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A New Method for Structural Assessment of Topside Structure subjected to Hydrocarbon Explosions

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Abstract

The primary aim of this study is to propose a new method for structural assessment of topside structures on offshore installations subjected to hydrocarbon explosions. In the present study, lots of dispersion and explosion scenarios are selected by probabilistic approach, and analyzed for definition of actual explosion loads. Then, sets of actual explosion loads from CFD simulation are transferred by interface program between CFD and FEA, and nonlinear structural consequence analyses is performed. The structural consequences under actual explosion loads investigated by FEA are used for a consequence exceedance curve which is a new method for structural assessment proposed in this study. The consequence exceedance curve can reduce uncertainties from simplification of load, structure and procedure. In addition, it can be directly found the structural behavior of topside structure under explosions at risk acceptance level by consequence exceedance curve.

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Keywords: *New method; structural assessment; topside structure; hydrocarbon explosions*

1. Introduction

The structural design of offshores against explosions has been the focus of attention, and risk-based structural design has been recommended to prepare for explosions and minimize the damage from accidents. In addition, the Deepwater Horizon accident is a reminder of the importance of structural design to resist hydrocarbon explosions.

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To design against damage from explosion events, structural design in respect of hydrocarbon explosions with/without risk assessment and management is mandatory. In industries, simplified methods are usually applied to the structural consequence analysis of offshore installations for the structural designer's and/or engineer's convenience [1-8]. Some of the simplifications and their representative methods are as follows;

- Simplification of load: idealized explosion loads (e.g., symmetric triangular load)
- Simplification of structure: single degree of freedom
- Simplification of procedure: dynamic amplification factor

Although these simplified methods are quick and easy to use, it is difficult to find a realistic structural consequence [9]. Therefore, technical development is needed to effectively replace the simplified methods for structural safety design to withstand explosions.

For identification of a more accurate structural response, two technical problems, namely the application of explosion loads and detailed structural modelling, should be resolved. In this study, a new method for structural assessment of offshore installations in respect of explosions is proposed to solve the technical issues, using CFD, FEM, and an interface program between CFD and FEM.

The aims of this study are to introduce a new method for structural assessment of offshore installations exposed to hydrocarbon explosions where explosion loads from CFD are directly applied to the structure, and demonstrate an application of the new method.

In this study, a topside module is adopted for application. With the module, gas dispersion and explosion scenarios considering related parameters are selected by a probabilistic approach and analyzed. In addition, the explosion frequency of each explosion scenario considering the gas cloud and ignition probability is calculated.

Explosion loads obtained from gas explosion simulations are directly applied to the finite element structural model using an interface program. Finally, the new method which is consequence exceedance curve using the explosion frequency and structural consequence are suggested.

2. A new method for structural assessment of topside structure under explosion loads

For investigation of realistic structural response, and assessment, a new method is proposed in this study. Fig. 1 illustrates a difference of approaches to structural assessment subjected to explosion loads between the existing and new methods. Some parts of the new method take advantage of the existing methods.

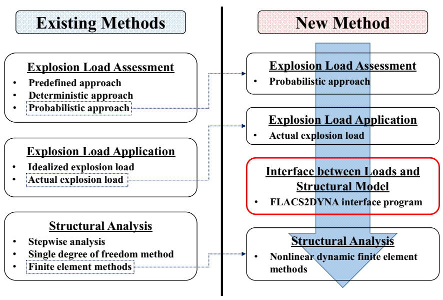


Fig. 1. Difference of approaches between the existing and new methods.

A big difference between the existing and new methods is that the new method adopts the interface program for transference of actual loads to structures. In addition, all parts, including explosion load assessment, load application, and structural analysis, are organically linked with one another using the interface program.

Another of new things in this study is that it suggests a consequence exceedance curve with the structural response considering actual explosion loads and explosion frequency for structural assessment of topside structure subjected to hydrocarbon explosions.

Fig. 2 presents a procedure for structural assessment of topside structure on offshore installation against explosions proposed in the present study. This procedure adopts a probabilistic approach to define explosion loads. Then, the actual pressure loads are directly applied to the nonlinear structural analysis using the interface between CFD and FEM.

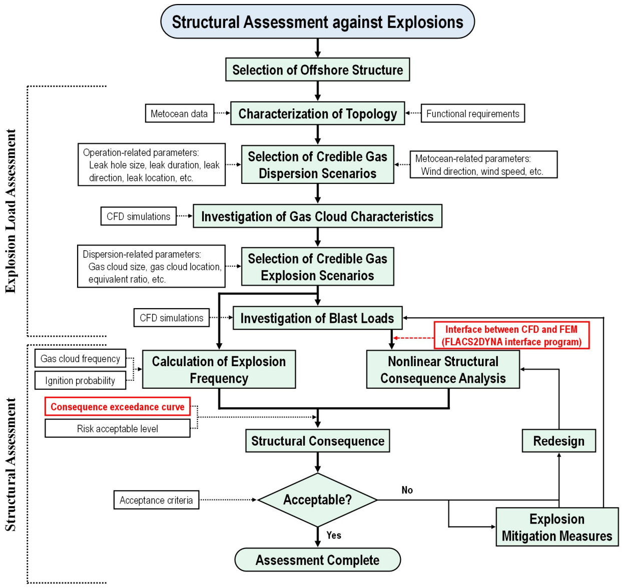


Fig. 2. A procedure for structural assessment of topside structure on offshore installation against explosions.

3. Target structure

In this study, the hypothetical FLNG vessel topside module is selected as a target structure for an applied examples including definition of explosion load, structural analysis, and structural assessment.

Fig. 3 presents the layout of VLCC class FLNG, and the layout and principal dimensions of the target structure. It is composed of three decks, blast wall, and process units (vessel and pipes).

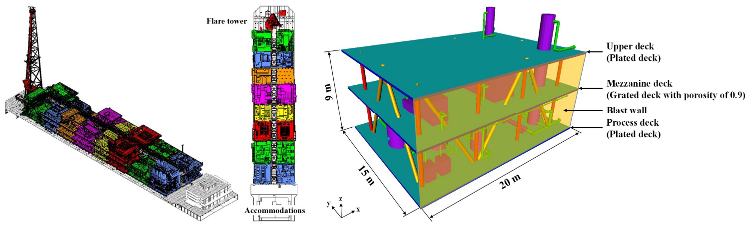


Fig. 3. Layout of FLNG installation (left), and layout and principal dimensions of the target structure (right).

4. Assessment of explosion loads

4.1. Selection of gas dispersion scenarios and simulations

In defining explosion loads using the prescriptive or qualitative approaches, gas dispersion simulation is not mandatory. In contrast, gas dispersion simulations with dispersion scenarios have to be conducted before the selection of explosion scenarios and analysis in the probabilistic assessment for obtaining the explosion loads.

When selecting gas dispersion scenarios, all possible parameters that can have an effect on gas dispersion associated with operating conditions should be considered. Gas dispersions can also be affected by environmental conditions, notably wind direction and speed [10].

In this study, the method for selection of 50 gas dispersion scenarios proposed by Paik and Czujko [10] is used, with seven parameters, namely wind direction, wind speed, leak rate, leak direction, and leak position.

For both dispersion and explosion simulations, the FLame ACceleration Simulator (FLACS) developed by GexCon AS is used. The FLACS code is a three-dimensional transient finite volume CFD program, and is used to simulate gas dispersion and explosion events [11].

For the gas dispersion simulations, a ground at the bottom of the structure also needs to be modelled to reflect the ground effect. The analysis extent of the model covers a much wider space compared to the structure size, in order to take into account the effects of turbulence associated with environmental conditions such as wind speed and direction. The gas composition of Liquefied Natural Gas (LNG) which is processed in FLNG is applied.

In the case of gas dispersion, it is recommended to use the grid size around the leak as per Eq. (1) [11].

$$A_{CV} < 2A_{leak} \tag{1}$$

where A_{CV}=the minimum area around the leak position and A_{leak}=the area of the leak.

Fig. 4(a) illustrates a relationship between the maximum flammable and equivalent gas cloud volumes which are results of gas dispersion simulations. The flammable gas cloud signifies the actual gas cloud in the range of combustion, which is between the Lower Flammable Limit (LFL) and Upper Flammable Limit (ULF). The equivalent gas cloud is the idealized gas cloud that has an ER equal to 1.

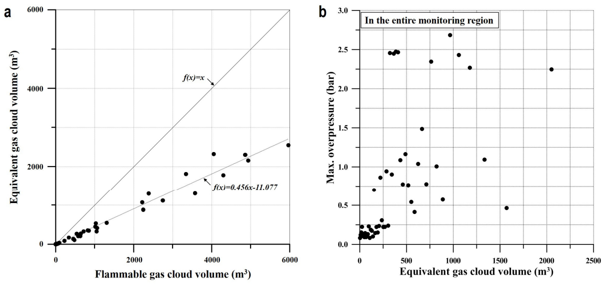


Fig. 4. (a) results of gas dispersion simulations, (b) results of gas explosion simulations.

4.2. Selection of gas explosion scenarios and simulations

When selecting gas explosion scenarios, all possible parameters that can have an effect on gas explosion should be considered, as in the selection of gas dispersion scenarios. Hydrocarbon explosions can be affected by dispersion-related parameters, which are size, location, concentration of gas clouds, and ignition point.

In this study, equivalent gas clouds are used, and the four parameters-size of gas cloud, center of gas cloud in X, Y, and Z directions-are considered in selecting the gas explosion scenarios.

The explosion simulation needs a smaller extent than the dispersion simulation, because there is no wind, and blast wave allows the boundary effect to be ignored. In the case of gas explosion simulation, there is no need to generate the fine grids around the leak area because the equivalent gas cloud without gas release is considered. The minimum grid size is recommended to be used, the value being calculated by Eq. (2) [11].

$$max.CV=0.1[V_{gas}^{1/3}] \tag{2}$$

where $max.CV$=maximum size of control volume, and V_{gas}=size of gas cloud volume.

Fig. 4(b) shows representative result of gas explosion simulations which is the effect of the equivalent gas cloud volume size on maximum overpressure. It shows that the size of gas cloud volume can have a decisive effect on the explosion loads when it has gas cloud smaller than 1000m^3 of volume.

Explosion loads of each scenario obtained from CFD simulations are directly applied to structural model for structural consequence analysis.

5. Calculation of gas explosion frequency

For generating the consequence exceedance curve and structural assessment proposed in the present study, a gas explosion frequency of scenarios should be calculated, and it can be calculated by Eq. (3).

[Explosion frequency]=[Gas cloud frequency]x[Ignition probability] (3)

5.1. Gas cloud frequency

In the case of fire accidents, the leak frequency can be directly used. However, the gas cloud frequency in the case of an explosion must be recalculated from release frequency because the explosion necessarily occurs after the release of gas.

The detailed steps for calculation of gas cloud frequency are as follows;

1) Categorization of gas cloud volume
2) Sum of release frequency of gas dispersion scenarios depending on categories
3) Calculation of the number of explosion scenarios included in each category
4) Calculation of gas cloud frequency of each scenario

5.2. Ignition probability

Cox et al. [12], Oil and Gas UK [13], and OGP [14] suggest ignition models for the hydrocarbon events on offshore installations. The ignition probability is generally related to release type (gas, liquid, etc.), leak rate, and type of offshore structures. In this study, the ignition probability of an offshore gas release event is considered. Among of ignition models, the ignition probability proposed by OGP [14] is applied in this study, because it calculates the ignition probability in detail.

6. Nonlinear structural consequence analysis

6.1. Finite element modelling

The entire module is used for the extent of analysis in finite element analysis as shown in Fig. 5(a). The model is generated with shell elements for all of structure using the ANSYS/LS-DYNA [15]. Fig. 5(b) shows the boundary conditions adopted in the present study.

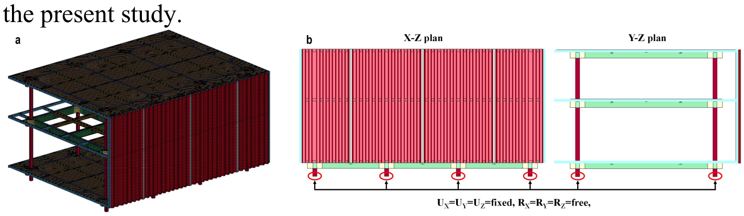


Fig. 5. (a) finite element model of the target structure, (b) applied boundary conditions.

In the material modelling, all the members involved in the present study are made of mild steel. Table 1 shows the material properties of mild steel under static load.

When the dynamic load is applied in the form of explosion load, the strain rate effect, which is the dynamic effect, should be considered. There are various methods for considering the dynamic effect of the material. The standard methods apply the DLF [1], SDOF [1, 6], or Cowper-Symonds equations [16]. Among them, Cowper-Symonds equations are used in this study to get a more accurate structural response.

Table 1. Material properties of mild steel under static load.

Density (kg/m^3)	Elastic modulus (MPa)	Yield stress (MPa)	Poisson's ratio (-)	Fracture strain (-)	Cowper-Symonds coefficients C (1/s)	Cowper-Symonds coefficients q
7.890	205.800	235	0.3	0.3	40.4	5

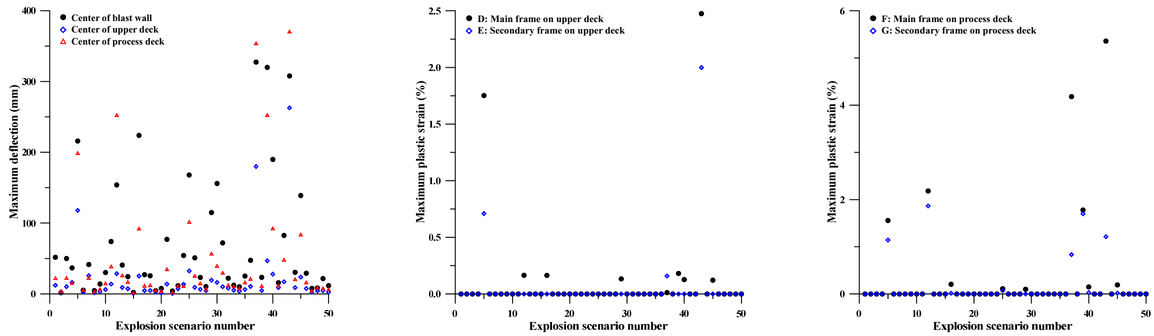
For effectiveness and accuracy, the 150x150 (mm) size of element is selected as the proper mesh size in terms of time and accuracy.

In this study, the FLACS2DYNA [17] interface program is adopted to transfer the actual explosion loads obtained from FLACS CFD simulations to ANSYS/LS-DYNA. FLACS2DYNA transfers the explosion loads taking into account the control volume system in CFD and elements in FEM.

Deflection and plastic strain are investigated as the structural response in this study. The strains are obtained at structural members, and the deflection is investigated at the center of blast wall.

6.2. Results of nonlinear structural response under explosion loads

Fig. 6 illustrates results of structural analysis which are deflection at the center of blast wall, and plastic strains at the frames. The response of the main and secondary frames on the process and upper decks, as shown in Figs. 6(b) and 6(c), signify that the explosion has a more serious effect on the main frames.



(a) On blast wall (b) On upper deck (c) On process deck

Fig. 6. Maximum deflection and plastic strain at blast wall, frames and column.

7. Structural assessment

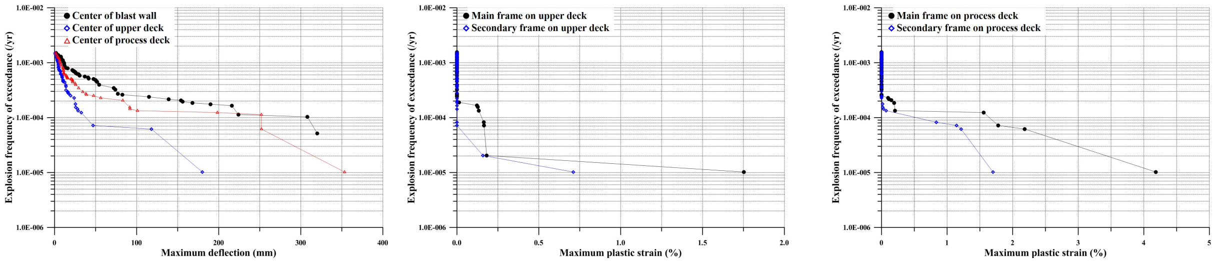
7.1. Consequence exceedance curve

Czujko and Paik [18] suggested a method for the accidental limit design of structures subjected to hydrocarbon explosion, in which the explosion loads and structural consequence are combined with consequence probability of exceedance. This study proposes the new method as named consequence exceedance curve based on the method proposed by Czujko and Paik [18] for structural assessment.

With the results of 50 structural analyses, the consequence exceedance curves are generated. An approach to obtaining the consequence exceedance curves is similar to the explosion load exceedance curve proposed by Paik and Czujko [10]. The method can be expressed by following steps;

1) Establish a table listing the gas explosion frequency and maximum structural response for all explosion scenarios considered.
2) Based on the table established in Step 1, rearrange the order of scenarios in such a way that the scenario with the smallest response comes first and that with the largest one comes last.
3) Based on the table established in Step 2, calculate the exceedance frequency in association with the consequence. This is equal to the total frequency minus the cumulative frequency at the corresponding maximum consequence.

Fig. 7 shows the maximum structural consequence (deflection and plastic strain) exceedance curves at the blast wall, decks, and frames.



(a) Maximum deflection at blast wall (b) Maximum plastic strain at upper deck (c) Maximum plastic strain at process deck

Fig. 7. Probability exceedance of explosion frequency versus maximum structural consequence.

The designers can now more accurately predict the structural response directly using the consequence exceedance curves relating to the actual loads of all explosion scenarios.

7.2. Structural consequence at risk acceptance level

The plastic strain is generally used for structural assessment in explosions, and is used in the present study for defining the structural consequence at acceptance level. 10^{-4}/yr of risk level is adopted to be acceptable in this study, and Table 2 shows the plastic strain at risk acceptance level in the consequence exceedance curves shown in Fig. 7.

Table 2. Plastic strain at 10^{-4}/yr of risk acceptance level in consequence exceedance curves (in %).

Location		Plastic strain at risk acceptance level
Upper deck	Main frame	0.15
	Secondary frame	0.00
Process deck	Main frame	1.66
	Secondary frame	0.57

8. Conclusions

The objectives of this study were to develop a new method for the structural assessment of topside structure on offshore installations in explosion events, and demonstrate the method with an applied example. The new method uses the actual explosion loads for the analysis of structural responses, in contrast to the existing procedure, which uses the idealized loads.

In the new procedure, an interface program named FLACS2DYNA is applied to transfer the actual loads from CFD to FEM. In addition, the consequence exceedance curve based on the structural response under actual explosion loads and explosion frequency is suggested for the structural assessment of topside structure.

Based on the results of this study, the following conclusions and insights can be drawn.

- A new method for the structural assessment considering the actual explosion loads is introduced.

- The series analysis of structural response with the actual explosion loads of a number of explosion scenarios is performed.
- A method for the structural assessment of the topside structure using consequence exceedance curves is suggested.

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