



GUIDANCE NOTES ON

STRENGTH ASSESSMENT OF MEMBRANE-TYPE LNG CONTAINMENT SYSTEMS UNDER SLOSHING LOADS

APRIL 2006 (Updated February 2014 – see next page)

**American Bureau of Shipping
Incorporated by Act of Legislature of
the State of New York 1862**

**Copyright © 2006
American Bureau of Shipping
ABS Plaza
16855 Northchase Drive
Houston, TX 77060 USA**

Updates

February 2014 consolidation includes:

- July 2009 version plus Corrigenda/Editorials

July 2009 consolidation includes:

- April 2006 version plus Corrigenda/Editorials

Foreword

As a supplement to the hull structural strength requirements of LNG carriers, these Guidance Notes provide procedures for determination of the sloshing load on LNG cargo tanks and subsequent strength assessment of membrane type containment system. The technical approach adopted in these procedures is based on direct calculation method of applying sloshing load to the containment system using finite element analysis. Determination of sloshing load from numerical simulation and scaled model test is presented. The structural analysis of the containment system considers fluid-structure interaction between liquid cargo and the LNG containment system. The procedures also consider the effect of viscoelasticity when the containment system utilizes foam material. Acceptance criteria are provided for different part of the containment system considering the material properties and possible failure modes.

Users are referred to [Part 5C, Chapter 12 of the ABS Rules for Building and Classing Steel Vessels](#) which provides guidance on the requirements for the strength of hull structure of the membrane type LNG carriers. ABS also provides guidance on strength assessment of pump tower inside of LNG tanks in the *ABS Guidance Notes on Sloshing and Structural Analysis of LNG Pump Tower (2006)*.

GUIDANCE NOTES ON

STRENGTH ASSESSMENT OF MEMBRANE-TYPE LNG CONTAINMENT SYSTEMS UNDER SLOSHING LOADS

CONTENTS

SECTION 1	Introduction	1
1	Background	1
3	Overview of Sloshing Analysis and Strength Assessment Procedures	2
	FIGURE 1 Flowchart of Sloshing Analysis and Strength Assessment of LNG Containment System	3
SECTION 2	Design Sloshing Loads	4
1	Overview	4
3	Environmental Conditions	4
3.1	Basic Considerations	4
3.3	Wave Scatter Diagram	4
3.5	Wave Spectrum	5
5	Loading Conditions	6
5.1	Tank Location and Geometry	6
5.3	Filling Levels	6
5.5	Loading Conditions for Seakeeping Analysis	6
7	Analysis of Ship Motion and Extreme Value	8
7.1	Overview	8
7.3	General Modeling Considerations	8
7.5	Diffraction-Radiation Methods	8
7.7	Panel Model Development	8
7.9	Vessel Motion and Tank Acceleration Response Amplitude Operators	9
7.11	Ship Speed	9
7.13	Roll Damping Model	10
7.15	Extreme Values for Ship Motion	10
9	Selection of Critical Wave Conditions for Design Sloshing Load	10
9.1	Sea States for Sloshing Model Test	10
9.3	Regular Wave Conditions for Sloshing Analysis	11
11	Determination of Design Sloshing Load	12
11.1	Overview	12
11.3	Sloshing Model Test	12
11.5	Panel Pressure	14

11.7	Idealization of Impact Load.....	15
11.9	Damage Index	18
11.11	Statistical Analysis.....	21
11.13	Design Sloshing Load for Level 1 Assessment	21
11.15	Design Sloshing Load by Level 2 Assessment.....	22
11.17	Design Sloshing Load for Level 3 Assessment	22
11.19	Fluid-Structure Interaction	23
TABLE 1	IACS Wave Scatter Diagrams for the North Atlantic.....	5
TABLE 2	40-year and 1-year Waves for Sloshing Model Test Conditions	11
FIGURE 1	LNG Cargo Holds and No. 2 Tank Location	7
FIGURE 2	Definition Sketch of Membrane-Type LNG Tank	7
FIGURE 3	Flowchart for Evaluation of Design Sloshing Loads from the Model Test	13
FIGURE 4	Model Tank and Pressure Sensor Setup.....	13
FIGURE 5	Clustered Sensors at Tank Corner	14
FIGURE 6	Time History of Local Impact Pressure at Sensors A~P and Panel Pressure.....	15
FIGURE 7	Triangular Impulse for Uniform Pressure	16
FIGURE 8	Idealization Pressure Impulse by a Triangular Impulse	16
FIGURE 9	Sloshing Impact Pressure Time History.....	17
FIGURE 10	Sloshing Impact Patterns from a Model Test.....	18
FIGURE 11	Critical Locations for Level 2 Strength Assessment for a Layered Foam Type Containment System	20
FIGURE 12	Stress Response at Critical Locations for Different Impact Durations	20
FIGURE 13	Failure Load, $P_{failure}$, from the Failure Model at the Critical Locations.....	20
FIGURE 14	Two Different Scenarios for the Level 2 Strength Assessment.....	22
FIGURE 15	Selection of the Response-based Design Sloshing Load for Level 3 Assessment for the Scenario Shown in Figure 14(b).....	23
SECTION 3	Strength Assessment Overview of LNG Containment System	24
1	Containment System Configuration	24
1.1	Layered Foam Type Containment System	24
1.3	Box Type Containment System	25
3	Static and Dynamic Material Properties.....	25
3.1	Isotropic Elasticity.....	26
3.3	Orthotropic Elasticity	26
3.5	Viscoelasticity	27
3.7	Acoustic Medium	28
3.9	Material Properties of Mastic, Plywood, Polyurethane Foam and LNG	28
5	Overview of Strength Assessment of LNG Containment System.....	29

TABLE 1	Material Properties of Mastic, Plywood, Polyurethane Foam and LNG.....	29
FIGURE 1	Schematic Drawing of GTT Mark III Containment System	24
FIGURE 2	Schematic Drawing of GTT NO 96 Containment System.....	25
FIGURE 3	Schematic Showing Coordinate System and Sample Labels for Plywood (PW)	26
FIGURE 4	Schematic Representation of Relaxation Modulus as a Function of Time in SLS.....	27
FIGURE 5	Three Levels of Strength Assessment for LNG Containment Systems	30
SECTION 4	Finite Element Analysis of Containment System (Level 1).....	31
1	General	31
3	Geometry and Material Properties of Individual Components	31
5	Finite Element Mesh and Coordinate System	33
7	Loading and Boundary Conditions.....	35
9	Solution Procedures.....	36
9.1	Procedures for Layered Foam Type Containment System	36
9.3	Procedures for Box Type Containment System	36
FIGURE 1	Simplified Model for Mark III Containment System	32
FIGURE 2	Simplified Model for NO 96 Containment System	33
FIGURE 3	FE Mesh for Simplified Model of Mark III Containment System	34
FIGURE 4	FE Mesh for Simplified Model of NO 96 Containment System	34
FIGURE 5	Loading and Boundary Conditions for Simplified Model of Mark III Containment System.....	35
FIGURE 6	Loading and Boundary Conditions for Simplified Model of NO 96 Containment System	35
SECTION 5	Finite Element Analysis of Containment System (Level 2).....	37
1	General	37
3	Geometry and Material Properties of Individual Components	38
5	Finite Element Mesh and Coordinate System	38
7	Loading and Boundary Conditions.....	39
9	Solution Procedures.....	39
9.1	Procedures for Layered Foam Type Containment System	39
9.3	Procedures for Box Type Containment System	40
FIGURE 1	FE Mesh for Simplified Model of Mark III Containment System	38
FIGURE 2	FE Mesh for Simplified Model of NO 96 Containment System	39

SECTION 6	Finite Element Analysis of Containment System (Level 3)	41
1	General	41
3	Geometry and Material Properties of Individual Components	41
5	Finite Element Mesh and Coordinate System	44
7	Loading and Boundary Conditions	45
9	Fluid-Structure Interaction	47
11	Solution Procedures	48
11.1	Procedures for Layered Foam Type Containment System	48
11.3	Procedures for Box Type Containment System	49
FIGURE 1	Coupled Model for Mark III Containment System	42
FIGURE 2	Coupled Model for NO 96 Containment System	43
FIGURE 3	FE Mesh of Mark III Containment System	44
FIGURE 4	FE Mesh of NO 96 Containment System	45
FIGURE 5	Loading and Boundary Conditions for Coupled Model in Mark III Containment System	46
FIGURE 6	Loading and Boundary Conditions for Coupled Model in NO 96 Containment System	47
SECTION 7	Acceptance Criteria	50
1	General	50
3	Failure Modes	50
3.1	Yield/Rupture Failure	50
3.3	Buckling Failure	50
3.5	Serviceability Limit	50
5	Yield/Rupture Criterion	51
7	Buckling Criterion	52
9	Serviceability Limit Criterion	52
TABLE 1	Applicable Values of Strength Reduction Factor (SRF)	52
APPENDIX 1	Sloshing Model Test	53
1	Overview	53
3	Test Facility	53
3.1	Tank Model	53
3.3	Ullage and Density Effect	53
3.5	Pressure Sensors	53
5	Tank Motion	54
5.1	Generation of Tank Motion	54
5.3	Verification of Tank Motion	54
7	Data Acquisition	55
7.1	Specification of Data Acquisition System	55
7.3	Data Filtering	55
7.5	Data Format for Submission	55

9	Spatially-Averaged Panel Pressure	55
9.1	Basic Considerations	55
9.3	Load Cell vs. Spatial Averaging	55
11	Search of Critical Sea States	55
11.1	Selection of Headings	55
11.3	Selection of Filling Levels	56
11.5	Repeated Test for Critical Condition	56
APPENDIX 2	Sloshing Analysis.....	57
1	General	57
3	Wave Conditions for Sloshing Analysis	57
3.1	Critical Sloshing Wave Domain (CSWD)	57
3.3	Critical Sloshing Wave Conditions	58
5	Sloshing Simulation	58
5.1	Requirement for CFD Tool.....	58
5.3	Validation of CFD Tool.....	58
5.5	Modeling of LNG Tanks	58
5.7	Mesh Size and Time Stepping.....	58
5.9	Duration of Simulation	59
5.11	Panel Pressure	59
5.13	Numerical Results for Impact Pressure	59
7	Design Sloshing Loads	59
7.1	Combination of Sloshing Load.....	59
7.3	Comparative Evaluation of Design Sloshing Load	60
FIGURE 1	Modeling of LNG Tank for Two-Dimensional Sloshing Analysis	60
FIGURE 2	Example of Segment Paneling: Segment 1 for Transverse Motion	60
APPENDIX 3	Triangular Impulse Response Function	61
1	Definition	61
3	Synthesis of Structural Response.....	61
FIGURE 1	Synthesis of a Triangular impulse by Shorter-Duration Pulses	62
FIGURE 2	Synthesis of a Stress Response by a Triangular Impulse Response Function	63
APPENDIX 4	Material Properties	65
TABLE 1	Material Properties of Mastic	65
TABLE 2	Material Properties of Plywood	65
TABLE 3	Material Properties of Polyurethane Foam	65
TABLE 4	Material Properties of LNG	66
TABLE 5	Ultimate Strengths of Polyurethane Foam, Plywood, and Mastic.....	66

APPENDIX 5 Parametric Study of Material Properties and Loading Patterns..... 67

FIGURE 1	Effect of Material Properties on Stress Response at Interface from Hydro-elastic/Hydro-visco-elastic Analysis on Mark III Containment System	68
FIGURE 2	Hydro-elastic/Hydro-visco-elastic Load Factor for Different Skewness and Durations in Mark III Containment System.....	69

This Page Intentionally Left Blank

SECTION 1 Introduction

1 Background

The design and construction of the hull, superstructure and deckhouses of an ocean-going vessel are to be based on all applicable requirements of the *ABS Rules for Building and Classing Steel Vessels*, (referred to as *ABS Steel Vessel Rules*). In particular, the LNG carrier specific requirements are provided in *ABS Steel Vessel Rules*, Part 5C, Chapter 8. ABS also provides alternative strength requirements of hull structure based on dynamic loading approach, known as the ABS SafeHull approach, in *Part 5C, Chapter 12 of the ABS Rules for Building and Classing Steel Vessels*.

Inside of the membrane-type LNG tank hull structure, there are two major structural systems – LNG containment system and pump tower structure. These Guidance Notes provide procedures for determination of the sloshing load inside of LNG cargo tanks and subsequent strength assessment of membrane-type containment systems. ABS also provides guidance on strength assessment of the pump tower inside LNG tanks in the *ABS Guidance Notes on Sloshing and Structural Analysis of LNG Pump Tower*.

The membrane-type LNG containment system consists of thin metal membranes to prevent cargo leakage, foam or powdery insulation material to maintain the low temperature to keep the LNG cargo in a liquid state and an associated structure to retain the membrane and insulation material and to secure them to the hull structure.

Sloshing of LNG cargo can cause high impact loads on the supporting and containing structures. This is particularly critical for membrane-type tanks since these will have flat surfaces and corner regions which can lead to increased peak pressures for sloshing impacts. Sloshing loads are typically estimated using a scaled model test or numerical simulation using computational fluid dynamics (CFD) methods. In the scaled model test, a tank partially filled with water is subjected to oscillatory motions to simulate the ship motions. The resulting pressures on the tank wall are then measured. Sloshing in a real LNG tank involves many complicated physical phenomena such as wave breaking, phase transition between liquid and gas during the impact, gas entrapment, cushioning effect due to corrugation, etc.

The membrane-type containment system is much more flexible compared to the steel hull structure. As a result, fluid-structure interaction plays an important role in the structural analysis of the containment system under sloshing load. Furthermore the property of foam material is viscoelastic that the structural response of containment system is dependent on the time rate of sloshing impact loading.

These Guidance Notes are prepared in response to the need to offer a more advanced strength assessment of the containment system beyond the simpler comparative method. The technical approach adopted in these procedures is based on the direct calculation method of applying sloshing loads to the containment system using finite element analysis. Determination of sloshing loads from numerical simulation and scaled model test is presented. The structural analysis of the containment system considers fluid-structure interaction between liquid cargo and the LNG containment system

The procedures also consider the effect of viscoelasticity when the containment system is partly made of foam material. Acceptance criteria are provided for different members of the containment system, considering the material properties and possible failure modes.

The safety is of paramount concern to ABS and all the parties involved in design, construction and operation of the LNG carriers. ABS considers the procedures in these Guidance Notes “best engineering practice” to determine the safety of the containment system, in assisting the ship builders and the containment system developers.

3 Overview of Sloshing Analysis and Strength Assessment Procedures

The flowchart of the sloshing analysis and strength assessment of LNG containment system is shown in Section 1, Figure 1. Two major approaches are provided in the assessment procedure: namely the comparative approach and the absolute approach.

The comparative approach may be used for the standard size tank or conventional designs that are similar to proven previous designs with a good service experience. The scale model test is to be used to determine the sloshing load of new design. Alternatively sloshing simulation using CFD method may also be used if it is validated adequately with model tests. CFD simulation is often used on a comparative base for slightly deviated design from the base design or for different environmental conditions from the existing scale model tests. The measured sloshing load of the new design is to be compared with the sloshing load of the previous design. Comparative evaluation of sloshing load is then made to ensure that sloshing load of new design does not exceed the load of previous proven design.

If the strength of new containment system is changed or increased from the previous design, the beneficial effect on the strength may be considered in the final assessment. The dashed arrows in Section 1, Figure 1 represent the analysis path for the comparative method. However, the comparative method may not be reliable when a major design parameter, such as the size, configuration, and proportion of the cargo tanks, changes significantly beyond the proven design range. For a novel design, or a new design that goes beyond the proven design, the absolute approach based on the direct calculation is to be used.

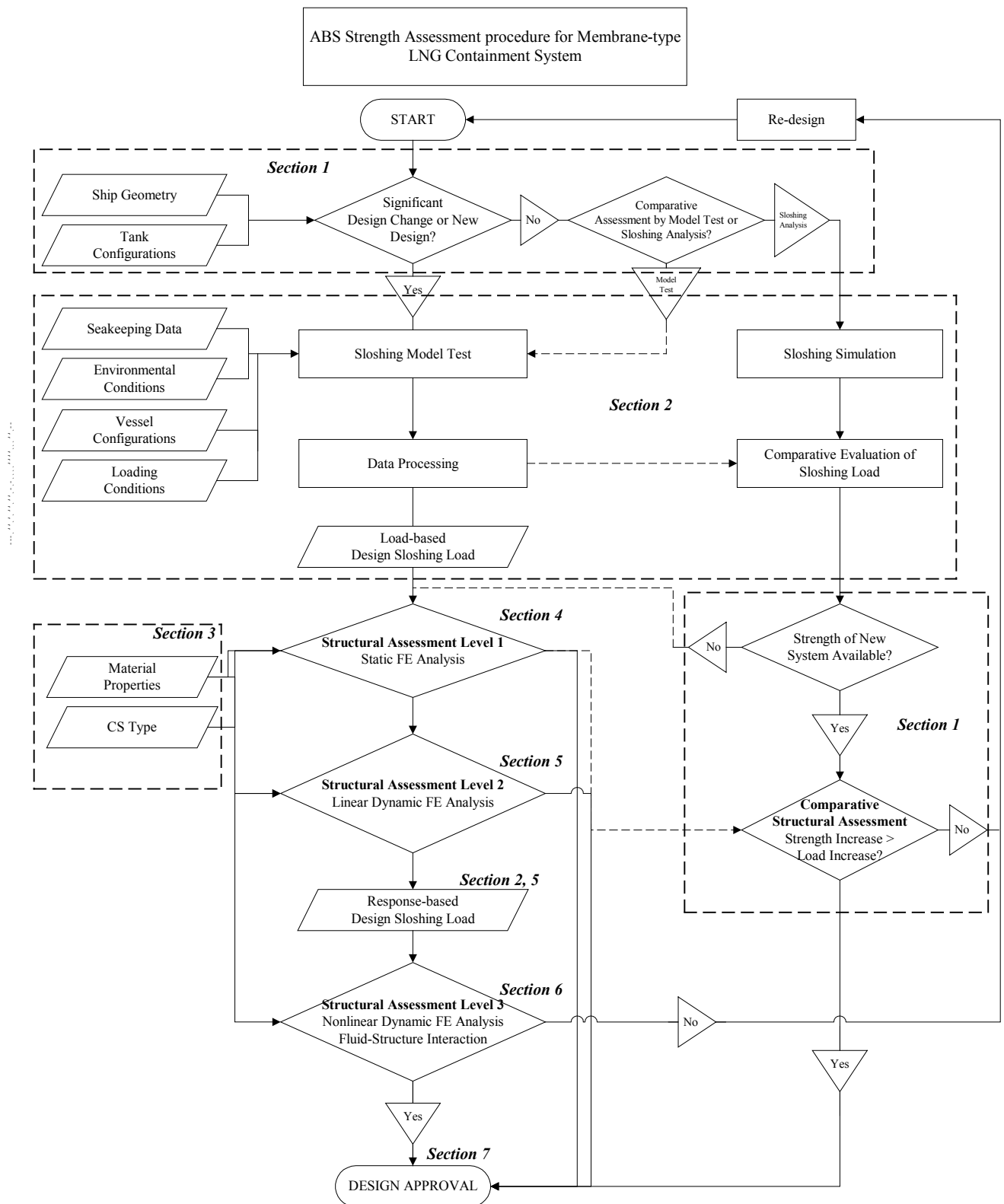
In the analysis procedures for the absolute approach, the sloshing load is first determined based on sloshing load measurement that is conducted in small model scale. The measured sloshing load is further evaluated considering dynamic structure response subject to sloshing impact load in order to determine the critical load cases for FE analysis. For this purpose, a simpler linear FE structural analysis may be used accounting for fluid-structure interaction and visco-elastic property of the containment systems. Sloshing impact pressure is represented by a triangular pattern to model duration and rising time of the sloshing impact. Section 2 describes the design sloshing loads for three different levels of structural analyses.

Once the design sloshing load is determined, structural analysis is to be performed to calculate the critical responses for various failure modes. Section 3 describes an overview of the strength assessment of LNG containment system and followed by FE analysis procedures for three different levels of complexity in Section 4, 5 and 6. Level 3 assessment requires a nonlinear FE analysis using coupled fluid-structure model.

It should be noted that any of the three assessment levels in these guidance notes might be independently applied for the strength evaluation of LNG containment systems. A more advanced analysis than the Level 3 considering directly sloshing and fluid-structure interaction may also be used in the strength assessment of LNG containment systems.

Finally strength assessment is to be made based on the acceptance criteria for various failure modes described in Section 7.

FIGURE 1
Flowchart of Sloshing Analysis and Strength Assessment
of LNG Containment System



SECTION 2 Design Sloshing Loads

1 Overview

To meet the design objective of a nominal 25-year service life in the North Atlantic Ocean, the extreme sloshing loads during the lifetime of an LNG carrier need to be evaluated for the structural assessment of containment system. The wave scatter diagram to represent the design environmental conditions is described in Subsection 2/3. The long-term statistics of ship and tank motion can be calculated by spectral-based statistical analysis, which relies on linear superposition principle of wave and ship motion. Ship and tank motion Response Amplitude Operators (RAO) for each wave heading and frequency are calculated to evaluate the long-term extreme value of the motion responses. The required input parameters and requirements of the seakeeping analysis are described in Subsections 2/5 and 2/7.

Spectral-based long-term analysis is not feasible for the sloshing loads since sloshing-load RAOs are not available due to severe nonlinearity in liquid motion response. Instead, sloshing model tests and simulations are performed for the limited number of sea or wave conditions that have been selected based on return period of sea states, proximity of wave period to sloshing resonance period and magnitude of dominant motion parameters. The selection process for the critical sea states and wave conditions is described in Subsection 2/9.

The time history of sloshing impact loads obtained by the sloshing model test is processed to identify the most critical sloshing load on the containment system structure. Panel pressure averaged over a specified area is preferred to the local impact pressure measured at individual pressure sensor locations. Magnitude, duration and rise time of each impact pulse are examined to evaluate their structural influence of each pulse. Statistical analysis of the impact loads is performed to determine design sloshing loads for the detail structural analysis of the LNG containment system. The processing of model test data to obtain design sloshing loads is described in Subsection 2/11.

3 Environmental Conditions

3.1 Basic Considerations

For unrestricted service, a 25-year return period using wave statistics of the North Atlantic is ordinarily specified to establish design values for controlling environmentally induced effects.

For an LNG carrier, environmentally induced loads are dominated by waves, which are characterized by significant heights, spectral shapes and associated wave periods.

Unless special consideration is granted, an LNG carrier is assumed to operate for unrestricted service in the North Atlantic. The standard wave data for the North Atlantic is given by the wave scatter diagram provided by the IACS Recommendation No.34 (Nov. 2001). The wave scatter diagram is used to calculate the extreme sea loads with a return period of about 25 years, corresponding to 10^{-8} probability of exceedance per wave cycle.

3.3 Wave Scatter Diagram

A wave scatter diagram provides the probability or number of occurrences of sea states in a specified ocean area. Section 2, Table 1 shows the wave scatter diagram by IACS to be used for sloshing analysis. The number in each cell gives the probability of the sea states for the given zero-crossing period, T_z , and significant wave height, H_s . The probability of each sea state is given in terms of the number of occurrences among 100,000 occasions.

3.5 Wave Spectrum

The two-parameter Bretschneider spectrum is used to model open sea wave conditions in the seakeeping analysis and the “cosine squared” spreading is applied to model short crest waves. The wave spectrum is given by:

$$S(\omega) = \frac{1.25\omega_p^4 H_s^2 e^{-1.25\left(\frac{\omega_p}{\omega}\right)^4}}{4\omega^5}$$

where

- S = wave energy density, in $\text{m}^2 \text{sec}$
 ω = angular frequency of wave component, in rad/sec
 ω_p = peak frequency = $2\pi/T_p$, in rad/sec
 T_p = $1.41T_z$
 H_s = significant wave height, in m

TABLE 1
IACS Wave Scatter Diagrams for the North Atlantic

	T_z (sec)																	
H_s (m)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	Sum	
0.5	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3050	
1.5	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22575	
2.5	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23810	
3.5	0.0	0.2	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19128	
4.5	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0	13289	
5.5	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8328	
6.5	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806	
7.5	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586	
8.5	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1309	
9.5	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626	
10.5	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285	
11.5	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124	
12.5	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51	
13.5	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21	
14.5	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8	
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3	
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1	
Sum	1	165	2091	9280	19922	24879	20870	12898	6245	2479	837	247	66	16	3	1	100000	

5 Loading Conditions

5.1 Tank Location and Geometry

LNG carriers usually have 4 to 5 tanks. Section 2, Figure 1 illustrates an LNG carrier with four tanks. The forwardmost cargo tank (No. 1 tank), is usually smaller than the other tanks and may have a tapered shape to conform to the bow area. The other cargo tanks are usually similar in size with a uniform transverse cross-sectional shape. In most cases, the No. 2 tank is considered to have the highest sloshing motion due to its size and distance from the ship motion center. For sloshing model test and numerical simulation, the geometry of the tank inside of the containment system should be exactly modeled. If the surface of the containment system is corrugated, as in the Mark III system, the obstruction due to corrugation can be neglected. Section 2, Figure 2 shows definition of principal dimensions of a typical membrane-type LNG tank.

5.3 Filling Levels

Filling levels for the sloshing analysis are to be selected based on the loading manual provided by the designer. Otherwise, the standard filling levels plus selected representative partial filling levels are to be analyzed. Filling levels are usually given in terms of relative filling height to the tank height, h , (%H) or the tank length, ℓ , (%L). Section 2, Figure 1 shows a definition sketch of a typical membrane-type LNG tank. All of the dimensions are defined for the inner surface of the LNG tank. The thickness of the containment system is to be deducted when calculating tank dimensions from hull drawing.

“Standard filling level” denotes filling levels higher than 70%H and lower than 10%L for LNG carriers with capacity lower than 150,000 m³. The following filling levels are to be considered in the sloshing analysis for pump tower analysis: 10%L, 70%H, 80%H, 90%H and 95%H.

When there is no restriction on filling level, the following filling levels are to be considered in the sloshing analysis in addition to the standard filling levels: 25%H, 30%H, 40%H, 50%H and 60%H.

5.5 Loading Conditions for Seakeeping Analysis

The draft, metacentric height and center of gravity of ship, which are important parameters for seakeeping analysis, can be different for each filling levels. In general, seakeeping analysis for each filling level should be performed with the loading conditions provided in the loading manual.

For standard filling levels, the following two representative loading conditions can be used for high and low filling levels:

- *Filling levels higher than or equal to 70%H:* Full load condition at arrival
- *Filling levels lower than or equal to 10%L:* Ballast condition at arrival.

FIGURE 1
LNG Cargo Holds and No. 2 Tank Location

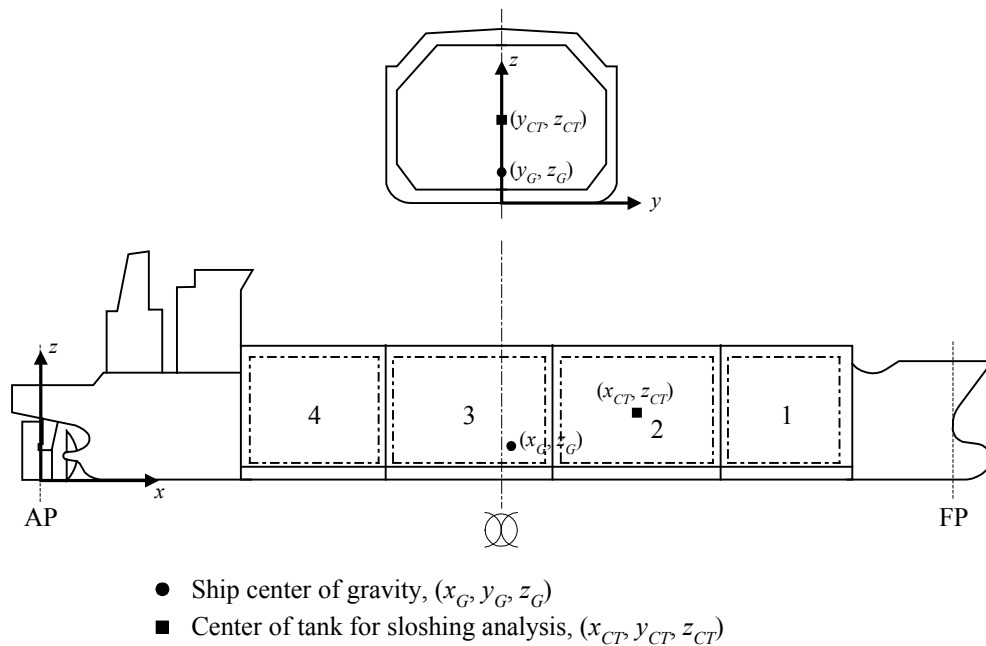
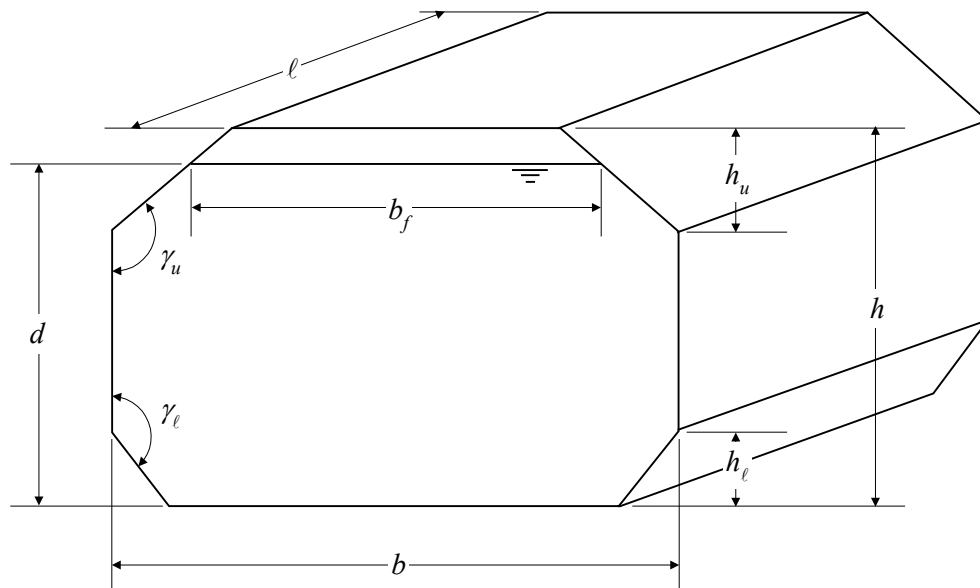


FIGURE 2
Definition Sketch of Membrane-Type LNG Tank



b : tank breadth
 b_f : breadth of the still water surface
 Filling level = d/h (%H) or d/l (%L)
 h_l : low chamfer angle
 γ_l : low chamfer angle

h : tank height
 d : filling height
 h_u : upper chamfer height
 γ_u : upper chanfer angle

7 Analysis of Ship Motion and Extreme Value

7.1 Overview

This Subsection lists the essential features about the calculation of ship and tank motions. It is expected that such calculations will be made using the Spectral-based approach, which, by definition, relies on the use of *Response Amplitude Operators* (RAOs). Each RAO is to be calculated for regular waves of unit amplitude for ranges of wave frequencies and wave headings that will be given below. RAOs of tank motions will be utilized to synthesize irregular tank motion for the sloshing model test. Details are described in Appendix 1.

This Subsection also specifies the expected outcome of seakeeping analysis to establish an Extreme Value of ship and tank motions. The RAOs and extreme values will be used to determine the wave condition and tank motion for the sloshing analysis based on regular tank motion.

7.3 General Modeling Considerations

The hull-geometry of an LNG carrier is to be accurately modeled from the offset data provided by designer. The location of center of gravity, mass and radius of gyrations for each loading conditions and filling levels are to be obtained from the loading manual provided by designer.

Sometimes, radii of gyration of an LNG carrier are not provided in the early design stage of the vessel. The following empirical value can be used when those data are not available:

$$r_{xx} = \begin{cases} 0.35B, & \text{for full load condition} \\ 0.45B, & \text{for ballast condition} \end{cases}$$

$$r_{yy} = r_{zz} = 0.25L_{pp}$$

where

r_{xx}	=	roll radius of gyration
r_{yy}	=	pitch radius of gyration
r_{zz}	=	yaw radius of gyration
B	=	breadth of vessel
L_{pp}	=	length between perpendiculars

7.5 Diffraction-Radiation Methods

Computations of the wave-induced motions are to be carried out through the application of seakeeping analysis codes utilizing three-dimensional potential flow based diffraction-radiation theory. All six degrees-of-freedom rigid-body motions of the vessel are to be accounted for. These codes, based on linear wave and motion amplitude assumptions, make use of boundary element methods with constant-source panels over the entire wetted surface of the hull on which the hydrodynamic pressures are computed.

If seakeeping analysis tools other than those provided by ABS are used, the results of the seakeeping analysis for the benchmark LNG vessels provided by ABS are to be submitted to ABS to ensure that the seakeeping tools are compatible with the procedures provided in these Guidance Notes.

7.7 Panel Model Development

Boundary element methods, in general, require that the wetted surface of the vessel be discretized into a large number of panels. The panel is to be fine enough to resolve the incoming and diffracted wave with reasonable accuracy. It is recommended that at least four panels be included within one wavelength.

7.9 Vessel Motion and Tank Acceleration Response Amplitude Operators

RAOs are to be calculated for the six degrees of freedom global vessel motion and local accelerations at the center of the tank. Only these responses need to be considered for the calculation of extreme values. The transverse and longitudinal acceleration at the tank center is defined in the moving coordinate system fixed at the tank and includes the effect of inclination and gravity:

- Longitudinal acceleration at tank center:

$$A_x = \ddot{X}_1 + (z_{CT} - z_G) \ddot{X}_5 - (y_{CT} - y_G) \ddot{X}_6 + gX_5$$

- Transverse acceleration at tank center:

$$A_y = \ddot{X}_2 - (z_{CT} - z_G) \ddot{X}_4 + (x_{CT} - x_G) \ddot{X}_6 - gX_4$$

- Vertical acceleration at tank center:

$$A_z = \ddot{X}_3 + (y_{CT} - y_G) \ddot{X}_4 - (x_{CT} - x_G) \ddot{X}_5$$

where

x_G, y_G, z_G	=	ship center of gravity, in m
x_{CT}, y_{CT}, z_{CT}	=	center of tank for sloshing analysis, in m
g	=	gravitational constant (= 9.8065 m/s ²)
$X_1, \ddot{X}_1$	=	surge and longitudinal acceleration at the ship C.G., in m, m/s ² , respectively
$X_2, \ddot{X}_2$	=	sway and lateral acceleration at the ship C.G., in m, m/s ² , respectively
$X_3, \ddot{X}_3$	=	heave and vertical acceleration at the ship C.G., in m, m/s ² , respectively
$X_4, \ddot{X}_4$	=	roll and roll acceleration, in rad, rad/s ² , respectively
$X_5, \ddot{X}_5$	=	pitch and pitch acceleration, in rad, rad/s ² , respectively
$X_6, \ddot{X}_6$	=	yaw and yaw acceleration, in rad, rad/s ² , respectively

The locations of center of gravity of the ship and tank are shown in Section 2, Figure 2.

The RAOs are to represent the pertinent range of wave headings, θ , in increments not exceeding 15 degrees, from following seas (0 degrees) to head seas (180 degrees).

It is important that a sufficiently broad range of wave frequencies is considered. The recommended range is 0.2 radians/second (rad/s) to 1.2 rad/s, in increments of 0.05 rad/s.

In these Guidance Notes, RAOs for surge, sway, heave, roll, pitch and yaw motion will be referred to as RAO₁, RAO₂, ..., RAO₆, respectively. The longitudinal, transverse and vertical RAOs will be referred to as RAO₇, RAO₈ and RAO₉, respectively.

7.11 Ship Speed

For the calculation of RAOs to be used for the long-term statistics of ship motion and sloshing analysis, ship speed of 75% of design speed should be considered.

For the calculation of RAOs to be used for the tank motion in sloshing model test, different ship speeds may be used for different sea states. The reduction of ship speed at severe sea states may be estimated from towing tank test or operational experience of LNG carriers with similar hull form and propulsion system. Alternatively, if those data are not available, ship speed of 5 knots may be used for sea states with significant wave height, H_s , higher than 15 m. For mild sea states with significant wave height, H_s , lower than 9 m, ship speed of 75% of design speed can be used. For the intermediate sea states with significant wave height, H_s , higher than 9 m and lower than 15 m, ship speed linearly interpolated between the two values are to be used.

7.13 Roll Damping Model

The roll motion of the vessel in oblique waves is greatly affected by the viscous roll damping of the hull, especially near the roll resonance. For seakeeping analysis based on potential flow theory, a proper viscous roll damping modeling should be introduced in the panel method. Experimental data or empirical methods for the roll damping model can be used for the determination of the viscous roll damping of the hull in consultation with ABS. The roll damping effects due to the rudders and bilge keels should also be considered in the seakeeping analysis. If this information is not available, 10% of critical damping may be used for the overall viscous roll damping.

7.15 Extreme Values for Ship Motion

Extreme value analysis is to be performed to determine lifetime maximum values of for each ship motion and acceleration, which will be used when selecting wave conditions and tank motions for sloshing simulation. Preference is given to an Extreme Value method that follows the so-called long-term approach commonly used for ship structure.

Note: A useful reference to explain concepts and terminology associated with extreme value analysis is “Wave Statistics for the Design of Ships and Ocean Structures”, by M.K.Ochi, SNAME Transactions, Vol. 86, 1978, pp. 47-76.

The relevant lifetime maximum value to be obtained from the Long-term Analysis is the Long-Term Response (LTR) having an exceedance probability level of 10^{-8} . This probability level is ordinarily considered to be equivalent to a return period of 25 years.

In these Guidance Notes, lifetime maximum values for surge, sway, heave, roll, pitch and yaw motion will be referred to as LTR_1 , LTR_2 , ..., LTR_6 , respectively. The lifetime maximum values of longitudinal, transverse and vertical accelerations will be referred to as LTR_7 , LTR_8 and LTR_9 , respectively.

9 Selection of Critical Wave Conditions for Design Sloshing Load

9.1 Sea States for Sloshing Model Test

Sloshing model tests are to be performed with irregular tank motions corresponding to the most severe sea conditions that can occur during the lifetime of LNG carrier. The severity of sea conditions should be judged based on the severity of sloshing loads on the containment system, which means that the most severe sea conditions can be identified only after sloshing model tests are performed. As a result, a group of sea states are selected for the model test based on probability of occurrence of the sea states, tank motion response and proximity of encountering wave period to the tank natural period. Qualified sloshing simulation tool can also be used to pre-screen the sea states to cause most significant sloshing loads.

The design sloshing loads should be defined based on a probability level (probability of exceedance, to be more precise) of 10^{-8} in the long-term probability. Unlike ship motion, spectral-based long-term statistical analysis is not available for sloshing load due to its high nonlinearity. Alternatively, an equivalent short-term approach is introduced to estimate long-term extreme value. The procedures can be summarized as:

- Define design sea states that represent most severe storms that vessel can encounter during designated lifetime of the vessel. Considering ship operation practice in the severe wave condition, different sea states are used for head- and beam sea conditions. Higher sea states, which are referred to as ‘40-year’ is used for head sea conditions, whereas milder sea states, which are referred to as ‘1-year’ sea conditions are used for beam seas. Section 2, Table 2 shows the sea states for 40-year and 1-year sea conditions, which are selected based on the occurrence (or probability) level given by wave scatter diagram provided in Section 2, Table 1. The 40-year sea conditions are utilized for head seas (180 – 150 deg) and the 1-year sea conditions are utilized for beam seas (90 – 120 deg). For quartering seas, one may use an interpolated wave height.
- Select sea states for model test among the 40- and 1-year sea conditions, based on tank motion response, sloshing resonance period and sloshing simulation results.
- Sloshing model test for each selected sea state under long-crested assumptions. It has also been model-test practice to assume long-crested waves when calculating tank motions for sloshing model tests, which will give higher response than the more realistic short-crested seas.

- Evaluation of short-term extreme value of sloshing loads for each sea state. The storm duration for each sea states are assumed to be 3 hours.
- Find sea state that gives maximum sloshing load.
- Perform model test and statistical analysis for sloshing loads at additional sea states and/or headings if necessary.

Further details on the selection of sea states during sloshing model tests can be found in Appendix 1.

TABLE 2
40-year and 1-year Waves for Sloshing Model Test Conditions

T_z (sec)	H_s (m)	
	40-year Waves	1-year Waves
4.0	1.9	0.5
4.5	3.1	1.6
5.0	4.4	2.7
5.5	5.9	3.8
6.0	7.3	5.0
6.5	8.7	6.2
7.0	10.0	7.3
7.5	11.1	8.3
8.0	12.1	9.2
8.5	13.0	10.0
9.0	13.8	10.6
9.5	14.4	11.1
10.0	14.9	11.5
10.5	15.2	11.8
11.0	15.5	12.0
11.5	15.7	12.0
12.0	15.8	12.0
12.5	15.8	11.8
13.0	15.7	11.5
13.5	15.5	11.0
14.0	15.3	10.3
14.5	14.9	9.3
15.0	14.5	7.4

9.3 Regular Wave Conditions for Sloshing Analysis

Theoretically, a direct simulation of the sloshing response in random seas can be performed following the same procedures that have been used for the sloshing model test. However, with the current state of CFD tools, the sloshing simulation takes much more time than the sloshing model test. Even in the two-dimensional analysis, it will require tremendous computing time to obtain reasonable statistical values of sloshing loads.

Alternatively, a regular wave approach to maximize the sloshing load within the design environmental condition is introduced. For each wave period and heading, a regular wave system is defined by maximizing wave amplitude under the restriction that the motion and acceleration response of the vessel should not exceed the lifetime maximum value of the responses for the given environmental condition and design service life. The wave periods and headings are selected based on magnitude of acceleration at the center of tank and the proximity of the encountering period to the sloshing resonance period. The selected wave conditions are referred to as “Critical Sloshing Wave Conditions”. The selection procedures can be summarized as follows:

- Evaluate long-term extreme value of ship motion and acceleration at the probability level of 10^{-8} .
- Define critical sloshing wave domain where:
 - Encountering period is within 30% range of the sloshing natural frequency.
 - Acceleration at the center of tank is at least 30% of the lifetime maximum response of the acceleration.
- Determine regular wave conditions within the critical sloshing wave domain:
 - Wave heading and period is within the critical sloshing domain.
 - Wave amplitude is maximized within the limit that ship motion and tank acceleration do not exceeds the lifetime maximum, and within the breaking limit.
- For beam sea and near beam sea conditions, wave amplitude is reduced to 72% of the calculated value to consider the weathervane operation.

More detailed description of the critical sloshing wave domain and critical sloshing wave condition can be found in Appendix 2.

11 Determination of Design Sloshing Load

11.1 Overview

The sloshing model test should be performed for the selected sea states following the procedures described in Appendix 1. The measured time histories of the sloshing pressure are to be used to determine design sloshing load for the LNG containment system. The following steps are to be followed to evaluate the design sloshing load:

- Panel averaging of pressure signal from clustered pressure sensors
- Idealization of panel pressures by triangular impulse
- Evaluation of damage index for each pulse
- Prediction of short-term extreme sloshing load

As will be described in Subsection 5/5, different types of design sloshing loads are required for different levels of structural assessment complexity. Section 2, Figure 3 shows a flowchart of the data analysis procedures to evaluate design sloshing loads for different levels of structural assessment.

11.3 Sloshing Model Test

Sloshing model tests are to be performed for the selected loading and wave conditions (filling levels, sea states and headings). For each condition, model tests are performed for five hours to evaluate extreme value of sloshing load of probability level of 10^{-3} . A detailed model test procedures including requirements on test facilities, pressure measurement and statistical analysis of impact load can be found in Appendix 1. Section 2, Figure 4 shows a model test set up with model tank, pressure sensors and wiring for measurement.

FIGURE 3
Flowchart for Evaluation of Design Sloshing Loads from the Model Test

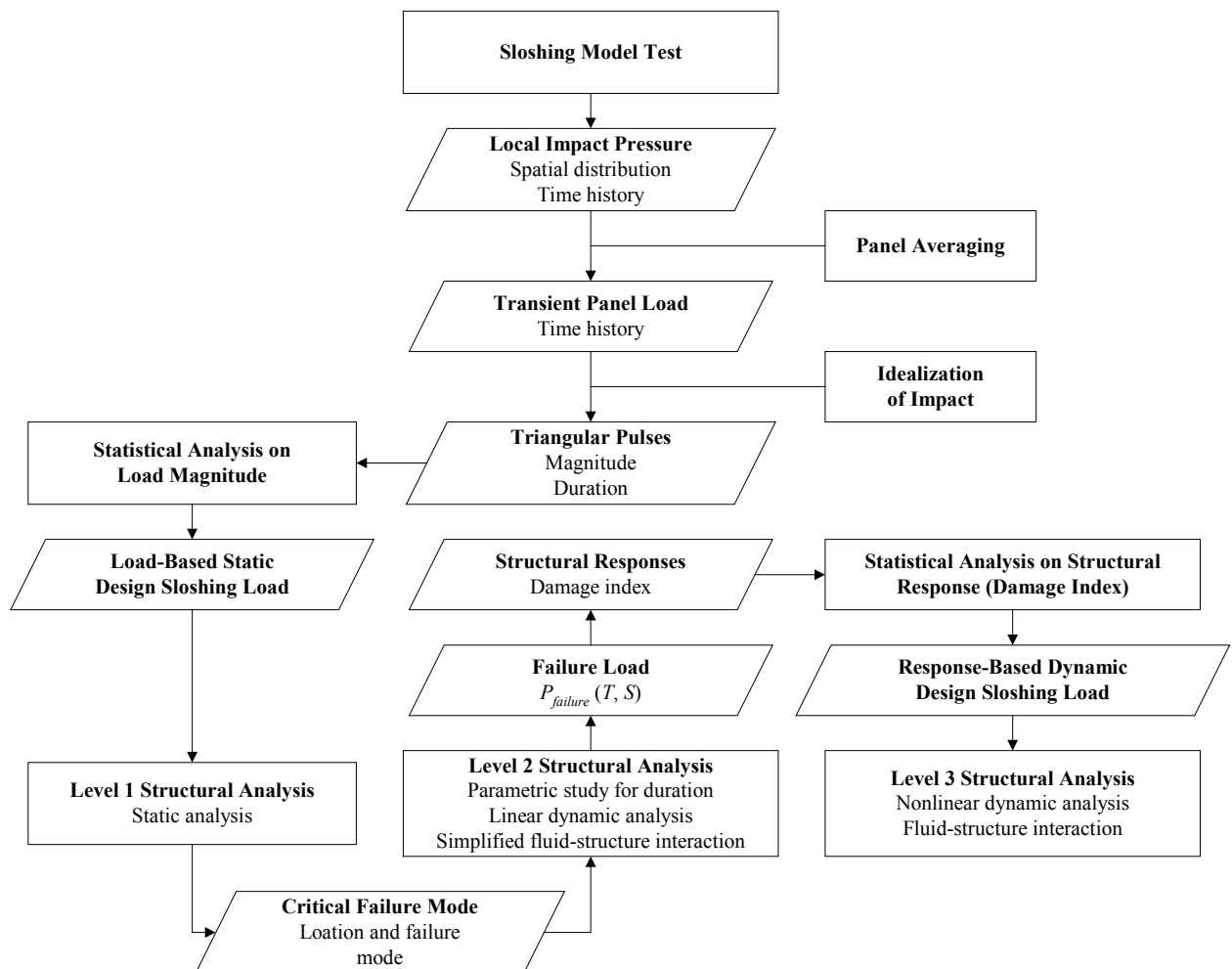
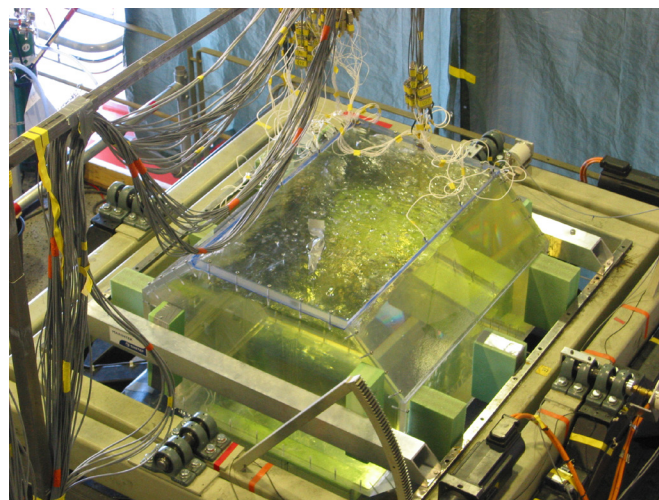


FIGURE 4
Model Tank and Pressure Sensor Setup



11.5 Panel Pressure

The sloshing impact load recorded by a single pressure sensor provides impact load on a restricted area. The diameter of the sensing area of a modern pressure sensor is only a couple of millimeters at most. For a 1:50 scale model, this area covers about 10 cm in the full-scale LNG tank, which will not affect structural response significantly if the load is concentrated only on that area.

There is also the scale law issue when evaluating localized pressure value at full-scale LNG tank from the model test measurements. There are many controversial theories about which scale law should be used for the local impact pressure. The local pressure is very sensitive to local flow phenomena such as air trapping, liquid jet impact and capillary waves, which cannot be covered by existing scale laws based on Euler (pressure scale is proportional to tank length and liquid density) and Froude (time scale is proportional to square root of tank length) scaling.

For these reasons, panel pressure is preferred to the local impact pressure when defining design sloshing loads for the structural assessment of an LNG membrane system. The size of the panel should be large enough such that the averaged pressure will be affected not by local flow phenomena but by the global liquid motion, which is governed by the conventional scale law based on Euler and Froude scaling. At the same time, the panel size should not be too large to lose the main characteristics of sloshing load for structural analysis. ABS recommends panel averaging to be performed over a square area of 1 meter by 1 meter size. Accordingly, the design sloshing load is defined as a single uniform transient pressure acting over a comparable area of the panel averaging.

Panel averaging is usually made by clustered sensors. Section 2, Figure 5 shows an example of clustered sensors installed at a tank top corner. A total of 16 sensors made of a 4-by-4 array have been used. Section 2, Figure 6 shows the time history of local impact pressure measured at each sensors in the cluster, together with the panel average pressure. It can be seen that maximum peak value of the local impact pressure is localized only in the vicinity of the tank corner.

FIGURE 5
Clustered Sensors at Tank Corner

