# Strength Assessment of LNG Membrane Tanks under Sloshing Loads

**May 2011**

**Guidance Note**
**NI 564 DT R00 E**

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# MARINE DIVISION
# GENERAL CONDITIONS

**ARTICLE 1**

**1.1.** - BUREAU VERITAS is a Society the purpose of whose Marine Division (the "Society") is the classification (" Classification ") of any ship or vessel or structure of any type or part of it or system therein collectively hereinafter referred to as a "Unit" whether linked to shore, river bed or sea bed or not, whether operated or located at sea or in inland waters or partly on land, including submarines, hovercrafts, drilling rigs, offshore installations of any type and of any purpose, their related and ancillary equipment, subsea or not, such as well head and pipelines, mooring legs and mooring points or otherwise as decided by the Society.

The Society:

- prepares and publishes Rules for classification, Guidance Notes and other documents ("Rules");
- issues Certificates, Attestations and Reports following its interventions ("Certificates");
- publishes Registers.

**1.2.** - The Society also participates in the application of National and International Regulations or Standards, in particular by delegation from different Governments. Those activities are hereafter collectively referred to as " Certification ".

**1.3.** - The Society can also provide services related to Classification and Certification such as ship and company safety management certification; ship and port security certification, training activities; all activities and duties incidental thereto such as documentation on any supporting means, software, instrumentation, measurements, tests and trials on board.

**1.4.** - The interventions mentioned in 1.1., 1.2. and 1.3. are referred to as " Services ". The party and/or its representative requesting the services is hereinafter referred to as the " Client ". **The Services are prepared and carried out on the assumption that the Clients are aware of the International Maritime and/or Offshore Industry (the "Industry") practices.**

**1.5.** - The Society is neither and may not be considered as an Underwriter, Broker in ship's sale or chartering, Expert in Unit's valuation, Consulting Engineer, Controller, Naval Architect, Manufacturer, Shipbuilder, Repair yard, Charterer or Shipowner who are not relieved of any of their expressed or implied obligations by the interventions of the Society.

**ARTICLE 2**

**2.1.** - Classification is the appraisement given by the Society for its Client, at a certain date, following surveys by its Surveyors along the lines specified in Articles 3 and 4 hereafter on the level of compliance of a Unit to its Rules or part of them. This appraisement is represented by a class entered on the Certificates and periodically transcribed in the Society's Register.

**2.2.** - Certification is carried out by the Society along the same lines as set out in Articles 3 and 4 hereafter and with reference to the applicable National and International Regulations or Standards.

**2.3.** - **It is incumbent upon the Client to maintain the condition of the Unit after surveys, to present the Unit for surveys and to inform the Society without delay of circumstances which may affect the given appraisement or cause to modify its scope.**

**2.4.** - The Client is to give to the Society all access and information necessary for the safe and efficient performance of the requested Services. The Client is the sole responsible for the conditions of presentation of the Unit for tests, trials and surveys and the conditions under which tests and trials are carried out.

**ARTICLE 3**

**3.1.** - **The Rules, procedures and instructions of the Society take into account at the date of their preparation the state of currently available and proven technical knowledge of the Industry. They are not a standard or a code of construction neither a guide for maintenance, a safety handbook or a guide of professional practices, all of which are assumed to be known in detail and carefully followed at all times by the Client.**

Committees consisting of personalities from the Industry contribute to the development of those documents.

**3.2. - The Society only is qualified to apply its Rules and to interpret them. Any reference to them has no effect unless it involves the Society's intervention.**

**3.3.** - The Services of the Society are carried out by professional Surveyors according to the applicable Rules and to the Code of Ethics of the Society. Surveyors have authority to decide locally on matters related to classification and certification of the Units, unless the Rules provide otherwise.

**3.4.** - **The operations of the Society in providing its Services are exclusively conducted by way of random inspections and do not in any circumstances involve monitoring or exhaustive verification.**

**ARTICLE 4**

**4.1.** - The Society, acting by reference to its Rules:

- reviews the construction arrangements of the Units as shown on the documents presented by the Client;
- conducts surveys at the place of their construction;
- classes Units and enters their class in its Register;
- surveys periodically the Units in service to note that the requirements for the maintenance of class are met.

**The Client is to inform the Society without delay of circumstances which may cause the date or the extent of the surveys to be changed.**

**ARTICLE 5**

**5.1. - The Society acts as a provider of services. This cannot be construed as an obligation bearing on the Society to obtain a result or as a warranty.**

**5.2. - The certificates issued by the Society pursuant to 5.1. here above are a statement on the level of compliance of the Unit to its Rules or to the documents of reference for the Services provided for.**

**In particular, the Society does not engage in any work relating to the design, building, production or repair checks, neither in the operation of the Units or in their trade, neither in any advisory services, and cannot be held liable on those accounts. Its certificates cannot be construed as an implied or express warranty of safety, fitness for the purpose, seaworthiness of the Unit or of its value for sale, insurance or chartering.**

**5.3. - The Society does not declare the acceptance or commissioning of a Unit, nor of its construction in conformity with its design, that being the exclusive responsibility of its owner or builder, respectively.**

**5.4.** - The Services of the Society cannot create any obligation bearing on the Society or constitute any warranty of proper operation, beyond any representation set forth in the Rules, of any Unit, equipment or machinery, computer software of any sort or other comparable concepts that has been subject to any survey by the Society.

**ARTICLE 6**

**6.1.** - The Society accepts no responsibility for the use of information related to its Services which was not provided for the purpose by the Society or with its assistance.

**6.2. - If the Services of the Society cause to the Client a damage which is proved to be the direct and reasonably foreseeable consequence of an error or omission of the Society, its liability towards the Client is limited to ten times the amount of fee paid for the Service having caused the damage, provided however that this limit shall be subject to a minimum of eight thousand (8,000) Euro, and to a maximum which is the greater of eight hundred thousand (800,000) Euro and one and a half times the above mentioned fee.**

**The Society bears no liability for indirect or consequential loss such as e.g. loss of revenue, loss of profit, loss of production, loss relative to other contracts and indemnities for termination of other agreements.**

**6.3.** - All claims are to be presented to the Society in writing within three months of the date when the Services were supplied or (if later) the date when the events which are relied on of were first known to the Client, and any claim which is not so presented shall be deemed waived and absolutely barred. Time is to be interrupted thereafter with the same periodicity.

**ARTICLE 7**

**7.1.** - Requests for Services are to be in writing.

**7.2.** - **Either the Client or the Society can terminate as of right the requested Services after giving the other party thirty days' written notice, for convenience, and without prejudice to the provisions in Article 8 hereunder.**

**7.3.** - The class granted to the concerned Units and the previously issued certificates remain valid until the date of effect of the notice issued according to 7.2. here above subject to compliance with 2.3. here above and Article 8 hereunder.

**7.4.** - The contract for classification and/or certification of a Unit cannot be transferred neither assigned.

**ARTICLE 8**

**8.1.** - The Services of the Society, whether completed or not, involve, for the part carried out, the payment of fee upon receipt of the invoice and the reimbursement of the expenses incurred.

**8.2. Overdue amounts are increased as of right by interest in accordance with the applicable legislation.**

**8.3. - The class of a Unit may be suspended in the event of non-payment of fee after a first unfruitful notification to pay.**

**ARTICLE 9**

**9.1.** - The documents and data provided to or prepared by the Society for its Services, and the information available to the Society, are treated as confidential. However:

- clients have access to the data they have provided to the Society and, during the period of classification of the Unit for them, to the **classification file** consisting of survey reports and certificates which have been prepared at any time by the Society for the classification of the Unit;
- copy of the documents made available for the classification of the Unit and of available survey reports can be handed over to another Classification Society, where appropriate, in case of the Unit's transfer of class;
- the data relative to the evolution of the Register, to the class suspension and to the survey status of the Units, as well as general technical information related to hull and equipment damages, are passed on to IACS (International Association of Classification Societies) according to the association working rules;
- the certificates, documents and information relative to the Units classed with the Society may be reviewed during certificating bodies audits and are disclosed upon order of the concerned governmental or inter-governmental authorities or of a Court having jurisdiction.

The documents and data are subject to a file management plan.

**ARTICLE 10**

**10.1.** - Any delay or shortcoming in the performance of its Services by the Society arising from an event not reasonably foreseeable by or beyond the control of the Society shall be deemed not to be a breach of contract.

**ARTICLE 11**

**11.1.** - In case of diverging opinions during surveys between the Client and the Society's surveyor, the Society may designate another of its surveyors at the request of the Client.

**11.2.** - Disagreements of a technical nature between the Client and the Society can be submitted by the Society to the advice of its Marine Advisory Committee.

**ARTICLE 12**

**12.1.** - Disputes over the Services carried out by delegation of Governments are assessed within the framework of the applicable agreements with the States, international Conventions and national rules.

**12.2.** - Disputes arising out of the payment of the Society's invoices by the Client are submitted to the Court of Nanterre, France.

**12.3.** - **Other disputes over the present General Conditions or over the Services of the Society are exclusively submitted to arbitration, by three arbitrators, in London according to the Arbitration Act 1996 or any statutory modification or re-enactment thereof. The contract between the Society and the Client shall be governed by English law.**

**ARTICLE 13**

**13.1.** - **These General Conditions constitute the sole contractual obligations binding together the Society and the Client, to the exclusion of all other representation, statements, terms, conditions whether express or implied. They may be varied in writing by mutual agreement.**

**13.2.** - The invalidity of one or more stipulations of the present General Conditions does not affect the validity of the remaining provisions.

**13.3.** - The definitions herein take precedence over any definitions serving the same purpose which may appear in other documents issued by the Society.

BV Mod. Ad. ME 545 k - 17 December 2008

GUIDANCE NOTE NI 564

NI 564

# Strength Assessment of LNG Membrane Tanks under Sloshing Loads



May 2011

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## Appendix 1 Pump Mast Strength Assessment

# SECTION 1 GENERAL

## 1 Introduction

### 1.1 Context

**1.1.1** 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. Within the membrane type concept, which is of main concern here, the LNG is kept at very low temperature (– 163°C) by means of a complex insulation system which is attached to the ship structure.

**1.1.2** At the same time 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 in 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 systems and the associated ship structure. Violent sloshing motions may occur and the direct consequence is the occurrence of different impact situations, which can induce the large structural loadings possibly damaging both the containment system and the ship structure.

**1.1.3** The present Guidance Note:

- should apply to the LNG carriers and the offshore LNG floating units using the membrane technology
- focuses on the strength assessment of cargo containment systems and hull structure under sloshing impact loads. Strength assessment of pump mast and its supporting structure is described in App 1.

**1.1.4** The determination of the sloshing impact loads is described in the separate Guidance Note NI554 “Design Sloshing Loads for LNG Membrane Tanks”. The analysis of navigation conditions, the sea-keeping calculations, CFD calculations and small-scale sloshing tests allow to define the design sloshing loads on the different areas of the tanks.

### 1.2 General methodology

**1.2.1** When trying to reproduce the sloshing phenomenon, either experimentally or numerically, the complexity of the associated physics is emphasized:

- its stochastic nature
- its both local and global behavior
- the scaling from small to real scale
- the cryogenic environment
- the dynamics of the phenomenon
- the hydro-elastic effects occurring between the hydrodynamic loading and the structural response of the cargo containment system
- the non-linear structural response of the cargo containment system
- ...

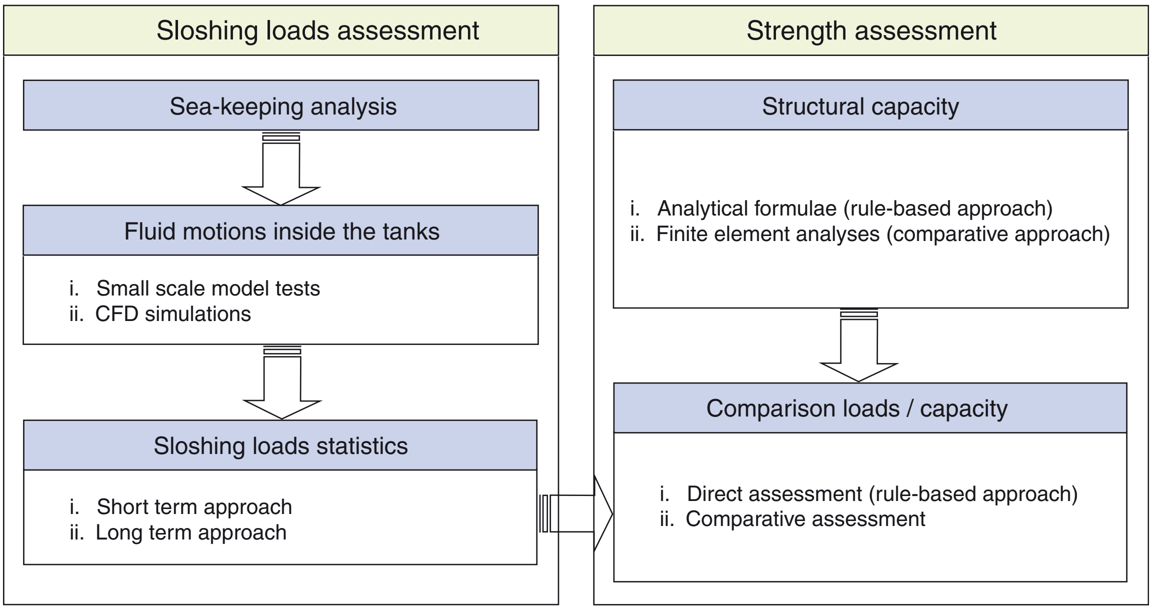
All these difficulties make it impossible to perform a direct evaluation of the strength of the insulation systems and hull structure, at least with the current knowledge and the numerical and material resources. Therefore, this Guidance Note proposes simplified procedures that can be applied. Whenever a simplification is needed, it is clearly stated and its effects are discussed.

**1.2.2** The first level of assessment, very simplified, uses a rule-based approach to derive extreme values of allowable sloshing pressures; it is currently available for NO96 containment system only. This method relies on analytical formulae, and thus, considers many simplifying hypotheses. It should therefore only be used in a screening phase: if some areas of the LNG tank present design sloshing loads (impact pressures) larger than, or of the same order of magnitude as, the allowable values analytically calculated, then a more refined analysis should be performed.

**1.2.3** Then, given the very large feedback available, a comparative approach may be considered. The philosophy of this approach is that, if a target ship is more resistant than a reference ship and if the latter has never sustained damages due to sloshing impact loads, then the target ship will not sustain damages either. This approach is characterized by the use of non-linear and dynamic finite element analyses, which allow to take into consideration most of the physics involved in the structural response of cargo containment systems under sloshing impacts.

**1.2.4** The global sloshing assessment procedure is summarized in Fig 1.

**Figure 1 : Sloshing assessment procedure**




**1.2.5** During the review of a new concept or in case of substantial modification of a containment system, the Society requests wet drop tests or equivalent tests are performed.

A wet drop test consists in letting a sample of the analyzed containment system fall onto calm water. It should be carried out for different drop heights (to get different impact velocities) and drop incidences (relative angles between the surface of the containment system and the liquid surface). The principal advantage of the wet drop test is the representation of the fluid/structure impact interaction in realistic conditions with real cargo containment system.

Drop tests have been investigated several times in the past, by containment system designers and by shipyards, with the support of the Society. The aims of these tests were different, depending on their characteristics. Some of them were carried out to define a relation between the pressure and the fluid velocity, others were carried out in a comparative way to determine the best insulation system regarding sloshing impacts.

**1.2.6** This note is a guidance note and, as such, proposes only a method and gives the corresponding recommendations on the procedure to be applied. It is the designer's responsibility to opt either to use the methodology proposed in this guidance note, or to propose any other procedure. In any case, this choice should be discussed with the Society.

## 2 Description of cargo containment systems

### 2.1 General

**2.1.1** The two major containment systems - NO96 and MarkIII, designed by GTT - are covered here and described respectively in [2.2] and [2.3].

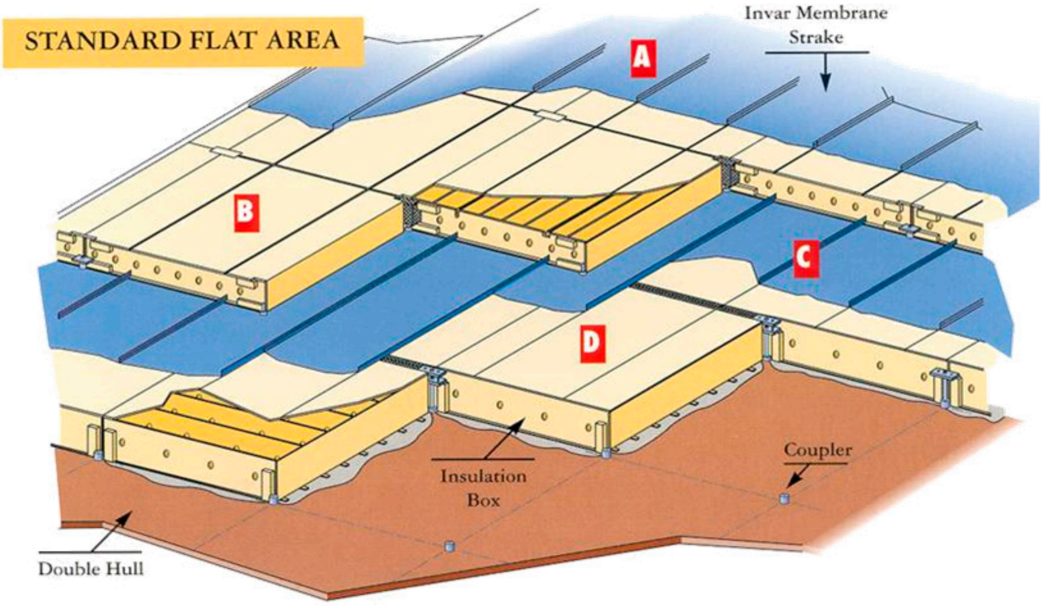
**2.1.2** They both consist in a two-layer system, insulating the hull structure from the cryogenic temperature of the LNG. They only differ in the way the insulation is achieved.

### 2.2 NO96 system

**2.2.1** NO96's basic element consists in two plywood boxes corresponding to the two insulation layers: the primary box (tank side) and the secondary box (double hull side). They are filled with an insulation material called perlite. Each box covers a 1-$m^2$ surface and is stiffened by internal bulkheads. All plywood parts are fixed one to another by staples.

The secondary box is fixed to the inner hull structure at its four corners by couplers and lays on mastic ropes. It is separated from the primary box by an invar (steel-nickel alloy) membrane and the primary box is separated from the inside of the tank (i.e. the LNG) by another invar membrane. The global arrangement is shown in Fig 2.

**Figure 2 : NO96 system general arrangement (courtesy of GTT)**




A : Primary invar membrane

B : Primary box

C : Secondary invar membrane

D : Secondary box.

**2.2.2** Plywood primary and secondary boxes exist in four levels of reinforcement (standard, reinforced, super reinforced and ultra reinforced), differences consisting mainly in the thickness of the plywood sheets and the number and height of bulkheads.

The main dimensions of the plywood boxes and the characteristics of each reinforcement level are detailed in Tab 1.

**Table 1 : Reinforcements of NO96 primary and secondary boxes**

| Reinforcement level | Dimensions of the primary box (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | h | S | $t_c$ | $t_{w\_i}$ | $t_{w\_e}$ | $h_{comb}$ | $t_{comb}$ | b |
| Standard | 209 | 116 | 1 x 12 | 9 | 9 | 30 | 12 | 1132 |
| Reinforced | 209 | 113 | 2 x 12 | 12 | 9 | 30 | 12 | 1132 |
| Super reinforced | 209 | 113 | 2 x 12 | 12 | 12 | 30 | 12 | 1135 |
| Ultra reinforced | 209 | 110 | 2 x 12 | 15 | 15 | 30 | 12 | 1135 |

| Reinforcement level | Dimensions of the secondary box (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | h | S | $t_c$ | $t_{w\_i}$ | $t_{w\_e}$ | $h_{comb}$ | $t_{comb}$ | b |
| Standard | 300 | 166 | 9 | 9 | 9 | 30 | 12 | 981 |
| Reinforced | 300 | 166 | 9 | 12 | 9 | 30 | 12 | 981 |
| Super reinforced | 300 | 166 | 9 | 12 | 12 | 200 | 12 | 485 |
| Ultra reinforced | 300 | 166 | 9 | 15 | 15 | 200 | 12 | 334 |

**Note 1:**

b : Length of the bulkheads (distance between sidewalls or, in case of 200-mm combs, between sidewall and comb or between combs)

S : Cell width (spacing between two primary bulkheads)

h : Height of the box

$t_c$ : Thickness of the cover plate. When two cover plates are indicated, they are stapled together.

$t_{w\_i}$ : Thickness of the internal primary bulkheads

$t_{w\_e}$ : Thickness of the external primary bulkheads

$h_{comb}$ : Height of the comb(s)

$t_{comb}$ : Thickness of the comb(s).

Primary and secondary boxes are stiffened by the following bulkheads:

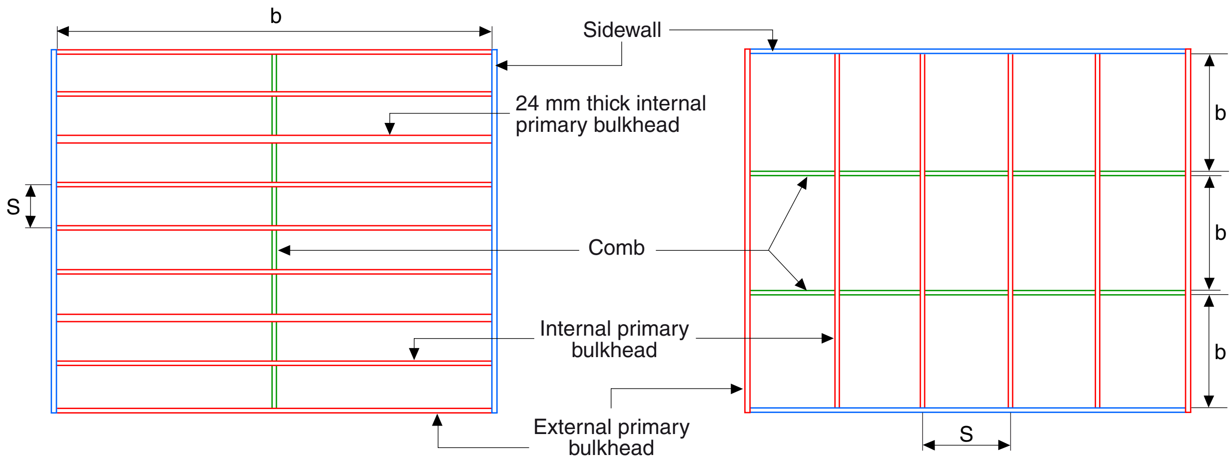
- Primary bulkheads
  - external bulkheads: 2, at the edges of the boxes
  - internal bulkheads: 7 for primary boxes (the 2nd and the 6th being always 24 mm thick) and 4 for secondary boxes.

  The primary bulkheads of the primary boxes are oriented perpendicularly to those of the secondary boxes
- Additional bulkheads perpendicular to the primary ones

  These additional bulkheads are called combs and their height $h_{comb}$ is equal to:
  - either 30 mm (standard height): such combs (at mid-span of primary bulkheads) are only used to make the manufacturing easier and are not taken into consideration for the stiffening. It is the case for all the primary boxes and the standard and reinforced levels of secondary boxes, or
  - 200 mm: in this case, the combs have a stiffening role. It is the case for super reinforced secondary boxes (one 200-mm comb, at mid-span of primary bulkheads) and ultra reinforced secondary boxes (two 200-mm combs, at 1/3 and 2/3 of the span of primary bulkheads).

Examples of a primary box and an ultra reinforced secondary box are shown in Fig 3.

**Figure 3 : NO96 primary box (left) and ultra reinforced secondary box (right) - Top view**




## 2.3 MarkIII system

**2.3.1** MarkIII system ensures the insulation, using two layers of reinforced polyurethane foams separated one from the other by a membrane, called secondary barrier, consisting in a triplex membrane (composite material made of an aluminum sheet between two glass fiber sheets). The secondary foam layer (double hull side) is made in one continuous block, whereas the basic primary foam layer (tank side) presents slots. A plywood sheet is fixed on the top of the primary foam layer (called "top plywood"), and another is fixed on the back of the secondary foam layer (called "back plywood"). All components are glued together, and the whole system is fixed to the hull structure using mastic ropes positioned between the back plywood and the hull.

Unlike NO96 containment system that uses 1 $m^2$ boxes, MarkIII system is based on larger pre-assembled panels: a basic flat panel approximately covers a surface of 3 $m^2$.

The global arrangement of the MarkIII system is shown in Fig 4.

**2.3.2** A corrugated stainless steel membrane, called primary barrier, is fixed on the top plywood. Three types of membranes can be used, depending on the level of reinforcement: standard membrane and membrane with ribs, with or without wooden wedges devices inside the corrugations.

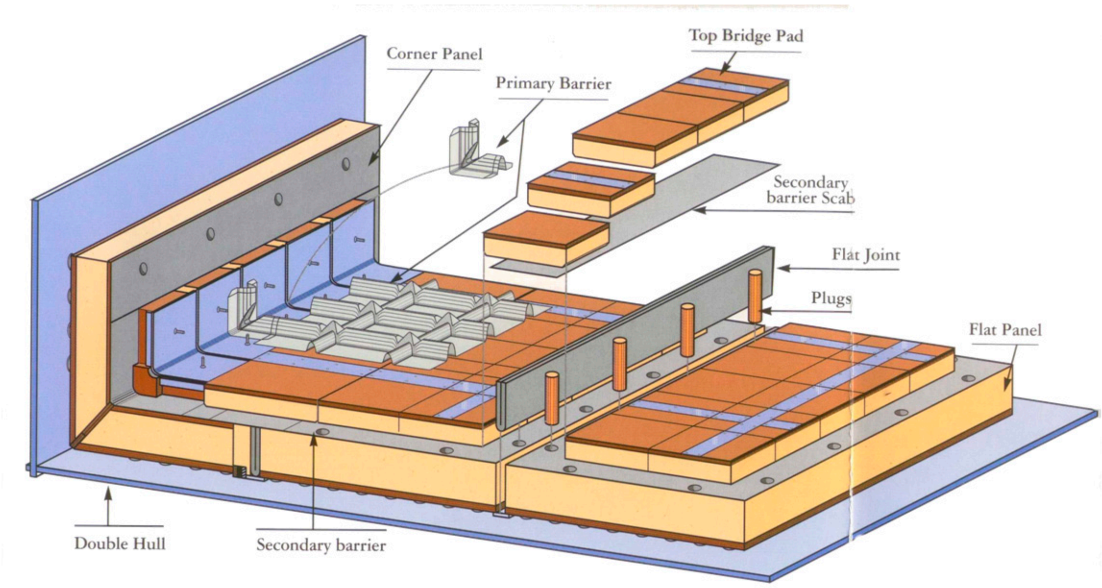
**2.3.3** The MarkIII panel can be reinforced by reducing the gap between mastic ropes from 140 mm to 100 mm. The main dimensions of the containment system and the corresponding scantlings are detailed in Tab 2.

**Table 2 : Reinforcement of MarkIII panel**

| Reinforcement level | Dimensions of the panel (mm) | | | | |
|---|---|---|---|---|---|
| | $L_{prim}$ | $L_{sec}$ | $t_{top}$ | $t_{back}$ | G |
| Standard | 90 | 160 | 12 | 9 | 140 |
| Example of reinforcement | 90 | 160 | 12 | 9 | 100 |

**Note 1:**
$L_{prim}$ : Thickness of the primary foam layer
$L_{sec}$ : Thickness of the secondary foam layer
$t_{top}$ : Thickness of the top plywood
$t_{back}$ : Thickness of the back plywood
G : Gap between two mastic ropes.

**Figure 4 : MarkIII system general arrangement (courtesy of GTT)**



# SECTION 2 RULE-BASED STRENGTH ASSESSMENT

## Symbols

S, b, h, $t_{w\_i}$ , $t_{w\_e}$ , $t_c$: Dimensions and thicknesses of the NO96 box, as defined in Sec 1, Tab 1. These symbols may concern primary or secondary boxes, this indication being, if necessary, specified in index (e.g.: $S_{primary}$ , $t_{c,\ secondary}$).

## 1 Strength assessment NO96 system

### 1.1 Pressures

**1.1.1** The pressures to be taken into account are:

$P_p$ : Peak pressure, in kPa, corresponding to the maximum statistical pressure given by small scale model tests (at scale 1:50 or 1:40) in a unique sensor (with diameter 5mm)

$P_{qs}$ : Quasi-static pressure, in kPa, corresponding to the maximal pressure to be taken in the numerical simulations.

**1.1.2** Alternatively, if there is no model test result (and so $P_p$ is not known explicitly) or no numerical simulation result (and $P_{qs}$ is not known explicitly), the following relation may be used:

$P_p = 7 \cdot P_{qs}$

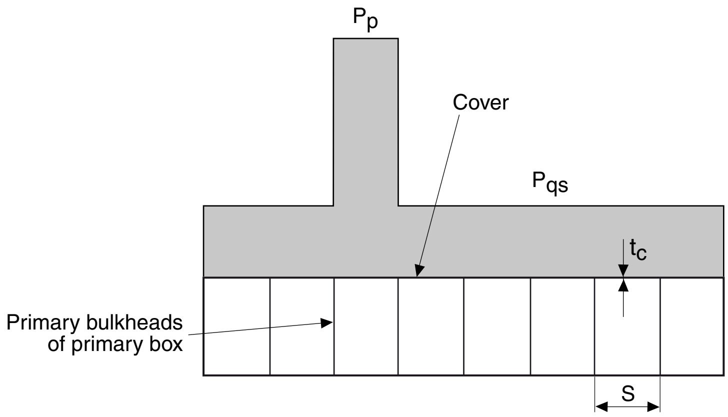
Factor 7 is coming from the analysis of wet drop tests and impact full scale tests.

**1.1.3** In this simplified procedure, no amplification factor due to dynamic characteristic of the load (rise time) is taken into account.

### 1.2 Structural assessment of the cover plate

**1.2.1** The load is to be applied according to Fig 1.

**Figure 1 : Load distribution for the cover plate assessment**




#### 1.2.2 Bending

As the cover is cut by groves for membrane fixation, it may be assumed semi clamped. Then, the moment M is given by:

$$M = \frac{P_p \cdot S^2}{10}$$

Therefore the bending stress σ in the cover plate is equal to:

$$\sigma = \frac{6 \cdot P_p \cdot S^2}{10 \cdot t_c^2}$$

Finally, the allowable peak pressure corresponding to bending failure is equal to:

$$P_{p,\,allowable} = \sigma_{allowable} \cdot \frac{10 \cdot t_c^2}{6 \cdot S^2}$$

with:

$\sigma_{allowable}$ : Allowable bending stress, determined from material mechanic tests in cryogenic environment.

### 1.2.3 Shear

The shear stress $\tau$ in the cover plate is given by:

$$\tau = \frac{P_p \cdot S}{2 \cdot t_c}$$

Therefore, the allowable peak pressure corresponding to shear failure is equal to:

$$P_{p,\,allowable} = \frac{2 \cdot \tau_{allowable} \cdot t_c}{1,5 \cdot S}$$

where:

$\tau_{allowable}$ : Allowable shear stress, determined from material mechanic tests in cryogenic environment.

## 1.3 Buckling assessment of the primary boxes

**1.3.1** The load is to be applied according to Fig 2.

Test results show that the peak pressure $P_p$ applies to a small surface. The considered surface to determine $P_p$ being a cell surface, the same surface is used for the buckling verification. The strength of the internal and external primary bulkheads of the primary boxes is to be assessed according to the following load per unit length, as shown in Fig 3:

- for the internal primary bulkheads:

  $P = P_p \cdot S$

- for the external primary bulkheads:

  $$P = P_p \cdot \frac{S}{2}$$

**Figure 2 : Load distribution for the primary bulkhead assessment**

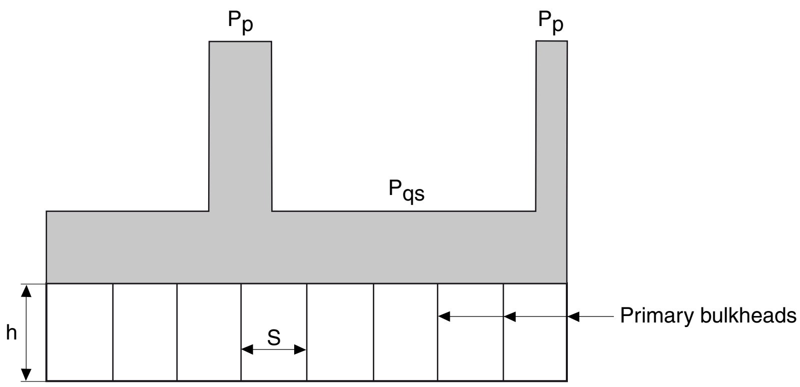
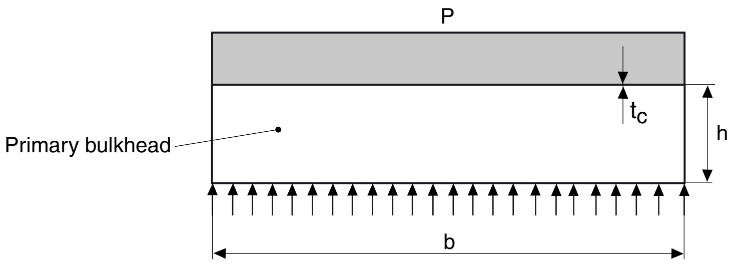



**Figure 3 : Buckling assessment**



**1.3.2** Assuming that the bottom part of the bulkhead is fully supported, the buckling limit load is given in NR467 Rules for Steel Ships, Pt B, Ch 7, Sec 1, [5.3]:

$$P_{allowable} = \sigma_{allowable} \cdot t_w = \frac{\pi^2}{12} \cdot \frac{E}{(1-\nu^2)} \cdot \left(\frac{t_w}{b}\right)^2 \cdot K \cdot \varepsilon \cdot t_w$$

with:

$t_w$ : $t_{w\_i}$ or $t_{w\_e}$, depending on the bulkhead under consideration

K : Factor, to be taken as:

$$K = 4 \quad \text{for } \alpha = \frac{h}{b} \geq 1$$

$$K = \left(\alpha + \frac{1}{\alpha}\right)^2 \quad \text{for } \alpha = \frac{h}{b} < 1$$

ε : Factor to be taken equal to 1,30

E : Young modulus of the bulkhead in the direction of the load (strong direction of the plywood).

**1.3.3** Assuming a safety factor of 1,5, the allowable peak pressure corresponding to the failure of the primary bulkheads is defined as:

- for the primary external bulkheads:

$$P_{p,\,allowable} = \frac{2}{3} \cdot \frac{\pi^2}{12} \cdot \frac{E}{(1-\nu^2)} \cdot \left(\frac{t_{w-e}}{b}\right)^2 \cdot K \cdot \varepsilon \cdot \frac{t_{w-e}}{S/2}$$

- for the primary internal bulkheads:

$$P_{p,\,allowable} = \frac{2}{3} \cdot \frac{\pi^2}{12} \cdot \frac{E}{(1-\nu^2)} \cdot \left(\frac{t_{w-i}}{b}\right)^2 \cdot K \cdot \varepsilon \cdot \frac{t_{w-i}}{S}$$

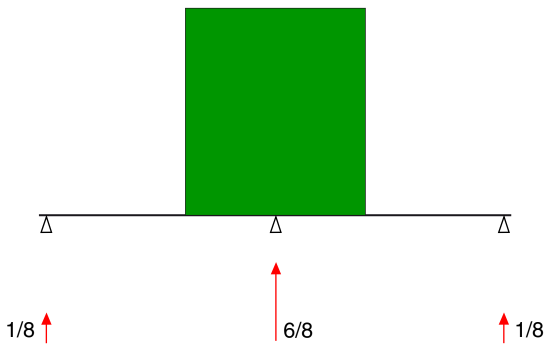
## 1.4 Buckling assessment of the secondary boxes

### 1.4.1 Damping effect

For the analysis of the buckling of the secondary boxes, the following damping effect is to be taken into account: the peak pressure on the primary box is distributed on the two primary bulkheads of the secondary box as shown in Fig 4.

A quarter of the total reaction force is distributed on the two adjacent primary bulkheads. Consequently, a coefficient of damping on the load on the most loaded primary bulkhead of the secondary box may be applied. This coefficient may be taken equal to 3/4. However, this damping coefficient is applicable to the internal primary bulkheads, but not always to the external primary bulkheads.

**Figure 4 : Damping effect for secondary boxes**




### 1.4.2 Case of lower filling levels

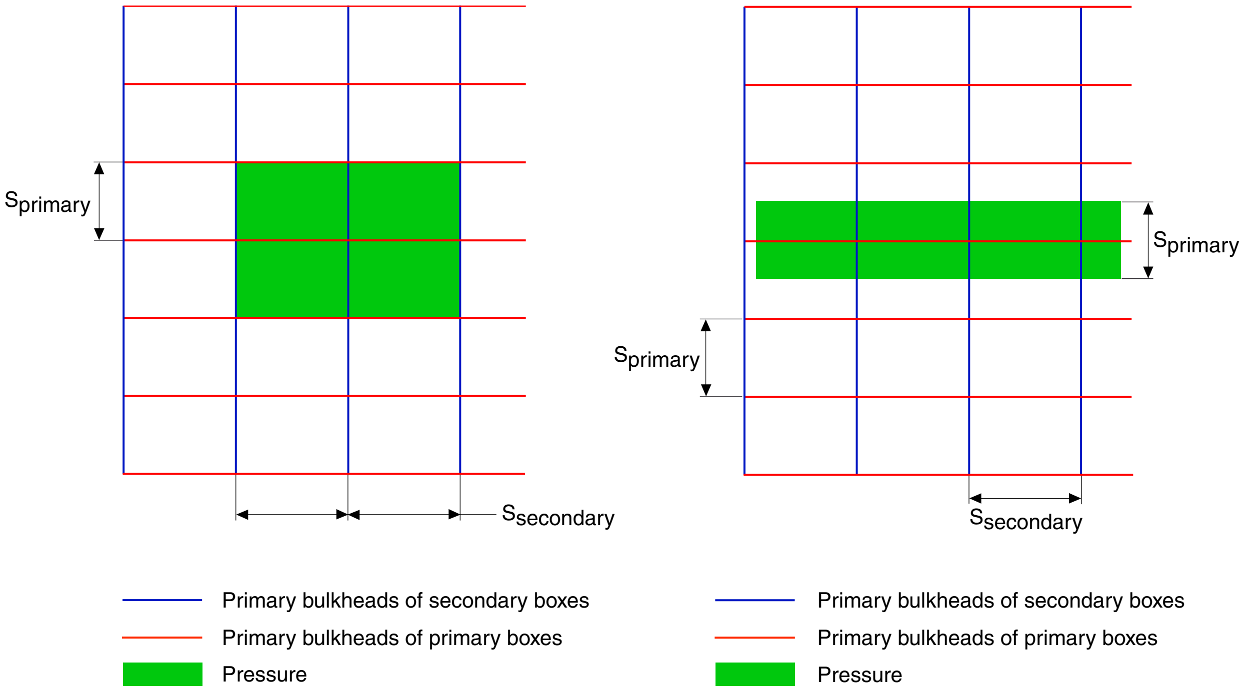
This requirement aims at the assessment of the boxes located in way of the foot of longitudinal and cofferdam bulkheads. In this case, the pressure from the wave is as given in Fig 5.

The critical stress is multiplied by a proportionality factor k, equal to:

$$k = \frac{S_{primary}}{S_{primary} + h_{secondary}}$$

and the critical load calculated using formulae in [1.3.3] is multiplied by 1/k.

**Figure 5 : Load distribution for lower (sketch on the left) and upper (sketch on the right) filling levels**




### 1.4.3 Case of upper filling levels

This requirement aims at the assessment of the boxes located in way of the longitudinal ceiling and upper chamfer. The organisation of the boxes is shown in Fig 5.

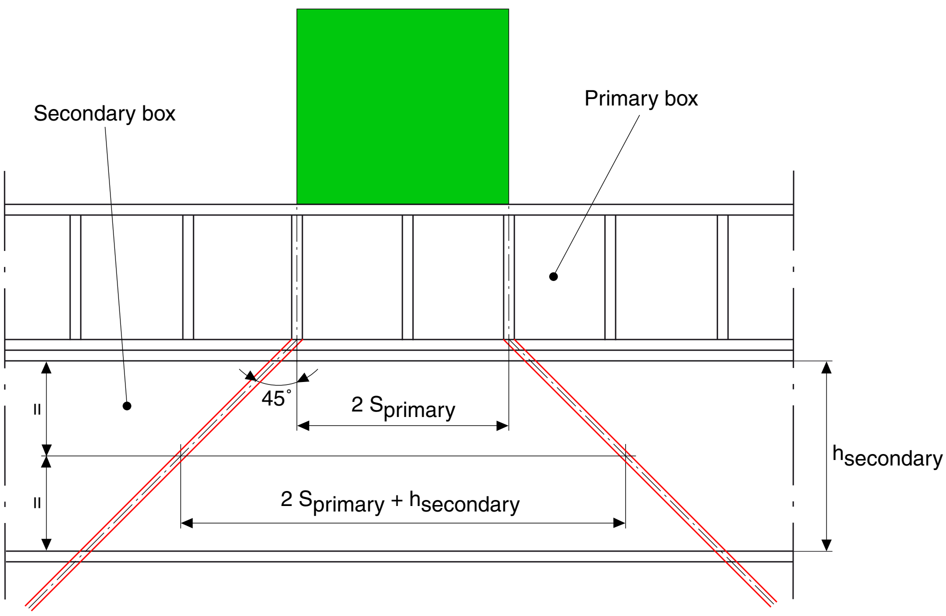
The distribution of the stress on the bay of buckling on the primary bulkhead of the secondary box is increased as shown in Fig 6.

The critical stress is multiplied by a proportionality factor k, equal to:

$$k = \frac{2 \cdot S_{primary}}{2 \cdot S_{primary} + h_{secondary}}$$

and the critical load calculated using formulae in [1.3.3] is multiplied by 1/k.

**Figure 6 : Determination of proportionality factor k**



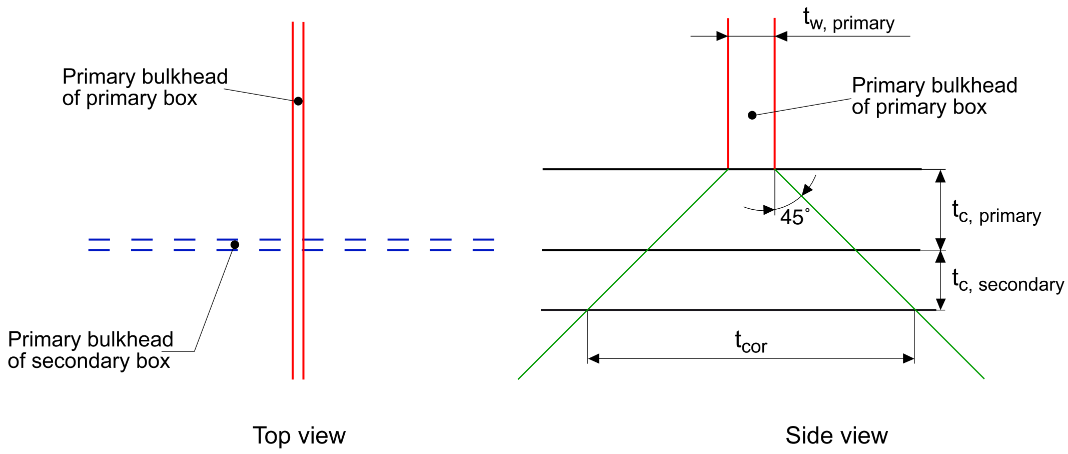
### 1.5 Assessment of the connection between primary and secondary boxes

**1.5.1** The assessment of the connection between the primary and secondary boxes is to be assessed against peak pressure $P_p$.

**1.5.2** An angle of 45° may be taken into account for the definition of the corrected thickness $t_{cor}$ , which is equal to (see Fig 7):

$t_{cor} = t_{w,\ primary} + 2\ (t_{c,\ primary} + t_{c,\ secondary})$

**Figure 7 : Thickness correction for assessment of the connections**




**1.5.3** The allowable peak pressure on the box cover for each box type (primary and secondary) is given by the following formula:

$$P_{p,\ allowable} = \sigma_{allowable} \cdot \frac{t_{w,\ secondary} \cdot t_{cor}}{S_{primary} \cdot S_{secondary}}$$

The damping effect defined in [1.4.1] is applicable to the allowable pressure.

## 2 Local scantling of double hull structure

### 2.1 General

**2.1.1** The rule assessment of the structure is based on the results of the numerical simulation.

### 2.2 Plating

**2.2.1** The net thickness of the plating in way of the impacts is to be assessed using the formulae given in NR467 Rules for Steel Ships, Pt B, Ch 7, Sec 1, [3.3.1].

**2.2.2** The partial safety factors are given in NR467 Rules for Steel Ships, Pt B, Ch 7, Sec 1, Tab 1, in column Sloshing pressure.

**2.2.3** The quasi-static pressure $P_{qs}$ may be:

- either directly calculated by the CFD software, or
- based on the velocity from the numerical simulation:

  $P_{qs} = K_i \cdot \rho \cdot V^2$

  where coefficient $K_i$ depends on the impact location.

**2.2.4** The quasi-static pressure is to be combined with the setting pressure of the safety valves.

**2.2.5** The quasi-static pressure may be applied as a uniform pressure on the structure.

### 2.3 Stiffeners

**2.3.1** The net thickness of the stiffeners in way of the impacts is to be assessed using the formulae given in NR467 Rules for Steel Ships, Pt B, Ch 7, Sec 2, [3.3.1].

**2.3.2** The partial safety factors are given in NR467 Rules for Steel Ships, Pt B, Ch 7, Sec 2, Tab 1, in column Sloshing pressure.

**2.3.3** The quasi static pressure $P_{qs}$ may be:

- either directly calculated by the CFD software, or
- based on the velocity from the numerical simulation:

  $P_{qs} = K_i \cdot \rho \cdot V^2$

  where coefficient $K_i$ depends on the impact location.

**2.3.4** The quasi static pressure is to be combined with the setting pressure of the safety valves.

**2.3.5** The quasi static pressure may be applied as a uniform pressure on the structure.

# SECTION 3 COMPARATIVE STRENGTH ASSESSMENT

## 1 Introduction

### 1.1 General

**1.1.1** In general, up today, assessment procedures have been essentially comparative, since they can rely on a very large feedback from experience. The bases for the comparison are:

- the sloshing loads, which analysis is described in the Guidance Note NI554 "Design Sloshing Loads for LNG Membrane Tanks", and
- the containment system capacities, which analysis is described in this Section.

They should be evaluated for both reference and target vessels.

**1.1.2** In this approach, the experience of containment system in service gives a base, either for the comparative strength of the new containment systems design, or for the existing systems in the new service conditions. The acceptance criterion is based on the comparison between the design load and the strength of the reference and target cases.

**1.1.3** The comparative approach ensures that the uncertainties due to impact loads and containment system structural capacities become less important than in a direct or rule-based strength assessment procedure, provided that the analyses are made in the exactly same manner for both target and reference vessels.

### 1.2 Overview of the procedure

**1.2.1** As it was explained before, this approach relies on the comparison of both loads and capacities of the target and reference vessels. In this Guidance Note NI 564, we focus on the evaluation of the structural capacities, which can be decomposed into the following steps:

a) first, one needs to build the finite model corresponding to the structure being analyzed. In this NI 564, the best practices for the modelling of GTT's NO96 and MarkIII cargo containment systems are given in Article [2]

b) then, the mechanical properties of the materials used in the containment systems need to be analyzed and input in the finite elements models, as described in Article [3]

c) finally, each possible failure mode is analyzed, allowing the definition of failure criterion. In this NI 564, the failure modes of GTT's NO96 and MarkIII cargo containment systems are analyzed, and the best practices for the evaluation of dynamic capacities as functions of loaded surfaces are defined in [4] and [5.1].

**1.2.2** Once the dynamic capacities of the analyzed structures are evaluated (see [4] and [5.2]), they are compared with the design sloshing loads. The comparison of the ratio capacity/load between the target and the reference vessels allows to define an acceptance criterion (see [5.3]).

## 2 Finite elements modelling

### 2.1 Extent of the model and boundary conditions

#### 2.1.1 Modelling of the hull structure

If possible, relevant elements of the hull structure should be modelled to assess their influence on the structural response of the containment system.

The areas where the modelling of hull has the strongest effect on stress concentrations in the containment systems are the locations where the containment system boxes (for NO96 containment system) or panels (for MarkIII containment system) sit on top of the stiffest hull structure elements, i.e. of the primary hull structure, for example: stringers, girders, web frames, etc. The most severe location for the containment system should be considered.

In accordance with the positions of pressure sensor clusters used for small-scale tests, the following areas of the tank have to be analyzed: upper and lower trihedron areas, 90° and 135° dihedron areas, ceiling, and sidewalls.

If the hull structure is modelled, the extent of the finite element modelling has to be chosen as follows:

- It has to be large enough, so that the boundary conditions do not directly influence the structural response of the loaded area
- The boundary conditions (simply supported condition) must be applied at one stiff hull structure element: stringers, girders, web frames, etc. Secondary hull structure elements may also be considered to reduce the extent of the finite element model.

All parts of the hull structure should be modelled with shell elements, and the model should include the secondary hull structure elements (longitudinals, webs). The corresponding containment system panels (in case of MarkIII system) or boxes (in case of NO96 system) should be modelled.

### 2.1.2 Simplified approach

If the choice is made to simplify the methodology by not considering the influence of the hull structure flexibility onto the structural response of the containment system, only one basic element of containment system needs to be modelled. In case of symmetric loads and geometries, symmetry boundary conditions could be considered to reduce the size of the model, as shown in Fig 1 that represents one half of a NO96 box, and Fig 2 that represents one sixth of a MarkIII panel, with the corresponding symmetry boundary conditions:

- in case of NO96 containment system, the modelling of a single box (assembly of the primary and secondary boxes) is enough
- in case of MarkIII containment system, a panel is 1-m large and 3-m long and it is not necessary to model all of it: approximately one third of the MarkIII panel should be modelled.

For both NO96 and MarkIII systems, a simply supported boundary condition should be imposed at the back of the mastic ropes while the primary membrane is loaded. The sides of the finite element models can remain free.

**Figure 1 : Example of symmetry boundary condition for NO96 system**

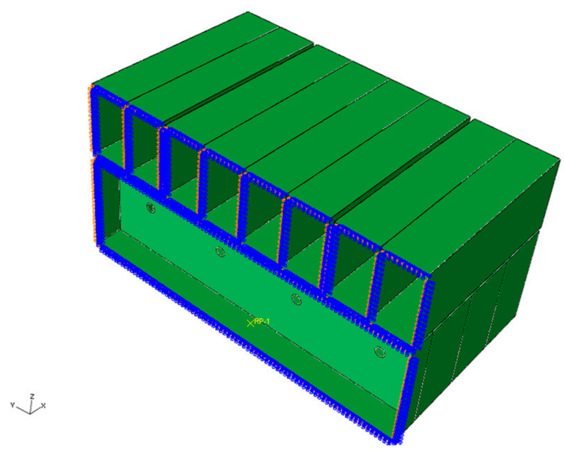
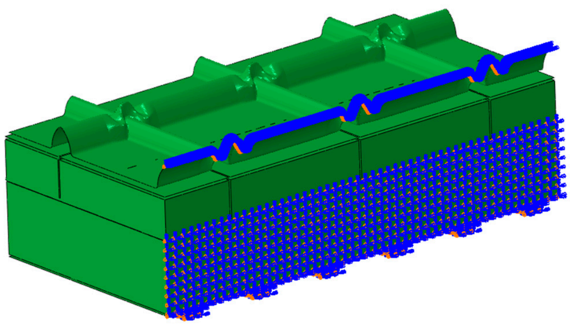


**Figure 2 : Example of symmetry boundary condition for MarkIII system**



## 2.2 NO96 system modelling

**2.2.1** Plywood sheets composing the NO96 system should be modelled with four-nodes shell elements. The insulation material (perlite) does not influence the structural response of the NO96 system and therefore it is not necessary to model it.

### 2.2.2 Modelling of the stapled assembly

As explained in Sec 1, NO96 containment system is based on a stapled assembly of plywood sheets, which should be modelled with four nodes shell elements. The use of staples to attach the different parts of the boxes modifies the structural behavior of the assembly: it allows a relative rotation between the two parts considered, as shown in Fig 3.

Then, two different approaches can be considered to model the NO96 primary and secondary boxes, depending on whether the effect of the staples on the structural behavior is considered or not:

- the first one considers this effect by modelling separately each part of the boxes, and constraining the rotational degrees of freedom of the bulkhead edges with those of the cover plate by a proportionality factor $\chi$, as described by the equation:

  $UR_{coverplate} = \chi \cdot UR_{bulkhead}$

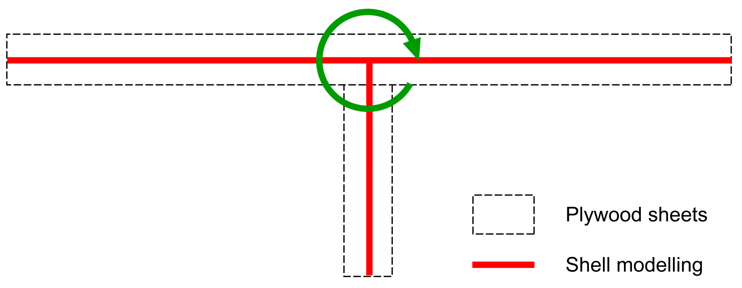
  with:

  UR : Rotational degree of freedom, represented by the arrow in Fig 3

  $\chi$ : Proportionality factor, calibrated through comparison with experimental results

- the second one disregards this effect and consists in modelling each box as a whole entity, which amounts to define the proportionality factor $\chi$ equal to 1 in the previous equation; it could however lead to larger uncertainties in the structural response, notably regarding the buckling strength of the bulkheads.

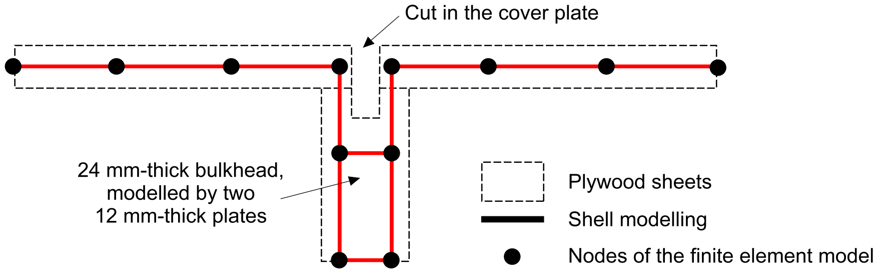
**Figure 3 : Modelling of the staple effects**




### 2.2.3 Modelling of the cover plate

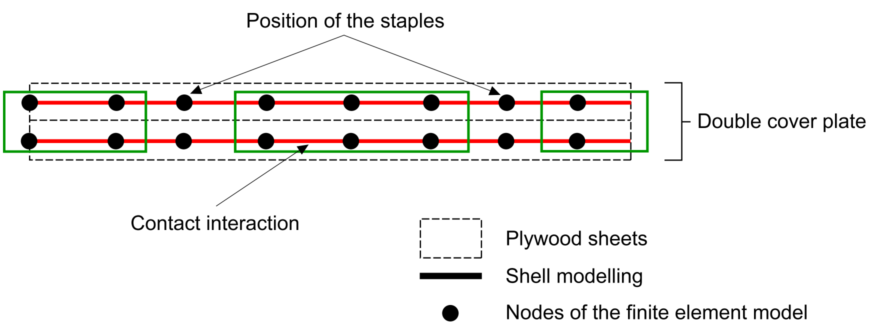
The cover plate presents two cuts to let the invar tongues go through it, which modifies the stiffness of the cover plate. Thus, the cover plate is in fact composed of three different parts, which should be reproduced by the finite element modelling. At the position of these cuts, the primary bulkheads are 24-mm thick. These bulkheads should be modelled by two 12mm-thick plates attached one to another, as shown in Fig 4.

**Figure 4 : modelling of NO96 cover plate**



If a reinforced primary box is considered, the cover plate is made of two plywood sheets stapled together. This should be modelled by attaching the two plates at the location of the staples and defining a contact interaction between the two surfaces, as shown in Fig 5. The contact interaction creates a non-linearity in the model, and therefore non-linear finite element analyses should be used for the strength assessment of the NO96 containment system.

**Figure 5 : Modelling of NO96 double cover plate**



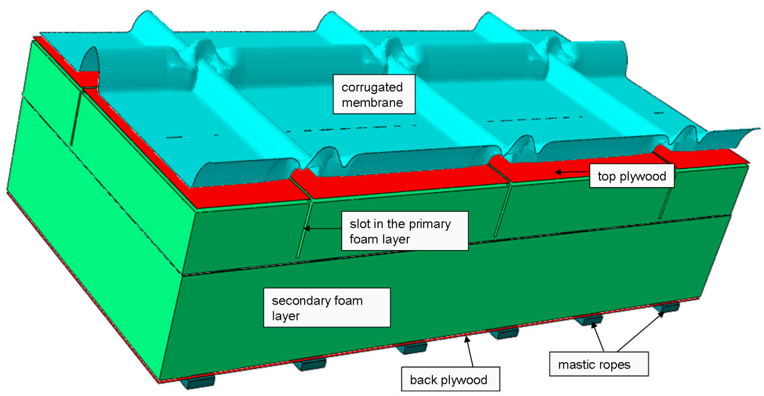

## 2.3 MarkIII system modelling

**2.3.1** Two types of finite elements should be used, depending on the component being considered:

- plywood sheets, triplex and corrugated membrane should be modelled with four-node shell elements
- reinforced polyurethane foams should be modelled with eight-node continuum elements; reduced-integration elements should be used to avoid numerical shear locking.

**2.3.2** The primary foam layer presents slots, designed to allow contraction of the reinforced polyurethane foams under thermal loads due to the cryogenic environment. They influence the structural response of the containment system and therefore have to be modelled as shown in Fig 6.

**Figure 6 : Modelling of MarkIII system**




**2.3.3** The MarkIII panel is assembled by gluing all parts together; therefore, the corresponding shell and continuum elements should be constrained one to another:

- back plywood sheet with mastic ropes and secondary foam layer
- secondary barrier (triplex membrane) with both foam layers (primary and secondary)
- top plywood sheet with primary foam layer.

**2.3.4** The primary barrier (corrugated stainless steel membrane) is welded to the anchoring strips (that are riveted onto the top plywood sheet). This connection should be modelled by constraining the primary barrier to the top plywood sheet at the corresponding locations. Then two possibilities can be considered:

- either to constrain the whole membrane to the top plywood sheet, or
- to define a non linear contact interaction between the areas of the membrane and those of the plywood sheet that are not attached.

**2.3.5** As long as the material properties are modelled using linear behavior (see [3.3]), the strength assessment of the MarkIII containment system does not require non-linear finite element analyses.

## 2.4 Mesh requirements

### 2.4.1 General

The dimensioning consideration for mesh size is to ensure that the bending of plywood sheets is correctly captured, i.e. that a good precision for the calculated bending stresses is reached:

- for NO96 containment system:

  the concerned part is the cover plate, and at least seven elements should be put in the space between two consecutive primary bulkheads
- for MarkIII containment system:

  the concerned part is the back plywood plate, and at least seven elements should be put in the space between two consecutive mastic ropes.

The same size (or almost the same size) shall be used for the rest of the containment system modelling, to ensure a good quality (in terms of element shapes) of the mesh.

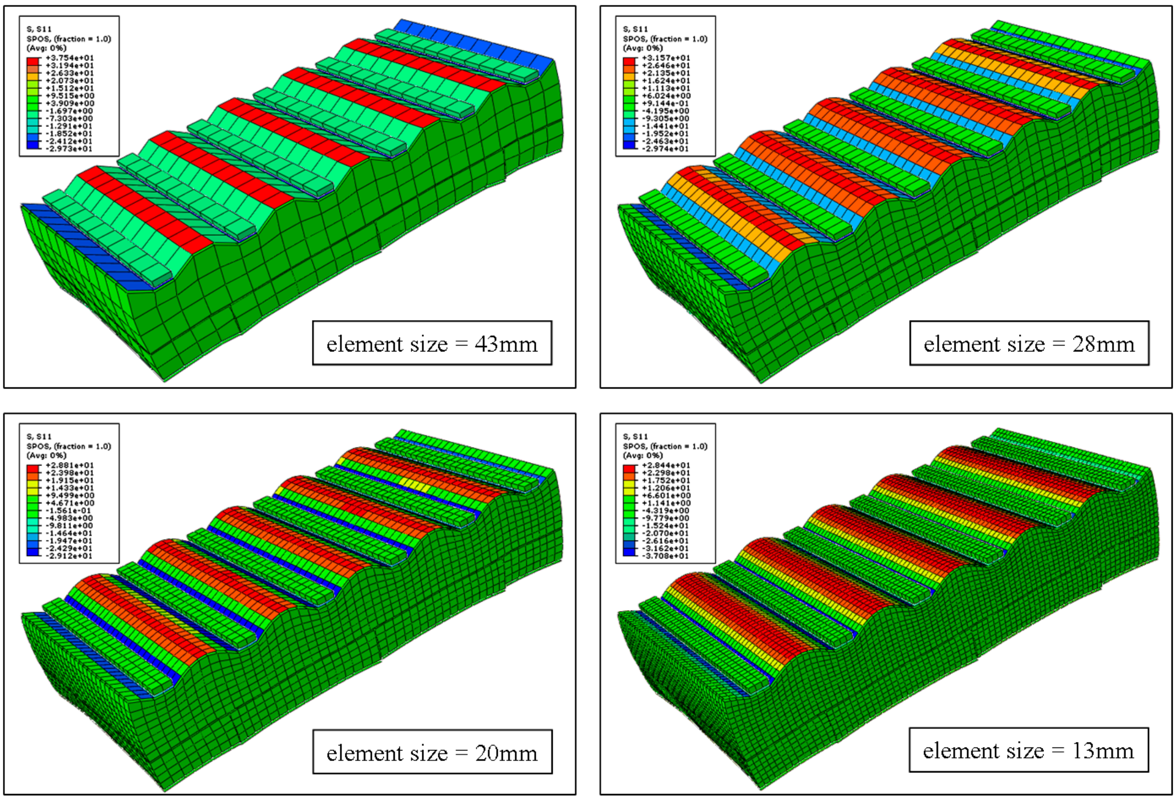
If the influence of the hull structure is considered, more than one containment system panel (either NO96 or MarkIII) are modelled, corresponding to the extent of the hull structure being represented. To improve the efficiency of the analysis, the mesh density away from the loaded area can be largely reduced, but at least three elements between primary bulkheads (for NO96) or between mastic ropes (for MarkIII) are to be kept. The size of the hull elements should be chosen so that they match the mesh of the containment system; this will ensure that deformations are correctly transmitted from one part to another.

### 2.4.2 Example

Fig 7 shows how much important it is to define a proper size of elements. The containment system is loaded with static and uniform pressure. The bending stresses in the back plywood of MarkIII containment system are represented for four different element sizes: 43 mm, 28 mm, 20 mm and 13 mm, corresponding, respectively, to three, five, seven and eleven finite elements between two consecutive mastic ropes.

Compared to the most refined case, considered as converged (11 elements between two mastic ropes), the case with three elements gives an error of +13%, while the cases with five, and seven elements give respectively an error of +11% and +1,5%.

**Figure 7 : Influence of mesh size - MarkIII containment system**



# 3 Material properties

## 3.1 General

**3.1.1** The evaluation of the proper mechanical characteristics of the material used for the containment systems is important for their correct strength assessment. The materials involved are well known and already used in many constructions, but the conditions in this case are particular:

- the temperature inside LNG tanks is cryogenic (about −163°C), and
- the sloshing impact loads have a very short duration.

The material properties can be influenced by each of these particular conditions.

**3.1.2** It is the designer responsibility to evaluate the mechanical characteristics of the materials, including the effects of cryogenic environment and of the dynamic loads.

**3.1.3** Prior to any other strength calculation, a first thermal computation should be performed to assess the distribution of the temperature through the containment system, so that the correct temperature-dependent mechanical characteristics are applied.

## 3.2 Primary and secondary insulation barriers

**3.2.1** Insulation barriers (NO96 invar membranes, MarkIII corrugated membrane and triplex sheet) should be modelled by linear isotropic elastic material laws, using the following standard parameters (values to be derived from material testing):

- density (necessary for the dynamic calculations)
- Young's modulus E
- Poisson's ratio.

**3.2.2** If non-linear analyses of the MarkIII corrugated membrane were to be performed, the exact plastic behavior should be implemented in the finite element modelling.

## 3.3 Reinforced polyurethane foam layers

**3.3.1** For the MarkIII foams, orthotropic elastic material laws should be considered, defining the following parameters (values to be derived from material testing):

- density
- Young's moduli $E_1$ and $E_2$ in the direction of the fiber reinforcements
- Young's modulus $E_3$ in the orthogonal direction, which usually defines the compression axis of the foam layers during the sloshing impacts
- Poisson's ratios
- shear modulus.

**3.3.2** Reinforced polyurethane foams mechanical properties present a high strain-rate dependency, especially regarding the crushing limit of the material. Mechanical tests should be performed to assess this strain rate dependent behavior.

**3.3.3** If non-linear finite element analyses could be performed, crushable foam modelling could also be defined to get a better modelling of the behavior and failure of the MarkIII foam layers. The parameter of the crushing law should be derived from material testing.

## 3.4 Plywood sheets

**3.4.1** Plywood is a composite made of several layers of woods; its behavior should be modelled with orthotropic elastic law. Considering the two directions being in the plan of the plywood sheet, one defines a strong direction and the other a weak one, depending on the arrangement of the layers. The following values should be defined:

- density
- Young's modulus in the three directions
- Poisson's ratios
- shear modulus.

### 3.5 Mastic ropes

**3.5.1** Mastic ropes connecting the containment system to the hull structure should be modelled using a linear isotropic elastic material law. The following parameters (values to be derived from material testing) should be defined:

- density
- Young's modulus
- Poisson's ratio.

## 4 Definition of failure modes

### 4.1 General

**4.1.1** The acceptance criteria for the strength assessment of cargo containment systems are based on the characterization of the possible failure modes, which is usually performed using a combination of physical tests and numerical calculations; in these latest calculations, the finite elements analyses should be performed according to the best practices described in Articles [2] and [3]. The failure modes for NO96 and MarkIII containment systems, as well as how the associated dynamic capacities can be derived, are detailed in the following sub-article.

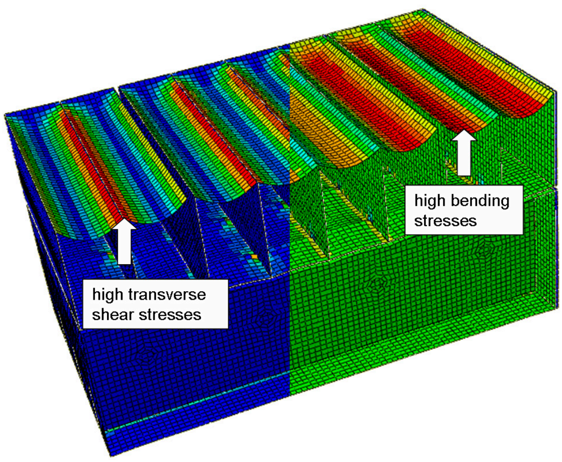
### 4.2 Failure of plywood sheets

#### 4.2.1 General

The first failure mode observed is the failure of the plywood sheets. This failure mode may be observed for both GTT's cargo containment systems, NO96 and MarkIII:

- for NO96 system, the primary cover plate, which is directly impacted by the LNG, is involved. The high impact pressure can either cause bending of the plywood sheets between two bulkheads, or create high transverse shear stresses at the junction between the bulkheads and the cover plate. Fig 8 shows both the transverse shear stresses and the bending stresses existing in the NO96 cover plate
- for MarkIII system, the back plywood sheet, which is supported by the mastic ropes, can be involved. The sloshing impacts can create high stress concentrations, i.e. either bending stresses in the middle of the non-supported part of the plywood sheet, or transverse shear stresses at the corner between mastic rope and plywood sheet. Fig 9 shows both the transverse shear stresses and the bending stresses existing in the MarkIII back plywood sheet.

**Figure 8 : Failure modes of NO96 cover plate**




#### 4.2.2 Transverse shear failure

The transverse shear failure of the cover plate, caused by the sharp corner between cover plate and bulkheads, is highly localized. The maximal value of the transverse shear stresses depends mainly on the element size. This is a limitation of the model but, as the approach remains comparative, the stresses are evaluated using the same procedure for the reference and target vessels. The following acceptance criterion is used for shear failure of cover plate:

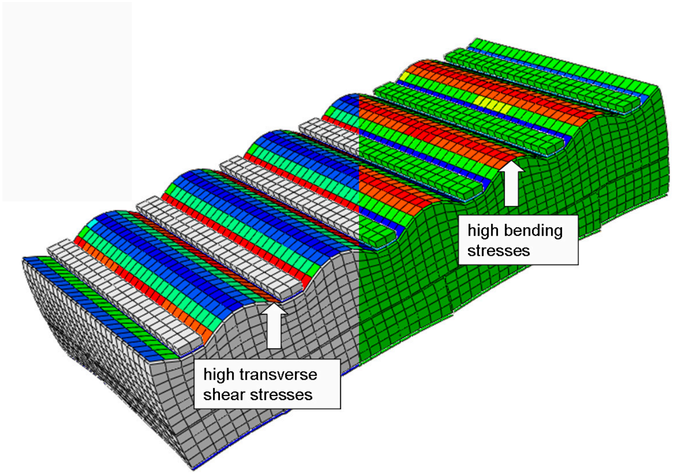
$\max(|\tau|) < \tau_{allowable}$

with:

$\tau$ : Calculated shear stresses in the plywood sheets

$\tau_{allowable}$ : Allowable shear stresses in the plywood sheets, determined by material testing.

**Figure 9 : Failure modes of MarkIII back plywood sheet**




### 4.2.3 Bending failure

Regarding the bending failure, the acceptance criterion is expressed as:

max (σ) < $\sigma_{allowable}$

with:

σ : Calculated bending stresses in the plywood sheets

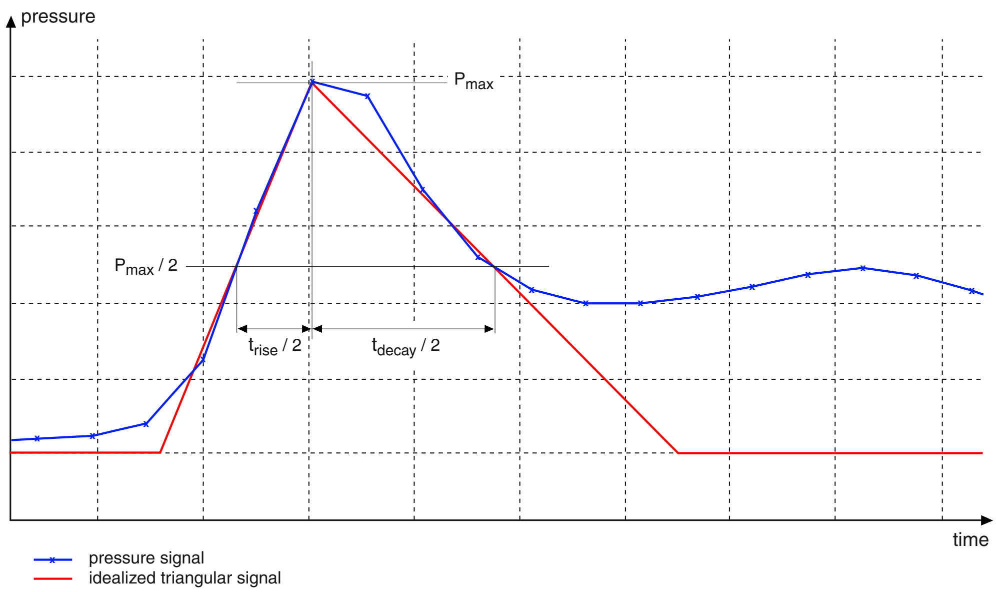
$\sigma_{allowable}$ : Allowable bending stresses in the plywood sheets, determined by material testing.

### 4.2.4 Dynamic capacity of the NO96 cover plate

Sloshing impacts are a highly dynamic phenomenon and, therefore, the dynamic capacity linked to the possible failure of the cover plate needs to be determined. The crucial parameters to describe the dynamic characteristic of an impact pressure are the rise and decay times. To assess the full dynamic capacity of the containment system, the range of rise and decay times to be analyzed should be determined from the results of the small-scale tests.

The capacity $C(t_{rise}, t_{decay})$, associated to one given pair ($t_{rise}$, $t_{decay}$), should be assessed by means of dynamic finite elements analyses and the dynamic sloshing pressure signal be idealized by a triangular impulse signal, as shown in Fig 10.

**Figure 10 : Idealized pressure signal**



In the case of NO96 containment system, the finite element modelling should be non-linear (refer to the definition of contact interactions given in [2.2.3]). For each pair ($t_{rise}$, $t_{decay}$) to be analyzed, a whole set of analyses is performed, in which the value of $P_{max}$ varies. The capacity of the cover plate is defined as the minimum $P_{max}$ value for which the bending or the transverse shear failure is obtained.

#### 4.2.5 Dynamic capacity of the MarkIII back plywood sheet

The dynamic capacity associated to the failure of the MarkIII back plywood sheet is determined by means of a method close to the one used for the failure of the NO96 cover plate (see [4.2.4]), using an idealized pressure signal to load the finite element model (see Fig 10).

However, for MarkIII containment system, linear finite element analyses are most of the time used (see [2.3.5]); therefore, for each pair ($t_{rise}$, $t_{decay}$), only one calculation needs to be performed. An arbitrary value of $P_{max}$ is taken and defined as the nominal pressure $P_{nom}$, and the maximal value of calculated compression stresses is recorded. Then, the dynamic capacity C of the MarkIII back plywood is determined as follows:

$$C(t_{rise},t_{decay}) = P_{nom} \cdot \min\left(\frac{\tau_{allowable}}{\max(|\tau|)}, \frac{\sigma_{allowable}}{\max(\sigma)}\right)$$

where:

$\tau$ : Calculated shear stresses in the plywood sheets

$\tau_{allowable}$ : Allowable shear stresses in the plywood sheets, determined by material testing

$\sigma$ : Calculated bending stresses in the plywood sheets

$\sigma_{allowable}$ : Allowable bending stresses in the plywood sheets, determined by material testing.

### 4.3 Buckling of NO96 bulkheads

#### 4.3.1 General

Due to the nature of NO96 containment system, i.e. plywood boxes stiffened with bulkheads, the second major failure mode is the buckling of the bulkheads. Fig 13 shows the first buckling mode of a reinforced NO96 box subjected to uniform and static pressure (from finite elements analysis).

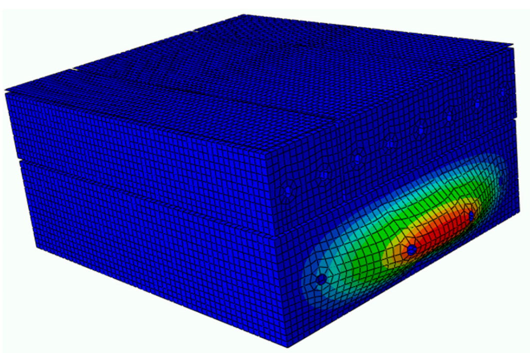
It is also noteworthy that the buckling strength of the box is likely to be influenced by the presence of the double hull structure.

Two types of buckling can be distinguished: static buckling and dynamic buckling, described respectively in [4.3.2] and [4.3.3].

#### 4.3.2 Static buckling

The static buckling can be assessed either experimentally, by performing buckling test on NO96 boxes, or numerically, by calculating the buckling eigen-modes of the structure with the help of finite elements analyses (see Fig 11).

**Figure 11 : First buckling mode of a reinforced NO96 box**



### 4.3.3 Dynamic buckling

Sloshing impact is a highly dynamic phenomenon and, therefore, the dynamic buckling for the strength assessment of NO96 containment systems is to be determined. To do that, the same methodology as for the cover plate dynamic capacity (see [4.2.4]) is used: for each pair ($t_{rise}$, $t_{decay}$), a set of $P_{max}$ values (see Fig 10) is analyzed, using non-linear finite element calculations.

The initial geometric imperfection should be:

- introduced in the model to trigger the buckling modes, and
- defined as the multiplication of the first static buckling mode of the structure (see Fig 11) by a factor ξ, chosen so that the maximal geometric imperfection is equal to 0,5mm.

For each calculation (i.e. each $P_{max}$ analyzed), global compression of the bulkhead (see Fig 12) should be monitored and compared. Then the buckling is detected by a discontinuity in the maximal bulkhead compression, as shown on Fig 13 the time evolution of the bulkhead compression for three different values of $P_{max}$ is plotted.

**Figure 12 : Dynamic buckling of NO96 bulkheads**

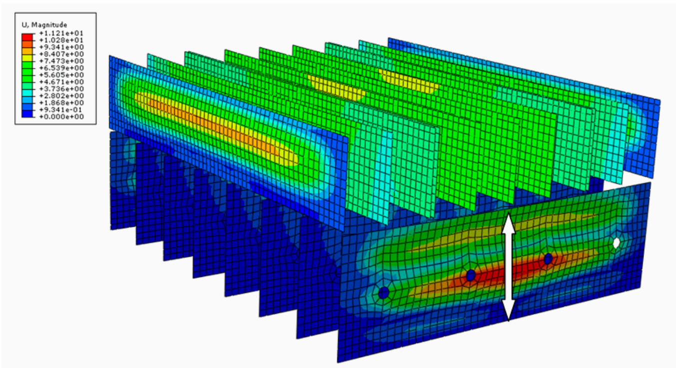
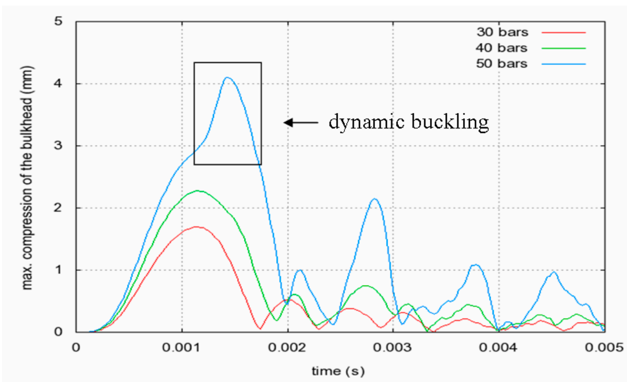



**Figure 13 : Detection of the dynamic buckling**

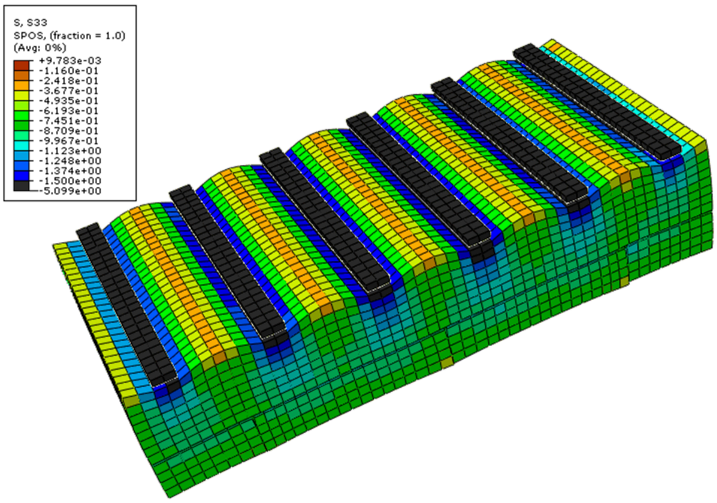



## 4.4 Crushing of MarkIII reinforced polyurethane foams

### 4.4.1 General

The first possible failure mode of MarkIII containment system is the crushing of the primary or secondary foam layers, subjected to compressive stresses (as shown in Fig 14). This failure mode is critical for MarkIII system: if the global deformation of the foam layer is too high, the primary corrugated membrane is not supported anymore, which could result in the creation of cracks in it, and the loss of its tightness.

**Figure 14 : Crushing of MarkIII foam layers**




### 4.4.2 Maximal stress criterion

One way of expressing the acceptance criterion corresponds to a maximal stress condition:

$\max(\sigma) < \sigma_{allowable}$

with:

$\sigma$ : Calculated compression stresses in the plywood sheets

$\sigma_{allowable}$ : Allowable compression stresses in the plywood sheets, determined by material testing.

The allowable compression stress refers to the compression stresses in the direction perpendicular to the fiber reinforcements; it is evaluated by material testing. Its rate-dependent behavior could also be assessed for a more correct evaluation of the containment system strength.

In this case, the dynamic capacity associated to the failure of the MarkIII foams is determined using the same method as for the failure of the MarkIII back plywood sheet (see [4.2.5]): an arbitrary value of $P_{max}$ is taken and defined as the nominal pressure $P_{nom}$, and the maximal value of calculated compression stresses is recorded for each pair ($t_{rise}$, $t_{decay}$). Then, the dynamic capacity C of the MarkIII foam is determined as follows:

$$C(t_{rise}, t_{decay}) = P_{nom} \cdot \frac{\sigma}{\max(\sigma_{allowable})}$$

### 4.4.3 Residual compression criterion

If the correct non-elastic material law of the foam is known (see [3.3]), non-linear finite element analyses can be performed, and a criterion of global permanent deformation of the two foam layers can be used:

$\max(U) = U_{allowable}$

with:

$U$ : Calculated permanent deformation of the foam

$U_{allowable}$ : Allowable permanent deformation of the foam.

In this case, the dynamic capacity associated to the failure of the MarkIII foams is determined using the same method as for the failure of the NO96 cover plate (see [4.2.4]): for each pair ($t_{rise}$, $t_{decay}$) analyzed, a whole set of analyses is performed, in which the value of $P_{max}$ varies. The capacity of the MarkIII foams is defined as the minimum $P_{max}$ value for which the maximal allowable residual displacement is obtained.

# 5 Acceptance criterion

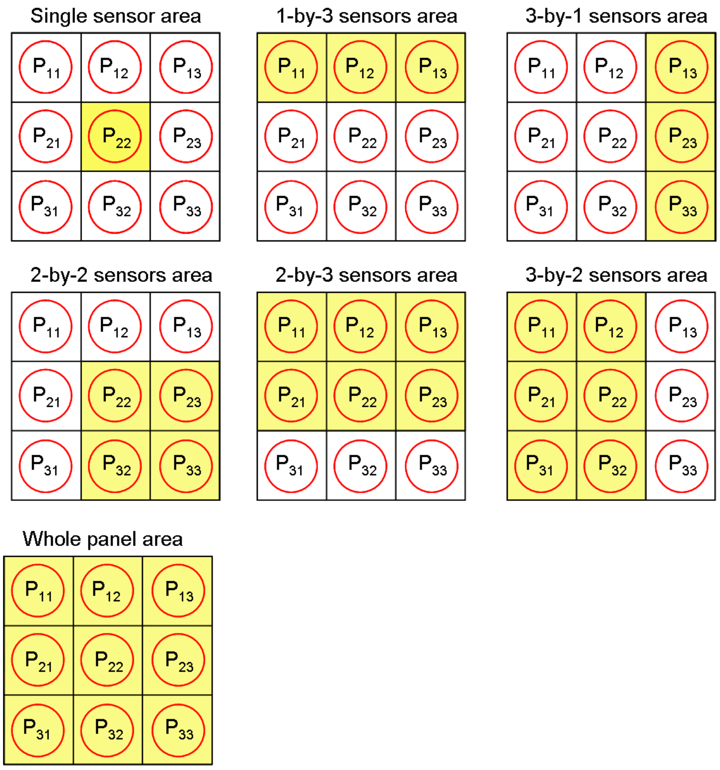
## 5.1 Capacity versus loaded surface curves

**5.1.1** Sloshing impact pressures, as well as containment system capacities, are dependent on the loaded surface considered: the same pressure, depending on whether applied on a very small surface or on the whole surface of the cargo containment system, will not have the same consequences on the structural capacity of the system. Therefore, it is recommended, instead of comparing only one value of design pressure with one value of structural capacity, to compare the curves giving the design pressure and the structural capacity as functions of the loaded surface curves.

**5.1.2** As the goal is to compare the loading and the containment system capacities, the surfaces used for the evaluation of structural capacities should be the same as for the evaluation of sloshing loads. For the small scale sloshing tests, surfaces of 1 m$^2$ are usually covered by panels of 3-by-3 or 4-by-4 pressure sensors. In Fig 15 and Fig 16, the example of a 3-by-3 panel is taken. The different set of pressure sensors can then be extracted:

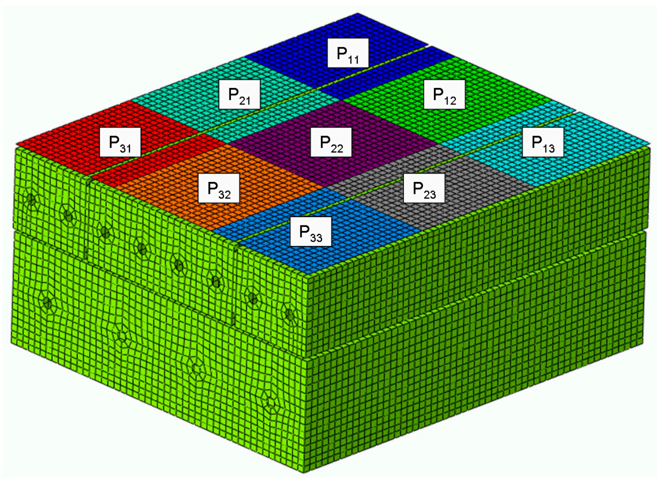
- 9 sets of single sensor: $\{P_{ij}\}_{i,j=1,2,3}$
- 6 sets corresponding to 3-by-1 and 1-by-3 sensors areas
- 4 sets corresponding to 2-by-2 sensors areas
- 4 sets corresponding to 3-by-2 and 2-by-3 sensors areas
- 1 set corresponding to the whole panel (3-by-3 sensors area).

**Figure 15 : Definition of the loaded areas**




**5.1.3** Then, the same area sets should be used in the finite element analyses for the evaluation of structural capacities, to define the loaded areas on which dynamic pressures should be applied (see Fig 15). Fig 16 illustrates the definition of the 9 loaded areas (corresponding to the 9 pressure sensors) in the finite element model of a NO96 box.

**Figure 16 : Definition of the loaded areas for the finite element analyses**



## 5.2 Dynamics of the impacts

**5.2.1** The structural capacities of the containment systems are highly dependent on the dynamic characteristics of the loads, and more precisely to the rise and decay times of the peak pressures (see Fig 10). To get the correct dynamic capacities of the containment system, it is therefore necessary to know which pair ($t_{rise}$, $t_{decay}$) needs to be considered. Two possibilities can be considered:

- the first option consists in calculating the probability density function for the pairs ($t_{rise}$, $t_{decay}$) measured during small-scale model tests, and retaining the most probable for the evaluation of structural capacities
- the second approach, more conservative, consists in evaluating the structural capacities for the whole range of pairs ($t_{rise}$, $t_{decay}$), and retaining the most severe for each failure mode.

**5.2.2** The rise and decay times measured from small-scale model tests should be scaled up to full scale. Froude similitude is generally considered as appropriate for sloshing impacts.

## 5.3 Comparative assessment

**5.3.1** At this stage of the strength assessment procedure, the four curves giving the following design loads and capacities for reference and target vessels, as functions of the loaded surfaces, are known:

$P_{ref}$ : Design sloshing loads for the reference vessel - measured from small-scale model tests

$P_{target}$ : Design sloshing loads for the target vessel - measured from small-scale model tests

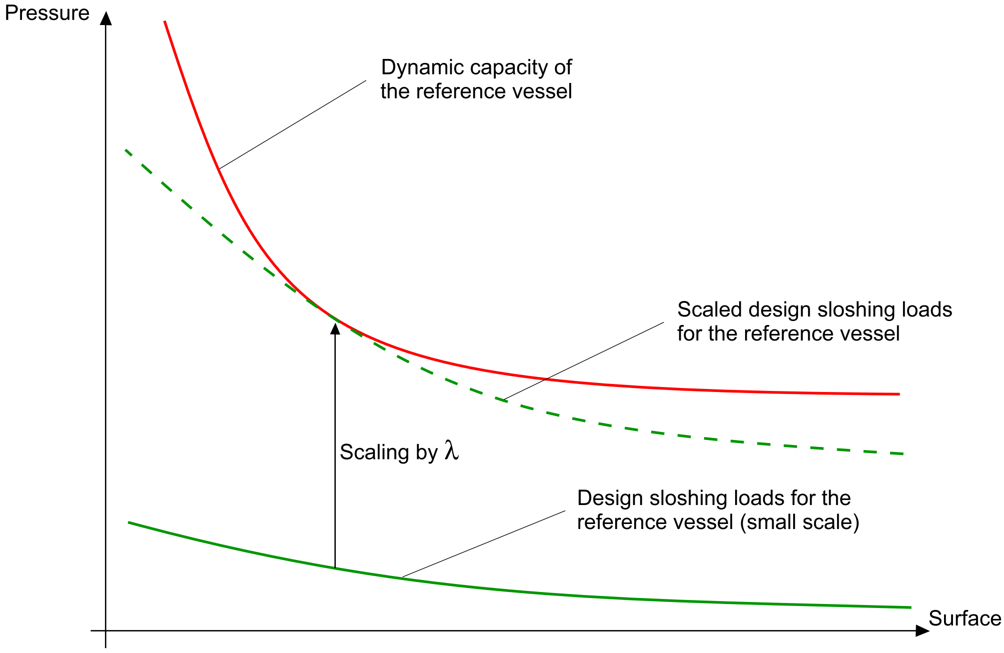
$C_{ref}$ : Dynamic capacity of the containment system used in the reference vessel - full scale values

$C_{target}$ : Dynamic capacity of the containment system used in the target vessel - full scale values.

**5.3.2** The reference vessel is used to determine the scaling factor λ from small-case to full-scale. The reference vessel is considered having not encountered any damage, so its scaled design load curve is necessarily below its capacity curve. The λ factor is chosen so that the scaled design load curve of the reference vessel is tangent to the corresponding capacity curve, as shown in Fig 17. Therefore, it can be expressed as:

$$\lambda = \min\left(\frac{C_{ref}}{P_{ref}}\right)$$

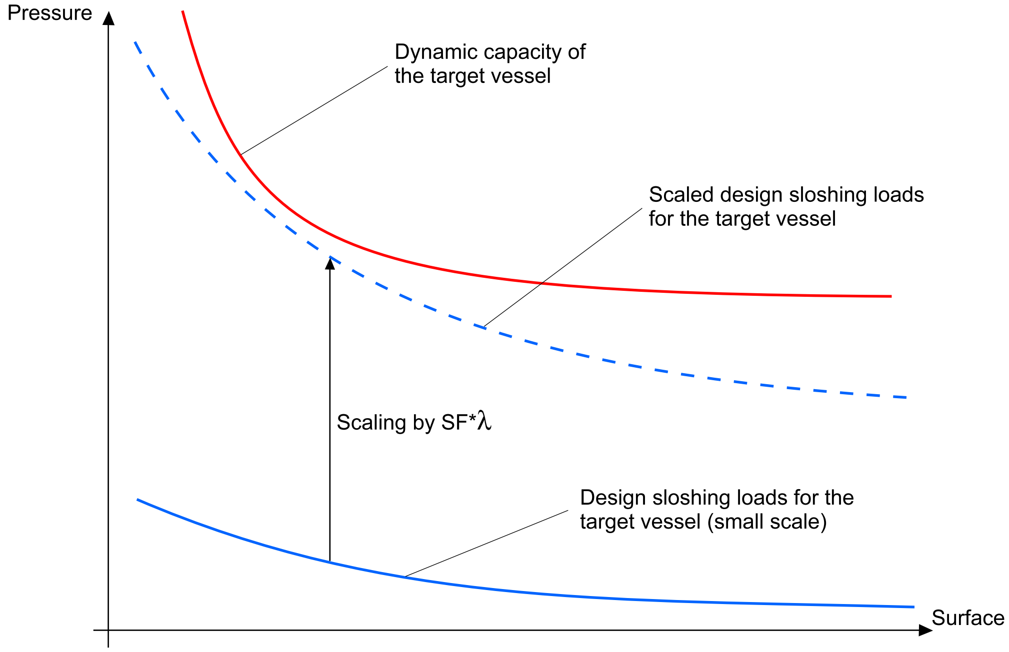
**Figure 17 : Comparative strength assessment - step 1**



**5.3.3** Finally, to assess the target vessel, the small-scale design loads are scaled by the factor λ obtained previously and by a safety factor (SF), and compared to the capacity of the target vessel, as shown in Fig 18. This assessment could be summarized by the following formula:

$C_{target} \geq SF \cdot \lambda \cdot P_{target}$

**Figure 18 : Comparative strength assessment - step 2**



# APPENDIX 1 PUMP MAST STRENGTH ASSESSMENT

## 1 Introduction

### 1.1 General

**1.1.1** The present Appendix defines how to check, for LNG tanks, the validity of the design of the tubular pump masts made of stainless steel.

**1.1.2** A typical pump mast disposition in a membrane-type tank of LNG carrier is presented in Fig 1.

**1.1.3** To approve the structural resistance of the pump mast exposed to the combinations of various loads, direct calculation of the mentioned structure is to be performed.

**1.1.4** A finite element analysis, or a similar method, is to be used to determine the suitability of the structure regarding:

- the structural strength
- the fatigue
- the vibration.

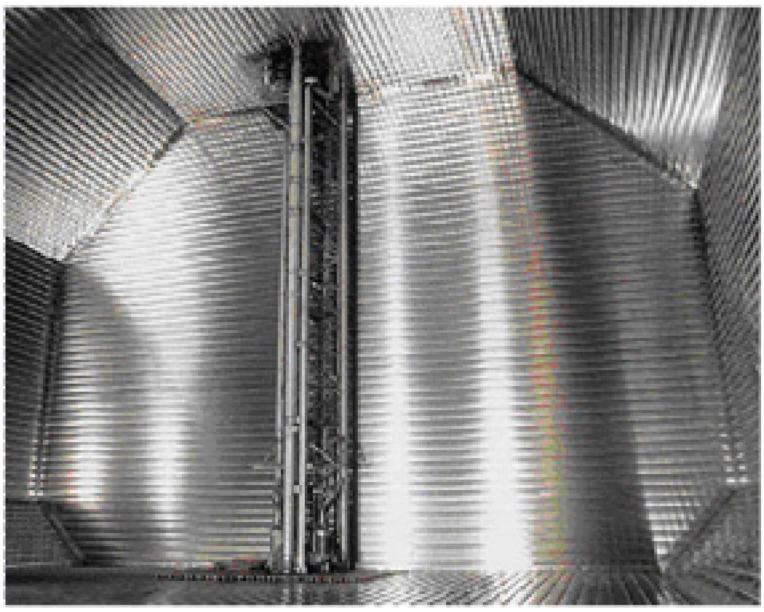
**1.1.5** The entire pump mast structure, comprising tubular elements, liquid dome, pump mast base support and base plate, should be verified for all the operational filling conditions.

**1.1.6** Structural strength under extreme static and dynamic loadings should be assessed by a direct finite element analysis, combining the hydrodynamic loads obtained from sloshing numerical simulation with other elementary loads in relation to each operational condition.

**1.1.7** The fatigue analyses of pump mast structure and mast supports are required to verify the structural fatigue life.

**1.1.8** The calculation of mast structure natural frequencies and comparison with the frequencies of main sources of vibration excitations is required.

**Figure 1 : Typical pump mast disposition in membrane-type LNG tank (courtesy of GTT)**



# 2 Finite elements model

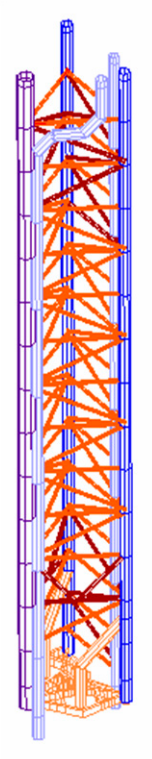
## 2.1 General

**2.1.1** The typical finite element model used in static, dynamic and fatigue analyses of the pump mast (see Fig 2) is built using the beam finite elements for the corresponding mast geometry.

**2.1.2** All the loading conditions need to be analyzed, depending on the vessel and mast design particularities. Operation in partial filling conditions, in general, will lead to reinforcement of the entire pump mast structure: tubular elements, liquid dome, pump mast base support and base plate, by comparison with the structure design of conventional vessels with similar tank and hull properties.

**2.1.3** The requirements regarding the mast finite element model are described from [2.2] to [2.4].

**Figure 2 : Finite elements model of the pump mast**



## 2.2 Global model of the pump mast

**2.2.1** Global three-dimensional finite element model of the entire mast structure is to be defined. In the global model, the entire supporting structure - liquid dome and supporting part of hull double bottom structure - may be included. If these supporting parts are not modelled, they shall be substituted with proper boundary conditions (see [2.3.1]).

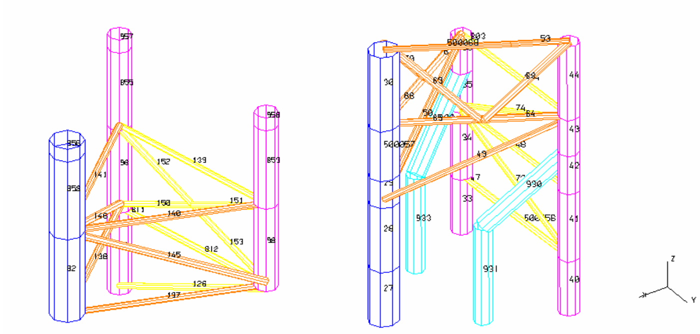
**2.2.2** For the tubular structure, beam type finite elements may be used. All main structural elements of the mast are to be included in the model. The beam elements are to be located on the axis of the modelled tubes; nodes are therefore at the intersections of the tube axis.

**2.2.3** A more refined shell model needs to be used only if considered necessary, owing to the beam model results or any other uncommon problems.

## 2.3 Boundary conditions

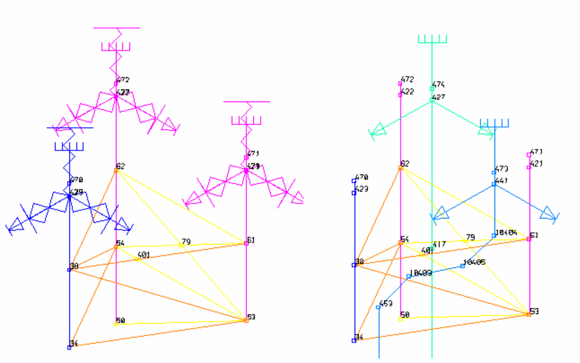
**2.3.1** If the supporting structures of the pump mast are not included in the model, the proper boundary conditions are to be defined in the corresponding contact points (see Fig 3).

**Figure 3 : Finite elements model of the upper and lower parts of the main column in the pump mast**



**2.3.2** Muffs at the three upper struts need to be modelled, as they ensure the axial displacement and rotation about the elements axis (see Fig 4).

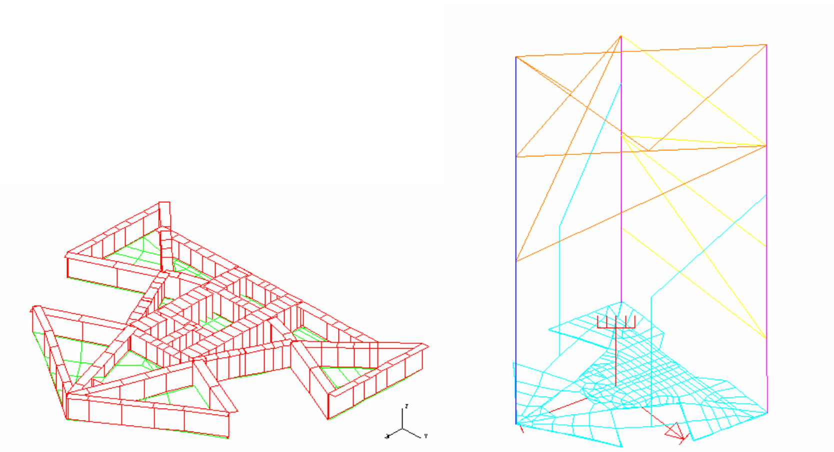
**Figure 4 : Boundary conditions in the upper part of the pump mast model (on the left: discharge and emergency pipes - on the right: filling and gauge pipes)**



**2.3.3** The upper part of the pump mast structure is supported with the deck structural elements in the liquid dome area. A separate analysis of the dome structure is to be performed to determinate the rotational stiffness in the connections between vertical columns of the pump mast and the structure of liquid dome. Deck plating could be considered as infinitely rigid for the in-plane displacements.

**2.3.4** The bottom ends of the pump mast columns are connected with the base plate. The mast structure at the lower end is connected to the lower support through the base plate. The lateral translations and torsion are constrained in the node of the lower support (see Fig 5).

**Figure 5 : Lower part of the pump mast model (on the left: base plate model - on the right: lower support)**



### 2.4 Material mechanic properties

**2.4.1** The pump mast tubular structure elements are made of stainless steel 304L. According to ASTM A312 and A409 standards, the mechanical properties of this steel, at a temperature of 20°C (ambient), are the following:

- limit strength: 483MPa
- yield limit: 172MPa
- shrink coefficient: $15 \cdot 10^{-6}$ °C$^{-1}$.

**2.4.2** For the structural parts subjected to temperatures lower than the ambient one, the material properties become different from those defined above. The temperature-dependent mechanical properties of stainless steel 304L are given in Tab 1.

**Table 1 : Material properties of stainless steel 304L**

| Temperature (C) | +20 | –50 | –106 | –163 |
|---|---|---|---|---|
| Yield limit (MPa) | 172 | 193 | 212 | 225 |
| Shrink coefficient (C$^{-1}$) | $15,0 \cdot 10^{-6}$ | $15,2 \cdot 10^{-6}$ | $14,3 \cdot 10^{-6}$ | $13,5 \cdot 10^{-6}$ |

## 3 Loading conditions

### 3.1 Representative tank

**3.1.1** A representative tank is selected, governed by the criteria of being the greatest capacity furthest from the ship's centre of gravity.

### 3.2 Filling levels

**3.2.1** For ships up to 155000 m$^3$ of cargo capacity, standard filling levels considered in pump mast analysis are:

- 10% H
- 70% H
- 80% H
- 95% H.

**3.2.2** Partial filling levels considered are at least:

- 20% H
- 30% H
- 50% H.

### 3.3 Loaded cases and their combination

**3.3.1** Loads applied on pump mast structure are composed of the following elementary loads:

- hydrodynamic loads from sloshing simulation
- inertia forces due to the ship motion from hydrodynamic computation
- thermal loads due to the temperature gradient in partial filling condition
- self weight of structural elements including entrapped liquid
- buoyancy of immersed structural elements
- pump torque effects in on/off-loading operation.

### 3.4 Hydrodynamic and inertia loads

**3.4.1** Hydrodynamic and inertia forces are obtained by sloshing and sea-keeping computations.

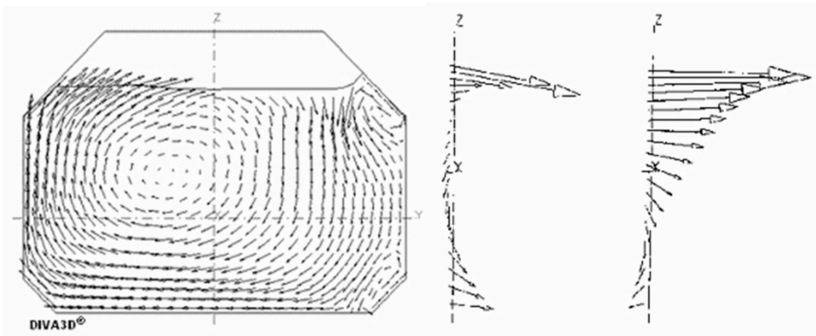
**3.4.2** For all the selected filling levels, relevant loading cases assuming to give the greatest total force are determined, as well as resulting hydrodynamic force due to the sloshing flow and corresponding inertial forces due to the ship motion.

**3.4.3** Sloshing simulations are performed by application of harmonic excitation derived from the sea-keeping analysis, and results are provided in the form of tank liquid velocity and acceleration time histories along the three vertical columns of pump mast.

**3.4.4** Hydrodynamic forces per unit length are obtained from Morison equations, with a drag coefficient CD determined from the Reynolds's number corresponding to the velocity obtained from sloshing simulation.

**3.4.5** From the time histories coming from resultant Morison and inertia forces, sloshing load applied on FEM (finite element model) is determined at the reference instant where the global force is maximal. One example of velocity field distribution obtained from numerical simulation is given in Fig 6.

**Figure 6 : Example of captured velocity from numerical simulation at pump mast cross-section (on the left) and along the pump mast (on the right)**




### 3.5 Thermal loads

**3.5.1** The temperature of the submerged part of the pump mast structure is assumed to be the same as the temperature of liquefied gas, i.e. −163°C.

**3.5.2** From the level of fluid free surface up to the top of the structure, the temperature distribution is assumed to be linear. The temperature on the top is assumed to be −30°C.

### 3.6 Pump torque effects, self-weight and buoyancy

**3.6.1** Pump torque effects are considered, for the ship, at the end of unloading case.

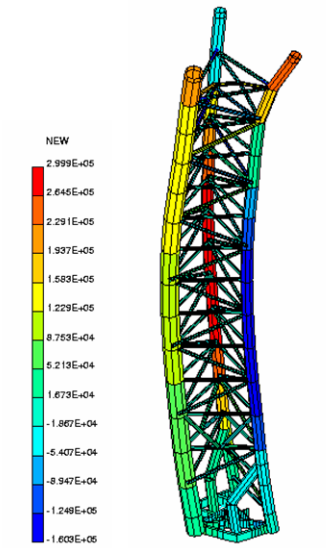
**3.6.2** Self-weight of the entire pump mast structure and buoyancy of immerged part are to be included in the load definition.

## 4 Structural strength analysis

### 4.1 General

**4.1.1** The structural element strength is to be verified for all the beam elements of the main structural part and the loads are to be taken as the largest loads to be possibly carried by the ship during its operating life.

**Figure 7 : Strength analysis of pump mast**




**4.1.2** Both the tubular elements and their intersections are to be verified.

**4.1.3** Distribution of total axial forces as one example of standard results from static analysis is presented in Fig 7.

## 4.2 Verification of tubular elements

**4.2.1** The calculated stresses on the different sections along the tubular elements are to be compared with the allowable values, taking into account the buckling of the element subjected to compressive axial load.

**4.2.2** The following stress components are to be computed for all the specified loading cases and for different sections along the elements:

$f_a$ : Axial compression stress

$f_x$ : Axial stress

$f_{by}$ , $f_{bz}$ : Bending stresses

$f_v$ : Beam shear stress

$f_{vt}$ : Torsion shear stress.

The following allowable stress values are to be compared with the calculated stresses:

$F_t$ , $F_a$ : Axial tension and axial compression stresses

$F_b$ : Bending stress

$F_v$ : Shear and torsion stresses.

The stress values are calculated for the extreme environmental conditions; therefore, the allowable stress may increase by one third.

**4.2.3** The tubes are considered correctly dimensioned if the following normalized ratios are smaller than 1,0 (for symbols not defined in the present NI564, see American Petroleum Institute publication: "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working stress design"):

- axial ratio:

$$\frac{f_x}{F_t}$$

- bending ratio:

$$\frac{\sqrt{f_{by}^2 + f_{bz}^2}}{F_b}$$

- combined axial compression and bending ratios:

$$\frac{f_a}{F_a} + \frac{C_m\sqrt{f_{bx}^2 + f_{by}^2}}{\left(1 - \frac{f_a}{F_e'}\right)F_b}$$

$$\frac{f_a}{0{,}6F_a} + \frac{\sqrt{f_{bx}^2 + f_{by}^2}}{F_b}$$

$$\frac{f_a}{F_a} + \frac{\sqrt{f_{bx}^2 + f_{by}^2}}{F_b}$$

$$\frac{f_a}{F_a} + \frac{\sqrt{\left[\frac{C_{mx}f_{bx}}{1 - \frac{f_a}{F_{ex}'}}\right]^2 + \left[\frac{C_{my}f_{by}}{1 - \frac{f_a}{F_{ey}'}}\right]^2}}{F_b}$$

- shear and torsion ratios:

$$\frac{f_v}{F_v} \text{ and } \frac{f_{vt}}{F_v}$$

### 4.3 Verification of tubular element intersections

**4.3.1** The following geometric condition is to be satisfied for the tubular element intersections:

$$\frac{F_{yb} \cdot \gamma \cdot \tau \cdot \sin\theta}{F_{yc} \cdot \left(11 + \frac{1,5}{\beta}\right)} \leq 1$$

where:

$F_{yc}$ : Yield strength of the chord member at the joint (or 2/3 of the tensile strength if smaller)

$F_{yb}$ : Yield strength of the brace member

$\gamma, \tau, \theta, \beta$ : Joint geometry parameters.

**4.3.2** Punching shear and nominal loads are to be checked for all the tubular element intersections, according to the type of tubular joints.

**4.3.3** The following values and corresponding ratios are to be calculated:

$P_a$ : Allowable capacity for brace axial load

$M_a$ : Allowable capacity for brace bending moment

$P$ : Axial load (positive for compressive, negative for tensile)

$M_{IPB}$ : In-plane bending moment

$M_{OPB}$ : Out-of-plane bending moment.

The tubular intersections are considered correctly dimensioned if the normalized ratios are smaller than 1,0 (for more details, see API's "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working stress design").

## 5 Fatigue analysis

### 5.1 General

**5.1.1** The fatigue analysis is to be performed for areas where high stresses or large stress concentrations are expected, analysis to be carried out in accordance with Guidance Note NI393, Fatigue Strength of Welded Ship Structures.

### 5.2 Loading conditions and calculation of hot spot stress range

**5.2.1** Ship's life profiles, distribution of time in resonance and loading cases for fatigue calculation are to be defined taking into account the following assumptions:

- sailing factor: 0,9
- ship's life profile: 10% harbor, 40% ballast, 50% sailing
- navigation direction: 25% head sea, 75% beam sea
- time in resonance: based on the probability of occurrence of wave zero-crossing period $T_z$ (see NI393) that induces motion in resonance (for each heading and speed).

**5.2.2** According to the fatigue calculation procedure, the design fatigue life is based on the world-wide trading sea condition spectrum (Global Wave Statistics, North Atlantic - Area 16), taking into account the S-N curve at minus two standard deviations.

**5.2.3** The fatigue analysis is performed with the hot spot stress ranges calculated at the pipe connections, by application of a stress concentration factor to the nominal stresses obtained from finite element analysis.

**5.2.4** Hot spot stresses at the tube intersection are to be determined by parametric formulae (M. Efthymiou: "Development of SCF formulae and generalised influence functions for use in fatigue analysis", OTJ88, Surrey, 1988), or similar with previous acceptance of the Society.

**5.2.5** At pipe connection, hot spot stress range is to be calculated at least for four points.

## 5.3 Long-term distribution of stresses

**5.3.1** The long-term distribution of stresses f(S) is described by the two-parameter Weibull distribution, with the following density function:

$$f(S) = \frac{\xi}{w}\left(\frac{S}{w}\right)^{\xi-1}\exp\left(-\frac{S}{w}\right)^{\xi}$$

where:

ξ : Shape parameter, equal to:

$$\xi = 1{,}1 - 0{,}35 \cdot \frac{L-100}{300}$$

w : Characteristic value of S, equal to:

$$w = \frac{S_R}{(\ln N_R)^{\frac{1}{\xi}}}$$

$N_R$ : Number of cycles corresponding to the probability of exceedance of $1/N_R$

$S_R$ : Stress range at the probability of exceedance of $1/N_R$

L : Rule length of the ship, as defined in NR467, Rules for Steel Ships, Pt B, Ch 1, Sec 2, [3.1].

## 5.4 Stainless steel S-N curve

**5.4.1** Usual two-slope S-N curve may be written as:

logN = logC – m · logS

with m and logC defined in Tab 2.

**5.4.2** For the connection of tubular structure exposed to variations of stress due to environmental and operational loads, the following S-N curve (minus two standard deviations) is to be used, using the parameters detailed in Tab 2.

**Table 2 : S-N curve parameters**

| Range | m | logC |
|---|---|---|
| $N \leq 10^7$ | 3 | 12,476 |
| $N > 10^7$ | 5 | 16,127 |

## 5.5 Calculation of Miner-Palmgren sum

**5.5.1** For the calculation of the Miner sum, the ship's life is considered to be composed of the following conditions:

- operational conditions:
  full load represented with 70% H - 98% H filling
  ballast load represented with 0% H - 10% L filling
- navigation conditions:
  head sea and beam sea.

**5.5.2** Assuming the Weibull distribution of stresses and a two-slope S-N curve, the cumulative damage ratio D is given by:

$$D = \frac{N_t}{K_P} \cdot \frac{S^m}{(\ln N_R)^{\frac{m}{\xi}}} \cdot \mu\Gamma\left(\frac{m}{\xi}+1\right)$$

where:

$N_t$ : Number of cycles for the expected ship’s life, taken as:

$$N_t = \frac{T}{4\log L}$$

$K_P$ : Coefficient of the first part of the S-N curve

S : Stress range, in MPa, at the probability of $10^{-8}$

m : First slope of the S-N curve

Γ : Gamma function

μ : Coefficient taking into account the change in slope of the S-N curve:

$$\mu = 1 - \frac{\left[\gamma\left(\frac{m}{\xi}+1,\upsilon\right) - \upsilon^{\frac{-\Delta m}{\xi}} \cdot \gamma\left(\frac{m+\Delta m}{\xi}+1,\upsilon\right)\right]}{\Gamma\left(\frac{m}{\xi}+1\right)}$$

with:

$$\upsilon = \left(\frac{S_q}{S_R}\right)^{\xi} \ln N_R$$

γ : Incomplete gamma function:

$$\gamma(a+1, x) = \int_0^x t^a e^{-t} dt$$

**5.5.3** The design fatigue life for each joint and member is to be at least twice the intended service life of the structure.

# 6 Modal analysis

## 6.1 General

**6.1.1** For the calculation of structure natural frequencies, the same finite element model as for the structural strength and fatigue analyses may be used, including entrapped liquid inside the tubular elements up to the filling level. See Fig 8.

**6.1.2** The main sources and the excitation frequencies of the possible vibrations of the pump mast are to be identified.

**6.1.3** The calculated mast bending and torsion natural frequencies for each loading condition are to be compared with the excitation source frequencies. The coincidence within ±10% is to be avoided.

**Figure 8 : Modal analysis of the pump mast**

# 7 Strength and fatigue analysis of mast supports

## 7.1 General

**7.1.1** In addition to above analyses of pump mast structure, the supports of mast are to be verified.

**7.1.2** The calculated reaction forces in the analyses described in Articles [4] to [6] are to be used as a loading in strength and fatigue calculations of supporting structure.

**7.1.3** The analyses are to be performed in accordance with Rule Note NR467, Rules for Steel Ships, and Guidance Note NI393, Fatigue Strength of Welded Ship Structures.

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