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A comparative study of sloshing in liquefied natural gas (LNG) carriers according the classification codes

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ABSTRACT: This paper assesses the design guidelines of different classification codes for the liquefied natural gas carriers considering the effect of liquid sloshing. With regard the increasing importance of LNG carriers in today's marine transportation, and also considering that the marine accidents involve significant loss, classification societies by regulating national and international standards aim to minimize the related risks. On the other hand, currently, industrial projects are being run in Iran for the design and construction of LNG carriers, and thus, the study of the liquid sloshing effect on the maneuvering ability of those ships is of prime importance. The present paper compares the approach of different marine classification codes in dealing with the sloshing effect in the design of LNG tanks. The outcome of this research is to introduce an integrated and complete procedure for the sloshing analysis.

Key words: *liquefied natural gas carrier; classification code; design standard; liquid sloshing.*

INTRODUCTION

With the start of liquefied natural gas transportation in the seas and oceans, issuing a class for the respective LNG carriers was first done in 1953 in Europe, and then as some marine accidents happened, the relevant codes were developed (Petroleum Economist, 2004). A Statistics of the LNG related accidents is available in Pitblado *et al*. (2004) and EIR (2006).

The enhancing market of the LNG carriers is evident: in 2005 the number was 199 ships, while in 2015 it is expected to be 397 ships. Also, the cargo capacity of the LNGCs has risen from 27,400 cubic meters in 1964 to about 250,000 cubic meters of LNG in 2010 (Offshore Energy, 2011), (Huang *et al*., 2007). Based on the above facts, the classification societies and research institutes are expected to take action and review the present design codes or develop newer codes. In other words, the only way to avoid damage and loss in this section is to assess different aspects of design of the tanks as well as the ships (Wang, 2007), (Vanem *et al*., 2008).

Some classification societies that have been publishing standards which involve the sloshing effect are as follow:

• American Bureau of Shipping-ABS
• Lloyd's Register-LR
• Bureau Veritas-BV
• Det Norske Veritas –DNV
• Germanischer Lloyd-GL
• International Association for Classification Societies-IACS
• Ship Structure Committee-SSC
• Seamanship International
• International Maritime Organization-IMO

The documents respective to the above mentioned organizations are summarized in Table 1.

In the January of 2007, the classification society of Norway (DNV) started a research project joint with the industry, in order to develop more reliable methods for the design of membrane type tanks carrying liquefied

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Table 1: Design codes for the liquefied natural gas carriers considering the effect of liquid sloshing

DOC. No.	TITLE	PUBLISHER	DATE	PAGES
1	DNV-OSS-303 RISK BASED VERIFICATION	DNV	APR-01	19
2	DNV-RP-A203 QUALIFICATION PROCEDURES FOR NEW TECHNOLOGY	DNV	AUG-01	42
3	DNV-OSS-103 LNG/LPG FLOATING P&S	DNV	OCT-08	18
4	DNV-OS-E201 HYDROCARBON PRODUCTION PLAN	DNV	OCT-2010	72
5	DNV-OS-C501 COMPOSITE COMPONENTS	DNV	OCT-2010	164
6	DNV-OSS-102 FLOATING PRODUCTION & STORAGE	DNV	OCT-2010	148
7	GL TECHNOLOGY SHIP VIBRATION	GL	2001	52
8	COMMON STRUCTURAL RULES FOR DOUBLE HULL OIL TANKERS	IACS	JAN-06	57
10	LNG CARGO TANKS: A SHIP MOTIONS ANALYSIS OF INTERNAL DYNAMIC LOADING	SSI	JAN-1974	39
9	EVALUATION OF LIQUID DYNAMIC LOADS IN SLACK LNG CARGO TANKS	SSC	1980	203
15	PREDICTION OF SLOSHING LOADS IN LNG SHIPS	SSI	JAN-1981	17
12	THE PREDICTION OF SLOSHING PRESSURE IN PRISMATIC TANKS OF LNG CARRIERS	SSI	JAN-1984	16
14	METHODOLOGY FOR LIQUID MOTIONS ANALYSIS	SSI	JAN-2000	14
10	ADVANCES IN ASSESSMENT OF LNG SLOSHING FOR LARGE MEMBRANE SHIPS	SSI	JAN-05	8
11	SLOSHING LOAD AND RESPONSES IN LNG CARRIERS FOR NEW DESIGN, NEW OPERATIONS AND NEW TRADES	SSI	JAN-05	34
13	PARTIAL FILLING OF MEMBRANE TYPE LNG CARRIERS	SSI	JAN-05	19
17	THE INTERNATIONAL CODE FOR CONSTRUCTION AND EQUIPMENT OF SHIPS CARRYING LIQUIFIED GASSES IN BULK -IGS CODE	IMO	JAN-1993	166
18	GUIDE FOR BUILDING AND CLASSING MEMBRANE TANK LNG VESSELS (HULL STRUCTURAL DESIGN AND ANALYSIS BASED ON THE ABS SAFEHULL APPROACH)	ABS	OCT-02	192
19	GUIDANCE NOTES ON STRENGTH ASSESSMENT OF MEMBRANE-TYPE LNG CONTAINMENT SYSTEMS UNDER SLOSHING LOADS	ABS	APR-06	90
20	GUIDE FOR BUILDING AND CLASSING OFFSHORE LNG TERMINALS	ABS	MAR- 08	150
21	STRUCTURAL DESIGN ASSESSMENT SLOSHING LOADS AND SCANTLING ASSESSMENT	LR	MAY-04	118
22	ADDITIONAL DESIGN PROCEDURES: PROCEDURE FOR ANALYSIS OF PUMP TOWER	LR	SEP-08	67
23	RULES FOR THE CLASSIFICATION OF OFFSHORE UNITS PT D, CH 1, SEC 3 STRUCTURE DESIGN PRINCIPLES	BV	APR-2010	11
24	PT B, CH 5, SEC 6 INTERNAL PRESSURES AND FORCES	BV	JUL-2010	10

natural gas. The main objective during the first phase of the project was to collect field data (using the actual ship) in response to the sloshing loads. During the next phase, prototype data were used to define the six degrees of freedom (DoF) motions of the laboratory model of the LNG tank and to record the sloshing pressures within the model tank. This way, validity of the DNV rules for sloshing, could be assessed (DNV, 2011). Also, the classification society of the United States (ABS), joint with the Daewoo shipbuilding (DSME), recently announced the results of a one-year research project which proposes a new method to indicate the most severe sea-states to be used in the sloshing model tests (Offshore Energy, 2011). Therefore, one may conclude that the design codes and standards for sloshing effect are the direct outcome of research studies.

Of course, within the limited pages of this paper, details of none of the codes in Table 1 may be completely explained; however, the highlights of sloshing effect in LR, BV and ABS are being compared. Strength assessment of membrane-type LNG containment systems under sloshing load which is discussed in the next section, illustrates a complete list of topics that should be covered in a sloshing code. In section three of this paper, the triangular impact function and the mathematic model of the sloshing load is introduced, which has a significant role in the design codes for the containment system design. Next, calculation of the internal pressures and loads due to liquid sloshing according the design codes and empirical formulas is presented. In section five, software application for the study of sloshing effect in the classification codes is pointed out. Finally, this research recommends that a complete course of sloshing study in LNGCs should analyze ship response amplitude operators (RAOs) and the tank inside, and the environmental conditions to which the LNGC is exposed, and should also cover the methods for sloshing model test, sloshing numerical simulation for different wave conditions and motion parameters, and also selecting critical sea-states and statistical analysis of sloshing impact loads. Also for extensive topics on sloshing the textbooks on dynamics of liquid sloshing in partly filled tanks may be referred to such as (Faltinsen and Timokha, 2009) and (Ibrahim, 2005).

MATERIALS AND METHODS

Strength assessment of containment systems under sloshing load

In this section, the major topics that should be covered in a sloshing code, according to the "Guidance notes on strength assessment of membrane-type LNG containment systems under sloshing loads" are discussed. The ABS sloshing code first introduces the sloshing phenomenon in the LNG carriers and then in the second part, explains the design under sloshing load. In order to design a LNG carrier with a 25 years service life in the North Atlantic, sloshing load on the containment system should be analyzed.

To represent the environmental conditions wave statistics in the North Atlantic is introduced in subsection 2–3 of the guidelines. Response Amplitude Operators (RAO) for the LNG carrier and the containment system in it, are described in subsections 2–5 and 2–7 of the guidelines so that to perform sea keeping analysis at every frequency and direction of waves. According the highly non-linear patterns of liquid sloshing motions, a long-term spectral analysis of the sloshing loads is impossible; instead, sloshing model test and numerical simulation for a selected number of wave conditions and motion parameters is required.

In subsection 2–9, critical sea-states and wave conditions are selected. To determine the sloshing deign load for the extensive structural analysis of the LNG containment system, statistics of the impact loads are analyzed. Data processing of the sloshing model tests to obtain the sloshing design loads is explained in subsection 2–11 of the ABS code.

In part three of the ABS code, three stages of the assessment of the containment system is introduced as follows:

1.Finite element analysis of static stresses and static buckling;

2.Linear dynamic analysis using a dashpot model for the liquefied gas;

3.Non-linear dynamic analysis accounting for the fluid-structure interaction.

The above stages are performed in a sequence: if the result is positive the design is approved and if it is negative the next stage is performed. If the result of all three stages is negative, then a newer design for the containment system is required. In parts four, five and six of the ABS code the above three stages are outlined respectively. Evidently, each stage of analysis requires a different definition for the material properties of the containment system.

Acceptance criteria for the loading on the containment system, that is the maximum load that the containment system may undertake before failure, is introduced in part seven of the ABS code for different failure modes, yield or rupture criterion, buckling criterion and serviceability limit criterion. Finally, the ABS code includes five appendices as follow:

1.Sloshing model test: requirements for the tank model, motion actuators, pressure sensors and the data acquisition system, and the method to define sea-states that produce critical sloshing condition.

2.Sloshing analysis: if the design of a LNG carrier is closely similar as previous designs, sloshing analysis may be used to decrease the sloshing loads in the newer design compared to the older one. First, the method to select the critical sloshing wave domain (CSWD) and then the sloshing analysis using computational fluid dynamics (CFD) tools are explained.

3.Triangular response function: sloshing impact is defined as a symmetric triangular function.

4.Material properties: material properties of the elements which are used in the construction of containment system as well as the properties of the liquefied gas are presented.

5.Parametric study of material properties and loading patterns: stress distribution inside the containment system for the layered foam type depends on if the containment system is assumed rigid or elastic.

Mathematic model of sloshing impact

In the study of sloshing effect according the design codes, a major step is to decide on the method to assess the sloshing wave impact on the structure. The triangular response function represents the time response of the structure to the short duration symmetric triangular impact. The structural system is assumed to be linear and the triangular response function , which is a function of time, is derived by solving the following linear system:

$$M\ddot{x} + C^{*}\dot{x} + Kx = p_N(t)f, \qquad t > 0$$
$$x = \dot{x} = 0, \qquad t = 0 \tag{1}$$

where M is the mass matrix, K the stiffness matrix, C the damping matrix which incorporates time convolution by * sign, to account for fluid-structure interaction and hydroelasticity effects, and f is a nodal unit force vector to account for the uniform unit force on the tank shell. The function   on the right-hand-side of (1), determines the magnitude and time change of sloshing impact force as follows:

$$p_N(t) = \begin{cases} 1 + \dfrac{Nt}{\Delta t}, & -\dfrac{\Delta t}{N} < t < 0; \\ 1 - \dfrac{Nt}{\Delta t}, & 0 < t \le \dfrac{\Delta t}{N}; \\ 0 & otherwise \end{cases} \tag{2}$$

The above relation expresses the impact force as a triangular function of time with a maximum value of identity, and its magnitude and duration may be changed by adjusting the N integer. Fig. 1 illustrates how to combine small magnitude triangular impact forces of duration one millisecond into an equivalent large impact force of duration 10 ms (say sloshing force). Similarly, in Fig. 2a, time response of stress in type MK-III containment system in response to a 1 ms impact is shown, which may be scaled and shifted on the time-axis in the same manner as in Fig. 1. The result as shown in Fig. 2b, is the combined stress response function to the 10 ms impact force which is shown in Fig. 2c and also it is consistent with numerical results.

Internal pressures and forces of sloshing

Next, it is necessary to introduce the internal pressures due to sloshing wave inside the tank and the approach used by the classification societies for modeling those pressures. The BV's code, titled internal pressures and forces, explains the partly filled tanks as they carry liquid cargo or ballast water. Notation "liquefied gas carrier" is used to indicate internal sloshing pressure is existing.

Resonance risk in partly filled tanks with liquid height dF where 0.1H ≤ dF ≤ 0.95H, and H is the tank height, according the criteria in Table 2, is investigated for two cases:

1.Ship pitch and longitudinal motion of liquid inside tank whilst ship upright.

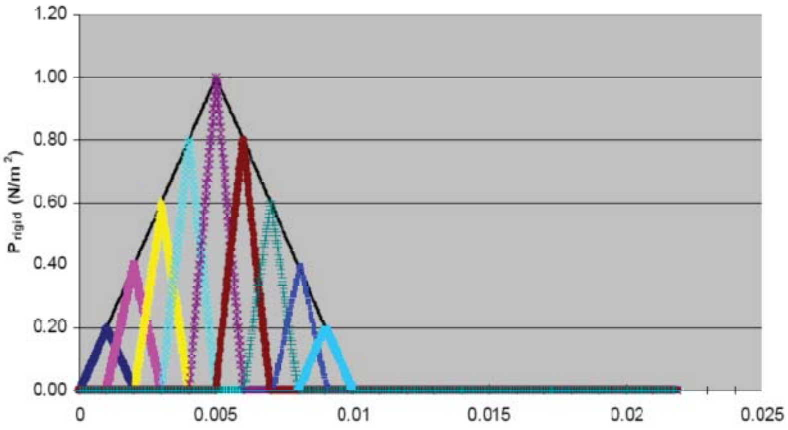

Fig. 1: Short duration one millisecond impact forces combined into a longer duration impact (ABS, Guidance for strength assessment).

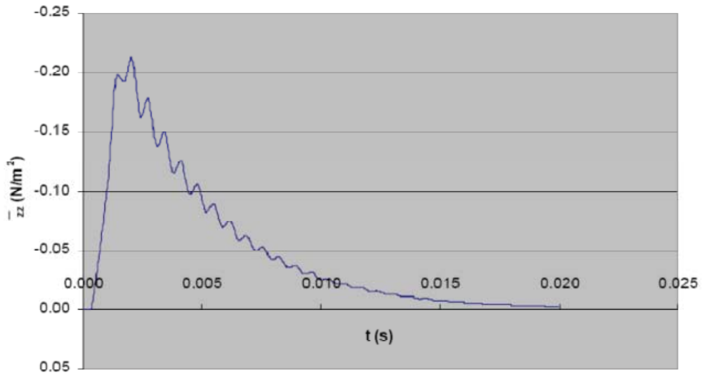

Fig. 2a

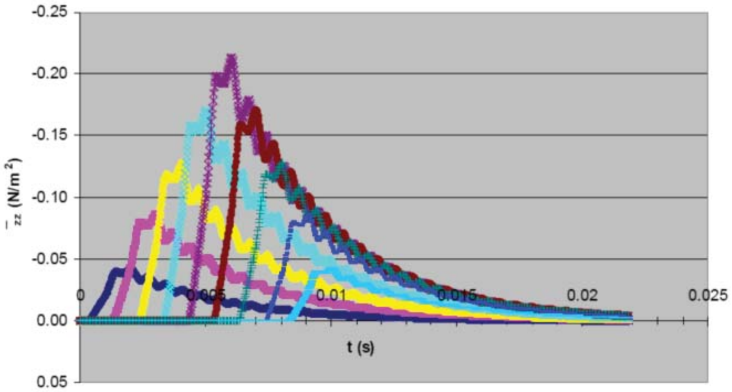

Fig. 2b

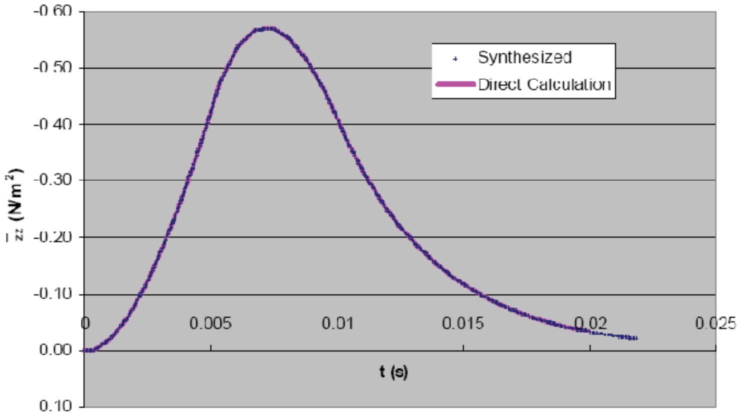

Fig. 2c

Fig. 2: Procedure to combine the triangular response and its comparison with numerical result (ABS, Guidance for strength assessment). a: Time response of stress in type MK-III containment system in response to a 1 ms impact. b: Time response of one millisecond stress which is scaled and shifted similar to the pattern in Fig. 1. c: Combined time response of stress in response to a 10 ms impact force

Table 2: criteria to investigate the risk of sloshing resonance in BV

Ship condition	Risk of resonance if:	Resonance due to:
Upright	$0.6<\frac{Tx}{Tp}<1.3$ and $\frac{d_F}{l_c}<0.1$	Pitch
Inclined	$0.8<\frac{Tx}{Tp}<1.2$ and $\frac{d_F}{l_c}>0.1$	Roll

2.Ship roll and transverse motion of liquid inside tank whilst ship inclined.

In Table 2, lC and bC respectively are the longitudinal and lateral distances between the watertight bulkheads of the tank. Also, TP and TR are respectively the pitch and roll period of the ship in seconds. Natural period of the liquid inside tank in longitudinal direction is TX in seconds which is calculated as follows:

$$T_X = \sqrt{\frac{4\pi l_S}{g\tanh(\frac{\pi d_F}{l_S})}} \quad (3)$$

Also, TY natural period of the liquid inside tank in lateral direction in seconds is as follows:

$$T_Y = \sqrt{\frac{4\pi b_S}{g\tanh(\frac{\pi d_F}{b_S})}} \quad (4)$$

where lS is the length and bS is the width of the liquid free surface, which are measured in metres while the ship is stationary horizontal, and depend on the filling height as shown in Figs. 3 and 4. As shown in Fig. 4, the transverse bulkheads reduce the free surface.

Dynamic pressure of the sloshing wave pSL for a filling height dF, where there is a risk of resonance, and the ship is upright, is considered as loading in a range 0.2dF higher and lower than the water level, on transverse bulkheads which are the boundaries of the tank. If there is no risk of resonance, but the tank length is more than 0.15 of ship length, the code accounts for sloshing dynamic pressure. Fig. 5 demonstrates the sloshing dynamic pressure distribution as triangular impact function in both longitudinal and transverse directions.

Where there is a risk of resonance, sloshing pressure, which was shown for a filling depth of dF in Fig. 5, is derived as a function of vertical distance z in KN/m^2:

$$\begin{aligned}
p_{SL} &= 0 && \text{for} \quad z \le 0.8d_F + d_{TB} \\
p_{SL} &= \left(5\frac{z-d_{TB}}{d_F} - 4\right)\alpha p_0 && \text{for} \quad 0.8d_F + d_{TB} < z \le d_F + d_{TB} \\
p_{SL} &= \left(6 - 5\frac{z-d_{TB}}{d_F}\right)\alpha p_0 && \text{for} \quad d_F + d_{TB} < z < 1.2 d_F + d_{TB} \\
p_{SL} &= 0 && \text{for} \quad z \ge 1.2 d_F + d_{TB}
\end{aligned} \quad (5)$$

where d_{TB} is the vertical distance between the bottom-line of the ship to the bottom of the tank, dF is the filling height, and p_0 is a reference pressure, the value of which is defined in Table 3 for upright and inclined ship conditions.

Factor alpha in (5) is defined as follows:

$$\begin{aligned}
\alpha &= \frac{d_F}{0.6H} && \text{for} \quad d_F < 0.6H \\
\alpha &= 1 && \text{for} \quad 0.6H \le d_F \le 0.7H \\
\alpha &= \frac{H-d_F}{0.3H} && \text{for} \quad d_F > 0.7H
\end{aligned} \quad (6)$$

In Table 3 the parameters l_C and b_C respectively are the longitudinal and transverse distance between the tank bulkheads, p_t density of liquid inside tank, and g is the gravity acceleration and the rest of parameters are defined inside the table.

Software application for sloshing analysis in classification codes

In this section, software application for sloshing analysis in classification codes is studied. The LR code, to analyze sloshing loads, describes the procedure for structural analysis of partly filled tanks. In this code, there are three layers of assessment to estimate the maximum sloshing pressure as follow:

• The first layer assessment is based on equivalent static loads due to angular motions during the vessels's lifetime.

• The second layer assessment utilizes the Structural Design Assessment (SDA) code, which has been specifically developed as a SDA Tank Assessment program No. 10603, to evaluate fluid pressures on the tank boundaries.

• The third layer assessment utilizes SDA Fluids program, which uses a finite difference method, to evaluate fluid pressures on the tank boundaries as well as the internal elements.

Structural assessment based on collapse resistance is performed by SDA Ultimate Strength program No. 10604.

The second layer assessment, as introduced above, is focused on rectangular tanks and tanks with inclined corners. To account for the corner effects correction factors are applied using the experimental data. The third layer of assessment includes different types of meshing and boundary conditions, as well as the spectrum of the excitation motions of the tank and time-step of the numerical iterations which may be adjusted accordingly.

RESULTS AND DISCUSSION

Comparing the three classification codes for sloshing respectively LR, ABS and BV codes arises the following discussion highlights:

1.The ABS sloshing code, emphasizes strength assessment for the containment system, and for this end, investigates the following items:

a- Determining the design environmental conditions and the method of selecting critical sea-states.

b- Processing the model test data in order to obtain sloshing design load.

c- Strength assessment of the containment system

Table 3: Definition of the reference pressure for upright and inclined ship conditions

Ship condition	Reference pressure p0 in KN/m²:	Definition of terms:
Upright	$0.84\varphi_U \rho_L g S l_c A_p$	φ_U equals one for the tanks with horizontal bottom or tanks with bottom transverse heights less than 0.1H, otherwise it equals 0.4. S is a factor defined as follows: S= 1+0.02L if $L \le 200$; S= 3+0.01L if $L > 200$. A_p is ship pitch amplitude in radians.
Inclined	$1.93\varphi_I \rho_L g b_c A_R \sqrt{B}\left(1-0.3\frac{B}{b_C}\right)$	φ_I equals zero if $bc/B \le 0.3$; and if $bc/B > 0.3$ equals one for the tanks with horizontal bottom or tanks with bottom transverse heights less than 0.1H, otherwise it equals 0.4. A_R is ship roll amplitude in radians.

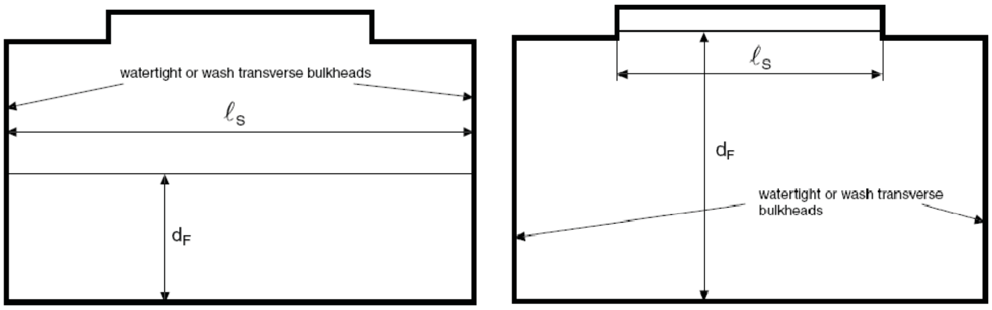

Fig. 3: Length of free surface which depends on the filling height (BV, Internal pressures and force)

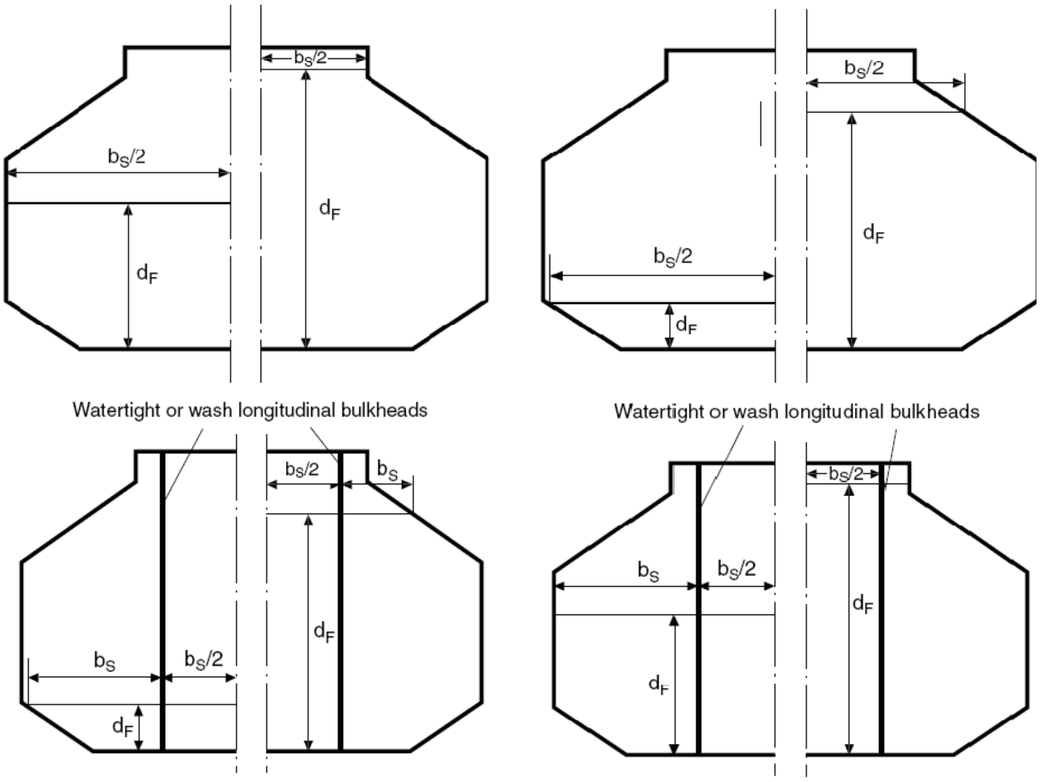

Fig. 4: Width of free surface which depends on the filling height and decreases if there are bulkheads (BV, Internal pressures and force)

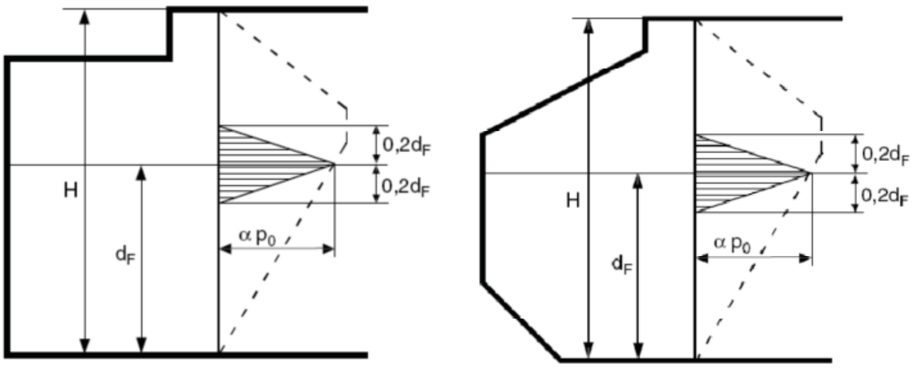

Fig. 5: Sloshing dynamic pressure distribution as triangular impact function in both longitudinal and transverse directions (BV, Internal pressures and force)

by defining its material properties in both static and dynamic analyses.

d- Defining the failure modes, the criterion for yield or rupture, buckling and serviceability limit under sloshing loads.

Also, a design software SH-LNG performs a design assessment with regard to the ABS safe hull guidelines, to ensure the design of the liquid containment system for a 40-year fatigue life-time and also under partly filled loading conditions.

2.The BV code however, classifies the vessels under the term liquefied gas carrier to indicate that sloshing pressure also applies within the tank. The BV code determines sloshing dynamic pressure in longitudinal direction due to ship pitching and longitudinal motion of liquid in tank while ship is upright; also, determines sloshing dynamic pressure in transverse direction due to ship rolling and lateral motion of liquid in tank while ship is inclined. Structural strength of the tank is analyzed as a part of the ship structure. Sloshing pressure and its wave impact is considered in the design of the tank bulkheads and its stiffeners.

3- In the LR code, strength assessment of the tank under sloshing loads, is presented by defining the tank walls geometry and their stringers, and the sloshing pressure as the analysis inputs and then, the plastic collapse stresses for the walls and stringers and the safety factors to prohibit collapse are the analysis outputs. For safe operations of the liquid cargo carrier, natural periods of the carrier are determined from where the loading conditions to prohibit sloshing resonance with ship motions are proposed.

CONCLUSION

In this research, the classification codes for sloshing effect in liquefied natural gas (LNG) tanks were introduced and reviewed. As was revealed in the discussions, BV code categorizes the sloshing effect under additional services and basically does not provide a stand-alone and integrated document for this purpose. Although, helpful empirical formulas and explanations both for the evaluation of sloshing pressures from a fluid mechanics point of view and for structural analysis under those pressures are presented in BV, a planned course of steps to assess the sloshing effect is lacking.

On the other hand, LR in its structural design assessment code, presents the sloshing load assessment and also provides a separate document for the pump tower analysis under sloshing loads. The LR class although provides a consequence to assess the structural design of the LNG tanks under sloshing loads, lacks to cover different aspects of sloshing analysis. In its guidelines, LR ignores major headlines such as sloshing model test, field study and numerical modeling of sloshing. In other words, LR is not concerned with leading the user through an integrated and complete sloshing analysis, but it presents a method to design the LNG tank under sloshing loads.

Eventually, the ABS guidelines for strength assessment of membrane-type LNG containment systems under sloshing loads, in 90 pages, covers a complete course of sloshing analysis in liquid carriers. The document, initiates with an introduction to ship response amplitude operators (RAOs) and the tank inside, and the environmental condition to which the LNGC is exposed, and follows into sloshing model test, sloshing numerical simulation for different wave conditions and motion parameters, and also selecting critical sea-states and statistical analysis of sloshing impact loads. The tanks considered are of membrane type with rectangular shape with fillet corners; however, the analysis procedure for other types of tanks is similar. Moreover, the ABS sloshing code, involves several supplementary material such as the pump tower design, software analysis SH-LNG, construction and classification of offshore LNG terminals, monitoring systems for ship hull conditions, materials and welding guidelines, and LNGC inspection guidelines.

To summarize, the approach of different marine classification codes in dealing with the sloshing effect in the design of LNG tanks were compared and the headlines for an integrated and complete procedure for the sloshing analysis were introduced.

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