SOME ASPECTS OF DIRECT CALCULATION METHODS FOR THE ASSESSMENT OF LNG TANK STRUCTURE UNDER SLOSHING IMPACTS

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ABSTRACT

Industrial importance of vessels operating liquefied gas grows along with present LNG market expansion. Increased demand for new LNG transportation concepts requires larger vessel capacities and more flexible operation in partly filled condition. Consequently, it becomes indispensable to incorporate more rational methods in qualification procedure of new LNG designs.

The paper deals with calculation methods necessary to put in practice for the evaluation of containment system and associated ship backup structure of LNG tanks in a membrane type of LNG vessels. Extremely complex problem of hydro-elastic interactions in the tank is reduced to the simplified ones; combining standard CFD tools (FLOW3D), conventional FEM tools (ABAQUS) and idealized hydrodynamic loading models based on asymptotic theories (Wagner, Bagnold, Korobkin etc.). Actually, direct fully-coupled methods, using commercial tools presently available on the market, do not seem capable to treat properly violent LNG sloshing impact events, for several practical reasons such as prohibitive CPU time, convergence problems, extremely complicated physics etc. Thus, the only practical way appears to be the composite approach which combines different tools which were independently validated for particular applications. Recent developments of Bureau Veritas Research Department are presented in this paper and their application to the practical situations discussed.

INTRODUCTION

Expected shortage of the petrol supplies in coming future and overall increased energy consumption turns us towards the potential substitutes, as found in new reserves of environmental friendly natural gas. The times of “easy-energy” seems to be over and dislocation of natural gas fields and major consumer markets reflects in the huge industrial importance of vessels operating liquefied gas. In the last couple of years, LNG market is undergoing rapid expansion and LNG shipping industry is expected to double the fleet within this decade. Moreover, the ship sizes on order drastically increase and new-designed vessels are considerably exceeding conventional limit of 155 000 m^3 cargo capacity. Driven either by the need to produce, store and deliver gas at the spot or to minimize unit transportation costs, the development of new LNG seaborne concepts with improved flexibility becomes the ultimate goal of LNG shipping industry. These issues move towards the utmost industrial challenges in development of feasible LNG designs, carrying great volumes of liquefied gas between distant LNG terminals, providing flexible cargo handling and partial filling operation.

In the development of new technical concepts for LNG exploitation, the basic consideration is given to the selection of appropriate cargo containment system (CCS). Beside the primary function of containment system to ensure adequate thermal insulation and maintain natural gas below its boiling point, the major designer concerns are governed by the tank capability to withstand sloshing impulsive loads. There are several available conceptions of LNG containment system and all alternatives are currently under the investigations. Even though, the advantages of membrane containment systems, demonstrated on standard vessels and onshore LNG terminals over the past decades, led to the recent take-over of membrane technology on LNG shipping market. Hence, the existing technical solutions require to be reexamined and the advanced methods are introduced to assess sloshing feasibility of new designs.

Sloshing may be defined as a violent behaviour of the liquid contents in tanks that are subjected to the external forced motions. Sloshing is a highly non-linear phenomenon that is affected by many parameters and may appear in different forms depending on tank geometry, tank filling height, predominant direction of excitation and magnitude of vessels’ motion. Sloshing flows and their consequences can not be generalized, and dedicated studies have to be carried out to confirm feasibility of LNG vessels exceeding 155 000 m^3 cargo capacity or operating beyond conventionally accepted filling limits of 10% and 70% of the tank height.

The physics of the sloshing impacts is extremely complex since there are numerous physical phenomena involved, such as non-linearity and randomness of fluid flows, various impact jet geometries including the gas entrapment and gas/fluid mixture, cryogenic environment and boiling surface of liquefied gas, complex structural characteristics of composite cargo containment system, rapid change in fluid-structure interface etc.

The current state of the art in sloshing assessment is essentially a comparative one, due to the limited knowledge of the real physical models. There is an outstanding work in current Bureau Veritas R&D, aiming at improving the existing physical models for hydro-elastic impacts and coupling effects. These developments lead to the improvement of design criteria of LNG tank structure and safety margin of new LNG vessel designs.

CARGO CONTAINMENT SYSTEM

Nowadays, there are two basic types of cargo containment system sharing LNG Carriers' fleet (Figure 1): independent B-types (such as spherical Moss or SPB IHI) and membrane types (GTT No96, Mark III or CS1).

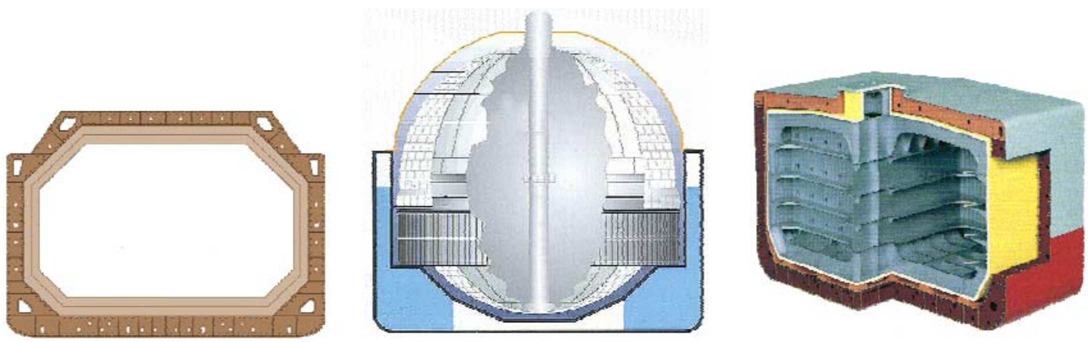


Figure 1. Membrane (left), Spherical Moss (middle) and SPB IHI (right) LNGC Tank

Independent B-type Cargo Containment System. Independent B-type LNG Carriers are generally not susceptible to the local sloshing impact phenomena; nonetheless, they have some important drawbacks. Spherical Moss type has low hull volume efficiency, high windage area which limits the passage under the bridges at some terminals and restricted deck area for the installation of regasification equipment. Moss type is limited in increase of the sphere diameter, so larger LNG capacity can be gained only by the extension of the vessels' length what is undesirable from the stability and global strength aspect. Large spherical Moss types LNG Carriers might experience excessive torsion response of the hull due to the wide openings in the strength deck and non-continuous tank covers. Critical structural details from the fatigue point of view include side longitudinals, inner hull hopper knuckle, tank skirt foundation, inner hull side connection to the foundation and tank cover connection to the main deck. Compared to the spherical Moss tank, a self-standing SPB IHI type introduces the advanced "sloshing-resistant" design with the low flush deck, however being yet too expensive solution for the wide practical use.

Membrane Cargo Containment System. Membrane technology benefits from compact cargo containment system design, providing low depth, small windage area, maximized cargo capacity and lower building and investment costs. LNG membrane type vessels provide the flat deck compatible for the process installation as well the increased safety and easier cargo tank exploitation (fast or no cool down in operation). These advantages led to the recent take-over of prismatic membrane tank types on LNG shipping market, however, flexibility and resistance of the containment system against sloshing flows generated in prismatic tank with flat boundaries and steep slopes has to be carefully investigated. This issue is particularly important in the technical challenges of partial filling operation and designs of LNG Carriers with large cargo capacity. Large membrane types LNG Carriers are more susceptible to the vertical bending moment. Critical structural details from the fatigue point of view are inner hull hopper knuckles, foot of the cofferdam, cofferdam stringers, cofferdam girders in the double bottom and liquid cover dome.

Among the membrane types, the most employed are GTT cargo containment systems No96 and Mark III types (Figure 2). GT No96 insulation is made of plywood boxes containing perlite powder, using flat 0.7 mm thick invar (36% Ni steel) membrane on the primary and secondary barrier. TGZ Mark III insulation is made of fiber glass reinforced polyurethane foam panels, where the primary barrier is a corrugated plate of 1.2 mm thick 304L stainless steel and the secondary barrier an assembly of glass cloth with an aluminum foil (triplex). CS1, being a kind of hybrid system, combines the advantages of both: prefabricated polyurethane foam insulation panels with triplex secondary membrane from TGZ Mark III and flat invar primary membrane from GT No96.

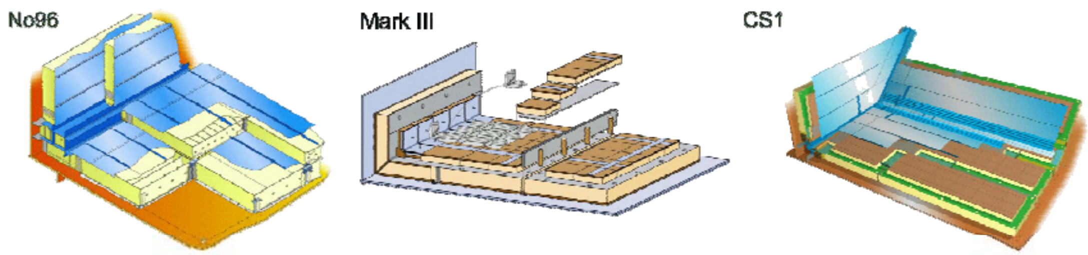


Figure 2. GTT Membrane CCS: No96 (left), Mark III (middle) and CS1 (right)

SLOSHING ASSESSMENT METHODOLOGY

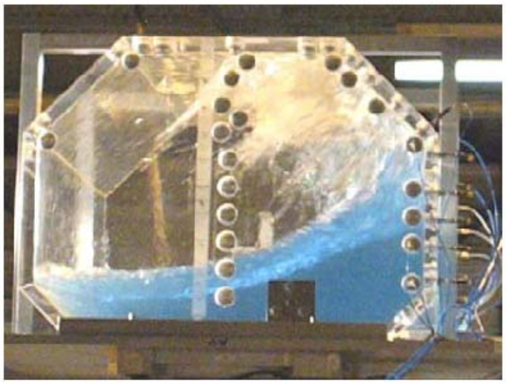
Resulting from the involvement in LNG Carriers since early 60's and extensive research and development over the several past decades, sloshing assessment methodology has been developed by Bureau Veritas aiming to:

- Evaluate feasibility of the design regarding induced sloshing effects related to the specific tank/vessel interaction during forced motion in the specific environment,
- Qualify cargo containment system resistance against generated sloshing impacts,
- Verify structural scantlings of supporting steel inner-hull members with regard to the sloshing loads transmitted through the containment system,
- Outline operational scenario regarding the cargo tank handling and vessels' heading control within sea-state limits,
- Recommend possible enhancements of the design and specification of particular reinforcements, if necessary.

Bureau Veritas design verification procedure relies on the variety of information, tools and methods incorporated in comprehensive sloshing assessment methodology. Some general observations and conclusions on the applicability of particular techniques in current methodology are summarized hereafter.

Sloshing Loads

Liquid motion analysis aims to evaluate sloshing loads and their distribution on inner tank walls, generated by the forced imposed motion. Prior to the investigation of liquid flows in the tank, seakeeping analysis have to be carried out to predict vessels' behaviour in the seaway, using hydrodynamic computation by validated hydrodynamic software or by basin model tests in qualified test facility. Generally, liquid motion analysis is carried out using small-scale experiments in adequate test laboratory and numerical computation using recognized CFD (or other appropriate) software for confirmation of critical cases and identification of relevant impact conditions (Figure 3).



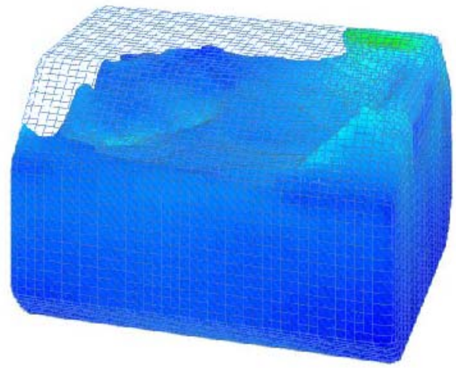


Figure 3. Small-scale sloshing model test (left) and CFD computation (right)

Small-Scale Sloshing Model Tests. Extrapolation of LNG impact pressures from small-scale sloshing model tests is delicate. It depends on many physical parameters of liquid, gas and structure involved in the impact (such as density, viscosity, ullage pressure, surface tension, compressibility, hydroelasticity, viscoelasticity, cryogenic environment with free surface condition at boiling point of gas etc.). Generally, the current practice of qualified sloshing test laboratories is to apply Froude scaling without any restriction. This may be a good approximation for the prediction of the wave-loads in ship and offshore hydrodynamics where water impact duration is longer and pressure pulse is small compared to LNG; and viscosity, compressibility and surface tension are less important. Unlike the water/steel impact, this approach may be too conservative for LNG impact with complex structure (i.e. composite CCS and steel back-up structure). Froude scaling may be appropriate for the evaluation of global average sloshing loads; contrary, very localized impact pressures should be interpreted with precaution. Due to the deficiency of applicable scaling law, it is preferable to exploit sloshing model test pressures in the comparative manner.

Numerical CFD Analysis. Evaluation of LNG impact pressures by numerical CFD analysis is not reliable. High impact pressure is strictly localized in the space and the time, being very sensitive to the local effects (such as small surface wave, gas entrapment, roughness of the wall and local wall deformation). Impact pressure peak is also associated to the pressure wave propagation through the fluid and stress wave propagation through the containment system. Such complex phenomena (at least the fluid part) might be numerically simulated using much more refined mesh and computation time-step. However, when running a long-duration LNG sloshing simulation (aiming to capture relevant impact events of random character and assure adequate sample for statistical analysis), the general CFD software is neither sufficiently efficient nor robust. Due to the limited computer resources with rather prohibitive CPU time and storage capacity, numerical CFD simulations are actually restricted to a quite coarse model. Relevant information gathered by CFD sloshing simulation remains on the level of liquid kinematics, where sloshing impact is being “quantified” by the impact velocity with associated angle relative to the wall and geometry of LNG flow before the impact.

Structural Response

Currently used techniques for the evaluation of sloshing loading are obviously insufficient to identify the most severe conditions from the viewpoint of structural resistance. Thus far, there is no satisfactory numerical model capable to treat LNG sloshing impact with extremely complex fluid-structure interaction in fully consistent manner. Based on the comprehensive R&D work, Bureau Veritas introduces the advanced methodology for strength assessment of CCS with adjacent steel inner-hull structure. Proposed approach focus on the evaluation of structural response by controlled procedure for fluid-structure interactions, validated with the appropriate experimental results. Some experimental aspects of the problem are given in the following.

Material and Mechanical Characteristics. Material and Mechanical properties represent the essential data required for the evaluation of cargo containment system capacity and validation of numerical model. Generally, basic material characteristics are provided from the suppliers of CCS components; however they may suffer of some divergences. Necessary data gathered from dedicated material and mechanical tests concern material stiffness and ultimate strength, under static and dynamic loading, at environmental and cryogenic temperature.

Structural Capacity of Containment System. Specific "panel capacity" tests should be performed for the identification of failure modes and for determination of limit states of different CCS partitions. Static and dynamic tests with measurement of vertical displacements under uniform pressure over different loaded area should provide at least:

- Foam crushing limit and shear capacity of back plywood (for Mark III and CS1),
- Strength capacity of cover plywood due to the plate bending and buckling of the vertical bulkheads (for No96),
- Buckling and shear capacity in cargo tank perimeter areas.

Wet Drop Tests. Wet drop tests (or other equivalent) should be performed using full-scale CCS specimen, with back-up support comparable to the steel inner-hull structure. Drop tests should be performed in as much as controlled conditions, providing relevant data for the analysis of hydroelastic impact effects and validation of the numerical model:

- Pressure and strain variation due to the change of drop height, incidence angle and mass of specimen,
- Strain history at different locations of CCS, bearing mastic and housing.

Experience Feed-Back. Investigation of sloshing-induced damages and available full-scale measurement data aims to integrate experience feed-back in current physical model and to predict more reliable safety margin. LNG fleet has an excellent track-record of the safety over the past decades, and the available database of sloshing accidents is (fortunately) very poor. Certainly, full-scale monitoring with sophisticated measurement on-board LNG Carriers during their service would be very beneficial. However, this issue is still accompanied with practical and safety problems related to feasible tank instrumentation and maintenance of CCS integrity. Presently, a significant effort is put into the development of advanced full-scale measurement techniques, dedicated to the better understanding and controlling of sloshing phenomena on large LNG Carriers.

HYDROELASTIC FLUID-STRUCTURE INTERACTION

General

Probably one of the most important and the most uncertain aspects in sloshing impact problem concerns hydroelastic interactions. During the sloshing impact events, extremely high pressures of very short rise time can be observed; however their direct application for structural assessment would not be reasonable neither correct. Sloshing impact loads should be considered together with their temporal and spatial distribution. When considered in this way, the fully coupled hydroelastic simulations demonstrate that even when the extreme local peak pressures occur, they do not have decisive effect on the stress levels in the structure. In particular, it may be shown that even very small changes of the relative geometry during the impact might significantly change the maximum impact pressure, but the stress distribution inside the structure will remain almost unaffected.

Comprehensive research work is carried out in Bureau Veritas R&D on the key issues for hydroelastic impact analysis: semi-analytical models are developed combining asymptotic fluid flow models with commercial FE software for different types of LNG sloshing impact. The approach introduced by Bureau Veritas focus on the evaluation of structural response by controlled hydroelastic analysis procedure; using the advanced fast dynamics FE analysis of cargo containment system together with the adjacent steel inner-hull structure submitted to the sloshing impact loads. These developments are of the essential importance for sloshing assessment of large LNG Carriers, where currently employed comparative approach might be insufficiently pertinent.

Procedure

From the fundamental knowledge of general impact phenomena, the impact stage is of extremely short duration; for LNG cargo containment systems it's even about some tenths of millisecond. This permits us to disregard some restrictive entities in CFD analysis (such as viscosity, surface tension, gravity effects etc.) and to focus on other major local effects (such as compressibility of the fluid, presence of the gas and rapid fluid flow rate in impact region, "aeration" of the wave front, flexibility of the wall etc.). Moreover, it allows simplification of local analysis and combining analytical and numerical methods in place of direct numerical computation, when CFD analysis becomes inappropriate.

From the existing theoretical knowledge and experience gained in practical applications, it may be demonstrated that violent flows described by semi-analytical models are comparable with fully nonlinear calculations with high spatial and temporal resolution. The method introduced by Bureau Veritas proposes using simplified hydrodynamic impact models together with complex structural models during the impact stage.

Up to date, the most appropriate procedure for evaluation of sloshing impact effects on structural response can be established through:

- Identification of critical impact events and impact conditions using available tools (sloshing small-scale model tests and numerical simulation),

- Structural examination of CCS and supporting steel structure; using material and mechanical tests for determination of structural properties in static, dynamic and cryogenic conditions,
- Impact tests with full-scale CCS specimen (such as drop tests or equivalent) in controlled impact conditions, using reliable test laboratory and technically practical installation, for the assessment of structural capacity and strength,
- Dynamic FE analysis using validated numerical model, for the assessment of structural capacity in limit states beyond the feasibility of test set-up (e.g. high impact velocities of LNG at its boiling point, structure in cryogenic environment).

Impact Types. Based on numerous model tests and numerical computation from Bureau Veritas practice, sloshing impact type can be identified and classified in three basic groups (Figure 4, Figure 5):

- Steep wave impact,
- Braking wave impact,
- Aerated fluid impact.

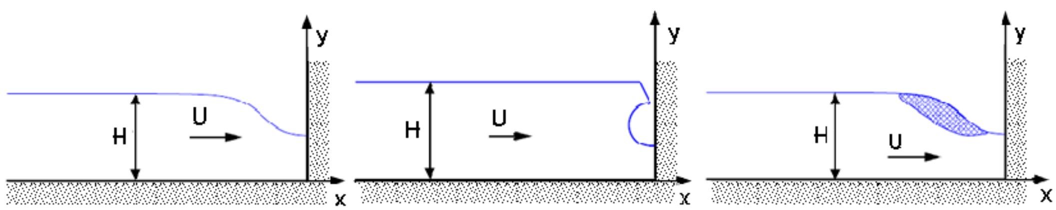


Figure 4. Different impact types:
Steep wave (left), Breaking wave (middle) and Aerated impact (right)

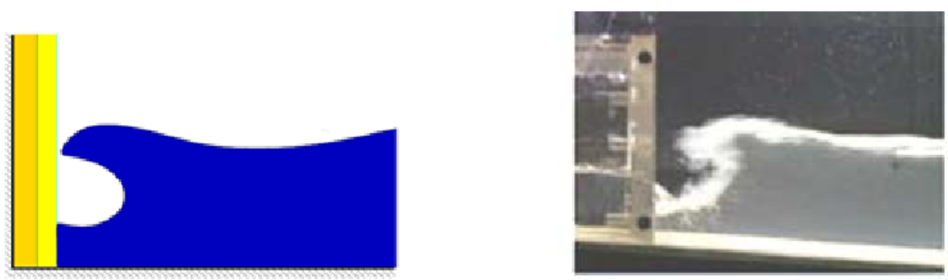


Figure 5. Identification of impact type (left), Controlled generation of impact (right)

Analytical solution. In the present paper, the steep wave type is discussed as a generic case of the sloshing impact. Depending on the shape of the wave front and flow field before the impact, fluid is treated as incompressible or compressible. The fluid is considered compressible if the expansion rate of wetted area is very high, comparable with the celerity of the sound in fluid (acoustic approximation). Otherwise, the incompressible fluid model is used and can be generally described with Wagner approximation. Beside its importance in direct fluid-structure analysis of sloshing impact problem, proper analytical model is very important to provide useful formulation for design needs in practical application.

Wagner Approximation. Sloshing impact problem can be classified as a Wagner type when the wave front hits the wall with an angle. The most important parameter in Wagner type of impact concerns evaluation of expansion rate of the wetted part, which directly affects pressure time history and pressure peak value. Advantages of Wagner solution are lying in the simplicity of hydrodynamic model and its efficiency in both, rigid and elastic impact problem. Detail of analytical solution using Wagner approximation for sloshing impact problem is elaborated in [8].

Relevance and applicability of the proposed method is demonstrated with an example of free-falling rigid wedge (Figure 6), where pressure distribution during the impact is compared between analytical solution (Wagner approximation) and numerical results using refined 2D CFD model (FLOW3D). Using very high resolution of VOF mesh with about 2.5×10^6 elements and time step of 10^{-6} s, CPU time reaches almost 5h what is far inappropriate for the practical use of CFD.

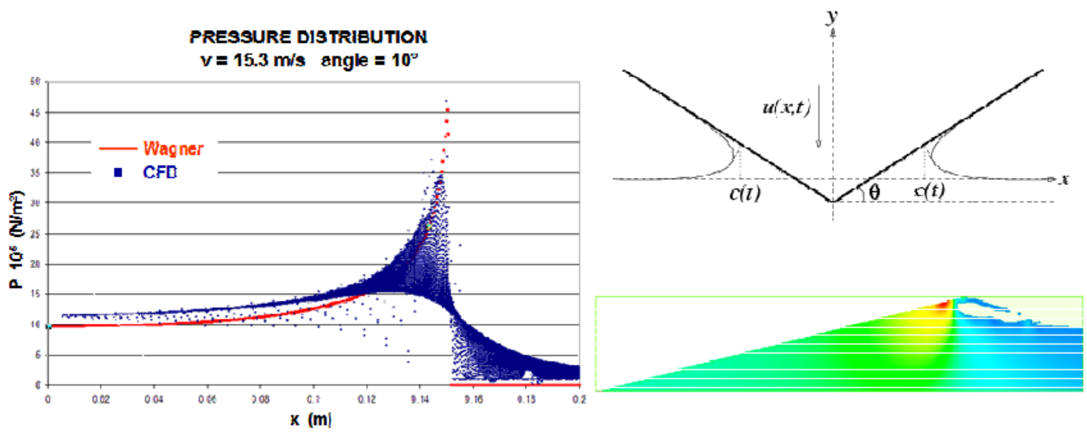


Figure 6. Comparison of pressure distribution during impact:
Wagner approximation – local CFD model with high resolution

Example of pressure time-histories measured on CCS specimen (one drop height with angle 4°) and calculated using Wagner approach (dead-rise angle 4° and three different impact velocities) is given on Figure 7.

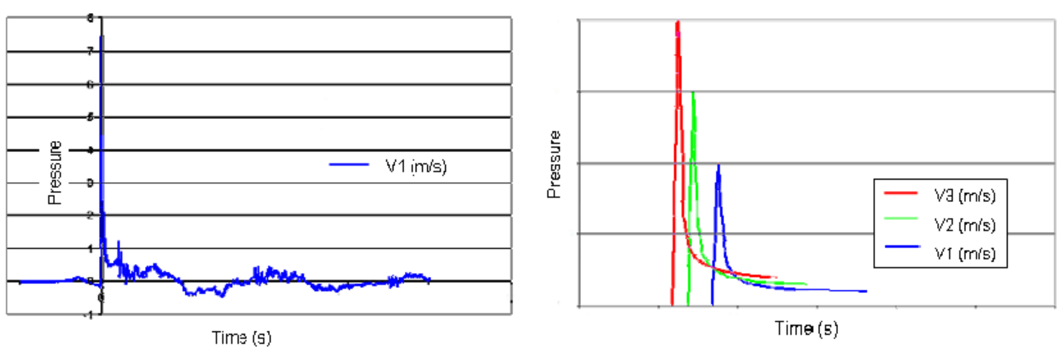


Figure 7. Pressure time-history: Measured, for one drop-height (left),
Calculated (Wagner), for three different impact velocities (right)

Application

Validation of numerical models for fluid-structure interaction problem should be performed very carefully, since the comparison of measured pressures peaks might be unreliable (possible pressure scattering) or irrelevant (insignificant influence on stress distribution in the structure). Measurement of the strain ought to be much more stable (repetitive) and should provide much more important information on the physics of fluid-structure interactions.

It should be underlined that, even simplified, hydroelastic impact problem remains extremely complex from numerical point of view. Once the impact conditions identified and properly defined by their geometry, impact velocity and incident angle relative to the wall, semi-analytical models based on asymptotic theories are utilized to solve hydrodynamic part of impact problem and define representative sloshing loads.

In the next step, sloshing load is transferred to the local FE model comprising both, containment system and adjacent ship's inner hull structure. Local structural analysis can be performed using uncoupled (direct pressure transfer) or coupled (hydro-elastic) approach. Fully coupled analysis is necessary for special impact conditions, such as high impact velocity, small impact angle and very elastic structure. Example from simulations for CS1 containment system, demonstrating the difference between fully coupled and uncoupled analysis, is shown in Figure 8.

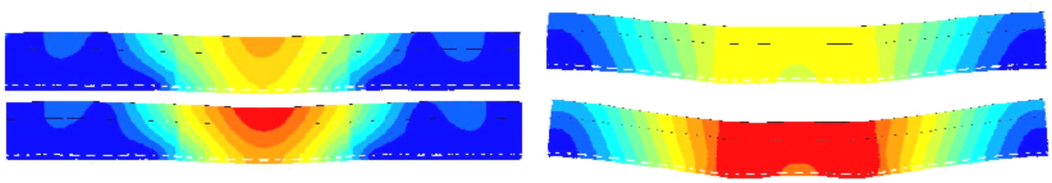


Figure 8. Deformations in local FE model of CS1:
Difference between fully coupled (left) and uncoupled approaches (right)

So far, only 2D hydroelastic simulations were fully successful and efficient, due to the efficiency of Wagner solution that fundamentally exists for 2D case. Over the past couple of years, 3D simulations are under the development and validation in Bureau Veritas, involving two different techniques: strip approach and full 3D Wagner solution.

Strip approach has been successfully put in the practice for slamming type of problems. Using slamming impact analogy for some types of sloshing impact model, the fluid flow is supposed to be basically 2D for each strip while the structure is considered 3D. 3D strip approach is likely to be conservative compared to full 3D solution, as the 3D hydrodynamic effects tend to reduce loading.

Example from the numerical simulations (ABAQUS) using 3D strip approach for No96 CCS model including adjacent steel inner-hull panel is illustrated on Figure 9. Other example for Mark III CCS (without corrugation included in the model), presenting the strains in back plywood and bearing mastic under sloshing load modeled with three different impact velocities, is given on Figure 10.

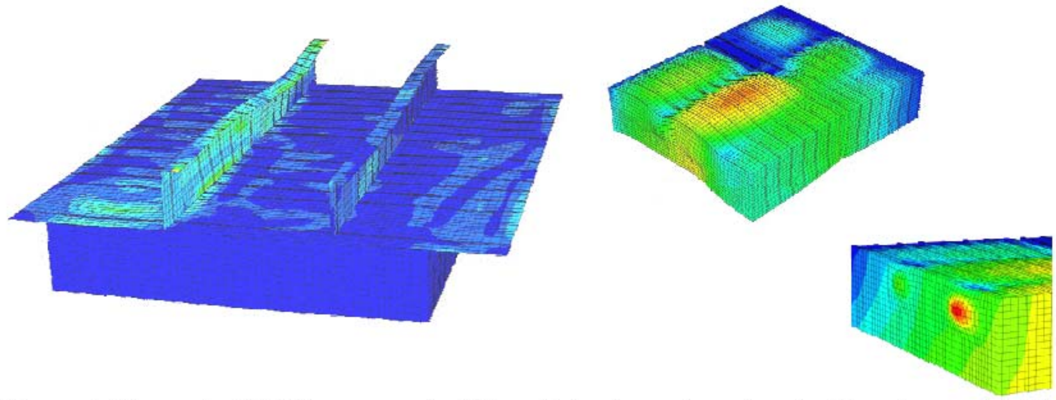


Figure 9. Stress in No96 boxes and stiffened steel panel under sloshing impact (left), Buckling of box cover-plate and vertical bulkhead (right)

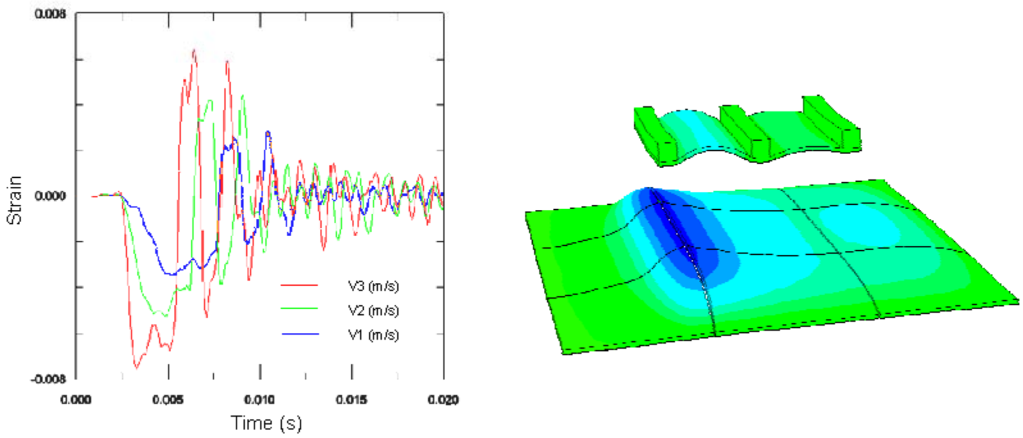


Figure 10. Calculated strain in back plywood of Mark III for 3 impact speeds (left), Deformation of back plywood and membrane (right), corrugation is not included

CONCLUSION

This paper exhibits the essential issues related to the sloshing phenomena occurring in cargo tanks of LNG vessels during their service. Complexity of sloshing impact problem with extremely difficult hydroelastic interaction is subject of thorough investigations and R&D studies over the several past years. Up till now, there is no suitable experimental or numerical method capable to treat LNG sloshing impact in fully consistent manner.

Advanced developments in Bureau Veritas R&D are presented and the methodology adopted for adequate analysis of fluid-structure interactions is discussed. Bureau Veritas approach is of a composite nature, based on the classification of different impact types, association of each impact type with appropriate analytical solution, validation with adequate experimental results and integration of different tools in the final scheme for the structural assessment of cargo containment system and supporting inner-hull structure. This work demonstrates applicability of the proposed procedure on the practical examples of LNG tank structure under sloshing impact loads. Further developments of analytical methods and their validation are currently on-going within several research projects.

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