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Improving the ductile behaviour of offshore topside structures under extreme loads

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Abstract

This study investigates the behaviour of a typical offshore topside structure subjected to blast loading caused by hydrocarbon explosions. The pressure load caused by the explosion is idealised as a linearised triangular impulse which is simultaneously applied on two deck levels modelled using the finite element program, ABAQUS Explicit. Two cases were developed: the original case representing a typical offshore fabricated deck flooring with sniped bottom flanges at connections for stringer beams and the strengthened case which was a modified form of the original case but with rolled steel angles welded at sniped bottom flanges of stringer beams and plate girders. Results from the analysis show that load directions and structural configuration play a prominent role in the response of the topside. The strengthening indicates the beneficial redistribution of local yielding at the sniped connections of the beams to mid-spans which consequently improve the performance level of the structural system. Haunch details are found to cause local failures on plate girders but the failure mechanism is useful for developing a technique to avert further damage. Finally, generalised ductility ratios derived from normalisation of responses at end-spans and mid-spans of the structural components are compared with commonly used design values to justify the damage levels and performance under this extreme loading condition.

Keywords: Hydrocarbon explosions; Ductility; Connections; Performance based design; Topside structures

1. Introduction

A conventional offshore installation with piled foundations comprises a substructure, usually fabricated from steel for supporting topsides which consist of a number of deck levels. Typically, topsides are compact process plants which together with the confinement, can lead to the generation of damaging explosion overpressures if a gas release occurs. A structural steel framing supports the entities of the process areas which consist of: the wellheads area at which lines carrying hydrocarbon fluids from the reservoir terminate; the production separators in which these fluids are separated; the compression facilities at which the gases from the separators are compressed, dried, purified and prepared for export; and a living quarters (LQ). Offshore structures especially in the oil and gas industry are designed for unique load combinations which include the pre-service conditions (fabrication and installation), the in-service conditions (criteria based on the process and inherited hazards of the plant aspects) and the environmental factors. Constraints in technology to process some hydrocarbon products and corrosion caused by carbon dioxide and sulphur from crude oil/gas and seawater can make maintenance work difficult and costly. Often, offshore installations have to be operated in a hostile environment. As a result, design must be kept as simple as possible with maximum throughput at all times but at the same time not scarifying the safety aspects and protection of personnel and assets.

One of the worse scenarios that can occur on offshore installations is a hydrocarbon gas explosion, defined as a process which combustion of a premixed hydrocarbon gas–air cloud causes a rapid increase of pressure that generates blast loadings. In an unconfined area, these pressure waves are emitted in all possible directions within the duration of few milliseconds as a pressure impulse. A topside on which most facilities are in-place consists of structural members, piping, equipment, cables and other appurtenances that can obstruct the free movement of these waves. This congestion and confinement can significantly increase overpressures capable of

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Table 1
Offshore installations—Performance based engineering [1–3]

Design considerations	Parameters
Sources of blast loading	• Type of explosions – deflagration (maximum 8 bar) or detonation (maximum 20 bar) • Location and area – degree of congestion and confinement • Intensity of loads – category of the overpressures - duration of peaks
Engineering demands	Demand to capacity ratios for the following structural components :- • Primary members (members that support structures, equipment supports and part of the truss system), columns, girders and beams—axial load, moment, shear, ductility. • Secondary members (members that support appurtenances e.g. walkway, staircase, wall support and etc.)—axial load, moment, shear and plastic deformation. • Tertiary members (deck plate and walls)—displacement and development of membrane forces.
Damage measures	• Casualties and loss of lives • Platform shutdown times • Damage and repair costs
Decision variables	Performance objectives :- • Explosion return period (occasional, rare and remote) • Performance levels (see Table 2)

causing structural damage. Entities having large surfaces such as walls or vessels, will attract high loads from an explosion. For small entities such as piping lines or cable trays, the effect of blast pressure is minimum, but the blast waves will drag and pull these entities off the supports, leading to possible rupture which may escalate the initial event. The combination of these two effects can also damage the fire compartmentation of the topside, which may also threaten the nearby living quarters.

This paper presents the detailed analysis of a topside structure to a hydrocarbon explosion in order to assess the adequacy of using a performance based design methodology. At present, most design of structural members for offshore installations are based on working stress or load resisting factor/limit state design which are quite safe but not economical due to the unknown levels of performance for structures and degree of protection for platforms' assets under this extreme loading condition, particularly when assessing ductility as this can vary depending on the complexity of the modelling adopted.

2. Performance based design

The methodology of performance based design for blast loadings includes procedures for estimating risk on a design-specific basis, where risk is expressed based on either a deterministic or a probabilistic basis of possible events. The risk is related to specific losses [1,2] while the structure performance levels are related to behaviour and response during and after the blast scenarios. A summary of the design consideration in performance based for offshore installations subjected to hydrocarbon explosions is shown in Table 1 while Table 2 summarises the system level in terms of risk, collapse, fatalities, repair work and post-explosion functionality of the platform.

For offshore installations, performance based design against blast loadings emphasises more on functionality, minimise loss, repairable conditions, operable and avoiding conservatism. Two major difficulties as noted by Yasseri [1] occur in the uncertainties of explosion hazard assessments and evaluations of the structural performance. Hazard assessment is the combined studies of the computational fluids dynamics (CFD) and quantitative risk assessment (QRA), which define the concept of return period or the probability of exceedance diagram of explosion events; the structural performances that inherent in multi disciplines of engineering and the complexities of overpressures/blast loads which are the function of strength, stiffness, structural configuration and the dynamic nature of the loading. Hazard assessment is excluded in this study but the magnitude from the criteria will be used to determine the performance levels of topsides.

Both seismic and blast conditions in the approach of Performance based design optimise the limit states of materials. Seismic loads depend on the location for which new additions will not change the hazard level whilst blast loads are specific to an installation and new additions can be new potential hazards.

3. The structural configuration

The performance level of structures is dictated by the arrangement of the structural frame. Studies have shown that response and behaviour of structural components subjected to blast loads depends heavily on the performance of the connections. Investigations by Krauthammer [4] on connections showed that in the strengthened concrete connection study with diagonal bars, plastic hinges tend to develop where the bars are terminated inside concrete column–beam while for steel connection, a local deformation of flanges with welds fractured on the interface between a beam to a column. Addition of cover plates to existing flanges at steel column–beam connections by