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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. Consideration shall be given to the installation and safety matters of gas and dual fuel propulsion systems, fitted onboard conventional vessels. Needs for revision of current codes and regulations shall be addressed.

COMMITTEE MEMBERS

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KEYWORDS

Cargo containment systems, Liquefied Natural Gas Carrier, Floating Liquid 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.

CONTENTS

1. INTRODUCTION

The Committee V.2 is a follow up of a new specialist committee for natural gas storage and transport whose mission was 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 emerged. Based on the committee's mandate and the specialties 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 chapters deal with the measures that must be taken to assure the safety of the Cargo Containment System per mode of failure. Also structural integrity management issues are 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 LNGas fuel.

2. BACKGROUND

According to The IEA WEO2014 data, world primary energy demand rises about one-third between 2012 and 2035, or 1.2% per year on average. This compares with 2% per year over the previous 27-year period. Oil and coal consumption grow more slowly than the overall rise in energy demand (12% and 16%), while natural gas, nuclear and modern renewables rise much more quickly (44%, 74% and 134%) (Fig. 1 & Table 1).

Table 1. World energy consumption by primary energy sources, IEA WEO2014 data (Source: IEA WEO2014 (New Policies).

	1990	*2000*	*2012**	*2020*	*2025*	*2030*	*2035*	*2012 - 2035***
Oil	3231	3663	4158	4469	4545	4600	4666	0,50%
Gas	1668	2072	2869	3234	3537	3824	4127	1,60%
Coal	2230	2357	3796	4137	4238	4309	4398	0,60%
Nuclear	526	676	642	869	969	1051	1118	2,40%
Hydro	184	225	313	391	430	466	501	2,10%
Bioenergy***	893	1016	1318	1488	1598	1718	1848	1,50%
Other renewables	36	60	142	311	432	566	717	7,30%
Total (Mtoe)	8768	10069	13238	14899	15749	16534	17375	1,20%

*2012 data are preliminary estimates
** Compound average annual growth rate
*** Includes traditional and modern biomass uses
Mtoe = million tonnes of oil equivalent

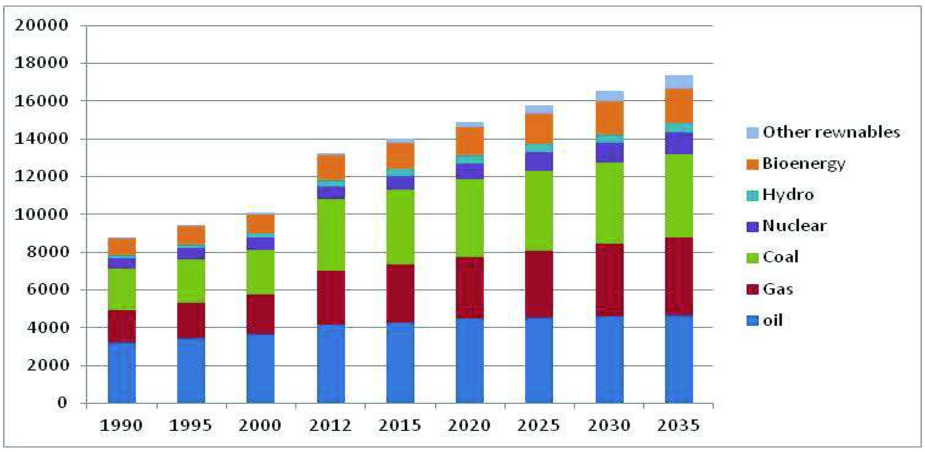


Figure 1. World primary energy demand in Mtoe (million tonnes of oil equivalent) (EA WEO2014 (New Policies)).

The “Fukushima effect” is an opportunity for the development of natural gas energy. After the catastrophe, Japan and many other countries decided to limit the use of nuclear energy and to turn back to LNG. Because of low CO2 and NOx emissions and the reduced impact of natural gas on environment compared to oil or nuclear energy, development of offshore gas fields becomes one of the most suitable solutions to sustain our needs in energy and to reduce the use of dangerous and polluting materials. Finally, the evolution of the technologies with the implementation of new installations such as LNG Regasification Vessel (LNG RV), LNG Floating Production Storage and Offloading (LNG FPSO) or Floating Storage Regasification Unit (FSRU) allows gas companies to explore and develop not only deeper fields but also remaining fields, exploited during the last decades for oil but abandoned because of the lack of technology to exploit gas, or marginal fields which were considered not profitable a few years ago. Nowadays, it exists a wide range of offshore solutions that allow gas companies to fit as close as possible to the world needs (Benyessaad *et al*, 2014).

On the other hand there are two issues regarding fuel of ships– high fuel oil price and carbon emission control. Particularly, The IMO (International Maritime Organization) requires 90% of SOx and 80% of NOx reduction in exhaust gas by 2015 and 2016, respectively. Essentially, both of these issues have equal economic significance since expensive low sulfur fuel oil or additional exhaust gas treatment is required to meet the emission regulation. Therefore, it is natural that many ship owners take a profound interest in LNG fueled large commercial ship these days (Kim *et al*, 2013).

Figure 2 shows the trend of long term energy price. Compared to rapid increase of crude oil, gas price is almost stable with the discovery of shale gas.

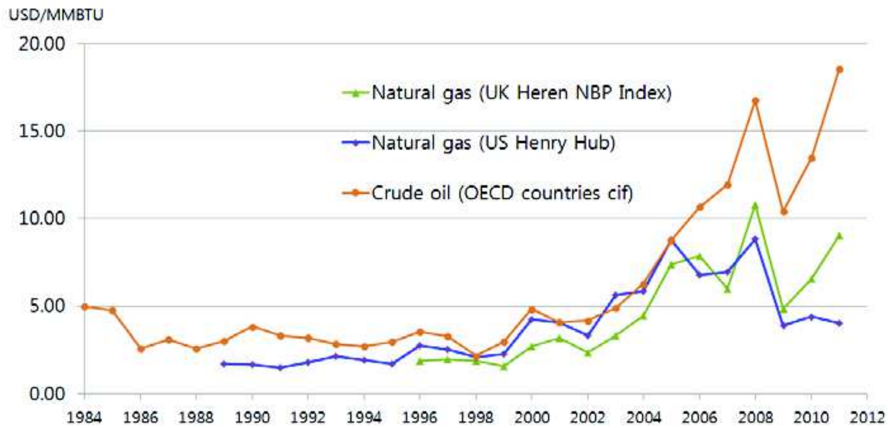


Figure 2. Long term energy price trend (Kim et al, 2013).

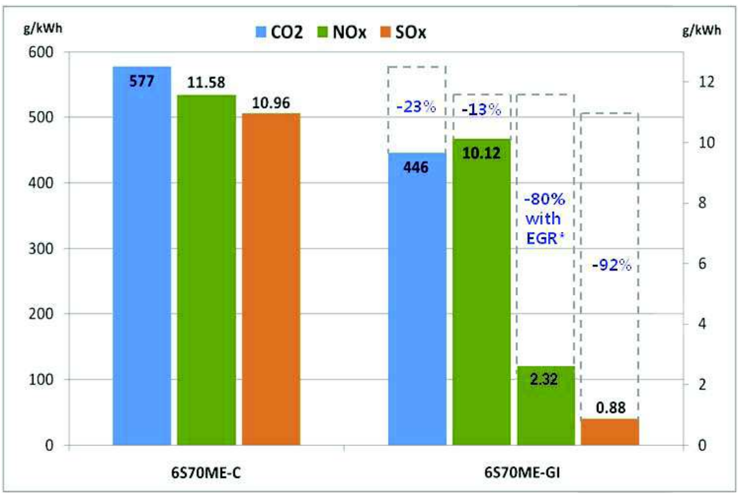


Figure 3. Comparison of emissions for ME diesel engine (left) and gas fueled engines (right).

Figure 3 shows the characteristics of LNG fuel in the view point of gas emission. In this figure, 6570 ME-C and 6570ME-GI represent the use of oil and LNG as fuel, respectively. It shows that LNG fueled ship can reduce nearly all of SOx emission and some amount of NOx emission, and besides it can also reduce CO2 by 23%. ME-GI with EGR (Exhaust-Gas Recirculation) system reduces NOx up to 80% (Kim et al, 2013).

3. SAFETY AND DESIGN

3.1 Cargo containment

3.1.1 Non-self-Supporting Tanks–Membrane Tanks

Membrane tanks are non-self-supporting structures with design vapor pressure of 0.25~0.7 bar. These tanks consist of a thin membrane layer which is supported by insulation such as plywood, triplex, reinforced polyurethane foam and mastic to keep the temperature. This type has benefits in efficiency of storage capacity (no void space) and containment weight reduced with strong and simple structure of cargo tanks. However LNG membrane tanks may have structural problems on partial filling caused by large impact loads due to sloshing, and first of all, safety for collision, being stranded and sloshing should be approved for arctic LNGC, LNG Floater and LNG fuelled vessels (Bang et al, 2012).

The sloshing problem on membrane type tanks has become a big issue in LNG tanks industries (LNGC, FSRU and FLN). The massive researches have been done to solve the problem. The challenge in sloshing assessment is how to accurately predict the sloshing loads due to the motion of structure, calculate the impact on structure (structural strength) and validate with full scale measurements. Considerable research efforts have been made and more details will be presented in the following subsection.

3.1.2 Independent tanks

According to IGC code, the independent tanks are classified as Type A, Type B and Type C. The advantage of the independent tank of LNG especially for IMO type is structural safety to withstand the sloshing, internal flow and external impact. Bang et al. (2012) have evaluated structural stability of the independent tank focusing on the cargo tank support structure between cargo tank and hull structure. It is noted that there is no significant research on LNG cargo independent tank only limited studies have been reported on IMO type B.

3.1.2.1 Compress Natural Gas Tanks

CNG is one of the methods for storage of natural gas in high-pressure tanks at pressure levels of 20–25 MPa (200 to 250 bars, or 2900 to 3600 psi). Migration from fuel oil to fuel gas recently has encouraged the invention of new concept for storage and transport of natural gas including CNG concept. In beneficial, CNG is easily available from existing infrastructure without liquefaction process and easy to store in room temperature (no cryogenic hazard) and short bunkering time. However the safety aspect regarding pressured storage is the main drive to use CNG method for storage of natural gas. Nevertheless CNG is more feasible for users with short routes. The table below shows a comparison of CNG vs. LNG (Wang et al, 1992).

While LNG dominates the market for sea transport of natural gas, a number of recent studies have shown that compressed natural gas (CNG) is economically more attractive than LNG for sea transport of relatively smaller volumes of gas over shorter distances (Wang et al. 2009).

Vernengo et al. (2013) established an automatic and integrated preliminary design procedure to generate and evaluate feasible technique for a trade of CNG and a first trial application has been carried out for a specific case. The procedure covers the typical aspects of ship design: selection of main hull dimensions, identification of weight (steel, outfitting, pressure vessel and cargo), propulsion and fuel consumption at nominal speed, trim and stability checks. Related to the gas containment systems, an issue was identified in combination of the properties of the compressed gas with very small specific gravity with characteristics of the gas containment system which are large pressure vessel in steel, with significant weight and dimensions. Further developed of the procedure is necessary to consider different solutions for the gas containment systems including the use of innovative materials. This will allow an evaluation of such solutions in a cost/benefit perspective.

Table 2. Process & cargo differences between CNG and LNG (Wang et al., 2008).

Aspect	*CNG*	*LNG*
Physical state	Gas	Liquid
Pressure	100 –50 bar	1 bar
Temperature in tank	30°C to –40°C	–163°C
Loading	Dehydrate, compress	Treat, liquefy, store
Terminals	Jetty or buoy	Jetty, or regas offshore
Ships	Simple, like bulk-carrier	Sophisticated, efficient
Receiving	Heat & decompress – utilize energy released	Store, regasify
Loading/offloading	Gas under pressure	As liquid
Compression ratio	~200 –250:1	~600:1
Containment D/t (diameter/wall thickness?)	~25 –60	~1000
Material	Fine grain normalized C-Mn steel, FRP	Aluminum, Stainless, Ni steel

3.1.3 New Development of CCS

The new IGC Code has been totally revised by IMO during MSC 97 with effective date on 1 July 2016. There are many changes including the requirements related to the cargo containment system (CCS). It has specific requirements based on the types of the tanks related to the design, structural analysis, ultimate design condition, fatigue design condition, accidental condition and testing. For membrane tanks there are new requirements related to the potential incidents that could lead to loss of fluid tightness over the life of the membranes to be evaluated, these include:

Ultimate design events:
1. tensile failure of membranes;
2. compressive collapse of thermal insulation;
3. thermal ageing;
4. loss of attachment between thermal insulation and hull structure;
5. loss of attachment of membranes to thermal insulation system;
6. structural integrity of internal structures and their supporting structures; and
7. failure of the supporting hull structure.

Fatigue design events:
1. fatigue of membranes including joints and attachments to hull structure;
2. fatigue cracking of thermal insulation;
3. fatigue of internal structures and their supporting structures; and
4. fatigue cracking of inner hull leading to ballast water ingress.

Accident design events:
1. accidental mechanical damage (such as dropped objects inside the tank while in service);
2. accidental over pressurization of thermal insulation spaces;
3. accidental vacuum in the tank; and
4. water ingress through the inner hull structure.

Table 3 shows the new requirements for independent tank types of cargo containment system.

3.2 Structural Integrity and rules

Rules and Standards, Partial Fillings, Structural Assessment Procedures

All major classification societies have reacted to the need for guidance on the treatment of partial filling levels of LNG Carriers and FLNGs. Bureau Veritas places a strong emphasis on numerical sloshing analyses whereas several other classes recommend experimental investigation. Regardless of the hydrodynamic part of the sloshing investigations, the main emphasis of the class recommendations are focused on the structural assessment with the aim of equal or even higher safety levels against sloshing damages as for the proven concepts of the existing fleet of LNG Carriers. The individual approaches differ slightly among the major classification societies, but in general a comparative approach as well as a direct assessment of sloshing loads and responses is covered by the updated Rules.

Structural integrity Management is a means of ensuring the ability of an asset or structure and its component to perform its planned function effectively and efficiently for its intended application throughout its service life. Survey and inspection are important inputs in the structural integrity management of the structure or system. In case of floating structure unit (FPSO, FLNG, FSRU, etc) maintenance methods, the prescriptive rules with frequent intervals (5 years) in dry docks are to be used if the structure is based on ship shaped type. However, floating offshore structure is subject to operate without dry dock for inspection, maintenance and repair, so that integrity management system with Risk Based Inspection (RBI) method may be considered to establish rational maintenance program (Survey and Inspection) for floating hull.

In case of FPSO structure, many methodologies and concepts of structural integrity management based on Risk Based Inspection have been introduced. Bisotto et al. (2004) have presented the methodology to establish inspection and survey plans combining RBI analysis and the industry expertise. The general simple work-flow of the inspection plan is illustrated in Fig.5. The effort to set inspection & survey plan is highly linked to the choice of the risk assessment method: qualitative and/or quantitative. The research in the area of integrity structural management or sometime called asset integrity management is ongoing especially in offshore industry to maintain safe production and to ensure the lifting of oil & gas production. Wisch et al. (2009) have derived various methods regarding to the structural integrity management of FPSO structure which can be used as references for FLNG and FSRU. Furthermore the recent study on structural integrity management of FPSO by Ku et al. (2012) proposed the structural reliability methodology and demonstrated its application to the RBI planning of an FPSO. Structural reliability based methods can assist in providing a framework for assessing site-specific loading and degradation mechanisms (such as fatigue and corrosion) through a systematic consideration of the uncertainty in each degradation mechanism.

Table 3. Benchmark of The new IGC Code requirements for Independent tanks.

Item	*Independent tanks*		
	Type A	Type B	Type C
Design Basis	Based on classical structural analysis procedure using recognized standard Design vapour pressure (P_0) < 0.07 Mpa Full Secondary barrier for –55°C ≤ T< –10°C	The tanks designed using model tests, refined analytical tools and analysis methods to determine stress level, fatigue life and crack propagation characteristics. Design vapour pressure P_0 < 0.07 MPa Partial Secondary barrier with small leak protection system shall be provided for T< –10°C	The tank designed based on pressure vessel criteria modified to include fracture mechanics and crack propagation criteria.
Structural Analysis	Internal pressure and the interaction loads shall be applied. Direct strength calculation shall be conducted for parts which are not cover by the codes. The tanks with supports shall be designed for the accidental loads	The structural analysis (Plastic deformation, buckling, fatigue failure, crack propagation) shall be determined using all of dynamic and static loads. FEA or similar method and fracture mechanics analysis, three dimensional analysis shall be carried out. A complete analysis of the particular ship accelerations and motions in irregular waves, and of the response of the ship and its cargo tanks to these forces and motions shall be performed, unless the data is available from similar ships.	N/A
Ultimate design condition	Nominal membrane stress (primary and secondary members) Buckling check	Plastic deformation check Buckling check	Plastic deformation check Buckling check
Fatigue design condition	N/A	Fatigue and Crack propagation analysis	For Tanks with temperature below –55°C it is to be ensured an initial surface flaw will not propagate more than half the thickness of the shell during the lifetime of the tanks
Accidental design condition	The tanks and tanks suports shall be designed for accidental loads and design condition.	The tanks and tanks suports shall be designed for accidental loads and design condition.	The tanks and tanks suports shall be designed for accidental loads and design condition.

(*New methodology → FLNG*)

FLNG and FSRU are the typical types of floating offshore structures with increased order in recent years. With same basis as FPSO, FLNG/FSRU has more complicated topside process for handling the gas processing on the topside (Production, liquefaction and regasification). The challenge is how to build gas plant on limited space and ensuring efficient and safe operations and that is the main reason for the choice of such system. FLNG as LNG production platforms and FSRU as LNG regasification platforms, imply a blend of technology from land-based LNG industry, offshore oil and gas industry and marine transportation technology (Arronson 2012).

In contrast to trading ships, FLNG & FSRU is not easy to drydock, and they have additional specific issues regarding to handling the gas (storage and gas process on the topside). These reasons will be a challenge in Structural Integrity Management in FLNG and FSRU structure in way to conduct Risk assessment with limited rules and codes related. Arronson (2012) has identified the risks relevant to FLNG. The risks are compared to conventional LNG carriers and whether or not regulatory alignment possibilities exist. To identify the risks, a risk analysis was performed based on the principles of formal safety assessment methodology. In table 4, the list of hazards of FLNG with the risk level have been presented by Arronson (2012).

The list described in Table 4 was the outcome of a brainstorming event and followed the IMO FSA guidelines. However the study was limited to the first step of the FSA, risk identification and the results have been used to estimate a rough value. Nevertheless the study provides a preliminary analysis for risk assessment of FLNG & FSRU with less experience in design and operation in the world. The further study is needed.

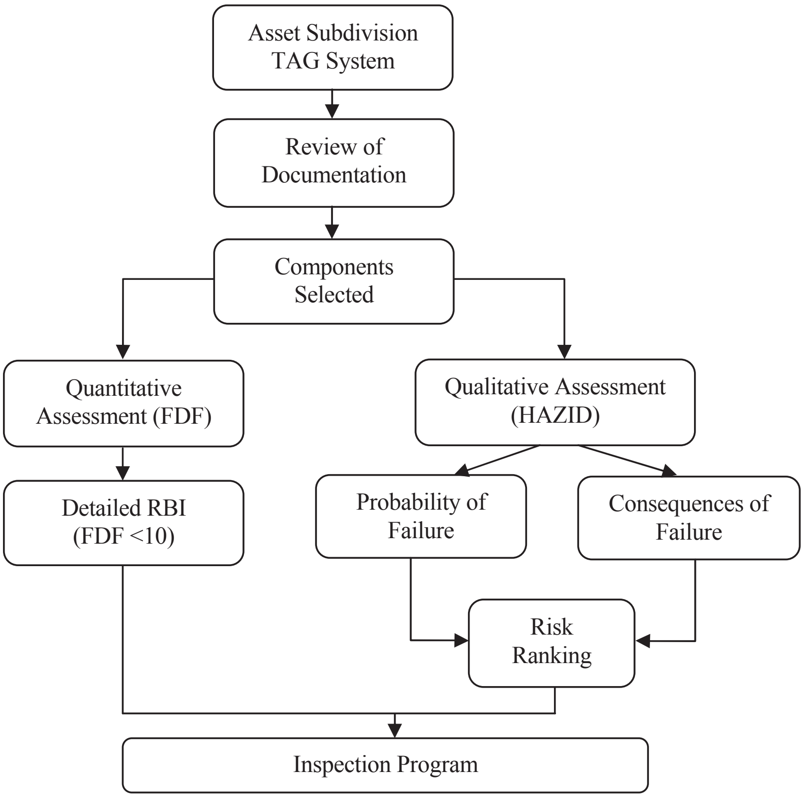


Figure 4. Work-flow of simple maintenance program based on Risk Assessment, Bisotto *et al.* (2004).

Table 4. List of hazard to FLNG & FSRU by Arronson (2012).

Area	*Hazard*	*Frequency*	*Consequence*	*Risk level*
Feedstock*	Blow out	3	1	4
	Hydrocarbon release from the turret	2	3	5
Gas processing and Liquefaction /Regasification	Hydrocarbon release in process area	2	3	5
	Cryogenic spill in liquefaction area (regasification plant in case of FSRU)	1	3	4
	Spill of hazardous substance	2	1	3
	Fire/explosion in process area	2	3	5
Cargo handling	Fire/explosion in containment area	2	4	6
	Inert gas release in containment area	2	1	3
	Sloshing in cargo tanks	4	1	5
Offloading And vessel overall	Ship collision	1	2	3
	Cryogenic leak during offloading (loading in case of FSRU)	1	3	4

*) The area and list of hazards are possible only for FLNG

3.3 Sloshing

3.3.1 Global Flow and Sloshing-Ship Motion Coupling, Online Sloshing Prediction

One of the critical areas in the design of FLNG/FSRU systems as well as floating LNG terminals is the transfer of LNG between the floating structures. During this transfer, intermediate filling levels at least in one tank at a time are inevitable. Thus sloshing can occur in the partially filled tanks and affect the motions of the vessels in the seaway. Furthermore the close proximity of the LNG Carrier and the FLNG or floating terminal has a significant influence on the motion behaviour as compared to the open water situation. Therefore dedicated motion analyses have been carried out including the coupling effect of the ship motion and the motion of the liquid inside the tanks as well as accounting for the presence of two floating bodies in close proximity. Park et al. (2013), for example, investigated the motion behaviour of an FLNG with tank capacity of 220,000 m^3 and an LNG Carrier with a capacity of 145,000 m^3 in side-by-side configuration with a separation distance of 5 m. The RAOs of the vessel motions were calculated by three-dimensional potential theory. The liquid motion in the tanks was also determined by linear potential theory, reasoning that the global fluid motion and the resulting forces relevant for the vessel motions were covered by this approach. In this study one-row and two-row tank arrangements for the FLNG were investigated.

The coupled motions of an LNG Carrier and the sloshing liquid are also investigated by Zhao et al. (2014). The authors use linear potential theory for the ship motions and a non-linear potential theory approach for the fluid motion inside the tank. Furthermore, a number of references to other studies of coupled motions using different approaches are given there.

Huang et al. (2013) transform the hydrodynamic coefficients and wave loads of the outside flow from frequency domain to the time domain and calculate the liquid sloshing motion inside the tank based on incompressible Reynolds-averaged Navier-Stokes equations and the Volume of Fluid method for the interface capturing using the OpenFOAM framework.

There are several approaches using computationally highly efficient methods to predict the occurrence of severe sloshing conditions. Godderidge et al. (2012) present a Rapid Sloshing Model based on a pendulum equation. Cao et al. (2013) used in-house software LTS (Linear Time-domain Sloshing) based on Desingularized Rankine Singularities. Kayal and Berthon (2013) employed an analytical approach augmented by a set of designated model tests for tuning the analytical model. These methods cannot simulate the highly complex violent sloshing flows in the tanks, but they effectively determine the onset of severe sloshing conditions in the tanks based on the current ship motions in faster than real time. Thus these methods are likely to form the basis of sloshing prediction systems and decision support systems on board of LNG Carriers and other vessels operating with large partially filled tanks.

Zheng et al. (2013) follow a different approach and determine the so-called Sloshing Severity Index SSI as a pre-screening tool to limit the number of sloshing model tests to those sea conditions likely to result in the most severe sloshing loads. To this end, a coupled linear potential theory method for the ship motions and sloshing is employed. The SSI is calculated from a global parameter, the total energy of the sloshing liquid in a tank, and a local parameter, the maximum vertical velocity of the sloshing liquid at the free surface.

Park et al. (2012) studied the coupled sloshing and motion analysis of FLNG in Side-by-Side Arrangement. In this study, both coupled effects between two-body motion and sloshing in the LNG tanks are considered. The methodology for coupled ship motion analysis is based on 3-dimensional potential theory in the frequency domain. For the sloshing analysis, the violent liquid motion inside tank is treated with SHI-SLOSH CFD code to calculate sloshing impact pressure. The time series of ship motion is generated with the ship motion results considering both two-body and sloshing coupled effect.

In a study on coupling effect between seakeeping and sloshing for membrane-type LNG carrier, Wang et al. (2012) evaluate the performance of membrane-type LNG carriers under half-loading conditions. The simulations for the coupled ship motion and sloshing have been carried out by using a newly developed time domain scheme. The external fluid field was solved by potential theory, while the internal fluid field was solved by a 3D finite difference method. The ship motions in different wave direction and frequencies were calculated. The coupling effect was found to have significant influence on transverse motions, while the longitudinal motions were not influenced. The slosh flow inside tanks was also investigated.

3.3.2 Long-Term Assessment

The long-term assessment of sloshing loads is usually carried out based on a limited number of sloshing model tests, where a three-dimensional model of an LNG tank under consideration is subjected to time series of irregular ship motions in all six degrees of freedom. The difficulties of this approach comprise the proper selection of the test conditions by pre-screening methods, as described above, and the meaningful stochastic interpretation of the test results. The aim of this stochastic interpretation is the reliable prediction of the maximum sloshing loads in an LNG tank and their probability of occurrence. Therefore the probability of exceedance is calculated for the peak sloshing pressures from the model tests. The estimation of peak pressures at a certain probability level is then achieved by fitting stochastic distribution functions such as the Weibull distribution or a Generalized Pareto distribution to the test results. The influences of the data preprocessing and the selection of the fitting distribution for sloshing pressures have recently been discussed by Fillon et al. (2013) as well as Dematteo and

Gervaise (2014). Diebold et al. (2013) investigated the statistical behavior of global sloshing parameters such as the tank accelerations due to the ship motions and the sloshing global forces as well as additional local parameters such as the fluid velocity normal to the tank boundaries at a certain distance from these boundaries. In this context Dematteo and Ratouis (2013) present a method to stochastically simulate the spatial pressure distribution over the tank boundaries in the vicinity of the limited number of physical pressure sensors. This approach may help to identify high pressure sloshing impacts that have been missed by the physical sensors.

Numerical simulations in combination with model tests have been carried out by Park et al. (2014) to optimize the cross-sectional shape of an LNG tank for unrestricted filling levels. Here the Weibull distribution is employed for the stochastic interpretation of sloshing pressures. Oh et al. (2014) used model tests and the Generalized Pareto distribution to identify the relevant sloshing pressures for an FLNG design and subsequently carried out the structural assessment of the FLNG cargo containment system based on these data.

The sloshing model tests for the long-term assessment are usually carried out using water and air at ambient conditions and Froude-scaling is employed for the motions and the resulting pressures. This approach might result in overly conservative pressure estimates, see Scaling section.

3.3.3 Experimental Methods, Benchmark

As mentioned in the previous section, the long-term assessment of sloshing pressures mostly relies on experimental model testing, since this is the only commonly accepted source of pressure data, as pointed out by Pistani and Thiagarajan (2012). Given the importance of the sloshing model test data for the design of LNG tanks and their cargo containment systems great efforts are undertaken to obtain reliable data. Pistani and Thiagarajan (2012) assess the complete measurement chain from the test rig to the data acquisition system including first steps of data processing. The authors address the influence of each component of the chain on the final data and identify the susceptibility of the employed pressure sensors as one important challenge to overcome. Ahn et al. (2013) investigated the behaviour of four different models of pressure sensors commonly in use for sloshing model tests in great detail. Baudin et al. (2012) present the peak memory cards, originally dating back to the 1980s, now revisited for sloshing model tests as an alternative means to capture the maximum peak pressures of sloshing impacts at reduced sampling rates.

3.3.4 Sloshing Model Test Benchmark

The Sloshing Model Test Benchmark (SMTB) was initiated in 2011 and is now organized by the ISOPE Technical Committee on Sloshing Dynamics and Design. The long term aim of the benchmark is to advance the quality and comparability of sloshing model tests and thus increase the fidelity of the results in the sloshing assessment of new LNG tank designs or applications. This SMTB recognizes that model tests are still the state of the art in the sloshing assessment of LNG tanks on floating vessels. The tank for the benchmark tests is a simple rectangular tank subject to exciting motions with reduced number of degrees of freedom. In the period of 2011 to 2012 nine institutions participated in the benchmark. The test conditions and results are summarized by Loysel et al. (2012). Based on the spreading in the results of 2012 the focus for the period of 2012 to 2013 was laid on the repeatability of single-impact waves in the same rectangular tank. The results are summarized again by Loysel et al. (2013) and were discussed during the ISOPE 2013 conference. The Sloshing Model Test Benchmark will now be continued on a biennial schedule with the next round to be concluded in 2015.

3.3.5 Sloshing Physics, Scaling ELPs, dominating physics and relevant scaling laws

Important results for the phenomenological and physical interpretation of breaking wave impacts such as sloshing impacts on a vertical tank wall have been reported by Lafeber et al. (2012). The authors identified three elementary loading processes (ELP) that can be related to different physical processes in sloshing impacts. The first ELP is associated with the direct impact of the liquid on the tank wall. This highly localized phenomenon is named the direct impact ELP (ELP1). The next pressure pattern derives from the formation of a jet of liquid travelling along the tank wall. This ELP2 is called the building jet ELP. The third discrete process identified from the test results is the oscillating pressures of a gas pocket entrapped by the overturning wave crest and the tank wall. This loading process is titled the pulsating gas pocket ELP (ELP3).

Starting from the ELPs analytical and numerical investigations have been carried out in order to find scaling laws for the different loading processes. The results for pulsating gas pockets based on an extension of Bagnold's piston model are reported by Ancellin et al. (2012) and Brosset et al. (2013). Several other authors have also been working on scaling effects.

Furthermore, the first results of full-scale onboard sloshing measurements of an LNG Carrier were presented by Pasquier and Berthon (2012). Several papers have been published on the comparison of results obtained at different scales.

Karimi et al. (2013) studied the global and local effects of gas-liquid density ratio on shape and kinematics of sloshing waves and their scaling considerations. The authors concluded that the effects of gas-liquid density ratio (DR) on sloshing wave shapes when investigated globally (far from impact zones) by 2D sloshing model tests with irregular excitations at two different scales and for low-fill levels appear to be small for the tested range of density ratios which implies similar wave shapes far from impact zones. When repeating the same irregular motions, global flow keeps the same phase regardless of tested DRs which enables to recognize an accurate impact-by-impact relation between model tests at similar and different scales and adds a deterministic side to post-processing model test results, The local effects of DR (right before impact) on breaking wave shapes were also investigated by 2D sloshing model tests with single breaking waves at two different scales and for low-fill levels. The local effects of DR clearly modify the impact geometry before gas compressibility interference with significant consequences on induced pressures.

Brosset et al. (2013) presented a Generalized Bagnold Model in which experimental and numerical studies have shown that the behavior of gas pockets entrapped by a breaking wave when impacting a wall is well described by the piston model first modelized with a single Ordinary Differential Equation (ODE) by Bagnold under the assumption of a perfect gas and isentropic conditions. As for a sloshing impact inside the tank of LNG vessels, an inertial acceleration is always involved during the impacts and as several authors observed some evidence of the influence of liquid compressibility during wave impact tests. A 1D model of the liquid piston problem including a constant inertial acceleration is proposed based on isentropic compressible Euler equations, as an extension of the previous 0D model. A parametric study is performed with the first one looking at the influence of each dimensionless number on the maximum pressure at wall. The scaling of the 1D liquid piston model is studied giving insight on the scaling process when several similarity laws are at work.

In Rafiee et al. (2012) numerical simulations of 2D liquid impact benchmark problem using two–phase compressible and incompressible methods were compared. The authors simulated the benchmark impact problem (as proposed in ISOPE 2009) using a two–phase compressible Smoothed Particle Hydrodynamics (SPH) method and an incompressible Level–Set method. A 2D impact benchmark problem is simulated for two different liquid–gas combinations, namely air–water and NG–LNG. The results highlight the effect of aforementioned parameters on the impact pressure and the capability of the proposed SPH and Level–Set schemes in accurately predicting complex impact pressure.

3.3.6 Numerical Methods

A whole myriad of papers have emerged that treat sloshing using SPM methods or related methods such as e.g. MPS, moving particle semi-implicit methods. In Zhang et al. (2013), liquid sloshing is simulated based on Moving Particle Semi-Implicit (MPS) method, which is a meshless method. However, the traditional MPS method suffers from strong unphysical pressure oscillation. To overcome this, some improvements had been made, such as: nonsingular kernel function, mixed source term for pressure Poisson equation (PPE) and an accurate surface detection method. Smooth pressure field is obtained based on the present MPS method. The predicted pressure at resonance on the wall of the LNG tank by MPS method shows a good agreement with experimental data and other numerical results. The impact behavior induced by liquid sloshing is accurately predicted. In addition, violent free surfaces are observed.

To include hydro-elastic effects, methods based on finite particle methods have shown progress as reported by Baeten et al (2013). Here one observes a LNG tank shape in terms of sloshing impact pressure and focuses on an innovative modelling approach of elastic tank walls. This approach is based on finite particles, which provide similar properties as finite elements in classical structure mechanics. It features a particle-based liquid model and provides time accurate hydrodynamic pressure results in three dimensions and 6 Degrees-of-Freedom. Based on the results of specific tank geometries using a rigid wall model, unsteady sloshing loads are computed for elastic tank walls. The stresses and strains are discussed to optimize the structure in terms of impact pressure loading. Thereby, the LNG tank geometry is flexible in terms of wall friction, elasticity laws and damping coefficients.

Hwang et al. (2014) reports on a simplified impinging jet model for practical sloshing assessment of LNG cargo containment. A simplified numerical modelling is conducted to create an assessment procedure for sloshing impact in partially-filled LNG cargo tanks. A computational procedure based on an impinging jet of LNG acting on an insulation panel is employed in order to evaluate the sloshing impact on a real cargo tank. The velocity of the impinging jet is determined by a similarity rule that scales up the impact velocity from a small scale to that of actual scale. Several procedural components are introduced for a structural response calculation based on transient pressure.

A variety of numerical methods are compared by Fossa et al. (2012), using FEM-CFD and FEM-FSI approaches. Simulations were done in two-dimensions, i.e. an infinitely long tank. Investigation was carried out first by Finite Element Method (FEM) Computational Fluid Dynamics (CFD) approach, considering the structure as rigid wall. Thereafter, fluid structure interaction (FSI) model using finite element method for both fluid and structural degrees of freedom was implemented. Typical test cases were considered, for which experimental results were available in open literature and already compared with other CFD results in previous works.

3.3.6.1 Smooth Particle Hydrodynamics

Cao et al. (2014) study sloshing in a rectangular tank. Their study focuses on the SPH core issues, such as the accuracy and the stability of the kernel function and boundary treatments. Firstly, the accuracy and computational stability of four common SPH kernel functions are simply investigated by two simple cases, and a more appropriate kernel function is selected. Secondly, the dummy particles and a novel boundary treatment considering the boundary motion are applied. Furthermore, the laws of impact pressure of the two-dimensional tank under forced rolling with different excitation frequencies and excitation angles are studied. Then, the influences of a baffle for the liquid sloshing in a two-dimensional tank under forced surging are analyzed, and the action mechanisms of the baffle are summarized. Finally, the coupled motion of swaying and surging for a three-dimensional tank is studied, which aims to lay a foundation for further study on the influence of sloshing loads on real ship motions.

Chowdhury et al. (2014) studied a δ-SPH model that has been proven to be superior to standard SPH for solving fluid flow problems covering a broad range of Reynolds (Re) numbers including violent fluid motion involving free surface fragmentation. Analysis has been carried out to identify major factors affecting the present δ-SPH model from predicting higher order harmonics. The role of XSPH factor as used in SPH in smoothening of velocity has further been revisited. The model prediction for different physical quantities of sloshing has been found to be in good agreement with results from other experimentally, numerically and analytically based studies. Suitable scales for the tuning factors are proposed for the development of robust SPH models which are expected to simulate sloshing waves defined by relatively broader d/L (ratio of initial water depth to tank length) ranges.

Gotoh et al. (2014) present two schemes for enhancement of Incompressible SPH (Smoothed Particle Hydrodynamics)-based methods in simulation of violent sloshing flows, and in particular, sloshing induced impact pressures. The enhanced schemes include a Higher order Laplacian and an Error-Compensating Source of Poisson pressure equation, abbreviated as HL and ECS, respectively. These two schemes correspond to those derived within the framework of MPS (Moving Particle Semi-implicit) method and are proposed for the first time within the framework of SPH. The enhancing effects of HL and ECS schemes are shown by simulating violent sloshing flows induced by sway excitations and rotation alone. The significance of dynamically adjusted coefficients in the ECS-related schemes is highlighted by considering a previously applied scheme comprising of a constant coefficient and a corresponding newly proposed one which incorporates a dynamic coefficient. Concise insights are presented on appropriate choice of kernel function.

3.4 Leakage

In the analysis of two main LNG CCS (cargo containment system) insulation boxes for leakage safety, Woong et al. (2012) conducted an experiment to measure the thermal conductivity of insulation materials used in a LNG CCS under various temperature conditions ranging from room temperature to cryogenic temperature. Using the experimentally determined thermal properties a steady-state thermal analysis of a CCS insulation box was investigated. In addition, a thermal analysis was conducted for the hull part of a carrier ship in a scenario in which LNG leaked through the secondary barrier of the insulation due to an accident. The safety of the hull was considered based on the ductile to brittle transition temperature of the hull.

Choi et al. (2013) analyzed the flow and thermal characteristics of leaked LNG in glass wool for the Mark III CCS. They evaluated pressure distribution of the glass wool with the condition that cryogenic liquefied material leaked into the insulation box with constant pressure of leaked liquid. Furthermore, flow analysis was carried out with different glass wool to investigate how the leaked cryogenic liquid behaves in the glass wool. Simulation result was compared favorably to experimental results to realize cryogenic liquid in the glass wool.

3.5 Fatigue

Song et al. (2013) present a study to investigate the load effects due to sloshing impact on the fatigue assessment of an independent type B LNG tank. The selection of the cargo containment system type for an FLNG (Floating LNG) is mainly related to the sloshing problem. FLNG are considered to be operating at an intermediate loading condition prone to sloshing inside the containment system. One of the most popular LNG containment systems for the FLNG is an independent prismatic tank categorized as IMO (International Maritime Organization) type B tank, in which the ship hull supports the LNG tanks. It is recognized that the independent type B tank is free from possible liquid sloshing inside the tank from the standpoint of its strength due to its stiffened panel structure. In the present study, the sloshing impact pressures on the internal structures of an independent type B tank are predicted based on scaled sloshing model tests using a 2D rectangular tank with internal structures. Finally, a fatigue assessment based on the sloshing model results is carried out to quantify the effects of sloshing loads on the fatigue strength of an independent type B tank.

Kim et al. (2011) study cryogenic fatigue assessment for Mark III insulation system. The authors investigated the typical failure mode and obtained the stress range versus number of cycles to failure (S-N) data of MARK III type liquefied natural gas (LNG) insulation system under the fatigue loading at actual cryogenic environment. A systematic experimental research is carried out for the assessment of the fatigue strength of MARK III insulation system at cryogenic temperature. Three different types of test specimens are tested for the evaluation of fatigue performance of MARK III insulation system. Test specimens are determined considering the fatigue vulnerable locations such as mastic area, slit area, and top bridge pad area inside the actual LNG cargo tanks. All test specimens are fabricated as close as possible to the actual yard practice. A series of fatigue test results is represented as S-N curves. Cyclic fatigue loadings were carefully considered similar to the actual sloshing loads. The effect of sloshing impacts is considered by selecting the stress ratio ($R=-10$). Different cryogenic temperatures are employed according to the test locations in consideration of temperature gradient within the insulation system. Consistent S-N curves of MARK III insulation system at both room and cryogenic temperatures are obtained and compared. It is observed that the slopes of S-N curves from both fatigue test results are almost identical, and the fatigue strengths are found to exhibit similar trend.

3.6 Collision, grounding, flooding

Based on the previous ISSC(2012) report, collision and flooding are one of the dominant issues related to hull-ice interaction and iceberg collision. To continue the previous research, there are several studies addressing collisions and flooding which are presented in this report. Lee et al. (2013) carried out full scale collision simulation to estimate a more reliable and realistic collision impact response, using Fluid-Structure Interaction (FSI) analysis technique of LS-DYNA code, and current load to iceberg instead of current velocity.

In the new IGC Code 2014 which is effective by 1 July 2016, there are some fundamental amendments related to the ships intended to operate for periods at a fixed location in re-gasification and gas discharge mode or gas receiving, processing, liquefaction and storage mode (it may mean temporary liquefied gas terminals). The risk of collision during berthing maneuvers shall be ensured with appropriate steps by the administrator and port administrations. Additional requirements shall be established based on the principle of the IGC Code. Also there is some modification of requirement for tank location based on tank types which shall meet the collision criteria (shall be protectively located and withstand the collision loads without deformation of the supports, or the tank structure in way of the supports, likely to endanger the tank structure) and also flooded compartment criteria causing buoyancy on tank (the anti-flotation arrangements shall sustain the upward force and there shall be no endangering plastic deformation to the hull). Additional accidental loads included collision loads and loads due to flooding on ship shall be determined as consideration in the design as well as some accident design that are potential accidents which could lead to loss of fluid tightness over the life of the membrane tanks included accidental mechanical damage (such as dropped objects inside the tank while in service). The comprehensive requirements have been provided in the new IGC Code.

Hu et al. (2011) presented a verification of a simplified analytical method for the prediction of structural performance during ship groundings over seabed obstacles from numerical simulations. This simplified analytical method was developed by Hong and Amdahl and calculates grounding characteristics, such as resistance and distortion energy, for double-bottomed ships in shoal grounding accidents. Two finite-element models are presented. One was built for a hold, and the other was built for a hold and a ship hull girder also considering sectional properties, ship mass, added mass and the hydrodynamic restoring force. The verification was completed by comparing horizontal and vertical resistances and the distortion energy between seven numerical simulation cases and a set of corresponding cases computed by a simplified analytical method. The results showed that the resistances obtained by the simplified analytical method are close to the mean values of the resistance curves obtained by numerical simulations. The comparisons demonstrated that the energy dissipation prediction capability of the simplified analytical method is valuable. Thus, the simplified analytical method is feasible for assessing ship groundings over seabed obstacles with large contact surfaces and trapezoidal cross-section. Finally, a new method for predicting the structural performance of the time-consuming complete-ship model by applying a combination of normal numerical simulations and ship-motion calculations is proposed and proven.

In Yu et al. (2013) an investigation is reported on structural performance predictions of double-bottom tankers during shoal grounding accidents. This investigation is carried out for the predictions of structural performance of double-bottom tankers during ship grounding over the "shoal" type seabed obstacles. Hong and Amdahl developed a simplified analytical model for the unstiffened double bottom. This method is carefully studied, verified and then used as the first stage of the prediction. The second stage is concerned with stiffeners since stiffeners are indispensable components for double-bottom tankers. A prevailing way to handle is to smear stiffeners onto their attached plating known as the smeared thickness method. However, the effective ratio in this method is dubious in such shoal grounding accidents. Proper values of this parameter are determined in stage two, and then together with the method in stage one, constitute a reliable and efficient tool for structural performance predictions of double-bottom structures in shoal grounding accidents. A double-bottom tanker is chosen as object for the case study. Finite element models of the hold both stiffened and unstiffened are created for numerical simulations using the LS_DYNA software. Simulation cases cover a wide range of slope angles of the indenter and indentations. Numerical results show that Hong and Amdahl's model in stage one is capable of predicting energy dissipation with high precision but poor accuracy for grounding resistances, and a possible reason may be the neglect of vertical resistance. The updated smeared method proposed in stage two is also proved to be capable of grasping major characteristics of stiffeners. Results and conclusions drawn from this paper can be conveniently applied for assessments of the performance of ship double-bottom structures during shoal sliding grounding scenarios, and will benefit the application of accidental limit state design concept in the ship design stage.

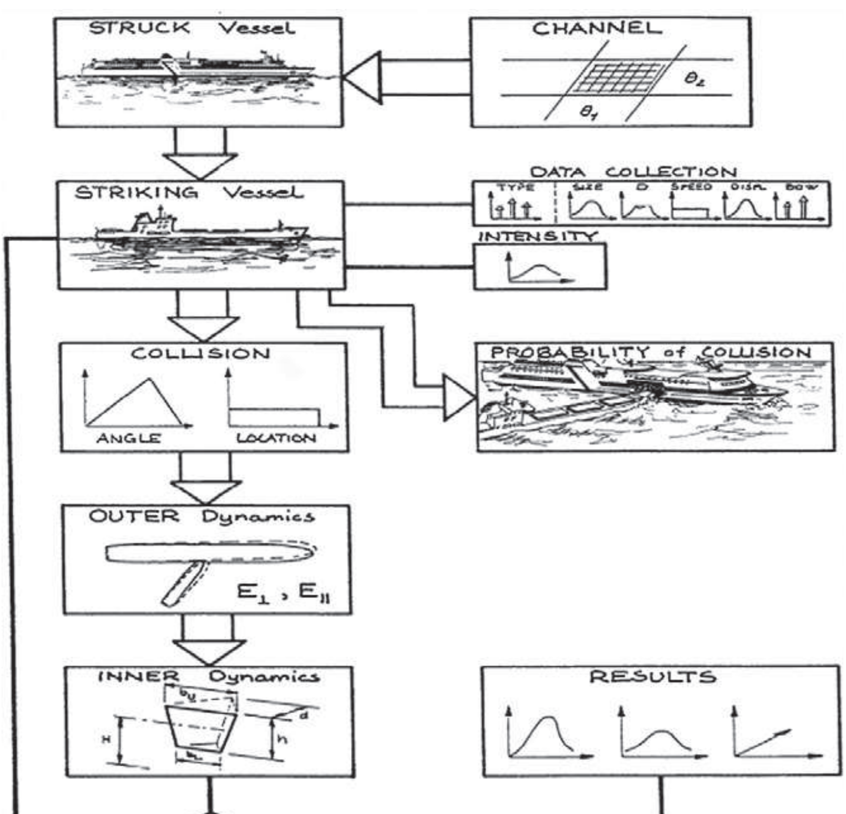


Figure 5. Overview of steps in a comprehensive collision risk analysis, from Pedersen et al. (2010).

Hogström et al. (2012) reported an extensive study of a ship's survivability after collision. The International Maritime Organization strives towards a more risk-based view on addressing the damage stability of ships. The study addresses the survivability following a ship collision by the use of a sequential (de-coupled) computational methodology. The methodology is comprised of structural analysis of a collision scenario followed by dynamic damage stability simulations of the struck ship in order to establish the time to capsize of the struck ship.

According to the ISSC committee V.I–Collision and grounding (2006), the following elements outline the principles of collision and grounding design standards.

The emphasis of the investigation is on the structural computations of the collision event; explicit finite element analyses are presented for a case study of a collision scenario. In particular, uncertainties of input parameters in the finite element simulations and their impact on the shape and size of the damage opening area, and time to capsize of the struck ship, are addressed. Material modelling aspects are studied including material properties within a material class as well as damage modelling. In addition, the effects of using a deformable or rigid striking bow section, the friction coefficient, the collision angle and the speed of the striking ship are studied. Recommendations for a sufficient level of simplifications for arriving at reliable results in numerical simulation of ship collisions are made. Based on these findings, recommendations on how ship collision analyses should be set up have been made: 1. The dispersion of the material: The analyst should be aware that the properties of a material may have a dispersion that gives large consequences on the outcome of the analysis and account for this. 2. Failure criteria: The study has shown that the choice of failure criterion has a significant influence on the outcome of the analysis. 3. Modelling of striking bow section: In the variance analyses this factor is shown to have the highest influence on the results of the surveyed factors. Using a rigid bow section is a very crude assumption that should only be used in comparative studies. When an analysis of a real collision scenario is to be carried out, a deformable bow section should be used if the results are to have any significance. 4. Friction coefficient in contact conditions: This factor has minor influence on the outcome of the analyses. However, a conservative analysis should use a low friction coefficient; a realistic value for wet plates is 0.1. 5. Collision angle and striking ship speed: The speed of the striking ship has major influence on the results since it determines the amount of kinetic energy that needs to be absorbed by the structures. The effect of the collision angle has no statistical significance for the geometries used in the current study. A conclusion is that the solution is highly dependent on geometrical effects that are hard to predict. Thus, different collision angles should be analysed in order to find which one gives the most severe results for the geometry being studied.

In Lee et al. (2012a) a Safety Assessment of Ship Collision using FSI Analysis Technique is presented. Structural safety assessment was performed for the collision accident of specialized ship structure and its cargo. To ensure reasonable and reliable safety assessment, accurate and correct full-scale ship collision simulation was carried out using FSI analysis technique of LS-DYNA code and propulsion force instead of velocity in collision simulation.

Lee et al. (2012b) used this approach for iceberg collisions. In this study, full-scale collision simulation was carried out to estimate a more reliable and realistic collision impact response. For the investigation of the effects of the type, mesh size, material model and property of iceberg on the collision responses, full-scale collision simulations were also performed in the void (air) condition.

3.7 Sloshing Control

Kim et al. (2013) studded the use of an anti-sloshing blanket system to prevent sloshing. A comparative study is presented for the development of a new device for the reduction of the sloshing impact load on an LNG cargo containment system. A floater-type blanket is proposed as a new device. The floater floats and deforms on the free surface inside an LNG tank, and the floater's material can work properly at extremely low temperature. To observe the efficiency of this device, a series of 3D model tests is performed at 1/50 model scale. Slosh-induced impact pressures are measured on the inner side of the tank wall in irregular motion excitations, with varying filling depths and sea states. It is observed that this floater-type device can reduce the slosh-induced impact pressure in most conditions.

3.8 Fire safety, temperature control of hull structures

Li et al. (2012) reported the application of Safety Science and Technology to LNG ships, in which analyses were carried out for the fire fatalness of LNG ships. The risk evaluations of fire and explosion in the LNG ship were made at a different angle by use of the Dow method, BLEVE (boiling liquid expanding vapour explosion) model and VCE (vapour cloud explosion) model. The clear, accurate, comprehensive evaluation findings were obtained, in which the fire and explosion hazard index F&EI is 168 and the degree of risk is 'very large' before the security measure compensations. However, after security measure compensations, fire and explosion risk index F&EI falls to 67 and the degree of risk is reduced. The results could be applied as references to the scientific management and the adoption of safety measures for the shipping enterprises that plan and participate actively to import LNG project.

In addition to their 2004 (Sandia Laboratories) report on spillage of LNG, Blanchet et al. (2013) presented a study on LNG ship insulation experiments using large LNG pool fire boundary conditions. The tests were conducted on a large scale in an LNG pool, using liquid methane.

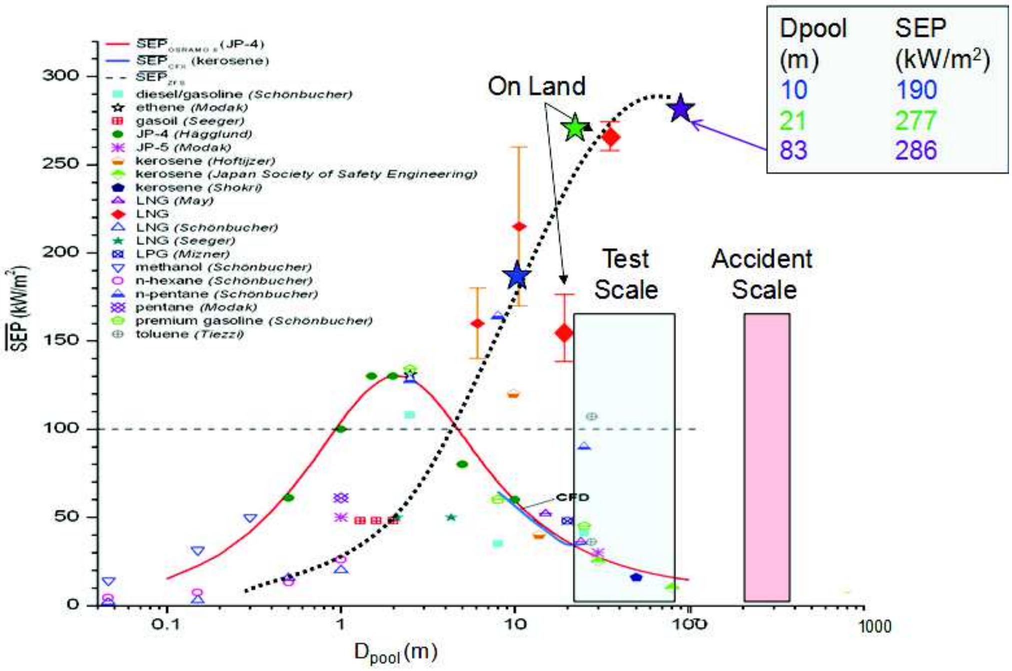


Figure 6. Surface Emissive Power vs. Pool Diameter for various hydrocarbon fuels Reference should be given for this and the next figure.

Figure 7. LNG pool fire test site–Sandia Lab.

From the Fire Test for Tank Insulations, the following observations were taken: The steel plate approached 1100^{0}C and the insulation layers closest to the steel plate reached 800^{0}C; and all insulation systems suffer degradation and reduction in mechanical strength.

From the effect of Large Spill as described in table 5, the following conclusions were taken:

- Significant reduction in strength
- Simultaneous multi-cargo tank cascading damage spill are unlikely
- Risk mitigation categories identified:
  - Options to help reduce the possibility of spills, especially large spills,
  - Options to reduce ship damage if a large spill did occur, and
  - Ship design modifications that could help protect the ship from damage and the crew from danger from a large spill and fire

Table 5. spill.

LNG Vessel	Insulation Type	Thickness	Time for Thermal Front to Reach LN_2 Tank	LN_2 Tank Heat Flux
Moss	Extruded polystyrene panel	~300 mm	< 40 min	< 7 kW/m^2
Moss	Polyurethane foam/ phenolic resin foam composite panel	~300 mm	> 40 min	< 5 kW/m^2
Membrane	Polyurethane foam and plywood panel	~300 mm	> 40 min	< 5 kW/m^2
Membrane	Perlite-filled plywood boxes	~500 mm	> 40 min	< 5 kW/m^2

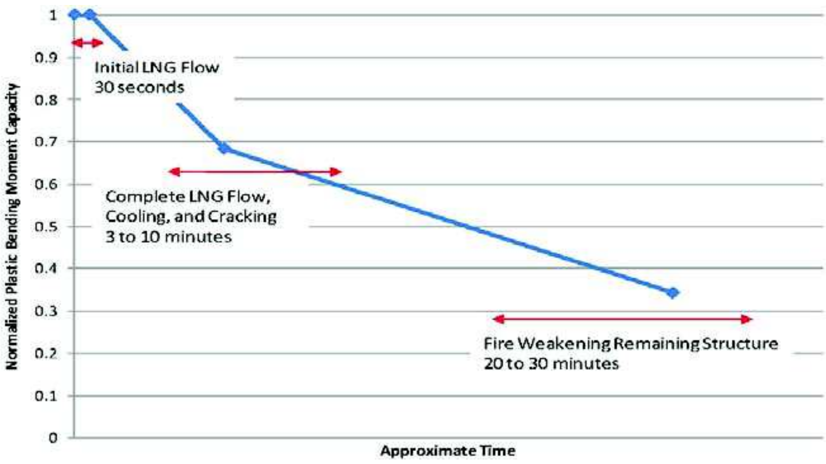
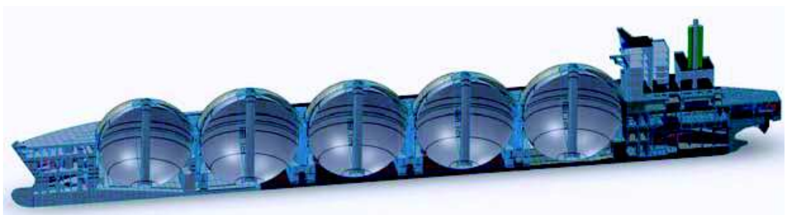


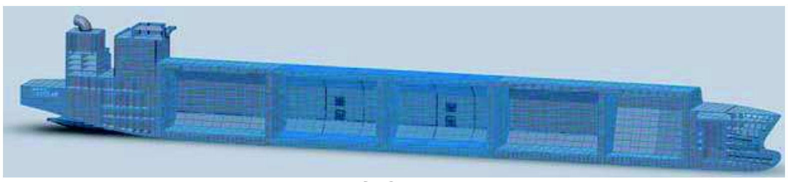
Figure 8. Progression of fire.

Petti et al. (2013) analyzed the structural and thermal consequences of LNG vessel cascading damage. The authors examined susceptibility of an LNG ship and cargo tanks to cryogenic and fire damage from a large LNG spill. Moss and Membrane type LNG ship design were investigated.

As a conclusion the structural integrity can be severely compromised for large spills with significant sections of the hull cracked and no longer capable of effectively resisting any loads. Both ships are judged to be disabled and severely damaged due to a large cargo tank breach and spill. Neither ship would be capable of movement and would need to have any remaining LNG cargo transferred. Simultaneous multi-cargo tank cascading damage spill scenarios are judged to be unlikely, though sequential tank spills are possible. These sequential spills are not expected to increase the hazard distances, but could increase the duration of the fire.



Moss LNG Ship cross-section



Membrane LNG Ship cross-section

Figure 9. Moss and membrane tanker.

4. LNG AS FUEL

A note from the GL and LR brochure.

4.1 Why LNG as Fuel

Using liquefied natural gas (LNG) as ship fuel has recently gained more attention not only in Europe, but also in Asia and the USA. There are three drivers visible which make LNG as ship fuel one of the most promising new technologies for shipping:

- First, using LNG as ship fuel will reduce sulphur oxide (SOx) emissions, which are created when using fuel with high sulphur content, by between 90% and 95%. This reduction level will become mandatory within the so-called Emission Control Areas (ECAs) from 2015. A similar reduction will be enforced for worldwide shipping from 2020 on, pending a review at the IMO which may shift the introduction to 2025.
- In addition, the reduction of nitrogen oxide (NOx) emissions to comply with IMO Tier III limits, applicable in ECAs from 2016, can be achieved for both pure gas engines and four-stroke dual-fuel engines, which are typically used on board ships engaged in short sea and coastal shipping.
- Second, due to the lower carbon content of LNG compared to traditional ship fuels, a 20%–25% reduction in carbon dioxide (CO2) emissions is possible. The actual reduction depends on engine type and the range of possible measures for reducing the unwanted release of unused methane.
- Third, current LNG prices in Europe and the USA suggest that LNG could be offered at a price comparable to heavy fuel oil (HFO), taking into account its energy content and the costs of small-scale LNG distribution (not yet available). This means that LNG will certainly look commercially attractive compared with the low-sulphur marine gas oil (MGO) which will be required to be used within the ECAs if no other technical measures are implemented to reduce SOx emissions.

A more systematic analysis of costs and benefits for LNG-fuelled container vessels was recently completed by GL and leading engine manufacturer MAN, who is currently preparing to launch a range of LNG-fuelled two-stroke engines in 2013. Five container vessel sizes and three different operational profiles were investigated by systematically changing the price of LNG and the proportion of time spent operating within ECAs.

Results for using LNG as fuel were compared with the principal other technical alternatives, the implementation of exhaust gas cleaning systems (scrubbers), to reduce emissions to required levels. The decision to use LNG as ship fuel as opposed to using a scrubber system would depend on the price differential between LNG and HFO, the proportion of time spent operating within ECAs and the starting year for the vessel. Most LNG systems are expected to become profitable in 2020, when a global low-sulphur fuel standard is expected to be implemented.

4.2 LNG Supply Chain

A number of initiatives are taken regarding LNG-bunkering stations in order to make shipping more environmentally friendly and competitive. One possible supply chain for LNG as fuel as an example is described by Wang et al. (2014) as follows:

A small LNG tanker could load, say, 10,000 m^3 of LNG at an LNG terminal, e.g. Zeebrugge, and transport her cargo to an intermediate LNG terminal. Several small LNG tankers already exist and are thought to be available to fulfil this task. Intermediate terminals have been built, such as the one near Stockholm, and more are planned for Gothenburg and several other locations in the Baltic region. The port of Hamburg also considers this to be an option for the future supply of LNG to ships.

The last step of supplying LNG to the end-user is performed by LNG bunker vessels, none of which have yet been built. These would be small LNG tankers, too, and would deliver the LNG to the ship in a fashion similar to the present bunker delivery of HFO. It is noted, however, that technical and regulatory challenges need to be overcome before LNG bunkering in ports becomes standard.

Regulatory Development

Class society GL has been working on a number of projects involving gas as a ship fuel and is participating in the development of the IMO rules for gas as a ship fuel on behalf of the German government.

Ship Design

The development of rules and design concepts of LNG-fuelled vessels

The “Bit Viking” is the world’s first vessel in service whose main machinery has been converted to burn LNG as fuel. She is also the largest commercial vessel which is not an LNG tanker, to use LNG as fuel. The conversion saw the main engines replaced and two large LNG tanks installed on deck, each with a capacity of 500 m³, giving the vessel a range under LNG of 12 days. Conversions of existing vessels to use LNG as ship fuel, however, are assumed to be limited due to a lack of engine type retrofit options and available space for LNG tanks. The first vessels to use LNG as ship fuel were large LNG tankers using boil-off gas as fuel. Later generations of LNG tankers also used traditional ship fuels such as HFO. The first vessels built to use LNG as fuel, and to thus benefit from lower emissions levels, were a ferry (in 2000) and two offshore service vessels (in 2003) operating in Norwegian waters. To date, another 13 such vessels have been commissioned, making Norway the country with the largest fleet of LNG-fuelled vessels. At the same time, an LNG supply infrastructure has been established along the Norwegian coast.

At present, there are a number of vessels on order which are designed to use LNG as ship fuel. A ferry has been ordered by Viking Line for operation between Finland and Sweden, and a general cargo ship has recently been ordered by Norline for operation in the North Sea. In addition, a number of offshore service vessels are on order, two of which are intended for an operation in US waters off the Gulf of Mexico.

The first study on an LNG-fuelled container feeder vessel was published by GL in early 2009 and demonstrated the concept's technical feasibility and commercial attractiveness for operations within an emission control area (ECA), as compared with a standard vessel of today. In addition, GL has issued approval in principle (AIP) certificates, on the basis of the GL guidelines, to two container vessels designed to use LNG as ship fuel and with capacities of 4,100 TEU and 14,000 TEU, respectively. Noteworthy article in "Der Spiegel" English edition: http://www.spiegel.de /international/business/new-imo-regulations-push-shipping-industry-toward-cleaner-fuel-and-lng-a-916811.html.

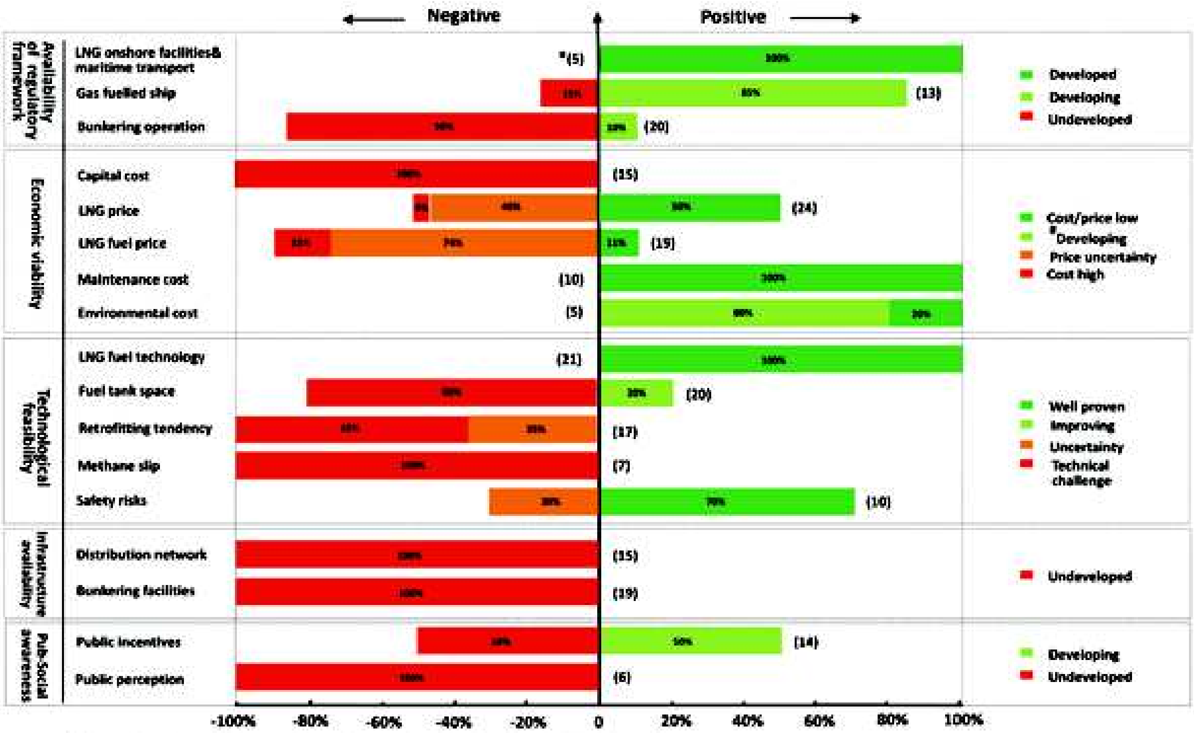
In the Netherlands a strong initiative is taken by the inland ship owners to look for LNG as fuel alternative. This is heavily supported by the Harbour of Rotterdam in order to meet its exhaust goals for 2020. (in dutch) http://www.deenshipping.com/nl_NL/nieuws.html/nieuwsbericht/29

In a recent study Wang et al. (2014) showed the pitfalls in regulatory issues to use LNG as fuel for both sea going as well as inland vessel. There is no international rule recognising that LNG can be used as a marine fuel, apart from the IGC code which allows LNG carriers to use boil-off gas as a part of the ship's propulsion. In order to fill this gap, the IMO has started to draft the international code of safety for ships using gases or other low flashpoint fuels (IGF code) which will cover safety and operational issues for gas-fuelled seagoing vessels. The code is expected to be finalised by 2014. In addition, the lack of a set of comprehensive LNG bunkering regulations is one of the key barriers to the new application. So far, no international standards have been established which incorporate minimum requirements for the bunkering procedures, training and equipment necessary to ensure safe LNG handling for gas-fuelled ships via both shore-based and ship-to-ship bunkering operations".

The ISO is working on/issued a first draft of such international guidelines for harmonising LNG bunkering standards.

Other hindrances are related to the use of LNG on inland vessels in Europe. In line with the relevant European agreement concerning inland shipping e.g. the international carriage of dangerous goods by inland waterways (ADN) and the Rhine vessel inspection regulations (RVIR); the regimes prohibit the installation on inland ships of combustion engines that use a fuel with a flashpoint below 55degC. This means LNG is restricted to be used as a fuel since its flashpoint is -180degC. To close this regulatory gap, the EU authority has started to establish a specific permit process for LNG-powered inland vessels and later may develop appendices under the existing regulatory framework. (http://www.porttechnology.org/images/uploads/technical_papers/LNG_LR.pdf). A conclusion from their study is that one can see that LNG as a clear clean fuel can reach all environmental targets without any abatement technology. However, the current lack of bunkering infrastructure and operation standards imply that the use of LNG as a ship fuel is expected to first gain momentum in niche markets, like small ferry routes and regional liner traffic. In the longer run (perhaps from 2020) the adoption of LNG as a ship fuel on a global scale rests on three main factors: the price difference between LNG and low sulphur fuel oil; the global emission regulations e.g. the global SOx limits enforced in 2020 or 2025; the availability of LNG bunkering facilities in a global context.

For sea-going vessel, Kim et al. (2013) have conducted a study for structural development of LNG as fueled in a large container ship. There is a growing interest in the appearance of LNG fueled large commercial ship with rising oil price and stronger emission regulation of these days. Though small or middle size LNG fueled vessels have been already operated, the application of LNG fuel to large commercial vessels is now under development. The report describes engineering works such as structural analysis, crack propagation & leakage analysis and temperature distribution analysis for the application of ACT-iB (Aluminum Cargo Tank Independent type B) to LNG fueled vessel. From this development, it was concluded that LNG fueled technologies are ready to large container ship application in structural point of view. However, the engineering works are limited to the design safety construction of LNG tank without risk of collision. The specific research in collision issue for LNG tanks is needed in the future.



Notes: * *the number in parenthesis means the number of studies where the relevant issue is discussed*

Environmental cost is not yet established now except in Norway, but some studies expect that environmental cost will be developed in the future which can make LNG fuel more attractive

Figure 10. Positive and negative factors in the adoption of LNG as a ship fuel. The percentages refer to the share on a total of 33 studies.

5. SAFETY AND DESIGN SPECIAL APPLICATIONS

5.1 Floating LNG, FLNG, FSRU

Chen et al. (2013) reported the analysis of advanced hydrodynamic of FLNG terminals. They consist of the complex interaction of multiple bodies and the coupling effect of seakeeping (wave diffraction and radiation around bodies) and sloshing (liquid motions in tanks). Based on the recent development to introduce the dissipation in potential flows and new formulations of boundary element method, the seakeeping analysis is enhanced to be able to make accurate predictions of gap resonances and major dynamic effect of liquid motion in tanks.

The report has presented the numerical models that BV has developed in order to properly predict the relative motions between the FLNG and LNGC during offloading by taking into account all the complex hydrodynamic phenomena. According to BV there are three focus operations, which must be examined and result in a series of advance studies for FLNG Terminals:

- Liquefaction process with regards to limited deck space and floating unit motions and acceleration (FLNG & FSRU)
- Containment system with regards to offshore conditions for continuous operation.
- LNG offloading from the FLNG to LNGC or from the FSRU to LNGC.

  Regarding the containment system, one of major issues to be addressed is the operation at all filling levels on the contrary to standard LNGC which can navigate only at low (below 10% of the height) and high filling levels (above 70% of the height) and not at partial fillings (between 10% and 70% of the height). In LNG Terminal both of FSRU or FLNG as BV experience with LNGRV that can operate at all filling levels for some given locations. Furthermore BV has issued new guidelines ([NI554], [NI564]) for sloshing assessment for LNG terminals.
- [NI554] → seakeeping analysis, CFD calculations and sloshing model test which allow to determine the design sloshing loads → on the cargo containtment system, the inner hull structure and the pump mast.
- [NI564] → two levels of strength assessment (a rule based approach and more refined approach using non-linear and dynamic FEA) → on the cargo containtment system, the inner hull structure and the pump mast.

The LNG offloading operability and reliability (FLNG to LNGC) is one of the critical point for the FLNG development.

- If FLNG is turret moored, this FLNG should be weathervaned. A heading analysis is then mandatory to determine the dominant wave heading.
- Multibody interaction with a small gap between both units may induce some unexpected motions.
- Coupling between seakeeping and liquid motions inside the tanks is to be taken into account for each unit.

In advance, Clauss et al. (2013) have presented the study about side by side LNG transfer at rough sea since the side by side LNG transfer method is limited regarding flexible pipe design. It is because of hydrodynamic characteristics of this multibody system, one key aspect is the analysis of the exciting forces and motions due to wave amplification between the ships. In the gap between the hulls, the incoming wave field is amplified and changes dramatically. Clauss et al. (2013) conducted the numerical approaches in frequency domain of investigating the gap effects. Finally suitable transfer configurations that ensure safe LNG offshore transfer up to Hs = 3 m have resulted with typically offloading scenario.

Also, Wilde et al. (2013) have addressed the major findings in terms of weather limitations, tugboat requirements and other critical aspects for the berthing and offloading operation with hydrodynamic and nautical studies for offshore LNG operations. These were based on full mission bridge simulations, model tests campaigns, time domain simulations, fast time maneuvering simulations and downtime assessments.

5.2 *Side by side or Tandem mooring?*

The choice of mooring the LNG carrier close to the FLNG is quite different from traditional mooring of FPSO and shuttle tankers. The latter can operate in tandem which gives quite some operational benefits. There is a tendency to develop a tandem cryogenic solution for offloading LNG.

Mauries et al. (2014) describe the development of an LNG Tandem Offloading System using floating cryogenic hoses. Their system is composed of a compact hose storage system on the LNG Terminal allowing to store the hoses between two offloading operations, of a connection head (hose end termination piece) to ease the deployment/retrieval of the hoses and of a storage and maintenance platform for the connection head at the aft of the LNG Terminal, also allowing to replace a hose section in offshore conditions. On the LNG Carrier side, a bow loading platform is installed to ensure hoses connection even in exposed environmental conditions.

Figure 11. Possible LNG-FLNG tandem configuration using Dynamic Positioning next to traditional side-by-side solution (Prelude) (see www.eshiptrading.com)

Zhao et al. (2013) describe the hydrodynamics of an FLNG system in tandem offloading operation. In their study, the hydrodynamic characteristics of a single point turret-moored FLNG system in tandem offloading operation are investigated by using a time-domain coupled dynamic analysis program and a set of comparative model tests. The numerical simulation model features well the hydrodynamic performance of the coupled system obtained from the experiments. The influence of distance between the two vessels on their hydrodynamic performance has been investigated. Furthermore, two different ways of connecting FLNG vessel and LNG carrier have also been comparatively studied. The numerical results show that there is significant difference at the hydrodynamic performance in the two ways of tandem offloading operations, which means that the connection between FLNG vessel and LNG carrier plays an important role. The outcome of this study would offer better understanding on the hydrodynamics of multi-bodies, which can further lead to more practical applications for the design and operation of FLNG.

5.3 Arctic

Developments of arctic LNG projects

At present there are 11 arctic LNG projects at various stages of development. Some have been put on hold, e.g. extension of Snohvit (NOR), Shtokman (RUS), others are on track or even accelerating, e.g. Pechora (RUS), Yamal (RUS), or Kitimat (CAN). Western Russian projects intend LNG export through arctic waters to European markets. Therefore there is demand for specialized arctic LNG carriers. Designs and actual vessels are already under development. With the start of shale gas production in North America, project interests have been shifted but still demand for arctic LNG shipping remains.

Oh et al. (2013) studied the safety assessment of membrane LNG carrier under ice impact. This study described the new technique of numerical analysis and safety assessment procedure for repeated ice impact. Tryaskin et al. (2012) presented the mathematical modeling of the liquid impact on the tank walls of the membrane-type LNG carrier after impact with an ice barrier. Apart from the semi-empirical methods described in the Rules of classification and construction an alternate method based on OpenFoam CFD modeling is presented. In this paper the problem of jamming of the ship hull into the heavy ice conditions is solved, that allowed to estimate the parameters of the ship stopping. The simulation of the liquid gas flow in the prismatic membrane-type LNG tank after impact with ice barrier is presented. Unfortunately no validation experiments were shown. The results of the pressure loads on the wall of the tank and flow patterns are presented.

6. CONCLUSIONS

For the safety of the transport of LNG there is a need for development of consistent regulations and LNG spillage and safety handling and protection are areas where further investigation work may also be beneficial.

Further study is required on LNG Offshore Process and systems operability of LNG. Accurate prediction and evaluations of sloshing loads at any filling levels is necessary for the safety assessment of the containments. Semi-empirical approach for 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. For the FLNG development, the LNG offloading operability and reliability (FLNG to LNGC) is one of the critical issues. The nautical aspects of side by side mooring need further investigation. Further study on the viability of tandem offloading solutions for LNG transfer should be pursued.

Implication of the new IGC code

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 to handle new innovative containment system designs.

LNG as fuel both for inland as well as seagoing vessels

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.

A new IGF code is currently under development and its implications should be studied. Also regulatory gaps e.g. in LNG bunkering should be revisited. One can see that LNG as a clear fuel can reach all environmental targets without any abatement technology. However, the current lack of bunkering infrastructure and operation standards imply that the use of LNG as a ship fuel is expected to first gain momentum in niche markets, like small ferry routes and regional liner traffic. In the longer run (perhaps from 2020) the adoption of LNG as a ship fuel on a global scale rests on three main factors: the price difference between LNG and low sulphur fuel oil; the global emission regulations e.g. the global SOx limits enforced in 2020 or 2025; the availability of LNG bunkering facilities in a global context.

In-situ measurements and inspections

Hull structures and containment inspection systems still need a connection with the operation of the vessel e.g. those used on FPSOs.

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