FULL SCALE EXPERIMENTS AND NEW METHODOLOGY TO ASSESS THE STRUCTURAL BEHAVIOUR OF A MEMBRANE LNGC CONTAINMENT SYSTEM UNDER BREAKING WAVES
PROJECT "SLOSHEL"

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ABSTRACT
Development of an offshore LNG sector and increasing demands for operational flexibility in LNG shipping bring the new challenges for sloshing assessment in partially filled LNG tanks. Since 2005, the *Sloshel* project has been undertaking a joint industry programme to improve the assessment of structural response of the LNG containment system and associated ship structure under sloshing impacts. Full-scale tests were conducted to simulate the sloshing impacts within LNG membrane tanks. The structural responses of segments of actual LNG containment system were measured under controlled and realistic wave impacts using an 800 KW coastal engineering wave flume. Unidirectional waves were generated in a 240m long open flume tank and focused so that they impact a rigid wall on which a fully instrumented membrane NO96 containment system had been mounted. The different impact types that are observed during small scale sloshing tests at low or partial fill conditions were reproduced. A large database of measurements was gathered during 110 wave impacts. At the same time theoretical and numerical developments were carried out in order to adapt the so-called generalized Wagner and Bagnold methods to simplified conditions idealizing typical impact types such as jet flow impacts, air-pocket impacts and aerated impacts. This paper presents an overview of the *Sloshel* project.

The *Sloshel* project consortium comprises the containment system designer GTT, classification societies, industry and research establishments. Initiated by GTT, Bureau Veritas, MARIN and Shell, the consortium includes Ecole Centrale de Marseille, American Bureau of Shipping, Chevron, Lloyd's Register EMEA, Det Norske Veritas, and Class NK.

INTRODUCTION
Sloshing became a very important practical problem in the last decade due to the increased activities in the LNG transport. Large numbers of LNG carriers were built or are under construction with the capacities which almost doubled as compared to the classical LNG carriers (from 138 000 m^3 to 240 000 m^3). The most common LNG carriers belong to the, so called, membrane type and a typical example of the structural arrangement is shown in Figure 1. Within the membrane type concept, which is of main concern here, the LNG is kept at very low temperature (-165 °C) by a complex insulation system which is attached to the ship structure.
At the same time as the size of LNG carriers increased, the operational requirements became more and more severe. Indeed, in the past, LNG carriers were allowed to operate either in full or empty tank conditions, while today there is sometimes necessity to allow for operating at any filling level. This requirement introduces serious difficulties in the design of both the containment

system (CS) and the associated ship structure. Violent sloshing motions may occur (Figure 2) and the direct consequence is the occurrence of different impact situations which can induce the large structural loadings possibly damaging both containment system and the ship structure.

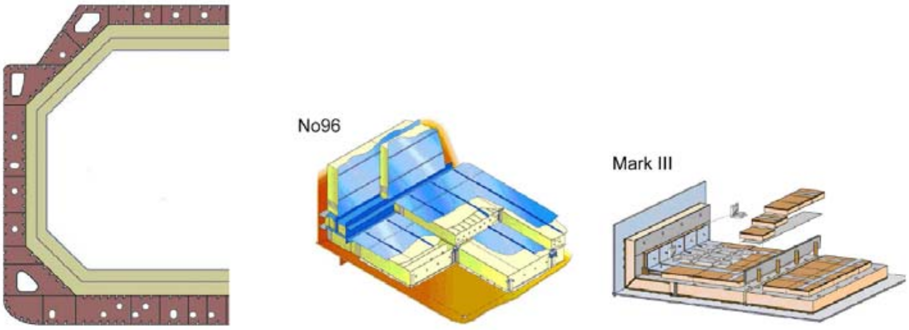

Figure 1 *Membrane type LNG tank and different containment systems*

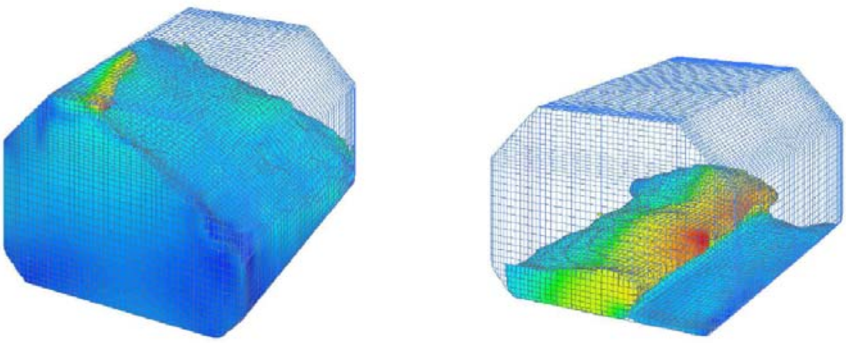

Figure 2 *Typical sloshing motions*

The correct numerical modeling of the fluid-structure interactions during the sloshing impacts is extremely complex, and it is fair to say that up to now, there is no fully satisfactory numerical model able to treat these situations in a fully consistent manner. Indeed, even without considering the interaction with the structure (hydroelasticity) the modeling of the pure fluid flow makes serious problems due to several complex physical phenomena which are involved (like: rapid change of the free surface geometry, two (three) phase flow in some situations, gas cushion, thermal interactions due to the low temperature of the LNG (-165 °C), important 3D effects, compressibility, surface tension, viscous effects and ullage pressure). In addition to these pure fluid mechanics problems, and due to the flexibility of the CS, another important aspect, which seems to be essential for correct evaluation of the structural responses, is the effect of hydroelasticity. Indeed, due to the violence of the impacts, the hydrodynamic pressure will often depend on the structural response so that fully coupled hydro-structure modeling is necessary. In order to better understand the modeling difficulties related to hydroelasticity, in Figure 1, two typical containment systems which are predominantly in use today are shown. The first one is the so called NO96 system, which is composed of plywood boxes filled with perlite, while the second system, called Mark III, is composed of two different layers of PU foam. On the side in contact with LNG, NO96 systems have the membrane made of special metal alloy called invar while Mark III CS has the stainless steel membrane. In the case of NO96 CS, this membrane is flat, while it is corrugated for Mark III CS. Correct structural modeling of such complex structures is still challenging even for most sophisticated numerical tools based on well mastered finite element method.

The sloshing investigations of the LNG containment system are usually performed by different means:

- In-service measurements
- Small scale model tests
- Full scale tests
- Large scale model tests
- Numerical simulations

The small, large and full scale tests are carried out in a laboratory conditions whereas the in-service measurements are carried out during operation of an LNG carriers. However, none of these methods separately can give the final answer to this difficult problem, and that for several technical reasons which we briefly discuss hereafter.

In-service measurements

There were some initiatives to perform the in-service measurements in the LNG tanks but it is unclear yet if these measuremens were performed successfully since the information remains confidential. In any case the in-service measurements would be of importance for validation of different numerical methods and for better understanding and interpretation of the small, large and full scale tests. However, we can guess that these data will not include the sloshing impact geometry (like that shown in Figure 7) so that the type of sloshing impact would have to be determined from pressure measurements only. Such data would most probably include a relation between sloshing excitation (i.e. tank motions) and pressures on instrumented tank areas.

Small scale model tests

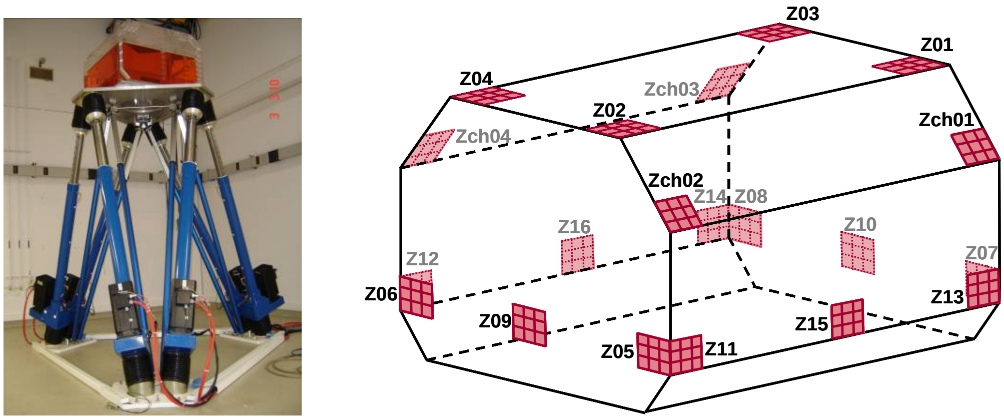

Figure 3 *Small scale sloshing model tests (GTT) using hexapod and typical pressure sensors positions*

The small scale sloshing model tests are employed most often The scale usually varies in between 1:20 and 1:70 and different mounting scheme are used. The most advanced mounting scheme is based on 6DOF hexapod concept (Figure 3). The pressure sensors are usually employed in cluster configurations at different locations in the tank, which are most likely to experience the severe impacts. The small scale model tests give a reasonable overview of the overall sloshing motions inside the tank but the local pressures measurements are still difficult to analyses due to the highly localized (in time and space) pressures which occur during impact. In addition to the difficulties related to the pure pressure measurements the problem of transferring these pressures to a full scale represents a big challenge. Scaling is often considered only to be related to post processing of the pressures and not the structural responses. However, for many impact situations, the scaling can not be decoupled from the structural response due to the strong hydroelastic effects which occur during impact (e.g. Faltinsen, 2009 and Graczyk & Moan ,2009).

When the assumptions of incompressible fluid, rigid tank, no viscosity, no surface tension and a zero density ratio between gas and liquid hold the Froude scaling applies. These assumptions need to be revised for sloshing in LNG tanks due to the presence of gas (i.e. saturated methane vapour) in the impact region as well as tank structure elasticity.
It is important to note that most of the present methodologies for the sloshing assessment are fully or partially based on the small scale tests within the so called comparative approach.

Full scale tests
In the absence of the in-service measurements, full scale tests were undertaken. These tests (see Figure 5) involve impacting the real containment system structure through the drop tests technique reported by Kim *et al.* (2008), or through the more sophisticated wave generated impacts as in the present *Sloshel* project, also described by Brosset *et al.* (2009).

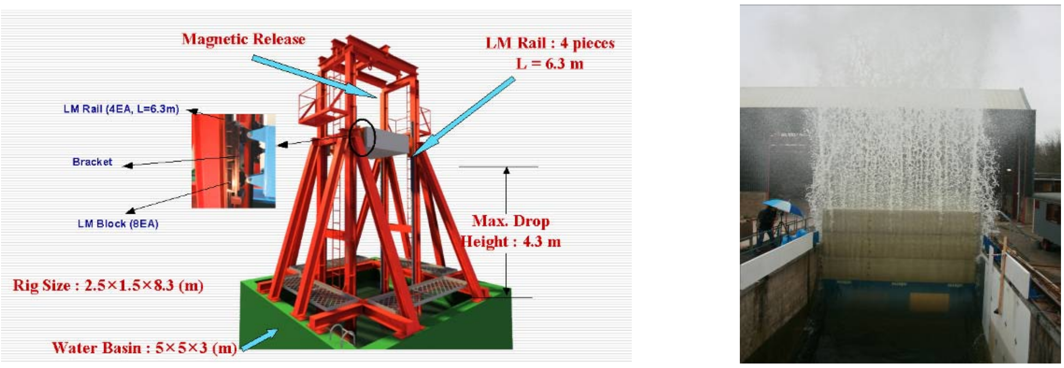

Figure 4 *Full scale impact tests (left – drop tests, right – impacts in wave flume – Sloshel project)*

Important databases of the full scale measurements were realized using these tests in various previous research projects, but lot of problems were reported with respect to the repeatability of the measurement which makes the proper interpretation and use of the results very difficult. The reported measured maximum strains showed much smaller scatter for given impact velocity even though the maximum pressure varied strongly. These led to a conclusion that it can be misleading from a structural point of view to measure the peak pressures for the effect of hydrodynamic impact when hydro-elasticity matters. In the case of the complex structure such as containment system the situation is even more complicated because the strains themselves can also show very important scatter which makes the interpretation of the results very difficult.

In the *Sloshel* project a significant effort has been made to ensure proper pressure measurements. Contrary to the abovementioned conclusion the results of the *Sloshel* project show that pressures and strains are correlated and show the similar scatter. Still, however, it has been found that both pressures and strains are highly sensitive to very small changes in the physical impact conditions. This sensitivity makes the full-scale tests for the most violent sloshing impact types hardly repetitive and requires therefore multiple tests in order to collect sufficient statistical data. This is quite expensive and therefore the large tests offer here an attractive alternative.

Large scale model tests
The difficulties related to the exploitation of the small and full scale tests led to another type of experiments at intermediate scales. These experiments are similar to the *Sloshel* type but are performed in smaller wave flume where the very precise measurements of the fluid flow (PIV technique) and hydro structure interactions are possible, Scolan *et al.* (2007). Different waves are generated leading to the different well controlled impact situations. At the same time the impacting wall is made with controlled elasticity which can be easily adjusted in order to control the hydroelastic effects. An example of typical impact situations is presented in Figure 4.

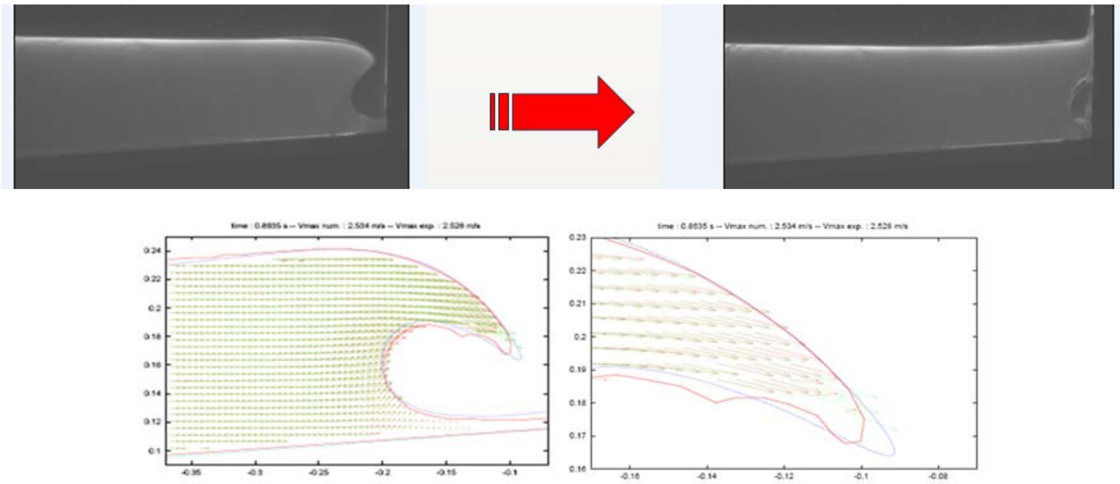

Figure 5 *Hydroelastic impact tests in the wave flume at moderate scale and numerical simulations of the wave kinematics before impact*

These tests allow for the detailed validation of the simplified semi analytical and more sophisticated numerical models. Indeed, all the important impact parameters can be measured with very good precision (wave geometry, fluid velocities, air pocket extension, aeration, structural deformations …) allowing for proper validation of all the intermediate modelling steps. Having said that, the scaling is still a problem in these tests, and the impacted structure is simplified. The exploitation of these types of tests is in progress and no clear conclusions have yet been reported. Recently also within the Sloshel project the large scale tests on a rigid structure have been carried out and the exploitation of results is in progress.

Numerical simulations

Numerical modeling of coupled hydro-structure interactions during sloshing impacts is very challenging problem both from hydrodynamic and structural sides. Indeed, even decoupled two problems are very difficult to model properly. Even if some attempts were made to solve the 3D impact problems, e.g. Scolan & Korobkin (2001), Korobkin & Scolan (2006) and Gazzola (2007), the 2D modeling of the fluid flow is used most often. The main reason for that are the difficulties associated with the determination of the free surface flow and the exact wetted part of the structure during the impact. On the structural side the 3D effects of the response can be treated by the standard FEM codes provided the correct characteristics of the structure of containment system are available. The determination of the FEM characteristics is far from trivial due to the complexity of the containment system (stapled plywood, foam, steel, mastic ropes, couplers…) and the associated ship structure.

As far as the fluid flow is concerned, the methods which are used most often in practice can be subdivided into the pure CFD methods, potential flow methods based on numerical or semi-analytical models.

The CFD numerical simulations are often used to model sloshing problem. Due to the strong variation of the free surface during sloshing, the most popular methods belong to the family of the VOF (Volume of Fluid) technique and to the so called SPH method (Smoothed Particle Hydrodynamics). SPH method has the advantage to be gridless allowing for very strong free surface variations, e.g. Landrini *et al.* (2003) and Oger *et al.* (2009). However, all CFD methods suffer from numerous numerical problems when it comes to the evaluation of the highly localized pressures. The mesh requirements for proper evaluation of the hydro-structure interactions during the impacts become prohibitive and the stability of different numerical schemes is hard to ensure, especially when hydroelastic analysis needs to be performed. The CPU time is also a big issue which makes their use for statistical estimates of tank response variables, very difficult. Having said that, the CFD methods are continuously improving both from accuracy and CPU time points of view and are likely to become much more important in the near future.

The particular nature of the impact problems allows, most often, for ignoring some otherwise important physical parameters such as viscosity, flow separation andthermal interactions, so that the models based on the potential flow theory can be justified, e.g. Korobkin & Malenica (2006), Faltinsen (2009) and Gazzola (2007). Potential flow models are attractive because they allow for higher precision and lower CPU time. Only these models will be discussed in details in this paper because they were integrated part of the Sloshel project. This is especially true for the semi-analytical models. The main idea with the semi-analytical models is to identify the most typical impact situations and then simplify them in order to be able to describe them with simple geometries including the few most important physical parameters. The structural part of the problem is kept 3D and is treated by common 3DFEM structural numerical codes. An overview of these hybrid methods can be found in Korobkin & Malenica (2006) and will also be discussed more in details in the sections to follow.

SLOSHEL PROJECT

Having in mind all the difficulties discussed above, the *Sloshel* project was undertaken in order to bring more light on this important issues. As already mentioned, the project contains 2 main parts: experimental and numerical one. They are briefly described in the following sections.

Sloshel test method and setup

In this section we recall the basic principles of the experiments only, and more details can be found in Kaminski & Bogaert (2009).

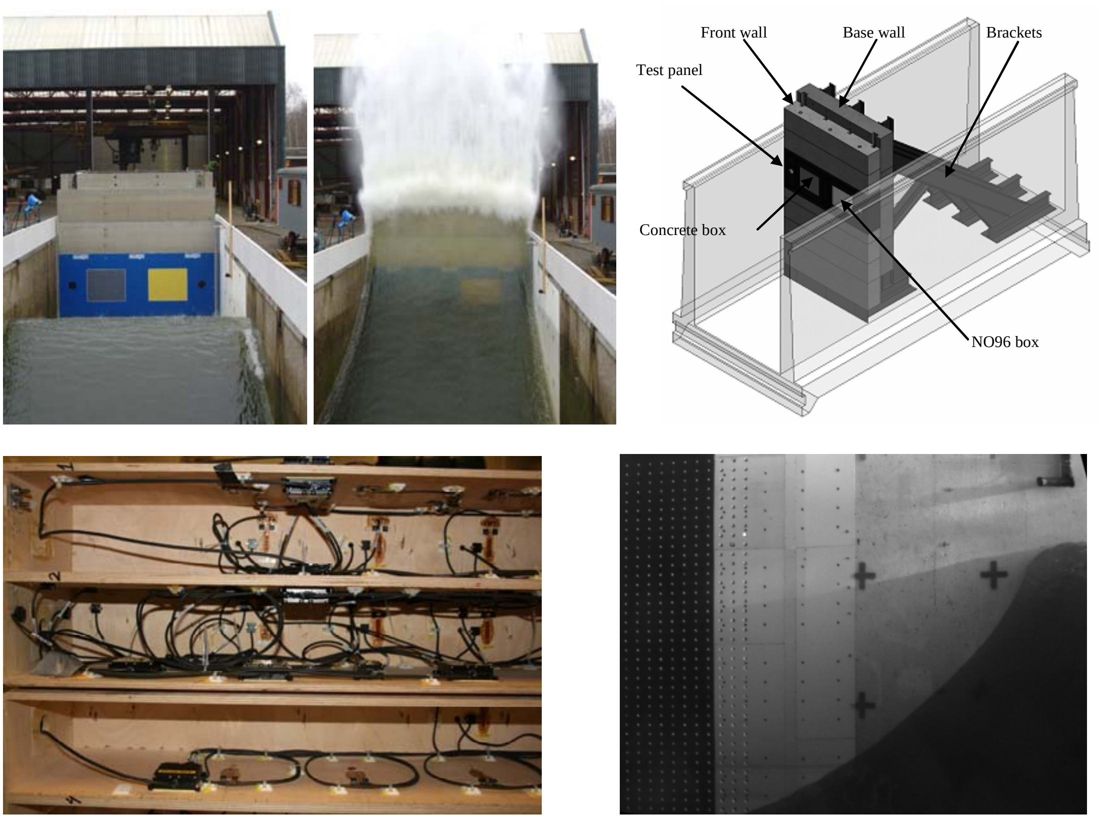

Figure 6 *Sloshel model tests (clockwise: wave flume, mounting scheme, iCAM sensor and instrumented NO96 box)*

After considering several options the consortium decided to generate breaking waves in a coastal engineering flume by a wave focusing method because this method produces sloshing impacts which are close to sloshing in the membrane LNG tanks. The Delta flume, shown in Figure 6, operated by Deltares was selected as the test facility. The open-air part of the flume is 5 m wide and 7 m deep. At the South end of the flume there is a huge piston of 800 kW power and 5 m stroke. This piston with the second-order wave steering system was used for wave generation. At a certain distance from the piston a transverse test wall was placed as shown in Figure 6. The process of generating a breaking wave is based on the so called focusing method. The piston generates successive waves of increasing length and height. The longer the waves the faster they propagate. The wave train is generated in such a way that all waves add at one lengthwise position of the flume and produce a single, large breaking wave. The position where the wave breaks is called the focal point.

Anticipating that different containment systems will be tested in the future it was decided to make a modular design of the test wall. The final design is shown in Figure 6. The test wall is an assembly consisting of the front wall with the test panel, the base wall and three propped support steel beams (brackets).

The test panel was designed modularly and can accommodate two test structures. In the reported project the reinforced NO96 boxes and the concrete block were tested. The front area of both tested structures was the same. It was decided to test the NO96 boxes without their primary and secondary invar membranes. The boxes were not filled with perlite granules. The concrete block was tested for the reference purposes.

Instrumentation

Table 1 overviews measured important quantities and sensors. A state of the art, shock resistant, compact data acquisition system for 300 channels with sampling rate of 50 kHz per channel was used.

Table 1.- Overview of instrumentation

Medium	Quantity	Sensor description
Water	Wave elevation	3 wave probes
		7 video cameras
	Wave velocity	5 video cameras (idem)
		iCAM (640 sensors)
	Impact type	
	Impact aeration	
NO96 box		
Interaction surface	Pressures	20 pressure gauges
	Velocities	20 accelerometers
Response	Strains	142 strain gauges
	Accelerations	24 accelerometers
Supporting structure	Forces	24 load cells
		4 couplers with load cells
	Accelerations	5 accelerometers
Concrete block		
Interaction surface	Pressures	10 pressure gauges
	Velocities	5 accelerometers
Supporting structure	Forces	24 load cells
		4 couplers with load cells
	Accelerations	5 accelerometers
Test panel		
	Pressures	2 pressure gauges
	Accelerations	3 accelerometers
Test wall		
Front wall	Pressures	11 pressure gauges
Base wall	Accelerations	8 accelerometers
Brackets	Forces	4 strain gauges

A very important aspect of hydrodynamic impacts is their type. For this reason MARIN developed the impact capturing matrix sensor (iCAM). The iCAM sensor (see Figure 6) consisted of 640 single optical sensors capable to distinguish air, aerated water and solid water. The iCAM sensor was placed on the East wall of the Delta flume just in front of the test panel. The iCAM sensor performed very well and delivered important data that allowed for identification of the impact types and for validation of hydro-dynamic computations. One example of iCAM measurements is shown in Figure 7.

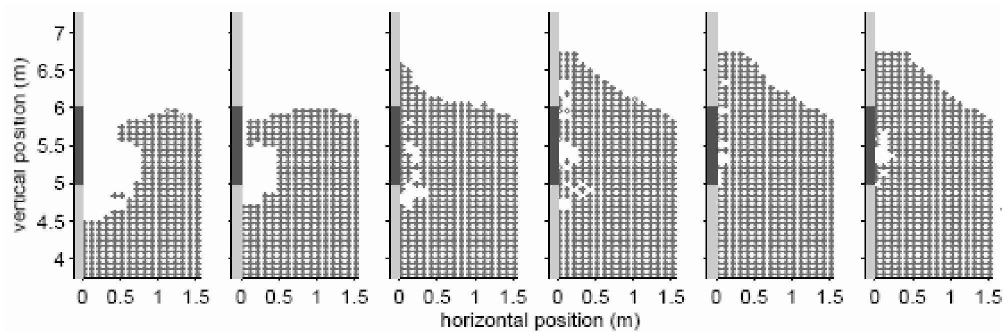

Figure 7 *Example of iCAM measurements*

Test program

In total 110 full scale tests were carried out. Although, it was found that the same piston settings were resulting in different impact types, the full scale tests could be classified as shown in Table 2 based on the iCAM, video and pressure data. Figure 8 shows the typical shape of the breaking waves just before impacting the wall and the associated values of the focal point divided by the water depth.

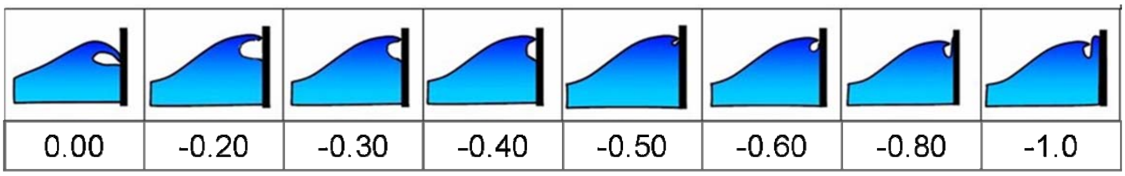

Figure 8 *Wave shape before impact as a function of the focal point w.r.t. the wall.*

Table 2. Overview of full scale tests

Impact type	Panel position	Water depth	Test numbers
Units-	m	m	-
Aerated Impact (AE)	3.5	3.50	4, 7, 10, 14, 18
	4.5	4.25	49, 61, 65
	4.5	4.00	86
Air Pocket Impact (AP)	3.5	3.50	2, 8, 15, 19, 20, 21, 22, 28, 29, 42, 43, 44, 45, 46, 47
	3.5	3.30	33, 36
	4.5	4.25	50, 58, 59, 60, 62, 63, 64
	4.5	4.00	66, 67, 68, 69, 70, 71, 72, 79, 80, 81, 89, 90, 91, 92, 93, 94, 95, 96, 98, 101, 102
Flip-Through Impact (FT)	3.5	3.50	1, 5, 11, 25, 26
	3.5	3.30	30, 31, 32, 34, 35, 37, 38, 39, 40, 41
	4.5	4.25	51, 52, 53, 54, 55, 56, 57
	4.5	4.00	73, 74, 75, 76, 77, 78, 82, 85, 88, 97, 99, 100, 103, 104, 107, 108, 109, 110
Slosh Impact (SL)	3.5	3.50	3, 6, 9, 12, 13, 16, 17, 23, 24, 27
	4.5	4.25	48
	4.5	4.00	83, 84, 87, 105, 106

The tests were not repeatable in particular because the wind was changing the wave focusing process. The analysis is still in progress and the conclusions regarding the hydro-elastic and the scale effects, and validation of different numerical tools will be published by the consortium in the near future. Nevertheless, the tests showed that the flip-through type of impact producing the largest pressures on both tested structures was very sensitive to surface perturbations of the breaking wave. These perturbations were in the range of 10 cm. In this paper the Sloshel data will be used to validate simplified numerical tools developed by Bureau Veritas within the Sloshel project.

SLOSHEL **NUMERICAL DEVELOPMENTS**

As already mentioned, within the *Sloshel* project, it was decided that the effort in the numerical part will be put on the development of semi-analytical methods for the local fluid flow, which will be combined with the complex structural FEM models for containment systems. The use of the classical CFD methods for the local analysis of extremely complex sloshing phenomena was avoided at the beginning of the project, but was included later. The simplified semi-analytical models for fluid flow, keeping the main physical parameters allow for the assessment of the phenomena within the reasonable computational effort. The drawback is that the impact situations should be highly simplified.

In Korobkin & Malenica (2006), the classification of different impact types is proposed and corresponding semi analytical models described. The models concentrate on the low filling level sloshing scenarios and impact types were classified into 3 main categories (see Figure 9):

- Impact without air inclusion (Wagner, steep wave impact or slosh impact - SL)
- Impact with entrapped air pocket (Bagnold type, air pocket impact - AP)
- Impact with aerated fluid (aerated impact - AE)

The different sub variants of these models and more complex geometrical situations are also proposed, one of the most important being the so called flip through type of impact which produces the highest local pressures.

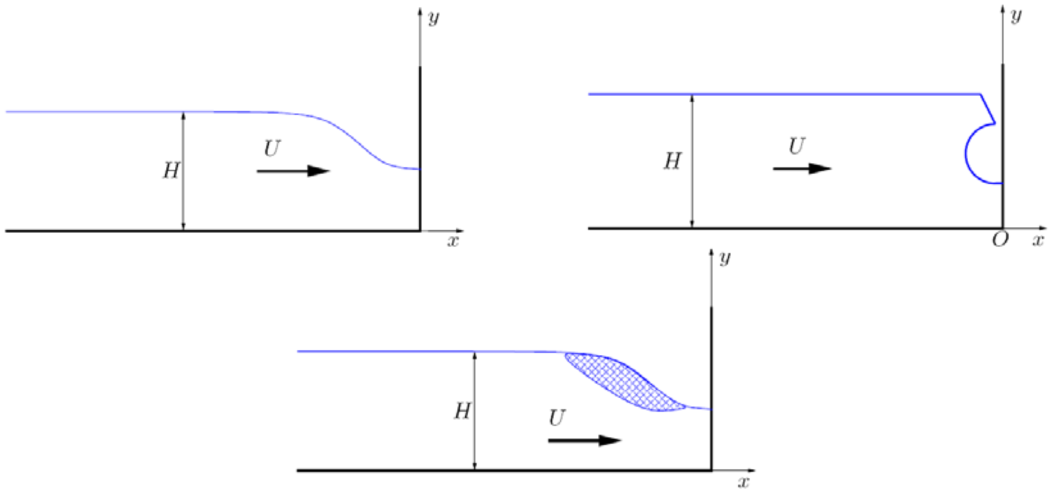

Figure 9 *Different impact types for low filling situation: steep wave, breaking wave and aerated*

As an example, in Figure 10 the methodology for simplification of the aerated impact is presented. In spite of quite severe simplification, the main physical parameters are kept. The strong point of the methodology is the possibility to describe the fluid flow with analytical solutions which are computationally very efficient and in addition can be easily fully coupled with the general 3DFEM structural software for hydroelastic simulations.

On the structural side, the general 3D-FEM models are used. This allows for realistic representation of the complex structural dynamics which should include both the membrane containment system and the ship structure (Figure 11).

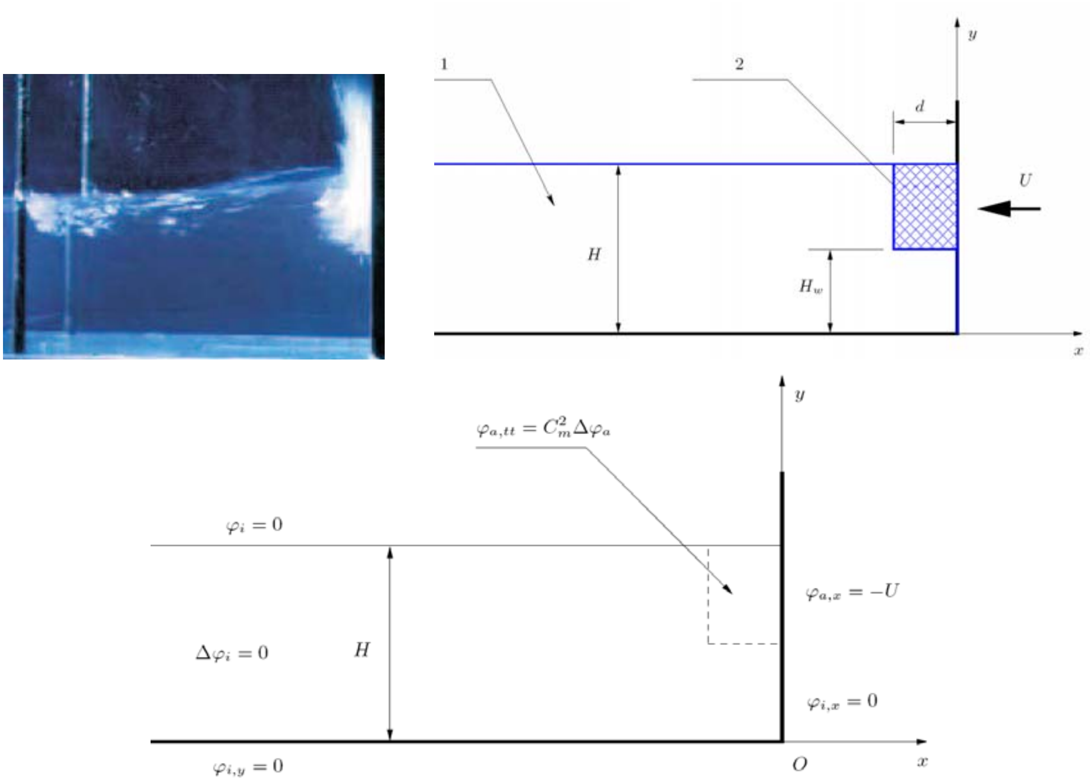

Figure 10 *Aerated impact and corresponding simplification (Top –real situation and its geometrical simplification, Bottom – mathematical model)*

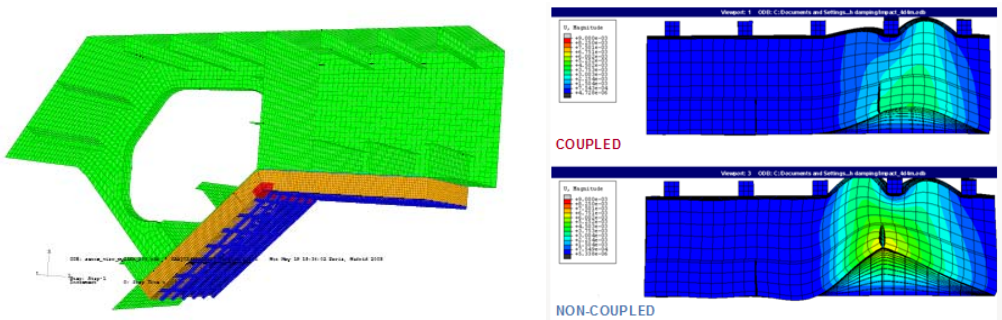

Figure 11 *3DFEM structural model and comparison of the quasi static and hydroelastic structural responses*

Overall methodology

The overall methodology of the hydroelastic coupling was developed for a general case of violent sloshing in LNG tanks, see Korobkin & Malenica (2006) for more details. In this paper the methodology for the sloshing assessment at low fillings only, is discussed. Low filling situation is characterized by possible formation of steep and breaking waves which were the main concern in the *Sloshel* project. In the proposed hydroelastic models it is assumed that the global kinematics of the sloshing is independent of the tank flexibility but the local impact pressures and their distributions are affected by the elastic properties of the containment system and the associated ship structure. The wall elasticity is accounted for only during the impacts and only near the places were such impacts happen. It is assumed that the analysis of global fluid motion in LNG tank by using CFD simulations has been performed, and both the places and times of the different impacts were identified. Alternatively this can be also done by proper analysis of the small scale model tests which are believed to be representative of the overall sloshing motion inside the tank in spite of the possible scale effects.

The local hydroelastic models are applicable only during the impact stages, when the hydrodynamic loads are high and the elastic response of the structure is maximal. By definition the impact stage is of short duration. This makes it possible to disregard many effects, which are of main concern in the CFD analysis, such as large dimensions of the tank and its real shape, real profile of the free surface far from the impact region, viscosity of the fluid, its surface tension and gravity effects. However, some effects, which are believed to be of minor importance in the CFD analysis, should be taken into account in the local analysis. These effects are compressibility of the fluid, presence of the gas above the fluid surface and in the impact region, aeration of the fluid in the impact region, jetting and fine details of the flow in the jet root region, rapid increase of the wetted surface of the tank wall and the flexibility of the wall. Short duration of the impact stage allows us to simplify the local analysis and to use a combination of analytical and numerical methods instead of direct numerical calculations as in the global sloshing analysis by CFD. By introducing small time scale and appropriate scales of other variables and unknown functions which describe coupled hydrodynamics and structural response, we arrive at the complex boundary-value problem of hydroelasticity with a small parameter, see Korobkin *et al*. (2006), section 2.3. The small parameter has the order of the ratio between the liquid displacement and the length scale of the original problem. This ratio is small for impact situations. This fact allows us to use perturbations methods of asymptotic analysis to distinguish effects providing minor contributions and formulate the coupled problem of hydroelasticity with proper account for physical effects providing the most important contributions to the local loads and structure response. The asymptotic analysis of local fluid-structure interaction in the impact region is performed only for the hydrodynamic part of the problem. The structural part is presented by the original FEM model. Computations for simple structures were done by FEM and by analytical models with the aim to verify the local models of hydroelasticity, e.g. Korobkin *et al.* (2004), Malenica *et al.* (2006), Korobkin & Malenica (2006), and Ten *et al.* (2008). It is well accepted that very fine details of the fluid flow and pressure distribution are not very important for the stress distribution caused by the impact. Even the calculated pressures vary significantly; the stress evolution is believed to be much less sensitive to such variations. This implies that, in some sense, attempts to reproduce all details of the flow and pressure distribution during the impact have no meaning in practice, even if they lead to very interesting mathematical problems (Malenica *et al.,* 2006).

Basic principles of hydroelastic coupling

As already mentioned, due to the fact that the sloshing impact loads are most often characterized by extremely high pressure peaks localized in space and in time, the evaluation of the structural response can not be decoupled from the evaluation of the fluid flow and coupled hydro-structure numerical models are necessary. Usually we talk about the fully coupled or hydroelastic analysis, in contrast to the most common quasi static approach where the hydrodynamic loading is calculated independently by assuming the rigid structure and the resulting pressure field is simply applied to structural model as a static loading at each time step. Unfortunately most often, it is not possible to avoid the complex hydroelastic calculations in the present context where the duration of impact load is very short so that the dynamic amplification factor can vary significantly. This can be clearly seen from Figure 12, where the well known dependence of the maximum dynamic response of an elastic system on the impulse duration, is presented.

The main parameter here is the ratio of the impulse duration to the natural period of the elastic system. In sloshing impact situations this parameter can take any particular value. This Figure also shows that the hydroelastic effects can be both beneficial and dangerous, depending on t_1/T_0 ratio.

The methods for hydroelastic coupling are fundamentally different for the cases of incompressible and compressible fluid flow. Here below we briefly explain the basic principles.

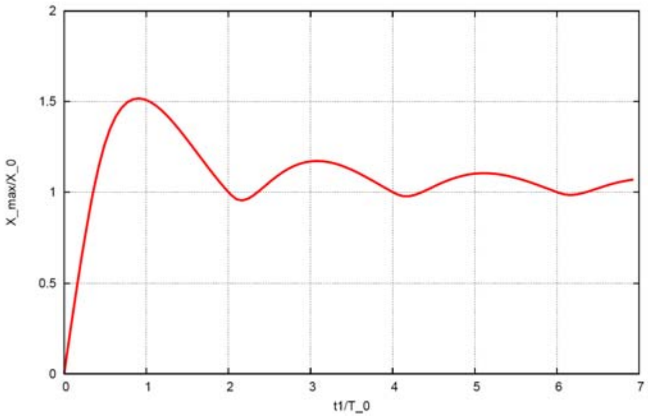

Figure 12 *Dynamic amplification factor for triangular impulsive loading (t_1 impulse duration, T_0 – natural period of the dynamic system). The loading is symmetrical around t = t_1/2 where it takes the maximum value $F_0 = kx_0$*

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It was shown in Korobkin and Malenica (2006), that the fully coupled hydroelastic equation for incompressible liquid impact can be written in the following form:

$$\frac{\partial^2}{\partial t^2}\Big\{[M + S(b)]\mathbf{W}\Big\} + K\mathbf{W} = \mathbf{Q}_r(b) \qquad (1)$$

where b(t) defines the dimension of the contact region, M and K are structural mass matrix and stiffness matrix of the structure, S(b) is the added mass matrix, which is calculated at each time instant during the impact stage, $Q_r(b)$ represents the generalized hydrodynamic loads with respect to the natural modes of the structure calculated without account for the structure deflections. There are also additional equations for the dimensions of the contact region between the fluid and the elastic structure. These equations are not shown here. Once the added mass matrix S(b) is known, the problem of hydroelasticity is reduced to a system of ordinary differential equations with respect to the dimensions of the contact region and the generalized coordinates W(t) of the structure response.

In the models with compressible fluid one needs to solve a system of integro-differential equations of the form

$$\frac{\partial^2}{\partial t^2}\Big\{M\mathbf{W} + \int_0^t S(t-\tau)\mathbf{W}(\tau)\mathrm{d}\tau\Big\} + K\mathbf{W} = \mathbf{Q}_r(t) \qquad (2)$$

It is important to notice that equations (1) and (2) do not require calculations of the hydrodynamic pressures but the time integrals of the pressure distribution is used instead. This highly improves accuracy and robustness of hydroelastic computations. Moreover, for several configurations the added mass matrix *S* was calculated analytically which allows the use of very large number of modes. In both methods the mode shapes are calculated using the 3D-FEM software (*Abaqus*).
Parallel to the semi analytical models of steep wave impact, the developments of an equivalent numerical model based on variational inequality method was also undertaken. The method was developed in the context of the 3D hydroelastic Wagner impact which is much more complicated than the 2D one, because of the difficulties related to the determination of the wetted part of the structure at each time step. This method is strong in the applications to truly 3D cases and to

complex geometrical configurations. The details of the method are explained in Gazzola (2007) and the method was validated against the semi-analytical results.

Comparisons with *Sloshel* experiments

In the following section we present few preliminary comparisons of the numerical results and the *Sloshel* experiments. First of all it is important to note that it is not straightforward to classify the impact types and some assumptions have to be made. This is illustrated in more details below.

For slosh impacts; with large (SL1) and small angle (SL2) between the breaking wave front and the wall; and for the air pocket (AP) impact Figure 13 shows pressures measured by gauges located on one vertical line. There are three typical pressure histories. In the different figures each line corresponds to the pressure history measured by a single gauge.

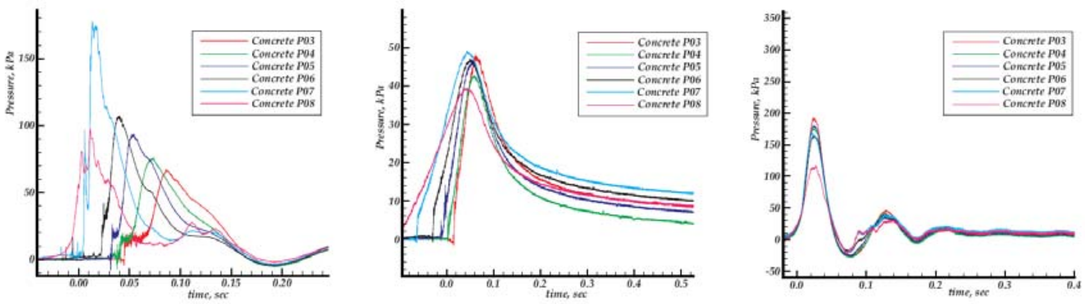

Figure 13 *Three typical pressure histories in the experiment: Wagner (SL1), steep (SL2) and breaking wave (AP) impacts. Pressure gauges are counted from the top.*

The gauges are numbered from highest to the lowest position. From the Figure 13 left, we can see that there is a shift between two adjacent gauges. It is due to the angle between the wall and the wave front. On the other hand, if the wave front is almost vertical, all gauges record the change of the pressure almost at the same time, so the figure in the middle corresponds to the steep wave impact - SL2. Finally, because of the oscillation of the air pocket in the system, there are oscillations after the impact. This is shown in Figure 13 right.

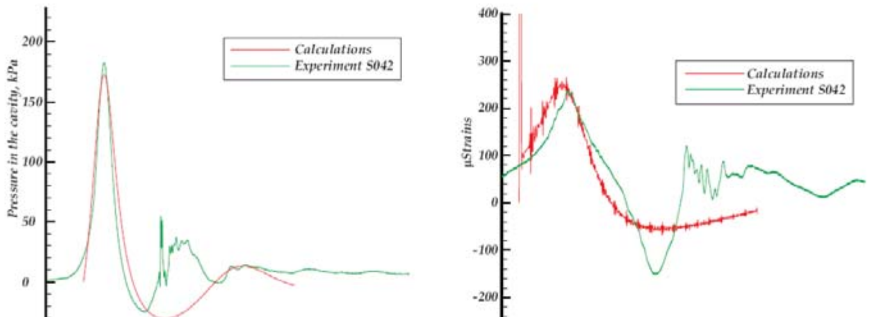

Figure 14 *Pressure in the air pocket (left) and strain (right) in the cover plate during the breaking wave impact.*

From the theory, the maximum pressure during the impact is estimated as *ρUc*, where *ρ* is the fluid density, *U* is the impact velocity, and *c* is the sound velocity in the fluid. If during the steep wave impact, the maxima of peaks happen almost in the same time, but the values are different, then we can suppose that it is because of variation of the sound speed and, thus, aerated wave impact should be considered. Following the described method above, we classified the experimental data to the Wagner (SL1), steep (SL2), breaking (AP) and aerated (AE) fluid impacts. In Figure 14 comparison between numerical and experimental results for breaking wave impact is presented.

Both the pressure in the air pocket and the strain in the cover plate are shown. Impact parameters are derived from *Sloshel* iCAM measurements, which allow us to determine the shape of the wave just before it impacts the wall. The strains are obtained by multiplying the general modal coordinates by the modal contributions which are obtained by Abaqus. As we can see the agreement is reasonably good.

The most violent impacts observed during *Sloshel* measurement campaign were of flip-through type. The code developed using Wagner approximation is used for the simulation of these impacts: actual shape of the wave front just before the impact was used with polynomial interpolation of the iCAMs measurements. In Figure 15 structural response calculated for one impact at two locations on the cover plate of the NO96 box is presented. The numerical results obtained with and without hydroelastic coupling are presented. A reasonably good agreement is observed.

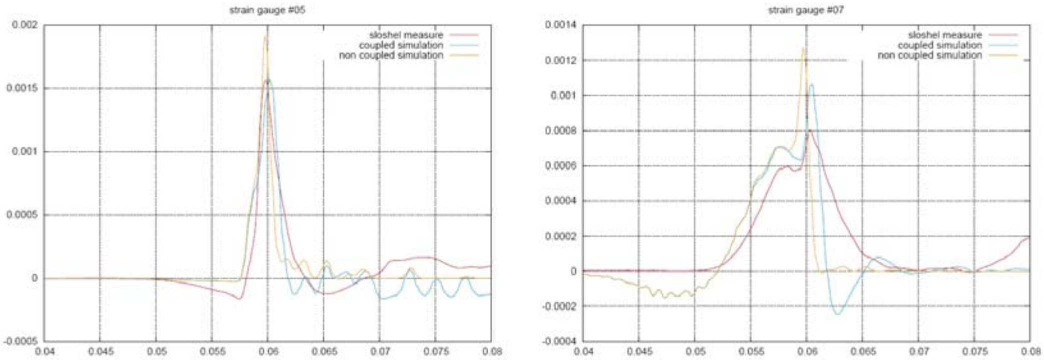

Figure 15 *Comparison of calculated and measured strains at strain gauges #5 (left) and #7 (right) for a flip through impact.*

DISCUSSIONS & CONCLUSIONS

In spite of all the efforts which were done up to now, in order to properly solve the sloshing impact associated hydro-structure issues, it is fair to say that still lot of uncertainties persist and it is not fully clear how they could be fully consistently solved in the near future. The in-service measurements of the LNG carriers during their normal operation would certainly be very helpful but, for the time being, it seems to be very difficult to perform these kinds of measurements. In the absence of the in-service measurements, a very ambitious *Sloshel* project was organized with the main goal to provide full scale sloshing impact data in laboratory conditions. The main ideas and achievements of the *Sloshel* project were briefly presented in this paper.

The *Sloshel* project can be considered as the first Full Scale Impact Tests of the NO96 containment system with wave impact conditions close to real sloshing impacts. The different systems and techniques that have been developed during *Sloshel* project, such as the rigid wall, the data acquisition and evaluation systems and the iCAM sensors, are now available to the consortium for further tests. An extensive and sound database from 110 full-scale tests has been compiled. Each test represents an impact of a breaking wave onto a wall equipped with a fully instrumented NO96 containment system and a rigid concrete block. Each impact has been recorded from the wave generation to the vibration of the supporting wall via the video recording of the wave, the pressure measurements, the strains and accelerations in the structure. The database gathered 185 Gigabytes of raw data. In the tests, a maximum local pressure of 26 bar and a maximum force of 5.4 tons was measured on the NO96 boxes without any structural damage. The analysis is still in progress and the conclusions regarding the hydro-elastic and the scale effects, and more validations of different numerical tools will be published by the consortium in the near future.

At the same time, important numerical developments have been carried as a part of the *Sloshel* project with the aim to propose and validate different models of fluid structure interaction in typical idealized impact conditions. The combined semi-analytical approach for fluid flow and 3DFEM model for structural response was chosen because it was judged that only relatively simple models can afford for a quick sensitivity analysis of the structural responses with respect to the different physical phenomena which occur during the sloshing impacts. In fact, it appears to be hopeless to try to look for quantitative assessment of the structural responses during the lifetime ship operations, because of an infinite number of cases which need to be considered. Only approximate approaches, as those presented in this paper or even simpler approaches based on estimates of loads and stresses but not on their evaluations, seem to be of practical meaning. In spite of rather important assumptions which are included in these models, we believe that the proposed semi-analytical models are representative enough of what happens in reality. We also believe that the combination of either small scale model tests, or global CFD sloshing analysis, for determination of the impact types and impact conditions, with the simplified local hydroelastic analysis, is a good candidate to provide the new rational methodology for structural assessment of the containment system and the associated ship structure. Having said that, it is clear that more validations of the numerical models are needed, and the *Sloshel* project seems to be an excellent place to get the realistic experimental database.

Let us finally note that another programme of Full Scale Impact Tests is scheduled for beginning of 2010 with the Mark III Containment System.

ACKNOWLEDGEMENTS

The opinions expressed in this paper are those of authors alone and do not necessarily represent the views of the *Sloshel* JIP Consortium.

The authors would like to acknowledge the support of the project partners which makes the *Sloshel* project possible: GTT, Shell, Ecole Centrale de Marseille, Chevron, American Bureau of Shipping, Lloyd's Register EMEA, Det Norske Veritas, Class NK. In particular the authors would like to acknowledge a valuable contributions from Prof. Y.M. Scolan (Ecole Centrale de Marseille), Prof. A.A. Korobkin (University of East Anglia) and B. Hofland (Deltares)

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