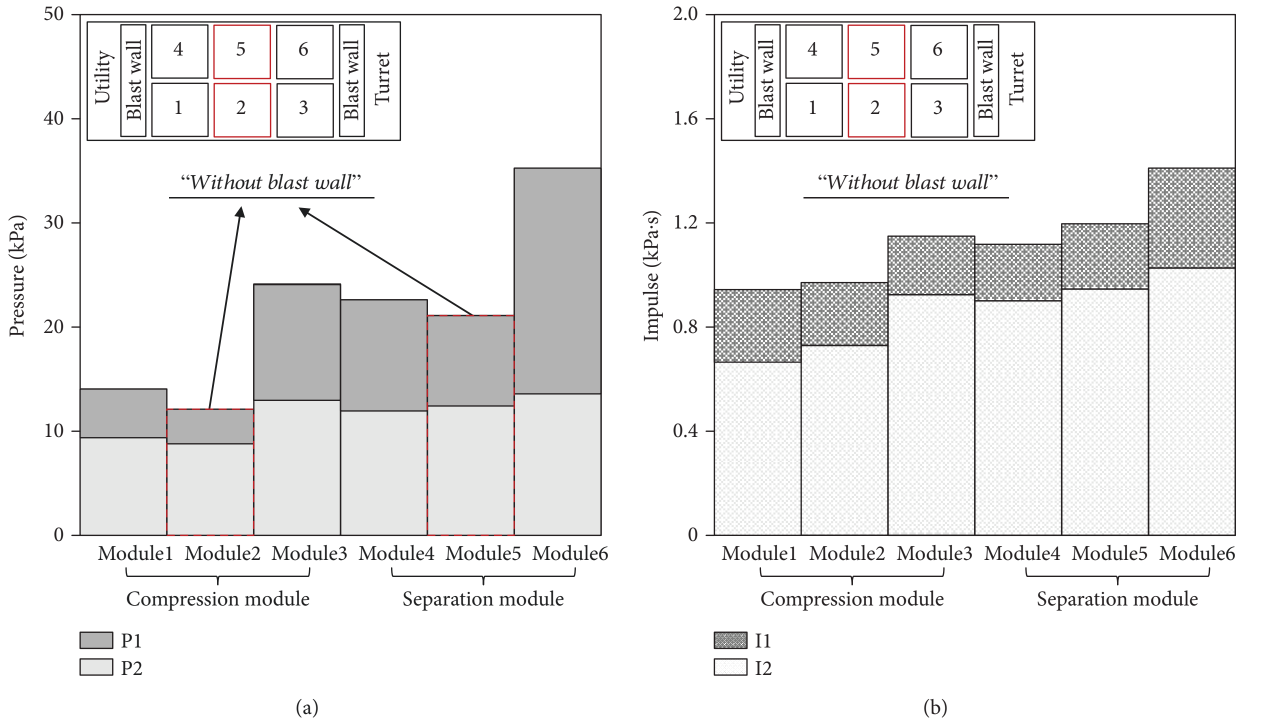


Figure 6: The average peak pressure and impulse in each pressure phase at the modules. (a) Average peak pressure; (b) average impulse.

Table 3: The consequence for risk elements of blast wave in each module.

Module types	Risk elements from blast wave					
	P_1 (kPa)	P_2 (kPa)	I_1 (kpa·s)	I_2 (kpa·s)	R_1 (s)	R_2 (s)
Module 1	14.12	9.25	0.63	0.92	0.045	0.099
Module 2	12.08	9.12	0.07	0.94	0.058	0.107
Module 3	24.34	13.15	0.09	1.13	0.037	0.087
Module 4	23.16	12.47	0.087	1.09	0.041	0.088
Module 5	21.19	12.21	0.092	1.18	0.040	0.099
Module 6	35.27	14.01	0.102	1.16	0.028	0.085

considered. Explosion load profiles are dependent on factors such as gas leak rate/direction, wind condition, and ignition location. Therefore, they could be regarded as random variables affecting the explosion. In probability and statistics, a random variable is a variable whose possible values are outcomes of a random phenomenon. Thus, all of the properties chosen from the explosion pressure profile, such as pressure, duration time, and impulse, have been used as random variables and their probability distribution has been investigated to understand the variability of explosion pressure properties. First, probability density function (PDF) was computed using an explosion pressure data set. PDF is normally used for specifying the probability of a random variable falling within a particular range of values, as opposed to taking on any one particular value. Therefore, applying PDF to explosion pressure distributions could be helpful in understanding the variation of gas explosion pressure in predefined scenarios. The considered explosion pressure properties are peak pressure (in the positive phase), rebounded peak pressure (in the negative phase), duration time, and impulse in each pressure phase. Impulse means the integrated area under the explosion pressure-time curve. The consequence of each property had been calculated in the author's previous paper [20]. In this paper, the range of precalculated load properties has been established, and subsequently, the proportion and probability density function of each group have been investigated by extracting a hundred thousand data points from pressure-time profiles of explosion waves based on predefined explosion scenarios. The resulting median value and deviation of each data point have been indicated in the figures. Besides, the coefficient of variation was calculated in order to compare the probability distribution for chosen properties. It means the ratio of the standard deviation to the average, and it can be used to

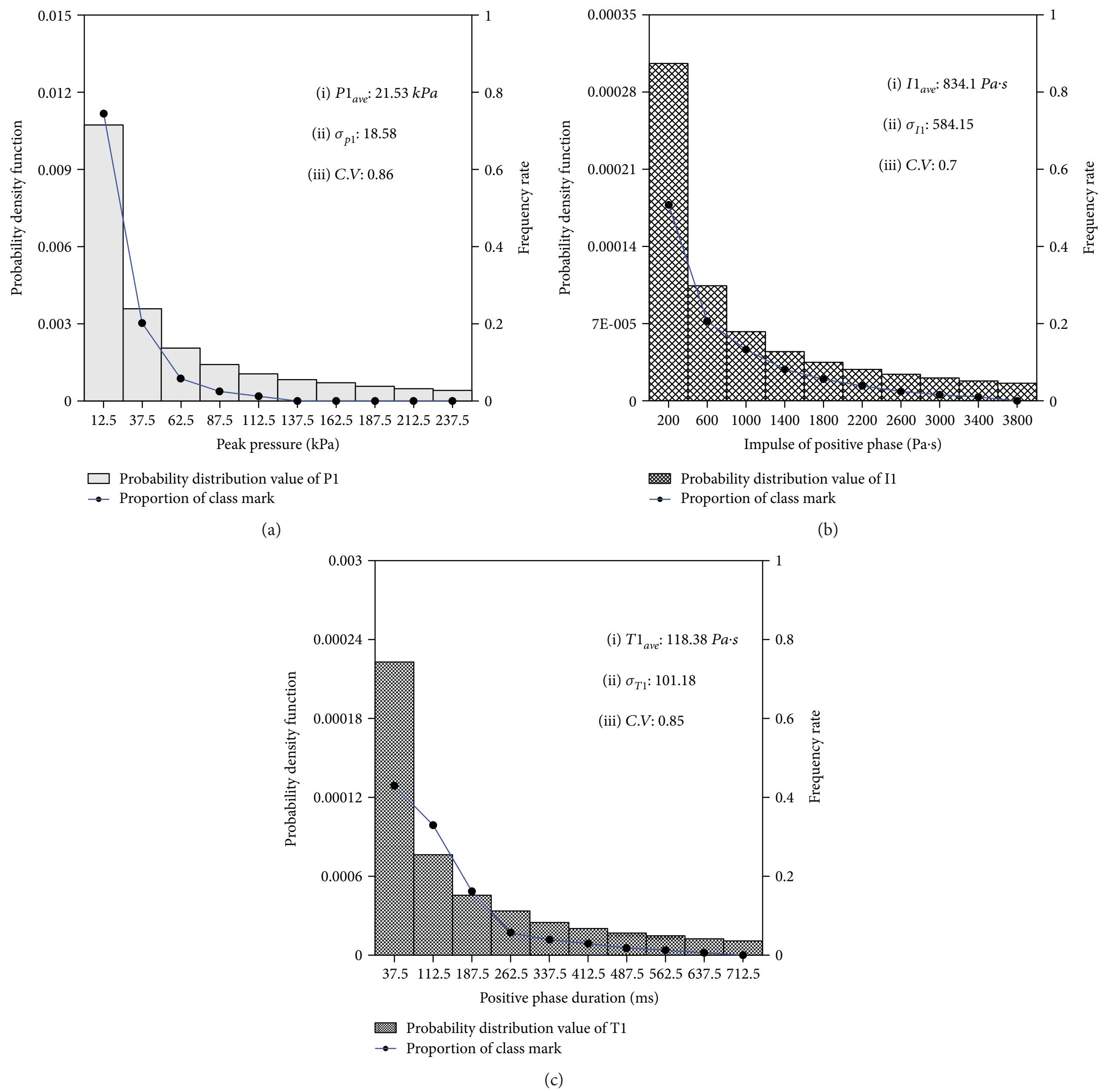


Figure 7: Probability density function for parameters in the positive pressure phase. (a) As for the peak pressure; (b) as for the impulse; (c) as for the duration time.

compare the degree of variation from one data series to another type, even if the average value is totally different.

The coefficient of variation (CV) for parameters in the positive pressure phase is 0.86, 0.7, and 0.85. In addition, in the other data series, for parameters of the negative phase, the CV is 0.28, 0.32, and 0.34, having relatively small values compared to their counterparts. This means that the scattering degree of the positive phase's data sets is bigger compared to the negative phase and more sensitive to explosion scenario factors such as ignition resources, wind state, and operation condition. As a result, the lognormal PDF of the positive phase's properties, shown in Figure 7, has been obtained but a totally different type of distribution was measured in the negative phase as indicated in Figure 8. Although the distribution for peak-reflected pressure was the normal distribution type, impulse and duration time were not the normal PDF. This is because of the influence that duration time has as described in Figure 9. The relationship between peak pressure and the corresponding impulse is shown. Although no obvious linear relationship can be observed, it is clear that the positive pressure-impulse dependence is more linear compared to the negative-phase combination. Data with higher positive peak pressure usually has longer duration compared to other data. However, this does not hold in the case of the negative phase.

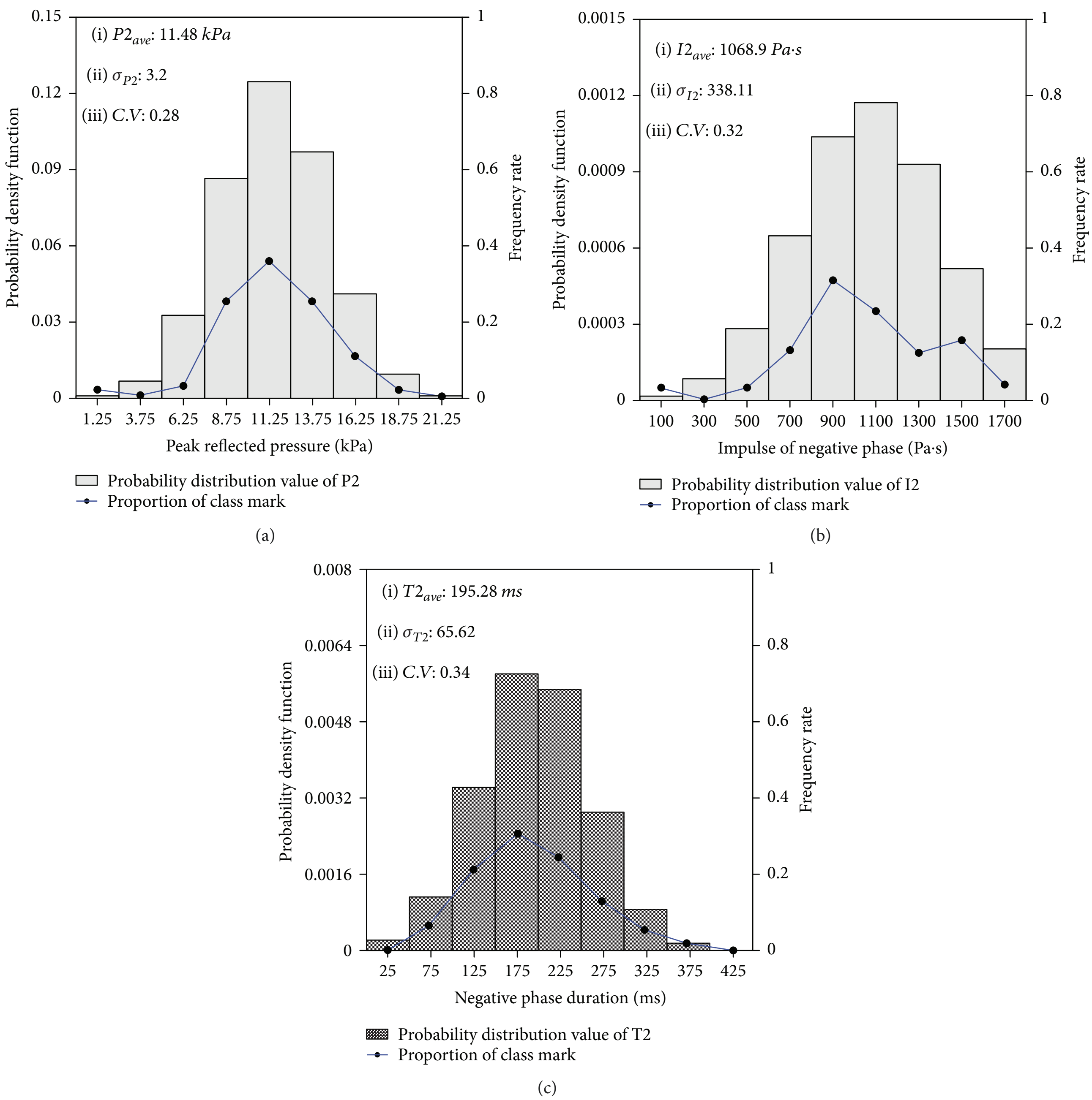
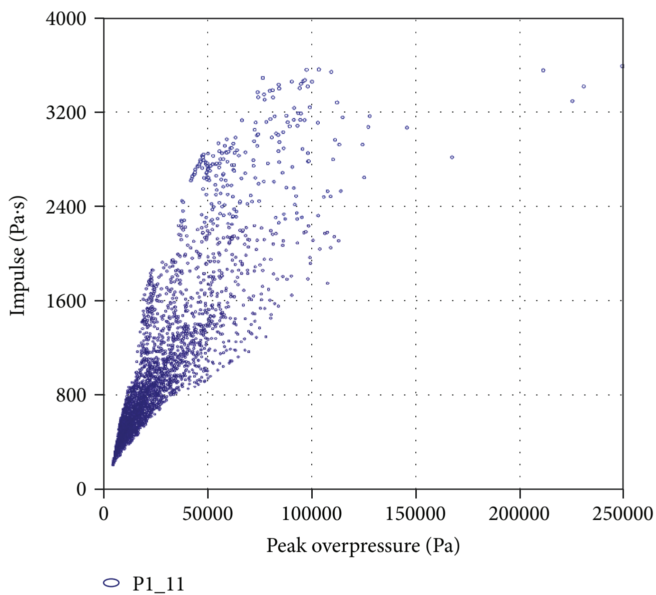


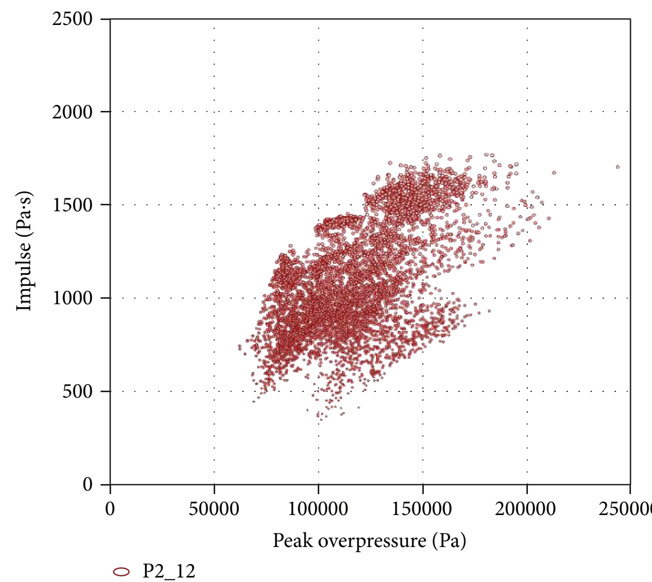
Figure 8: Probability density function for parameters in the negative pressure phase. (a) As for the rebounded peak pressure; (b) as for the impulse; (c) as for the duration time.

Hence, the distribution of the positive pressure and the distribution of impulse are similar, while in the negative phase, they are different from each other. The results corresponding to each distribution are summarized in Table 4.

4.2. Correlation Coefficient Analysis. In the ERA, the general approach for correlation analysis of explosion load is to investigate the relationship between peak pressure and its impulse. The explosion pressure-impulse diagram shows the three categories of loading zone like impulsive, quasi-static, and dynamic loading as per its duration time and severity of peak pressure [31–33]. It is usually used to define the explosion pressure type and to assess the structural damage as well as even the human injury by explosion load [34]. The method considers only positive pressure and impulse. Furthermore, short or long duration time cannot be defined based on only absolute values. Rather, they should be classified based on the ratio between the loading duration and natural period of the target structure. Therefore, it is necessary to identify more specific explosion pressure profiles before considering the natural period of the structure. In this chapter, Pearson product-moment correlation coefficients have been computed to evaluate the degree of correlation between different explosion pressure profiles. The



(a)



(b)

Figure 9: The scatter diagram between peak pressure and impulse. (a) Positive peak pressure and impulse; (b) negative peak pressure and impulse.

Table 4: The results for probability distribution of parameters in both pressure phases.

(1) Probability distribution for parameters in the positive phase								
Peak pressure			Positive-phase impulse			Positive-phase duration time		
$P_{1ave.}$ (kPa)	σ_{P1}	CV	$I_{1ave.}$ (Pa·s)	σ_{I1}	CV	$T_{1ave.}$ (ms)	σ_{T1}	CV
21.53	18.58	0.86	834.1	584.15	0.7	118.38	101.18	0.85
(2) Probability distribution for parameters in the negative phase								
Rebounded peak pressure			Negative-phase impulse			Negative-phase duration time		
$P_{2ave.}$ (kPa)	σ_{P2}	CV	$I_{2ave.}$ (Pa·s)	σ_{I2}	CV	$T_{2ave.}$ (ms)	σ_{T2}	CV
11.48	3.2	0.28	1068.9	338.11	0.32	195.28	65.62	0.34

correlation coefficients have been calculated using the following equations.

$$\mathrm{Cov}(X,Y)=\frac{1}{n-1}\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y}),\quad \left(\bar{X}=\frac{\sum X_i}{n},\ \bar{Y}=\frac{\sum Y_i}{n}\right),$$
$$\sigma_X^2=\frac{1}{n-1}\left\{\sum_{i=1}^{n}X_i^2-\frac{\left(\sum_{i=1}^{n}X_i\right)^2}{n}\right\},$$
$$\sigma_Y^2=\frac{1}{n-1}\left\{\sum_{i=1}^{n}Y_i^2-\frac{\left(\sum_{i=1}^{n}Y_i\right)^2}{n}\right\},$$
$$r(X,Y)=\frac{\mathrm{Cov}(X,Y)}{\sigma_X\cdot\sigma_Y}=\frac{n\sum_{i=1}^{n}X_iY_i-\sum_{i=1}^{n}X_i\sum_{i=1}^{n}Y_i}{\sqrt{n\sum_{i=1}^{n}X_i^2-\left(\sum_{i=1}^{n}x_i\right)^2}\cdot\sqrt{n\sum_{i=1}^{n}Y_i^2-\left(\sum_{i=1}^{n}Y_i\right)^2}},\tag{1}$$

where $\mathrm{Cov}(X,Y)$ is the covariance of X and Y and σ_X and σ_Y means the standard deviations of X and Y, respectively. Therefore, the correlation for peak pressure, impulse, and duration in both phases could be evaluated using those equations. If the correlation coefficient, r, is close to either +1 or −1, it means that the relationship is a positive or negative linear state, respectively. The results of each correlation variables were summarized in Table 5. The variables have been described as follows:

(i) $r(P_p,P_R)$; correlation between peak pressure and rebounded peak pressure

(ii) $r(I_p,I_R)$; correlation between positive and negative impulse phases

(iii) $r(T_p,T_R)$; correlation between duration times in each phase

As shown in Table 5, all of the parameters have a quite positive linear relationship and this means that the positive pressure stage definitely influences on the state of the negative pressure phase. The larger magnitude peak pressure is more likely to generate more severe rebounded peak

Table 5: The results of correlation coefficient for explosion pressure parameters.

Strength of association	Range (positive)	Coefficient, r	Value
Small	0.1 to 0.3	$r(P_p, P_R)$	0.458
Medium	0.3 to 0.5	$r(I_p, I_R)$	0.798
Large	0.5 to 1.0	$r(T_p, T_R)$	0.554

pressure, and it also means that the longer positive phase could be reason for the occurrence of the long-term negative phase. Generally, when designing the structure under the risk of impact-type load, it should be required to avoid resonance frequencies between structural members and design load in order to maintain structural stability. Besides, the dynamic effect of structural response is totally different according to the ratio between the structural natural period and loading duration. If the loading duration is much longer than the natural period of the targeted object, the dynamic effect is small by the effect of the negative pressure phase, but if the loading duration is similar with the natural period or much shorter compared to it, the dynamic effect is relatively large [20]. Therefore, it is crucial to figure out the possible range of explosion impact loading duration. At the explosion pressure wave, total duration is determined by combining the period of positive and negative pressure phases, so the correlation investigation for duration time could be one of the key issues in terms of resonance avoidance design. Hence, quantifying explosion pressure properties and predicting their correlation conservatively are necessary to assess explosion risk and to arrange a practical use in the design stage.

5. Risk Estimation

Most of the damage criteria associated with gas explosion just consider the effect of positive peak pressure as shown in Table 6 [35]. However, as mentioned above, rebounded peak pressure and duration time are also important factors for describing the structural damage by explosion wave. Generally, the positive pressure phase can last for about 10–250 ms and the negative pressure phase is longer than it. The degree of damage could be remarkably different according to duration time even if the peak pressure is of the same magnitude. Therefore, it should be required to consider not only overpressure but also the other factors in order to estimate the explosion risk more reasonably. This chapter explores the types of explosion pressure profiles that could be dangerous and their probability of occurrence. The explosion pressure profiles were divided into two sections, namely, the positive pressure phase and negative pressure phase. Structural changes first occurred during the positive peak pressure; subsequently, secondary effects were observed during the negative peak pressure. It is a series of events in spite of the extremely short time. Thus, event tree analysis (ETA) could be applied to investigate the mentioned issue since it is usually used to identify the outcomes of a certain system which has a probability of occurring after an initiating event. In terms of the total explosion wave profile, peak pressure could be considered as an initiating event, and then the other factors are considered in a regular sequence. Figure 10 shows the result of ETA for explosion pressure wave which can be a potential risk to the structure.

Table 6: The influence of peak overpressure.

Peak overpressure (MPa)	Description of damage	Criteria
0.001	Crack in glass	Negligible
0.003	Shattering of glass	
0.01	*Repairable damage to equipment and structural member*	*ALARP region*
0.02	*Minor damage to steel frame*	
0.03	Major damage to equipment and structural member	Dangerous
0.17	Severely damaged or demolished	

The initiating event, peak pressure in the positive phase, has been divided into three categories based on Table 6. And, rebounded peak pressure could be classified into two groups taking into account the normal distribution characteristic. One is the case below its average value; the other case is over the average. Lastly, three groups of duration time have been separated based on its average value. The duration time can affect the degree of damage to the equipment or structural components regardless of the peak pressure. The excessive vibrations can be generated in the structural components of the topside module when the natural period of the target structure and duration of the exerted explosion pressure are the same. Such vibrations are one of the major reasons for mechanical failure of equipment like reciprocating compressors. Therefore, the duration time should be selected to avoid resonance frequencies. The ETA results have something in common with the correlation analysis result. The rebounded peak pressure is more likely to be less than its average value when the peak pressure is less than or equal to the ALARP range. But the risk degree should not be concluded based on only this matter. Impulse is a dominant factor to the structural damage if it was not for the resonance issue. This means that if relatively lower peak pressure is exerted for a longer time, it could be a more dangerous situation than its opposite case [20]. So, the range of impulse for each event has been considered to identify the degree of risk, as shown in Figure 11. This range would be changed if the different explosion scenarios are considered. The notable thing is the overlapping region between the ALARP and dangerous damage criteria. The negligible region could be acceptable, but it is quite difficult to sort ALARP and the dangerous region, since there is pretty much an overlapping part between them considering the total impulse range. Therefore, judgment of explosion risk criteria only reflecting peak pressure magnitude could be inaccurate. It should definitely be required to consider the other factors such as peak pressure in each phase and duration time for a more accurate assessment of explosion risk criteria.

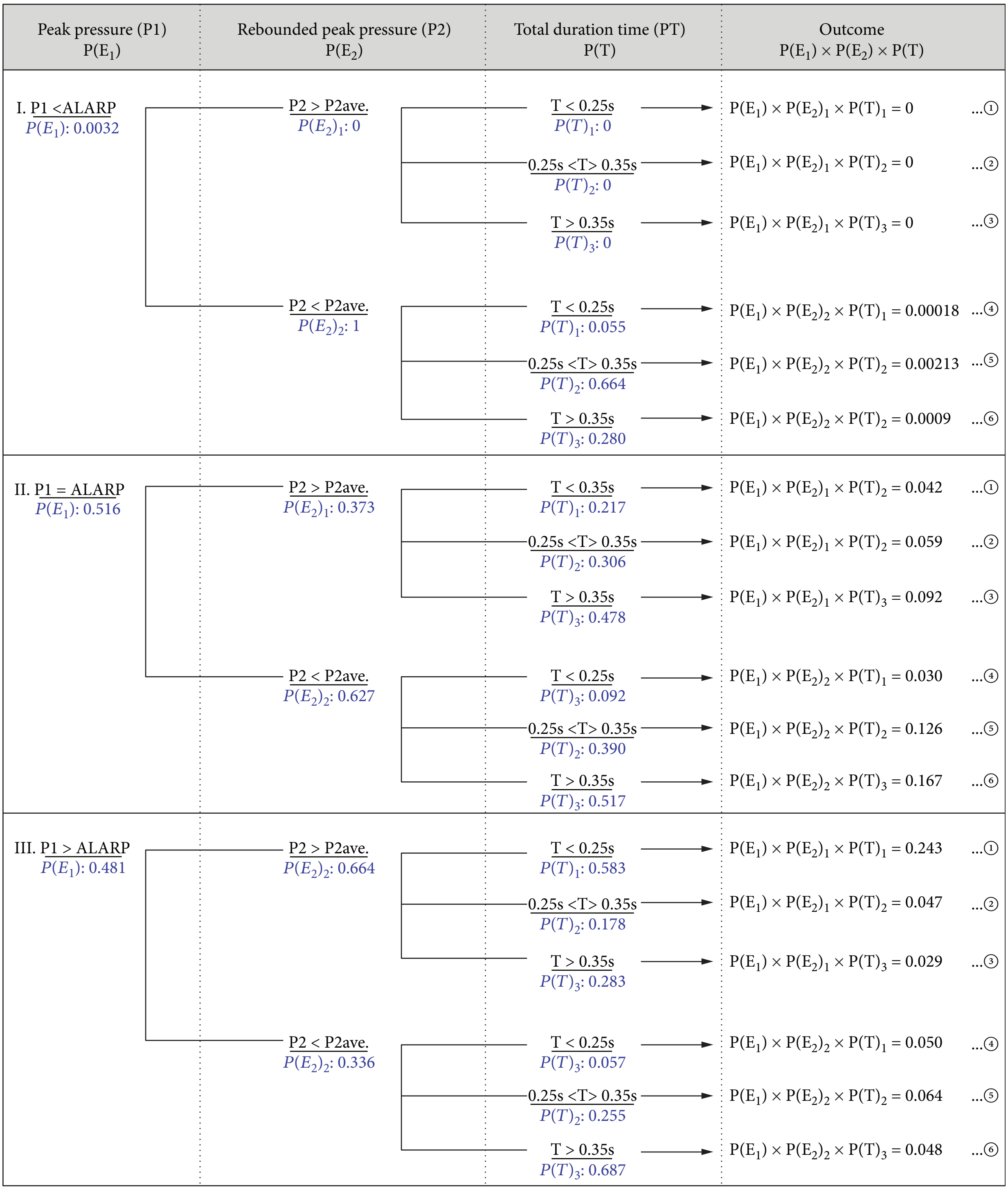


Figure 10: Event tree analysis for explosion pressure considering both positive- and negative-phase parameters.

6. Conclusion

The objective of this study is to establish a multilevel explosion risk analysis taking into account potential risk elements associated with explosions. A number of factors related to uncertainties in explosion risk estimation have been investigated for the specific case of gas explosion in FPSO topside modules. In conventional ERA, the focus lies solely on the maximum explosion pressure in the positive phase. Hence, FPSO topside modules are usually defined as high-risk facilities if the maximum pressure exceeds the design value. However, such a scenario could be considered to have low potential risk if other factors are taken into account. In this work, the risk criteria for

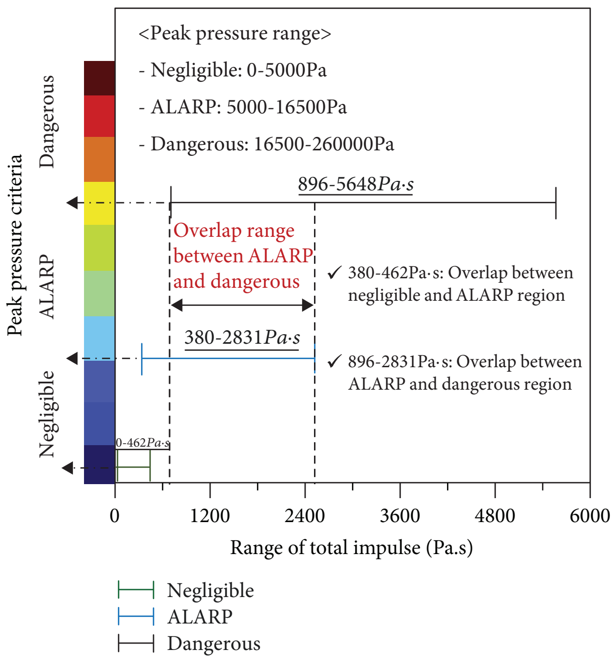


Figure 11: Impulse range based on the peak pressure criteria.

gas explosion have been categorized using both quantitative and qualitative analyses as well as probabilistic analysis for explosion loading factors. The primary results are listed as follows.

(i) The qualitative analysis for explosion risk elements has been performed with a risk screening process considering safety function and maintenance doctrine and risk level in the consequence severity, and likelihood has been categorized reflecting safety function. Besides, it has also revealed that the congestion level could directly influence the potential explosion risk through the explosion pressure contour analysis

(ii) In the quantitative risk assessment for explosion event, the risk acceptance criteria have been described based on the ALARP application

(iii) Through the risk screening for explosion wave data set, it is revealed that the risk elements from the explosion wave profile could be divided into three things; peak pressure, impulse, and duration, and their properties was thoroughly investigated considering possible explosion circumstances

(iv) Probability distribution for chosen factors from the explosion wave profile has been investigated, and then it was found that the distribution type of the positive and negative phase's factors is completely different. The relationship between peak pressure and its impulse was also studied. There is no obvious linear relationship, but positive pressure and impulse are more close to linear relationship compared to its counterpart

(v) Correlation analysis between mentioned explosion wave profile's factors has been done. Through the result, a positive linear relationship is found among all of the parameters and this means that there is a powerful correlation in each other

(vi) The risk criteria based solely on the positive peak pressure could be inaccurate. It should definitely be required to consider the other factors such as peak pressure in each phase with duration time for more accurate assessment of explosion risk criteria

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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