Leading Technology for Next Generation of LNG Carriers

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ABSTRACT

Leading edge research to support the LNG industry with emerging technologies makes the next generation of very large LNG carriers a safe reality. With the global market for LNG growing at more than three times the growth rates for oil or traditional gas markets, operators are continuously looking for efficient and safe ways for containing, transferring and transporting LNG. LNG carrier design issues and technology innovations in LNG transport have resulted in an influx of new LNG carrier contracts in the last two years. The advanced technology can permit the approval of new LNG designs for a 40-year fatigue life, partial loading and strength assessment of the insulation in membrane type containment systems that have been a key issues in LNG technology.

Sloshing is of particular importance as the membrane-type containment systems must be designed to withstand dynamic loads and sloshing pressure of the LNG when the tank is partially filled. This research has allowed owners, builders and designers to move forward in a safe yet commercially viable way as designers develop the next generation of LNG carriers that exceed 200,000m³.

Advancing industry knowledge drives to the other key technical areas such as a new concept of tank design, vibration analysis and fatigue assessment of containment system. Through an overview of recent projects currently being undertaken collaborating with industries, the most critical areas in LNG technology are presented for development of the next generation of large LNG carrier and offshore LNG terminal.

KEY WORDS: composite scale law, insulation system, LNG carrier, LNG terminal, sloshing

INTRODUCTION

Leading edge research to support the LNG industry with emerging technologies makes the next generation of very large LNG carriers a safe reality. With the global market for LNG growing at more than three times the growth rates for oil or traditional gas markets, operators are continuously looking for efficient and safe ways for containing, transferring and transporting LNG. ABS has over 50 years of experience classing LNG carriers and has the distinctive approach to have classed large LNG carriers built with all types of currently accepted containment systems. And it continues to facilitate industry innovation by providing technical guidelines for new LNG containment concepts.

LNG carrier design issues and technology innovations in LNG transport has resulted in an influx of new LNG carrier class contracts in the last two years. Advanced technology permits the approval of new LNG designs for a 40-year fatigue life, vibration analysis and strength assessment of LNG insulation systems, alternative propulsion system, and new concept of the cargo tank configuration.

Sloshing is of particular importance, as the membrane-type containment systems must be designed to withstand dynamic loads and sloshing pressure of the LNG when the tank is partially filled. This research has allowed owners, builders and designers to move forward in a safe yet commercially viable way as designers develop the next generation of LNG carriers that exceed 200,000m³.

A review of technology development currently being undertaken by ABS has practical and timely application for operators considering orders for next generation of LNG carriers follows.

STRENGTH CRITERIA OF INSULATION SYSTEM

The strength of LNG insulation system can be characterized as the maximum load that the system can sustain before it fails.

Fig.1 LNG Carrier
The load on the insulation system is due to the sloshing motion of liquid in the LNG tank. Since the sloshing load is a short duration impact load, the impact strength tests have been performed to evaluate the strength and failure mode of the insulation system.

The sloshing model test and extensive numerical simulation have been performed to identify the critical sloshing load during the lifetime period of the LNG carrier. However, the calculated and measured sloshing load is usually given in terms of impact pressure on a rigid wall that is highly localized in space and time. On the other hand the impact strength is measured from the full-scale impact test where the actual non-rigid insulation system is used.

The tank inner skin in the LNG tank is covered by insulation system that consists of the thin metal membranes for the containment of liquid cargo, insulation material to maintain the temperature of the cargo in the cryogenic condition. Besides the steel hull structure, all other structural members are flexible. As a result, more active fluid-structure interaction is expected because the insulation system consists of more flexible materials such as plywood and polymer foams. The failure mode of the insulation system is also quite different from the hull structures.

The impact pressure from the sloshing analysis and model test cannot be directly used for the strength assessment of insulation system without considering the combined effect of the following phenomena:

- Gas trapping and cushioning effect during the impact
- Compressibility of Liquid
- Liquid-structure interaction (hydroelasticity)
- Structural damping of the insulation system (viscoelasticity)

A number of impact strength tests have been performed to address the impact strength of the insulation system. None of them was successful to draw the final conclusion on the strength of the insulation system with the full account of the above issues yet. More rational analysis tool and procedure are necessary to assimilate the impact test results to find the correct correlation between the impact load from the sloshing model test and the impact strength of the insulation system from the impact strength test.
The analysis procedure consists of the following steps as shown in Fig. 3:

- Identification of the spatial and temporal pattern of the impact pressure at the moment of the critical sloshing load on the rigid tank wall
- Impact test for hydroelastic effect due to fluid-structure interaction
- Impact test for dynamic response of the structure and failure mode
- Validation of the hydroelastic and dynamic structural analysis schemes from the comparison with impact tests
- Evaluation of the resultant sloshing impact load on the insulation system with the full account of fluid-structure interaction and dynamic structural response
- Final assessment of the impact strength and the factor of safety of the insulation system

**Sloshing Numerical Simulation and Model Test**

**Numerical Simulation**

Once the wave condition and tank motions are selected based on the environmental condition and seakeeping behavior of the LNG carrier, numerical simulation of the sloshing motion is performed to evaluate the maximum sloshing load. The numerical results from the simulation can also be utilized to narrow down the number of test conditions for model test.

A finite-element code, SLOFE, computes the impact pressure on the rigid tank wall in time domain. The method is based on the stream-function theory and Hamilton’s principle. The impact pressure is calculated by solving a boundary value problem for the impulsive pressure to capture the impact pressure more accurately.

**Model Test**

Model tests are performed to evaluate the maximum sloshing load on a typical LNG carrier of 138,000 m³ capacity at partial filling conditions. The carrier has four LNG tanks. The No. 1 tank at the bow area has smaller size than the other three tanks, which are in similar size. Based on the local motion response at each tank center, No. 2 tank is selected for the model test. For each selected sea states, the tank is excited for 5 hours in full-scale time.

![Fig. 5 Sloshing test rig at MARINTEK](image)

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![Fig. 6 Extreme value (3 hr) of impact pressure on LNG tank for different filling levels. Full-scale value based on Euler scaling is given.](image)

Fig. 6 Extreme value (3 hr) of impact pressure on LNG tank for different filling levels. Full-scale value based on Euler scaling is given.
The statistics of the pressure peaks measured during the 5 hours (in full scale) of model test are used to estimate the extreme value of the impact pressure during 3 hours for each filling levels. Fig. 6 shows the estimated maximum impact pressure at each filling levels. The pressure values are given in full-scale value following the Euler scale, where pressure magnitude is proportional to the length of the tank and density of liquid cargo. In this scale law, the impacts are assumed to be hydrodynamic impact and no effects from compressibility of liquid and air are considered. During the model test, large amount of air bubble has been observed whenever the liquid hit the tank corners where the pressure maximum occurs. This indicates that the Euler scale may not be appropriate to evaluate the impact pressure in the full-scale LNG tank. In the scale law for compressible fluid, pressure is proportional to the square root of the tank length. As a result, the pressure value given in Fig. 6 may be overly conservative to be used for the structural assessment of the containment system.

**Composite Scale Law**

The validity of the existing two scale laws are investigated by inspecting the time history of the impact pressure signal measured during the model tests. It has been found that both the incompressible (hydrodynamic) and compressible (cushioned) impacts occur randomly during the sloshing simulation. If the only incompressible scale law were applied, the estimated full-scale pressure would be overly conservative. On the other hand, if the compressible scale law is used, one may end up non-conservative conclusion on the safety of the containment system.

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**Dynamic Material Property**

Some insulation systems, such as the GTT Mark III system, use polymer materials as the insulator. It has been known that the strain-stress relation and yield stress of the polymer materials depends on the time rate of the strain. The plywood in the NO 96 system may also have strain-rate dependency when the duration of the impact load is extremely short. The linear elastic and damping model may not be adequate for these cases. More detailed visco-elastic and/or visco-plastic properties of the polymer materials may be necessary. Experimental testing on these dynamic material properties of the polymer material and plywood is planned and under progress. The dynamic structural response numerical model is implemented from the experimental results.

This experiment was conducted at University of Illinois using the split Hopkinson pressure bar (SHPB) technique in which the polymeric specimen is sandwiched between two metal bars, one of which is impacted by a striker projectile from a gas gun. Also, embedded piezo-electric X-cut quartz crystals are used in place of surface mounted strain gauges. The schematic of SHPB is shown in Fig. 9. The polymer and plywood materials are tested over a range of strain rates in order to obtain valid dynamic stress-strain curves for high rate dynamic elastic modulus.

**Impact Strength Assessment**

From impact strength test as shown Figure 10, 11 and 12, the fluid-structure interaction and dynamic structural response have been investigated and numerically simulated for the calibration of ABS DYNA program including dynamic material properties. Another very important information from the impact test is to define the dynamic failure mode of each insulation system, which is different to the critical failure case based on the static loading. A number of joint development projects are performed to define the dynamic strength and failure mode including the following drop tests.

**Fig. 9 Schematic of the SHPB Used in the Dynamic Material Property Test**
A water drop test of Mark III system by SHI in Fig. 12 finds the hydroelasticity, corrugation membrane cushioning, structural damping and the strength of insulation system. A numerical calibration for hydroelastic effect is followed for comparison with experimental measurement.

**Insulation System Vibration Analysis**

Slow or medium speed diesel propulsion systems have been selected to power the large LNG carriers. A technical concern that this switch from steam to diesel propulsion has given rise to is the local plate vibration effect on insulation. Most LNG carriers have a design speed between 19.5 and 21 knots. It is expected that the new generation of large ships will be designed for the same speeds. This, of course, will require an increase in propulsion horsepower. The need to move to more efficient internal dual fuel combustion engines with diesel electric propulsion or a combination of one or more slow speed engines with a re-liquefaction plant is proven technology but has not yet been incorporated on a large LNG carrier in service. Given the expected future use of these systems, the issue of vibration associated with their operation must be examined to ensure that resonance frequencies are avoided during operations.

First of its kind vibration research is being conducted by ABS in a cooperative program with Hyundai Heavy Industries, Korea. The purpose of the study is to observe any vibratory influence from the propulsion to the containment systems. More specifically, the study in process is focusing on the insulation system and the mastic attachment between the inner hull plating and plywood back layer.

The study is addressing the question of what effect vibration has on the containment insulation material such as plywood, foam or material like epoxy resin.

Diesel engine vibration on membrane systems, particularly in terms of structural resonance interacting with membrane resonance, is an important factor in operational safety. Researchers are determining if the vibration can be expected to damage the containment system by studying the global and local vibration levels on selected locations inside the adjacent cargo hold of the engine room.

The stress levels in the containment system at plywood, foam and mastics have been determined to verify the adequacy of the containment system. The natural frequency of the insulation system has been investigated for the potential resonance due to the excitation induced by the engine and fluctuating propeller forces. Data generated from this study is the most advanced look at the subject of engine vibration on a LNG carrier’s containment insulation.

**New Tank Configuration Design AIP**

ABS is currently working with energy major ConocoPhillips (COP) to provide an Approval In Principle (AIP) for COP’s proprietary Prism/Pyramid Tank concept for large LNG carriers. Engineers from ABS Technology have been actively involved with the model testing program for this concept which is being carried out by one of the leading hydrodynamic laboratories in the world, Marine Technology Research Institute (Marintek) in Norway.

The impact pressure due to sloshing motion in the cryogenic liquid cargo tanks is one of the most critical load factors when designing containment systems for LNG carriers. The magnitude, effective area and duration of the impact load are all important when considering structural response of the containment system. It is also important to examine the spatial and temporal pattern of the impact load in concert with structural response. In conjunction with the model tests, ABS developed numerical modeling techniques which were used to examine the sloshing impact load to gauge structure response in these novel tanks.

One feature of the unique tank shape is that the design reduces free surface area thus reducing the high impact sloshing loads and resonance period in the tank. With the Prism/Pyramid Tank Design, ConocoPhillips tested a four tank scenario for an LNG vessel with 235,000m$^3$. This compares to vessel designs for this size which usually call for five or six tanks. Comparison and pressure tests were conducted to see if the design was acceptable. The critical ship motion response and sloshing impact conditions were calculated at North Atlantic environment conditions.

The tank design was tested simulating irregular wave conditions and with three different filling levels for the tanks and various ship headings. The test results have so far shown that the loads on the COP Prism/Pyramid Tank for the large LNG carrier are equal to or less than those experienced on a traditionally designed 138,000m$^3$ ship.

ABS has analyzed the sloshing effect on the tank membrane with proprietary numerical simulation tools. These two-dimensional (2-D) and three-dimensional (3-D) programs apply North Atlantic wave database information to conduct a direct simulation on a particular LNG vessel. These programs perform complex calculations that predict the dynamic and sloshing pressures acting on the membrane tanks in a seaway.

Currently, the ConocoPhillips Prism/Pyramid Tank Design has move forward in the process from sloshing analysis studies to undergoing the ABS AIP process. This process draws upon engineering, testing and risk assessments in order to determine if the concept provides acceptable levels of safety in line with current offshore and marine industry practice. The methodology relies heavily on risk assessment techniques as a way to better understand and anticipate structural and
operational issues related to a new or novel concept. ABS is evaluating the overall tank design including an assessment of the tank containment system to the requirements of ABS Rules and the IGC Code a structural strength feasibility study and an analysis of the tank support system.

Throughout the year ABS has been involved in and issued other AIP design reviews of new tank and vessel designs developed by other operators and manufacturers that have been proposed for the efficient and safe handling of the expected increased loads to which the significantly larger LNG carriers will be subject. The larger LNG carriers have increased in size nearly 40 percent over previous designs and there is every indication that this trend in size increase will continue.

CONCLUSIONS

Classification societies role has changed to become a key play in enabling LNG designers and operators to meet the growing demand for LNG by creating new technical standards to keep pace with the unique demands of the new generation of LNG vessels.

Safety is the critical issue that must be considered as industries consider a new generation of very large LNG carriers. This transition requires a comprehensive approach toward the handling of LNG, a fully integrated approach that considers production, storage, transportation, discharge and regasification. Although the basic technology for handling and transporting LNG is well established according to the successful past 50 years’ industry experience, these new innovations have posed the significant technical challenges that ABS and other classification societies are meeting through the advanced research and close cooperation with industry.

REFERENCES
