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18th INTERNATIONAL SHIP AND
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ROSTOCK, GERMANY

VOLUME 2

COMMITTEE V.2

NATURAL GAS STORAGE AND TRANSPORTATION

COMMITTEE MANDATE

Concern for the safety and design of containment systems for the storage and transportation of natural gas in connection with floating platforms and terminals, and onboard ships. This is to include assessing the performance of various containment systems for gas under compression (CNG), liquefaction under cooling (LNG), and combinations of the two methods. Particular attention shall be given to the integrity and safety aspects of containment systems under pressure and thermal loads, and the interaction between fluid and structure under static and dynamic conditions. Needs for revision of current codes and regulations shall be addressed.

COMMITTEE MEMBERS

Chairman: Makoto Arai
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KEYWORDS

Cargo Containment Systems, Liquefied Natural Gas Carrier, Floating Liquefied Natural Gas, Floating Storage and Regasification Unit, membrane tank, spherical tank, prismatic tank, Compressed Natural Gas, sloshing, offshore terminal, arctic, structural integrity, collision, flooding, fatigue, vibration, fire safety, corrosion, Boil off Gas, cryogenic spillage, fuel Liquefied Natural Gas.

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1 INTRODUCTION

The Committee V.2 is a new specialist committee, the mission of which is to outline the safety and design aspects of containment systems used for natural gas storage and transportation on the ocean. With the increase in the worldwide demand for natural gas as a relatively clean energy source compared to other fossil fuels, new concepts and technologies related to the storage and transportation of natural gas have been emerging recently. Based on the committee's mandate and the specialities of its members, the Committee has reviewed the performance of existing and new containment systems and has discussed their safety.

The initial section of the report describes the safety records, transportation and market trends as the background of the Committee's work. Next, the safety aspects of LNG are discussed and an overview of Cargo Containment Systems (CCSs) and operational features related to the safety and design of natural gas storage and transportation systems are described.

The following chapter deals with the measures that must be taken to assure the safety of the Cargo Containment System per mode of failure, including brief summaries of the phenomena. At the beginning of the chapter, structural integrity management is outlined. Possible failure modes caused by several incidents such as sloshing, collision, fatigue, and the like, together with the measures to mitigate them, are discussed.

The necessity of establishing new rules and regulations is emphasized with regard to the new concepts of natural gas storage and transportation, for example in applications such as Floating Liquefied Natural Gas (FLNG), Arctic and for applications of LNG as fuel.

2 BACKGROUND

2.1 LNG Transportation Safety Records

Over the LNG industry's 60-year history of 40,000 voyages, there has not been recorded a spill from a ship into the water from either a collision or grounding (Ostvik *et al.*, 2005 and Foss, 2006). During the period from 1964 to 2008 (44 years) with over 30,000 shiploads of LNG delivered and more than 100 million miles travelled in the loaded condition, the overall safety record of LNG carriers (LNGCs) has been remarkably good with no fatalities, no record of fire occurring in the deck or in the cargo area or cargo tanks of any LNG ship (CH-IV International, 2009). Typical incidents include failure of containment tanks, tank cover and deck fractures due to LNG released, valve leakage, rollover incidents, tank overfilled, broken moorings, hull fatigue cracks, collision, and other incidents.

Statistical data showing the safety of LNG transportation today in comparison with general ship transportation is shown in Figure 1 (Data developed based on Lloyds World Fleet Statistics). The statistics show that the safety records of LNG transportation is better than the safety records for general ship transportation. It can be assumed that the good records are due to several reasons: LNG ships have traditionally been built and maintained to high standards. Well trained personnel onboard with a relatively low turnover. Operation of LNG ships has been based on trading on fixed routes on long term contracts. The LNG fleet has also been growing slowly and steadily with about 4 ships per year from 1970 to 2000.

From about year 2000 the orders of LNG shipping increased drastically to about 25 ships per year until 2010. The increase in both size and number (Figure 2 and

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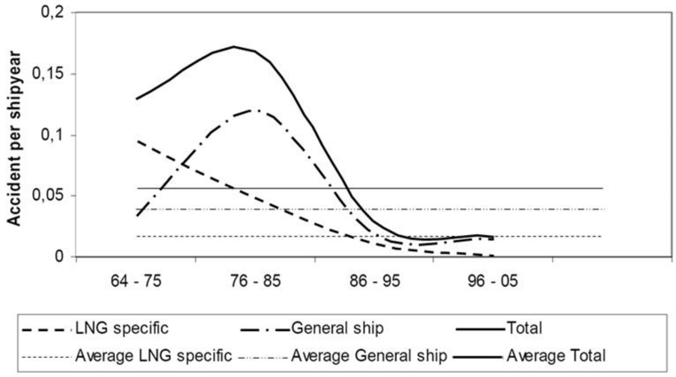

Figure 1: Safety records for LNG ships compared to general ship transportation

Figure 3) may have an impact on the safety records. It will be of great interest to study what impact the large orders of ships and the corresponding shortage of qualified and experienced personnel may have on the statistics of safety. Larger ships (Figure 2) and with some new operation profiles together with loading and offloading at more exposed locations with more harsh environmental conditions may also have an impact on the safety. LNG handled in offshore applications give new challenges to the safety aspects of LNG transportation. Another new application is the use of LNG as fuel for all type of ships. Here LNG will be handled by a wide range of operators. New safety aspects and ways to handle LNG from a safety perspective are required.

2.2 LNG Market and Trends

Figure 4 shows the current and future worldwide LNG trades. At the moment, main consumers of LNG are East Asian countries (Japan, Korea, Taiwan, etc.), and some European countries (Spain, France, etc.). China and India are expected to increase LNG import in the near future.

Figure 3 shows the historically accumulated number of LNG carriers with different cargo containment systems. As illustrated in this figure, LNG transportation continues to expand, and in particular the number of completed LNG carriers has dramatically increased since the year 2000. This increase in LNG ship deliveries was driven largely by the massive expansion of LNG production in Qatar. This trend is unlikely to continue at the pace of the past decade and many factors such as the exploitations of

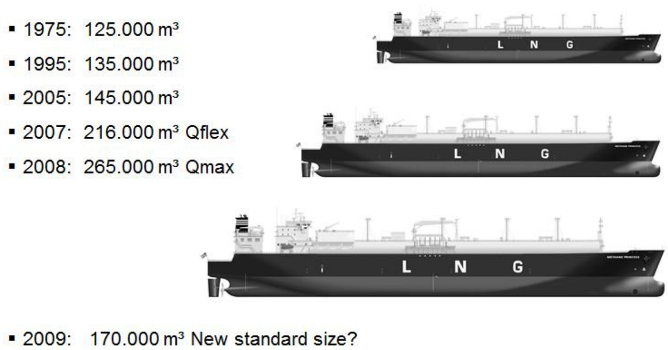

Figure 2: The development of standard LNG ship size

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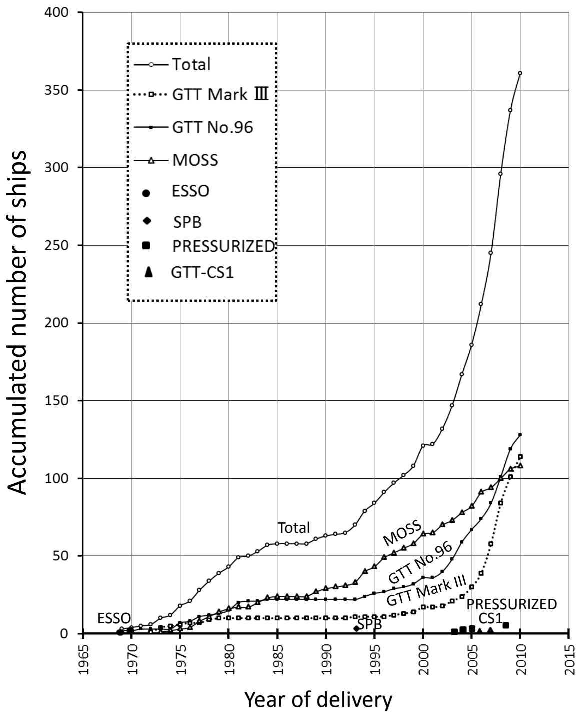

Figure 3: Accumulated historical number of LNG carriers

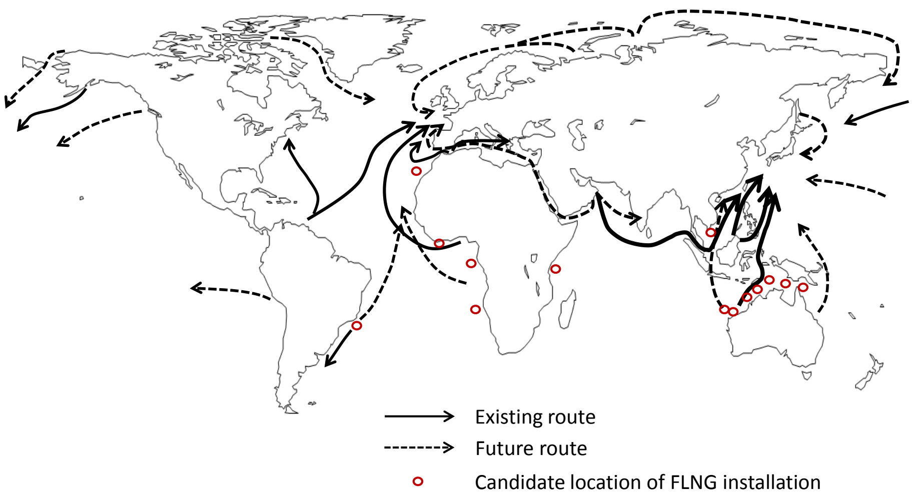

Figure 4: Current and potential future trades

natural gas with new technologies (shale gas) at the fields closer to consumer markets, and the development of new power sources such as wind, solar, etc., will determine the future requirements for LNG ships. Other factors might be the usage of LNG as ships' fuel, secession of some countries from using nuclear power after the accident of Fukushima nuclear power plant, etc. As an indication of such uncertainties, it can be

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noticed that membrane LNG tankers ordered in 2010 was less than 10, but more than 45 in mid-2011.

The cargo containment systems used today for LNGCs are mainly of the membrane type (GTT's Mark III & NO. 96), and spherical type (MOSS) and in a few cases the structural prismatic design (SPB). Membrane systems and Moss type spherical tanks have different advantages. Suez Canal fees, which are dependant on the internal volume of a ship, penalize the spherical type design compared to the membrane type design, due to void space around the tanks being counted in computing canal charges. This has in large part contributed to there being more LNG ships built with Membrane CCS than Spherical type designs in recent years. The Membrane type has, in addition, a relatively higher utilization of the hull volume for the cargo capacity. That is, for the same cargo capacity, the ship dimensions of the membrane carriers are somewhat smaller than those of the spherical carriers.

Moreover, new aspects and issues of LNG appears with the offshore exploration, dedicated to gas fields or to monetization of gas associated with oil production. Similar to the FPSOs in the last decade, FLNGs need specific rules and regulations considering their specific design and operation. For example, large FLNGs may require longitudinal bulkheads considering both the sloshing in cargo tanks with intermediate filling levels and the strength of deck structure required to support the weight of the onboard liquefaction plant.

Songhurts (2009) reported that eight Floating Storage and Regasification Units (FSRUs) were in operation, three under development and seven projects were in the planning phase. On the other hand, more than fourteen FLNG projects were in different stages from feasibility studies to Engineering, Procurement and Construction (EPC) contracts. According to different sources the first FLNG system could be delivered in 2015.

Historically, when involving LNG transportation by ships:

- gas is transported from production area to onshore plant by pipes
- gas is liquefied and stored onshore at an export terminal
- liquefied gas is transferred on LNGCs for transport to market
- liquefied gas is delivered to a receiving terminal and offloaded to onshore storage tanks
- liquefied gas is then regasified as required and distributed to local consumers, by pipeline.

With new producing locations as offshore gas fields, for example SHELL PRELUDE or associated gas monetization, such as Petrobras PNBV Gas floating liquefaction, storage and offloading unit (FLNG of Gas FPSO), some operators are now choosing not to liquefy onshore, but directly at sea. In recent years, on the receiving terminal side, the FSRU concept has appeared, consisting of ships moored offshore supplying natural gas to shore after regasification in their onboard vaporization plants. FSRUs can be permanently moored, or temporary moored in case of ships which are both transport and regasification units.

In addition, the use of LNG as fuel for ship propulsion has started to be adopted, not only for LNGC but also other ship types. This will require LNG tanks to be installed on many different ship types, where in the past fuel oil tanks only have been installed. Distribution network of LNG will extend accordingly to more places than now, and LNG handling facilities use will become more widespread. This may also

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drive the development of marine distribution systems where coastal navigation and inland waterways may be used to deliver LNG to smaller more distributed markets than at present. These new market developments will require dedicated rules and guidelines, together with training of all these crews and distributors to LNG handling.

3 SAFETY AND DESIGN

The Cargo Containment Systems for LNG for ship transportation are regulated by the International Maritime Organisation (IMO) through the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code). The Safety aspects to LNG transportation are linked to handling Liquefied Natural Gas (LNG).The precautions and safety measures related to handling of LNG is mainly due to the following safety aspects:

- To carry LNG as a liquid at atmospheric pressure the LNG temperature has to be -163° C. Any spillage of Liquid Natural Gas on the ship steel would be hazardous and can cause immediate damage to the ship hull.
- Natural Gas in a mixture of between 5 to 15 % with air is explosive and shall be avoided.
- Liquid Natural Gas contains about 600 times the volume of Natural Gas in the gas phase. The boiling temperature is -163° C and heating Liquid Natural Gas may cause rapid increase of gas volume and if it is enclosed the gas will cause significant pressure build up.

The below discussed areas under this chapter can be directly addressed to these core safety issues.

3.1 Cargo Containment Systems

3.1.1 Non-self Supporting Tanks - Membrane Tanks

Membrane tanks are non-self-supporting tanks which consist of a thin layer (membrane) which is supported through insulation by adjacent hull structure (Figure 5). The membrane is designed in such a way that thermal effects are compensated for without significant stressing of the membrane. To control the effects on ship structure from the potential leakage of cryogenic liquids, a secondary barrier is required, by the IGC Code (Deybach, 2003). A secondary barrier is a liquid-resistant outer element of the cargo containment system designed to provide temporary containment of potential LNG cargo leakage and to prevent lowering the temperature of the hull structure to unsafe levels. The full secondary barrier of membrane tanks is fitted within the insulation system (Figure 5). This space is kept purged by inert gas which is circulated and has hydrocarbon detectors present so that any increase in the presence of methane can be readily detected and appropriate action should be taken. More details about the leakage control of membrane tanks are described in Chapter 3.11.

3.1.2 Independent Tanks

The IGC code categorises independent type of tanks in following tank types: Tank Type-A, Tank Type-B and Tank Type-C. In Figure 6 parts of the safety philosophy between the independent tank types is illustrated. All tank types are designed to comply with a comparable level of safety. The Type-A tank has a full secondary barrier with the function of providing a redundancy to any possible leakage regardless of the leakage is caused by fatigue cracks or due to over load of the tank causing a rupture of the tank primary barrier. The tank is designed with strength utilisation similar to a deep tank in a ship structure. The Type-B tank on the other hand is

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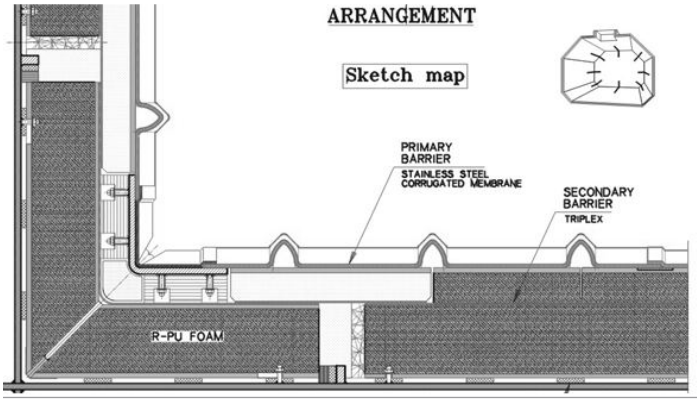

Figure 5: Build-up of a Mark III membrane tank (by courtesy of GTT)

designed with a partial secondary barrier that provides redundancy to fatigue cracking only. The size of the secondary barrier is dimensioned to the worst possible leakage that may occur. The tank design requires detailed control of the possible fatigue strength and the corresponding crack propagation properties. It is required by the IGC code to document that, if a crack occurs and grows through the thickness, the crack will remain stable for a sufficiently long time (normally 15 days). This is to allow the crack to be detected and the tank closed down to empty the cargo and to make necessary repairs. The Type-B tank is accordingly designed for redundancy to fatigue damage but has no redundancy for a damage caused by extreme loads. The material utilisation for extreme loading is therefore stricter as compared to a Type-A tank. This is to provide a larger safety factor against over loading. A Type-C tank on the other hand has no redundancy to either fatigue damage or damage caused by extreme loading. The material utilisation for a Type-C tank is therefore as strict as a B-type tank for extreme loading but more strict with respect to fatigue loading. For a Type-C tank the fatigue safety is incorporated in the formulation of a minimum design pressure, i.e., designed for large static loads compared to the dynamic loads resulting in small dynamic stress amplitudes.

The secondary barrier has the primary functions to provide temporary containment

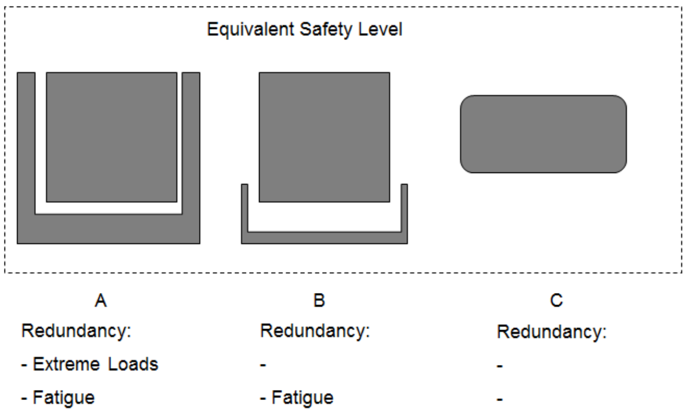

Figure 6: Different application of the safety philosophy between independent tank types

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of cargo and to prevent the hull structure from being cooled to an unsafe level. The partial secondary barriers shall be designed to safely contain any envisaged leakage of cargo for a certain period of time (15 days). Continuous monitoring of the secondary barrier space is required to detect leakage of the primary barrier. The partial secondary barrier in the case of Type-B tanks (spherical or independent prismatic tanks) is usually designed as a drip tray capable of containing the estimated quantity of leaking cargo for sufficient time for corrective action to be taken.

For A-type tanks the hull structures are normally permitted as secondary barrier for cargoes with boiling temperature not lower than - $55^{\circ}\,C$. The ship hull is accordingly not relevant as a secondary barrier in connection with LNG transportation. Type-A tanks are therefore normally not considered as a realistic alternative for LNG transportation. Type-A tanks are applied for cargoes such as Propane, Butane and Ammonia. These liquid gases are transported at temperatures above -$50^{\circ}\,C$ and therefore the ship hull itself can function as a full secondary barrier in case of a leakage from the cargo tank.

Independent tanks Type-B

Type-B tanks are divided into two main categories: Spherical tanks (MOSS type tanks) and Prismatic tanks primarily constructed by plane stiffened panels (IHI prismatic tank). The design pressure Maximum Allowable Relief Valve Setting (MARV) is normally $0.25\,bar$ but shall not exceed $0.7\,bar$. These tank types are applied in LNG carriers with capacities up to $135{,}000\,m^3$. However, larger ships have been designed. The tanks are built by Aluminium grade 5083-0 or Stainless steel L304/316 grade (Figure 7). Typical analyses required to document a Type-B tank are:

- Detailed FE based stress analysis
- Fatigue analysis
- Crack propagation calculation
- Calculation of leak rates
- Leak before failure analysis
- Tank support loads including interaction with ship hull deflections

Type-C tanks

The Type-C tanks are designed to a minimum design pressure. The Type-C tanks are usually not used for LNG transportation except for LNG carried as fuel where the advantage with the Type-C tanks is the possibility to handle boil off gas (BOG) by increased tank pressure. The tanks have the disadvantage compared to the other tank alternatives by a higher weight of the containment and a lower effective utilisation of space.

Figure 7: Cross sections of independent tank types A and B (with courtesy to DNV, Moss Maritime and IHI respectively)

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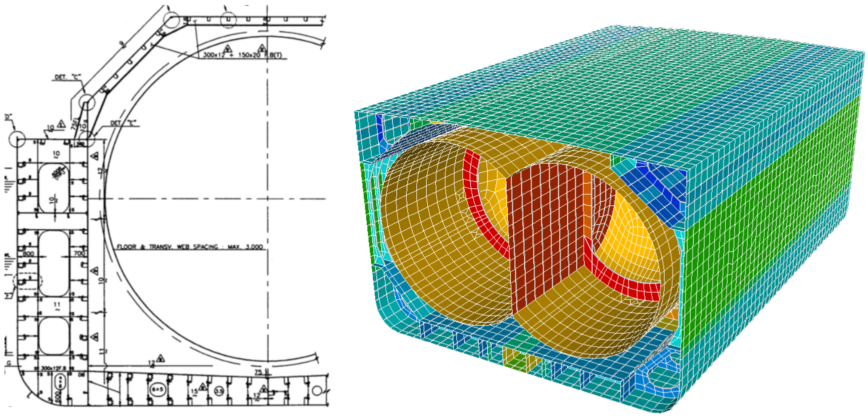

Figure 8: A cross section of a FEM model of a Bi-lobe Type-C tank (with courtesy to DNV)

The Type-C tanks can also be designed as bi-lobe tanks, see Figure 8. Bi-lobe tanks are normally designed for large tank sizes. Detailed finite element stress analyses are often required as documentation for these types of tanks.

3.1.3 New Tank Systems

Containment systems for LNG carriers have been well established and the regulation regime through Class Societies and the IGC code have been maintained without major changes for decades. However, the recent development in the offshore business, the offshore loading and offloading terminals have challenged the established designs and required the designs to be suitable for any filling height. These issues have forced changes to the established designs and new designs have been developed. Also the stricter emission requirements have made LNG an interesting alternative as fuel. Containment systems suitable for LNG fuel have resulted in new design proposals that do not directly fit with the existing regulations. In this section some of the new design features are discussed and safety issues are addressed.

Pressurized Prismatic Tanks

When LNG is used as fuel there is a need for boil off gas (BOG) handling when the ship is not in operation. This is commonly solved by increasing the tank pressure. A Type-C tank is therefore ideal for this application. The Type-C tank on the other hand is not ideal when space usage is limited. A new type of LNG tank design has been developed by Aker, the ADBT tank, where both pressure is handled and a prismatic shape is applied to utilize the required volume more efficiently in a ship installation (Lund, 2011). The IGC code is developed for particular tank designs but does not give guidelines for new designs not directly fitting into the existing tank definitions. New regulations need to be developed that give design guidelines that consistently maintain the safety level.

Type-A tank Designs

To develop a Type-A tank applicable for LNG transportation is a challenge as the hull is functioning as a full secondary barrier and need to be insulated from the low LNG temperature. Marine Gas Insulation AS (MGI) has developed such insulation systems.

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Double Barrier Designs Based on Extruded Aluminium Profiles

Several new LNG tank concepts have been developed based on welded Aluminium profiles where the flanges are welded together and forming a double barrier system (GASTECH 2009 ADBT tank by Aker yards). The interpretation of the double barrier system may be a challenging issue as the barriers may be considered a secondary barrier system for fatigue damages but not for Ultimate strength loads. How strength criteria shall be applied need to be developed and consistently applied to maintain the safety on equal level with other LNG containment systems.

Compressed Natural Gas (CNG)

Natural gas can be brought to the consumer by ships with compressed natural gas (CNG) technology. These ships may serve for both storage and transportation. The cargo can be discharged directly into a land based gas grid via an on/offshore discharge terminal, an offshore platform or offshore buoys. The CNG technology does not require a liquefaction process and a regasification unit on each end of the transportation chain, but may require pressurized storage if ships are to minimize loading and discharging time. The natural gas is transferred in a gas to gas phase at a high pressure (but may have to be let down in pressure to match pipeline pressure specifications). A CNG system may also be an alternative to pipelines between the gas field and the consumer, although no such alternative had proved to be sufficiently competitive to be implemented at this time. The weight of the pressure containment system for CNG ships is significant. Several different CNG concepts have been developed the last years. The CNG Coselle system with coiled pipe in stacks, the Knutsen design with vertical steel pipes, the FRP wrapped steel pipes by Trans Canada, the horizontal Composite CNG tanks by CETech and Vertical steel pipes by EnerSea (Marine CNG Transport and Development Forum, London 22–23 Sept 2010).

There are no international common rules or regulations for CNG carriers such as the IGC code for LNG carriers. The Classification Societies apply different basis for their CNG rules. Some are designed based on pressure vessels codes such as ASME VIII, Division 3 code combined with additional specific requirements (ABS Guide for Vessels Intended to Carry Compressed Natural Gases in Bulk) and others based on modified offshore pipeline codes where improved production quality and stricter tolerance requirements open possibilities to optimize weight without reducing the safety levels (DNV Rules for Classification of Ships. Compressed Natural Gas Carriers), alternatively CNG designs may be designed based on Goal based standards. Commonly the CNG rule standards are benchmarked with the safety levels of LNG carriers. It may be a need for common international regulations covering CNG designs.

3.2 Unrestricted Filling

The LNG containment systems for transportation are large in size and a free surface of LNG may cause violent sloshing and high impact pressures due to tank oscillations generated by ship motions. Sloshing impact loading on the containment boundaries is especially an issue for the large membrane containment systems and not as critical for the spherical tank design where the spherical shape reduces the effect of sloshing impact on the tank boundaries. In all tank designs pump tower arrangements may be exposed to large loading due to sloshing. Traditionally the sloshing loading in membrane tanks has been limited through filling level restrictions. Normally the operation of ships are with almost full tanks (70 % – 98 % filling height) or alternatively at ballast with less than 10 % of the filling level in the tanks. However, LNG carriers and tanks filled and

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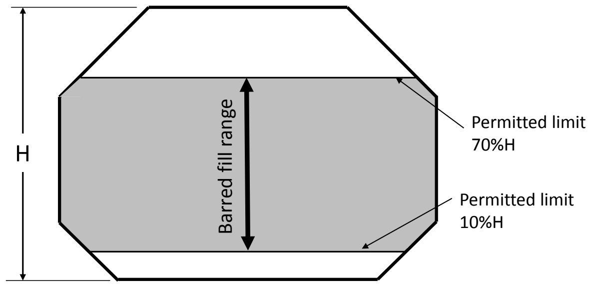

Figure 9: Membrane tank typical fill range limitation (GTT)

emptied at offshore installations require tanks to be able to operate at any filling level. The importance of controlling the sloshing loading for these applications is therefore extremely important to maintain the integrity of the containment system.

Ships with partial filling of liquid cargo may suffer the problem of liquid sloshing inside their tanks. The long safety record history of LNG carriers mentioned in the section 2.1 demonstrates the effectiveness of the filling level limitation of the cargo that has been applied in the traditional operation of the membrane carriers (see Figure 9). Basic idea of the filling level limitation is as follows. Since sloshing occurs mainly by a resonant motion of a liquid free surface inside a storage tank with a frequency close to the lowest natural frequencies of the tank-liquid system, the practical measure to mitigate the sloshing is to avoid the resonance by a proper design of the tank dimensions and the selection of a suitable fill level, as well as operating the ship in a manner such that sea-state conditions and ship speed do not encourage resonance.

The recent development with offshore terminals and FLNG applications has raised a new requirement of being able to handle unrestricted filling. This has required new investigations of the consequences due to possible sloshing effects on the tank containment system and pump tower arrangements. See further section 3.5 about sloshing.

3.3 Operation and Human Error

LNG storage and handling need to be considered in connection with the evolution of LNG usage and LNG industry.

Concerning LNGC, the hazards are well identified and controlled at present time. The good safety records (Section 2.1) of these ships are evidence of this assessment. Meanwhile, however, the increased fleets may be exposed to the risk of less skilled crews, less conscious ship owners regarding training and maintenance, and less demanding flag states. Mainly during transfer phases, the ship's crew is involved in cargo handling and is the focus point for human errors. With emergence of LNG as propulsion fuel for any kind of ships, these operations will be more widespread, while always critical. Authorities need to establish the correct procedure and safety knowledge accordingly.

Regarding FLNG, and to a lesser extent FSRU, their increased complexity may lead to increased exposure to human error. These new dual concepts (a ship and a plant in the same unit) shall be operated with good interface between process and marine crews, even more than for an FPSO considering the highest potential hazards (processing, handling and storage of very cold and volatile hydrocarbon products compared to crude oil) occurring in LNG treatment and storage. This duality should not be a culture clash, but rather a perfect integration of each ones' requirements and limitations.

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The high complexity of LNG plant increases the number of possible failure modes. This requires a high level of operators' knowledge and competency of the integrated control systems. This pinpoints the need for the operator to be strongly involved in the design of the control system to gain the complete knowledge of this complex tool.

Less complex, but not to be neglected, is the fact that FLNG is a continuous flow process. These flows are to be managed and stored. Some FLNG plants produce several products (LNG, LPG, condensates) that cannot be mixed after separation. Particular attention in design, procedures and operators' training shall be paid to avoid mixing of highly incompatible products (LNG/LPG) during the following processes: a) during production, b) during offloading, using common loading hoses (non simultaneously), c) after offloading during purging process and d) redirecting in storage or any dedicated tanks.

As interlock systems may not solve this problem, the human factor is of major importance in that case. Additionally, inerting systems that can also be designed with common headers for cost/simplicity reasons may be a source of mixing products in case of overflow with more severe consequences than for FPSOs.

3.4 Structural Integrity Management

The modes of failure listed in Sections 3.5 to 3.12 along with associated hazards for the main components of the structural system should be considered in the integrity management plan, which is an integrated and focused effort that includes inspection and monitoring, with the goal of maintaining the integrity of the asset over its service life. Figure 10 presents a flowchart of the integrity management process, Quinn *et al.* (2007). As part of the integrity management plan, hazards need to be identified along with probabilities and consequences of failure to perform risk analysis. Based on risk assessment results the structural components can be prioritized to optimize inspection, maintenance and monitoring resources. Risk mitigating measures can be implemented in components with high risk. Findings could trigger local or global integrity assessment.

According to Lee *et al.* (2008) risk assessment is required at the early stages of design for mooring in survival conditions, off-loading operation, vessel collision, fire, hazardous operation of topside process, etc.

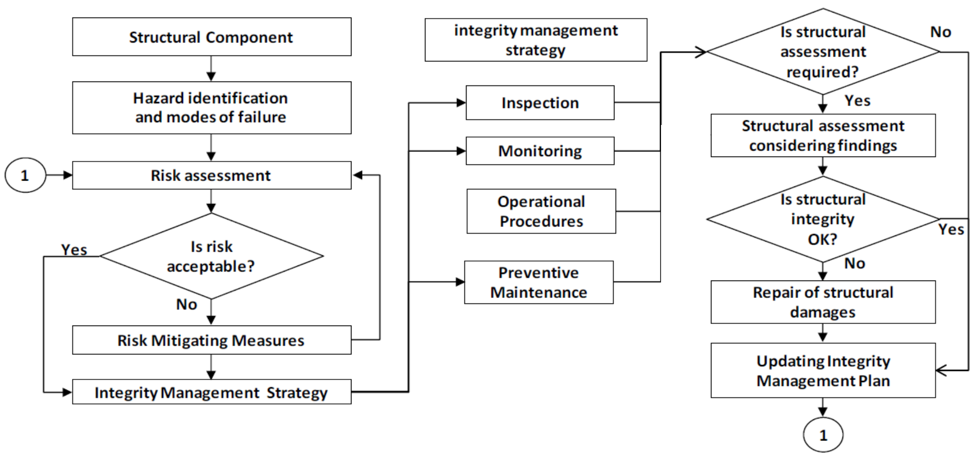

Figure 10: Integrity management process flowchart

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Typically the integrity programs from the shipping industry are based on the detailed inspection performed at frequent intervals (5-year) in dry docks, along with thousands of ship years of service resulting in effective empirical inspection practices. In the past decade Reliability Based Inspection practices have supplemented the historic empirical approaches. In recent years integrity management programs have incorporated risk based inspections (RBI) for hulls, marine systems and specific components such as mooring components and risers, Wisch *et al.* (2009). Similar practices should be considered for the future FLNG systems.

FLNG systems will be designed and constructed/converted for continuous operation during their service life in a fixed offshore position. FLNG systems cannot easily be taken to dry dock for inspection, maintenance, and repair. These activities will normally be performed in situ. Therefore, permanent means of access have to be provided to facilitate these activities. The reliability of containment systems including second barrier construction will be more important in FSRU and FLNG applications where long term, continuous operation at a fixed site is required (Lee *et al.*, 2008). Consequently, the activities previously mentioned have to be risk assessed and performed with the required safety measures.

Verghese (2011) reported that the major hazards resulting from the release of flammable material can be controlled by suitable design. Effective measures can reduce the consequences of incidents that could compromise the integrity of the FLNG unit to an acceptable level.

3.5 Sloshing

One of the design issues for the membrane-type LNG carriers is the sloshing phenomenon, because the containment systems have almost no internal structures and they are prone to violent liquid motion. Many studies of sloshing in the membrane-type CCSs have been carried out and reported in conference proceedings of ISOPE, OMAE, PRADS, and related organizations, and also in some related technical journals (e.g., Kaminski *et al.*, 2010; Iwanowski, 2010; Kim *et al.*, 2010). When violent sloshing occurs, complex phenomena are generated, such as a mutual interaction between ship motions and sloshing, high impact load on the tank ceilings and walls, dynamic response of the tank structures, etc.

As a most practical measure to mitigate the sloshing, tank dimensions and selection of a suitable filling level has been considered in the design and operational phase of membrane LNG carriers (Section 3.2). However recent development of FLNG concepts requires a new investigation of sloshing since FLNGs should be operated without any filling limitation.

In view of new concepts and other changes the LNG market undergoes, the new designs or operational conditions should provide equal or higher level of safety as for the vessels currently operated. From a sloshing point of view the position of the tank is important – generally forward tanks have been more susceptible to sloshing than aft tanks. Also there is a possibility to operate one or more slack tanks. A practical solution might be to design the cargo storage and transfer system such that LNG is produced into smaller tanks (i.e., slack tanks) as it comes from the liquefaction train and then is transferred into empty tanks to quickly fill them to capacity. Based on a similar idea, Rokstad *et al.* (2010) proposed an optimization model for the redistribution of cargo to reduce sloshing loads in LNG cargo tanks during regasification of LNG from an FSRU.

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To minimize sloshing events, rather than trying to design structures to withstand the sloshing loads, can be more reasonable measure against sloshing. Noble *et al.*, (2005) proposed tank geometry to minimize sloshing loads. Anti-slosh devices proposed by Anai *et al.* (2010) and Chun *et al.* (2011) might be another potential measure.

3.5.1 Rules and Standards

Sloshing loading may be determined either by direct calculation or model tests. Classification societies have rules of minimum sloshing loads to apply to the tank boundaries and pump towers, for example DNV Rules for ships Pt.3 Ch.1 Sec.4 C300. DNV Classification note 30.9 describes how sloshing loads for membrane cargo containment systems shall be determined. A guideline for sloshing loading on pump towers is defined by ABS "Sloshing and Structural Analysis of LNG Pump Tower". Similar rules, procedures and guidelines are provided also by other classification societies.

Differences in the rules may however be observed. Most of the classification societies adopt the comparative approach (by comparing the loads or responses in the new designs to those of existing and operating ones), while others suggest applying more direct approaches.

The comparative procedure is relatively simple and straightforward, but Zheng *et al.* (2010) pointed out that it is only applicable to a target design (including the ship, CCS and filling range) that is similar to a service-proven reference design and uses CCS's from the same designer.

Due to all the uncertainties involved in the sloshing phenomenon for a cryogenic liquid operating at its boiling point, an absolute approach may not be considered as fully reliable and must be applied with care.

3.5.2 Long Term Assessment (Including Screening Techniques)

The estimation of long-term sloshing response in LNG tanks is a challenging task. This is due to uncertainties related to determining the local fluid motion and loads acting on the tank structure, structural load effects, and their comparison with appropriate resistance criteria.

Performing experiments to provide sloshing pressures in the tank can be a time consuming step in this procedure (nevertheless experimental methods are the most usual technique for this purpose). The common practice of determining the critical conditions has been a screening procedure of the extreme conditions with a given return period. However, it is observed that more benign sea states with higher probability of occurrence may considerably contribute to the long term estimate; see for instance Graczyk *et al.* (2007), Rognebakke *et al.* (2009) and Ryu *et al.* (2009).

In order to limit the number of screening cases, methods for identifying conditions with large sloshing response are desirable. A simplified measure for sloshing response, developed on the basis of the idea of RAO for linear systems, may be utilized for this purpose. This measure is formulated so that it expresses sloshing severity in an approximate but effective way.

A semi-analytical method is applied by Graczyk *et al.* (2007) with the quasi-RAO calculated from tank acceleration spectra, with emphasized frequencies close to the tank natural frequency, considering nonlinearities in the response. This method shows reasonable accuracy while maintaining the computational efficiency of semi-analytical approaches.

A more refined approach is presented by Kim *et al.* (2010). They solve the internal sloshing problem by use of potential solver and formulate a quasi-RAO by analysing

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the total sloshing wave energy in the tank. They assume a linear, damped free surface flow. The results indicate that the method may be an efficient tool for determining the critical cases.

Similarly, Cao *et al.* (2011) illustrate that potential flow solvers may be utilized to assess the sloshing severity.

3.5.3 Global Fluid Motion

The current practices to determine the global motions include semi analytical approaches such as multimodal method (Faltinsen *et al.*, 2000), numerical methods based on CFD and experiments. Each approach has its advantages and weaknesses. Semi-analytical methods are very time effective but their application is limited to basic tank geometries and excludes very low filling levels. Such restrictions do not apply for numerical methods or experiments which are time consuming and costly. For the experimental approaches the number of acquired time series is physically limited by the number and location of sensors applied. As to numerical simulations the combination of the large domain with high resolution, both temporally and spatially, may constitute a computational challenge. In practice, experiments have to large extent been used in commercial applications.

Experimental methods

Experimental techniques are mainly used for determining the global motions. The standard testing procedures are based on 6 degree-of-freedom experiments with 3-dimensional rigid-walled tank scaled as 1:70 – 1:35 and filled with water and a heavy gas in ambient conditions. Up to a few hundred small-sized sensors, are typically arranged in rectangular matrices mounted over the most exposed areas, specifically for each considered filling level. A large amount of literature documents the experimental set-up and procedures, including actuator rigs, models and instrumentation, see for instance work by Kuo *et al.* (2009) and references therein.

Full scale in-service measurement campaigns have also been completed, Lund-Joannsen *et al.* (2011). They complemented the model test investigations and numerical simulations by providing valuable benchmark data.

Investigations of the global flow sloshing effects were in the previous decade typically related to transport with different tank systems. In the most recent years they were further developed towards new applications such as FLNG and FSRU, see for instance Ryu *et al.* (2009) and Diebold (2010).

Another trend is that more attention is devoted to investigating local phenomena, dedicated for instance to investigate local hydrodynamic mechanisms, scaling laws or fluid-structure interaction; see Sections 3.5.4 and 3.5.6.

Numerical methods

CFD based numerical simulations are often used to determine the global fluid motion. Previous ISSC Committee V.2 "Impulsive Pressure Loading and Response Assessment" (2009) carried out an intensive survey of the numerical methods and pointed out some numerical problems such as insufficient accuracy of localized pressure, stability problem of numerical schemes and high CPU load. Efforts to overcome those issues are still continuing.

Since sloshing is a violent liquid motion, accurate tracking of the deformation of the free surface is important in numerical analysis. With the advancement of the recent

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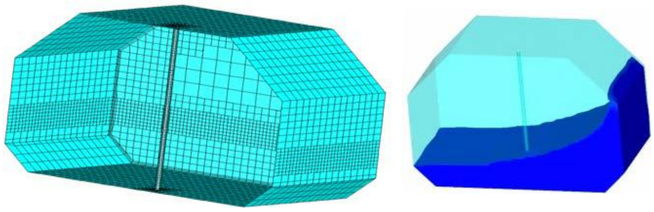

Figure 11: Fluid force analysis of pump tower (Reddy *et al.*, 2006)

Computational Fluid Dynamics (CFD) methodologies, many free surface tracking algorithms have been proposed. In view of their sloshing application, we may classify those algorithms into two groups, i.e. (1) using the Eulerian coordinate system with structured or unstructured grid systems (VOF, CIP, etc.; e.g., Moirod *et al.*, 2010, Liao *et al.*, 2011), and (2) application of a particle-based method without a grid system (SPH, MPS, etc.; e.g., Guicher *et al.*, 2010, Lee *et al.*, 2010). In the latter case, particle tracking is carried out based on the Lagrangian-type formulation.

In general, however, numerical techniques have significant problems when considering highly nonlinear waves and/or overturning waves, the effect of gas cushions and fluid–structure interactions. A comparison study of experimental and numerical sloshing loads in partially filled tanks is reported by Brizzolara, *et al.* (2011). A set of two-dimensional cases, for which experimental results are available, is considered to assess the merits and shortcomings of different numerical methods for sloshing evaluation, namely two commercial RANS solvers (FLOW-3D and LS-DYNA), and two academic software (Smoothed Particle Hydrodynamics and RANS).

An important application of numerical techniques is for calculating the interaction between ship motions and sloshing. Here Wang and Arai (2011a, 2011b) and Moirod *et al.* (2010) reported the results of coupling simulation using ship motion codes based on linear potential theory and CFD-based sloshing codes for wall force evaluation. A significant effect of sloshing on a ship's transverse motion was reported by Wang and Arai (2011a).

Most recently, nonlinear vibrations of an elastic structure with two partially filled liquid tanks subjected to horizontal harmonic excitation are investigated by Ikeda (2011). The equations of motion for the structure and the modal equations of motion for the first, second, and third sloshing modes are derived by using Galerkin's method, taking into account the nonlinearity of the sloshing. Then, van der Pol's method is employed to determine the frequency response curves. Bifurcation sets are also calculated to show the influence of the system parameters on the frequency response.

Yet another application of numerical techniques is for calculating the pump tower responses. The study by Reddy and Radosavljevic (2006) identified different uncertainties associated with present numerical and experimental techniques to obtain fluid forces on pump towers in an indirect way using Morison's equation. As an alternative to the use of the Morison equation, investigations into the feasibility of direct numerical estimation of fluid forces on a pump tower within an enclosed tank resulting from the sloshing of liquids was carried out (Figure 11). Experimental data obtained from 1:50 model for a typical 210k LNG ship for regular and irregular motions by Berget *et al.* (2006) were used as a reference, enabling both the enhancement of the design appraisal procedures and the validation of CFD techniques for assessing sloshing loads and their capability.

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3.5.4 Local Effects

It is observed that local phenomena such as jet creation, gas entrapment and escape, compression of the gas and fluid, the change of momentum, and hydro-structural interaction to a small degree influence global flow pattern in the tank. However, these phenomena certainly affect local pressures and structural response of the CCS. Even for repeatable global flow large spreading of the local pressures is observed. The spreading may to some extent be explained by the inherent instability of the fluid and chaotic nature of sloshing, but even more important is the sensitivity of the pressure to local physical phenomena, such as jets and sprays accompanying fluid impact, gas pocket entrapment, ventilation and gas escape or gas fraction in the fluid.

Moreover, scaling of attained pressure time series plays a vital role in post-processing of sloshing model tests. In order to determine a valid and consistent scaling law, the local flow mechanisms need to be well understood. It needs to be certain that the experiments represent all the hydrodynamic phenomena governing the full scale system. Among such local phenomena many are related to the raised elements of the membrane surface and their effect on the fluid flow. It is not an obvious question whether and how the surface protrusions should be modelled.

Investigations of the local effects are therefore intended either to determine the local flow and the following pressure distribution for different wave fronts impacting on a tank wall (with or without membrane surface modelling), or – more often – to study the underlying physics.

Raised element

Local flow investigations most commonly focus on single hydrodynamic impacts on the tank wall, or its part. This is in purpose of ensuring the best possible repeatability of the impact and − in case of the experiments with the simplified set-up − due to practical issues that the correct global sloshing flow may not be represented. Such simplified experiments are drop tests and breaking waves in a flume.

Both these forms for simplifying fluid-structure impacts are found to be an important research tool. Although the flow pattern differs from the global flow in a tank, these tests allow studying physical phenomena related to the local flow.

This is due to the fact that the impacting surfaces may easier be controlled than in the sloshing tank and much larger scales may be applied (for instance breaking waves in a flume up to the full scale have been studied in the Sloshel project, Bogaert *et al.*, 2010c).

Another simplified set-up offering possibilities to investigate local effects is 2-dimensional tanks undergoing 1-degree-of-freedom oscillations of small amplitudes. Here the local flow may be investigated under more realistic sloshing-specific impacts. An example here is studies by Kuo *et al.* (2009) and Graczyk *et al.* (2012), where the effect of membrane corrugation and raised Invar edges on the local pressures is demonstrated. The protrusions may both increase and decrease the local pressures depending on the impact type (wave steepness varies for different conditions) and location in relation to the protrusion. Similar effects are observed in the large/full scale experiments of the Sloshel projects.

Scaling

Studies on scaling laws have mainly been based on investigating physics governing the phenomena involved in sloshing. Focus has been placed on hydrodynamics and thermodynamics of the gas and fluid with local effects such as fluid impact on the wall with

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accompanying jets and sprays, gas pocket entrapment, possibility for condensation at the liquid/vapor phase boundary, ventilation and gas escape, gas fraction in the fluid and hydro-structural interaction.

Developing an experimental set-up representing the complete physical system of the violent fluid motion in the tank, including all mechanisms and phenomena involved in sloshing, would be a very challenging task. Usually, formulation that considers separately chosen elements of the system is developed and investigated. This is then validated through studying repeated experiments in different scales. This may also be challenging due to parameters that cannot easily be scaled together with the rest of the set-up, for instance sensors' size.

Yung *et al.* (2010) discuss importance of the ambient vapor during impact event. They introduce a dimensionless *interaction index* and by this illustrate how the ambient vapor properties, liquid properties and interaction between them influence the resulting pressures.

3.5.5 Structural Response

The strength assessment of structures exposed to transient dynamic loads such as those generated by sloshing impacts generally requires the assessment of the dynamic response of the structure. The structural response does not only depend on the pressure peak magnitude, but also temporal and spatial variation of the loading.

Dynamic structural response to sloshing excitation has been investigated independently by the scientific community, classification societies, and industry. To assess the structural response to sloshing loads, two methods are suggested by LR (2009): one is Direct Dynamic Finite Element Analysis (FEA) another is Indirect Dynamic FEA. The Direct Method applies the design sloshing loads scenarios directly to the containment system using a dynamic FEA, which is a more straightforward process. The Indirect Method applies representative sloshing loads, defined by a nominal sloshing pressure and a range of rise times, to derive a Dynamic Amplification Factor (DAF) Envelope curve. The results from a static FEA analysis are then factored by the maximum DAF value to obtain the dynamic structural response. The advantage using the indirect method is that the analysis results are effectively independent on the actual design sloshing load scenarios. However, it is more likely to provide a conservative estimate of the response.

The local response of the membrane system is actually coupled with the response of the steel plate supporting it. A common simplification is to assume that the steel structure does not respond to the sloshing loads and hence, the insulation system is rigidly supported. This is based on the assumption that the pressure duration is much shorter than the structural natural period of the steel plate. In practice, the steel panel that supports the insulation may be flexible under the relevant load conditions and in addition, the loading may cause the steel plate to deform. This effect may significantly affect the stress distribution in the structure (Graczyk and Moan, 2011).

To be consistent with the principles of the comparative assessment, the structural response analysis methodology needs to be capable of accurately predicting the structural response in the entire range up to a level where damages are likely to occur in the structure. Depending on the response characteristics of the considered structure, it may be required to consider non-linear structural response (DNV, 2006).

3.5.6 Fluid Structure Interaction

An important issue related to the sloshing responses is also fluid-structure interaction. Due to the complexity, many investigations on sloshing problems decouple structural

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response from fluid, which implies that the structure is assumed rigid. However, the interactive dynamic behaviour of liquid and elastic tank due to their interaction under various loading conditions can have vital impact on the integrity and safe operation of the system.

A wide review of fluid-structure coupling algorithms as well as fluid and structure models is presented by Kamakoti and Shyy (2004) with a specific attention to aeroelasticity. The degree of coupling between the fluid flow and structural response may be classified as loosely-, closely- and fully coupled. Problems associated with fluid impact on the marine structures are presented by Faltinsen (2000). Theoretical and experimental studies are described with a special attention to slamming on ship hulls.

Different approaches may be utilized to account for the hydro-elasticity. A simple method is to account for the hydrodynamic mass forces by modifying the structural mass by the constant, prescribed value of added mass. However, for sloshing impact in a tank a complex fluid flow in the impact region is observed. A number of parameters such as thickness of the fluid layer, its spatial extent and density (due to aeration) may influence the added mass.

Therefore approaches capable of determining an instantaneous value of added mass may be required for calculations of the coupled response. A number of approaches based on the Wagner theory have been developed. This theory describes the initial stage of a water entry problem and is valid when the penetration depth is much smaller than the body width. An important feature of these approaches is that the hydrodynamic coefficients can be calculated analytically, which makes the calculations very time efficient. Korobkin *et al.* (2006) present a two-dimensional method for the fluid-structure interaction with a coupling of the finite element (FE) method for the structural response with a Wagner theory-based approach for hydrodynamics. Malenica *et al.* (2006) show a possible application of this method to an analysis of two-dimensional coupled response of the membrane structure to a simplified impact.

An experimental and numerical investigation of the elastic response of the tank wall under sloshing impact is presented by Lee and Choi (1999). The authors apply the normal mode decomposition method with the thin plate theory and combine it with the boundary element method for the fluid solver. Similar approach is presented by Rognebakke and Faltinsen (2006) who analyse the coupled response to impact on the tank roof. Calculated strains are compared to experiments with an elastic upper part of a wall.

Investigations on dynamic responses of LNG ship most commonly focus on inner liquid ~ tank systems. However, coupling effect between liquid cargo sloshing and LNG ship motion can be significant at certain frequency range of partially filled tanks. This is of great concern to the LNG FPSO/FSRU operation. The coupling effects are expected to become more important as the size of LNG carriers significantly increases with rapidly growing demand. Therefore, natural characteristics of an integrated system consisting of inner LNG liquid ~ elastic membrane type LNG ~ external sea water is investigated by Xiong and Xing (2007a) and dynamic responses excited by regular waves and random motions are analysed by Xiong, *et al.*, (2007b). Figure 12 shows the two selected modes of the coupling system, in which mode 7 has an anti-symmetric pattern of both sloshing motions of internal liquid and external sea water, whereas mode 9 describes a tank rolling motion coupling with the sloshing effect of the internal liquid.

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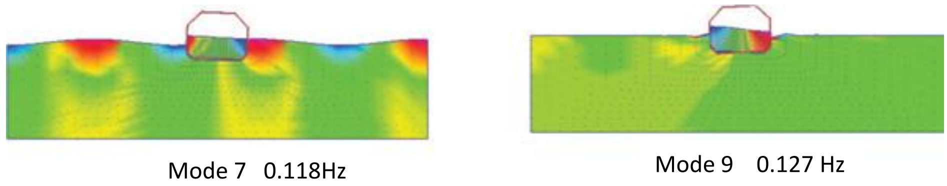

Figure 12: Natural vibration modes of the integrated fluid-structure interaction system (Xiong *et al.*, 2007a)

Studies on fluid-structure interactions are mostly on two phases of liquid-tank interactions. The air–water two-phase fluid flow systems are investigated by Price and Chen (2006) using a curvilinear level set method to simulate free surface waves generated by moving bodies or the sloshing of incompressible fluid in a 2D right tank. The air-water sloshing problem is also recently studied by Thiagarajan *et al.* (2011) in which fundamental analysis and parametric studies on excitation and fill levels are presented. Three-phase interactions, involving air, liquid and elastic tank are investigated by Xiong *et al.* (2006). The dynamic behaviour of an air-liquid-elastic tank interaction system is investigated numerically and experimentally. Based on these simulations, the guidelines to be considered in the dynamic design of LNG containers are provided. Dynamic response analysis of on-shore LNG storage tank with fluid-structure interaction effects has also been investigated (Xing *et al.*, 2009). It has been demonstrated that the developed computer code provides a useful numerical tool for free and forced vibration analysis in linear domain where fluid-structure interaction effect needs to be addressed in the design stage.

For violent sloshing impacts, nonlinear approaches have been developed in recent years. For example, the Meshless local Petrov-Galerkin method based on Rankine Source Solution (MLPG_R) (Ma, 2005,2008) has been employed to simulate the interaction between breaking waves and 3D fixed cylinders and dam breaking on a block (Zhou and Ma 2010). This method is found much faster than other methods for solving fully nonlinear water waves (Yan and Ma, 2010). In addition, the MLPG_R method works with a longer time step than the conventional Smoothed Particle Hydrodynamics (Ma and Zhou 2009, Zhou and Ma, 2010). The hydro-elastic behaviour of a 2D structure subjected to violent waves is studied using an improved MLPG_R method (Sriram and Ma, 2010). The comparison has shown reasonable agreement between the numerical results and the experimental data available in literature. However, there are still many uncertainties associated with wave breaking and splashing, formation of air pocket and air bubbles, and dynamic interaction between wave impact and structural response during violent sloshing.

Another interesting attempt to solve a fluid-structure interaction problem relevant for sloshing in LNG membrane tanks is presented by Nam *et al.* (2005). The finite volume method for the fluid is combined with the FE method for a structure. The analysis is stepwise. First, an uncoupled fluid simulation is performed in order to find time instants for sloshing impacts on the structure. Subsequently, the coupled analysis is carried out for limited temporal and spatial extent.

3.6 Collision/Grounding/Flooding

Issues related to hull-ice interaction and iceberg collision dominate the literature related to collisions and flooding. This is due to the growing interest in LNG transportation through the arctic seas leading to increased concern of CCS integrity due to hull-ice interaction. Recent literature on this topic is described in Section 4.3.

The structural response of CCS in both membrane and spherical types of LNG ships for selected ship-ice interaction scenarios have been investigated for possible operation routes in Arctic areas through the Joint Development Project (Wang *et al.*, 2008). In these studies, ice loads and loading areas in the hull structure were determined based on the energy theory. A local FE model including the partial hull structure with the skirt structure has also been developed for structural analysis. The critical loading location with respect to the deflection of inner hull is determined and deformation of CCS is analysed. Based on the linear buckling analysis and nonlinear static FE analyses it is found that the strength of the both CCS of membrane-type LNG carrier and the skirt structure of spherical-type LNG carrier is sufficient to resists the design ice loads.

As the structure of the containment system is based on materials that are non-standard in marine technology, understanding of the dynamic structural response is still limited. Sensitivity studies addressing the response and strength of the containment system such as by Paik (2006) or Lee *et al.* (2006) are essential.

Another issue is related to the considerable development of offshore LNG terminals. Here, attention is devoted to the risk for ship-to-ship or ship-to-terminal collision. On this topic, Deetjen *et al.* (2008) presented an analysis and consequences of collision between two ships for different event scenarios. Also Montewka *et al.* (2010) performed a risk analysis for an LNG carrier colliding with a tug, as a part of a mooring operation.

Existing codes play an important role for the safety under accidental conditions. IGC code defines the extent of damage that should be assumed and the location of cargo tanks in terms of permitted inboard distances.

Flooding condition is regulated by the IGC code in terms of permitted permeability of different compartments and guidance is provided on internal arrangement and effectiveness of the watertight bulkheads. There are additional requirement regarding withstanding unsymmetrical flooding, permitted position with respect to waterline as well as maximum heel angle and residual stability.

A new IGC code, which is planned to be issued in 2014, may impose more strict requirements to the distance requirement between the tank and the side shell and become a variable depending on the volume of the cargo tank. However, the stricter requirements will have limited, if any, effect on the existing LNG ship designs.

3.7 Fatigue

3.7.1 Introduction

Fatigue analysis is basically required to be carried out for independent tanks Type-B and may, in special cases, be required for independent tanks Type-C and semi-membrane tanks. The objective is to determine the fatigue life of all welds and plates that may lead to leakage of the tank. A fatigue analysis shall be carried out for parent material and welded connections at areas where high dynamic stresses or large stress concentrations may be expected. The fatigue properties shall be well documented for the parent material and welded connections being used in the design. For less investigated and documented materials, the data on fatigue properties shall be determined experimentally. Due attention shall be paid to effects such as: specimen size and orientation, stress concentration and notch sensitivity, type of stress, mean stress, type of weld, welding condition and working temperature.

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The fatigue strength of the structure considered is normally defined by Wöhler curves (S-N curves).

3.7.2 Crack Propagation Analysis

- The purpose of a fracture mechanics crack propagation analysis is to show that probability of an extensive cargo leakage due to a fatigue failure is small. This is verified by showing that a potentially growing fatigue crack fulfils one of the following criteria: If the crack grows through the tank thickness, it shall result in a cargo leakage of a rate not exceeding the capacity of the partial secondary barrier (the drip tray) draining system.
- If it can be shown that the resulting through-thickness crack will not reach a critical length during 15 days in the most probable largest load spectrum the ship will experience during 108 wave encounters North Atlantic, Leak-Before-Failure (LBF) has to be proven.

The fracture toughness properties of the tank material and its welded joints in the thicknesses used in the design are normally required to be documented. Crack propagation analysis is in general required to be documented for all welds that can cause a leakage. However, the amount of analysis can be reduced by a careful screening to define selected areas of stress concentration taking into account maximum fabrication tolerances. The size of the cracks assumed in the calculations shall be of minimum the size as those found by applicable NDT methods.

Dynamic stresses are driving fatigue crack growth, whereas the rupture of a fatigue crack of a given size is governed by a maximum ULS load situation. The primary parameter governing final rupture of a fatigue crack of a certain size is the most probable largest one time stress amplitude, static plus dynamic amplitude, during the design life in relevant environmental conditions (usually North Atlantic).

The size of initial defects used in the analysis shall be decided considering the production quality of the builder. As guidance the following initial crack sizes in way of Heat Affected Zone (HAZ) through thickness may be used for the builders who control high production quality standard. (BS7910:1999. "Guide on methods for assessing the acceptability of flaws in metallic structures.")

- Butt welds: $1.0\,mm$ depth and $5\,mm$ in length
- Fillets: $0.5\,mm$ depth and $5\,mm$ in length

The design crack propagation data are normally to be based on the mean-plus-two-standard-deviation of test data.

For the cargo tank, crack propagation data (C and m in Paris' equation) need to be determined for welded and base material together with the associated crack tip opening displacement (CTOD) values. Documented test data for both room temperature and cryogenic temperature should normally be available.

In order to evaluate the residual fracture of fatigue cracks over the lifetime of the vessel, fracture mechanics analysis has to be referred to the ULS stress range to be compatible with the total ULS stress amplitude that governs potential fatigue crack rupture. (DNV Rules for Ships Pt.5 Ch.5 Sec.5) The fatigue stress range can preferably be determined at a $Q = 10^{-4}$ probability level as for the SN – fatigue approach and extrapolated to the ULS stress range level using the long term Weibull stress distribution. As the IGC code specifies the Weibull shape parameter $h = 1$ this means multiplying the 10^{-4} stress range with 2 to arrive at the 10^{-8} stress range.

For use in the fracture mechanics analysis the principal stresses determined for SN-curve fatigue analysis is often to be further processed as given below:

a) In order to correctly evaluate crack propagation, the static value plus the dynamic design life ULS amplitude of the principal surface stresses shall be calculated in addition to the dynamic stress ranges.
b) Based on the inside and outside values of the principal surface stresses, the stresses are to be split into membrane and bending parts separately for dynamic stress ranges and for static plus ULS amplitude values. This is essential for the fracture mechanics analyses but is not necessary for the Miner-Palmgren fatigue analyses.
c) Select the largest membrane stress for the analysis. This will give the fastest crack growth through the thickness and hence the shortest fatigue life. However, in some cases it might be necessary also to check the maximum bending combination in which the crack will grow faster in length than in depth.

3.8 Vibration

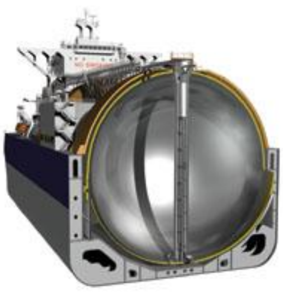
3.8.1 LNG Pump Tower System

The pump tower with its associated pumps and piping, as shown in Figure 13, is the main equipment for discharge and loading of LNG. For membrane type, it is located close to the aft bulkhead, hanging down from the liquid dome and connected to lateral support base at the tank bottom. The structure of pump tower is very slender and flexible, so its fundamental natural frequency is relatively low, which may cause resonance problem with the propeller excitations around normal operation range and hence cause a fatigue failure due to vibration to the pump tower structure. The vibration analysis on pump tower structure is important at the initial design stage for safe operation of the LNG carrier.

3.8.2 Vibrations of LNG Pump Tower

There are potential vibration risks in LNG ships that are magnified in the new larger LNG ships. These vibrations may have unavoidable sources such as propellers, main engines or cargo machinery. If these vibrations are in tune with the natural frequency of the tank system they may have disastrous consequences.

For LNG carriers driven by gas or steam turbines, the propeller is the main source of excitation and, therefore, the main engine may be ignored in the vibration analysis of the pump tower. However, for large LNG carriers driven by low-speed diesel engines,



(a)

(b)

Figure 13: Pump tower within (a) Moss and (b) membrane types of LNG tanks (http://explow.com/lng_carrier and Lee, 2006, respectively)

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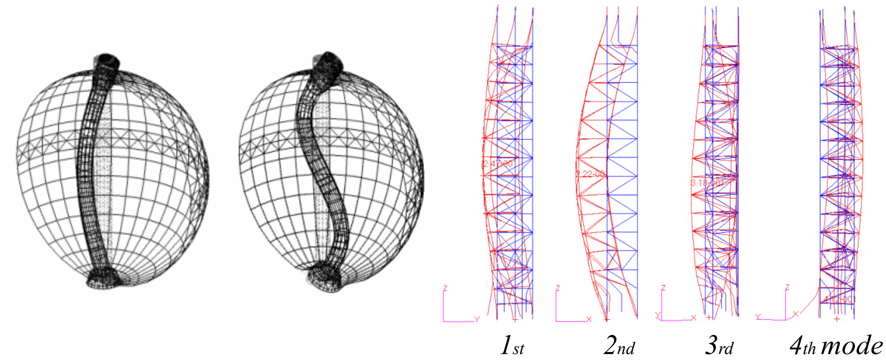

Figure 14: Mode shapes of pump tower in Moss type and membranes tanks (Lee *et al.*, 2006)

excitations from the main engine as well as propeller are to be considered in the vibration analysis.

Vibration assessment of the pump tower is described (American Bureau of Shipping, 2006; Lloyd's Register, 2008). The free and forced vibration of pump tower due to main engine and propeller are considered. The analysis procedure provides guidance on the selection of loading conditions, tank location and filling levels, boundary conditions and critical areas to investigate. Excessive vibration is to be avoided in order to reduce the risk of structural damage such as cracking on the liquid dome, base plate, or tubular joints of pump tower structure. The acceptance criteria for pump tower vibration are provided in terms of the vibration limits for local structures.

A vibration analysis for pump tower of both Moss and membrane type of LNG carriers was carried out by Lee *et al.* (2006) for empty and full loading conditions to reveal vibration characteristics (Figure 14). Added mass effect due to LNG is considered by the virtual mass method of MSC/NASTRAN fluid capability. Also the vibration measurements at sea trial were carried out to confirm the analysis results.

The Campbell diagram as shown in Figure 15 is very useful to identify potential vibration risks in LNG ships, particularly for the new generation of large gas ships (Lloyd's Register, 2006; Lee *et al.*, 2006) by checking the coincidence of vibration

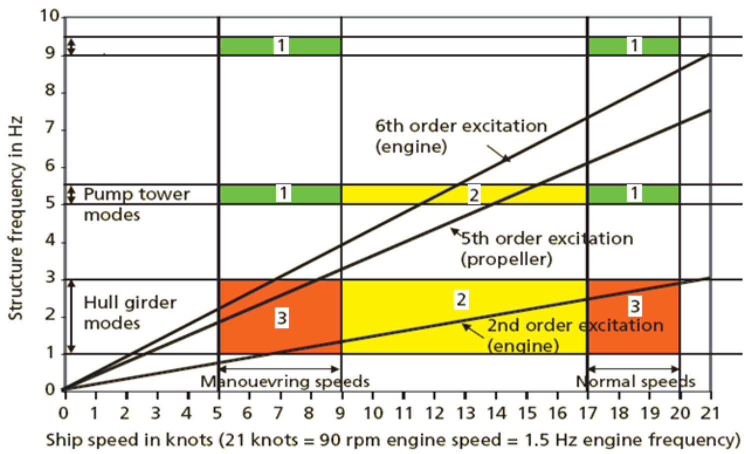

Figure 15: Campbell diagram

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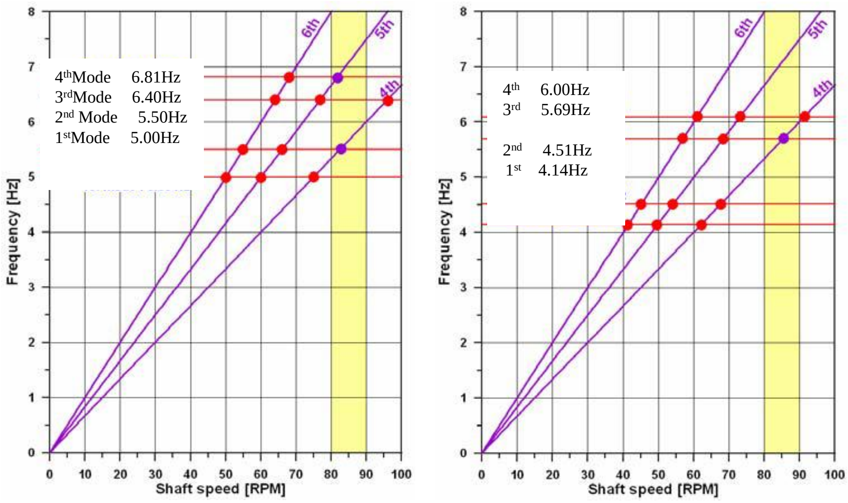

Figure 16: Campbell diagram for pump tower for empty (left) and fully filling (right) in membrane type (Lee *et al.*, 2006)

sources with natural frequencies, in which zone 1 indicates no resonance occurs; zone 2 the transitory resonances may occur while the zone 3 the permanent resonance occurs.

For LNG carriers, propeller blade number is generally selected among 4, 5 or 6 blades in view of ship propulsion performance. Propeller shaft speed is running mainly at the normal operation range, 80 – 90 rpm. Surface force and bearing force induced by the propeller are major excitation sources for longitudinal and transverse vibration, and their frequency components are propeller blade order component and higher harmonics. As shown in Figure 16, the resonance of longitudinal vibration will be predicted at 82.5 rpm when 4-blade propeller is adopted. Therefore an actual forced vibration response should be checked to ensure the structural safety.

3.8.3 Load on Pump Tower

The load on the pump tower is the combination of the following load components:

1. Hydrodynamic load due to sloshing on the pump tower structural members
2. Inertial and gravity load due to global ship motion on the pump tower
3. Thermal load due to low temperature of LNG cargo
4. Pump torque

The loads on the pump tower are calculated at each time step when the sloshing simulation was carried out. Instantaneous load distribution when the following dominant load parameters (i.e., transverse and longitudinal forces on pump tower as well as these forces on pump tower base support) reach maximum value is used for the structural analysis of the pump tower (American Bureau of Shipping, 2006). Fluid force measurements on LNG pump tower were also reported by MARINTEK (2006).

3.9 Fire Safety

For LNG carriers the fire safety requirements as measured in SOLAS related to tankers in general apply depending on flag state authorisation. In addition special requirements for LNG carriers apply. Special considerations are made to isolate gas safe

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spaces from gas dangerous zones. The cargo hold space is basically segregated from other areas on the ship. The superstructure and areas is to be insulated with A60 insulation toward the cargo area and special requirements to the fire main system and a fixed water spray system in the cargo area apply. For rules and regulations of LNG fuelled ships (DNV Rules Pt.6 Ch.13) equivalent safety philosophy is applied for the LNG containment systems as for LNG carriers where A60 fire insulation is applied between areas where LNG is stored and toward other areas. Fire main system and water spray systems are designed equivalently as for LNG carriers. In addition pressure relief valves shall be dimensioned for the maximum vapour generated for a defined fire heat exposure (IGC code Ch.8.5). For LNG handled on offshore installations similar fire safety measures apply (Offshore Service Specification DNV-OSS-103, "Floating Production and Storage Units or Installations"). Fire safety of LNG on board offshore units may require special considerations through Risk Assessments depending on designs and process equipment on board. Applicable methods are described in for example DNV-OSS-121 "Classification Based on Performance Criteria Determined from Risk Assessment Methodology".

3.10 Temperature Control of Hull Structures

The several safety-related criteria in the relationship between LNG cargo tank and temperature control should be established (IGC Code). The design condition of air temperature and seawater temperature for the Boil-Off Rate (BOR) evaluation must first be defined and temperature conditions that the structure during the lifetime can meet the extreme environmental conditions of poles or equator should be considered. In addition, it is important to how the boundary of temperature distribution will be established with respect to the structure to evaluate the structural safety of the inner hull which surrounds the cargo tank. This assumption has a major impact on the material selection of the structure surrounding cargo tank and the design safety. So the temperature condition is an important basis for analysing the structural safety and thermal characteristics (BOR). The interpretation of this condition is an important factor in the design of cargo tank, so accurate information or reasonable hypothesis is necessary. To determine the grade of plate and sections used in the hull structure, a temperature calculation must be performed for all tank types with following assumptions (IGC Code).

- The primary barrier of all tanks must be assumed to be at the cargo temperature.
- In addition, where a complete or partial secondary barrier is required it shall be assumed to be at the cargo temperature at atmospheric pressure for any one tank only.
- For worldwide service, ambient temperatures should be taken as +5° C for air and 0° C for seawater. Higher values may be accepted for ship operating in restricted area and conversely, lower values may be fixed by the Administration for ships trading to area where lower temperatures are expected during the winter months.
- Still air and sea water conditions shall be assumed, i.e. no adjustment for forced convection.
- The cooling effect of the rising boil-off vapour from the leaked cargo should be taken into account where applicable.

If the calculated temperature of the material in the design condition is below $-5°\,C$ due to the influence of the cargo temperature, the grade for material shall be selected in accordance with IGC code.

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The temperature of cofferdams between two cargo tanks is also calculated in the design conditions. This range of temperature would preclude the use of conventional steel grade for the bulkhead since such a design temperature is far under the grade E limit ($-30° C$); it requires special cryogenic steel, which are extremely onerous (materials procurement, special handling and welding procedures, special QA/QC procedures, connection to conventional steel fabricated blocks,…). A more economical solution is to provide a heating system with following requirement in accordance with IGC Code.

- The heating system shall be arranged so that, in the event of failure in any part of the system, standby heating can be maintained equal to not less than 100 % of the theoretical heat requirement.
- The heating system shall be considered as an essential auxiliary. All electrical components of at least one of the systems provided in accordance with item 1 shall be supplied from the emergency source of electrical power.

The new concept of FLNG with two-row tank arrangement unlike the normal LNGC which has the single-row tank is now emerging (SHELL FLNG in PRELUDE offshore gas field). This arrangement is driven by the very high deck loads imposed by the onboard liquefaction plant and the need to have at least one longitudinal bulkhead to support the deck structure. Regarding to the material selection of structural members in centre longitudinal cofferdam, it is needed to clarify the interpretation of the below clause in IGC code.

> In all cases referred to in 4.8.1 and 4.8.2 (IGC Code) and for ambient temperature conditions of $5° C$ for air and $0° C$ for seawater, approved means of heating transverse hull material may be used to ensure that the temperature of this material do not fall below the minimum allowable values. If lower temperatures are specified, approved means of heating may also be used for longitudinal hull structural material, provided this material remains suitable for the temperature conditions of $5° C$ for air and $0° C$ for seawater without heating.

This interpretation is highly critical since it may request very special material for this normal structure regardless of heating coil system application. The two-row FLNG is very new concept totally different from single-row LNG carriers. Then the Code should be updated reasonably considering this new novel concept.

3.11 Leakage Control

3.11.1 Soundness Control and Cargo Containment System Monitoring

The overall layout of a gas carrier is similar to that of the conventional oil tanker from which it evolved. The CCS and its incorporation into the hull is, however very different due to the need to carry extremely low temperature cargo under pressurized, or refrigerated, or under a combination of both conditions. So perhaps more than any other single ship type, the LNG tanks encompasses many different design philosophies. As the LNG CCS has its own unique characteristics such as a cryogenic cargo storage and material, extreme thermal and fluid stress, in-tank pressure deviation from Boil off Gas (BOG), double barrier concept under IGC requirement, and specially designed insulation structure for Boil off Rate (BOR) control, it is strongly required to cover all these parameters and extensive stresses. These kinds of CCS should resist against externally harsh condition such as wave and temperature for more than 20 – 30 years

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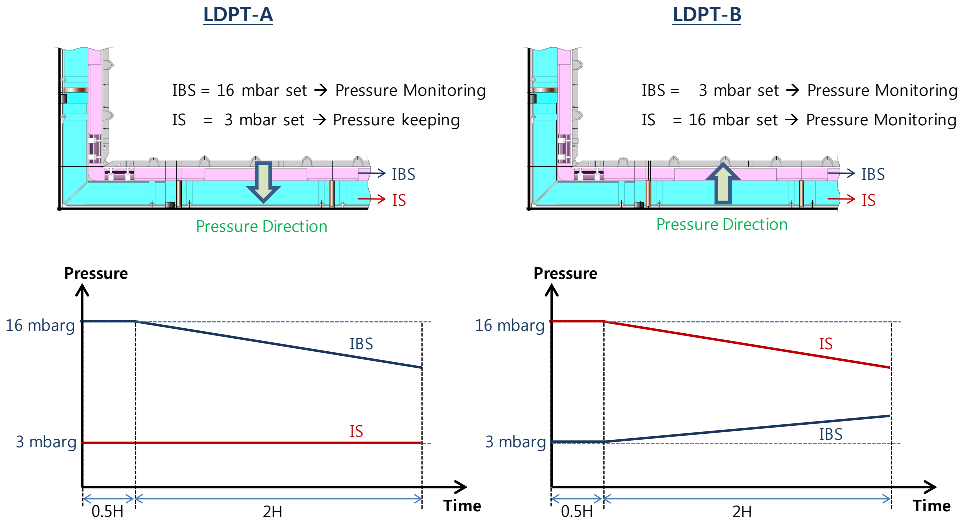

Figure 17: Low differential pressure test monitoring to detect leakage of secondary barrier on membrane type tank

and could be monitored its soundness throughout their lifetime including the construction stage. During construction, ammonia, NH_3, and helium, He, leak tests are well known method for CCS soundness inspection. Before delivery, differential pressure testing (DPT) is performed after the first thermal cool down test to check the soundness of primary and secondary barriers. During voyages pressure differences change between 1st and 2nd insulation spaces (IS: Insulation Space, IBS: Interbarrier Space) and inert/methane gas detection systems are used to monitor the system's soundness. In addition, periodic dry dock inspections, carried out every 2.5 years and 5 years, low differential pressure testing (LDPT, Figure 17) or differential pressure testing (DPT) is used to check the tightness of the CCS.

3.11.2 Primary Barrier Failure Detection

The IGC Code requires permanently installed instrumentation to detect when the primary barrier fails to be liquid tight at any location where a secondary barrier is required. However the Code does not require the instrumentation to be able to locate the area where liquid cargo leaks through the primary barrier or where liquid cargo is in contact with the secondary barrier. Temperature indicating devices and methane gas detectors are widely used to monitor the primary barrier condition. During construction, independent Type-B tank should be tested hydrostatically or hydro-pneumatically. For membrane type tanks helium or ammonia leak testing is used to control and confirm the primary barrier tightness at the construction stage. Periodically vacuum test for secondary barrier soundness control is used to confirm the primary barrier tightness in a similar procedure. More specifically, membrane type tanks such as the GTT MK III or NO96-2 adopt primary barrier leak inspection methods and membrane deformation inspections with guideline criteria. SPB tanks can be inspected by differential pressure test between internal and external area of the tank wall. Methane gas detection systems are used to monitor the insulation space during voyage condition. MK III membrane corrugation deformation inspection is performed using GTT's guideline.

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3.11.3 Secondary Barrier Soundness Control

According to the IGC Code, it is required to have a full secondary barrier for Membrane and a partial secondary barrier for Type-B tank LNG CCS. The purpose of the secondary barrier is to ensure that cryogenic liquid cargo cannot reach to the inner hull in the event of a breach of the primary barrier. The IGC Code also states that this containment of leaked liquid cargo should be for at least 15 days. The implication is that the secondary barrier is required to be liquid tight (not necessarily gas tight). Therefore a small leak in the secondary barrier can be tolerated without the risk of jeopardizing the integrity and safety of the vessel. For independent Type-B tanks which are fitted with a partial secondary barrier – i.e. a drip tray, the condition of the external spray shield that covers the insulation panel can be ascertained through visual inspection from the hold space. This spray shield is not required to be liquid tight but it must be capable of containing any leakage, directing it to the drip tray where detection can take place. Design of drip tray is confirmed by the so-called LBB (Leak before break or leak before failure) concept. It is also a requirement of the IGC Code that the secondary barrier of the membrane type tank is to be “capable of being periodically tested by means of a pressure/vacuum test or another suitable method approved by the administration” (IGC Code 4.7.7). Nowadays a vacuum test is the most widely adopted method to check the secondary barrier soundness of membrane type tanks by applying a vacuum condition to make a pressure difference at secondary barrier and monitoring the pressure decay rate. In case of MK III system, secondary barrier soundness is confirmed by differential pressure testing between IS and IBS.

3.12 Spillage Control

Specifically to offshore LNG plants, spillage refers to very large leaks due to failures in cryogenic systems, either LNG, or cold refrigerants used in the liquefaction process, leading to large amount of product exposing structures to major thermal shocks.

Industry is beginning to address this very new aspect for ship/offshore LNG industry and damage scenario simulations are currently based on more on engineering principles than on codes and regulations.

For design, depending on the client’s requirement, consideration may be made up to a pipe full bore rupture (e.g. may be in the range of more than 20”) which will result in a very large volume of cryogenic liquid spill until the deficient part is isolated from the process.

Designers may consider three main parts implicated by these risks: topsides structure, hull deck and hull sides, being treated differently.

The area in topsides or on deck subject to potential spillage are identified and localized. Where a full bore rupture is considered, the parts subject to contact with fluid are to be protected against thermal embrittlement (special coating, wood, stainless steel. . .). In the same time, the spill is to be enclosed by coamings and redirected by channels and scuppers, either to the sea or to drainage tanks. To ensure their function, materials of these barriers are to be carefully chosen, and any eventualities in drains are to be foreseen and planned for (e.g. ice plug in scuppers, overflow, vaporization return pressure. . .)

Where cryogenic liquid pools on structures may happen, and if not rapidly sprayed (e.g. main deck), coatings and protections are probably required. For vertical side shell, the approach may be different.

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Effects of large LNG spill in seawater are not really known. Between the two extreme suppositions 1) a smooth vaporization and 2) rapid phase transfer (RPT) equivalent to an explosion, there is a room for a temporary exposure of side shell to cryogenic fluids. Quantification of RPT is not easy, and shall mainly lead to consideration of overpressure in structural design more than thermal load design for hull.

When dealing with vaporization LNG pool above water, main unknowns are the time exposure and heat quantity taken to side shell steel. Even if this value is determined, next question is: shall we protect the side shell against this thermal ingress. Effectively, such approach may lead to unrealistic designs, such as special coatings or wooden plating of major parts of the units (400 m long, draft variation and wave elevation up to 25 m!). Moreover, offshore units design life is usually 20 to 40 years on site without dry-docking, which is far longer than any coatings design life, especially subject to continuous wave ingress. To avoid "over design", and considering that all these units are double sided, an alternative approach could be considered: The side shell gets damaged due to thermal embrittlement (shell plating, including or not the stiffeners), and assessment of the consequences of ingress and to evaluate the integrity of the hull with a locally damaged side shell – in the same manner as for a collision. Additionally to insurance of the unit design safety after such event, designers shall develop in-situ means of repair (in design repair philosophy), avoiding disconnection and dry-docking which will cause a major revenue loss for such installations.

Although these points remain in the field of research, decisions will be taken in the very next future, together with classification societies and international players, to allow the safest realistic approaches.

4 SAFETY AND DESIGN FOR SPECIFIC LNG APPLICATIONS

4.1 Offshore LNG Chain

As shown in Figure 18, the LNG chain that was commonly based on onshore plants is currently extended with offshore units such as Floating LNG (FLNG) and Floating Storage and Regasification Unit (FSRU). All these concepts differ from common LNGCs by following points:

- Whole or part of the chain is located in weather exposed offshore locations
- Intermediate fillings at sea (continuous production process, loading/offloading of products, roll-over)
- LNG ship to ship regular transfers at sea (FLNG offloading to LNGC or LNGC offloading to FSRU), demanding for some case up to two operations per week
- Several type of products onboard units (LNG, LPGs and condensates)
- Spillage risks in topsides, in cargo handling pipes used at sea, in offloading systems
- Continuous loading/offloading at sea, stressing hull concomitantly to wave loads
- Inspection, maintenance and repair at sea, without dry-dock, and as far as possible without production stops

At present time, codes are well developed for LNG carriers, following shipyard and cargo containment designers, with continuous progress of classification society and IMO in rules and approval of cargo containment and cargo handling systems. New offshore units, for which industry is in advanced phase compared to classification society rules and international regulation, introduce new aspects not already covered.

Regulations and codes/standards for the design, construction and operation of LNG facilities are summarized in Foss (2006), i.e. IMO-IGC code, which are applicable to

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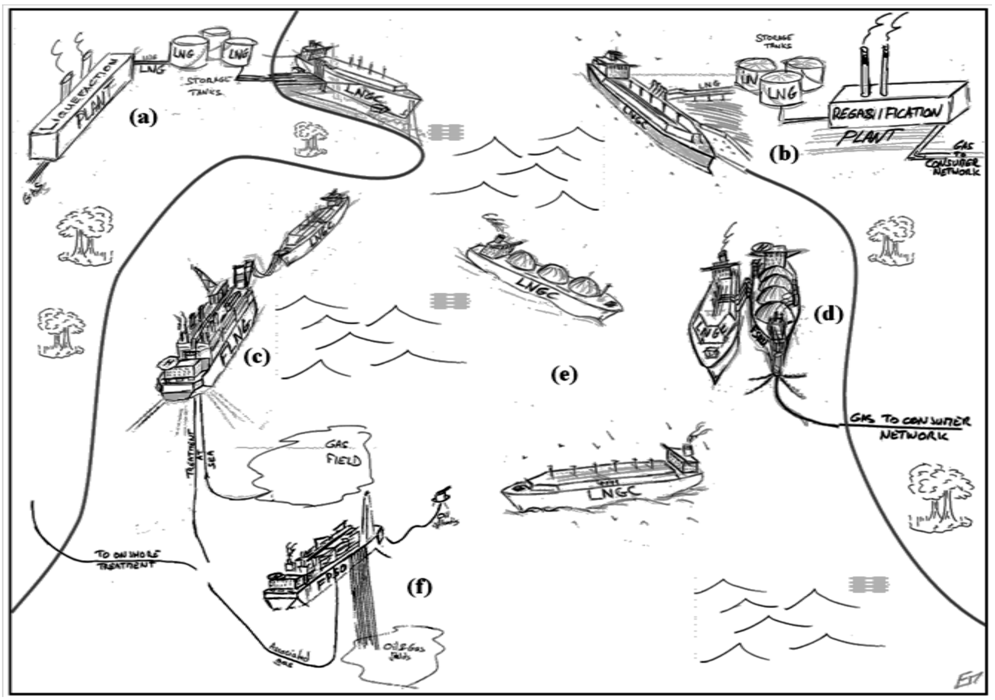

Figure 18: LNG chain involving LNG storage and handling at sea
(a) ***Onshore liquefaction plant****, with LNG storage and export facilities to LNGC (sheltered area)*
(b) ***Onshore regasification unit****, with import facilities from LNGC (sheltered area), LNG storage and distribution in consumer network*
(c) ***FLNG*** *or* ***Gas FPSO****: Offshore unit, with gas import (from gas field or FPSO associated gas line) treatment and liquefaction, LNG storage and export facilities to LNGC (open sea)*
(d) ***FSRU****: Offshore unit, with import facilities from LNGC (open sea), LNG storage, regasification distribution in consumer network*
(e) ***LNG*** *ship trading*
(f) ***FPSO****: Floating production, storage and offloading, for crude treatment, and eventual associated gas export to shore or FLNG.*

LNG/LPG transportation vessels and loading/unloading terminals. These codes can be used for FLNG systems with modifications to account for the new application and associated hazards.

Classification societies have developed and recently issued guidance and rules for FLNG systems, such as DNV's OTG-02, which addresses critical aspects to the integrity management such as: risk assessments, inspection and maintenance philosophies, RBI, inspection of containment systems, sloshing assessment, fatigue assessment, and corrosion issues as reported by Fagan (2011). The OTG-02 (2011) guide presents the rules/standards applicable to the hull, topsides, and cargo tanks of the FLNG systems.

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4.2 Floating LNG, FLNG and Floating Storage and Regasification, FSR, Units

As exploration for hydrocarbon resources has continued to expand in offshore waters, interest in the production of LNG at offshore locations has grown. The oil and gas industry has decades of experience with both onshore LNG liquefaction and offshore floating production storage and offtake, FPSO, units.

4.2.1 Floating LNG Production, Storage and Offloading, FLNG, Units

In recent years there have been moves to develop and deploy floating offshore LNG production, storage and offtake units, FLNG. While a few such units have been designed for marginal fields with production in the 1 million tonnes per annum range, most of these units have been conceived as very large, 2.5 – 5 million tonnes per annum or even larger to take into account the economies of scale from deploying large scale LNG plant.

Although a number of these projects are underway, no such unit is yet in service (as of December 2011).

The use of FLNG units has several unique challenges as compared to an LNG carrier. These units have to support a very large deck load; can be 50,000 t or greater and so require a hull structure that will support this. This has usually resulted in at least one longitudinal bulkhead being incorporated into the design, where LNG ships usually have no longitudinal bulkheads other than the side tank bulkheads. This leads to a reduction in the ship's athwart size of the cargo storage tanks which can be beneficial in reducing sloshing, but since these tanks are cold it may be necessary to treat any longitudinal bulkheads in the same way as the transverse bulkheads in an LNG carrier, i.e. cofferdam bulkheads with heating to maintain structure temperature in an acceptable range.

One of the biggest issues with FLNG units is the potential for loss of cryogenic containment within the deck mounted liquefaction plant. Leaks from valves, vessels, piping etc. in the liquefaction system that can result in direct contact of LNG with the structure of the hull can have severe consequences, although we have already dealt with this risk to some extent in LNG carriers during loading and discharging. The exposure to this risk on a production FLNG is higher due to the continuous nature of the process. A number of ways to deal with this are currently being applied including minimizing flange connections where leaks might occur, fitting of stainless steel drip trays to contain potential spills, and fitting of insulation material on deck in way of potential spill areas (wood or concrete have been examined alternatives).

Another area of concern for FLNG units is the transfer of cargo from the unit to offtake tankers. In most cases FLNG project will not be producing a single product and so must store and offtake LNG, LPG and condensate liquids. This will result on a complex set of offtake equipment and considerable planning and operating issue that need to be addressed with multiple offtake vessels servicing a single FLNG unit. To date most proposals are looking at LNG offtake in a side-by-side mode using the standard ship loading manifold on existing LNG carriers, but work has been undertaken to look for tandem loading of LNG where the offtake LNG carrier would approach the stern of the FLNG unit and take cargo over the bow with a special loading system, in the manner that FPSOs now routinely do.

4.2.2 Floating Storage and Regasification, FSR, Units

As import of LNG has expanded into regions of the world which have not previously seen much of that trade, a solution to provide LNG storage and regasification quickly has been developed. The Floating Storage and Regasification Units is usually a ship shaped unit (often a converted ship) which in addition to its LNG cargo containment system is fitted with regasification equipment which can pressurize the LNG up to pipeline discharge pressures and then vaporize the liquid back to gas for onward transmission to customers on shore. A few such units are in service today with some acting as combined transport and FSR units, loading LNG at the liquefaction port, transporting it to the destination and then sitting in port or offshore while regasifying the LNG for pipeline transmission to customers. Other units are permanently stationed at the receiving ports and simply act as storage and regasification installations.

Regasification equipment may derive the required heat from use of warm seawater in some locations or by heating using natural gas boil off as fuel for the process. It is also necessary to boost the pressure of the gas to be delivered to match pipeline requirements. This has usually been done by compressing the liquid LNG prior to vaporizing.

While the size and weight of regasification plants are small as compared to full-scale liquefaction plants some of the same issue as mentioned above do pertain, i.e. deck strengthening to take additional load, design features to mitigate effects of cryogenic spills and relating to ship to ship transfers.

4.3 Arctic

LNG shipping routes move towards more severe sea regions such as North Atlantic or ice-covered waters in the Arctic. These may bring about new technical and operational challenges as well as increased risk for human errors. The latter may for instance result from the demanding environmental conditions (cold, humidity, icing, darkness) or from the continuous icebreaker proximity that may lead to collisions. It is a "general perception" that the safety for operation in arctic areas will increase if the operation can be designed with less dependency of human assistance.

Enhanced environmental concern in the arctic may require special safety considerations for such transport. This is due to the limited access to any help or assistance (long distances and harsh environment) as well as challenging defeat of potential pollution. On the other hand, activities related to LNG transport and storage constitutes a lesser environmental concern as for instance oil related operations.

Problems associated with ship and offshore structures in the arctic are widely elaborated by the Committee V.6 Arctic Technology. In the present section issues specifically related to LNG transport and storage are only described.

The main technical and operational challenges related to shipping LNG in arctic waters may be found in e.g. Tustin (2005). Among them, the CCS integrity with hull ice interaction is stressed dominant. Here the risk may be related to the hull deformation that may result either in threatening its integrity or reducing the tank volume associated with rapid increase in tank pressure.

The CCS integrity is investigated by Han *et al.* (2008). They perform a risk analysis of the membrane CCS (No.96) investigating thoroughly the capacity of the double hull deflection and potential accidental ice loads. The authors considered various ice features for capacity calculations, including collision with level ice, ice ridge, ice floe, iceberg and ship stuck in level ice. It is found that the invar membrane can afford very large inner hull deflection before the chosen survival criteria are reached; also the integrity of the inner hull structure is to be checked before the invar limit condition due to a risk of ballast water leakage into the containment layer. The results are compared to the grounding accident case. The potential accidental ice loads are calculated for Baltic Sea and East Canadian coast operation.

Similar study is presented by Suh *et al.* (2008) for Mark III CCS. In a case study presented an ice class LNG carrier is considered under various design, accidental and fatigue scenarios in both ice and non-ice operation regimes. The results of the direct strength calculations or evaluations according to the class rules are analysed in view of the risk for the leak of the cargo. Similar study and supported by an experiment on the CCS specimen is also presented by Oh *et al.* (2010a).

Another interesting study on this topic is presented by Wang *et al.* (2008) for both membrane and spherical type LNG carrier. The authors investigate structural response of the CCS's under six different loading scenarios that may be caused by the ship-ice interaction. More detailed description of this work may be found in Section 3.6.

These studies analyse different, both accidental and design ship-ice interactions. Works focused specifically on the iceberg impact include Oh *et al.* (2009) who performed a study on the membrane type CCS response to the iceberg collision and Lee *et al.* (2010) presenting similar analysis with somehow refined parameters. On the other hand, iceberg-ship collision for the spherical tank type is investigated by Kim *et al.* (2008).

Reference to associated issues may also be found in Section 3.6 Collision, Grounding and Flooding.

Another challenge related to shipping LNG in arctic waters is vibrations due to hull-ice interaction and their effect on the integrity of CCS and pump tower. Problems related to vibration are described in more detail in Section 3.8 Vibration.

Another aspect pointed out by Tustin (2005) is ship operation in severe but ice-free waters. For such extreme wave environment a careful attention may need both fatigue strength - for example with respect to discontinuous decks commonly constructed of higher yield steels at Moss-type carriers, and large sloshing loads for membrane-type carriers. See section 3.7 and 3.5 for more details on fatigue and sloshing, respectively.

LNG carriers for arctic operations may require certain winterization adjustments both in terms of design, equipment and operation techniques; see e.g. Tustin (2005).

Berg and Bakke (2008) investigated ship-to-ship transfer of LNG in arctic environment. They analysed the risk related to different phases of the operation. It is also observed that climatic changes question applicability of historic metocean data for planning future operations.

Sun *et al.* (2009) investigated the motion and loading on the LNG ship with ice breaking hull. Analysis of ice breaking performance in various ice types was evaluated by model tests, while seakeeping and manoeuvring characteristics in high waves were investigated by a numerical tool.

An interesting concept for winterization of the transport, storage and production processes is possibility of applying unmanned systems and hence reducing the dependency on humans in such severe conditions.

4.4 LNG as Fuel

Alternative fuel for propulsion has come into focus especially the last decade when environmental issues and restrictions to emissions requirements have been addressed on the political agenda. Here LNG as fuel is an interesting alternative. There have

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been ships propelled on compressed gas (CNG) prior to year 2000, also LNG carriers have been using dual fuel boilers for decades. However the first commercial LNG fuelled ship was the ferry "Glutra" in year 2000. The year after DNV came with the first rules for LNG fuelled ships (DNV Rules for Ships Pt.6 Ch.15, 2001). In 2009 the first international interim guideline for LNG fuelled ships was published (MSC 285.86). There is currently development of an IGF code for LNG fuelled ships in IMO. The rules are expected to come into force in 2013/2014. Until 2010 about 30 ships have been built with LNG fuelled engines. The number of ships propelled on LNG is increasing rapidly and in 2 – 3 years more the number of LNG fuelled ships with almost double. The new ECA requirements coming into force in 2015 will likely facilitate a large number of LNG fuelled ships in the years to come. The rules and regulations for LNG fuelled ships take the safety of LNG handling from the experience of LNG carriers. The safety philosophy will have to be adjusted to that LNG will be placed in other locations than previously experienced as well as the handling of LNG will be with ship crew not educated with the main purpose of transporting LNG but with using LNG as a commodity fuel alternative with a much more frequent schedule of filling and handling of LNG. This is an area that still may require further risk assessment studies to mature the safety understanding of the new LNG application.

5 CONCLUSIONS

It is concluded that the investigation of safety of LNG transportation indicates following areas where there is a need to determine the safety aspects and to develop consistent regulations for:

- LNG at offshore applications. Process and systems operability of LNG need further to be investigated. Also evaluations of sloshing loads at any filling levels. Semi empirical experience from LNGC operation cannot be generalized and the safety aspects should be further investigated. LNG spillage and safety handling and protection are areas where further investigation work may also be beneficial.
- There are many new LNG containment systems under development that do not fit into the established IGC code definitions of tanks. New generic regulations need to be established for how to handle new innovative containment system designs.
- LNG as fuel is a new area coming quickly as an attractive fuel alternative in shipping. LNG will be applied for any type of ships and LNG fuel tanks may be located in other areas than in cargo areas. This may challenge the established safety philosophies applied for LNG containment systems. A new IGF code is currently under development but the safety aspects should be revisited and evaluated.
- To examine the sloshing response of CCS and associated structures at actual seas, development of holistic analytical methodologies that combine CFD analysis of the liquid, fluid-structure interaction analysis, ship motion analysis, wave modelling, etc. is recommended.
- Innovation is required for the in situ inspection and monitoring of the hull structures and containment tanks to watch the performance of critical components and acquire data from structural variables such as stress, accelerations, fatigue, etc. These data together with operating variables (i.e. temperature, pressure and sea monitoring devices) could be effective for not only early detection of potential failure but also in further studies such as fatigue assessments, validation of analytical methods, etc.

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