Chapter 2 Nonlinear Structural Responses Associated with Hydrocarbon Explosions

by

Jeom Kee Paik

Department of Naval Architecture and Ocean Engineering and The Korea Ship and Offshore Research Institute (The Lloyd's Register Foundation Research Centre of Excellence) at Pusan National University, Korea; and Department of Mechanical Engineering at University College London, UK

Sang Jin Kim

The Korea Ship and Offshore Research Institute (The Lloyd's Register Foundation Research Centre of Excellence) at Pusan National University, Korea

Junbo Jia

Aker Solutions, Norway

Abbreviation and Terminology

Actual gas cloud size	Flammable gas cloud size obtained from CFD simulation or experiment
Actual loads	Overpressures or drag forces obtained from CFD simulation or experiment
ALARP	As Low As Reasonably Practicable risk
ANSYS/LS-DYNA	A computer code for the nonlinear structural response analysis
Average loads	Average values of actual overpressures or drag forces
CFD	Computational fluid dynamics
Control volume	Mathematical abstraction employed in the process of creating mathematical models in CFD simulation
DAF	Dynamic load amplification factor
ER	Equivalent gas concentration ratio
Equivalent gas cloud size	Gas cloud size equivalent to the stoichiometric condition
FEM	Finite element method
FLACS	A computer code for simulating gas dispersion and explosion
FLACS2DYNA	A computer code for transferring the results of FLACS simulations to the input data of ANSYS/LS-DYNA
HSE&E	Health, safety, environment & ergonomics
Monitoring panel or point	A predefined area or point of interest where the computational results are monitored
Porosity	Volumetric measure of void spaces in the range of 0 to 1.0 in which 1 indicates an empty space and 0 indicates a solid condition
SDOF method	Single degree of freedom method using an analytical approach

Nomenclature

A	Effective area under the pressure load
b_f	Breadth of flange
C	Cowper-Symonds coefficient
$C_{1\varepsilon}$, $C_{2\varepsilon}$	Constant in the $k-\varepsilon$ equation
C_{A1-12}	Monitoring points at elevation level A
C_{B1-12}	Monitoring points at elevation level B
C_d	Drag coefficient
c	Speed of sound
c_p	Specific heat capacity at constant pressure
c_v	Specific heat capacity at constant volume
D	Diffusion coefficient
E	Component of rat of deformation
F	Applied blast force at instant of maximum dynamic reaction
F/O	Fuel-oxidant ratio
F_o	Obstruction friction force
F_w	Wall friction force
g	Gravitational acceleration
H	Hydrogen
H_s	Sensible heat flux from the surface

h	Specific enthalpy
h_w	Height of web
k	Turbulent kinetic energy
L	Monin-Obukhov length scale
l_{LT}	Mixing length in the β-model
M	Molecular weight of a mixture
m	Mass
$\dot{m}$	Mass flow
m_{fuel}	Mass of fuel (gas)
m_{oxygen}	Mass of oxygen in the fuel (gas)
n	Number of density
O	Oxygen
P	Gauge pressure
P_B	Monitoring panel on blast wall
P_M	Monitoring panel on mezzanine deck
P_P	Monitoring panel on process deck
P_U	Monitoring panel on upper deck
p_0	Ambient pressure
p_{air}	Absolute pressure
p_{peak}	Peak (maximum) overpressure
Q	Heat
$\dot{Q}$	Heat rate
q	Cowper-Symonds coefficient
R	Gas constant of a mixture
R_B	Maximum resistance to blast loading
R_{flame}	Flame radius
R_{fuel}	Fuel reaction rate
R_u	Universal gas constant
r_{inner}	Inner radius of column
r_{outer}	Outer radius of column
S_L	Laminar burning velocity
T	Natural period
T_{air}	Absolute temperature
t_d	Specific time
t_f	Thickness of flange
t_w	Thickness of web
u	Velocity of the fluid
u^*	Friction velocity
u_i	Mean velocity in the ith direction

V	Volume
W	Dimensionless reaction factor
X	Mole fraction
Y	Mass fraction
Y_0	Initial mass fraction
y_{el}	Deflection at elastic limit
y_m	Maximum total deflection
β	Transformation factor in the β-model
β_i	Area porosity in the ith direction
β_v	Volume porosity
γ	Isentropic ratio
γ_P	Pressure exponent for the laminar burning velocity
ε	Dissipation of turbulent kinetic energy
$\dot{\varepsilon}$	Strain rate
ε_f	Critical fracture strain under quasi-static load
ε_{fd}	Critical fracture strain under dynamic load
κ	Von Karman constant
μ	Dynamic viscosity
μ_{eff}	Effective viscosity, $\mu_{eff} = \mu + \mu_t$
μ_t	Dynamic turbulent viscosity
ρ	Density
ρ_0	Initial density
σ	Prandtl-Schmidt number
σ_{ij}	Stress tensor
σ_Y	Yield stress under quasi-static load
σ_{Yd}	Yield stress under dynamic load
Φ	Equivalence ratio
χ	Fuel-dependent constant

1. Introduction

While in service, ships and offshore structures are subjected to various types of actions and action effects, which are usually normal, but they sometimes are extreme and even accidental, as shown in Figure 2.1. Hydrocarbon explosions and fires are two of the most typical types of accidents associated with offshore installations that develop oil and gas.

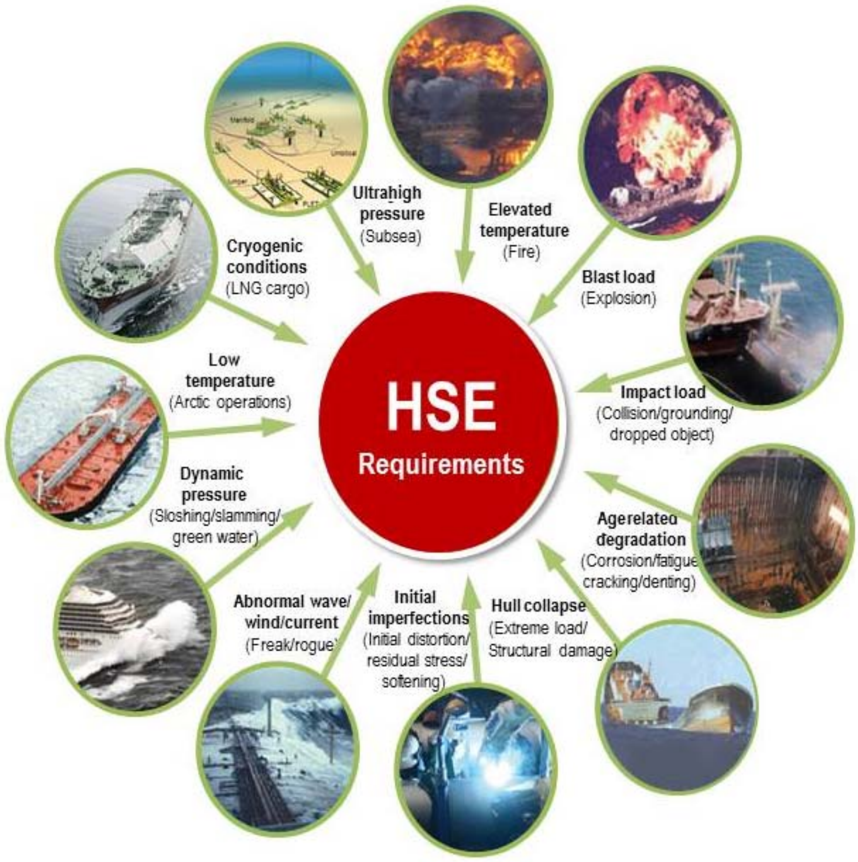


Figure 2.1. Various types of extreme and accidental events involving ships and offshore installations (Paik, 2015).

Explosions are a major type of accident on offshore platforms that develop offshore oil and gas, which are flammable. These explosions occur because hydrocarbons are often released from flanges, valves, seals, vessels, or nozzles of offshore installations and may be ignited by sparks. When hydrocarbons are combined with an oxidizer (usually oxygen or air), they can explode by ignition. Combustion occurs if temperatures increase to the point at which hydrocarbon molecules react spontaneously with an oxidizer. A blast or a rapid increase in pressure results from such an explosion. Offshore structures subjected to the impact of overpressure from explosions can be significantly damaged, and catastrophes may result, with casualties, asset damage, and marine pollution.

Successful engineering and design should meet not only functional requirements but also HSE&E requirements. Functional requirements address operability in normal conditions, and HSE&E requirements represent safe performance and integrity in accidental and extreme conditions. Normal conditions can usually be characterized by a solely linear approach, but more sophisticated approaches must be applied to accidental and extreme conditions that involve highly nonlinear responses, as shown in Figure 2.2 (Paik et al., 2014; Paik, 2015). The risk-based approach is known to be the best method for successful design and engineering to meet HSE&E requirements against accidental and extreme conditions.

In industry practices, prescriptive (predefined or deterministic) methods are often applied for risk assessment and management (FABIG, 1996; API, 2006; ABS, 2013; DNVGL, 2014). However, application of a fully probabilistic approach for quantitative risk assessment and management is highly desirable (Czujko, 2001; Vinnem, 2007; NORSOK, 2010; Paik and Czujko, 2010; Paik, 2011; ISO, 2014; LR, 2014).

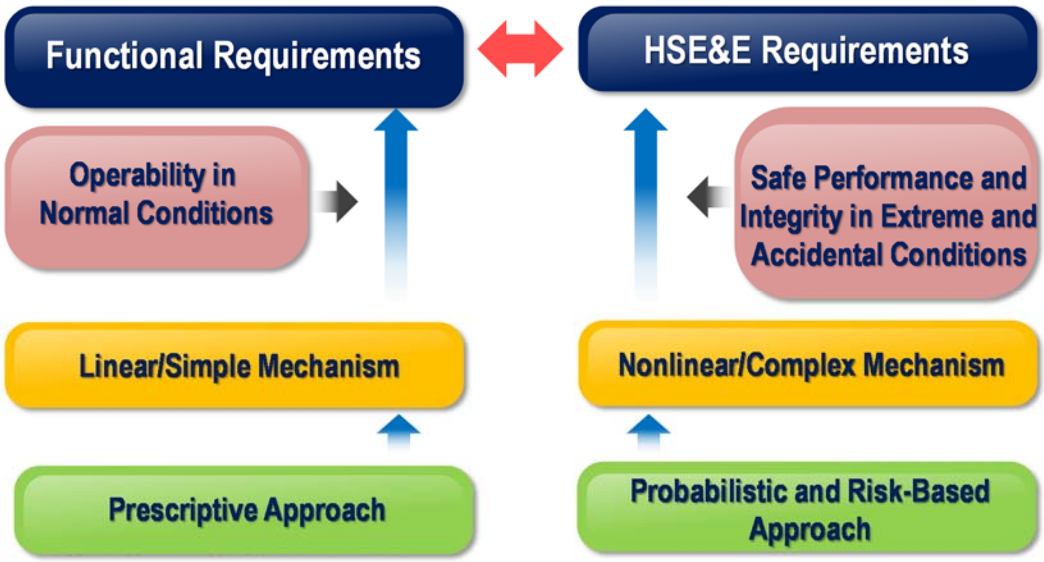


Figure 2.2. Paradigm change in engineering and design (Paik, 2015).

Within the framework of risk assessment and management, the characteristics of actions and action effects are identified by taking advantage of advanced engineering models associated with nonlinear structural mechanics. This chapter describes the nonlinear structural mechanics associated with hydrocarbon explosions. Current rules and industry practices for risk assessment are surveyed, and advanced procedures and recommended practices are investigated. For nonlinear structural response analysis due to explosions, the blast pressure actions must be defined. Therefore, both blast pressure actions and action effects are described.

2. Fundamentals - Theory

2.1 Profile of Blast Pressure Actions

Figure 2.3 represents a typical profile of the blast pressure actions caused by hydrocarbon explosions, which are generally characterized by four parameters: (a) rise time until the peak pressure, (b) peak pressure, (c) pressure decay type beyond the peak pressure, and (d) pressure duration time. The peak pressure value often approaches some two to three times the collapse pressure loads of structural components under quasi-static actions. However, the rise time of blast pressure actions is very short, only a few milliseconds. The duration (persistence) of blast pressure actions is often in the range of 10 to 50 ms. It is necessary to define the structural consequences (damage) of blast pressure actions within the quantitative risk assessment and management.

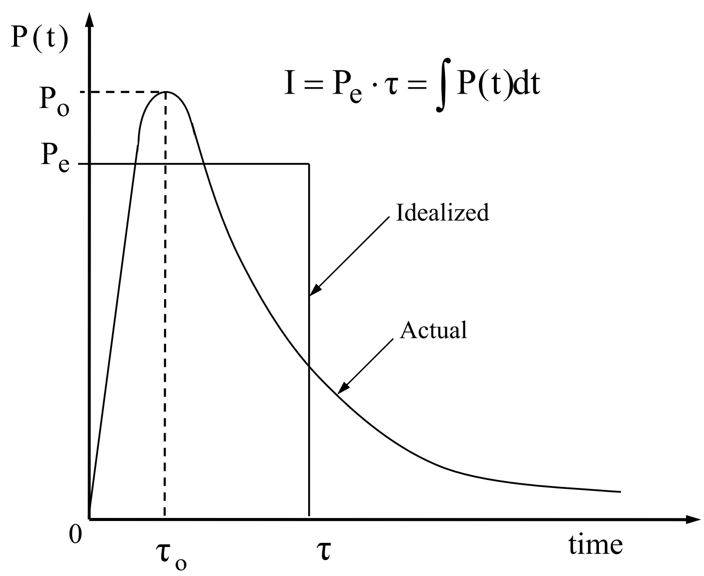


Figure 2.3. Typical profile of blast pressure action and its idealization (Paik and Thayamballi, 2007).

When the rise and duration times of blast pressure actions are very short, the blast pressure response is often approximated to an impulsive type of action characterized by only two parameters, the equivalent peak pressure P_e and the duration time τ, as long as the corresponding impulse is identical (Paik and

Thayamballi, 2007). The two parameters may be defined so that the actual and idealized impulses of the impact pressure action are equal, namely,

$$I = P_e \tau = \int P(t) dt \tag{2.1}$$

where I is the impulse of the impact pressure action, t is the time, P_e is the effective peak pressure, and τ is the duration time of P_e. Taking P_e as the same as P_o (peak pressure value) may be unduly pessimistic for obvious reasons, and thus P_e is sometimes obtained by multiplying a relevant knockdown factor to P_o. Once the impulse I and the effective peak pressure value P_e are defined, the duration time τ can be determined from Equation (2.1).

In analytical methods for prediction of structural damage due to blast pressure action, P_o and τ can be dealt with as parameters of influence. In computational models, however, the actual profile of blast pressure action is directly applied to simulate the nonlinear structural responses.

2.2 Thermodynamics of Hydrocarbons

2.2.1 Definitions of Physical Parameters

This section presents the definitions of the physical parameters associated with hydrocarbon explosions. When a single type of gas is involved, the number of moles of a species is defined as follows:

$$n_i = \frac{m_i}{M_i} \tag{2.2}$$

where n_i is the number density, m_i is the mass, and M_i is the molecular weight of a mixture of species.

The mole fractions are defined as follows:

$$X_i = \frac{n_i}{\sum_{i=1}^{N} n_i} \quad (2.3)$$

where X_i is the mole fraction.

Mass fractions are defined as follows:

$$Y_i = \frac{m_i}{\sum_{i=1}^{N} m_i} \quad (2.4)$$

where Y_i is the mass fraction.

The fuel-oxidant ratio is defined as follows:

$$\left(F/O\right) = \frac{m_{fuel}}{m_{oxigen}} \quad (2.5)$$

where F/O is the fuel-oxidant ratio, m_{fuel} is the mass of fuel, and m_{oxigen} is the mass of oxygen.

The equivalence ratio is then defined as follows:

$$\Phi = \frac{\left(F/O\right)_{actual}}{\left(F/O\right)_{stoichhometric}} = \frac{\left(m_{fuel}/m_{oxygen}\right)_{actual}}{\left(m_{fuel}/m_{oxygen}\right)_{stoichhometric}} \quad (2.6)$$

where Φ is the equivalence ratio.

When several gases are mixed in explosions, the mole fraction is defined by

$$X_i = \frac{Y_i/M_i}{\sum_{i=1}^{N} Y_i/M_i} \quad (2.7)$$

The mass fraction is defined as follows:

$$Y_i = \frac{X_i M_i}{\sum_{i=1}^{N} X_i M_i} \quad (2.8)$$

The ideal gas law for a mixture is given by

$$p = \rho RT \tag{2.9}$$

where p is the absolute pressure, ρ is the density, R is the gas constant of a mixture, and T is the absolute temperature.

For a perfect gas, Dalton's law is represented by

$$p = \sum_{i=1}^{N} p_i = \frac{R_u T}{V} \sum_{i=1}^{N} n_i \tag{2.10}$$

where R_u is the universal gas constant and V is the volume.

The isentropic ratio is defined as follows:

$$\gamma = \frac{c_p}{c_v} \tag{2.11}$$

where γ is the isentropic ratio and c_p and c_v are the specific heat capacities at constant pressure and volume, respectively.

The speed of sound is defined by

$$c \equiv \sqrt{\gamma RT} = \sqrt{\gamma \frac{\rho}{p}} \tag{2.12}$$

where c is the speed of sound.

The relation between blast pressure-density-temperature is given as follows:

$$\left(\frac{p}{p_0}\right) = \left(\frac{\rho}{\rho_0}\right)^{\gamma} = \left(\frac{Y}{Y_0}\right)^{\gamma/(\gamma-1)} = \left[1 + \frac{(\gamma-1)}{2}\left(\frac{u}{c}\right)^2\right]^{-\gamma/(\gamma-1)} \tag{2.13}$$

where p_0 is the ambient pressure, ρ_0 is the initial density, Y_0 is the initial mass fraction, and u is the flow velocity.

2.2.2 Stoichiometric Reaction

Combustion is a burning process by which a fuel is oxidized with an oxidant (usually air), producing heat and light. The chemical process of reaction can be given as follows:

$$C_{nc}H_{nh}O_{no} + \alpha O_2 \rightarrow ncCO_2 + bH_2O + Q \qquad (2.14)$$

When both the fuel and oxidant disappear entirely after the reaction is completed, the process is termed a stoichiometric reaction. The stoichiometric amount of oxidant on a molar basis can be defined by

$$\alpha = nc + \frac{nh}{4} - \frac{no}{2} \qquad (2.15)$$

where nc is the number of carbons, nh is the number of hydrogens, and no is the number of oxygens.

2.3. Governing Equations for Fluid Flow (Dispersion and explosion)

The conservation of mass is given by

$$\frac{\partial}{\partial t}(\beta_v \rho) + \frac{\partial}{\partial x_i}(\beta_i \rho u_i) = \frac{\dot{m}}{V} \qquad (2.16)$$

where β_v is the volume porosity, β_i and u_i are the area porosity and mean velocity in the *i*th direction, respectively, and $\dot{m}$ is the mass rate.

The momentum equation is given by

$$\frac{\partial}{\partial t}(\beta_v \rho u_i) + \frac{\partial}{\partial x_j}(\beta_j \rho u_j u_i) = -\beta_v \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\beta_j \sigma_{ij}) + F_{o,i} + \beta_v F_{w,i} + \beta_v(\rho - \rho_0) g_i$$

$$F_{o,i} = -\rho \left| \frac{\partial \beta}{\partial x_i} \right| u_i |u_i| \qquad (2.17)$$

where σ_{ij} is the stress tensor, $F_{o,i}$ and $F_{w,i}$ are the obstruction and wall friction forces, respectively, and g_i is the gravitational acceleration in the *i*th direction.

The transport equation for enthalpy is given by

$$\frac{\partial}{\partial t}(\beta_v \rho h)+\frac{\partial}{\partial x_j}(\beta_j \rho u_j h)=\frac{\partial}{\partial x_j}\left(\beta_j \frac{\mu_{eff}}{\sigma_h}\frac{\partial h}{\partial x_j}\right)+\beta_v \frac{Dp}{Dt}+\frac{\dot{Q}}{V} \tag{2.18}$$

where h is the specific enthalpy, μ_{eff} is the effective viscosity, σ_h is the Prandtl-Schmidt number of specific enthalpy (typically σ_h = 0.7), and $\dot{Q}$ is the heat rate.

The transport equation for fuel mass fraction is given by

$$\frac{\partial}{\partial t}(\beta_v \rho Y_{fuel})+\frac{\partial}{\partial x_j}(\beta_j \rho u_j Y_{fuel})=\frac{\partial}{\partial x_j}\left(\beta_j \frac{\mu_{eff}}{\sigma_{fuel}}\frac{\partial Y_{fuel}}{\partial x_j}\right)+R_{fuel} \tag{2.19}$$

where Y_{fuel} is the mass fraction of fuel, σ_{fuel} is the Prandtl-Schmidt number of fuel (typically σ_{fuel} = 0.7), and R_{fuel} is the fuel reaction rate.

The transport equation for turbulent kinetic energy is given by

$$\frac{\partial}{\partial t}(\beta_v \rho k)+\frac{\partial}{\partial x_j}(\beta_j \rho u_j k)=\frac{\partial}{\partial x_j}\left(\beta_j \frac{\mu_{eff}}{\sigma_k}\frac{\partial k}{\partial x_j}\right)+\beta_v P_k-\beta_v \rho \varepsilon \tag{2.20}$$

where k is the turbulent kinetic energy, σ_k is the Prandtl-Schmidt number of turbulent kinetic energy (typically σ_k = 1.00), P_k is the gauge pressure of kinetic energy, and ε is the dissipation of turbulent kinetic energy.

The transport equation for the dissipation rate of turbulent kinetic energy is given by

$$\frac{\partial}{\partial t}(\beta_v \rho \varepsilon)+\frac{\partial}{\partial x_j}(\beta_j \rho u_j \varepsilon)=\frac{\partial}{\partial x_j}\left(\beta_j \frac{\mu_{eff}}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right)+\beta_v P_\varepsilon-C_{2\varepsilon}\beta_v \rho \frac{\varepsilon^2}{k} \tag{2.21}$$

where σ_ε is the Prandtl-Schmidt number of the dissipation rate of turbulent kinetic energy (typically σ_ε = 1.30), P_ε is the gauge pressure of the dissipation rate of kinetic energy, and $C_{2\varepsilon}$ is the constant in the $k-\varepsilon$ equation (typically $C_{2\varepsilon}$ = 1.92).

2.4 Turbulence Model (k-ε Model)

In industry practice, the $k-\varepsilon$ model is often applied to model turbulence in association with hydrocarbon explosions. In this model, two additional transport equations are solved: one for turbulent kinetic energy and one for the dissipation of turbulent kinetic energy.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right)+2\mu_t E_{ij}{}^2-\rho\varepsilon \tag{2.22}$$

where E_{ij} is the component of rate of deformation.

The turbulence model for the dissipation rate of turbulent kinetic energy is given by

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}{}^2-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{2.23}$$

where $C_{1\varepsilon}$ is the constant in the $k-\varepsilon$ equation (typically $C_{1\varepsilon}$ = 1.44).

2.5 Wind Boundary (Dispersion)

In hydrocarbon explosions, structural responses are affected by wind boundaries, which may reproduce the properties of the atmospheric boundary layer near Earth's surface. In industry practice, the concept of a characteristic length scale is often applied in association with buoyancy effects on the atmospheric boundary layer (Monin and Obukhov, 1954).

$$L=\frac{\rho_{air}c_p T_{air}(u^*)^3}{\kappa g H_s} \tag{2.24}$$

where L is the Monin-Obukhov length scale, ρ_{air} and T_{air} are the absolute pressure and temperature of the air, respectively, u^* is the friction velocity, κ is the Von Karman constant (typically κ = 0.41), and H_s is the sensible heat flux from the surface. Table 2.1 indicates the Monin-Obukhov lengths and stability, which are an interpretation of the Monin-Obukhov lengths with respect to atmospheric stability.

Table 2.1. Monin-Obukhow lengths and stability

Monin-Obukhov length (m)	Stability
Small negative, $-100 < L$	Very unstable
Large negative, $-10^5 < L < -100$	Unstable
Very large, $\lvert L \rvert > 10^5$	Neutral
Large positive, $10 < L < 10^5$	Stable
Small positive, $0 < L < 10$	Very stable

2.6 Combustion Model

An explosion may be escalated by ignition of a premixed cloud of fuel and oxidant. However, a steady non-turbulent premix of fuel and oxidant may burn with a laminar burning velocity before escalation.

$$S_L^0 = S_L^0\left(fuel, \Phi\right) \quad (2.25)$$

The fuel and the equivalence ratio F affect the laminar burning velocity, which is zero, or mixtures with fuel contents below the lower flammability limit (LFL) or above the upper flammability limit (UFL) will not burn. In a hydrocarbon explosion, the flame accelerates and becomes turbulent. The turbulent burning velocity is much greater than the laminar one because the reactants and products are much better mixed. In numerical models of combustion, the correlations are used for both laminar and turbulent burning velocities that originate from experimental work.

In industry practice, a hypothesis is applied in which the reaction zone in a premixed flame is thinner than the practical grid resolutions. In this case, the flame needs to be modeled where the flame zone is thickened by increasing the diffusion with a factor b and reducing the reaction rate with a factor 1/b. In this regard, the flame model is often called the β-model.

2.6.1 Flame model

The diffusion coefficient D for fuel comes from the transport equation for fuel,

$$D = \frac{\mu_{eff}}{\sigma_{fuel}} \tag{2.26}$$

where D is the diffusion coefficient.

A dimensionless reaction rate W is defined by adjusting D and W as follows:

$$W^* = \frac{W}{\beta} = W\frac{l_{LT}}{\Delta g} \tag{2.27a}$$

$$D^* = D\beta = D\frac{\Delta g}{l_{LT}} \tag{2.27b}$$

where W is the dimensionless reaction rate, β is the transformation factor in the β-model, l_{LT} is the mixing length in the β-model, and D is the diffusion coefficient.

2.6.2 Burning Velocity Model

As far as a weak ignition source is associated with a combustible cloud under quiescent conditions, the initial burning process may be laminar. In this case, the front of the flame may be smooth, and the propagation of flame is governed by thermal and/or molecular diffusion processes. Immediately after the initial stage, the flame surface is wrinkled by instabilities from various sources (e.g., ignition, flow dynamics, Rayleigh-Taylor) where the speed of flame increases and becomes quasi-laminar. Depending on the flow conditions, a transition period may occur, and eventually, the turbulent burning regime is reached.

It is obvious that the laminar burning velocity depends on the type of fuel, the fuel-air mixture, and the pressure. For a mixture of fuels, the laminar burning velocity is estimated as the volume-weighted average. The laminar burning velocity is given as a function of the pressure as follows:

$$S_L = S_L^0 \left(\frac{P}{P_0} \right)^{\gamma_P} \tag{2.28}$$

where γ_P is the pressure exponent for the laminar burning velocity, which is a fuel-dependent parameter.

In the quasi-laminar regime, the turbulent burning velocity is given by

$$S_{QL} = S_L \left(1 + \chi \min \left(\left(\frac{R_{flame}}{3} \right)^{0.5}, 1 \right) \right) \tag{2.29}$$

where R_{flame} is the flame radius and χ is the fuel-dependent constant.

2.7 Numerical Models for Nonlinear Structural Responses

The equations of the dynamic equilibrium are solved numerically (Paik and Thayamballi, 2003). Implicit and explicit approaches are relevant. For the explicit scheme associated with the time integration of the dynamic equations of motion, the displacements at time $t + \Delta t$ are calculated from the equilibrium of the structure at time t when the effect of a damping matrix is neglected:

$$[m][\ddot{w}]^t = [F]^t - [S]^t \tag{2.30}$$

where $[m]$ is the mass matrix of the structure, $[w]^t$ is the vector of nodal displacements and rotations at time t, $[\ddot{w}]^t$ is the corresponding acceleration vector, $[F]^t$ is the vector of the external nodal forces, and $[S]^t$ is the vector of the internal forces-moments equivalent to the internal stresses at time t.

The vector $[S]^t$ varies depending on the configuration of the structure with the displacements at time t, the stresses, and the material constitutive models. For a linear elastic response, $[S]^t$ is given by

$$[S]^t = [K][w]^t \tag{2.31}$$

where $[K]$ is the constant in the time stiffness matrix.

The nodal point displacements at the next time step, $t+\Delta t$, are obtained by substituting an approximation for the acceleration vector into the above equation. The most common approximation used is that obtained by using the central difference operator, given by

$$[\ddot{w}]^t = \frac{[w]^{t+\Delta t} - 2[w]^t + [w]^{t-\Delta t}}{\Delta t^2} \tag{2.32}$$

By substituting Equation (2.31) into Equation (2.29), the displacements at time $t+\Delta t$ are calculated. In practical problems, $[m]$ is often a diagonal matrix. In this case, the equation is uncoupled, and therefore the structural responses at time $t+\Delta t$ are computed easily, where the inverse of any coefficient matrix of the system is not necessary. This is the main advantage of the use of the implicit time integration method. The major disadvantage is that relatively very small solution time increments must be used to obtain a stable and reliable solution.

For the implicit time integration scheme, the displacements at time $t+\Delta t$ are obtained from the equilibrium of the structure as follows:

$$[m][\ddot{w}]^{t+\Delta t} + [K]^t \Delta[w]^t = [F]^{t+\Delta t} - [S]^t \tag{2.33}$$

where $[K]^t$ is the tangent stiffness matrix of the structure at time t and $\Delta[w]^t = [w]^{t+\Delta t} - [w]^t$.

Several implicit schemes are available to approximate the acceleration $[\ddot{w}]^{t+\Delta t}$ in Equation (2.32). One is the trapezoidal rule, which is given by

$$[\dot{w}]^{t+\Delta t} = [\dot{w}]^t + \frac{\Delta t}{2}\left([\ddot{w}]^t + [\ddot{w}]^{t+\Delta t}\right) \quad \text{and} \quad [w]^{t+\Delta t} = [w]^t + \frac{\Delta t}{2}\left([\dot{w}]^t + [\dot{w}]^{t+\Delta t}\right) \tag{2.34}$$

By substituting Equation (2.33) into Equation (2.32), the equilibrium equation is transformed into the following equation:

$$\left([K]^t + \frac{4}{\Delta t^2}[m]\right)\Delta[w]^t = [F]^{t+\Delta t} - [S]^t + [m]\left(\frac{4}{\Delta t}[\dot{w}]^t + [\ddot{w}]^t\right) \qquad (2.35)$$

Equation (2.34) can be solved for the displacement increments, $\Delta[w]^t$, where the inversion of a matrix is required with a time step that is larger than the one required for the explicit solution scheme.

3. Current Rules and Industry Practices

3.1 American Bureau of Shipping (ABS)

The American Bureau of Shipping (ABS, 2013) specifies guideline for evaluation of the risk of explosion that consists of two steps, preliminary and detailed risk assessment, as shown in Figure 2.4, and the analysis of nonlinear structural responses is a key task. The ABS procedure applies three steps of the analysis: i) screening, ii) strength-level analysis, and iii) ductility-level analysis, similar to API (2006), considering that the profile of blast pressure loads is idealized as shown in Figure 2.5.

- Screening analysis is the simplest approach with which to assess the structural response under a blast event. This method applies an equivalent static load and evaluates the response by means of accidental limit state-based design checks. The equivalent static load is the peak overpressure in accordance with the strength level associated with the blast scaled by a dynamic load amplification factor.
- Strength-level analysis is a linear-elastic analysis of an equivalent static load corresponding to the blast overpressure, taking into account the effect of plasticity. The overpressure peak is represented by a dynamic load amplification factor.
- Ductility-level analysis takes into account the effects of geometric and

material nonlinearities as the most refined approach.

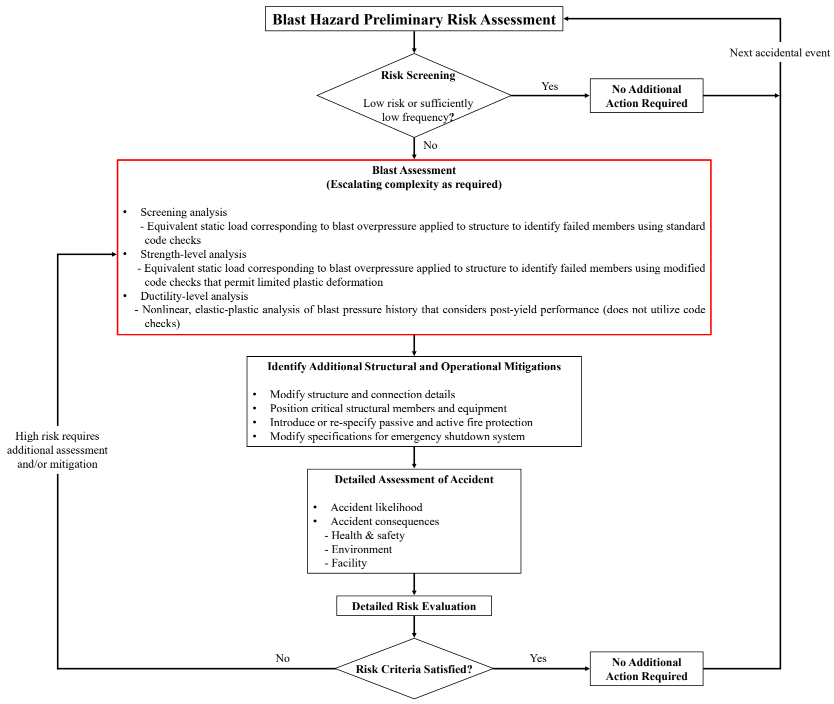


Figure 2.4. ABS procedure for assessment of structural safety against blast pressure loads (ABS, 2013).

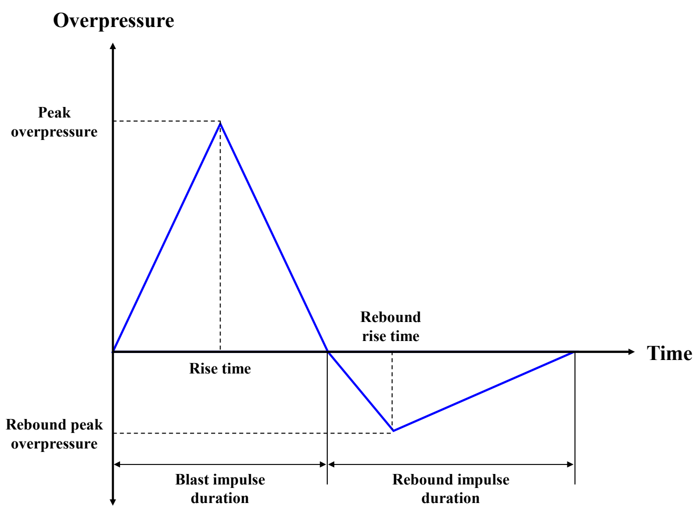


Figure 2.5. Profile of blast pressure loads (ABS, 2013).

3.2 American Petroleum Institute (API)

A prescriptive method is suggested by the American Petroleum Institute (API, 2006) to define the blast loads and assess the structural responses. Figure 2.6 shows the API procedure. Three kinds of models are relevant.

- Empirical models with overpressure correlated to experimental data associated with accuracy and applicability limited by the model database
- Phenomenological models with overpressure characterized by incorporating physical principles into empirical observations (i.e., interpreting observations so that they are consistent with fundamental theory)
- Numerical models with overpressure defined by solving the appropriate relationships for gas flow, combustion, and turbulence, that typically make use of computational fluid dynamics (CFD) principles

The numerical models are more refined than other models, but they require more time and effort. In this regard, the API procedure uses a prescriptive model associated with the nominal value of overpressure for specific areas of the structures. The API procedure is composed of four steps: selection of the concept type; establishment of the conditioning factors to apply; determination of nominal overpressures; and application of safety factors to account for data uncertainties.

Tables 2.2 and 2.3 indicate the nominal overpressures by the types of offshore installations and modification factors associated with the project parameters, respectively. For other cases not indicated in Table 2.3, design explosion loads from the explosion load exceedance curves with risk acceptance level are used. 10^{-3} to 10^{-4}/y of risk levels are generally recommended to be used depending on the performance criteria.

Methods for structural response assessment against blast pressure actions proposed by API are similar to those of ABS. The structural assessment is performed by a screening check, strength level analysis, and ductility level analysis, in that order.

Table 2.2. Nominal overpressures by the type of offshore installation (API, 2006)

Blast prone areas	Nominal overpressure in offshore installation type (bar)				
	Integrated production/drilling		Bridge linked production/ drilling (multiple platforms)	Production only	
	Single platform	TLP/Wet trees		Single jacket	Mono-hull FPSO*
Wellhead/ drill deck	2.50	2.50	2.00	-	-
Gas separation facilities	2.00	1.00	1.50	1.50	1.00
Gas treatment/ compression facilities	1.50	1.00	1.00	1.00	1.00
Turret (internal)	-	-	-	-	3.00
FPSO* main deck	-	-	-	-	2.00
TLP moon pool	-	2.00	-	-	-
TLP deck box	-	2.50	-	-	-
Other	1.00	0.75	1.00	1.00	0.50

* FPSO: Floating, Production, Storage and Offloading unit

Table 2.3. Load modifiers associated with project parameters (API, 2006)

Project parameters		Nominal blast load modifiers
Item	Range/rate/quantity	
Production rate	Less than 50,000 bbl/day	0.90
	50,000 to 100,000 bbl/day	1.05
	More than 100,000 bbl/day	1.10
Gas compression pressure	Less than 100 bar	1.00
	100 to 200 bar	1.05
	More than 200 bar	1.10
Gas composition	Normal	1.00
	Onerous	1.10
	More onerous	1.35
Production trains	1	0.90
	2	0.95
	4	1.10
Module footprint area	Less than 75,000 sqft	0.90*

	75,000 to 150,000 sqft	1.00
	More than 150,000 sqft	1.10
confinement	3 sides of more open	0.85
	1 to 2 sides open	0.95
	All sides closed	1.25
Module length to width aspect ratio	Less than 1.0	0.90
	1.0 to 1.7	1.05
	More than 1.7	1.10
Note: For small and very congested platforms (~10,000 sqft), the load modifier of 0.9 should not be applied to reduce the nominal explosion overpressure for module area. Note: Load modifier should not be applied to wellheads/drilling decks, moonpools, and FPSO main deck.		

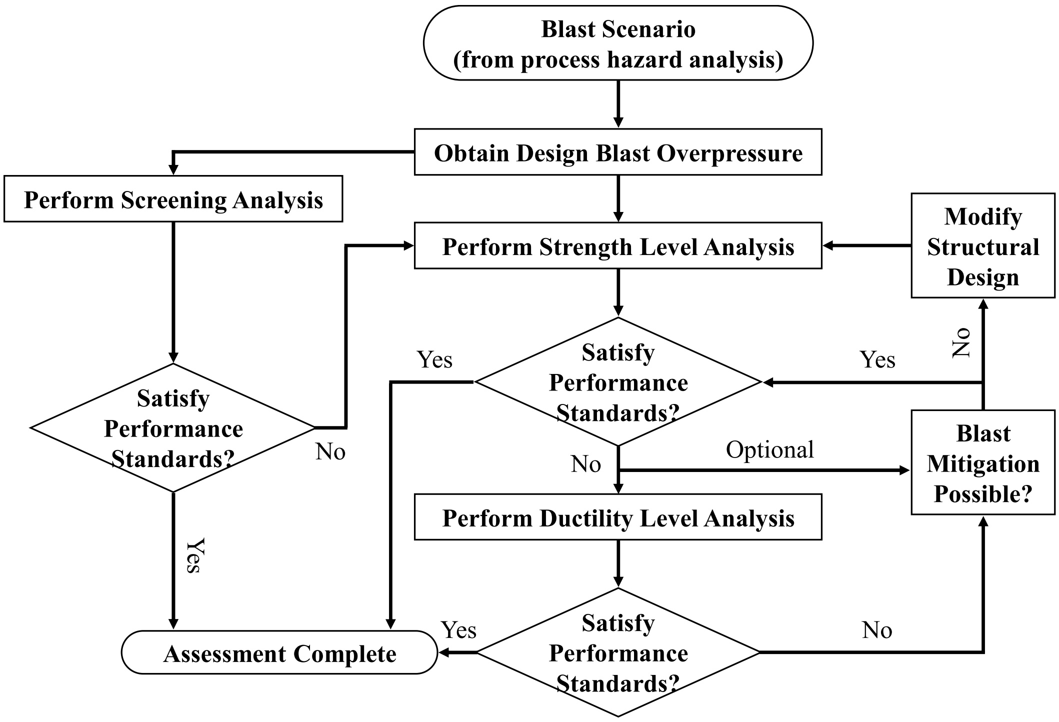


Figure 2.6. API procedure for assessment of structural safety against blast pressure loads (API, 2006).

3.3 Det Norske Veritas and Germanischer Lloyd (DNVGL)

Det Norske Veritas and Germanischer Lloyd (DNVGL, 2014) suggests a deterministic method for prediction of design explosion loads in terms of overpressure and pulse duration. The design loads are subdivided depending on the conditions of confinement and congestion. Table 2.4 summarizes the typical design explosion values. However, a specific analysis with the use of actual details is also recommended if accurate predictions are needed because the explosion overpressures depend on numerous variables.

Table 2.4. Nominal explosion design values proposed by DNVGL (2014)

Type of offshore installations	Working areas	Design blast overpressure (barg)	Pulse duration (s)
Drilling rig	Drill floor with cladded walls	0.1	0.2
	Shale shaker room with strong walls, medium sized	2.0	0.3
Mono-hull FPSO	Process area, small	0.3	0.2
	Process area, medium sized with no walls or roof	1.0	0.2
	Turret in hull, STP/STL room with access hatch	4.0	1.0
Mono-hull FPSO (Large)	Process area, large with no walls or roof	2.0	0.2
Production platform (Sumi-sub)	Process area, large with no or light walls, 3 storeys, grated mezzanine and upper decks	2.0	0.2
Production platform (Fixed)	Process area, medium sized, solid upper and lower decks, 3 storeys, 1 or 2 sides open	1.5	0.2
Integrated production and drilling	Process area and drilling module each medium sized on partly solid decks, 3 storeys, 3 sides open	1.5	0.2
	X-mas tree/wellhead area, medium sized with grated floors	1.0	0.2

For the structural design of offshore structures to protect against explosions, DNV-RP-C204 (DNVGL, 2010) proposes the use of nonlinear dynamic finite analysis or simple calculation methods based on single and/or multiple degree of freedom (SDOF and/or MDOF) analogies with idealized design blast loads. DNVGL (2010) classifies the analysis models that depend on the failure mode that a designer wishes to check. Figure 2.7 and Table 2.5 show the failure modes for two-way stiffened panel and recommended analytical models.

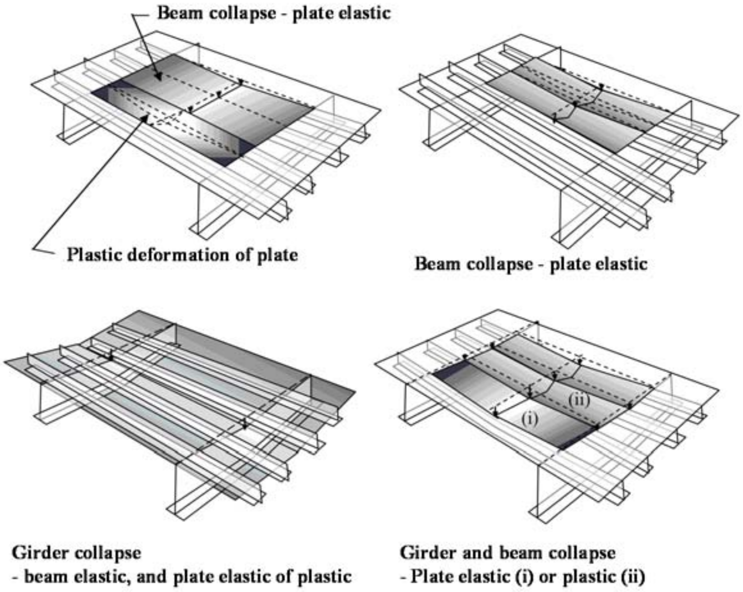


Figure 2.7. Failure modes for two-way stiffened panel for adoption of analysis models (DNVGL, 2010).

Table 2.5. Analytical models according to failure modes suggested by DNVGL (2010)

Failure modes	Simplified analysis models	Comments
Elastic-plastic deformation of plate	SDOF	-
Stiffener plastic – plate elastic	SDOF	Elastic, effective flange of plate.
Stiffener plastic – plate plastic	SDOF	Effective width of plate at mid span. Elastic, effective flange of plate at ends.
Girder plastic – stiffener and plating elastic	SDOF	Elastic, effective flange of plate with concentrated loads (stiffener reactions). Stiffener mass included.
Girder plastic – stiffener elastic – plate plastic	SDOF	Effective width of plate at girder mid span and ends. Stiffener mass included

Girder and stiffener plastic – plate elastic	MDOF	Dynamic reactions of stiffeners → loading for girders
Girder and stiffener plastic – plate plastic	MDOF	Dynamic reactions of stiffeners → loading for girders

3.4 Fire and Blast Information Group (FABIG)

The Fire and Blast Information Group (FABIG) Technical Note 4 specifies the necessity of establishing base, lower, and upper cases for the definitions of blast loads because realistic pressures cannot be obtained without the majority of the piping and structure congestion included in the geometry model for explosion simulations (FABIG, 1996).

Both SDOF and MDOF (finite-element method [FEM] in this section) can be used for structural response analysis, taking into account an idealized explosion load, as shown in Figure 2.3 (FABIG, 1996). FABIG also advises that dynamic effects such as a strain-rate effect should be considered when the structural response analysis under explosion is performed (FABIG, 1996).

3.5 International Standards Organization (ISO)

The International Standards Organization (ISO) specifies the international standard (ISO 19901-3), which suggests specific requirements for the design of topside structures against fires and explosions, as shown in Figure 2.8 (ISO, 2014). ISO proposes worst-case explosion actions with a fully detailed structure for escape routes and safe areas. Two probabilistic approaches used to assess explosion actions are suggested, as follows (ISO, 2014);

- Worst-case gas clouds containing stoichiometric mixes, for which it is certain or at least highly probable that the resulting actions are conservative;
- A distribution of gas clouds with associated probabilities, for which the resulting actions and their probabilities can be presented as a series of curves that show a range of overpressures with associated probabilities.

- In other areas, the design of explosion actions from explosion exceedance curves with acceptable risk levels are used (ISO, 2014). The risk levels proposed by ISO are as follows:
- Strength level explosion (SLB): an explosion with a probability of exceedance of around 10^{-2}/y;
- Ductility level explosion (DLB): an explosion with a probability of exceedance of around 10^{-4}/y.

This standard offers different action effect analysis methods depending on the probability of exceedance. For SLB, SDOF and/or linear finite-element analysis (FEA) are sufficient. Nonlinear FEA is also recommended for DLB.

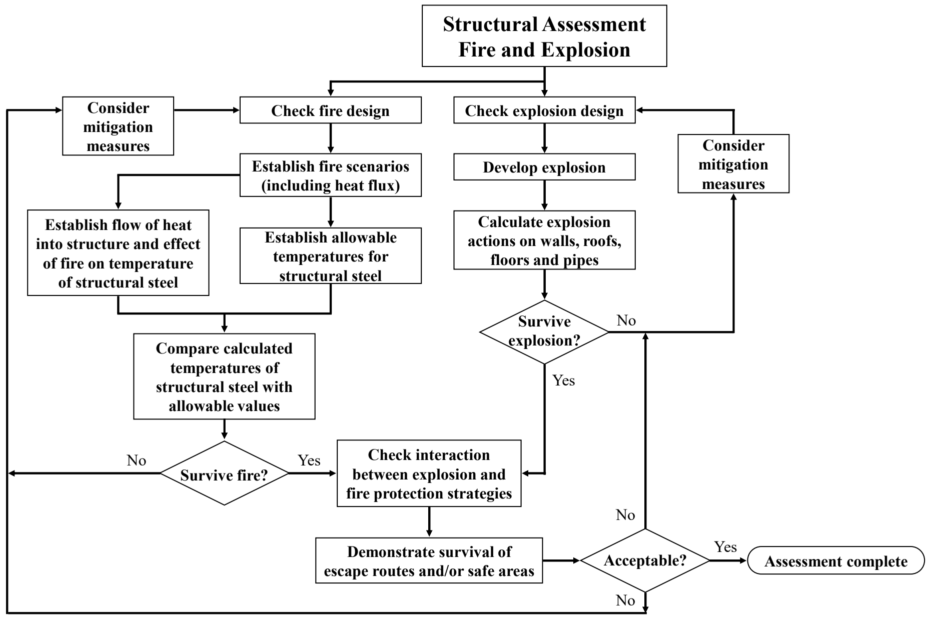


Figure 2.8. Procedure for detailed structural assessment for fires and explosions (ISO, 2014).

3.6 Lloyd's Register (LR)

The LR guideline recommends the use of a probabilistic approach to determine the design explosion loads (LR, 2014). It suggests CFD simulation of gas dispersion and explosion scenarios that consider various parameters.

This guideline suggests the use of a design chart such as a pressure-impulse (P-I) curve with the design load for the structural response assessment. A simple explosion design load can be determined where the design accidental load (DAL) is defined by the risk acceptance (i.e., frequency cut-off) criterion (LR, 2014).

3.7 NORSOK (Standards Norway)

NORSOK Z003 adopts a probabilistic approach to the determination of explosion loads. Figure 2.9 shows the schematics of a procedure for calculating explosion risk (explosion loads) (NORSOK, 2010). It considers the most influential factors regarding gas release (rate and direction), wind (speed and direction), ignition source, gas cloud (size, location, and concentration), and frequency/probability of each parameter in the definition of explosion loads, including the steps of gas dispersion and explosion (NORSOK, 2010).

This standard provides three different applications of probabilistic accidental loads to the structural response analysis as follows (NORSOK, 2010):

- Use the design explosion load calculated by both the pressure and impulse exceedance curves based on acceptance criteria;
- Evaluate the structural response based on the load-frequency relation, such as with a P-I diagram;
- Directly apply the calculated explosion-time history from each explosion scenario to the structural response analysis.

In another standard, NORSOK-N004, proposed by NORSOK (2004), processes for structural analysis and design against explosion events are noted in detail. The methods for structural response assessment of partial structures suggested by NORSOK (2004) are similar to the analysis proposed by DNVGL (2010), as shown in Figure 2.7 and Table 2.5. NORSOK (2010) recommends the proper use of SDOF, MDOF, linear FEM, and/or nonlinear FEM.

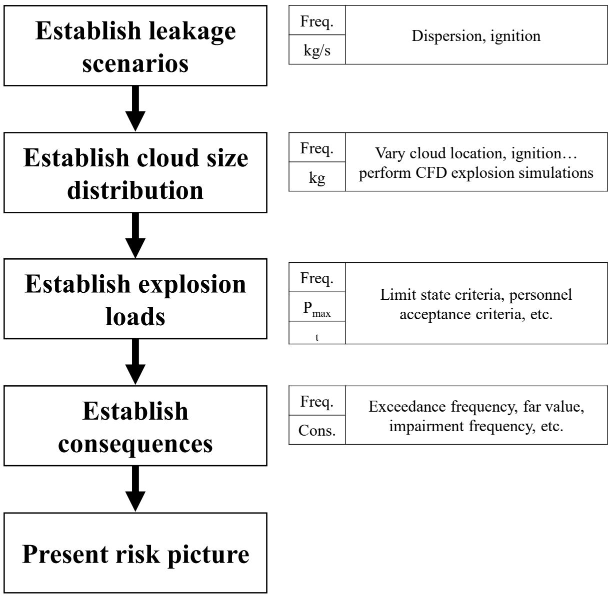


Figure 2.9. Schematics of the procedure for calculation of explosion risk (NORSOK, 2010).

4. Recommendations for Advanced Engineering Practice

4.1 Recommended Methods

To define explosion loads, either deterministic or probabilistic models may be used.

- Deterministic models for load prediction
  - Empirical models
  - Phenomenological models
  - CFD (FLACS) models
- Probabilistic models of explosion loads
  - Model proposed by NORSOK (2001)
  - Probabilistic explosion load assessment with the help of quantitative risk analysis

The following methods are also available for analysis of nonlinear structural responses under blast pressure loads associated with hydrocarbon explosions:

- SDOF
  - Static and quasi-static analysis with the dynamic amplification factor
  - Dynamic analysis (linear and nonlinear systems)
- Conservation of momentum and energy method
  - Impulsive analysis
- Design chart
  - P-I diagram based on FEA and SDOF
- FEM
  - Nonlinear static analysis to assess static resistance and the static failure modes
  - Nonlinear dynamic analysis with dynamic effects to assess the time-dependent response

In a probabilistic approach to define explosion loads, the following parameters may be considered:

- Location of the leak source
- Direction of the gas jet
- Flow rate of the leak
- Performance of barrier element

The profile of the blast pressure loads may be simplified as either a simplified triangular (or rectangular) pressure pulse considering the defined blast loads or a detailed pressure-time history calculated by CFD simulation. Nonlinear FEMs will be used to analyze the nonlinear structural responses:

- Dynamic responses to pressure-time histories (detailed or simplified, triangular loads)
- Nonlinear aspects of the structural response

In determining the explosion design loads, not only overpressure-related loads, but also drag force and drag force impulse, must be considered. The design loads are then defined in terms of four kinds of explosion load (overpressure, overpressure impulse, drag force, and drag force impulse) exceedance curves, with a 10^{-4}/y level of the risk acceptance criterion.

Three approaches are relevant for the computing actions and action effects of offshore installations against explosions, although the use of CFD and nonlinear FEM is strongly recommended for refined computations.

- SDOF
  - Application of an idealized explosion load
- Nonlinear FEM
  - Application of an idealized design load
  - Application of an actual explosion load using an interface between CFD and FEM
- Design chart
  - P-I diagram based on FEA and SDOF

Figure 2.10 presents the accidental limit state design procedure for explosion actions and action effects suggested by ISSC (2015), in which three methods are considered for the explosion load assessment, and four kinds of structural analysis approach with details for the structural design of topside structures under explosions are introduced depending on the design stages, as indicated in Table 2.6. Figure 2.11 presents an advanced procedure for the quantitative explosion risk assessment and management proposed by Paik et al. (2014).

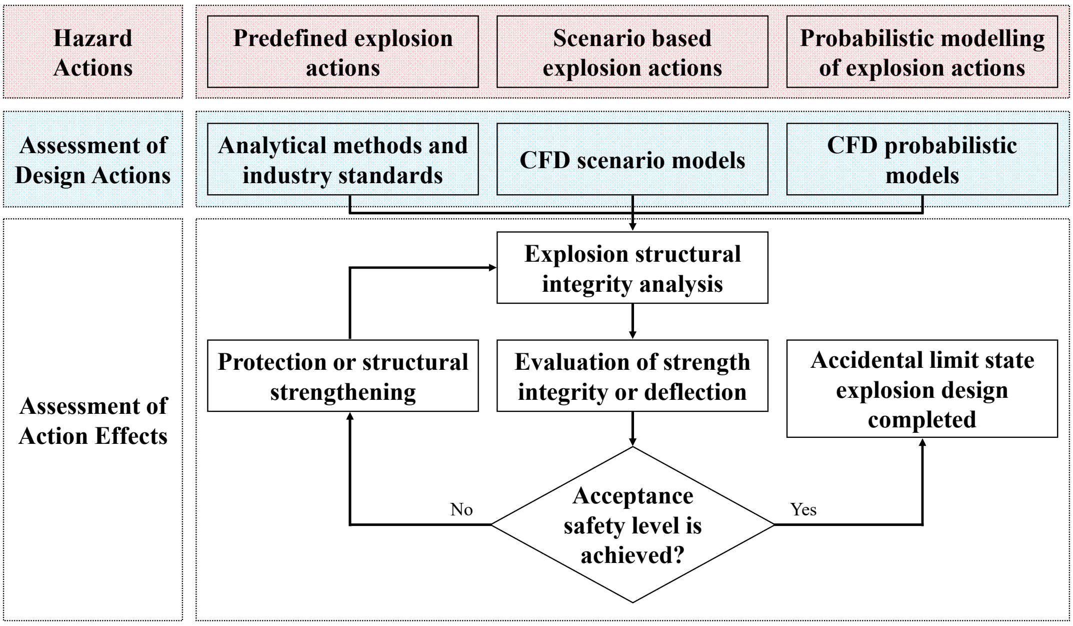


Figure 2.10. Accidental limit state design procedure for explosion actions and action effects (ISSC, 2015).

Table 2.6. Choice of design approach for topside structures under gas explosion loadings (ISSC, 2015)

Design stage	Analysis method	Dynamic behavior	Nonlinear behavior	Acceptance criteria	Structural model
Basic	SDOF method	- Intrinsic capability (or by DAF from response charts) - Enhanced yield stress (strain rate effect, ×1.2)	- Intrinsic capability - Enhanced yield stress (full plastic section, ×1.12) - Strain hardening (ultimate tensile strength /1.25)	- Ductility ratio	- Member by member - Plate only or Stiffened plate idealized as beam
Basic	Linear static FE analysis	- Intrinsic incapability and considered by DAF - Enhanced yield stress (strain rate effect, ×1.2)	- Intrinsic incapability and partially considered by modified code check - Enhanced yield stress (full plastic section, ×1.12) - Strain hardening (ultimate tensile strength /1.25)	- Yield Strength with modified code check (utilization factor ×1.5 for ASD*)	- Framed - Plate only - Stiffened plate (idealized stiffeners)
Detail	Nonlinear static FE analysis	- Intrinsic incapability and considered by DAF - Enhanced yield stress (strain rate effect, ×1.2)	- Intrinsic capability	- Strain limit (or ductility ratio)	- Framed - Plate only - Stiffened plate (idealized stiffeners)
Detail	Dynamic nonlinear FE analysis	- Intrinsic capability	- Intrinsic capability	- Strain limit (or ductility ratio)	- Framed - Plate only - Stiffened plate (idealized stiffeners)
Detail	Dynamic nonlinear FE analysis	- Intrinsic capability	- Intrinsic capability	- Strain limit (or ductility ratio)	- All structures

* ASD: Allowable Stress Design

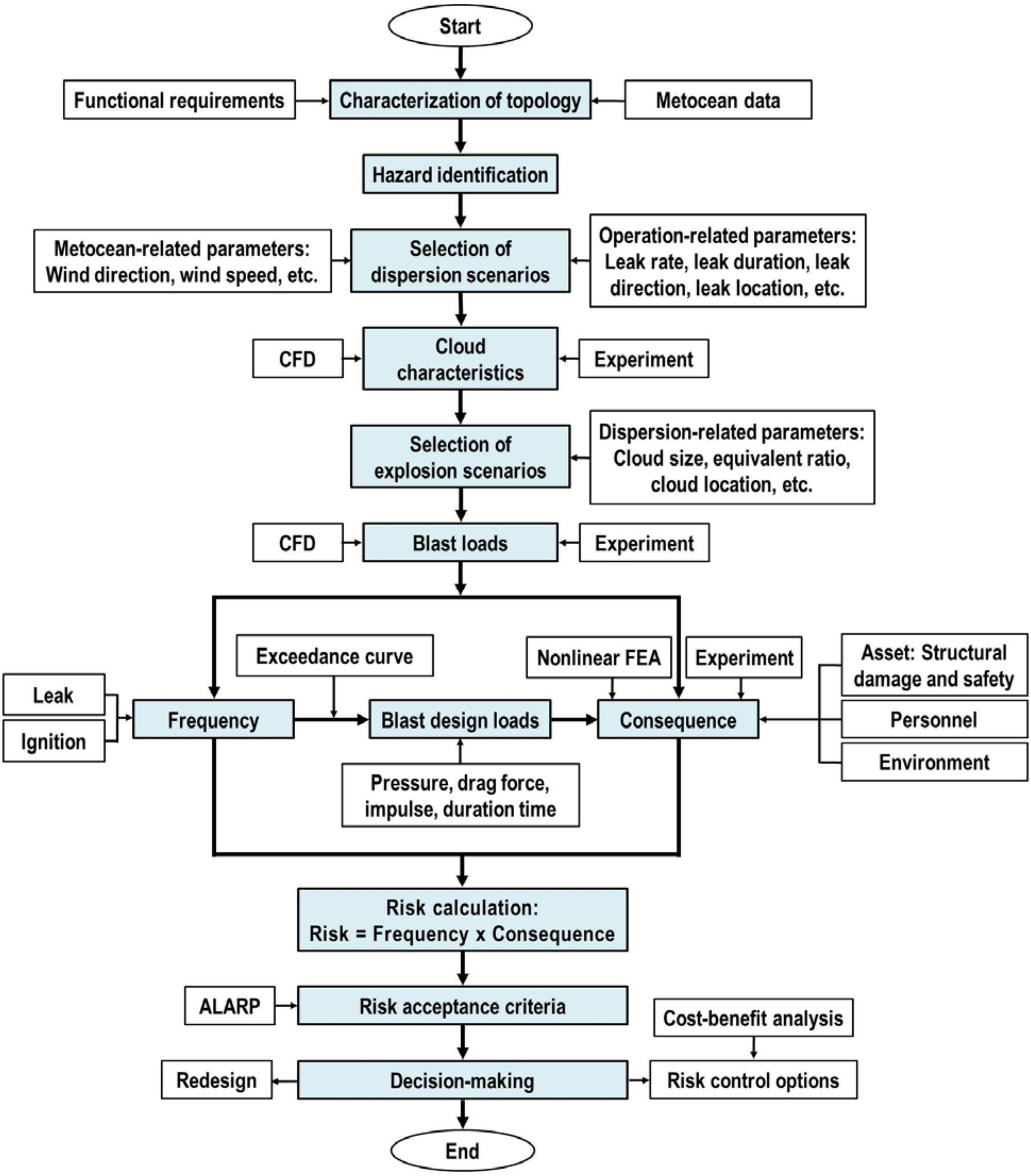


Figure 2.11. Procedure for quantitative explosion risk assessment and management. (ALARP = As Low As Reasonably Practicable risk) (Paik et al. 2014).

4.2 Comparisons between Recommended Practices

4.2.1 Definition of Explosion Loads

ABS, API, and DNVGL suggest a deterministic approach to the definition of design explosion loads (API, 2006; ABS, 2013; DNVGL, 2014), whereas LR and NORSOK propose a probabilistic method (NORSOK, 2010; LR, 2014). In contrast, FABIG (1996) recommends the use of explosion loads from predefined best- and worst-case explosion simulations. ISSC (2015) has issued good guidelines, including all possible and practicable approaches for the definition of hydrocarbon explosion actions.

4.2.2 Structural Assessment

For the structural response analysis, ABS and API use a stepwise analysis with screening, linear analysis, and nonlinear FEA (API, 2006; ABS, 2013). Others apply the linear, nonlinear dynamic finite analysis or simple calculation methods based on the SDOF or MDOF analogies with idealized design blast loads.

4.2.3 Comparison of Applied Methods

Table 2.7 summarizes a comparison of methods for the definition of explosion loads, application to structural assessment, and structural analysis methods. Most methods adopt an idealized explosion load obtained by a deterministic, predefined, or probabilistic approach. Simplified structural analysis methods with an idealized structural model are often recommended. However, the idealized approaches to explosion loads and/or structural analysis yield incorrect results compared with realistic models with respect to the actual explosion loads and the entire structural model.

Table 2.7. Comparison of methods for explosion load definition, structural analysis, and application of explosion load to structural analysis

	Approach to definition of explosion load	Application of explosion loads to structural assessment	Method for structural consequence analysis
ABS (2013)	Deterministic	Idealized explosion load	Screening analysis → linear FEM → NLFEM

API (2006)	Deterministic/ probabilistic	Idealized explosion load	Screening analysis → linear FEM → NLFEM
DNVGL (2010; 2014)	Deterministic	Idealized explosion load	SDOF or MDOF
FABIG (1996)	Predefined (lower and upper cases)	Idealized explosion load	SDOF or FEM
ISO (2014)	Probabilistic	Idealized explosion load of worst-case/ design load	SDOF or FEM
LR (2014)	Probabilistic	Idealized explosion load	P-I chart
NORSOK (2004; 2010)	Probabilistic	Idealized explosion load/ actual explosion load	SDOF, MDOF or FEM
Czujko (2001)	Deterministic/ probabilistic	Idealized explosion load	SDOF, analytical method, design chart or FEM
Vinnem (2007)	Probabilistic	Idealized explosion load	FEM
Paik and Czujko (2010) and Paik (2011)	Probabilistic	Idealized design explosion load	SDOF, NLFEM or design chart
Czujko and Paik (2015)	Probabilistic	Actual load	FEM
ISSC (2015)	Predefined, scenario based/ probabilistic	Idealized explosion load/ actual explosion load	SDOF, static or dynamic FEM

Note: FEM includes linear and nonlinear FEM in this table.

5. Applied Example

In this section, an applied example of structural response analysis subjected to the explosion is introduced.

5.1 Assessment of Explosion Loads

When the structural analysis with the quantitative explosion risk assessment approach is applied as shown in Figure 2.11, the explosion loads by the probabilistic method should be defined. In the assessment of explosion loads, gas explosion simulations are performed after gas dispersion simulations. Sometimes, however, the dispersion simulation can be skipped when the gas explosion scenarios are previously defined.

5.1.1 Gas Dispersion Simulation

Three-dimensional gas dispersion simulations are needed to investigate characteristics of gas clouds, which are used for gas explosion simulations. Gas dispersion simulations with probabilistic dispersion scenarios can identify the position and concentration of gas clouds.

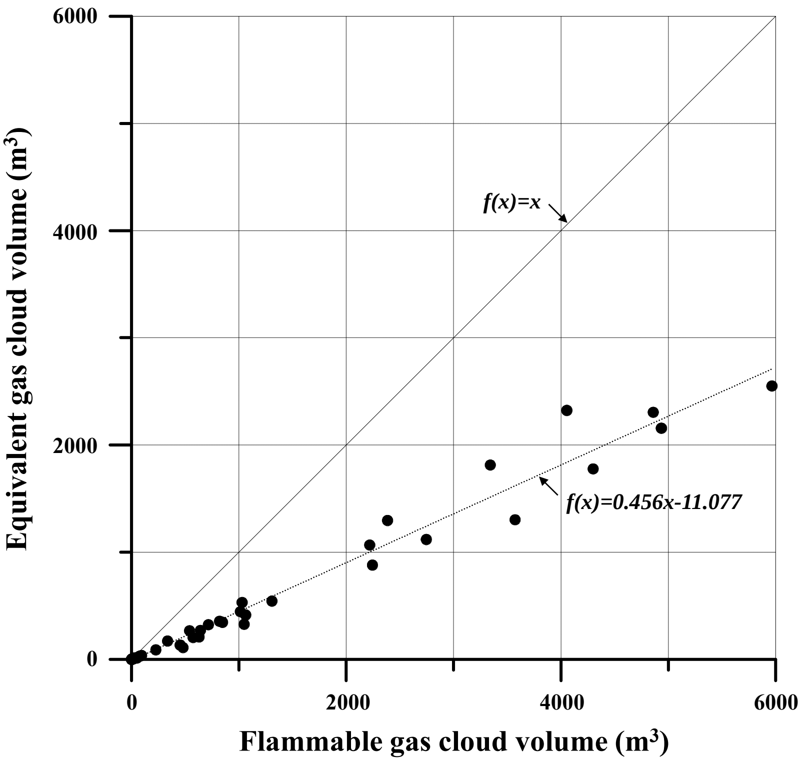


Figure 2.12. Relationship between the maximum flammable and equivalent gas clouds.

Figure 2.12 illustrates the relationship between the maximum flammable (actual) and equivalent gas clouds based on the gas dispersion simulations. The equivalent gas cloud has the perfect mixture of fuel and oxygen: no fuel or oxygen remain after combustion.

5.1.2 Gas Explosion Simulation

With the results of the gas dispersion scenarios, the explosion scenarios are defined for gas explosion simulations. Previously described explosion scenarios can also be used.

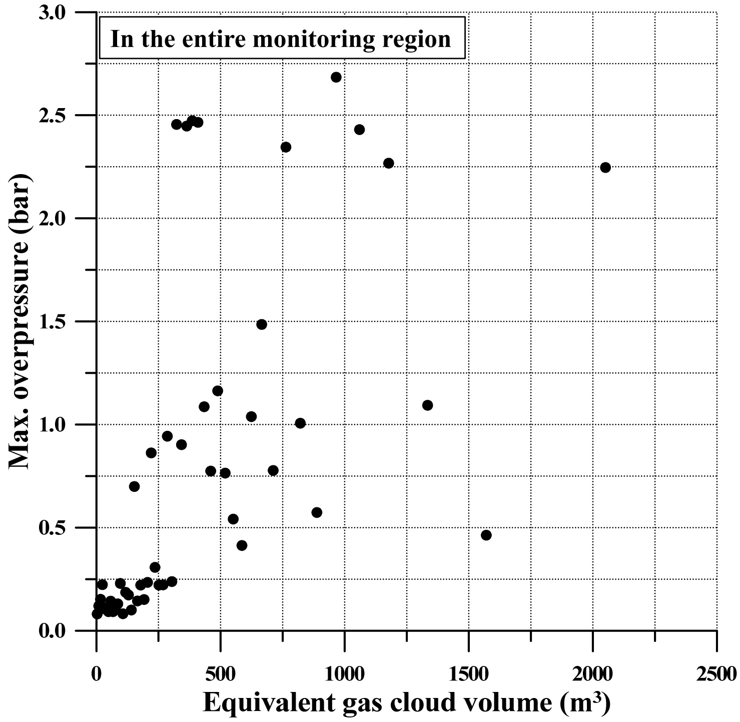


Figure 2.13. Effect of equivalent gas cloud volume on maximum overpressure.

Using the gas explosion simulations, the characteristics of explosion load, such as overpressure, impulse, drag force, and duration time, are investigated. Figure 2.13 shows an example of gas explosion simulation results that show the effect of gas cloud volume on maximum overpressure. The explosion load by gas explosion simulations with or without dispersion simulations is applied to the structure directly (actual explosion load) or indirectly (idealized explosion load).

5.2 Applying Explosion Loads to the Nonlinear Structural Response Analysis

There are two methods to apply the explosion load to the structural analysis, an idealized or an actual explosion load.

5.2.1 Idealized Explosion Loads

An idealized explosion load can be defined with several parameters, including peak positive pressure, peak positive pressure duration time (rising and decaying times), peak negative pressure, and negative pressure duration time, as shown in Figure 2.5.

Deterministic approach

In the deterministic approach, it is not necessary to perform both gas dispersion and explosion simulations because the explosion load is defined by rules and recommended practices, as described in section 3.

Probabilistic approach

In quantitative explosion risk assessment, which uses a probabilistic approach, the idealized design explosion load is defined with the characteristics of the explosion loads of many explosion scenarios, as introduced in section 5.1.2, and their frequency.

With the consequence (explosion load) and frequency, the exceedance curve for the definition of the design load is generated. The design load can then be defined with the As Low As Reasonably Practicable (ALARP) risk level. Figure 2.14 shows an example of the definition of maximum panel pressure, which is a parameter of design load in the explosion exceedance curve with an ARALP level of 10^{-4}/y, which is generally adopted for explosion risk assessment. The curve can be individually generated for factors such as panel pressure, overpressure, drag force, and duration time to define the idealized explosion load.

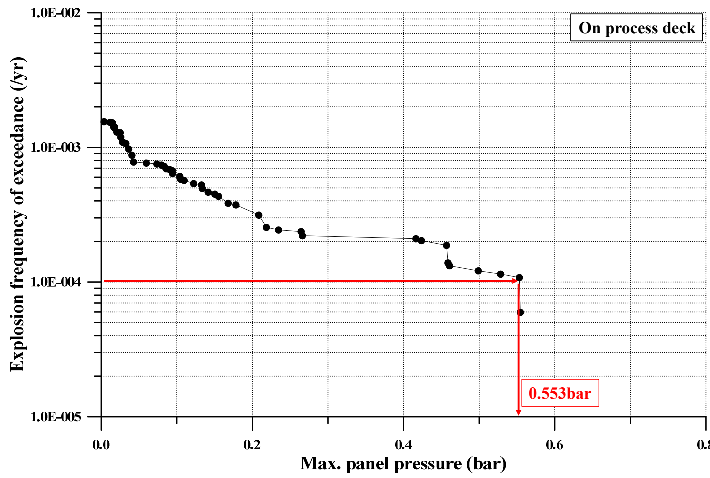


Figure 2.14. Example of the definition of design load with 10^{-4}/y of exceedance frequency.

5.2.1 Actual Explosion Loads

When actual explosion loads are applied, an interface program is needed to transfer explosion loads from the CFD simulation to nonlinear FE analysis. FLACS2DYNA is one of the interface programs. Figure 2.15 presents the concept of the FLACS2DYNA interface program. It deals with both the monitoring point and the control volume in FLACS. The pressure loads on the shell elements are mapped from the nearest monitoring points or the centers of the control volumes by the interface (FLACS2DYNA, 2013).

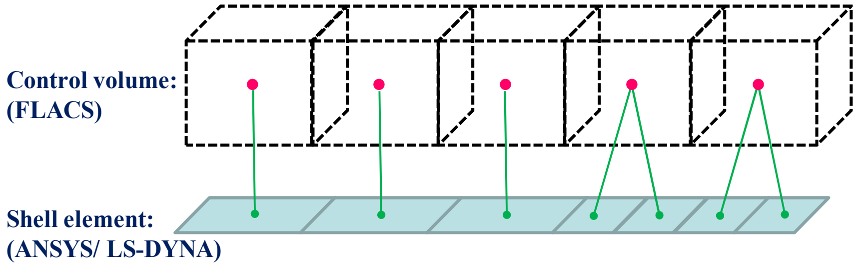


Figure 2.15. Concept of the FLACS2DYNA interface program (FLACS2DYNA, 2013)

Figure 2.16 shows a mapping view of the explosion loads between the FE model and monitoring points or control volume. Each actual explosion profile at each location can be transferred to the structure by the FLACS2DYNA interface program.

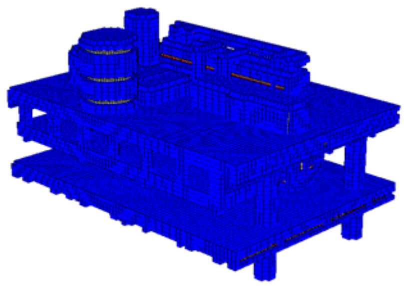
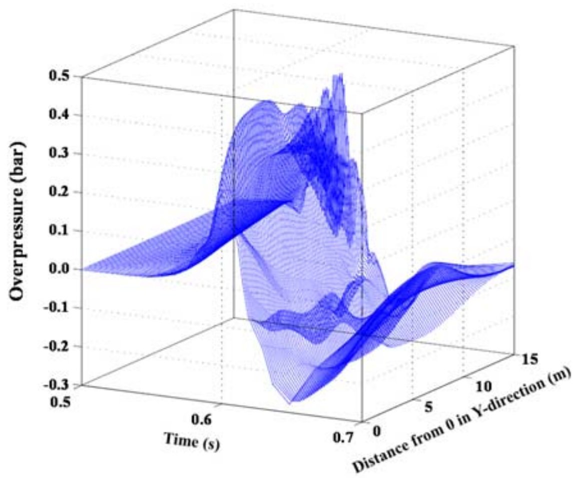
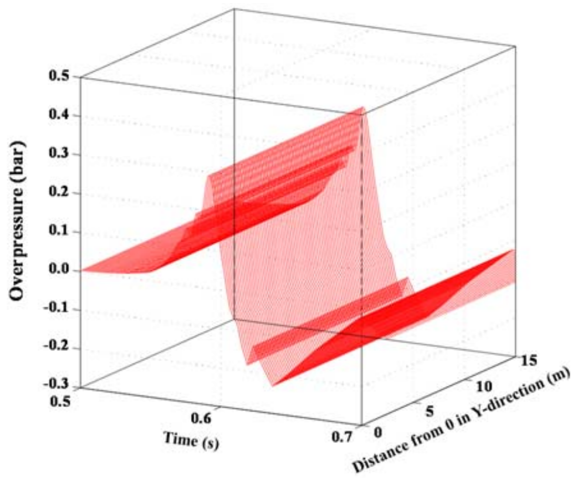


Figure 2.16. Mapping view of explosion loads between CVs in CFD and elements in FEM.

Figure 2.17 illustrates examples of the distribution of the actual and idealized overpressure time histories on specific scenario. The idealized load is uniformly distributed on an area. The figure shows large differences between the actual and idealized explosion loads.



(a) Actual overpressure profiles



(b) Idealized overpressure profiles

Figure 2.17. Distribution of actual and idealized overpressure-time histories.

5.3 Nonlinear Structural Response Analysis

After defining the explosion load by the deterministic or probabilistic approach, the nonlinear structural response analysis under the actual or idealized explosion load is performed.

Nonlinear FEA is generally used for structural response analysis, and factors (geometry modeling, element type, strain rate effect, boundary condition, etc.) that affect the structural responses under impact loads should be considered to obtain more accurate results in the nonlinear FE analysis. Figure 2.18 shows a generated FEM with shell elements.

Figures 2.19 through 2.22 show examples of structural response by nonlinear FE analysis under explosion loads to compare the responses by the actual and idealized explosion loads. Figures 2.19 and 2.20 present the deflection distributions of the blast wall and decks, respectively, and Figure 2.21 illustrates the total displacement. These figures show that the actual load application with nonuniform distributions causes the torsional moment, whereas the application of the idealized uniformly distributed loads could not capture this behavior.

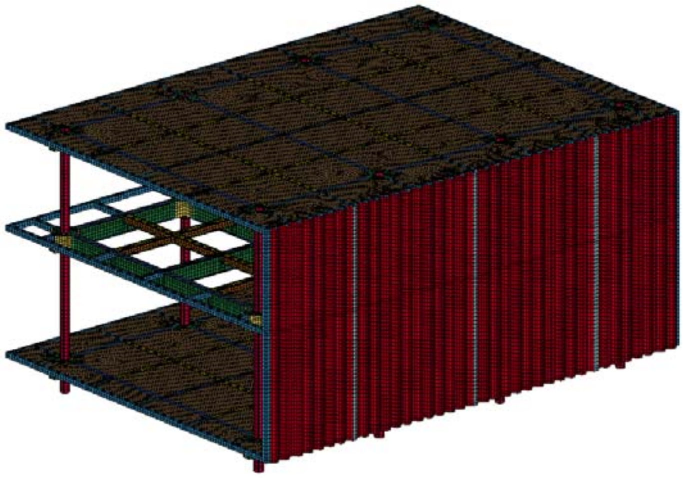
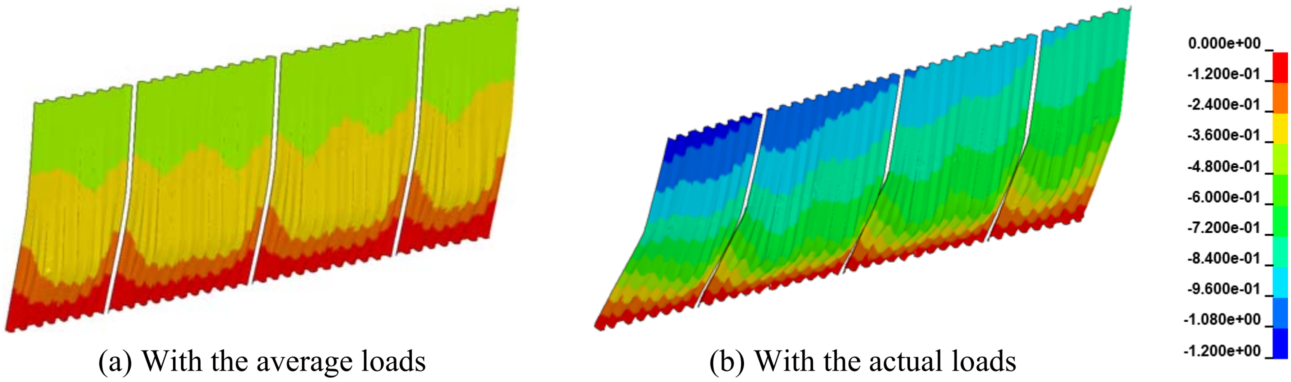


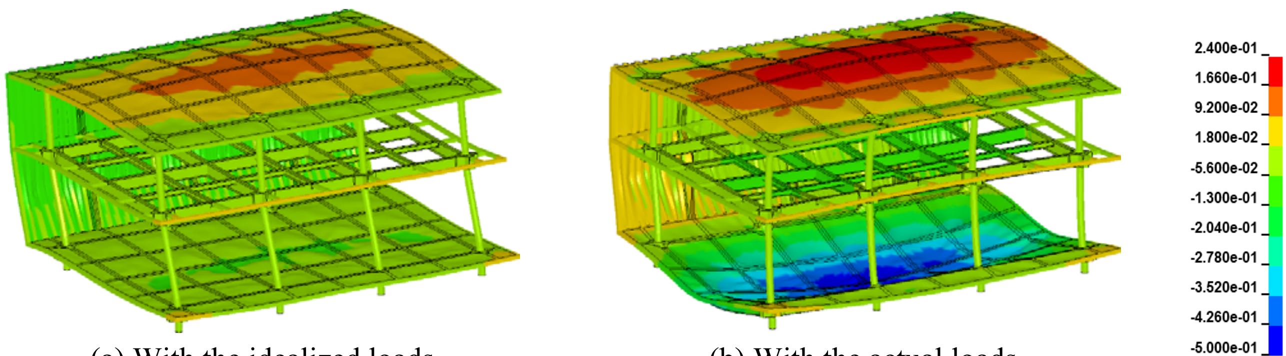
Figure 2.18. Example of the FEM for the topside structure with blast wall on FPSO



(a) With the average loads

(b) With the actual loads

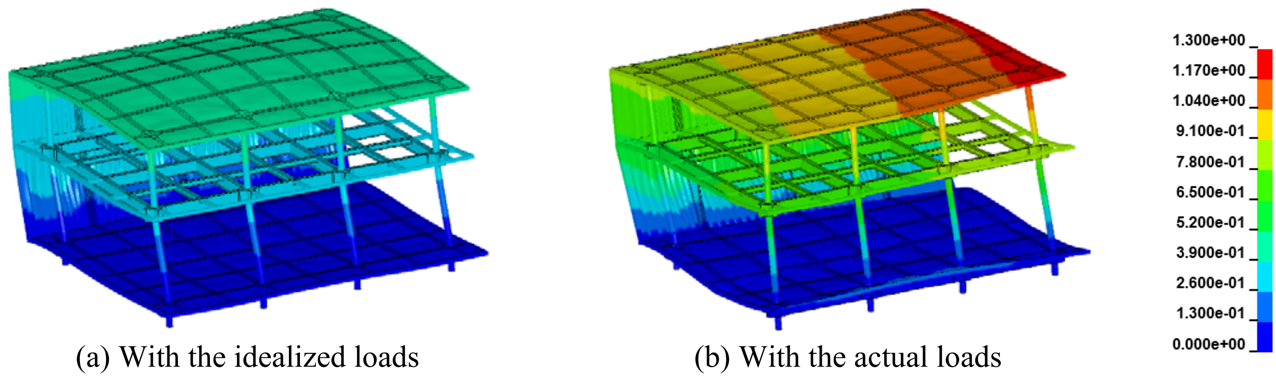
Figure 2.19. Deflection idealized of blast walls at 0.68 s plotted by an amplification factor of 5 (in m).



(a) With the idealized loads

(b) With the actual loads

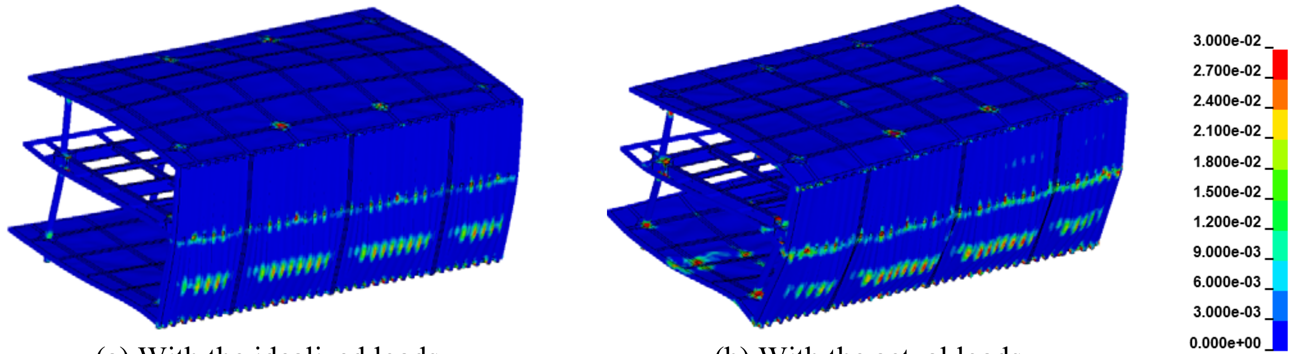
Figure 2.20. Deflection distribution of decks at 0.68 s plotted by an amplification factor of 5 (in m).



(a) With the idealized loads (b) With the actual loads

Figure 2.21. Total displacement distribution at 0.68 s plotted by an amplification factor of 5 (in m).

The structure subjected to the impact load is usually assessed by a plastic strain. Thus, the plastic strain should also be investigated as shown in Figure 2.22.



(a) With the idealized loads (b) With the actual loads

Figure 2.22. Plastic strain distribution at 1.0 s, with deformations plotted by an amplification factor of 5

6. Concluding Remarks and Further Studies

Risk is defined as either the product or a composite of (a) the probability or likelihood of occurrence of any accident or limit state that leads to severe consequences such as human injuries, environmental damage, and loss of property or financial expenditure, and (b) the resulting consequences (Paik and Thayamballi, 2007). The resulting consequences are associated with nonlinear structural responses, so the analysis of nonlinear structural responses is a key task within the framework of quantitative risk assessment and management. This chapter describes procedures for the nonlinear structural response analysis due to explosions. The definition of explosion loads is also described because it is required for analysis of structural responses.

In the conventional design of structures for explosion loads, it is usually assumed that the explosion loads are distributed uniformly among the individual structural members. However, actual explosion loads are not uniformly distributed, as illustrated in Figure 2.12. The structural responses as calculated with uniform or actual explosion pressure loads can differ greatly. The assumption of uniform loads can result in overestimation of structural damage in some cases and underestimation in others. Therefore, it is important to use the actual load distributions for accurate response analyses of structures.

A variety of influencing parameters are involved in the nonlinear structural responses associated with explosions. Some important factors include the blast load profile, strain rate, and temperature. The blast load profiles of explosions are the main factors to be considered in a structural integrity analysis. In general, idealized pressure loads are uniformly distributed. Four kinds of general idealization are available for blast loading shapes to different pulse shapes, as illustrated in Figure 2.13: the rise time until the peak pressure is reached, peak pressure, the decaying shape after the peak pressure is reached, and duration time. Among the options for analysis of these parameters, the symmetric triangular load approach is often adopted for dynamic structural analysis in considering hydrocarbon explosion accidents. Other approaches are used to analyze solid explosions, such as those caused by TNT associated with detonation.

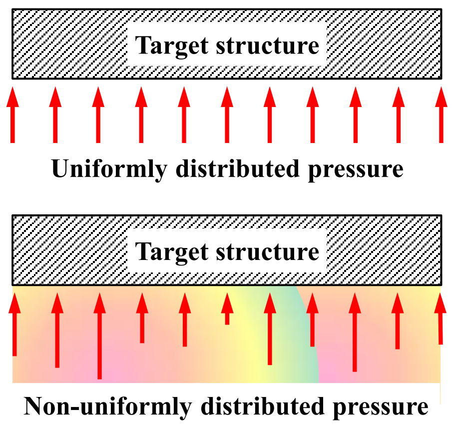
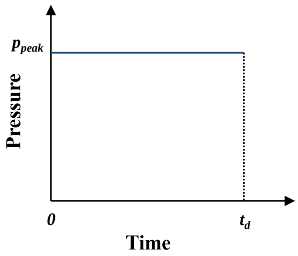
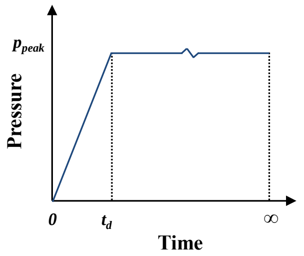


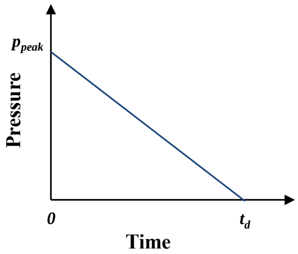
Figure 2.12. Uniform (upper) and non-uniform (lower) distribution of pressure loads in an explosion event.



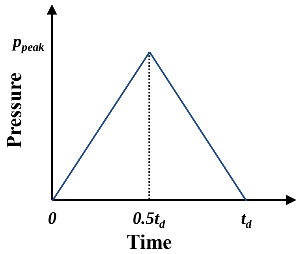
(a) Rectangular load



(b) Gradually applied load



(c) Linearly decaying load



(d) Symmetric triangular load

Figure 2.13. Different idealizations of blast loading shapes for structural analyses under explosion loads.

The uncertainties associated with load profile idealization can significantly affect the nonlinear structural responses. In this regard, the use of actual load profiles is recommended in addition to actual loads with non-uniformly distributed overpressure that are directly obtained from CFD simulations without any modifications.

Material properties are also major factors in the structural analysis of dynamic events. Structural analyses that make use of nonlinear FEM should consider the dynamic properties of the materials used. The material properties such as yield stress and fracture strain should be considered along with the dynamic effects, which are called strain rate effects. The duration time of explosions is extremely short—several milliseconds—thus, the effect of temperature is usually neglected for nonlinear structural response analysis because much more time is required to transfer the gas cloud temperature to the steel temperature due to heat and flame.

References

ABS, 2013, Accidental load analysis and design for offshore structures, American Bureau of Shipping, TX, USA.

API, 2006, Design of offshore facilities against fire and blast loading, API-RP2FB, American Petroleum Institute, WA, USA.

Czujko, J., 2001, Design of offshore facilities to resist gas explosion hazard: engineering handbook, CorrOcean ASA, Oslo, Norway.

Czujko, J. and Paik, J.K., 2015, A new method for accidental limit states design of thin-walled structures subjected to hydrocarbon explosion loads, Ships and Offshore Structures, 10(5): 460-469.

DNVGL, 2010, Design against accidental loads, DNV-RP-C204, Det Norske Veritas, Oslo, Norway.

DNVGL, 2014, Safety principles and arrangements, DNV-OS-A101, Det Norske Veritas, Oslo, Norway.

FABIG, 1996, Explosion resistant design of offshore structures, Technical Note 4, Fire and Blast Information Group, Berkshire, UK.

FLACS, 2016, User's manual for FLame ACceleration Simulator (FLACS) version 10.1, Gexcon AS, Bergen, Norway.

FLACS2DYNA, 2013, User's manual for an interface program between FLACS and ANSYS/LS-DYNA codes, The Korea Ship and Offshore Research Institute, Pusan National University, Busan, Korea.

ISO, 2014, Petroleum and natural gas industries - specific retirements for offshore structures - Part 3: topside structure, ISO 19901-3, International Standards Organization, Geneva, Swizerland.

ISSC, 2015, Committee V.1: Guidelines on the use of accidental limit states for the design of offshore structures, International Ship and Offshore Structures Congress, Rostock, Germany.

LR, 2014, Guideline for the calculation of probabilistic explosion loads, Report No. 104520/R1, Lloyd's Register, Southampton, UK.

Monin, A. S. and Obukhov, A. M., 1954, Basic laws of turbulent mixing in the surface layer of the atmosphere, Tr. Akad. Nauk SSSR Geofiz. 24: 163-187.

NORSOK, 2001, Risk and emergency preparedness analysis, NORSOK-Z013, Norway Standard, Lysaker, Norway.

NORSOK, 2004, Design of steel structures, NORSOK-N004, Norway Standard, Lysaker, Norway.

NORSOK, 2010, Risk and emergency preparedness assessment, NORSOK-Z003, Norway Standard, Lysaker, Norway.

Paik, J.K., 2011, Explosion and fire engineering on FPSOs (Phase III): nonlinear structural consequence analysis, Report No. EFEF-04, The Korea Ship and Offshore Research Institute, Pusan National University, Busan, Korea.

Paik, J.K., 2015, Making the case for adding variety to Goal-Based Standards, The Naval Architect, The Royal Institution of Naval Architects, UK, January 22-24.

Paik, J.K. and Czujko, J., 2010, Explosion and fire engineering on FPSOs (Phase II): definition of design explosion and fire loads, Report No. EFEF-03, The Korea Ship and Offshore Research Institute, Pusan National University, Busan, Korea.

Paik, J.K., Czujko, J., Kim, S.J., Lee, J.C., Seo, J.K., Kim, B.J. and Ha, Y.C., 2014, A new procedure for the nonlinear structural response analysis of offshore installations in explosions, Transactions of The Society of Naval Architects and Marine Engineers, 122: 1-33.

Paik, J.K. and Thayamballi, A.K., 2003, Ultimate limit state design of steel-plated structures, John Wiley & Sons, Chichester, UK.

Paik, J.K. and Thayamballi, A.K., 2007, Ship-shaped offshore installations: design, building and operation, Cambridge University Press, Cambridge, UK.

Vinnem, J.E., 2007, Offshore risk assessment - principles, modelling and application of QRA studies, Springer, Stavanger, Norway.