Challenges in a Multidisciplinary Approach for Explosion Design for Floating Facilities

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Summary

Floating-liquefied-natural-gas (FLNG) units have been under development for decades. They are now becoming a reality, combining the design and installation of liquefied-natural-gas (LNG) units with a traditional floating production, storage, and offloading facility. Because FLNG facilities handle large flammable-gas quantities in a relatively small and congested environment compared with onshore LNG plants, the explosion risk is expected to be higher than that for some other offshore floating facilities. As a consequence, the intensity of the resulting blast loads on the unit can be more severe, even if the likelihood of explosion in the design is considered to be low through frequency analysis.

Even if prevention and mitigation measures are implemented to reduce risk to as low as reasonably practicable, safety-critical elements (SCEs) such as main equipment and structures should be designed to withstand the blast event. Because the explosion events are very specific (high intensity and short duration), the common design rules and tools should be updated to take into account this accidental event. In addition, the associated performance criteria for SCEs should be modified. Finally, the entire design should comply with safety objectives (personnel protection, prevention of escalation).

This paper focuses on the philosophy of design against a blast event on floating facilities in general, but with a particular focus on FLNG units. It will review the critical functions of the unit that must be maintained during emergency evacuation to protect people and identify the key parameters governing the explosion strength on floating facilities. It will show that the derivation of effective explosion loads on structures and equipment on the basis of computational-fluid-dynamics simulations is not straightforward and requires expertise in explosion modeling and explosion response. The paper will also show how all the engineering disciplines in Technip individually apply these blast loads in their designs through nonlinear-finite-element analysis. Finally, the paper will highlight the interface between the engineering disciplines and how a consistent demonstration through the design can be achieved to fulfill the safety goals, taking engineering further.

Introduction

In this paper, the approach for explosion design of floating facilities in general will be discussed, and special requirements for floating-liquefied-natural-gas (FLNG) units will be identified. Because FLNG is a new technology, there are neither design rules nor industry standards available for the explosion engineering of such facilities. Proven standards and good engineering practices are usually the basis for the design, but they should be amended to account for the specificities of FLNG, especially because it involvs very-large flammable-gas quantities in a relatively small and congested environment compared with onshore liquefied-natural-gas plants or other floating offshore installations. As a consequence, the explosion risk is expected to be higher than that for some other offshore floating facilities.

Because of the general evolution of design practices, alternative approaches such as performance with risk-based design can be used. The performance-based approach relies on the explicit definition of the safety objectives and functional requirements (e.g., performance standards). The design process focuses on the objectives, not the means to reach them. Because it is based on the definition of realistic explosion scenarios, which could be deterministic (e.g., scenario-based approach) or probabilistic (risk-based), the design process requires more resources (skills, computational tools) that allow the contractor to demonstrate the compliance of the solution with the safety objectives. This could be a challenge because any design solution is specific to the installation and requires the acceptance of the operator, the local authority, and the classification society. All participants should ensure that they understand, agree with, and are aware of the limitation of the proposed design solution, to avoid further rework.

During the entire engineering process, different barriers are investigated to reduce the risk of potential losses (people, assets) from the potential explosion hazards to as low as reasonably practicable, as shown in **Fig. 1.** Even if inherent safety is a key driver during the design phase of the facility, additional risk-reduction measures that combine prevention, detection, control, and mitigation are usually implemented. Emergency response (e.g., rescue of people) remains the ultimate option.

Many of these barriers should be designed or verified against major-accident events to fulfill their function during and after the initial explosion event. This paper focuses on the design process and associated challenges of such barriers because they require an integrated multidisciplinary approach that combines the expertise of safety, structural, and equipment engineers.

Objectives of Explosion Assessment

According to industry guidelines (*API RP 2FB Ed. 1* 2006; UKOOA 2007), the health, safety, and environment objectives in case of an accidental event are

1. The protection of personnel onboard
2. The protection of the environment
3. The protection of assets (especially against escalation)
4. The reduction of loss of production

To achieve these goals in the case of a major-accident event (MAE), the following main safety functions (at least) must be maintained:

- Escape, evacuation, and rescue
  - Maintaining the main load-carrying capacity of primary structures until the facility has been evacuated
  - Protection of the control room until safe shutdown or until the installation has been evacuated
  - Protection of safe areas (muster area, temporary refuge)
  - Maintaining at least one escape route from every area in which personnel may be sheltering until evacuation

This paper (SPE 174556) was revised for publication from paper OTC 25230, first presented at the Offshore Technology Conference, Houston, 5–8 May 2014. Original manuscript received for review 19 June 2014. Revised manuscript received for review 9 April 2015. Paper peer approved 9 April 2015.

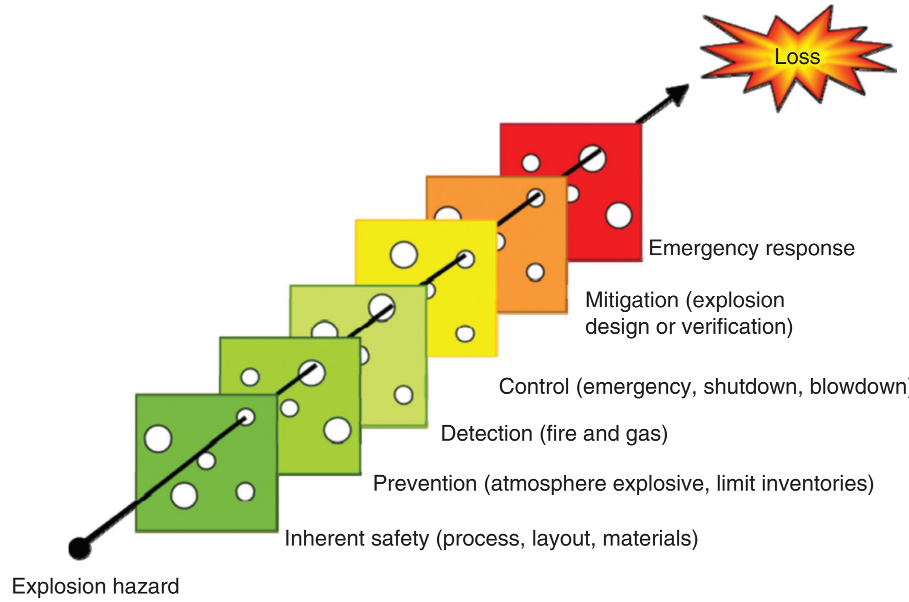

Fig. 1—Safety barriers to reduce explosion risk.

  - ○ Maintaining communication systems, emergency lighting, and uninterrupted power supply
- Prevention of escalation of accident situations outside the immediate vicinity of the accident
  - ○ Emergency shutdown and blowdown (emergency shutdown and flare system)
  - ○ Maintain containment of large hydrocarbon inventories
  - ○ Fire and blast walls
  - ○ Active fire protection

These functions are associated with safety-critical systems, which are broken down into safety-critical elements (SCEs). The SCEs are defined according to *API RP 2FB Ed. 1* (2006):

> *All parts of the structure, equipment; systems ensuring safety functions whose failure could cause or contribute substantially to a Major Accident Event (MAE) in case of failure. SCEs and equipment of the facility should in particular withstand an explosion, in order to fulfill their function, even if damages could be accepted to some extent.*

Finally, the explosion response of the SCEs should be performed to achieve the high-level goals defined in the preceding lists. In practice, from the explosion-mitigation strategy established in the safety concept (or any equivalent document), the following inputs are required by engineering disciplines to carry out the explosion-response calculations:

- The list of specific targets to be designed against blast
- The performance criteria to satisfy during an explosion event
- The corresponding effective-applied-explosion load (design-explosion load).

All the information in the preceding is provided by the safety engineer to the disciplines in charge of the explosion response by means of a standalone document called the "Design-Explosion-Loads Specification," as shown in **Fig. 2.** This document provides a consistent and unique interface between safety and the engineering disciplines that are in charge of the explosion response of the SCEs. Performance criteria and explosion-analysis inputs from this document are described in the following subsections.

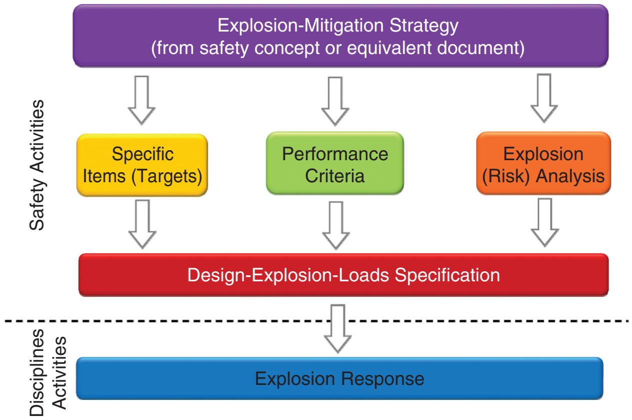

Fig. 2—Design flow chart for explosion response.

Performance Criteria of SCEs. The structural response (behavior) of an SCE against an explosion event requires the definition of performance criteria to ensure that the safety function associated with the event will be fulfilled. The performance criteria can be classified into the following categories:

- Resistance (or stability)
- Integrity (or containment)
- Operability

The performance criteria may be associated with the "survivability criteria" if the performance standards are set within the project.

The resistance (or stability) category refers to the capacity of the item (e.g., a blast wall) to remain in place, whether deformed or not, after an explosion event and without falling on adjacent items. The mechanical-resistance criterion is applied on all items that have to withstand a blast, but the effective blast loads should be broken down into

- Local loading to check the structural resistance of the individual components of an item because of the blast load
- Global loading (resultant) to check the structural stability of an item against sliding or overturning, or to check the design of the supports or foundations.

The differences between local and global loading are shown in **Fig. 3.**

In many cases, residual damage could be acceptable (e.g., equipment-support deformation) after a strong explosion event. However, the load-bearing capacity of primary structures should be guaranteed for normal operational loads (e.g., operating conditions and gravity loads) after the explosion event.

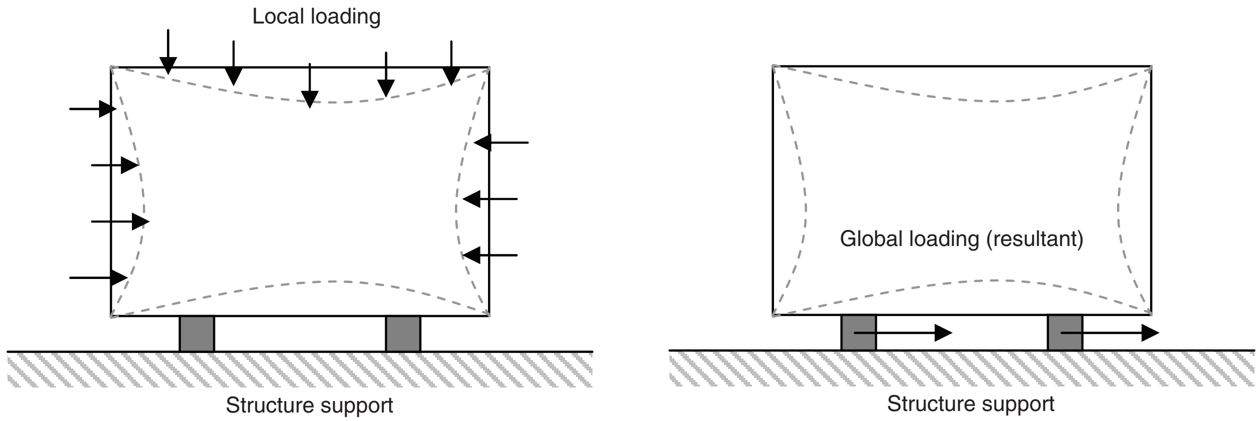

Fig. 3—Differences between local and global loading.

The integrity category refers to the capacity of the item to prevent

- Release of hazardous products into the atmosphere, leading to escalation (e.g., the item may be a vessel full of hydrocarbon); acting as containment.
- Hazardous effects (toxic, overpressure, thermal, cryogenic) reaching vulnerable areas (e.g., offshore, the item may be a blast wall separating the utilities from the process areas); acting as a partition.

The operability category refers to the capacity of the item to maintain its ability to fulfill its function after an explosion event (e.g., opening/closing of a safety valve). It should be noted that the operability criterion is more stringent than the integrity criterion, but both rely on the resistance/stability criterion. The operating criterion is often difficult to satisfy in practice based on calculation. Examples of performance criteria for common items are provided in **Table 1.**

For items that require integrity or operability after an explosion event, more-stringent mechanical criteria should be applied for the verification against explosion. However, for the large majority of equipment and facilities (which are not required to be maintained operable after a blast), permanent deformations are accepted, with the intent being to avoid general collapse of the equipment and loss of containment.

The main challenge arising from the performance criteria in the preceding is to define corresponding explicit mechanical criteria for the design by engineering disciplines. These could be any of the following:

Items	Resistance (Stability)	Integrity (Partition, Containment)	Operability
Primary structures and main-equipment support	×		
Buildings (LQ, TR)	×	×	
Pressurized vessels or containing large hydrocarbon and/or cryogenic inventories	×	×	
Piping	×	×	
Flare heater			
Fire water ring main			
Doors, safety valves	×	×	×

LQ = living quarters
TR = temporary refuge

Table 1—Example of performance criteria for common items (not a complete listing).

- An allowable stress (linear analysis)
- An allowable displacement or rotation at supports
- An allowable strain or ductility ratio (nonlinear analysis)
- An allowable side way for frame structures

These criteria should be defined on a case-by-case basis, depending on the discipline and design rules applicable for the project or depending on the methodology/tools chosen for the explosion response.

Explosion (Risk) Analysis (ERA). Because floating facilities handle large quantities of hydrocarbon, accidental gas explosion should be considered for the design. Hence, the rapid combustion of an air/fuel mixture and the expansion of the combustion products are the main causes of overpressure, which can reach values of several bar. The strength of a gas explosion depends on various parameters:

- Confinement and available venting areas
- Congestion
- Gas reactivity
- Cloud size and composition
- Ignition location and strength

All these factors contribute significantly to the explosion mechanism, but one of the main factors making the design process more complex in a new project is the lack of detailed geometry information early in the detailed design phase (i.e., before construction). Indeed, geometry completeness has a strong influence on the explosion results. If congestion because of small items is not implemented when undertaking the ERA, the design explosion loads will be severely underestimated. The explosion loads are required to verify the design of SCEs, but the design (e.g., size of the structural members and equipment) is needed for the ERA because it acts as congestion.

For these reasons, anticipated congestion (AC) is usually implemented from the early stage of the project [front-end engineering and design (FEED) or engineering/procurement/construction (EPC)/detailed design] to reflect the final state of the installation "as-built," as shown in **Fig. 4.** Safety margins are also applied on explosion results to cope with those uncertainties. The major issue is to estimate the degree of congestion accurately, especially for floating liquefied natural gas because it is a new technology. However, very large floating production, storage, and offloading facilities could be used as a basis, with adjustment factors (safety margins) to account for those uncertainties, especially in the liquefaction section, where the amount of congestion will be slightly increased as a result of the presence of larger equipment (e.g., columns) and large-bore piping.

The second challenge in the ERA is to provide explosion loads as soon as possible to engineering disciplines for structural response, in particular before discussion with and purchase of equipment from vendors. However, the performance of the ERA is hardly compatible with project schedule because it requires different steps, as shown in **Fig. 5,** and, finally, the study may require several months to be completed.

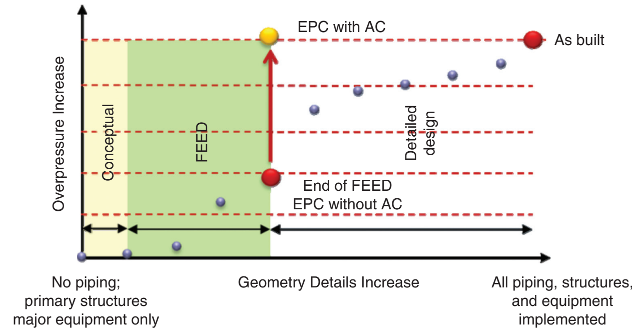

Fig. 4—Effects of geometry completeness on explosion results.

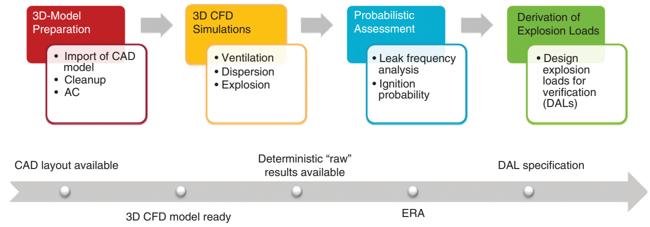

Fig. 5—ERA flow chart. (CAD = computer-aided design, CFD – computational fluid dynamics, and DAL = design accidental load.)

As a consequence, preliminary design explosion loads should be estimated early by the safety engineers and will be superseded as the results of the ERA become available. These results are based on experience from previous similar projects or the previous project stage (e.g., FEED results for detailed engineering) and expertise to set the provision margins properly, while accounting for design uncertainties. Simplified but conservative approaches could also be used to make decision support. In any case, the challenge is that the preliminary design explosion should be conservative enough to avoid further rework during the detailed design, but not too conservative—the final results are greater than expected, but not stringent enough to avoid overdesign and potential technical issues.

The explosion analysis may be either deterministic (scenario-based) or probabilistic (risk-based). The general approach remains the same. When a risk-based approach is chosen for the analysis, it is necessary to define an explosion-risk-acceptance criterion (RAC) corresponding to a predefined exceedance frequency (e.g., 10^{-4}/year), as shown in **Fig. 6.**

Design-Explosion-Loads Specification

The explosion analysis provides the raw results of the explosion simulations. These results should be processed and interpreted to provide proper inputs to engineering disciplines (e.g., structural, equipment, and piping) and equipment vendors for further verification against blast, whether the explosion analysis is consequence-based or risk-based.

The explosion effects on items can be categorized as follows:

- Overpressure (e.g., blast wave) because of expansion of burnt gases
- Drag pressure (e.g., blast wind) because of the flow of air, gases, and combustion products

The combined effects of overpressure and drag loads depend on the dimensions and shape of the safety-critical element (SCE) that is considered. Hence, each item should be associated with a representative geometrical shape for which one can derive explosion loads

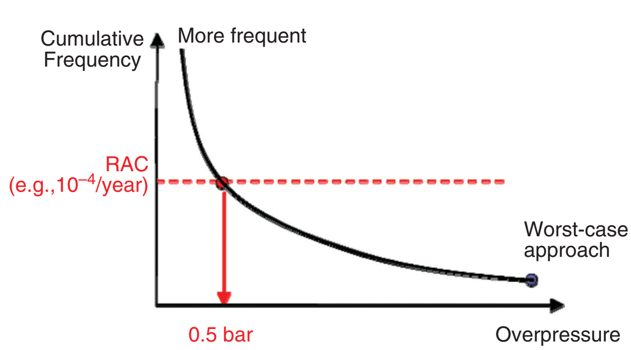

Fig. 6—Risk-based approach for the definition of explosion loads.

by setting blast parameters from the explosion analysis. This activity is carried out by experienced safety engineers who have sufficient knowledge of the interaction of the blast wave with obstacles (e.g., structure, equipment, and piping) to interpret the results from explosion computational-fluid-dynamics analyses correctly.

The purpose of the design-explosion-load specification document issued and updated at each phase of the project is to

- Ensure a clear and efficient interface between the safety discipline and other engineering disciplines
- Provide only the necessary data for the verification of SCEs to blast
- Avoid misinterpretation by disciplines regarding the definition of loads

The effective design-explosion loads are derived for a set of critical targets of interest from the results of the explosion analysis.

Explosion Response of Safety-Critical Elements (SCEs)

The calculation of the explosion response of structures and equipment requires a dedicated approach compared with other loading cases such as gravity or operating conditions. Explosion loading is very specific because it is high in magnitude, but short in duration; variable in space (not uniform) because of the propagation of the blast wave; and a low-frequency event. As a consequence, common design rules should be modified to take these factors into account; otherwise, the design will be highly conservative or not possible.

Magnitude and Duration. The blast wave can be roughly characterized by an idealized triangular shape, with a rise time (t_r) to a peak value (P_{max}) and a duration (t_d), as shown in **Fig. 7.** Sometimes, a negative phase may also be considered.

Propagation of Blast Wave. The propagation of the blast may also be accounted for in the response calculation by including both the arrival time and a decay of the peak overpressure. This may be the case for SCEs such as a flare header on the central pipe rack, which is distributed along the floating facilities for hundreds of meters, as shown in **Fig. 8.**

Blast-Load Cases Considering the Frequency of Explosion. The explosion exceedance frequency (return period) is considered in a risk-based approach through the definition of the risk-acceptance criteria (RAC) (exceedance frequency). This has a strong impact on the magnitude of the blast wave for the design. However, the selection of the RAC should be such that they are consistent with the

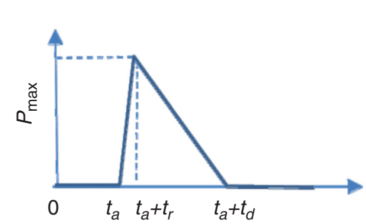

Fig. 7—Shape of the blast wave.

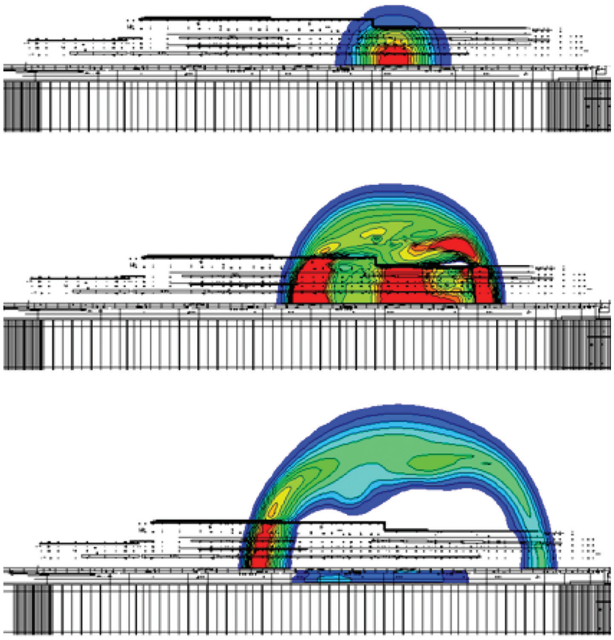

Fig. 8—Propagation of blast wave along pipe rack at different timesteps [from FLACS® (Gexcon 2014)].

criteria selected for other accidental loads such as fire, cryogenic events, or collision events.

For explosion events, two explosion events are usually considered, as per *API RP 2FB Ed. 1* (2006) for the response of structures:

- Strength-level blast (SLB)
- Ductile-level blast (DLB)

The SLB refers to a less-severe event, but with a higher frequency than a DLB. The main purpose is to ensure the robustness of the design and protection of the assets. The response analysis is usually performed with standard tools.

The DLB is a severe, but low-frequency, explosion event with an exceedance frequency of 10^{-4}/year. However, in some projects, the DLB refers to 10^{-5}/year, which is more stringent and involves potential technical-design issues. For DLB, residual damage of structures is therefore accepted as long as the load-bearing capacity after the explosion event is justified. The response analysis is usually nonlinear.

The main principle is to first perform a common elastic analysis with standard tools with SLB, and then verify the design with the DLB in an elasto-plastic analysis. However, structural engineers should take care when performing the SLB analysis with the RAC at 10^{-2}/year, as per *ISO 19901-3:2010* (2010) and *SCI P 112* (1993). If there is a large gap between the SLB and DLB acceptance frequencies, there will also be a gap between the design accidental loads (DALs). Because the DALs at the 10^{-2}/year frequency are often low or negligible, there will be no specific blast-design requirement. When carrying out the assessment for the DLB, the DALs will become significant. As a consequence, there will be potential rework if no provisions during SLB assessment were kept.

Therefore, in common practice (UKOOA 2007; *FABIG Technical Note 4* 1996), the DLB is usually taken as the 10^{-4}/year frequency (or lower frequency if required by the client), as per *ISO 19901-3:2010* (2010), but the SLB corresponds to one order of magnitude less in terms of frequency, thus leading to an SLB at 10^{-3}/year.

It should be kept in mind that these blast levels are also associated with performance criteria (implicitly included), and that SLB and DLB are only applicable on structures. There are no equivalent blast-load cases defined in the available design codes (e.g., American Society of Mechanical Engineers) for equipment and piping. Hence, when designing an entire safety-critical system (e.g., including structures, equipment, and piping), the engineering disciplines should ensure the consistency of the approach.

In addition, the definition of blast-load cases should take into account the combination with other loads such as gravity or operating loads (pressure, temperature) for equipment. These should be combined with explosion load in the structural response, but not with other low-frequency loads such as fire, collision, or extreme weather. In particular, it is not straightforward to combine with other loads considered generally as static loads.

Dynamic Behavior of Structures and Equipment. The calculation of the explosion response of structures and equipment requires a good knowledge of the dynamics of the structures. This requires specific skills in the project team to properly understand the expected behavior of the item, model it properly with sufficient accuracy in the definition of mass and stiffness, and ensure good interpretation and correctness of the results.

There are different approaches available to evaluate the response of structures and equipment, from the simplest (but always conservative), which are based on an equivalent static blast, to the most accurate (nonlinear finite-element analysis), which are time-consuming and require both experienced engineers and detailed information.

Equivalent static methods are preferred because they are easy to apply with standard engineering tools, especially when combining with other loads [e.g., MICROPROTOL® (Bentley Systems 2015) for pressure vessels, CAESAR II® (Intergraph 2015) for piping]. In most cases, the approach is to define an equivalent static blast load from the knowledge of the overpressure time history (P_{max}, t_d) and the natural period (T_n) of the item in the direction considered by applying a dynamic load factor or a dynamic amplification factor to the peak overpressure (P_{max}).

For nonlinear structural analysis of simple systems, design charts have been developed by Biggs (1964) and are reported in *FABIG Technical Note 4* (1996), UKOOA (2007), and *ISO 19901-3:2010* (2010). These charts allow for taking into account a predefined ductility ratio in a static analysis. These charts are based on a single-degree-of-freedom approach, which is an idealization of the item by means of a nonlinear mass/spring system. This approach applies only to simple or individual components (beams, plates, columns). Close-form solutions and charts have been developed for simple configurations only. It should be noted that the design is an iterative process because it is a nonlinear analysis.

For a more-complex loading or a complex SCE for which the expected dynamic behavior is not straightforward, a multiple-degrees-of-freedom analysis may be used. These analyses require the use of finite-element tools such as ANSYS® (ANSYS 2013), ABAQUS® (Dassault Systèmes 2014), or LS-DYNA® (LSTC 2014).

The recommended practice is to follow a gradual approach to check the design of SCEs against blast from the simplest approaches to the most-complex approaches, if the results obtained with the former are too conservative. In any case, it is strongly recommended to undertake a more-detailed calculation before modifying the design. The calculation methods and tools depend on the following parameters:

- Project phase: Conceptual, basic, front-end engineering and design (FEED), detailed engineering
- Type of SCE: Structures, piping, equipment
- Performance criteria to achieve stability/resistance, integrity/containment, or operability
- Complexity of the item: simple item or multicomponent item (single degree of freedom/multiple degrees of freedom)

Depending on the project phase, the requirements for the explosion response may be different because the accuracy of the inputs for design may not be available in the early stage of the project or may not be accurate enough. This will not be relevant to perform full nonlinear finite-element analysis in the conceptual stage or even before the end of the FEED phase, especially when the explosion results are not precise enough or are preliminary.

Engineering Discipline	Design Rules	Country	Calculation Methods: Linear/Nonlinear	Calculation Methods: Static/Dynamic	Accidental Load Case
Offshore structures	*ISO 19901-3:2014* (2014)	International	Linear/Nonlinear	Static/Dynamic	Yes
	NORSOK*	Norway	Linear/Nonlinear	Static/Dynamic	Yes
	AISC 303-05 (2005)	US	Linear/Nonlinear	Static/Dynamic	Yes
	Eurocode 3**	Europe (EU)	Linear/Nonlinear	Static/Dynamic	Yes
Equipment	ASME (2013)	US	Linear	Static	No
	EN 13445-3:2014 (2014)	France, EU	Linear	Static	No
	NORSOK*	Norway	Linear	Static	No
Piping	*EN 13480-3:2012* (2012)	France, EU	Linear	Static	No
	ASME B31.3-2014 (2014)	US	Linear	Static	No

*NORSOK L-002 (2009); NORSOK N-004 (2013); NORSOK P-100 (2010)
**EN 1993-1-1 (2005)

Table 2—Design rules for engineering disciplines (not a complete listing).

The type of SCE is also a key parameter because the design rules for structures or equipment are not usually consistent when dealing with blast as an accidental event. As shown in **Table 2,** the design rules for structures can account for different calculation methods because there is an accidental load case available and documented in *ISO 19901-3:2010* (2010). Whereas for equipment and piping, common design rules, such as those of the American Society of Mechanical Engineers, do not consider accidental blast as a potential design case. Therefore, the engineer should rely on a conservative approach that considers blast as an equivalent static load, with modified code checks discussed and agreed upon with the client on a case-by-case basis. Some guidance related to equipment and piping is provided in *FABIG Technical Note 4* (1996).

The performance criteria to be achieved will also drive the design process for equipment and piping. When integrity/containment of the item is required, an equivalent static approach may be preferred to justify the design. For stability verification, the performance of nonlinear analysis may provide a more-practicable design than that of an equivalent static approach by considering the acceptance of residual damage while achieving the safety objective.

The complexity of the SCE will drive the calculation method. Generally speaking, the single-degree-of-freedom analysis is used to compute the response of individual components, whereas the multiple-degrees-of-freedom analysis is used to compute the overall response of a structure or of equipment. Such tools are also used when the propagation of the blast wave should be accounted for in the calculation, especially for systems that span along the floating facilities.

Finally, experience gained from previous offshore projects will also guide the strategy for explosion response of SCEs; indeed, some items are less vulnerable to blast than others. For those items, it is not necessary to carry out a systematic calculation to demonstrate that they will withstand blast. Local strengthening or improving detailing provisions (e.g., design of supports, bolt sizes) will be sufficient in many cases.

Multidisciplinary Approach

The first challenge for a multidisciplinary approach is the consistency of the response analysis. All calculation methods mentioned so far in this paper are applicable only for isolated elements such as equipment, piping, or supporting structure. As per Table 2, the linear static-calculation method is common to any kind of element, but can lead to an excessive conservatism as a result of the stacking of margin at each step of the calculation by the disciplines. To limit the overall conservatism, the dynamic nonlinear method should be preferred for all disciplines. Considering that this is a problem of structural behavior of piping and equipment, the associated allowable criteria can be derived from those of structural items on the basis of strain hardening for the performance criteria to be achieved. For nonlinear analyses, the criteria are no longer allowable stress, but allowable strain, which should remain below the ultimate strain (e.g., elongation at break) for the material considered with a safety margin.

The second challenge for this approach is its integration into the overall project schedule. Each discipline should proceed in parallel with the available information (namely, the preliminary design explosion loads) to issue their initial design. They should also work closely with others to manage the interfaces properly and to update the sizing accordingly, as shown in **Fig. 9.** Local detailed analyses can be performed at the interfaces when required, such as complex load transfer or arrangement. The modification of the supporting condition of piping or equipment can lead to an iterative design process.

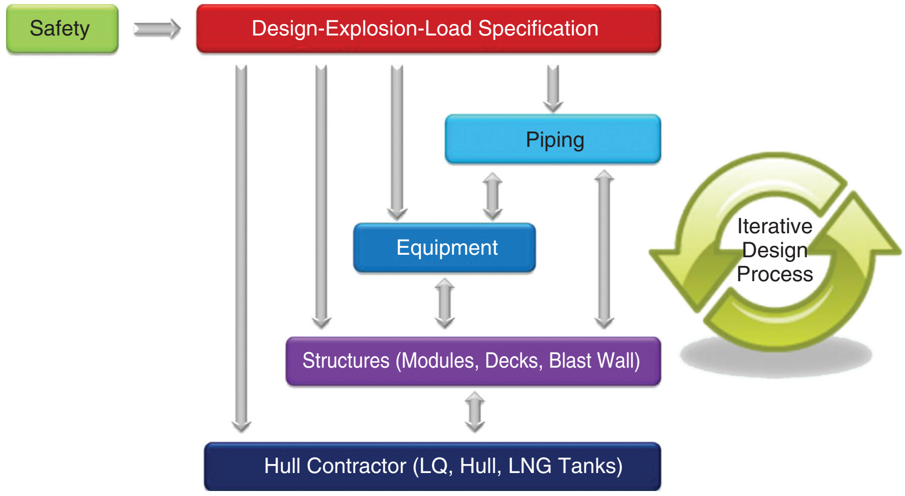

Fig. 9—Multidisciplinary approach. (LQ = living quarter, and LNG = liquefied natural gas.)

At the end of the design phase, once the explosion-risk analysis is completed, a comparison between the new and preliminary design explosion loads is made. At that time, any modification to the piping or equipment design will have serious consequences because purchase orders have already been placed and fabrication may have started. In the case of an incorrect estimation of the preliminary design explosion loads, there are two options:

- Estimation was too high, and was conducted to an overdesign with weight and cost impact.
- Estimation was too low, and the item cannot be considered as verified. Additional analyses must be performed to reduce the conservatism of the design approach or to update the design, with a schedule and cost impact.

Conclusions

This paper has focused on the philosophy of design against a blast event for floating facilities. It has also addressed the specifities of floating-liquefied-natural-gas units because they handle large flammable-gas quantities in relatively small and congested environments. It has recalled the objectives of explosion assessment, the definition of safety-critical elements (SCEs) and their associated performance criteria, the explosion-risk analysis, the design explosion loads, and the response of SCEs. It has made a comparison between the common design rules and tools available for the main disciplines individually, and highlights their limits to take into account this accidental event.

The multidisciplinary approach developed by Technip is based on a homogeneous verification method for all disciplines to achieve a consistent demonstration through the design to fulfill the overall safety objectives of the unit. Focusing on their interfaces and integrating the preliminary design accidental load (DAL), the key of this multidisciplinary approach lies mainly in the expertise of

- The safety engineers who provide accurate preliminary DALs, allowing all disciplines to work in parallel while minimizing conservatism as far as practicable, taking advantage of experience gained from previous similar projects.
- The knowledge of each discipline engineer who needs to know not only the design rules of his discipline, but also how to control the issues involved, including the definition of explosion scenario, the expected performance criteria, the complex calculation method, and the structural behavior of piping and equipment to dynamic loads. The engineer must master the way in which these issues interact in a global context and know when to act to obtain the validation of the whole.

Finally, the experience and anticipation of design explosion loads in the engineering/procurement/construction phase of the project can prevent over- or underdesign, leading to weight, cost, and schedule impact, while ensuring the required level of safety.

Nomenclature

P_{max} = peak value
t_a = time of arrival
t_d = duration
t_r = rise time
T_n = natural period

Acknowledgment

The authors would like to thank the management of Technip for granting permission to publish this paper.

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