GUIDE FOR BUILDING AND CLASSING

LIQUEFIED GAS CARRIERS WITH INDEPENDENT TANKS JANUARY 2010

NOTICE NO. 1 – June 2011

The following Rule Changes become **EFFECTIVE AS OF 1 JUNE 2011.**

(See http://www.eagle.org for the consolidated version of the Guide for Building and Classing Liquefied Gas Carriers with Independent Tanks 2010, with all Notices and Corrigenda incorporated.)

Notes - *The date in the parentheses means the date that the Rule becomes effective for new construction based on the contract date for construction. (See 1-1-4/3.3 of the ABS Rules for Conditions of Classification (Part 1).)*

FOREWORD

(Revise Foreword, as follows.)

Foreword *(1 June 2011)*

(Preceding text remains unchanged.)

The ABS *Guide for Liquefied Petroleum Gas Carriers with Type-A Independent Tanks* became effective 1 JANUARY 2006. In May 2009, the criteria was extended to cover liquefied gas carriers with Type B and Type C independent tanks. This revision adds guidelines for hull girder ultimate strength assessment and has an effective date of 1 January 2010. The June 2011 revision includes fatigue, fracture, and thermal analysis for type-B independent tanks which is required by IGC code. Paragraph 6/9.7 and Appendix 5 are added to the Guide.

SECTION 6 ACCEPTANCE CRITERIA

(Add new Paragraph 6/9.7, as follows.)

9.7 Fatigue and Fracture Analysis for Type-B Independent Tanks *(1 June 2011)*

IMO IGC requires advanced analyses for type-B independent tanks. Additional analyses are to be conducted for type-B independent tank in accordance with Appendix 5 “Fatigue and Fracture Analysis for Type-B Independent Tanks”:

- Fatigue damage analysis
- Fracture mechanics analysis
- Leakage analysis
- Thermal stress analysis

APPENDIX 5 FATIGUE AND FRACTURE ANALYSIS FOR TYPE-B INDEPENDENT TANKS

(Add new Appendix 5, as follows.)

APPENDIX 5 Fatigue and Fracture Analysis for Type-B Independent Tanks *(1 June 2011)*

1 General

IMO requires additional fatigue and fracture mechanics based analysis for type B independent tank. Structural members in independent cargo tanks are affected by dynamic loads from internal pressure caused by ship motion. The strength and safety of type B independent cargo tank are to be verified against dynamic loads through fatigue and fracture mechanics based analysis.

This appendix provides procedure and acceptance criteria for fatigue and fracture analysis of a cargo tank to verify compliance with IMO type B independent tank requirements. Fatigue and fracture analysis are to be carried out for a tank to verify adequate fatigue and crack propagation characteristics. Integrity of the structural member of an independent tank against fatigue and fracture is to be verified by:

- Fatigue damage analysis for high cycle and low cycle fatigue load
- Fracture mechanics based analysis for an initial crack
- Leakage of cargo analysis in case of a penetrating crack

The general procedure for fatigue and fracture analysis is shown in Appendix 5, Figure 1.

1.1 Selection of a Tank for the Analysis

The internal pressure on an independent tank due to the acceleration of the center of gravity of liquid cargo can be estimated following the procedure in Subsection 3/11. The tank under the most severe internal pressure is to be selected for the fatigue and fracture analysis. The forward most cargo tank is normally selected as a target cargo tank for the analysis if the shape and size is similar to other tanks.

1.3 FEA Model

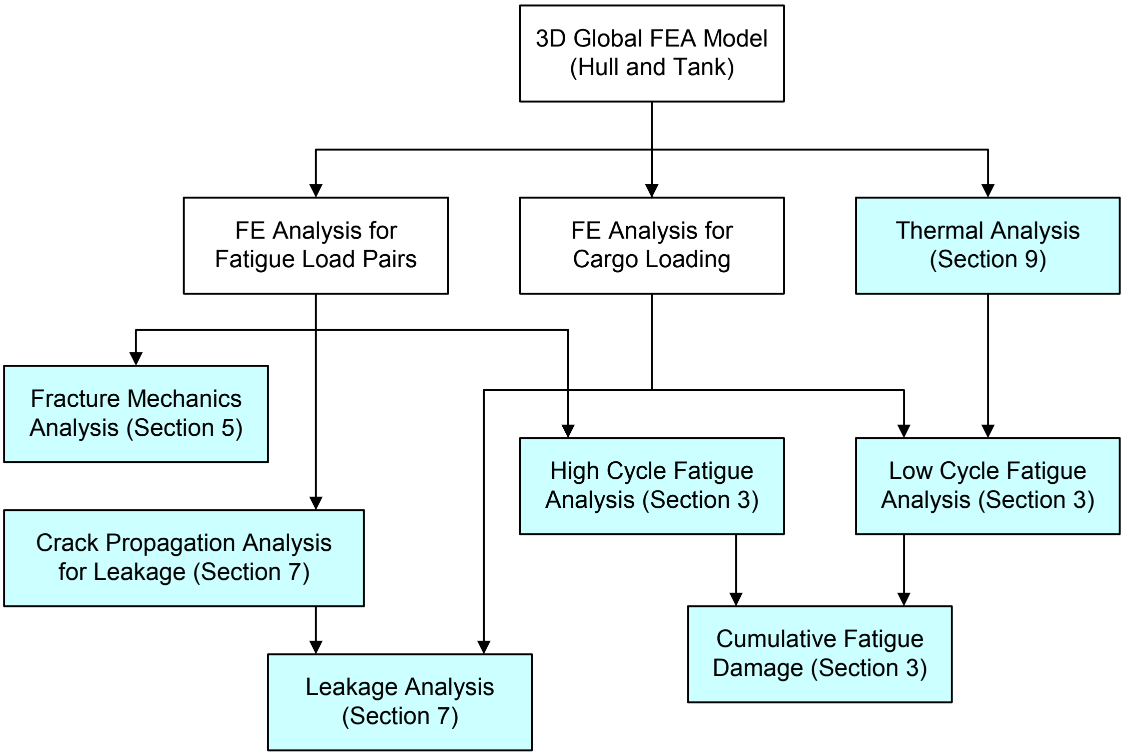
The global FEA model including hull, cargo tank, and supporting structure is to be used for the fatigue and fracture analysis. Global finite element modeling is described in Appendix 1. In the FEA model the target cargo tank is to be located in the middle of the model as shown in Appendix 1, Figure 1.

1.5 Critical Locations

Fatigue damage assessment and fracture mechanics analysis are to be carried out for areas of the tank with high stress concentrations. Critical locations with high stress include;

- Tank skin including bottom, top, side, front, and rear plates
- Bracket connections of transverse web frames
- Bracket connections of swash bulkheads
- Bracket connections of horizontal stringers
- Brackets attached to tank at vertical supports and chocks

FIGURE 1
Analysis Procedure *(1 June 2011)*



1.7 Hot Spot Stress with Global Course Mesh

Generally, it is recommended to use hot spot stress as a local stress for fatigue and fracture analysis in this appendix. For an initial screening purpose of critical areas, global coarse FEA model is to be used. When the stress result from global coarse FEA model is used for the analysis, hot spot stress can be estimated from nominal stress with appropriate stress concentration factors for stiffener attachments and skin plates with fillet welds.

The bending stress of a plate between stiffeners from internal pressure is to be considered for fatigue and fracture analysis of tank skin plates. The total stress amplitude is the sum of the membrane stresses from FEA results and local stresses caused by panel bending. Bending stress of a panel between stiffeners is to be calculated from 5C-1-5/3.5 of the *Steel Vessel Rules*.

1.9 Hot Spot Stress with a Local Fine Mesh

For a critical areas identified from the global course mesh, additional fatigue and fracture analysis are to be carried out with local fine mesh FEA models. The hot spot stress is to be calculated from the FEA results with a refined mesh. The mesh size of local area is to be small enough to detect the stress concentration and the element size at the critical location is to be equal to the plate thickness. The procedure to estimate the hot spot stress at a weld toe with refined mesh is specified in A3/11.5.

1.11 Plate Thickness Effect

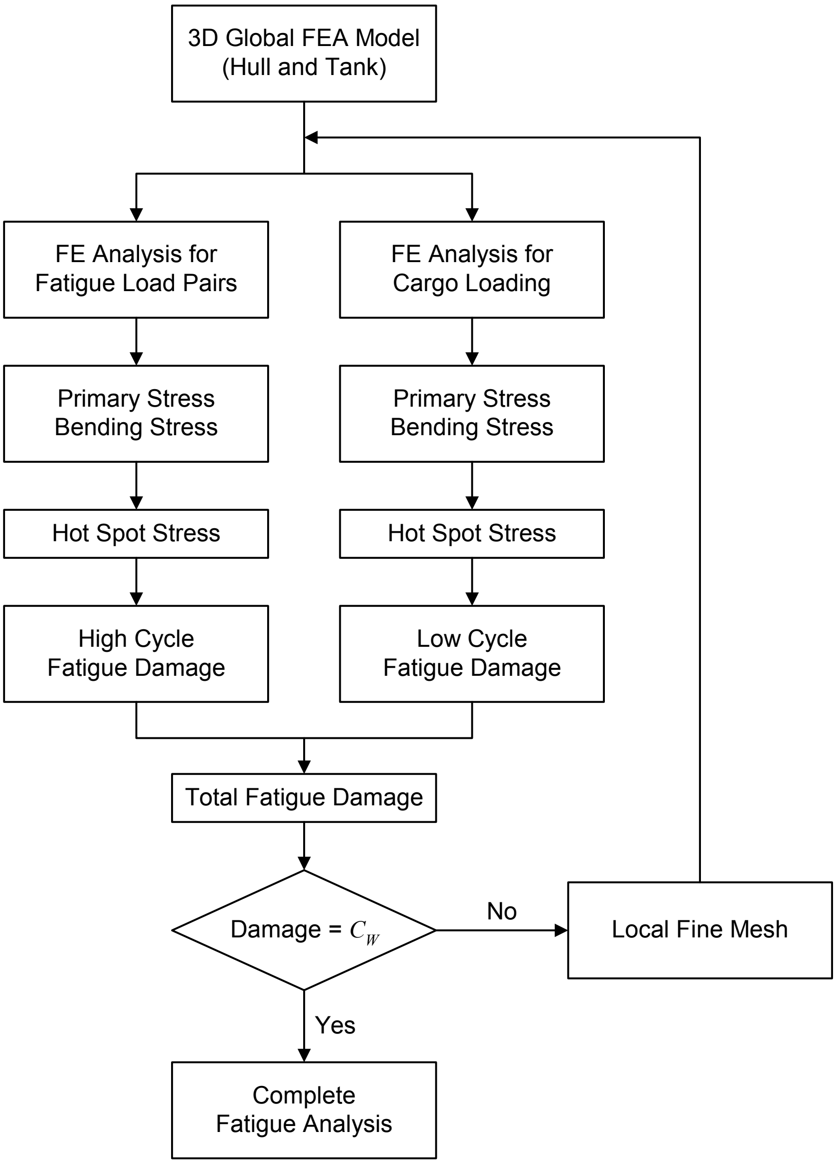
For the welded connections with thickness greater than 22 mm, stress range is to be adjusted by a factor $(t/22)^{0.25}$ as described in A3/5.7.

3 Fatigue Damage Assessment

Accumulated fatigue damage is to be assessed for high cycle and low cycle fatigue loading. High cycle fatigue damage is due to the internal pressure caused by the motion of a ship. For long term prediction of wave loads, wave spectra covering North Atlantic Ocean and a probability level of 10^{-8} are to be employed. Low cycle fatigue damage is caused by loading and unloading of a liquid cargo to the tank.

Fatigue damage is to be calculated based on the appropriate S-N curve with the assumption of linear cumulative damage (Palmgren-Miner rule). Highly stressed areas are to be selected from FEA results considering all fatigue loading cases. The hot spot stress can be calculated as described in A5/1.7 and A5/1.9. Fatigue damage estimation procedure is shown in Appendix 5, Figure 2.

FIGURE 2
Fatigue Damage Assessment Procedure *(1 June 2011)*



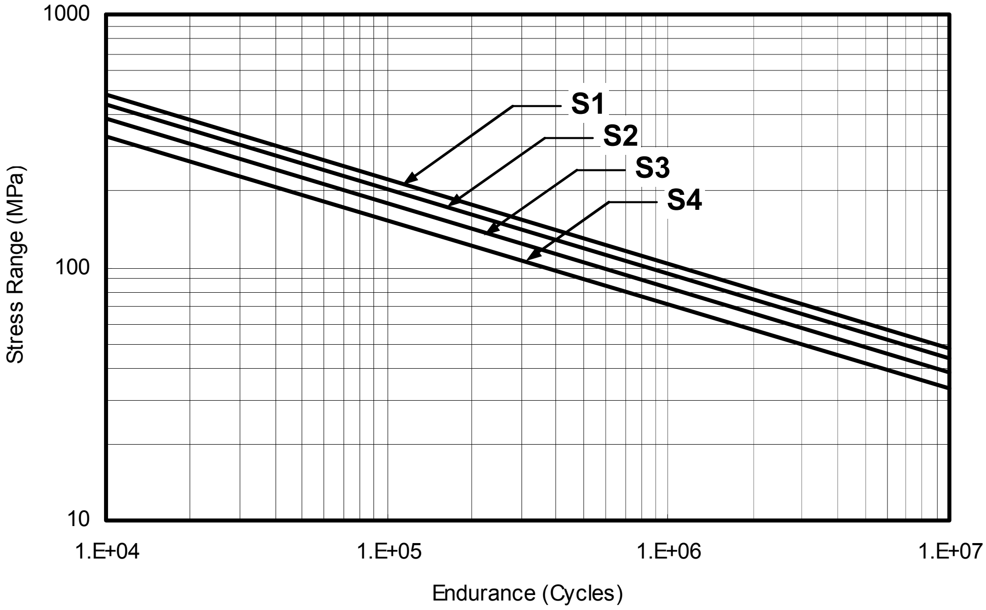
3.1 S-N Curves

Stress results from the global FEA model are to be used for high cycle and low cycle fatigue damage estimation. The maximum principal stress range is to be used for the analysis.

Appropriate S-N curves are to be used for the fatigue damage analysis. The selection of S-N curve depends on weld type, such as butt weld, transverse fillet weld, or longitudinal fillet weld.

S-N curves for stainless steel are shown in Appendix 5, Figure 3. Formulation of S-N curve is given in Appendix 3, Figure 5. Application of each S-N curve is to follow equivalent S-N curves for steel as shown in Appendix 3, Table 1.

FIGURE 3
Design S-N Curves for Stainless Steel *(1 June 2011)*

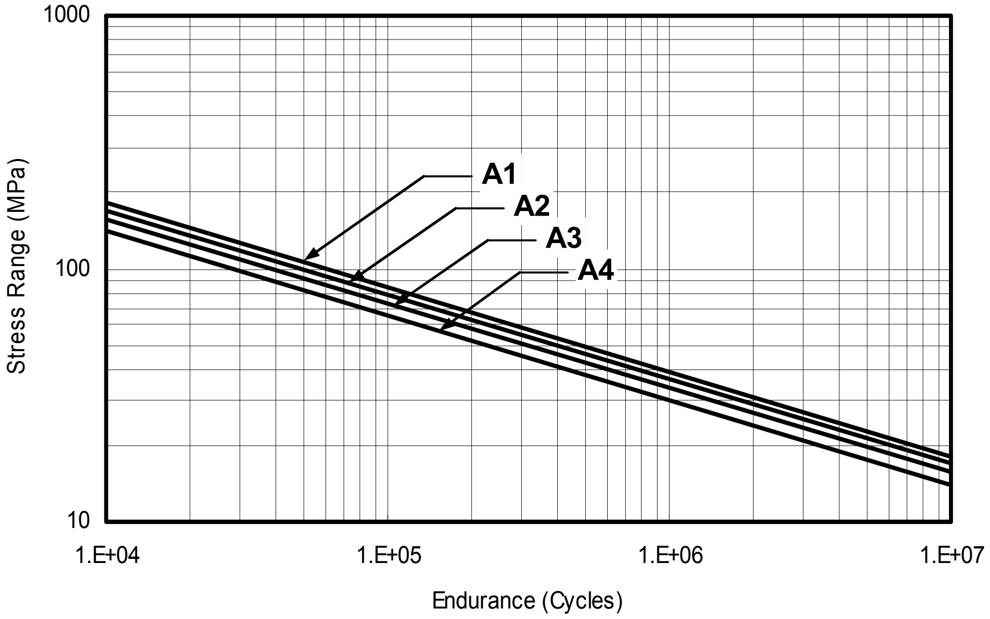


Details of S-N Curves

Class	*m*	*Log(K2)*	*Equivalent S-N curve for steel*
S1	3.0	12.05	D
S2	3.0	11.92	E
S3	3.0	11.75	F
S4	3.0	11.55	F2

S-N curves for aluminum are shown in Appendix 5, Figure 4. Application of each S-N curve is to follow equivalent S-N curves for steel as shown in Appendix 3, Table 1.

FIGURE 4
Design S-N Curves for Aluminum *(1 June 2011)*

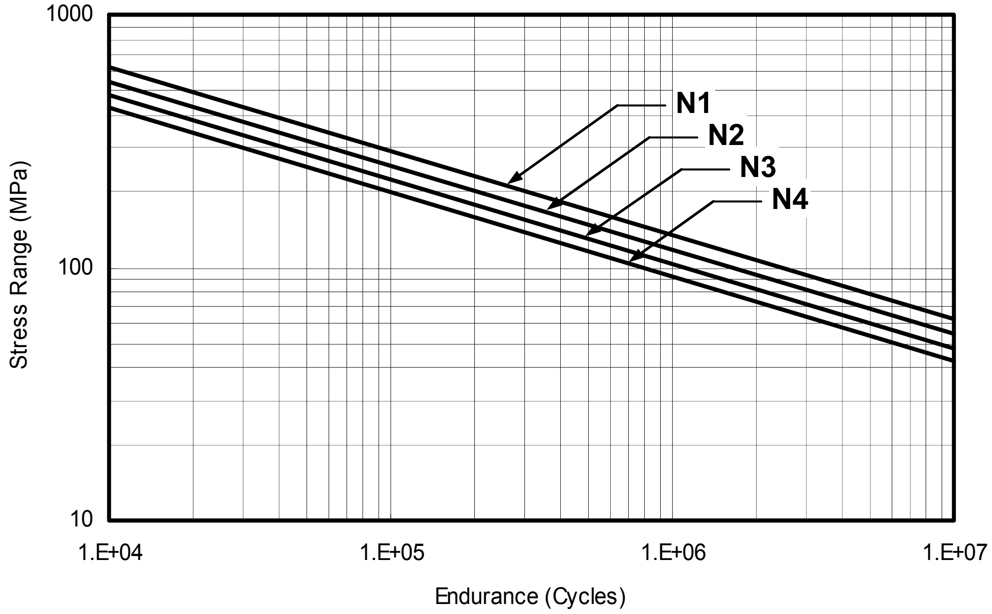


Details of S-N Curves

Class	*m*	*Log(K2)*	*Equivalent S-N curve for steel*
A1	3.0	10.78	D
A2	3.0	10.69	E
A3	3.0	10.59	F
A4	3.0	10.46	F2

S-N curves for 9% Ni are shown in Appendix 5, Figure 5. Application of each S-N curve is to follow equivalent S-N curves for steel as shown in Appendix 3, Table 1.

FIGURE 5
Design S-N Curves for 9% Ni *(1 June 2011)*



Details of S-N Curves

Class	*m*	*Log(K2)*	*Equivalent S-N curve for steel*
N1	3.0	12.37	D
N2	3.0	12.18	E
N3	3.0	12.03	F
N4	3.0	11.89	F2

3.3 High Cycle Fatigue Damage

High cycle fatigue damage is to be calculated for the critical areas from the wave loading by the ship motion. The stress result form integrated hull and tank FEA model is to be used for the analysis. Standard design load cases for fatigue strength assessment is shown in Section 4, Tables 3 and 4. Four load case pairs for full load and ballast conditions were considered in the tables. The stress amplitude is to be calculated from each load case pair. Each dynamic load case corresponds to a probability level of 10^{-4}.

Fatigue damage is to be calculated following the procedure in Subsection A3/5:

$$D_{fi} = \frac{1}{6}D_{fi\_12} + \frac{1}{6}D_{fi\_34} + \frac{1}{3}D_{fi\_56} + \frac{1}{3}D_{fi\_78}$$

where

D_{fi_jk} = fatigue damage due to the stress range from load case pairs *jk*

The long term stress ranges can be characterized using a modified Weibull probability distribution parameter as described in A3/5.5. Design life of 20 years is to be used to assess the high cycle damage of the structure.

3.5 Low Cycle Fatigue Damage

Low cycle fatigue damage is due to the cyclic stress from loading and unloading of liquid cargo to the tank. Pressure levels for the tank are to be calculated from the sum of liquid cargo and gas pressure. The densities of liquefied gas cargos are listed in Section 1, Table 2. The pressure envelope of the tank is to be applied to the global hull and tank FEA model to determine the stress at each critical location.

The bending stress of a panel between stiffeners is to be added to the membrane stress from the FEA model for skin plates. The total number of fatigue cycles from the loading and unloading of cargo is to be assumed as 1,000 for the lifetime of a vessel.

3.7 Total Fatigue Damage

Total accumulated fatigue damage is to be assessed as the sum of high cycle and low cycle damage. Total cumulative fatigue damage factor is to be calculated by:

$$D_T = D_F + \frac{10^3}{N_j}$$

where

D_T = total fatigue damage

D_f = high cycle fatigue damage calculated from Appendix 5/3.3

N_j = number of cycles to fracture for the fatigue loads due to loading and unloading of liquid cargo

3.9 Acceptance Criteria

The total fatigue damage is to be less than the allowable damage factor:

$$D_T \leq C_W$$

where

C_W = maximum allowable cumulative fatigue damage ratio

C_w is to be less than or equal to 0.5.

3.11 FEA with Refined Mesh

A detailed fine mesh FEA is required for the critical areas that do not meet the acceptance criteria. The hot spot stress is to be calculated from the FEA model with a refined mesh for the critical areas as described in A5/1.9.

5 Fracture Mechanics Analysis

A fracture mechanics based analysis is to be carried out for the critical locations of the tank structure with high dynamic stresses. A fracture mechanics approach assumes that an idealized crack propagates in relation to the stress intensity factor range.

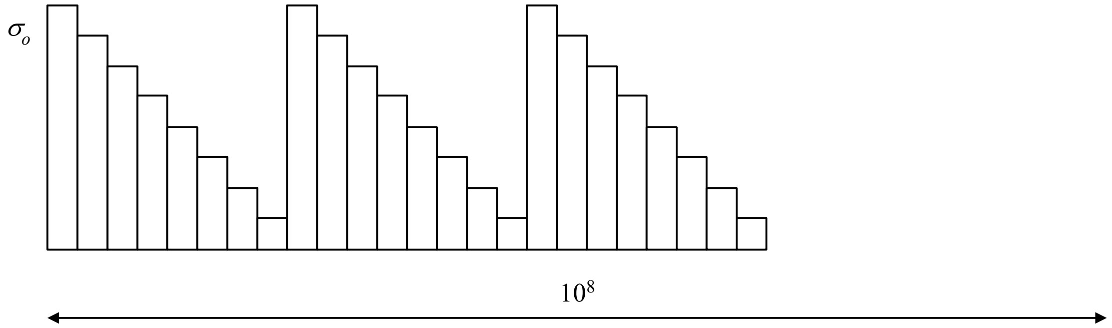
A fatigue crack propagation analysis is to be conducted for tank skin plates to verify the integrity of a cargo tank. Fatigue crack propagation is to be assessed from the growth of an initial existing crack to a critical size. High stress concentration areas or large fatigue damage locations identified in Subsection A5/3 are to be selected for the crack propagation analysis.

5.1 Load Distribution

The dynamic load spectrum is to be determined by long term distribution based on the design life of the ship corresponding to realistic wave spectra covering the North Atlantic and a probability level of 10^{-8}. The long term stress ranges can be characterized using a modified Weibull probability distribution parameter. Simplified linear load spectrum can be used for the load distribution.

The total load spectrum is to be divided into more than 10 groups to remove the effect of loading sequence to crack propagation life as shown in Appendix 5, Figure 6. σ_o in the figure is the most probable maximum stress range over the life of the ship. Two times of the FEA results from the high cycle fatigue analysis in A5/3.3 (based on 10^{-4} probability level) can be used as the maximum stress range for fracture analysis. The hot spot stress can be calculated from the nominal stress obtained from the FEA results with geometric stress concentration factor as described in A5/1.7.

FIGURE 6
Load Distribution for Crack Propagation Analysis *(1 June 2011)*



5.3 Initial Crack

The size of an initial crack is one of the main parameters for the crack propagation analysis. An initial surface crack is to be assumed in a fillet or butt weld areas of the tank structure. The dimension of the surface crack is to be assumed as 0.5 mm depth and 5 mm length.

5.5 Stress Intensity Factor

The stress intensity factor range is to be calculated from stress range, crack shape and size, and geometry. IIW or equivalent standard is to be used to assess the stress intensity factor for a surface crack. The stress range is to be based on the maximum principal stress.

5.7 Crack Propagation Analysis

Crack propagation at the critical location is to be calculated with the Paris Equation as follows:

$$\frac{da}{dN} = C(\Delta K)^m \qquad \text{for } \Delta K > \Delta K_{th}$$

$$\frac{da}{dN} = 0 \qquad \text{for } \Delta K \le \Delta K_{th}$$

where

da/dN = crack propagation rate

C, m = Paris constants

ΔK = stress intensity factor range

ΔK_{th} = threshold value of stress intensity factor range

The fatigue crack propagation path is to be assumed as perpendicular to the principal stress direction.

5.9 Material Properties

Appropriate fracture toughness is to be used to determine the critical crack size. Critical crack length, a_C, is to be determined from the maximum stress range and the fracture toughness of the tank material:

$$a_c = \frac{1}{\pi}\left(\frac{K_C}{\sigma}\right)^2$$

where

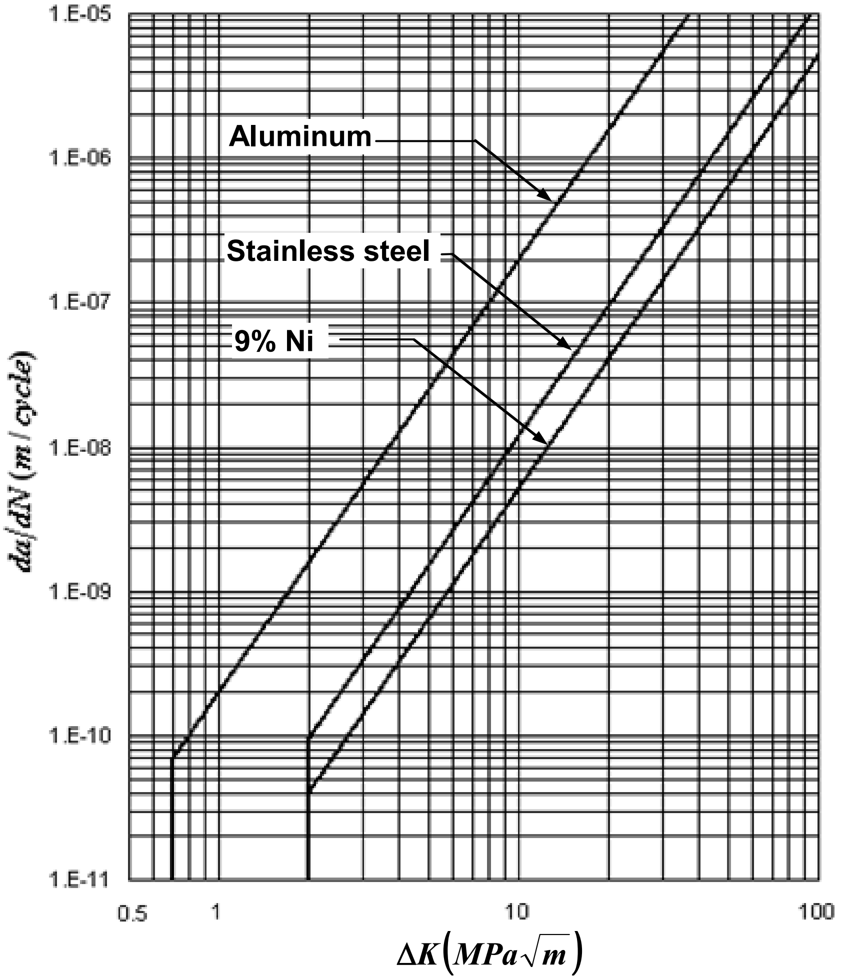
K_C = fracture toughness of a material

σ = applied stress

When the fracture toughness of the tank material is not available, the Master curve approach or equivalent process is to be used to determine the fracture toughness of ferritic steels from the Charpy V-notch impact test data. A detailed procedure and assumptions used to determine the fracture toughness are to be submitted for review.

Adequate Paris constants are to be used for the crack propagation assessment. Crack propagation tests are to be performed for base metal, weld metal and heat affected zone. Fracture mechanics analysis is to in general be based on crack growth data taken as mean plus two standard deviations of the test data. If test data is not available, crack growth curves defined in Appendix 5, Figure 7 are to be used for stainless steel, aluminum, and 9% Ni.

FIGURE 7
Crack Growth Curves *(1 June 2011)*



Details of Crack Growth Curves

Material	*m*	*C*	ΔK_{th}, $MPa\sqrt{m}$
Stainless steel	3.0	1.19×10^{-11}	2.0
Aluminum	3.0	2.03×10^{-10}	0.7
9% Ni	3.0	5.14×10^{-12}	2.0

5.11 Acceptance Criteria

The final crack length determined from the crack propagation analysis is to be less than the critical crack length of the material determined from the operating life of the ship corresponding to 10^8 wave encounter. The estimated crack propagation life to reach a through thickness crack is to be greater than the design life of the vessel.

5.13 FEA with Refined Mesh

A detailed fine mesh FEA is required for the critical areas that do not meet the acceptance criteria. The hot spot stress is to be calculated from the FEA model with a refined mesh for the critical areas as described in A5/1.9.

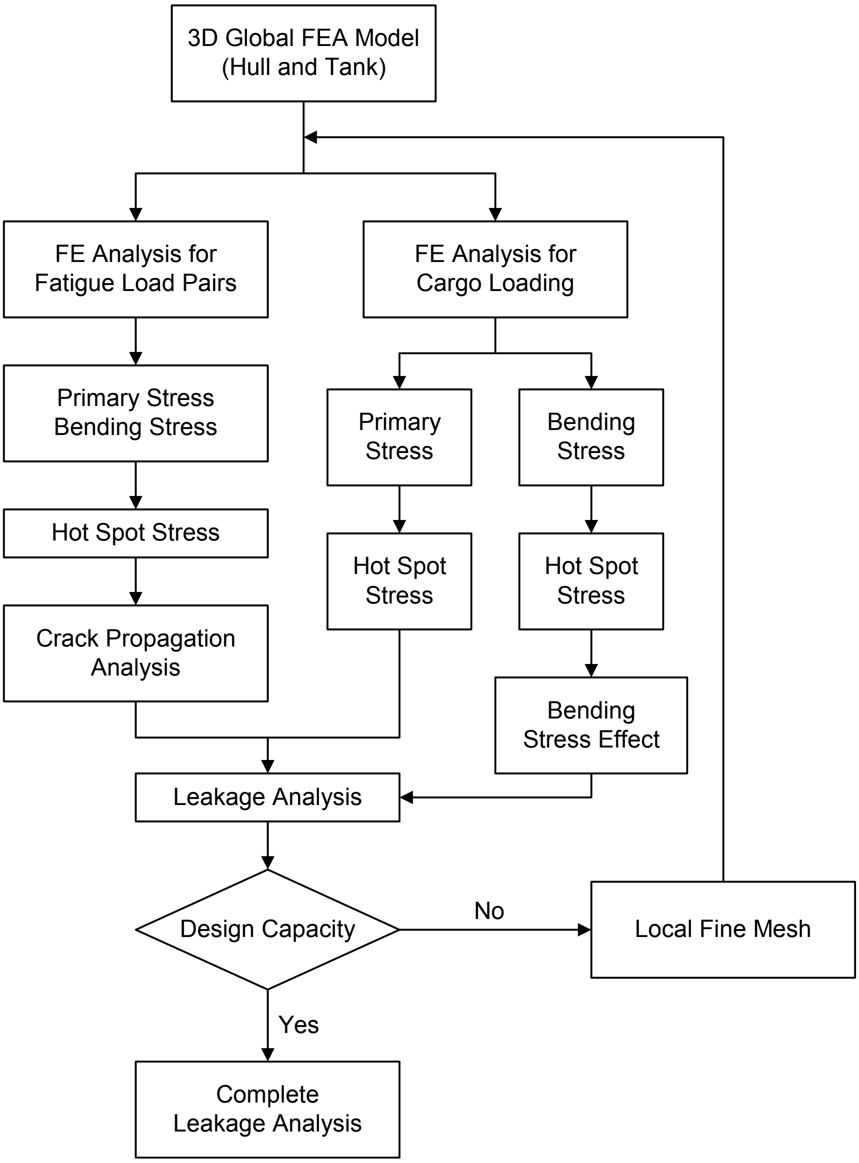
7 Leakage Analysis

The secondary barrier of an independent tank is to be designed to be capable of containing any envisaged leakage of liquid cargo for a period of 15 days. Leakage of cargo is to be contained by the secondary barrier for a period of 15 days after the detection of initial leakage. The leakage rate of liquid cargo from a crack in an independent tank is to be less than the design capacity of the secondary barrier.

The tank is to be verified against possible failure from a growing crack for 15 days after the detection of gas leakage. The final size of a crack growing from a penetrating crack is to be less than the critical size that can lead to a failure of the structure.

Leakage analysis procedure is shown in Appendix 5, Figure 8.

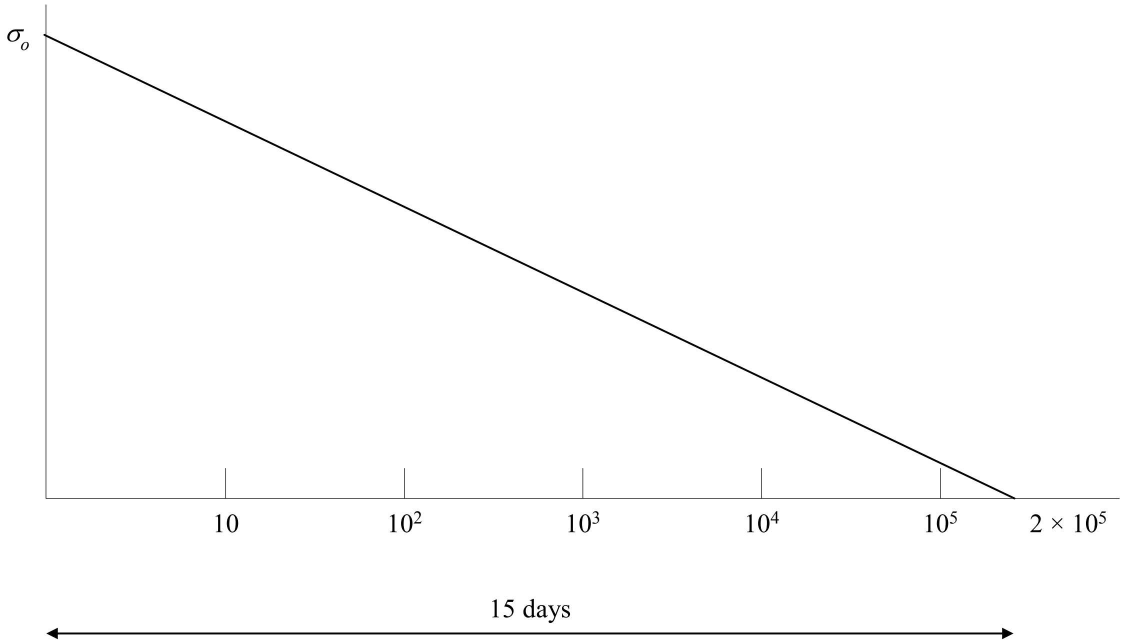
FIGURE 8
Leakage Assessment Procedure *(1 June 2011)*



7.1 Load distribution

The load spectrum is to be assumed to represent the worst 15 day period from the spectrum the ship will experience as specified in A5/5.1. Simplified linear distribution over a period of 15 days may be used for crack propagation analysis as shown in Appendix 5, Figure 9. The total cycle is to be divided into several groups to remove the effect of loading sequence as described in A5/5.1. σ_o in Appendix 5, Figure 9 is the most probable maximum stress range over the life of the ship as specified in A5/5.1. The hot spot stress can be calculated from the nominal stress obtained from the FEA results with geometric stress concentration factor.

FIGURE 9
Load Distribution for 15 Days Crack Propagation *(1 June 2011)*



7.3 Initial Crack

An initial through thickness crack is to be determined from a crack propagation analysis described in Subsection A5/5. The largest crack dimension at the penetration of a tank is to be assumed as an initial crack length for the leak analysis. For conservative assumption, two times the thickness of the plate at the location of the tank may be used as an initial crack size.

7.5 Stress Intensity Factor

IIW or equivalent standard is to be used to assess the stress intensity factor for specific shape of the crack and geometry. When the geometry of a structure is complicated, stress intensity factor can be also calculated from direct FE analysis of a local model with a refined mesh of a crack and the crack tip.

When the geometry of the plate is simple, stress intensity factor range for a through thickness crack can be calculated from the general equation for a crack in an infinite plate;

$$\Delta K = \Delta\sigma\sqrt{\pi a}$$

where

a = half of a crack length

$\Delta\sigma$ = stress range

7.7 Crack Propagation Analysis

A crack propagation analysis is to be carried out with the Paris Equation following the procedure specified in A5/5.7. A load spectrum of 15 days described in A5/7.1 is to be used for the analysis. The results of the crack propagation analysis will be used for the leakage analysis.

7.9 Estimation of Leakage Rate

The leakage rate of the liquid cargo from the penetrating crack is to be analyzed to verify the adequacy of the secondary barrier. The maximum membrane stress from full loading of cargo and gas pressure is to be used for the assessment of leakage rate. The stress results from A5/3.5 may be used as a membrane stress for the analysis.

The shape of a crack opening can be assumed as an ellipse with crack length and width as diameters. The final size of a crack propagated during 15 days from a penetrating initial crack is to be used to assess the leakage rate of a liquid cargo. The width of a crack may be determined from finite element analysis with very fine mesh. It can be estimated as a function of crack length, membrane stress, and Young's modulus. A parametric study may be needed to determine the relation between dominating parameters affecting the crack width. A detailed analysis procedure and assumptions of parameters to determine the width of a crack are to be submitted for approval.

The leakage rate of the liquid cargo through the crack opening, W, in mm^3/sec, may be determined by the following equation:

$$W = \left(\frac{\pi}{4\mu}\right)\left(\frac{P}{t}\right)\left(\frac{a^3 b^3}{a^2 + b^2}\right)$$

where

μ = viscosity of the liquid cargo, in kgf-sec/mm^2

P = internal pressure, in kgf/mm^2

t = plate thickness, in mm

a = a half of the crack length, in mm

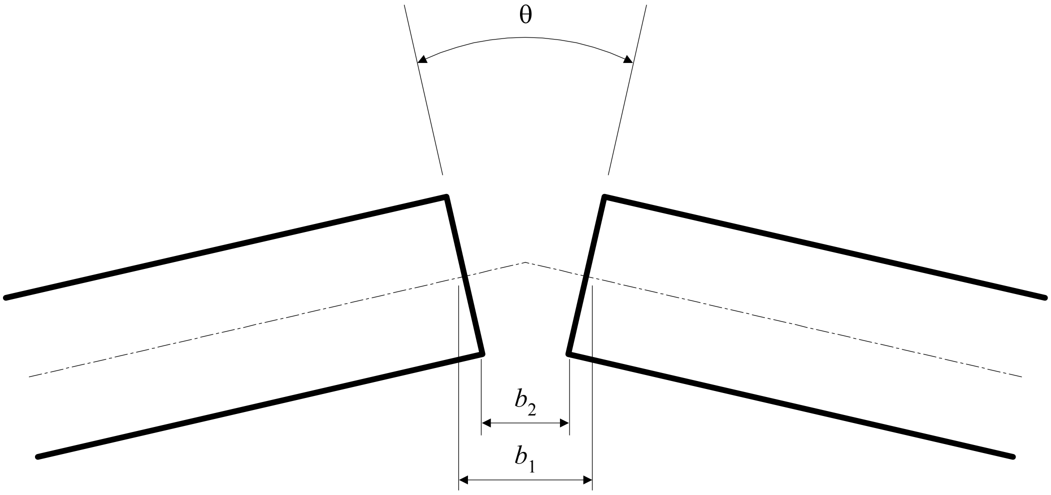
b = a half of the crack width, in mm

7.11 Effect of Bending Stress

The crack closing effect from local bending stress of a hull panel may be considered for the analysis. Bending stresses of a panel between stiffeners is to be calculated from 5C-1-5/3/5 of the *Steel Vessel Rules*, as described in A5/1.7.

A finite element analysis with localized very fine mesh is to be carried out to determine the rotated angle from the vertical line and the reduction of crack width. A detailed analysis is to be carried out to determine the reduced crack width as a function of crack length, bending stress, Young's modulus, and plate thickness. The reduction effect of a crack opening by the rotation of a panel is shown in Appendix 5, Figure 10. A detailed analysis procedure and assumptions of parameters to determine the reduced crack width are to be submitted for approval.

FIGURE 10
Crack Closing Effect by Panel Bending *(1 June 2011)*



Final crack width with bending of a plate accounted for can be calculated as:

$$b_2 = b_1 - \frac{t\theta}{4}$$

where

b_2 = width of a crack after bending

b_1 = width of a crack before bending

θ = rotation angle by bending of a panel

t = plate thickness

7.13 Acceptance Criteria

The fatigue crack propagated from the initial crack size is not to grow to cause total failure of the structure for 15 days. Final crack size after 15 days propagation is to be smaller than the critical crack size determined from the fracture toughness of the tank material.

The secondary barrier is to be capable of containing any envisaged leakage of liquid cargo through the tank for a period of 15 days. The extent of the secondary barrier is to be determined on the basis of the estimated cargo leakage. The estimated maximum leakage rate of liquid cargo through the crack opening is to be less than the design leakage rate of the secondary barrier.

7.15 FEA with Refined Mesh

A detailed fine mesh FEA is required for the critical areas that do not meet the acceptance criteria. The hot spot stress is to be calculated from the FEA model with a refined mesh for the critical areas as described in A5/1.9.

9 Thermal Stress Analysis

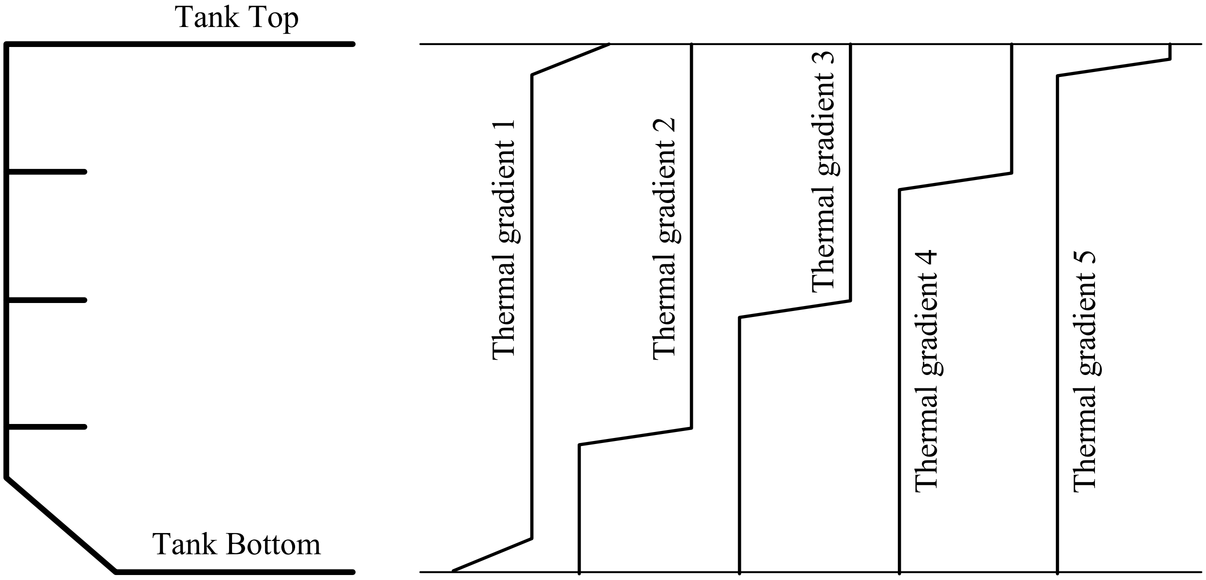
Non-uniform thermal contraction of an independent cargo tank from a temperature gradient produced by the loading of liquid cargo can create high local stresses. Thermal stress analysis is to be carried out to verify the structural integrity of a tank under thermal load during the loading of liquid cargo or initial cooling down period.

9.1 Loading Condition

Thermal loading produced by a temperature gradient from different filling level of a tank is to be considered. Filling levels up to each horizontal girder are to be considered separately as shown in Appendix 5, Figure 11. LNG tanks are cooled down with spray of LNG as part of a cool down cycle. Thermal load from this cool down period is to be included in the loading conditions.

Static internal pressure from the gas and corresponding level of liquid cargo are to be applied in addition to the thermal gradient.

FIGURE 11
Thermal Loading *(1 June 2011)*



9.3 Thermal Stress Estimation

The thermal stress of a tank is to be calculated from the contraction of a structure due to the thermal gradient. A global finite element model of a tank with support structure is to be used for the analysis. The proper thermal expansion coefficient for the tank material is to be used. Each thermal gradient specified in A5/9.1 is to be applied separately to assess the thermal stress at critical locations.

9.5 Fatigue Damage

Thermal stress from the temperature gradient may be considered as a cyclic fatigue loading for low cycle fatigue damage analysis. Critical areas are to be verified for possible fatigue damage from thermal loading. The procedure to assess low cycle fatigue damage from the loading and unloading of liquid cargo is specified in A5/3.5.

9.7 Acceptance Criteria

Yielding of the tank structure is to be checked following the guideline specified in Subsection 6/5. Allowable stresses are specified in Section 6, Table 1 for watertight boundaries, Section 6, Table 2 for main supporting members and structural details, and Section 6, Table 3 for supports and chocks.

Each panel and supporting structures are to be checked against buckling failure also. The failure criteria for buckling and ultimate strength were specified in Subsection 6/7.