PARTIAL FILLING OF MEMBRANE TYPE LNG CARRIERS

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ABSTRACT

Present paper summarises the state of the art of Bureau Veritas sloshing assessment of membrane type LNG vessels. Overall methodology is presented and applicability demonstrated on practical example of LNG Carrier with Regasification (LNG RV), the first vessel operating in partial filling conditions, classed by Bureau Veritas. Feasibility of partial fillings is demonstrated respecting aspects of both, containment system and double-hull structure resistance to the sloshing impact loads.

1. INTRODUCTION

The present environmental consciousness and awareness of the reduced long-term availability of petrol have given the emphasis on natural gas as a primary energy source. After a period of steady expansion, the LNG market to date is in phase of rapid growth, reflecting with important developments in Floating Production and Storage installations and LNG transportation concepts.

Preference for offshore on-loading and off-loading based on safety considerations accompanied by trends of small-spots trading, initiates the requirement for partial filling operation which relies on conventional LNG Carrier sizes. Application of membrane containment systems with ensured safety margin in range of conventional fillings is reconsidered with new issue of partial fillings.

Figure 1.1: BV Class membrane LNG Carriers and GTT containment systems (courtesy of GTT)
The EXMAR LNG RV (Liquefied Natural Gas Regasification Vessel) is a new class of product transportation vessels, being the first vessel operating in partial filling conditions, classed by Bureau Veritas. This special-fitted LNG Carrier based on standard DSME 138 000 m³ project, is designed for services in world-wide navigation together with turret-moored operation on the off-loading site (Figure 1.2). LNG RV connects to a terminal pipeline through an offshore buoy and internal turret system, regasifying LNG aboard the ship and discharging vaporized LNG through the buoy into sub-sea pipeline system.

Since late 2000, following the EXMAR's demand for the assessment of viable LNG off-shore discharging operation, Bureau Veritas provided overall technical support and assistance in extensive studies dedicated to the partial fillings operation of this particular LNG concept. Combination of continuous external and internal loads on partly filled vessels exposed to the rough weather may result in severe sloshing loads on the containment system and supporting structure. Operation complexity implies a variety of parameters to be considered in sloshing studies. Starting from selection of criteria for relevant cases based on a deductive approach, followed by advanced hydrodynamic computations, CFD sloshing simulations and FEM analyses, the feasibility of partial fillings is demonstrated on LNG RV vessels equipped with the GT NO96 containment system.

2. **OVERALL METHODOLOGY**

Industrial importance of vessels operating liquefied gas governs the basic concerns of Bureau Veritas. The Bureau Veritas methodology for sloshing assessment is the result of more than a quarter of a century of research and development which chronology and historical aspects are reminded hereafter.

During the seventies, many LNG carriers were built and some damages due to sloshing occurred. At that time, Bureau Veritas started to develop tools and methodology to study the damage cases to explain and fix the problems. Bureau Veritas contributed also within the Swedish Ship Research Foundation, in the 70's, in cooperation with Det norske Veritas and Lloyd's Register of Shipping [13] and SouthWest Research Institute [12].

At the end of the 80's, The Japanese yards performed many studies in cooperation with Bureau Veritas in order to develop their LNG carriers, using the Mark III containment system. At that time, the involvement of Bureau Veritas resulted in publishing a Guidance Note on “Partial Filling Study” in 1984 [10].

Another important technical breakthrough resulted from our contribution of the “AZURE” project at the end of the 90’s. AZURE consisted in the development of a “Full LNG Floating Chain”, including LNG-FPSO and FSRU. The project was led by Bouygues Offshore, partially funded by the European Community, and sponsored by major operators (CONOCO, ELF, CHEVRON, SHELL, TEXACO).

In AZURE, Bureau Veritas, together with GTT, Technigaz and IRCN [1], was in charge of developing the procedures for the sloshing assessment with partial fillings, which resulted in the initial version of the methodology outlined in this paper.
The overall methodology presented on Figure 2.1 comprises a complex set of methods, tools and information incorporated in basic principles of Bureau Veritas procedure of qualification of containment system and verification of double-hull scantlings.

All the steps of this methodology will be further detailed and discussed in the paper.

Finally, it should be highlighted that the current methodology is essentially a comparative one, since it relies on the very large return experience. As such, it allows evaluating the safety margin for vessels and operational conditions that stay within the current range of sizes and orders of magnitude of the dimensioning parameters. To fulfil this requirement, the limited knowledge of the real physical models is compensated by conservative assumptions, such as:

- the model tests pressures address rigid walls, whereas in reality an elastic behaviour is expected from the insulation system,
- real operating conditions are not expected to be as severe as the design one.

The above is largely confirmed by an excellent track record of the safety of the LNG fleet over the past decades.

To tackle the step changes toward the future Ultra Large LNG Vessels, current R&D aims at improving the existing physical models for hydro-elastic impacts and coupling effects. The variety of aspects considered in hydroelastic analysis of sloshing impact problem is illustrated on Figure 2.2.
3. BASIC CONSIDERATIONS

Basic considerations in general sloshing analysis are given to a selection of configurations to be studied, with respect to the following parameters:

- Type, size and capacity of the vessel,
- Service speed,
- Mooring type in the terminal operation,
- Vessel loading plan and service definition,
- General tank arrangement,
- Tank geometry and proportions,
- Tank filling levels with reference to loading plan,
- Environmental conditions with reference to service definition.

The definition of parameters considered in sloshing studies is specific for each particular project and will refer to design concept specified and provided by the designer.

Configuration of sloshing analysis test cases can be derived based on the experience from the past studies and proposed by designers or technical consultants in confirmation with classification societies according to the specific sloshing assessment procedure.

4. TEST CASES

The first stage of liquid motion analysis is the selection of an initial test cases list, aimed to benchmark the amount and type of studies to be performed. Initial selection is based on the first review of the design concept with respect to ship general arrangement, service specification and loading plan.

Aimed to define governing cases, basic considerations are given to determine the following parameters:

- Number and location of representative tanks,
- Relevant filling levels,
- Type and nature of the fluid flow inside tanks.

Initial test cases list is further developed into the test specification with respect to the subsequent analysis of ship and tank motion interaction.

4.1 Selection of Studied Tank

Primary tank selection for the sloshing study is governed by the criteria of the largest capacity being the most solicited on-board the vessel. Tank N°2 is representative from the common practice of ship general arrangement; however, other tanks might be considered according to the particular arrangement or specific shape.

4.2 Tank Fillings

Generally, selection of filling levels to be studied is based on the return experience from the sloshing studies and LNG vessels in operation in confirmation with requirements of classification societies and containment system designer.

Standard Filling Levels are considered within conventional intervals:

- From 70% of tank height to 98% of tank volume,
- From 0% to 10% of tank length.
Selection of relevant Partial Filling Levels is particular for each project, related to the service specification, tank geometry, size and proportion of main tank dimensions. Specification of partial filling levels results from the investigation of liquid flow types that are likely to be induced during the vessel's operation.

### 4.3 Liquid Flow Types

Liquid flow types may be roughly classified in several categories according to the observation of different phenomena, starting with one degree of freedom harmonic excitation and inducing two-dimensional flow by means of either sloshing small-scale model tests or CFD simulations.

In case of very moderate excitation, free surface remains flat moving in a succession of static-equilibrium states. Contrary, when the excitation velocity increases, two quite different kinds of fluid flows will appear according to the filling rate and tank proportions.

For the shallow filling depth, hydraulic bores and travelling waves appear moving back and forth between tank walls, also likely to entrap gas when front braking (Figure 4.3.1).

In the non-shallow liquid case, as observed for the liquid depth to length ratio higher than about 0.30, a standing wave appears moving upwards and downwards with one or two nodes depending on excitation period (Figure 4.3.2).

Sloshing represents violent fluid motion with strongly non-linear phenomena, even when tank being excited regularly. Furthermore, number of degrees of freedom included in excitation function will lead to three-dimensional flows causing breaking, spraying and swirling, impacting tank boundaries in oblique sense.

### 4.4 Conditions for Liquid Motion Analysis

Since sloshing is a typical resonance phenomenon [14,15] occurring when the ship motion contains energy in the vicinity of the highest tank natural period, the common sense through the past indicated Resonance Condition as a case of the prime interest to be studied.

Apart of the liquid motion characteristics, each vessel is designed to sustain extreme environmental conditions during its service. Consequently to the consideration of vessel design conditions, Maximum Motion Condition became additional criteria in sloshing studies, even if not necessarily inducing the most severe sloshing effect.

With respect to the non-linear three-dimensional flows that may occur in oblique seas, it appears that screening for Intermediate Oblique Condition, coinciding neither with resonance state nor with maximum solicitation, might be reasonable extension. However, it is to be noted that such an intermediate condition can not be identified straight forward from the results of hydrodynamic analysis: non-linear effect of tank fluid motion can be qualified only through the model tests and CFD simulation, confirming each other.

In practical case, a vessel exposed to irregular sea conditions will response randomly. This implies that in reality resonance condition is not likely to occur: since the tank natural period is one among all contained in the motion time history, they will rarely coincide. If it does, it will last for a short time.
segment. One of the guiding parameters in Irregular Condition approach is selection of valuable test duration that will fairly represent one steady sea-state condition and, in the same time, assure the results convergence.

Finally, when approaching the most realistic conditions for partial fillings studies, the coupling effects between vessel motion and tank liquid motion become the essential issue. Dynamic coupling phenomena are well-known and already witnessed on practical examples of anti-rolling free-surface tanks. It is obvious that consideration of Coupling Condition shall result in improvement of design procedure of the tanks on-board partly filled vessels.

5. SLOSHING EXCITATION

Hydrodynamic analysis is a key point in each particular sloshing study, with an objective to determine Sloshing Excitation. Directly calculated ship motion determined by such analysis are used to generate tank liquid response. Main criteria for determination of sloshing excitation concern all items elaborated before i.e. loading conditions, filling levels, liquid flow types and conditions for sloshing analysis.

5.1 Environmental Conditions

Environmental conditions for sloshing analysis of sailing ship are considered only through the description of wave data corresponding to the service specification. Wind and current contributions on the 1st order ship response are not accounted for, as they only influence the mean position of the vessel.

Environmental conditions considered in sloshing analysis correspond to one of following:

- North Atlantic wave scatter diagram IACS Res. 34 for world wide navigation,
- Directional wave scatter diagrams of all areas on expected routes (if required and specified).

In both cases, maximum wave scatter-diagram envelope will be considered (representing the maximum significant wave height associated with each wave period) and compared to:

- 40-years return period envelope (for 40-years ship life-time operation),
- 1-year return period envelope (for failure conditions).

Sea states from scatter diagram are modelled by spectral density function i.e. wave spectrum, presenting a distribution of wave energy per wave frequency. Pierson-Moskowitz spectrum formulation (derived from the North Atlantic observations) is applied for fully developed seas, whilst JONSWAP spectrum (resulted from measurement campaigns on North Sea) is applied for seas with limited fetch.

5.2 Vessel Motion Analysis

Ship motion analysis is aimed to determine 6 d.o.f. motion as a ship's response to the imposed environmental condition by means of hydrodynamic computation or by exploitation of basin model tests results.

Bureau Veritas hydrodynamic computations are performed by means of 3D-panel diffraction/radiation potential theory [6,7] using advanced in-house software HydoSTAR®, fully validated through the comparisons with semi-analytical studies, numerical results from recognized numerical tools and experimental results.

Developed by Bureau Veritas, HydoSTAR® is a powerful software using efficient and most-advanced algorithms, designed to enhance technical excellence and productivity. HydoSTAR® is constantly improved by integrating the most recent theories and powerful algorithms.
Following general considerations are taken into account for the hydrodynamic modelling:

- Ship hull form: providing under-water hull shape,
- Loading conditions: providing draught, hydrostatic and mass-inertia properties,
- Ship speeds & headings: providing a ship service benchmark.

One of the most advanced features in Bureau Veritas hydrodynamic analysis is related to the dynamic coupling between ship and tank liquid motion \([2,3]\). Dynamic influence of partly filled tanks is clearly demonstrated on roll RAO, as obtained by linear coupling module developed within HydroSTAR\(^\text{®}\) \((\text{Figure } 5.2.1)\). Direct non-linear coupling in time-domain between HydroSTAR\(^\text{®}\) (linear potential theory for sea-keeping) and FLOW-3D\(^\text{®}\) (CFD Navier-Stokes solver for sloshing) is important step forward in correct modelling of the sloshing phenomena in partly filled LNG tanks \((\text{Figure } 5.2.2)\).

Hydrodynamic model used in common practice is developed out of ship lines-plan or ship offsets, presenting a shape of buoyant volume by flat quadrilateral or triangular panels \((\text{Figure } 5.2.3)\). Hydrodynamic model accounting for coupling effects due to the interaction of vessel motion and tank liquid motion is composed of ship hull and tank 3D-panel meshes as presented with example of standard 138 000 m\(^3\) 4-Tank LNG Carrier \((\text{Figure } 5.2.4)\).

5.3 Sea-States Selection

Bureau Veritas sloshing assessment procedure recommends the introduction of response-based sea-states, to avoid penalisation of ship scantlings when accounting for non-realistic operation conditions. Limitation of extreme motions is performed through the procedure of wave height limitation based on selected relevant operability parameters (as roll angle and acceleration components) according to Bureau Veritas Rules recommendation. Other dominant parameters used in estimation of ship’s operability may be verified within a list of ship’s responses such as shear force, vertical bending moment, tank reactions (forces and moments), etc.

Wave height limitation is not neglecting occurrence of extreme sea-states but compensating for not operable ship conditions. Some particular combinations of ship speed and headings (e.g. navigation
on extreme head waves with maximum service speed) can result with extreme solicitations that are untenable, therefore not representative as a sloshing design condition. However, on the particular demand, environmental conditions will be considered without any limitation i.e. taking sea-states from maximum or 40-years scatter diagram wave-height envelope.

5.4 Determination of Sloshing Excitation

Sloshing excitation presents the ship response on selected sea-states that can be further imposed to either small-scale model test or numerical tank. All aspects of motion types and natures are considered in procedure of determination of sloshing excitation and are determined for each studied tank filling.

Sloshing excitation includes all 6 d.o.f motion and can be expressed in following forms:

- **Harmonic Excitation**: determined by means of spectral analysis, whereby each of 6 d.o.f. motion is described by amplitude on 1/10th level, zero-crossing period and phase.
- **Random Excitation**: specified for the same sea-state, as it would be selected for harmonic excitation. Frequency domain results are transformed in 6 d.o.f. motion time-histories in 3-hours duration that represents a steady sea-state.

6. LIQUID MOTION ANALYSIS

The liquid motion analysis is based on previously specified test cases, analysis of the ship and tank motion interaction and sloshing excitation obtained by hydrodynamic analysis.

Two types of liquid motion analysis are carried out:

- Small-scale model tests, usually by the containment system designer, or by an independent laboratory,
- Numerical simulations, using validated CFD tools: they can be performed by the containment system designer or by Bureau Veritas.

6.1 Sloshing Model Tests

Sloshing small-scale model tests are standard part of Bureau Veritas comprehensive sloshing assessment. Model tests facilities, test program, methodology, procedure and results have to be submitted to Bureau Veritas for review and approval.

As a general statement, sloshing model tests should be driven by 6 d.o.f. motion generator to describe realistic ship motion, hence realistic fluid flow inside tanks. Model tests carried out exclusively along the direction of main tank axes (longitudinal or transverse) should not be considered representative to comprehend the most critical sloshing phenomena.

Due consideration is given to the following relevant model test features and parameters, including:

- Model test facility features: model scale, tank model material, location and specification of pressure sensors, test liquid characteristics, ullage effects, degrees of freedom and capacity of motion generator, data acquisition system,
- Selection of relevant tank fillings,
- Selection of representative test cases: type and nature of liquid flow expected to be induced, specification of forced excitation associated to the selected tank fillings,
- Description of data analysis: filtering and statistical post-treatment of the measured data,
- Model test results: pressure time-history, maximum measured and statistical values of model scale impact pressures, impact location and sample size,
- Scaling laws applied for evaluation of full-scale impact pressures with justification and calibration.
Sloshing model tests campaign for LNG RV partial fillings study was performed in GTT model test facility [21] using 1/70th scale Tank N°2 model (Figure 6.1.1). Beside the initial selection of analysed filling levels (Figure 6.1.2), intermediate fillings between 10%H and 70%H were tested for the additional verification.

<table>
<thead>
<tr>
<th>SELECTED FILLING RATIO</th>
<th>FLOW TYPE</th>
<th>BACKGROUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% H</td>
<td>Interaction with ceiling</td>
<td>Corresponding to the damage of reference tank (Larbi Ben M’Hidi)</td>
</tr>
<tr>
<td>90% H</td>
<td>Experience of the most interactions with ceiling in tank design with large chamfers</td>
<td></td>
</tr>
<tr>
<td>80% H</td>
<td>Standing wave, Interaction with ceiling</td>
<td>Standard filling height limitation, Reference for acceptable filling level</td>
</tr>
<tr>
<td>70% H</td>
<td>Lower corner of upper chamfer, discontinuity of cross-section geometry, Extended upper filling height limitation</td>
<td></td>
</tr>
<tr>
<td>60% H</td>
<td>Standing wave</td>
<td>Critical partial filling height zone for extension of acceptable filling levels</td>
</tr>
<tr>
<td>50% H</td>
<td>Standing wave</td>
<td>Maximum progressive wave</td>
</tr>
<tr>
<td>30% H</td>
<td>Progressive wave</td>
<td>Reference for acceptable filling level</td>
</tr>
<tr>
<td>20% H</td>
<td>Progressive wave</td>
<td></td>
</tr>
<tr>
<td>10% H</td>
<td>Progressive wave</td>
<td></td>
</tr>
</tbody>
</table>

Results of the pressure measurements are statistically post-treated to obtain exceedance probability distributions of pressure peaks.

Weighted statistical pressures obtained in partial fillings study are presented on Figure 6.1.3 for six generic tank locations and three orientations of induced flow corresponding to head sea, beam sea and oblique sea conditions. It can be observed that oblique seas are particularly relevant with regard to the pressure levels.
6.2 Sloshing Numerical Simulation

Bureau Veritas carries out its own independent numerical simulations for the review of the model tests, submitted by the designer, and for the structural assessment.

The use of CFD simulations is essential for the assessment of the strength of both the containment system and the supporting hull structure. Indeed, the pressures measured by the small scale sloshing model tests can not be used as an input parameter in the physical model of the sloshing impact, which is essentially of hydro-elastic nature. Conversely, CFD calculations yield a realistic representation of the kinematics of the fluid flows, including the local speeds before impact. The latter being the essential input parameter of the available physical models for the hydro-elastic impacts.

In case of sloshing model tests employing 4 d.o.f. or less, numerical simulations allow additional verification for the 6 d.o.f. realistic cases.

In CFD software, such as DIVA-3D used by GTT or FLOW-3D® [8] currently used by BV, free surfaces are modelled by Volume of Fluid (VOF) technique, with three principal features: a scheme to locate the surface, an algorithm to track the surface moving through the computational grid and means of applying boundary conditions at the surface. Each cell of VOF mesh is filled either with liquid or gas; if there is a presence of the free surface, cell is defined by the corresponding fraction of fluid as the filling rate of the cell by the liquid phase.

FLOW-3D® incorporates a special technique, known as the FAVOR™ (Fractional Area Volume Obstacle Representation) method, which is used to define general geometric regions within the rectangular grid. For the inclined walls of membrane tanks chamfers, correction factors are introduced into discretization equations in order to take into account actual fluid/gas volume cut by the boundary plane.

Due to the fact that neither compressibility nor hydro-elasticity is taken into account by CFD software, liquid impact is quantified on the level of fluid kinematics, permitting to exploit results of impact velocity. Other important information gathered by CFD simulation is surface elevation traced during entire simulation, identification of impact events and impact jet geometry. Finally, pressures and forces of quasi-static nature (as forces on pump support tower structure or quasi-static pressure on double-hull structure) are directly calculated by CFD and provided for structural assessment.

Liquid flow and impact events can be observed through the animation. Some captured instants from FLOW-3D® animations showing different types of fluid flows for different filling rates in partial fillings study [23] are presented on Figure 6.2.1.

![Figure 6.2.1: FLOW-3D® fluid flow animations - Visualisation of impact events in partial fillings study](image)
Weighted impact velocities obtained by numerical sloshing simulation in partial fillings study are presented on Figure 6.2.2, for three orientations of induced flow corresponding to head sea, beam sea and oblique sea conditions.

**6.3 Statistical Analysis of Impact Data**

Statistical analysis is performed for post-processing of sloshing impact data, being:

- Impact pressures from sloshing model tests,
- Impact velocities from sloshing numerical simulation.

The aim of statistical analysis is to find out a distribution law that fits a recorded sample of sloshing peak pressures or computed set of peak impact velocities and evaluate possible maximum values at given probability level.

**7. MATERIAL AND MECHANICAL TESTS**

Drop tests and shock tests have been investigated several times in the past, by containment system designers and by shipyards, with the support of Bureau Veritas.

The aims of these tests were different depending on their characteristics. Some were carried out to define a relation between the pressure and the fluid velocity, other were carried out in a comparative way to determine the best insulation system regarding sloshing impacts.

The first tests were carried out after some damage was witnessed on Larbi Ben M’Hidi. Another series of test was carried out at the end of the 80’s by Japanese yards. The last tests were carried out during the AZURE project and during the development of the new membrane type CS1.

Today, drop tests or equivalent are requested by Bureau Veritas during the review of the new concept or in case of substantial modification of a containment system.

The drop tests show that the response of the insulation system is very different from one containment system to another (Figure 7.3).

Results of the drop tests performed for each particular type of containment system are mandatory to be submitted, providing the essential information for the evaluation of the following:

- Impact peak pressure,
- Impact peak duration,
- Ultimate strength of the containment system.
Drop tests ought to be carried out for different drop heights and drop incidences relative to the liquid surface, both in water and in liquid nitrogen. The principal exploitation of the drop tests is to model fluid / structure impact interaction in as much as similar conditions as on-board the ship.

Impact pressure is a complex physical phenomenon, being the function of at least containment system, incidence angle, impact velocity, impact duration, impact surface, deflection etc. Typical drop tests pressure signals recorded at one pressure gauge are presented on Figure 7.1.

![Figure 7.1: Drop test pressure time-history](image1)
![Figure 7.2: Impact pressure vs. incidence angle](image2)
![Figure 7.3: Drop test scheme for No96 and MarkIII](image3)

8. RETURN EXPERIENCE

The return of experience shows two types of damage recorded due to sloshing [16]. The first happened in 70's in the fore cofferdam bulkhead of the cargo Tank N°1 of a ship fitted with GT system. Unfortunately, the damage was not fully investigated as ship was not under Bureau Veritas class. The second happened at the end of the 70's on the ceiling of all cargo tanks of ships fitted also with GT system (Figure 8.1). As one ship of the series, Larbi Ben M'Hidi, was under Bureau Veritas class, the damage case was fully investigated, both by model test and by numerical simulation.

![Tank N°4](image4)
![Tank N°3](image5)
![Tank N°2](image6)
![Tank N°1](image7)

Figure 8.1: Observed damages on Larbi Ben M'Hidi

Model test on the tanks with small upper chamfers were performed several time after the damage occurred:
- At the end of 70's, just after the damage,
- In the 80's by NKK with Bureau Veritas support,
- End of the 90's within the AZURE project.

Navigation and sea-state conditions corresponding to the days when damage occurred were recorded and applied in both model test and numerical simulation.

The Larbi Ben M'Hidi midship section differs from other design because the main deck is flush and there is no trunk deck (Figure 8.2). Consequently, the upper chamfers are enlarged as shown on the Figure 8.3.
On a conventional LNG carrier of 138 000 m$^3$, both numerical simulation and model tests have shown that 30% H filling is the critical level with the impact on the cofferdam bulkhead. Consequently, on a 138 000 m$^3$ with large upper chamfers, the cofferdam bulkhead is the most critical location.

However, the impact on the cofferdam bulkhead is not more critical that the impact for high filling level on ship with small upper chamfers as Larbi Ben M'Hidi. The sloshing analysis have shown that in case of small upper chamfer (Larbi Ben M'Hidi design), the filling ratio giving the maximum impact pressure is about 95% H, as shown on the Figure 8.4. This figure was published in the Bureau Veritas Guidance Note for sloshing in 1984 [11], concerning model tests of Larbi Ben M'Hidi, and shows that the pressure for a filling ratio of 95% H is much higher than the pressure for 20% H.

After the damage on the Larbi Ben M'Hidi, two actions were undertaken:

- On all ships with small upper chamfer, reinforced boxes were fitted on the ceiling,
- All new design incorporated large upper chamfers and reinforced box on the ceiling.

After fitting reinforced boxes on the Larbi Ben M'Hidi and sister vessels, damage has not anymore been reported even vessel was navigating North Atlantic. According to our files, 4 vessels were built as sister vessels of Larbi Ben M'Hidi, and two of them are still in service under BV class. Two other vessels with small upper chamfers were built under an other classification society.

Consequently, the return of experience of the vessels with small upper chamfers equipped with reinforced box is at least of 25 years without any damage, despite there are still sloshing impacts occurring, including the service in North Atlantic sea conditions. It should be also noted that no damages have been reported on the hull structure on the Larbi Ben M'Hidi.
9. STRENGTH ASSESSMENT

The aim of the methodology described up till now is to obtain pressure from model tests or velocities from numerical simulations.

The challenge we are facing at this level is to have a similarity law to convert the model test pressure to the full scale pressure, or to convert the velocity from numerical simulation in safety factor for the containment system and hull structure.

9.1 General

The impact pressure due to sloshing is considered to be made up of two phases, as shown on Figure 7.3. The first phase consists of a high pressure impulse which occurs over a short time interval (in range of 1 ms) and covers a small area of the structure. The second phase consists of a hydrodynamic load with lower peak value, longer duration and larger impact area, and is called the "quasi-static pressure".

At this level, it should be noted that the pressures measured on model tests generally include a part of impact pressure and also a part of quasi static pressure. The first part of this profile last very short time, i.e. less than one millisecond. If the surface of the fluid is not completely flat, on a large surface, the peak pressure is reduced and the peak duration increases leading to similar result than the red curve on Figure 7.3.

However, the return of experience shows that it is the pressure on a small surface which has generated to the damage. For example, for No96, the peak pressure duration measured on drop tests is of about one tenth of millisecond.

Consequently, the containment system is to be assessed against both the peak pressure and pressure acting on a more extended surface, i.e. with lower peak but longer duration.

Impact pressure measurements from model tests are available and different laws for extrapolation to the full scale have been proposed [15,19,20].

Two theoretical laws are generally proposed to scale the pressure:

- Acoustic law: \( P = k \rho c V \),
- Bernoulli law: \( P = K \rho V^2 \),

In the two cases the scaling factors are:

- Acoustic law: \( s = f (r, \rho) \)
- Bernoulli law: \( s = f (r^2, \rho) \) (Froude scaling)

The application of the scaling factor based on the acoustic law on the case of Larbi Ben M'Hidi leads to the conclusion that there is no damage hence there is no need of reinforced boxes. In opposite, the application of Froude law leads to the conclusion that Larbi Ben M'Hidi is not acceptable with reinforced box, in spite of the 25 years of return experience.

The relation between pressure and velocity is \( P = K \rho V^2 \), however when the velocity reaches a high value, the relation becomes \( P = k \rho c V \). Both \( k \) and \( K \) values depend on the structure elasticity [18].

The fact that the fluid is LNG, with a viscosity, ullage pressure, surface tension, and boiling liquid effects, may also explain that no one of the two models give relevant result. The drop tests show clearly, in particular for No96 and CS1, that the relation between the pressure and the velocity is between the two laws.
In addition to the rule approach analyses of the containment system and ship structure, direct FE calculation is performed. The aim of direct FE analyses may be summarized as follows:

- Assessment of the containment system strength,
- Evaluation of the pressure peak filtration made by the containment system, in order to define the pressure which needs to be taken into account for the assessment of the ship structural strength against sloshing loads,
- Improvement of rationally based procedure for the structural and containment system strength assessment.

### 9.2 Containment System

Based on the results of both model test and numerical simulation, the reinforced box area of LNG RV has been extended compared to the conventional LNG Carrier as shown on the following Figure 9.2.1.


![Figure 9.2.1: Reinforced boxes on conventional LNGC - Additional reinforced boxes on LNG RV](image)

Based on the sloshing small-scale model test results for Larbi Ben M’Hidi, drop test results of No85 (non reinforced box of Larbi), sloshing small-scale test results of new design and drop tests of No96, the safety factor may be defined as follows:

#### Safety Factor from Model Tests:

The safety factor, based from model tests results and compared with Larbi Ben M’Hidi, is a function of the following parameters:

\[
SF = f(P_{ult1}, P_{ult3}, k_1, k_3, P_{m1}, P_{m3}, e_1, e_3)
\]

With:
- \(P_{ult1}\) = Ultimate strength of No85 containment system
- \(P_{ult3}\) = Ultimate strength of new containment system
- \(k_1\) = Coefficient of the acoustic law for No85 containment system from drop tests
- \(k_3\) = Coefficient of the acoustic law for containment system of new design from drop tests
- \(P_{m1}\) = Pressure from model test of Larbi Ben M’Hidi
- \(P_{m3}\) = Pressure from model test of new design
- \(e_1\) = Model scale of Larbi Ben M’Hidi
- \(e_3\) = Model scale of new design

#### Safety Factor from Numerical Simulation:

The safety factor, based on numerical simulation and compared with Larbi Ben M’Hidi is a function of the following parameters:

\[
SF = f(P_{ult1}, P_{ult3}, k_1, k_3, V_1, V_3)
\]

With:
- \(V_1\) = Velocity obtained from Larbi Ben M’Hidi numerical simulation
- \(V_3\) = Velocity obtained from numerical simulation of new design
9.3 Structural Reinforcement

Dynamic FE analysis show that impact peak pressures are filtered and averaged by the containment system when the impulse arrives to the structure. However, the peak pressure is taken into account by increasing the quasi static pressure.

The structure is assessed using Bureau Veritas Rule criteria against quasi static pressures obtained in the numerical simulations. Mainly the plating and the stiffeners are assessed, by application of Bureau Veritas Rule formula.

The locations candidate for structural reinforcement is shown on the Figure 9.3.1.

![Figure 9.3.1: Potential areas for structural reinforcement in partial filling operation](image)

A fatigue assessment is carried out according to Bureau Veritas Rules, using Bureau Veritas FE analysis software VeriSTAR®, taking into account loads from the numerical sloshing analysis and histogram of loading defined by the owner. Structural models for fatigue assessment, from coarse to very fine for fatigue analysis of details, are shown on the following Figure 9.3.2.

![Figure 9.3.2: Structural models for fatigue assessment](image)

From the fatigue point of view, the critical case has been identified in configuration where two adjacent cargo tanks are with the same partial filling level, particularly for the cofferdam bulkhead. Consequently, the cofferdam bulkhead is required to be reinforced.

9.4 Direct Analysis of Containment System and Hull Structure

Interaction between fluid (LNG) and structure (containment system/hull) is considered during the dynamic structural analysis, as fast dynamic problem with short impact time which duration is in range of millisecond. This means that extremely short time step is needed. The strength assessment of the insulation system needs to take into consideration dynamic material property on cryogenic temperature.
The containment system in LNG tank is composed of metal membranes, plywood laminate, polyurethane foam, resin rope and supported by steel hull structure. In order to capture stress propagation through the structure, very fine mesh should be used together with adequate time step.

Due to the violent nature of liquid motion inside the tank, different type of impact may occur. The associated impact pressure is influenced with gas trapping, fluid compressibility, hydro-elasticity and structural damping of the insulation. Due to physical limitation of the model test and also facts that numerical CFD simulations of sloshing, may not produce the detailed pressure distribution, idealized mathematical models are usually employed. When doing this, care should be taken in order to respect the 3 main loading parameters: maximum pressure, time duration (rise time, and full loading time) and affected surface.

For the so called Wagner type of impact (i.e. without air entrapment) the classical analytical solution for the wedge entering the water can be used. This solution contains two main parameters: entering velocity and deadrise angle, which completely determines the peak pressure, pressure time history and instantaneous pressure distribution. These two parameters can be estimated either by the model testing from the pressure time history, or by CFD calculations after evaluating the conditions (relative geometry and relative velocity) just before impact occur. In principle 3D Wagner solutions should be used, however more simple 2D solution, in combination with strip approach, can be applied in order to load 3D structural model. One example of spatial and temporal evolution of Wagner type pressure is shown in Figure 9.4.2 and corresponding structural response at one time instant is shown in Figure 9.4.3.

The strength of LNG insulation system is characterised with the max. load that the system can sustain before it fails. Dynamic failure mode of each insulation system is examined during impact model tests.
Depending on the severity of the impact, different complex phenomena may be of importance and should be addressed, like coupled fluid-structure interaction (hydro-elasticity), visco-elastic material properties etc.

An example of calculations using the fully coupled Wagner type hydroelastic model [4] is shown in Figure 9.4.4.

10. PUMP SUPPORT TOWER

Entire LNG RV pump tower structure, comprising tubular elements, liquid dome, pump tower base support and base plate, was verified for operation in all partial fillings condition. Structural resistance under extreme static and dynamic loading was assessed by means of Finite Element Analysis, taking into account hydrodynamic loads obtained from sloshing numerical simulation.

Loads applied on pump tower structure were composed of following elementary loads:

- Hydrodynamic loads from sloshing simulation,
- Inertia forces due to the ship motion from hydrodynamic computation,
- Thermal loads due to the temperature gradient in partial filling condition,
- Self weight of structural elements including entrapped liquid,
- Buoyancy of immersed structural elements,
- Pump torque effects in on/off-loading operation.
Finite element model used in static, dynamic and fatigue analysis is given on Figure 10.4. Distribution of total axial forces as one standard results from static analysis is presented on Figure 10.5. Bending modes of the tower are verified through the dynamic analysis for the evaluation of the risk of resonance with propeller excitation (Figure 10.6).

For operation in partial filling conditions, entire pump tower structure: tubular elements, liquid dome, pump tower base support and base plate are required to be reinforced.

11. OPERABILITY RECOMMENDATIONS

Partial fillings become the subject of interest even in consideration of conventional LNG Carrier designed to withstand sloshing loads in barred fillings range, for the following reasons:

- To assess full flexibility, operating the vessel safely with intermediate fillings during transient phase of LNG transfer,
- To provide operational criteria for the vessel subjected to different environmental and navigation conditions that might cause undesired sloshing effects.

Cartography of ship response presented in form of iso-curves (see examples for roll response given on Figure 11.1 and Figure 11.2) shall serve as instruction for ship operators to avoid critical environmental and navigation conditions while operating ship in partly filled conditions. Variables assigned to diagram axes are navigation conditions (ship speed and heading) and environmental conditions (sea-states) with ship responses (periods or amplitudes) plotted at contour levels.
Resonance analysis results provide an information how to operate the vessel out of resonance state (defined with ±5% margin in terms of resonant period) in relation to any particular partial filling that can occur. Reading the resonance map (Figure 11.1), combination of ship speed, heading and wave period can be identified to avoid resonance condition for any particular partial filling and regardless to the actual wave height. Blank areas present the safe domain in terms of ship response period being out of any resonance period of the tank.

Reading the maximum motion map (Figure 11.2), combination of ship speed, heading and wave period can be identified to avoid excessive ship motion that may affect any partial filing condition. Blank areas present the safe domain in terms of moderate ship response amplitude. In order to mitigate severe sloshing effects associated with resonance condition, the regions of pronounced maximum motion and resonance for particular filling shall not coincide.

Operability recommendations should be further refined by incorporation of the results of complementary analysis, such as:

- Ship motion study for additional ranges of ship speeds to demonstrate overall ship performance for the most likely navigation conditions in service.
- Tank liquid motion study to define the upper bound of sea-states that allows safe vessel operation.

12. CONCLUSION

Bureau Veritas, based on an experience of more than a quarter of century in sloshing issues have developed a comprehensive method for sloshing assessment.

It is based on hydrodynamic analysis, model tests, numerical simulation, finite element method, drop tests, and the most important, the complete analysis of return experience on board actual vessels.

At this stage, it should be underlined that during the last 25 years, since Larbi Ben M’Hidi was reinforced, no damage due to sloshing has been reported on ship under Bureau Veritas classification.

The application of this methodology has led to conclude to the feasibility of all filling levels on buoy and in navigation conditions, provided:

- Reinforced boxes of the containment system are significantly more extended compared to a conventional LNG Carrier,
Significant hull reinforcements have been provided,
The pump tower and supports have been reinforced.

Finally, the class statement for this LNG vessel with regard to the risk due to sloshing does not differ from another one in the sense that it results from the rigorous application of the methodology discussed in this paper and under publication [11], which stipulates a systematic study of the sloshing response for all the operating filling levels using a direct analysis.

13. REFERENCES

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