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Risk-based Structural Response against Explosion Blast Loads: Systematic One-to-one CFD (FLACS) / NLFEA (Impetus Afea solver) Coupling to Derive Quantified Response Exceedance

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This paper proposes an advanced and innovative methodology for risk-based structural response assessment against accidental explosions. Focus is shifted from dimensioning load to barrier integrity. A full spatial mapping of blast overpressure transients obtained with Computational Fluid Dynamics (CFD) modelling is used in combination with a Non-Linear Finite Element model (NLFEA). The GexCon-Impetus methodology is so-called advanced due to the innovative extensive one-to-one CFD-NLFEA job solution scheme used over several explosion runs. Using a detailed explosion loads mapping for the response evaluations provides a comprehensive probabilistic description of the response characteristics, easy to combine with risk acceptance criteria and performance requirements. The 3D codes involved are FLACS (CFD) and IMPETUS Afea solver (NLFEA). The response of an offshore fire partition wall is specifically studied against dynamic explosion loads. Detailed modeling of the wall is made in IMPETUS Afea solver. Systematic direct coupling between 90 FLACS risk-based explosion simulations and 90 IMPETUS Afea dynamic response calculations is used. The safety barrier performance is quantified using adequate wall response parameters reported for every explosions. The innovative outcome is a probabilistic picture of the response parameters exceedance. The barrier ability to perform the related safety function(s) is efficiently documented. Of utmost importance, mechanisms that cause possible lack of integrity are highlighted. The results are compared with existing offshore approaches based on the Dimensioning Accidental Load (DAL) concept. A uniform triangular loading and a realistic dimensioning explosion are used. Promoting more consideration of adequate response assessment as part of the safety studies, the paper shows how the advanced method pinpoints limitations of conventional approaches. For the risk owner, it improves the comprehension and implications upon the relation between explosion loads and their consequences on structures carrying critical safety functions. Several benefits result from the GexCon-Impetus approach among which: a more accurate streamlined workflow, an improved understanding of the safety barrier behavior, perception of safety margins, justifications for design optimization, cost & weight savings.

1. Introduction

1.1 Background and objectives

In the hazardous industries, safety studies are mandatory to document a safe design. These are either performed during design phase and/or during an assessment phase for existing installations. In the offshore industry, (Bakke & Hansen, 2003) introduced the consequence assessment workflow quite a long time ago. It implies extensive gas dispersion and explosion modelling to calculate Dimensioning Accidental Loads specifications (DAL spec.) for identified safety critical elements. Such an approach is formalized in several standards for offshore design e.g. (NORSOK Z-013, 2010) and is often taken on as a company standard in the oil & gas industry. Onshore, examples are illustrated in (Hoorelbeke, et al., 2006) and (Paris, et al., 2010). In the nuclear industry, similar consideration are used to document the protective effect of confinement (Daudey

& Champassith, 2014). Similar design requirements may also be suggested against fire or cryogenic hazards. In this presentation, a dedicated analysis is performed upon an existing partition firewall separating two offshore modules on a production platform. Advanced modelling is required to document the integrity of the wall in compliance with safety requirements. GexCon & Impetus suggest an advanced probabilistic characterization of the wall response to blast shifting from DAL to integrity, by means of an extensive coupling between FLACS and IMPETUS Afea simulations. This implies a streamlined embedded collaboration between safety and structural engineering in order to increase global accuracy. The probabilistic outcome focuses on safety functions performance providing a clear description of the barrier behavior to the risk owner – thus easing decision process. The results are compared against a selection of conventional DAL-based approaches.

1.2 The FLACS CFD code and the Impetus Afea NLFEA code

FLACS is a commercial Computational Fluid Dynamics (CFD) code developed by GexCon to model the dispersion and turbulent combustion (k-ε model) of flammable materials in large 3D geometries. FLACS is the industry standard for CFD explosion modeling in the Oil and Gas industries and is increasingly used in the nuclear industry. Current capabilities include flammable and toxic gas dispersion, pool spread and evaporation of liquefied gases (e.g. LNG). Latest improvements include a fire and heat load simulation solver (FLACS-Fire). Using 3D CFD to predict the consequences of hazardous scenarios, all contributing protective measures (ventilation, deluge, gas detection, confinement, physical protections…) are taken into account efficiently, increasing predictions accuracy. IMPETUS Afea solver is a commercially available system for non-linear explicit finite element analysis (NLFEA). It is primarily developed to predict large deformations of components exposed to extreme loads. It offers unique higher order solid element technology, explicit time integration and GPU adaptation for high-computational speed. The formulation is purely Lagrangian. All finite element and contact calculations are carried out in double precision. The higher order elements leads to high accuracy even for highly distorted meshes. The steel material is modeled after the minimum requirements of (EN10225, 2009) with regards to strength and ductility. A ductile damage model is used to account for stress tri-axiality and plasticity and assess the failure of the material as required in (EN10225, 2009).

2. Practical case

2.1 Geometry & numerical models

The offshore gas treatment module of interest is 42 m long, 17 m wide and 14 m high (over 2 levels, platted). Only the lower main deck of the module is studied (6 m high). Figure 1 (left) is illustrating the corresponding FLACS CFD model. Of particular interest is the eastern partition firewall protecting an adjacent module, modelled in IMPETUS Afea solver (Figure 1 (right)). A set of 3 x 3 m monitoring panels (14 horizontal panels over 2 rows) is used to map the explosion loads and apply them onto the IMPETUS Afea model.

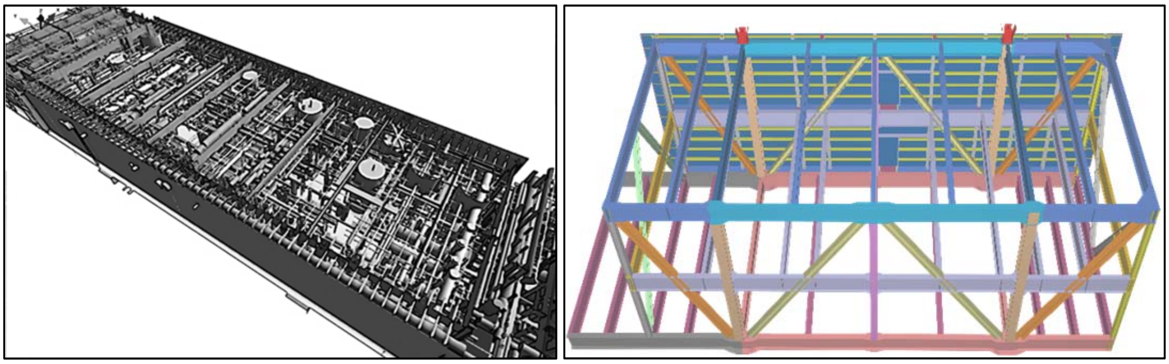

Figure 1: Numerical models used to perform the analysis. Left: FLACS CFD model seen from top south-west corner of module. Right: subset of IMPETUS Afea NLFEA model, main structure and firewall seen from west

2.2 Explosion Risk Assessment (ERA)

Explosion studies for offshore facilities will normally be performed according to (ISO 19901-3, 2010) and (NORSOK Z-013, 2010) estimating the 10^{-4} pr. year DAL. The former was used for the decks and walls of the studied module. A similar example is described in (Davis, et al., 2011). An extensive set of FLACS simulations is performed covering natural ventilation, time-dependent flammable gas clouds dispersion and idealized gas clouds explosion. The predicted heterogeneous explosive clouds are idealized as equivalent homogeneous clouds (Hansen, et al., May 2013) and are ignited at several locations. The simulation work combines with leak frequencies and ignition probabilities to derive a probabilistic description of the loads. For the firewall supporting the current study, Figure 2 shows the resulting explosion risk exceedance. The DAL (0.9 barg) is extracted at a return criteria of 10^{-4} pr. year. Load durations at this specific peak load ranges from 80 to 240 ms.

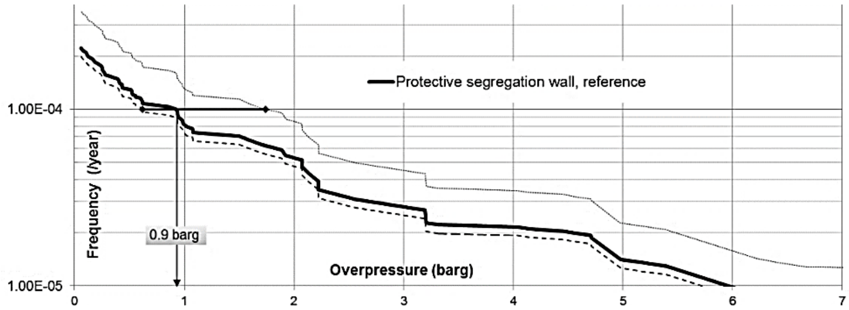

Figure 2: Explosion risk exceedance for the studied wall (main line, DAL of 0.9 barg); -25 % (dashed) / +60 % (dotted) variation over the 10^{-4} yearly return DAL criteria

2.3 Response criteria and barrier integrity

The response calculations are performed in order to check if the safety functions carried out by the barrier are met. The requirements for the wall are translated into a set of numerical parameters which become relevant indicators. Load bearing and prevention of escalation are the main functions identified as critical for safety. The structure displacement (can deflections hit other objects? Will the primary structure collapse? Could supporting structure fail and lead to progressive collapse?) and the material integrity (will the wall skin being damaged and will cracks or holes be observed?) are selected. The displacements of the constitutive elements of the firewall and of the main beams are monitored. The material damage *D* ranging from 0 (undamaged) to 1 (fully damaged) is also studied. Intermediate values shows regions where plasticity has occurred and integrity is met as long as D<1. Maximum over time are assessed. The indicators and NLFEA output can be tailored to specific purposes.

3. DAL-based approaches: uniform loading (baseline) and single realistic explosion case

Although far from a realistic propagation of a blast wave, an idealized uniform load profile combining the dimensioning load of 0.9 barg together with the conservative load duration of 240 ms is applied upon the entire wall (Figure 3, dashed). The corresponding Impetus Afea simulation predicts a displacement of 0.35 m and almost no damage to the wall skin. The wall response at the time of maximum displacement is illustrated on Figure 4 (left). A comparison is held using a realistic explosion with a 10^{-4} yearly exceeding probability. It requires the mapping of the realistic transient explosion loads monitored in FLACS onto the Impetus Afea model of the wall. It enables time and space dependencies. The selected design explosion case returns a maximum peak overpressure of 0.9 barg (at a given location and time) consistent with the previous DAL approach. Figure 3 shows the transient loads experienced by the 28 panels covering the wall and the corresponding mapping of peak overpressures. The transients are not uniform, with pulse durations between 100 and 220 ms. Blast arrival times also vary, showing a 150 ms time lag over the wall length. The Impetus Afea simulation reports a maximum displacement of 0.15 m (Figure 4, right) with very low damage level.

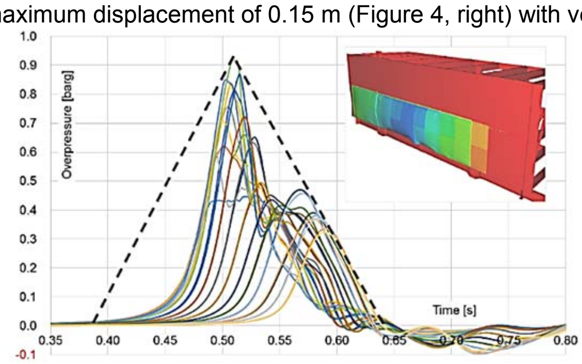

Figure 3: Overpressure load transients (plain) over the 28 panels covering the wall for one of the realistic explosion cases returning a cumulative probability close to 10^{-4} pr. year (here a 470 m^3 gas cloud located and ignited in the south-east corner). The uniform triangular design load (dashed) derived from the 10^{-4} yearly return DAL from the Explosion Risk Analysis is overlapped on this picture for comparison

Using a distributed loading, the response level is reduced by more than 2. Assumptions from the ERA are critical in this process: a different cloud close to the same criteria could load the structure differently. Accuracy, unicity and conservatism are challenging to justify. Hence, the selection range needs to be extended. Finally, the complete set of explosion scenarios is processed in the advanced extensive GexCon-Impetus methodology. A large database of response characteristics is elaborated against several load patterns and configurations.

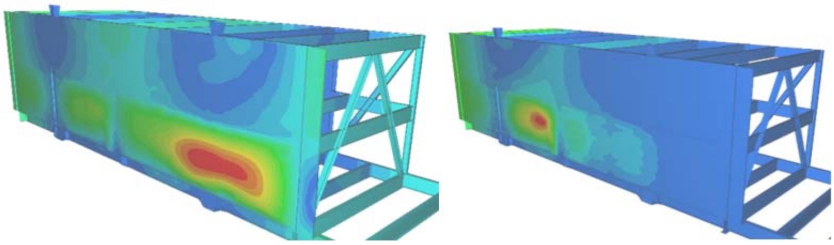

Figure 4: Maximum response of the wall for the dimensioning loads: - left, the uniform triangular loading (0.9 barg and 240 ms; 0.35 m); - right: the realistic explosion loading (0.15 m)

4. GexCon-Impetus advanced methodology

4.1 GexCon-Impetus methodology: extensive one-to-one FLACS and Impetus Afea solver coupling

The proposed advanced method is an alternative listed in (NORSOK Z-013, 2010). Due to lack of computer power and because of the common split between safety and response (structure) disciplines in project teams, this approach has never been achieved as far as the authors know. A full spatial mapping of overpressure transients obtained with FLACS is made available for Impetus Afea input. During the explosion simulations, FLACS dumps the explosion overpressure time-history with reference to a specific set of measuring panels, subsequently applied into the Impetus Afea NLFEA model. This coupling is repetitively used for a large set of explosion scenarios. The methodology is so-called advanced due to the innovative extensive one-to-one CFD-NLFEA job solution scheme. In other words, as many NLFEA response simulations are run as FLACS explosion simulations. Accuracy is increased considering exhaustive relevant parameters (e.g the dynamics) and removing simplifications no longer needed. Figure 5 illustrates this streamlined engineering workflow.

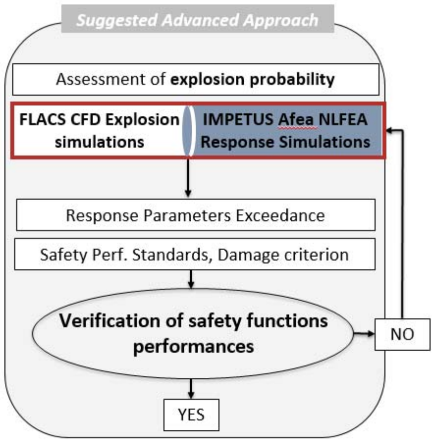

Figure 5: Simplified workflow from the advanced GexCon-Impetus approach

Despite the explosion load exceedance curve provides a picture of the (explosion) risk level, it is not correlated to barrier integrity and shall be completed. One could indeed claim that ignoring loads durations and loads mapping is too coarse. The extensive level of details available from CFD shall be maintained without excessive simplification by using an equivalently advanced tool for response assessment. Taking advantage of a one-to-one CFD-NLFEA scheme, a comprehensive probabilistic exceedance curve of the response parameter(s) is elaborated. In case of breach of the safety function, improvement and optimization are easily accessible either from a safety side (loading) or from a mechanical side (local weakness, failure mechanisms). Although it requires an additional step of advanced mechanical modelling, the new approach clears up the understanding of the barrier properties and subsequent barrier management for a risk owner, improving the decision making process.

4.2 Application of Gexcon-Impetus methodology: response exceedance of the segregation wall

The same 90 CFD FLACS explosion simulations are run and monitored using the refined load mapping from section 2.2 (1 week simulation work, no extra work needed). Subsequently, 90 IMPETUS Afea cases are run using the spatially distributed FLACS transient loadings (2-3 weeks time when the model is available). The wall behavior is predicted using the maximum damage level and maximum displacement listed in section 2.3. During the ERA (section 2.2), a given likelihood is assigned to each simulation leading to derive the explosion load exceedance curve from Figure 2. As an immediate mirrored result, the response parameters from the NLFEA calculations are presented in the same probabilistic way. Figure 6 shows the resulting plot for the maximum wall displacement. The outcome is a more comprehensive illustration of the safety barrier performance, useful to capture the compliance of the integrity against requirements. The 10^{-4} pr. year criteria returns a maximum displacement of 0.22 m (and a marginal damage level). The asymptotic behavior of the curve shows that the wall fails systematically above a given threshold. Safety margins embedded in the current design are directly accessible by comparing the design criteria stands vs. the asymptotic region.

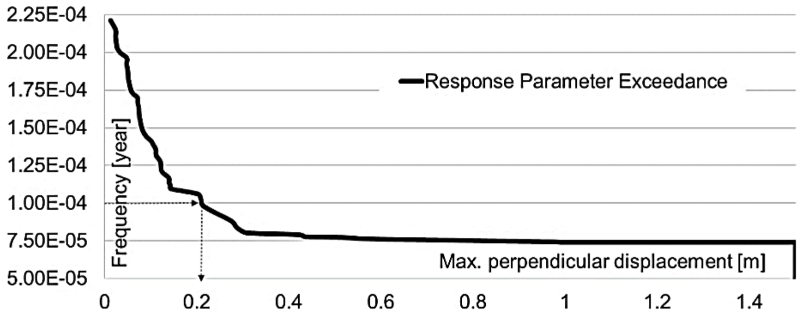

Figure 6: Maximum displacement exceedance curve resulting from the Gexcon-Impetus methodology

5. Discussion

First using the 10^{-4} pr. year criteria, the resulting wall responses are compared depending on the methodologies (Table 1). For the 0.9 barg DAL reference case, the use of the advanced methodology predicts a reduction of the maximum displacement by 50% compared to the uniform triangular loading. The damage indicator still shows no significant damage to the wall skin. Compared to the single realistic load case, larger deformations are predicted, suggesting that peak overpressures and response are not sorted the same way. Due to specific interactions, some explosion scenarios generating lower maximum overpressure can lead to larger damages.

Table 1: Results of the reference comparison study and extended sensitivity analysis

Dimensioning Accidental Load extracted from FLACS risk-based analysis	RESPONSE ASSESSMENT from Impetus Afea response calculations					
	UNIFORM triangular loading (~ 200-240 ms)		10^{-4} yearly return REALISTIC explosion		NEW METHODOLOGY (@10^{-4} yearly criteria)	
	Max Disp.	Damage	Max Disp.	Damage	Max Disp.	Damage
	m	-	m	-	m	-
0.6 barg (~ -25 %)	0.20	0.017	0.10	0.009	0.14	0.011
0.8 barg (~ -10 %)	0.32	0.042	0.14	0.016	0.2	0.018
0.9 barg (reference)	0.35	0.056	0.15	0.018	0.22	0.025
1 barg (~ +10 %)	0.4	0.07	0.23	0.10	0.31	0.13
1.1 barg (~ + 20 %)	0.42	0.08	0.39	0.13	Max 1.0	1 (locally)
1.5 barg (~ + 60 %)	0.58	0.23	0.42	0.27	Fails	1

A complementary sensitivity is held. The database of explosion scenarios frequencies is varied, shifting the exceedance curve from the reference case by -25 to +60% (Figure 2). Tailor-made DALs (higher or lower) are extracted. The analysis is repeated addressing the responses for updated values of DALs and using GexCon-Impetus tool with new sets of scenario frequencies (Table 1). Three regions are identified with respect to the wall integrity. First, the lower load region (< 1 barg) where extra capacity is documented by Gexcon-Impetus methodology and where the conventional approaches show conservatism. Secondly, an intermediate region (1 to 1.1 barg) where the conventional methods predict a continuous increase of the maximum displacement whereas the GexCon-Impetus method pinpoints a critical region for the wall capacity. The wall starts failing locally. Any larger loading results in the complete opening of the wall. This leads to the third region, above the critical region (> 1.1 barg), where the limit state of the wall is predicted by Gexcon-Impetus methodology although not being captured by the two other approaches. The question is not really how the results compare but rather which of these suggested practices are acceptable to use and when. Realistic transient loadings generate gradients that trigger local shear / weaknesses of the wall for extreme normal loading or for traveling loads. This aspect is not critical below a given range and the benefit from using the GexCon-Impetus there relies in quantifying extra-capacity, i.e. margins, related to robustness of existing design, which can derive into costs and weights optimization. It gives more perspective to the systematic use of the "10^{-4} pr. year criteria". At some point, the time/space distributions of the loading modify the conventional way of sorting explosion severity. The dynamic of the load cannot be neglected. The critical state is reached with the advanced methodology earlier than with the conventional approaches, then questioning the accuracy of systematic use of the simplified approaches. Using Gexcon-Impetus approach guarantees considering the relevant input parameters in a reliable response investigation. The high definition of the explosion loading is streamlined along the assessment without abusive simplifications. A better understanding of the wall failure mode(s) is accessible. Above all, a significant step forward is the way the results are presented, giving a better description of the barrier behavior. More understanding of the performance of the design is provided to the risk owner, increasing credibility, confidence, safety and cost effectiveness. Both onshore and offshore, the Gexcon-Impetus methodology is opening opportunities for deeper investigations and applications (fire heat loads, LNG cryogenic loads) and for consolidation as well (e.g. explosion loads from heterogeneous gas clouds).

6. Conclusions

An advanced innovative probabilistic methodology is proposed for blast loading structural response, based on a full mapping of pressure transients obtained with CFD FLACS modelling onto the NLFEA IMPETUS Afea model, for a large set of explosions. A one-to-one CFD-NLFEA job solution scheme is used. Mapping in time and space of the overpressure loads helps increasing the accuracy of the mechanical response. For a very specific firewall from a specific offshore module, the study compares the results of the proposed advanced method versus DAL-based approaches. It shows that a uniform DAL-based loading can be either conservative or incorrect depending on the intrinsic limit capacity of the wall. The comparison also shows that a safety margin of more than 50 % can be documented for the reference case using the new approach. However, it is also shown that this trend is not systematic. Failure modes (here due to large gradients) can be abusively neglected when considering a uniform loading thereof underestimating the limit state for the wall. Considering a large number of realistic loads, the critical wall capacity is triggered significantly earlier using the advanced approach. The integrity of the safety barrier is thus more adequately documented. The improvement suggested together by GexCon and Impetus consists of binding the explosion and response assessments more systematically in the safety examination. Instead of (or in addition to) focusing exclusively on explosion peak pressure, it is suggested to draw exceedance curves in terms of safety function(s) indicators, i.e. to move from a DAL concept to a probabilistic dimensioning response/performance indicator(s) concept.

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