Topics in Ship Structural Design (Hull Buckling and Ultimate Strength)

Lecture 6 Strength Assessment in Common Structural Rule (CSR)

Reference : Common Structure Rules for Double Hull Oil Tankers, IACS July, 2012

NAOE

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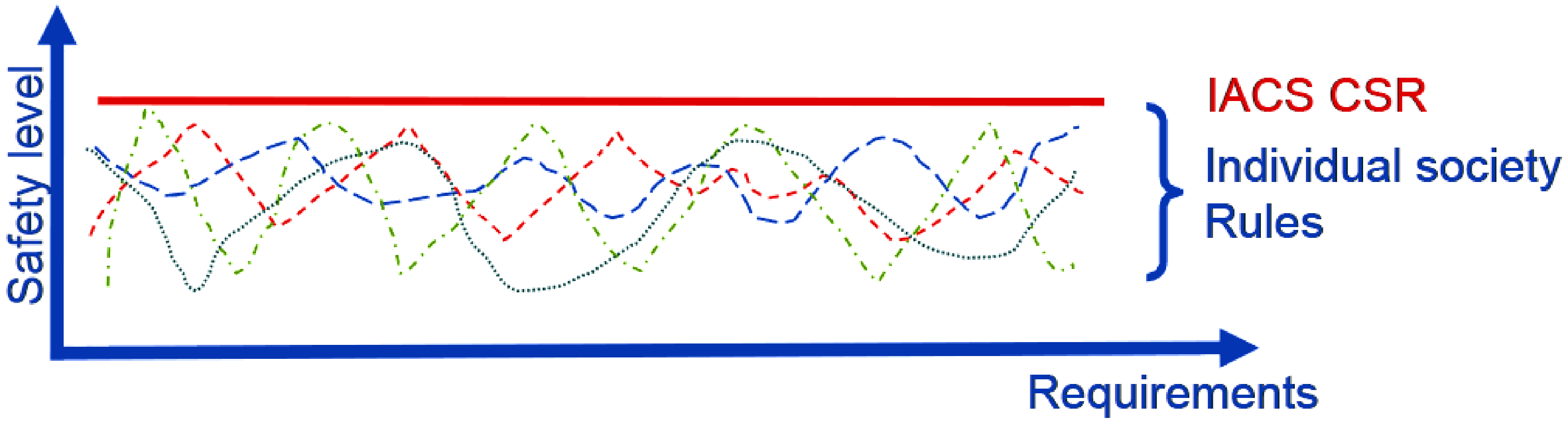
Why CSR ?

- To eliminate competition between class societies with regard to structural requirements and standards
- To employ the combined experience within all societies in IACS to develop a single agreed standard, or set of Rules
- To ensure that vessels meeting the new standard will be recognised by industry as being at least as safe, robust and fit for purpose as would have been required by any of the existing Rules
- To ensure sufficient durability throughout the operational life in terms of corrosion margins and fatigue strength
- To define the minimum state of the structure at which steel renewal is required in order to continue safe operation
- To embrace the intentions of the anticipated IMO requirements for goal based new construction standards

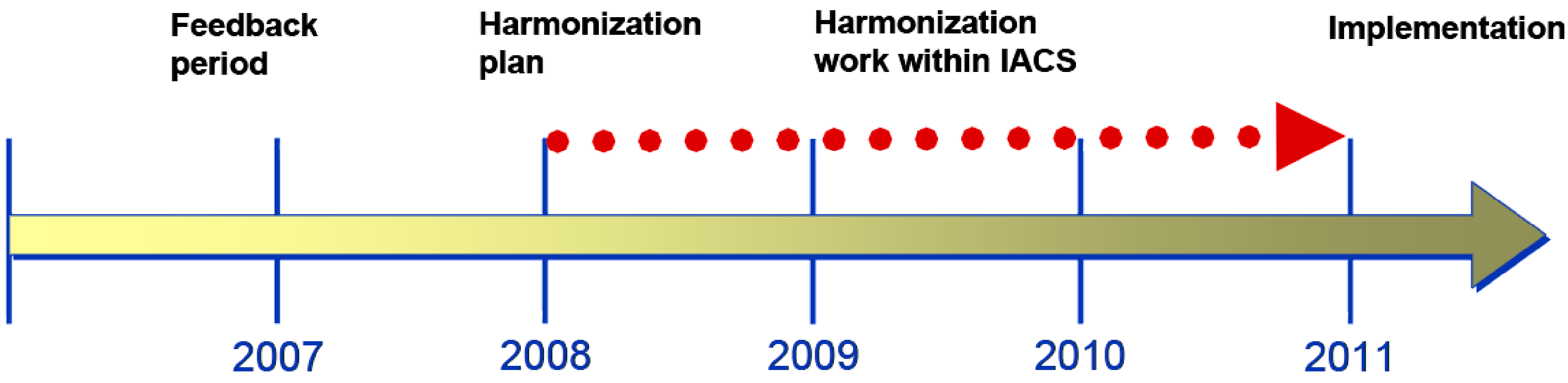
Why CSR ?

- Rules covering structural requirement for Bulk Carriers and Tankers
- A Rule set utilising state of the art computational methods for more extensive direct calculations
- Vessels built to CSR shall have overall safety of the hull structure equivalent to or better than that previously achieved by existing rules
- Safety level exceeding any IACS members existing Rules



Harmonized Structural Rules for Oil Tankers and Bulk Carriers

- Long term harmonisation deliverables
- Common Rules covering Oil Tankers and Bulk Carriers
  - 3 volumes: Common parts for both types
  - Specific part applicable to Oil Tankers
  - Specific part applicable to Bulk Carries
- Completion of draft 2011



Design life

- The design life of 25 years is an input parameter in CSR for:
  - the determination of the values of the scantling loads
  - fatigue loads
  - fatigue life expected
  - corrosion wastage allowances
- For the scantlings loads, the difference between 20 and 25 years of design life is insignificant (1% difference)
- For fatigue and wastage allowances, the influence of extension of design life from 20 to 25 years is important

Environmental conditions

❖ Technical Comments

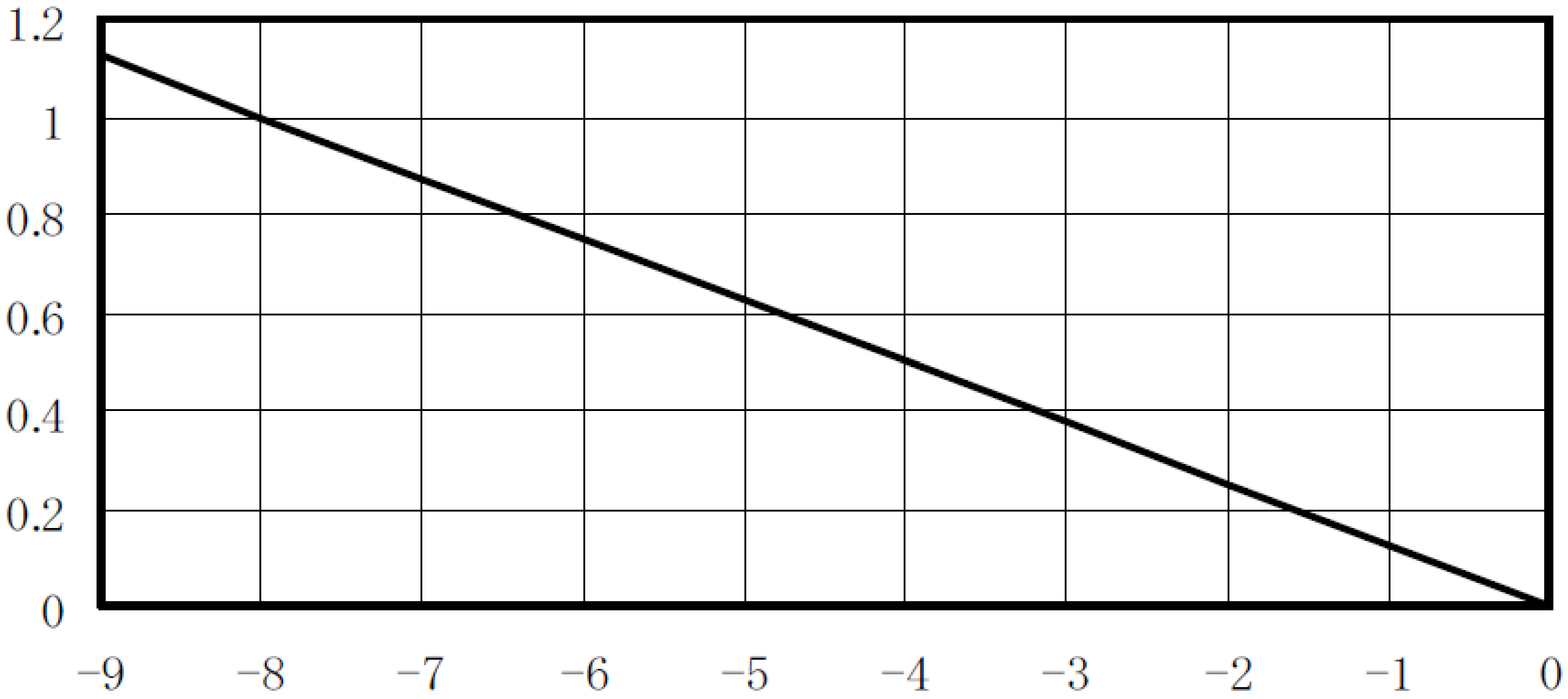
- The functional requirement is covered by CSR
- Rule requirements are based on North Atlantic environment
- Scatter diagram according to IACS Rec. No. 34
- Rule load formulations based on numerical wave load analysis

Scatter diagram

- IACS Rec. No. 34 scatter diagram for North Atlantic
- Revised in year 2000
- Wave data obtained from British Marine Technology
- Probability described as occurrences per 100,000 observations

Hs/Tz	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	SUM
0.5	0.0	0.0	1.3	133.7	865.6	1186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3050
1.5	0.0	0.0	0.0	29.3	986.0	4976.0	7738.0	5569.7	2375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22575
2.5	0.0	0.0	0.0	2.2	197.5	2158.8	6230.0	7449.5	4860.4	2066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23810
3.5	0.0	0.0	0.0	0.2	34.9	695.5	3226.5	5675.0	5099.1	2838.0	1114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19128
4.5	0.0	0.0	0.0	0.0	6.0	196.1	1354.3	3288.5	3857.5	2685.5	1275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0	13289
5.5	0.0	0.0	0.0	0.0	1.0	51.0	498.4	1602.9	2372.7	2008.3	1126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8328
6.5	0.0	0.0	0.0	0.0	0.2	12.6	167.0	690.3	1257.9	1268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4806
7.5	0.0	0.0	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2586
8.5	0.0	0.0	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1309
9.5	0.0	0.0	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
10.5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21
14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
SUM:	0	0	1	165	2091	9280	19922	24879	20870	12898	6245	2479	837	247	66	16	3	1	100000

Illustration of design life influence on scantlings loads

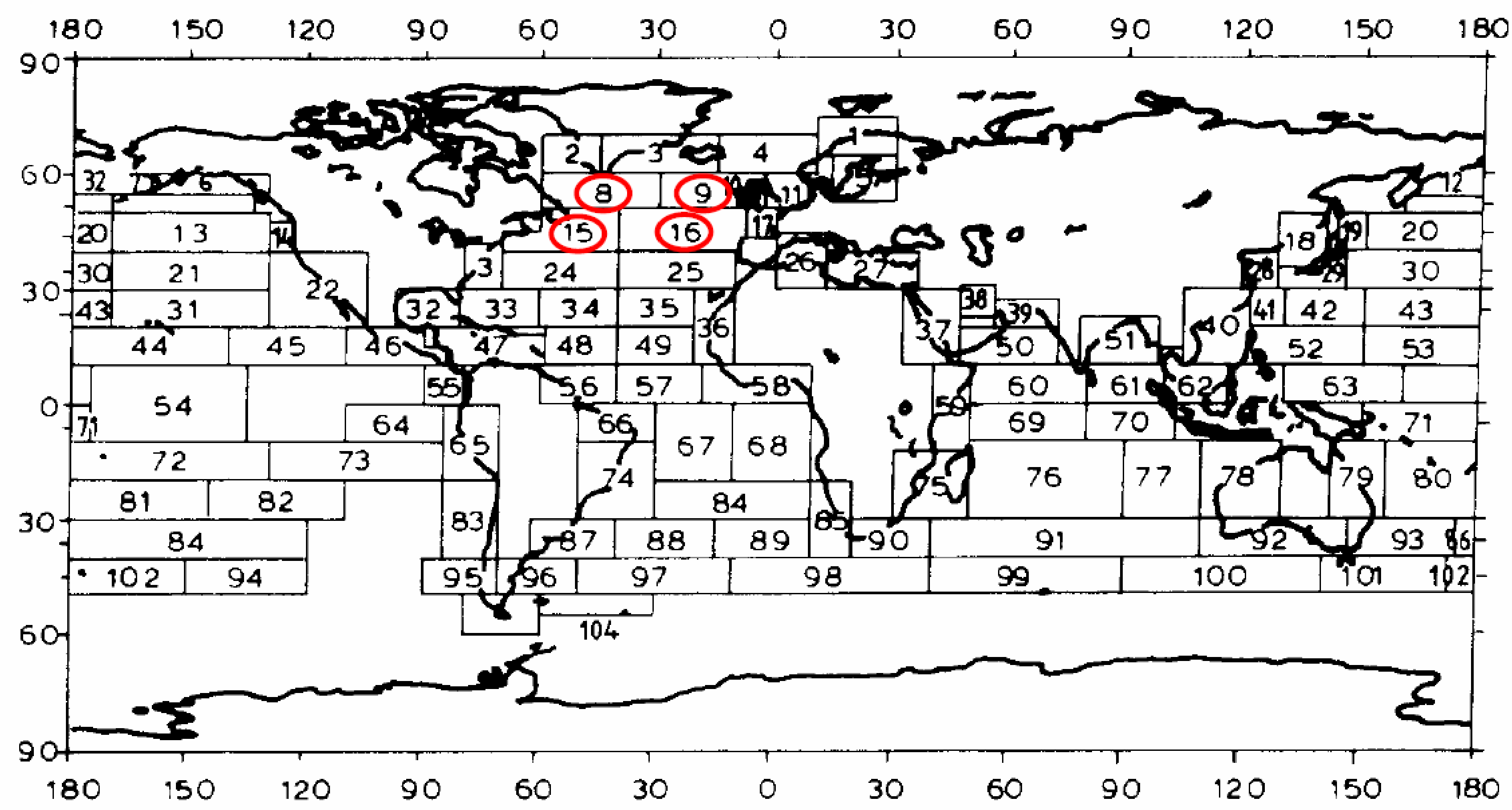


- **Long term extreme loads amplitude is distributed according to a Weibull law, exponent about 1**
- 10^8: 25 years = 10^x:20years ⇨ x=7.093

  Difference : only 1 % (8/7.093 = 1.012)

Environmental conditions

Geographical area covered



Derivation of rule loads

❖ Main principles:

- Numerical wave load analysis, using 3D hydrodynamic calculations
- Envelope values, considering all sea states and headings
- Regression analysis, together with calibration
- Correction factors applied to account for non-linear effects and operational considerations
- Speed effect included for fatigue loads
- Load formulations covered by existing Unified Requirements are maintained

Derivation of rule loads

❖ Hydrodynamic calculations:

- Pierson-Moscowitz wave spectrum
- Wave energy spreading function of cos2
- Equal probability of all wave headings
- 30 deg step of ship/wave heading

❖ Rule load formulations derived for:

- Ship motions and accelerations
- External and internal pressures
- Global wave bending moments and shear forces

Structural Strength

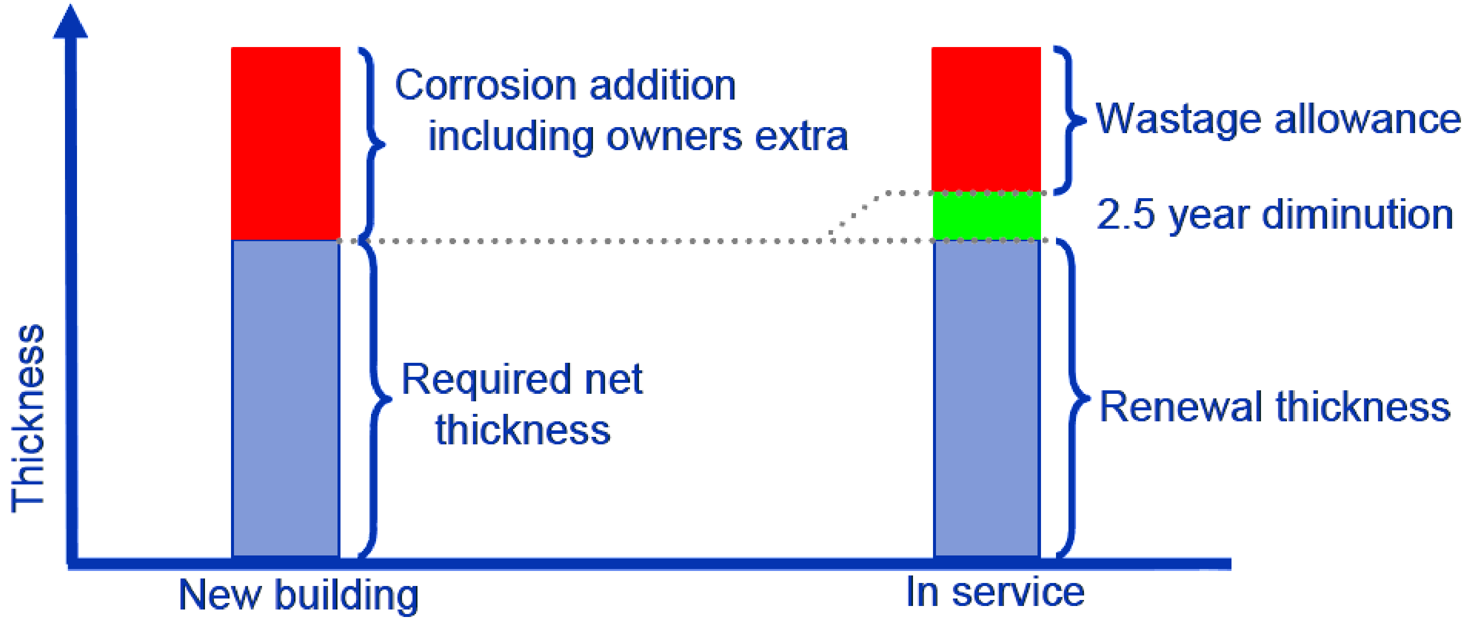
❖ Technical Comments

- The functional requirement is covered by CSR

- Tier II items to be addressed in the Rules include:
  - Safety Margins
  - Strength Assessments
  - Ultimate Strength
  - Structure Compatibility
  - Facilitate Loading/Unloading
  - Net Scantlings

CSR – Net thickness approach

- Net scantling to be maintained through the ship life
- Corrosion addition corresponding to the corrosive environment added on top of the net thickness
- Renewal thickness to be identified on drawings at new-building stage
- *2.5 year diminution (0.5 mm)* : wastage allowance in reserve for corrosion occurring in the two and a half years between Intermediate and Special surveys.



Net thickness approach - example

- t_{corr}*-2.5 (0.5 mm)* *:* wastage allowance in reserve for corrosion occurring in the two and a half years between Intermediate and Special surveys.

Bottom plate

Ballast tank ($t_{was\text{-}1}$=1.2mm)

Sea water ($t_{was\text{-}2}$=1.0mm)

2.5 year diminution

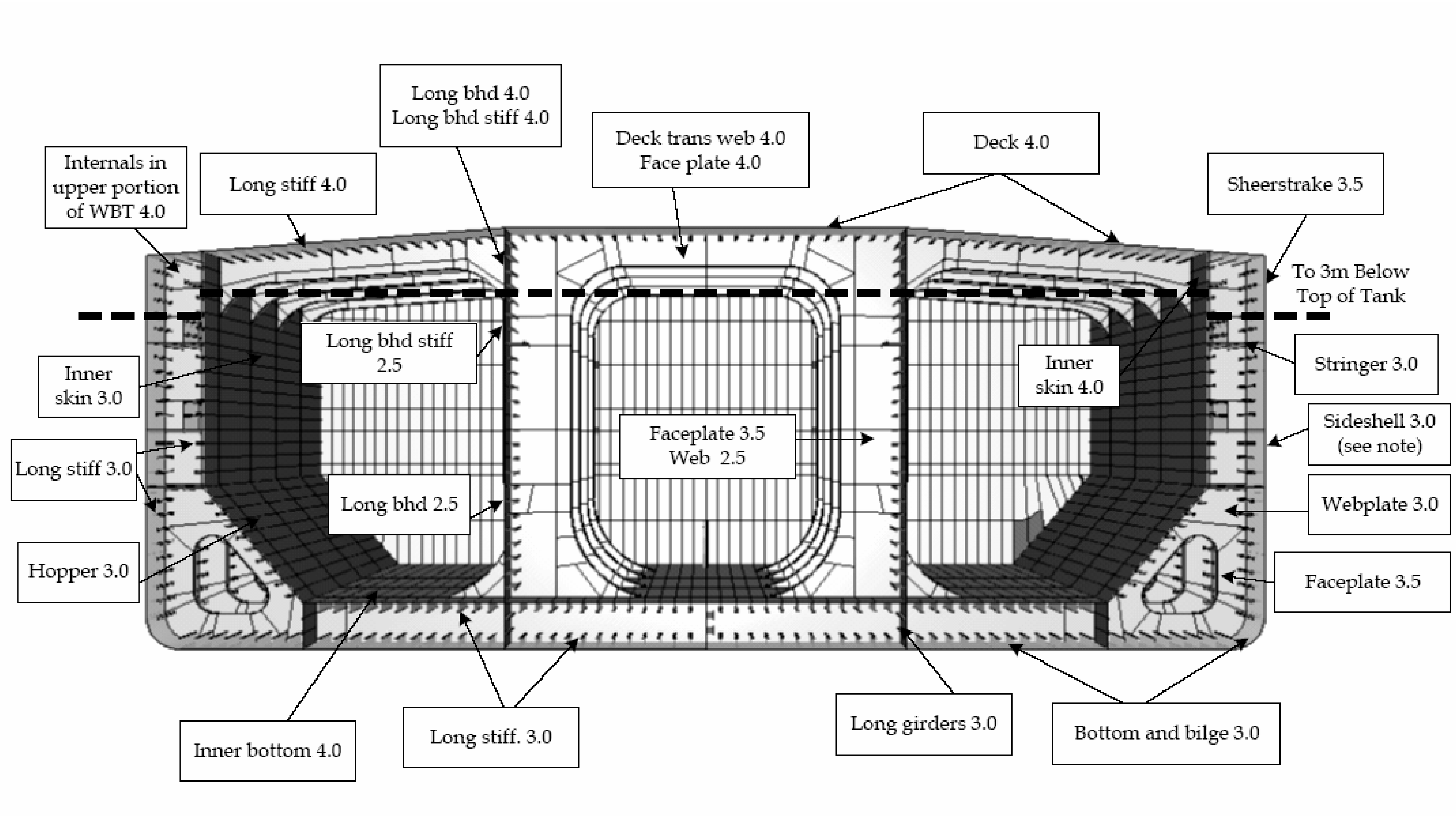
$$t_{corr} = t_{was} + 0.5\text{mm}$$

$= t_{was\text{-}1} + t_{was\text{-}2} + 0.5\text{mm}$

$= 1.2 + 1.0 + 0.5 = 2.7$

rounded up to 3.0mm

Net thickness approach



Local and Overall corrosion

Local plates and stiffeners	FULL corrosion margin
Hull girder incl. H-ULS	HALF corrosion margin
FEM cargo hold	HALF corrosion margin FULL for buckling capacity
Local FEM	FULL in local area HALF overall
Fatigue	HALF for local stress 0.25 for hull girder stress

Mechanical Property of Steel

❖ Brittleness과 Toughness

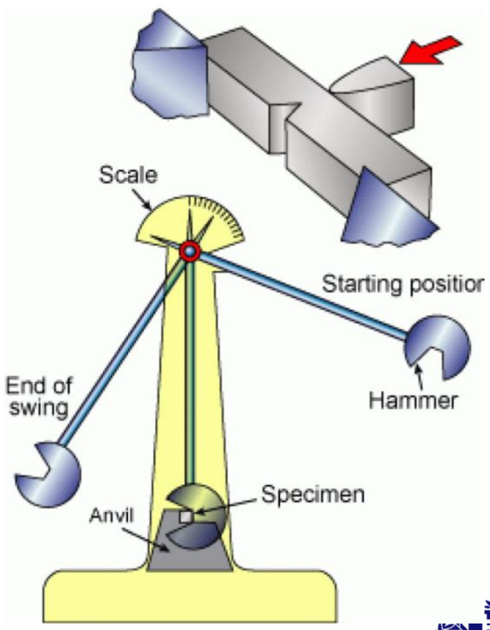
- Material that fail in tension at relative low values of strain are classified as brittle. (Ex. Concrete, stone, cast iron, glass and a variety of metallic alloys)
- Brittle materials fail with only little elongation after the proportional limit is exceeded.
- **Fracture toughness** is a property which describes the ability of a material containing a crack to resist fracture. Fracture toughness is a quantitative way of expressing a material's resistance to brittle fracture when a crack is present.
- If a material has much fracture toughness it will probably undergo ductile fracture. Brittle fracture is very characteristic of materials with less fracture toughness

Reference

❖ Charpy impact test

- a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture.
- This absorbed energy is a measure of a given material's notch toughness and acts as a tool to study temperature-dependent ductile-brittle transition.
- It is widely applied in industry, since it is easy to prepare and conduct and results can be obtained quickly and cheaply.

- The apparatus consists of a pendulum of known mass and length that is dropped from a known height to impact a notched specimen of material.
- The energy transferred to the material can be inferred by comparing the difference in the height of the hammer before and after the fracture (energy absorbed by the fracture event).



Mechanical Property of Steel

❖ Class Requirements

- Increase of ultimate strength is not as large as that of yield strength
- Elongation decreases as yield strength increases.

Rule requirement for Strength (ABS)

	Grade	Yield Stress (MPa)	Tensile Stress (MPa)	Elong. (%)
Mild	A,B,D,E	235 min.	400-520	22 min.
High Tensile	AH/DH/EH32	315 min.	440-590	22 min.
	AH/DH/EH36	355 min.	490-620	21 min.
	AH/DH/EH40	390 min.	510-650	20 min.

- AH32 = 32 kg/mm^2=32 X 9.81 N/mm^2= 314 N/mm^2
- DH36 = 36 kg/mm^2=36 X 9.81 N/mm^2= 354 N/mm^2

Mechanical Property of Steel

❖ Class Requirements

- More toughness at low temperature is required as the steel grade changes from A, B, D, E

Rule requirement for Charpy Impact toughness (ABS)

	Test Temp	Average Absorbed Energy J			
		t ≤50 mm		50<t ≤70 mm	
		Long.	Trans.	Long.	Trans.
A	20 °C	-		34	24
AH32	0 °C	34	24	38	26
AH36	0 °C	34	24	41	27
AH40	0 °C	41	27	NA	NA
B	0 °C	27	20	34	24
D	-20 °C	27	20	34	24
DH32		34	24	38	26
DH36		34	24	41	27
DH40		41	27	NA	NA
E	-40 °C	27	20	34	24
EH32		34	24	38	26
EH36		34	24	41	27
EH40		41	27	NA	NA

Mechanical Property of Steel

❖ Class Requirements

Rule requirement for Chemical composition (ABS)

	A / B / D / E	AH / DH / EH32, 36 & 40
C max.	0.21 / 0.21 / 0.21 /0.18	0.18
Mn min.	2.5xC / 0.8 / 0.6 / 0.7	0.9-1.6
Si max.	0.5 / 0.35 / 0.1-0.35 / 0.1-0.35	0.1-0.5
P max.	0.035	0.035
S max.	0.035	0.035
Ni max.	See Rule	0.4
Cr max.	See Rule	0.2
Mo max.	See Rule	0.08
Cu max.	See Rule	0.35
AL min.	-	0.015
Nb max.	-	0.02-0.05
V max.	-	0.05-0.10

Mechanical Property of Steel

❖ Z- steel (Steel specified with improved through thickness properties)

- Where tee or cruciform connections employ partial or full penetration welds, and the plate material is subject to significant tensile strain in a direction perpendicular to the rolled surfaces,
- consideration is to be given to the use of special material with specified through thickness properties. These steels are to be designated on the approved plan by the required steel strength grade followed by the letter Z (e.g. EH36 Z).

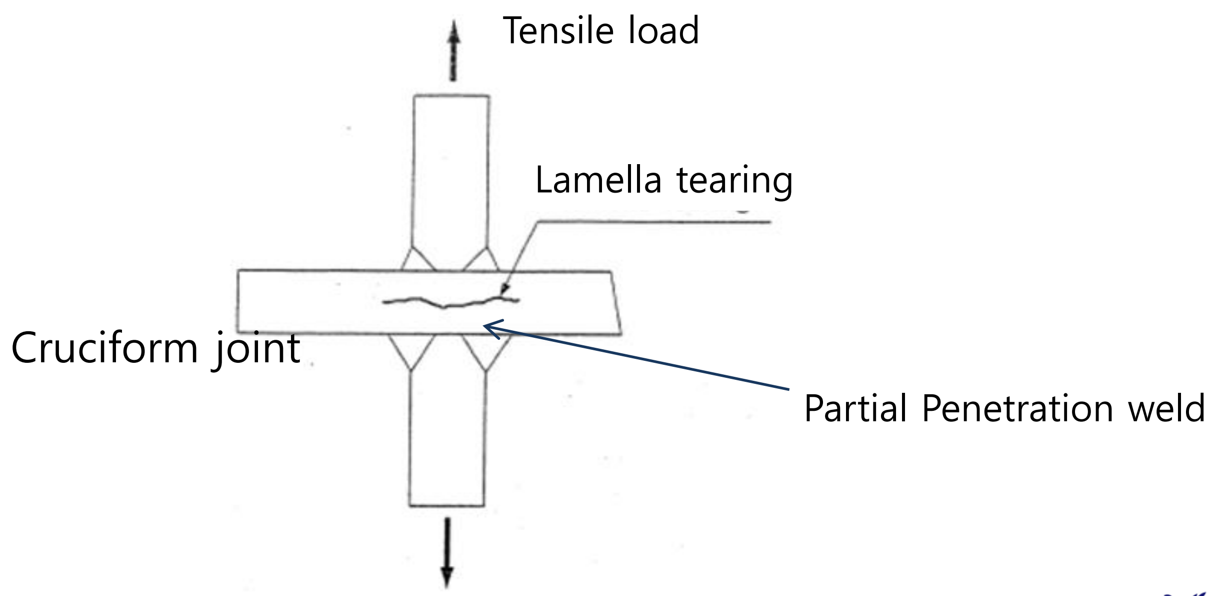


Figure 1.4 Lamella tearing

Selection of material grades

Material Grades (CSR Section5 Materials and Welding)

Table 6.1.2
Material Grades

Thickness, t in mm	Material Class		
	I	II	III
$t \leq 15$	A, AH	A, AH	A, AH
$15 < t \leq 20$	A, AH	A, AH	B, AH
$20 < t \leq 25$	A, AH	B, AH	D, DH
$25 < t \leq 30$	A, AH	D, DH	D, DH
$30 < t \leq 35$	B, AH	D, DH	E, EH
$35 < t \leq 40$	B, AH	D, DH	E, EH
$40 < t \leq 51$	D, DH	E, EH	E, EH

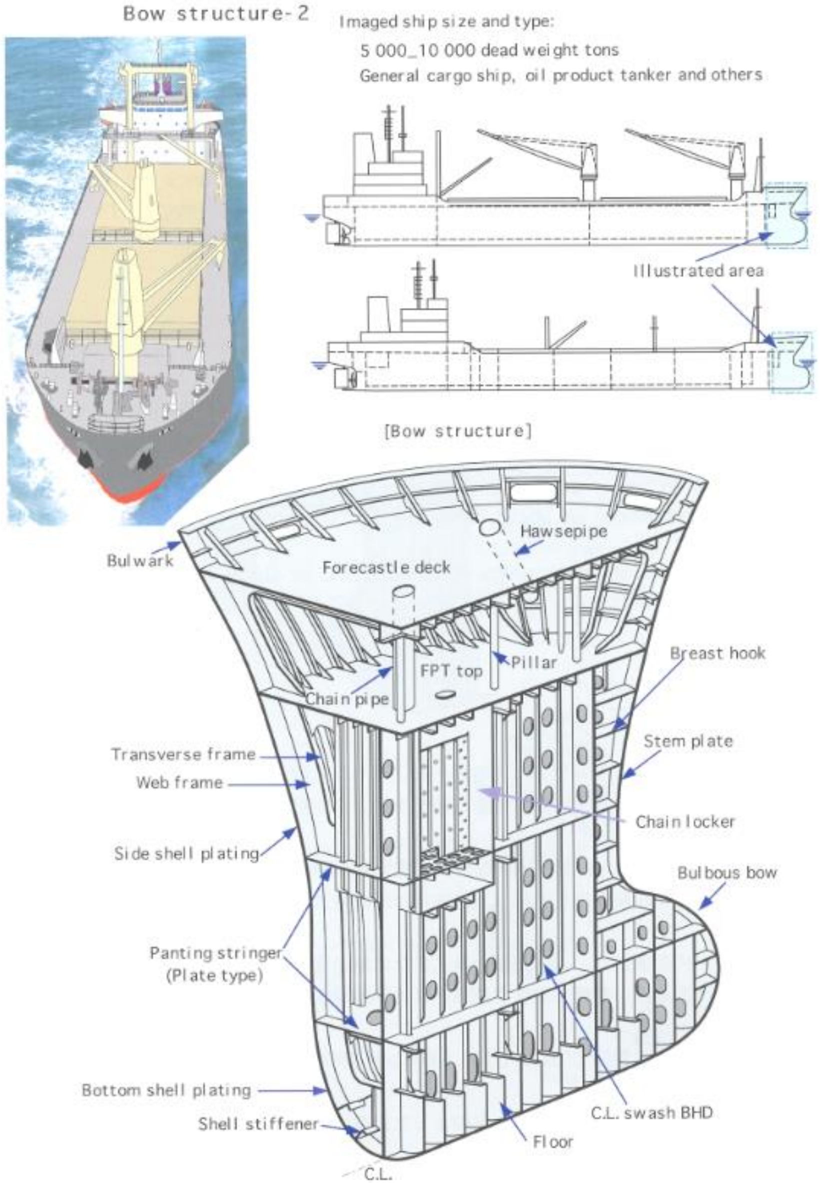
Reference : Common Structural Rules for Double Hull Oil Tanker July 2012

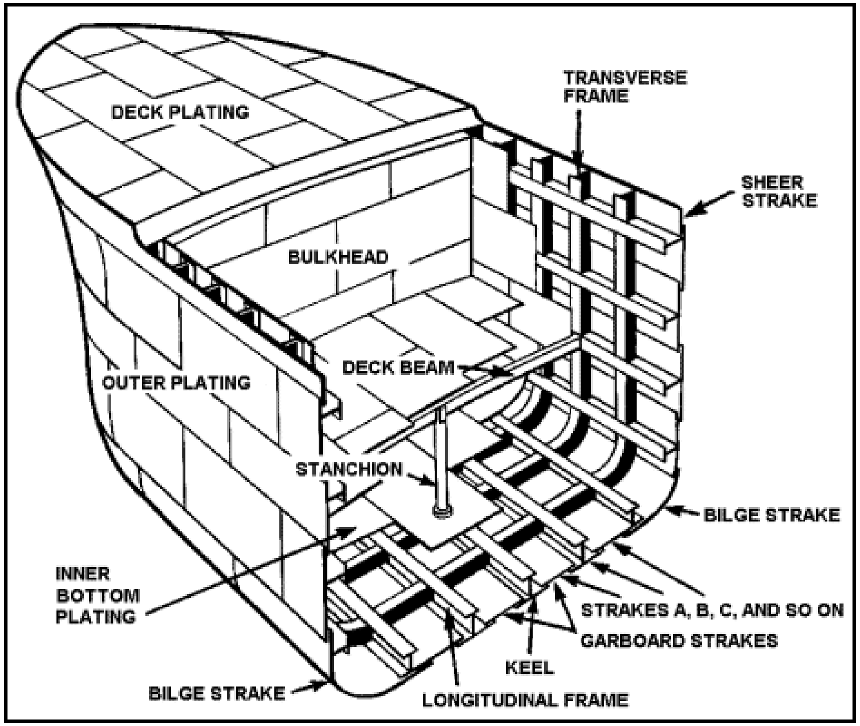
Selection of material grades

Material Classes or Grade of Structural Members
(CSR Section5 Materials and Welding)

Structural member category	Material Class or Grade	
	Within 0.4*L* Amidships	Outside 0.4*L*
Secondary Longitudinal bulkhead strakes, other than those belonging to primary category Deck plating exposed to weather other than that belonging to primary or special category Side plating	Class I	Grade A(8)/AH
Primary Bottom plating, Strength deck plating Continuous longitudinal members above strength deck Uppermost strake in longitudinal bulkheads Vertical strake (hatch side girder) and upper sloped strake in top wing tank	Class II	Grade A(8) /AH
Special Sheer strake at strength deck Stringer plate in strength deck Deck strake at longitudinal bulkhead, Bilge strake Continuous longitudinal hatch coamings	Class III	Class II (Class I outside 0.6*L* amidships)
Other Categories Plating for stern frames, rudder horns and shaft brackets Strength members not referred to in above categories	- Grade A/AH	Class II Grade A/AH

Selection of material grades





[Example 1-1]

❖ **Referring to CSR Rule, select steel grade of bilge strake within 0.4L zone**

(where, main dimension = LBP: 252m, Ls: 249m, Plate THK: 20mm)

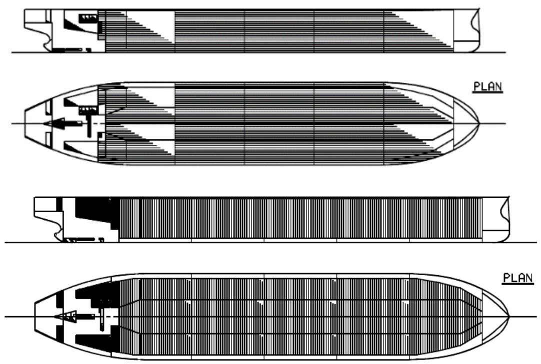
1) "A" Grade Steel
2) "B", "AH" Grade Steel
3) "D", "DH" Grade Steel
4) "E", "EH" Grade Steel

Still water bending moment

❖ Still water Bending Moment

Actual bending moments for all loading conditions (Trim & Stability booklet)

Minimum Rule still water bending moment



$$M_s = K_{sm} M_{so} \text{ (kNm)}$$

$$M_{so} = -0.065 C_{wu} L^2 B (C_B + 0.7) \text{ (kNm) in sagging}$$

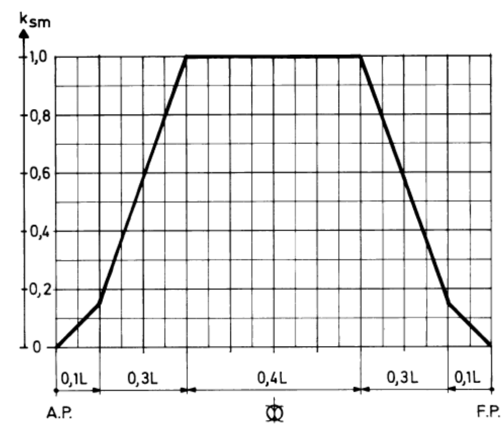
$$= C_{wu} L^2 B (0.1225 + 0.0015\, C_B) \text{ (kNm) in hogging}$$

$C_{wu} = C_w$ for unrestricted service

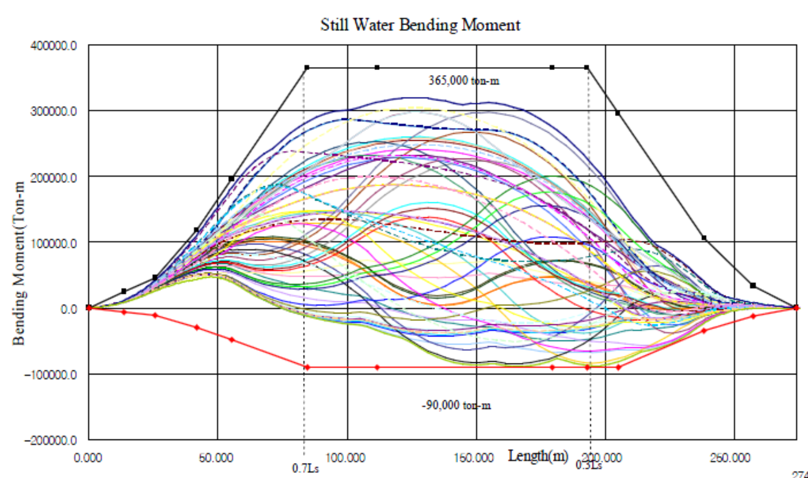
K_{sm} = 1.0 within 0.4L amiship

= 0.15 at 0.1L from A.P or F.P

= 0.0 at A.P or F.P



Select the max. actual bending moment and rule bending moment



Wave bending moment

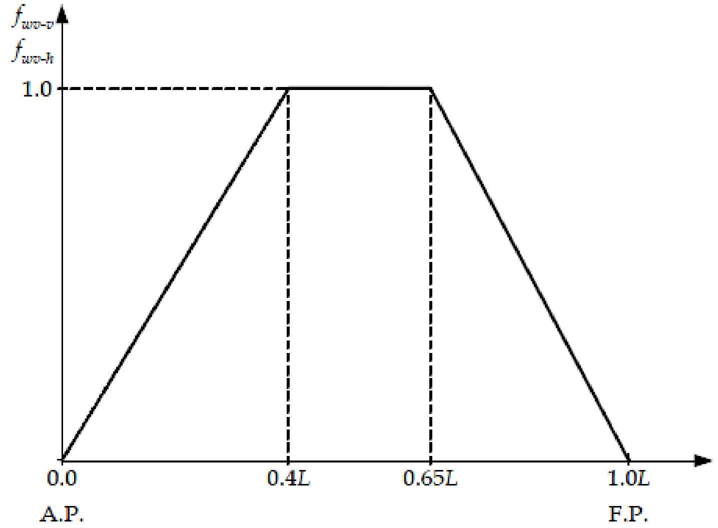
❖ Vertical wave bending moment

$$M_{wv-hog} = f_{prob}\, 0.19\, f_{wv-v} C_{wv} L^2 B C_b$$
$$M_{wv-sag} = -f_{prob}\, 0.11\, f_{wv-v} C_{wv} L^2 B (C_b + 0.7) \quad \text{kNm}$$

❖ Horizontal wave bending moment

$$M_{wv-h} = f_{prob}\left(0.3 + \frac{L}{2000}\right) f_{wv-h} C_{wv} L^2 T_{LC} C_b \quad \text{kNm}$$

Figure 7.3.1
Vertical and Horizontal Wave Bending Moment Distribution
for Scantling Requirements and Strength Assessment



Shear Force

❖ **Vertical wave shear force**

$$Q_{wv-pos} = 0.3 f_{qwv-pos} C_{wv} LB(C_b + 0.7)$$
$$Q_{wv-neg} = -0.3 f_{qwv-neg} C_{wv} LB(C_b + 0.7) \quad \text{kN}$$

Figure 7.3.3
Positive Vertical Wave Shear Force Distribution

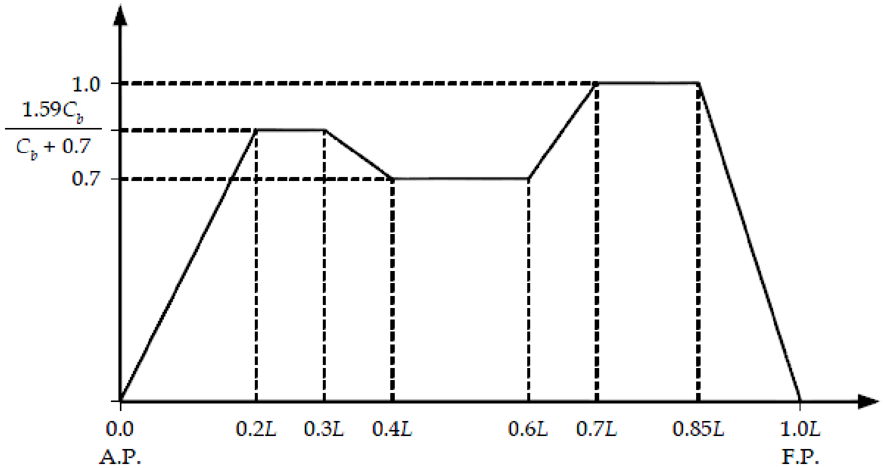
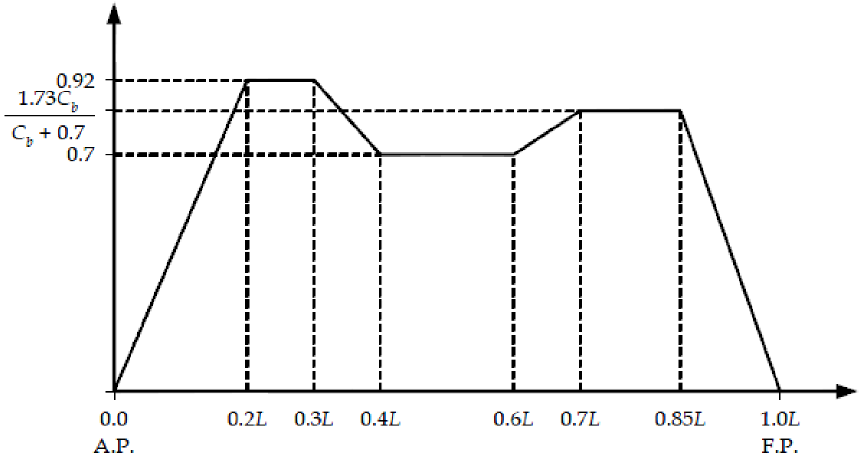


Figure 7.3.4
Negative Vertical Wave Shear Force Distribution



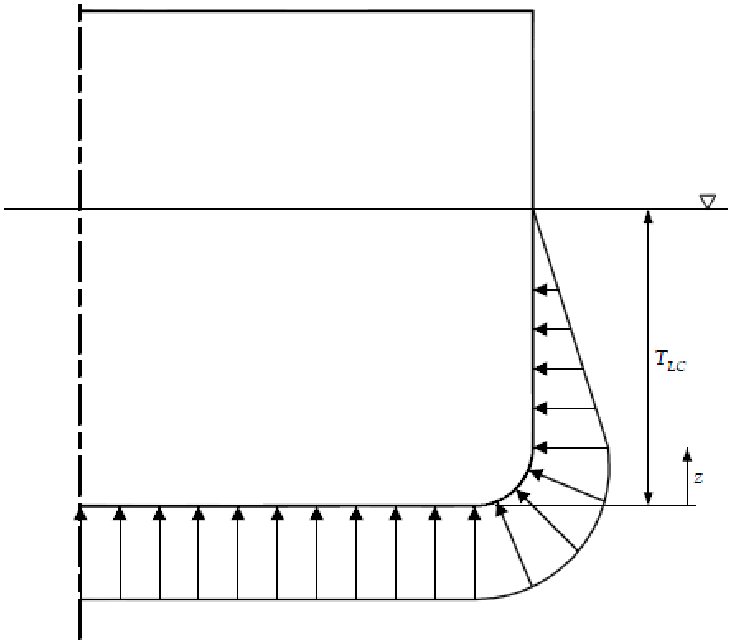
Static sea pressure

- **Static sea pressure**

$$P_{hys} = \rho_{sw} g (T_{LC} - z) \quad \text{kN/m}^2$$

Where:

z	vertical coordinate of load point, in m, and is not to be greater than T_{LC}, see *Figure 7.2.2*
ρ_{sw}	density of sea water, 1.025tonnes/m^3
T_{LC}	draught in the loading condition being considered, in m
g	acceleration due to gravity, 9.81m/s^2



Dynamic wave pressure

$P_{ex\text{-}max} = P_{ex\text{-}dyn}$ kN/m² below still waterline

$= P_{WL} - 10(z - T_{LC})$ kN/m² for $T_{LC} < z \leq T_{LC} + \frac{P_{WL}}{10}$

$= 0$ kN/m² for $z > T_{LC} + \frac{P_{WL}}{10}$

$P_{ex\text{-}min} = -P_{ex\text{-}dyn}$ kN/m² below still waterline

$= 0$ kN/m² above still waterline

Figure 7.3.5
Transverse Distribution of Maximum Dynamic Wave Pressure for Scantling Requirements and Strength Assessment

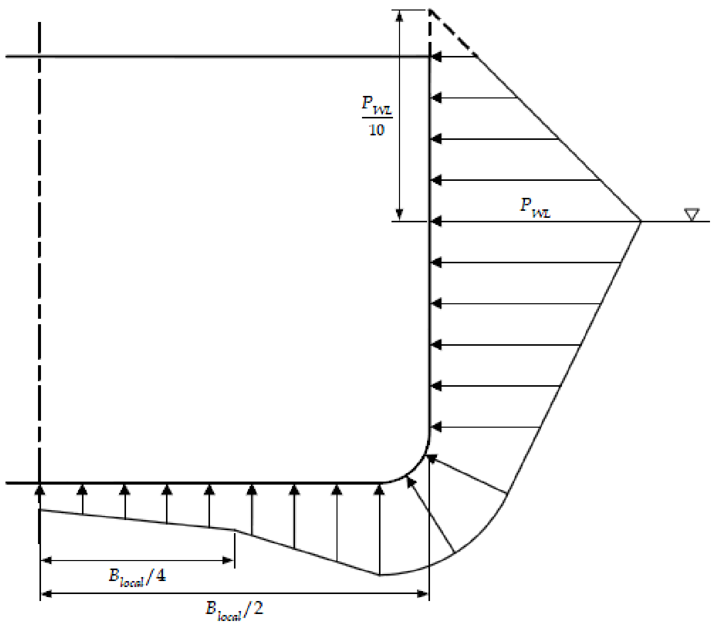
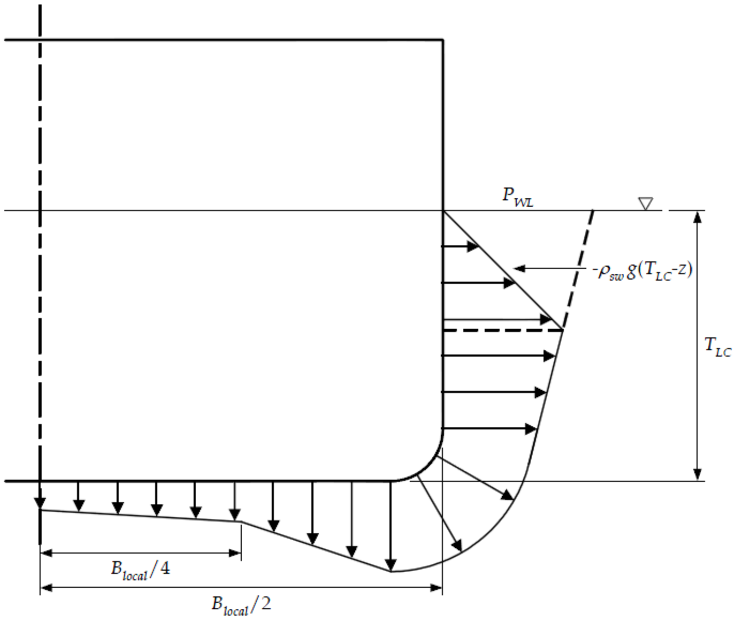


Figure 7.3.6
Transverse Distribution of Minimum Dynamic Wave Pressure for Scantling Requirements and Strength Assessment



Static tank pressure

- **Static tank pressure**

$$P_{in-tk} = \rho g z_{tk} \quad \text{kN/m}^2$$

Where:

z_{tk} vertical distance from highest point of tank

- in the case of overfilling or filling during flow through ballast water exchange

$$P_{in-air} = \rho_{sw} g z_{air} \quad \text{kN/m}^2$$

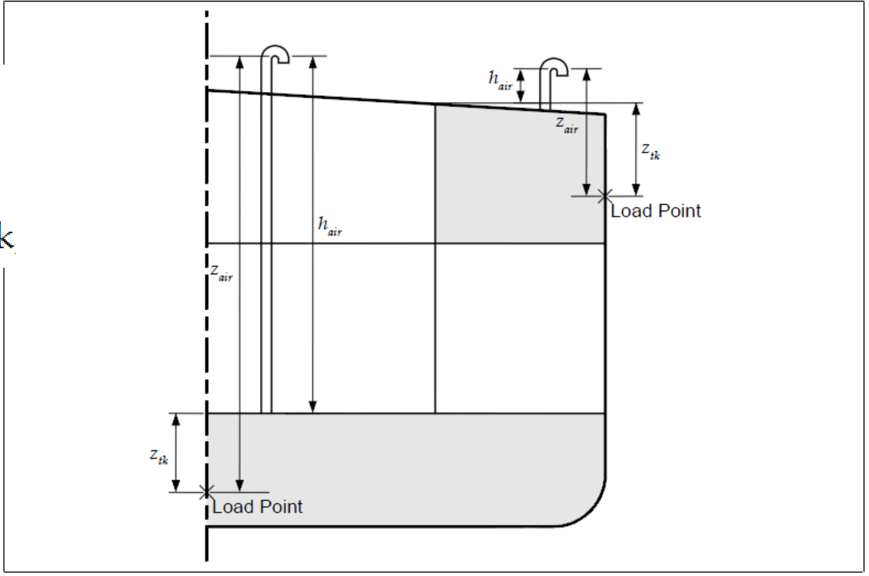
Where:

z_{air} vertical distance from top of air pipe or overflow pipe to the load point, whichever is the lesser, see *Figure 7.2.3*, in m

$= z_{tk} + h_{air}$

ρ_{sw} density of sea water, 1.025tonnes/m³

Figure 7.2.3
Pressure-Heads and Distances used for Calculation of Static Tank Pressure



Ship Accelerations

- **Vertical acceleration**

$$a_v = f_{prob}\sqrt{a_{heave}^2 + a_{pitch-z}^2 + a_{roll-z}^2} \quad \text{m/s}^2$$

- **Transverse acceleration**

$$a_t = f_{prob}\sqrt{a_{sway}^2 + (g\ sin\theta + a_{roll-y})^2} \quad \text{m/s}^2$$

- **Longitudinal acceleration**

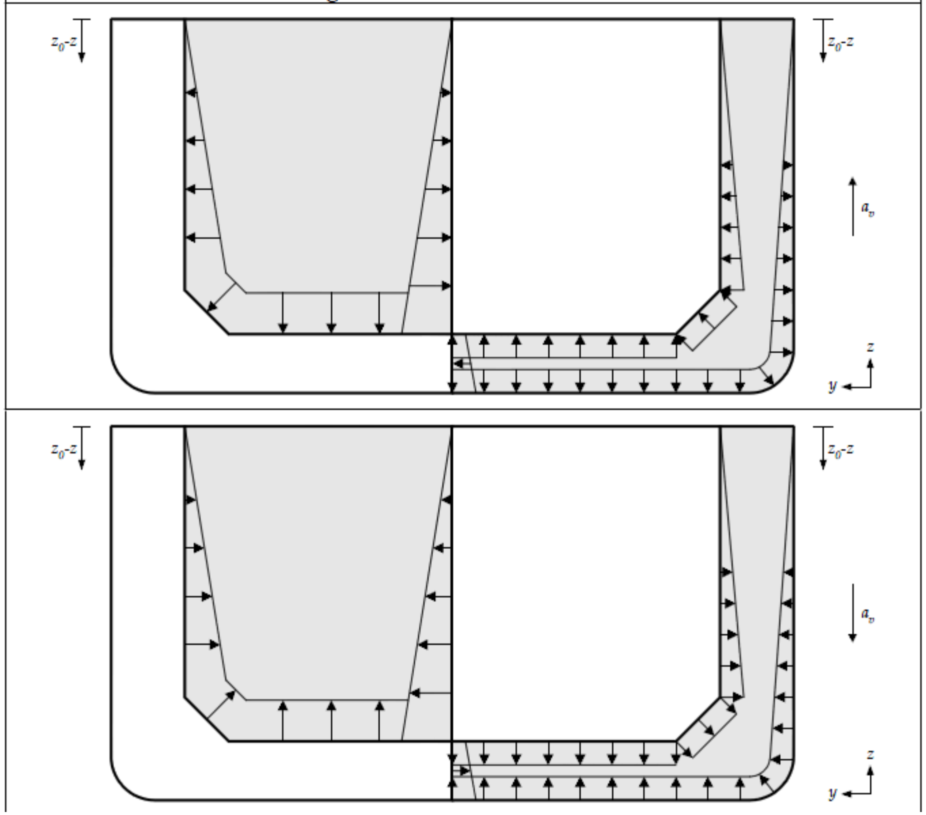
$$a_{lng} = 0.7 f_{prob}\sqrt{a_{surge}^2 + \left(\frac{L}{325}\left(g\ sin\varphi + a_{pitch-x}\right)\right)^2}$$

Dynamic tank pressure

- Dynamic tank pressure, $P_{in\text{-}v}$, due to vertical tank acceleration

$$P_{in-v} = \rho a_v (z_0 - z) \qquad \text{kN/m}^2$$

Figure 7.6.4
Dynamic Tank Pressure in Cargo Tank (Left) and Ballast Tank (Right) due to Positive and Negative Vertical Tank Acceleration

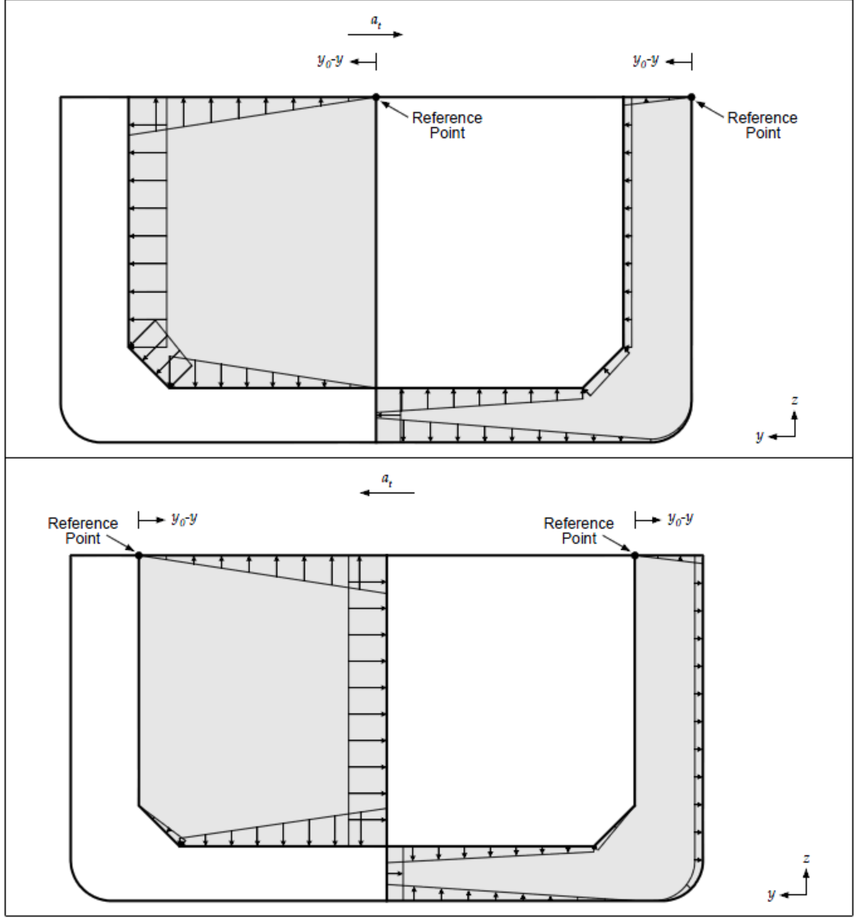


Dynamic tank pressure

- The envelope dynamic tank pressure, P_{in-t}, due to transverse acceleration

$$P_{in-t} = f_{ull-t}\,\rho a_t (y_0 - y)$$

Figure 7.6.5
Dynamic Tank Pressure in Cargo Tank (Left) and Ballast Tank (Right) due to Negative and Positive Transverse Tank Acceleration

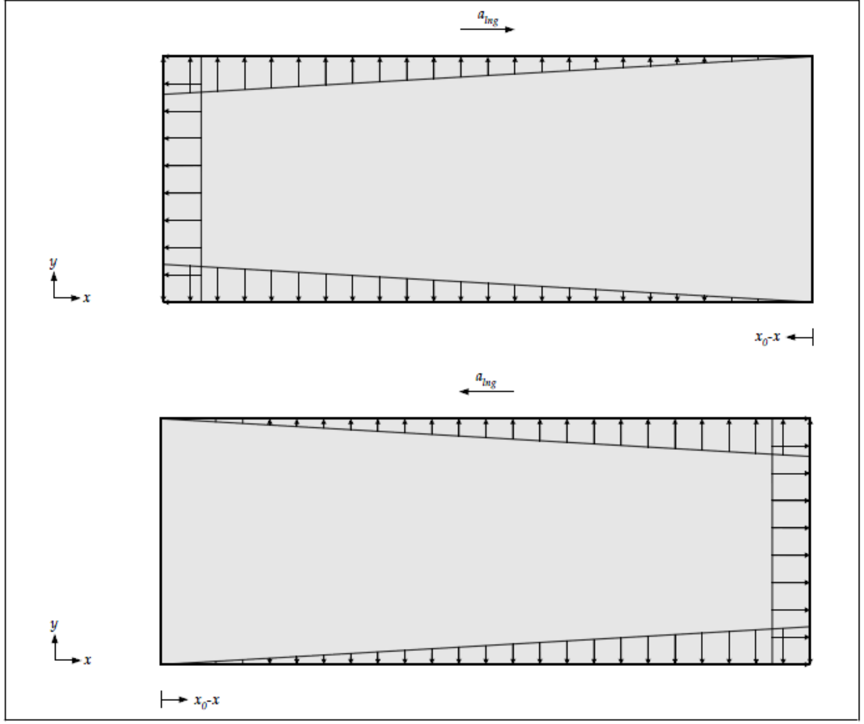


Dynamic tank pressure

- The envelope dynamic tank pressure, $P_{in\text{-}lng}$, due to longitudinal acceleration

$$P_{in-lng} = f_{ull-lng}\,\rho\,a_{lng}\,(x_0 - x)$$

Figure 7.6.6
Dynamic Tank Pressure in Tanks due to Positive and Negative Longitudinal Acceleration



General

❖ Cargo tank Analysis

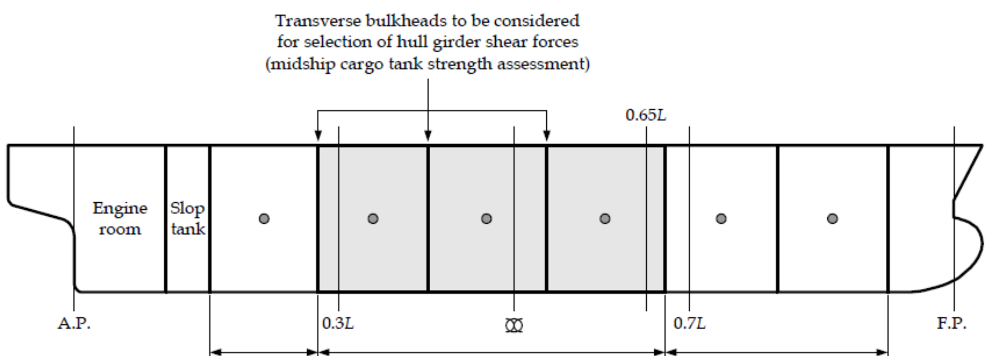
- Minimum covering midship cargo region
- Minimum 3-tank FE model
- General mesh size following stiffening system, e.g. 900 mm
- Model based on average corroded thickness $t_{gross} – 0.5\ t_{corr}$

❖ Objective

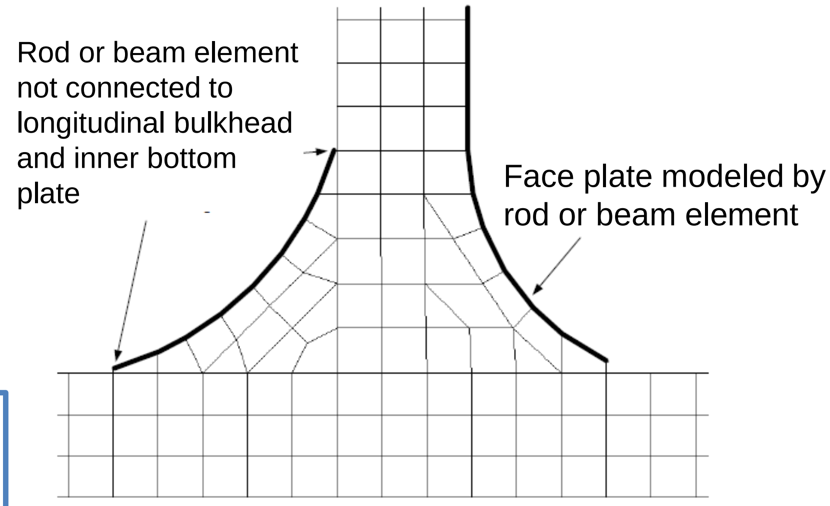
- Stress level and deflection in primary support members
- Buckling capability of plate and stiffened panels
- Hull girder capability

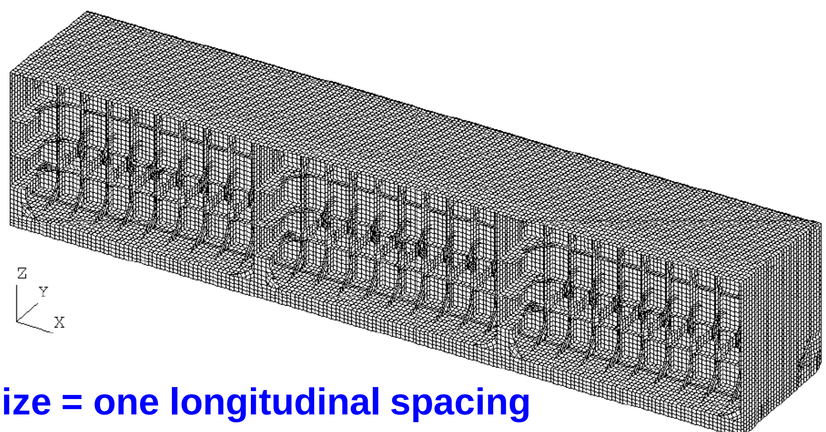
FE Analysis

(a) Midship cargo tank strength assessment



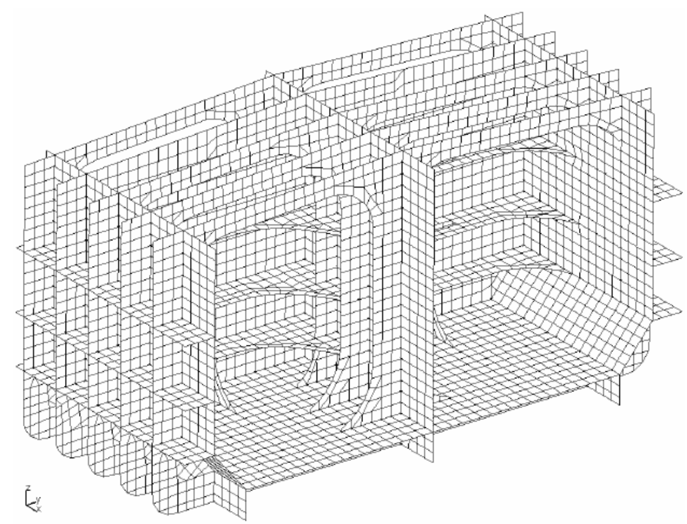
Definition of Cargo Tank Regions for FE Structural Assessment





Mesh size = one longitudinal spacing
=700~800 mm

FE model of Typical Cargo Tank Model of a VLCC



Aframax Oil Tanker

Dynamic Load Cases and Dynamic Load Combination Factors

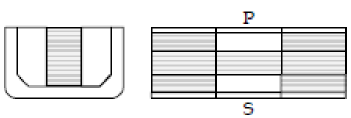
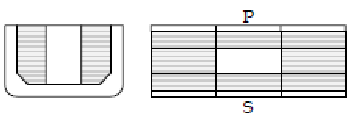
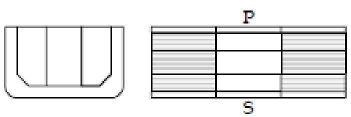
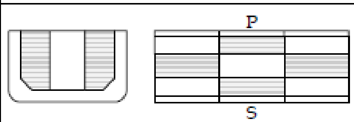
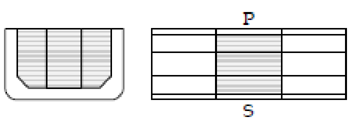
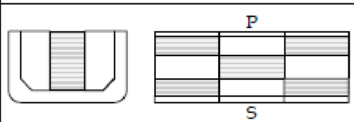
- Design Load Combination S+D
- The simultaneously acting dynamic load cases

Table 7.6.2
Dynamic Load Cases for Strength Assessment (by FEM)

Wave direction			Head sea				Beam sea		Oblique sea	
Max response			M_{wv} (Sagging)	M_{wv} (Hogging)	Q_{wv} (Sagging)	Q_{wv} (Hogging)	a_v		M_{wv-h} (Hogging)	
Dynamic Load Case			1	2	3	4	5a	5b	6a	6b
Global loads	M_{wv}	f_{mv}	-1.0	1.0	-1.0	1.0	0.0	0.0	0.4	0.4
	Q_{wv}	f_{qv}	1.0	-1.0	1.0	-1.0	0.0	0.0	0.0	0.0
	M_{wv-h}	f_{mh}	0.0	0.0	0.0	0.0	0.0	0.0	1.0	-1.0
Accelerations	a_v	f_v	0.5	-0.5	0.3	-0.3	1.0	1.0	-0.1	-0.1
	a_t	f_t	0.0	0.0	0.0	0.0	-0.6	0.6	0.0	0.0
	a_{lng}	f_{lng}	-0.6	0.6	-0.6	0.6	-0.5	-0.5	0.5	0.5
Dynamic wave pressure for port side	P_{WL}	f_{WL}	-0.3	0.3	0.1	-0.1	1.0	0.4	0.6	0.0
	P_{bilge}	f_{bilge}	-0.3	0.3	0.1	-0.1	1.0	0.4	0.4	0.0
	P_{ctr}	f_{ctr}	-0.7	0.7	0.3	-0.3	0.9	0.9	0.5	0.5
Dynamic wave pressure for starboard side	P_{WL}	f_{WL}	-0.3	0.3	0.1	-0.1	0.4	1.0	0.0	0.6
	P_{bilge}	f_{bilge}	-0.3	0.3	0.1	-0.1	0.4	1.0	0.0	0.4
	P_{ctr}	f_{ctr}	-0.7	0.7	0.3	-0.3	0.9	0.9	0.5	0.5

Loading Conditions

Table B.2.3
FE Load Cases for Tankers with Two Oil-tight Longitudinal Bulkheads

Loading Pattern	Figure	Still Water Loads: Draught	Still Water Loads: % of Perm. SWBM(2)	Still Water Loads: % of Perm. SWSF(2)	Dynamic load cases: Strength assessment (1a) Midship region	Dynamic load cases: Strength assessment against hull girder shear loads (1b) Forward region	Dynamic load cases: Strength assessment against hull girder shear loads (1b) Midship and aft regions
Design load combination S + D (Sea-going load cases)							
A1		0.9 T_{sc}	100% (sag)	See note 3	1	\	\
			100% (hog)	100% (-ve fwd) See note 4	2, 5a	\	\
A2		0.9 T_{sc}	100% (sag)	See note 3	1	\	\
			100% (hog)	100% (-ve fwd) See note 4	2, 5a	\	\
A3		0.55 T_{sc} see note 6	100% (hog)	100% (-ve fwd) See note 5	2	4	2
				100% (-ve fwd) See note 4	5a	\	\
A4		0.6 T_{sc}	100% (sag)	100% (+ve fwd) See note 4	1, 5a	\	\
A5		0.8 T_{sc} See note 7	100% (sag)	100% (+ve fwd) See note 5	1	3	1
				100% (+ve fwd) See note 4	5a	\	\
A6		0.6 T_{sc}	100% (hog)	100% (-ve fwd) See note 4	5a	\	\

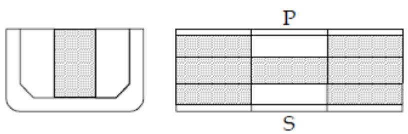
Dynamic Load cases (head sea)

Wave direction			Head sea	
Max response			M_{wv} (Sagging)	M_{wv} (Hogging)
Dynamic Load Case			1	2
Global loads	M_{wv}	f_{mv}	-1.0	1.0
	Q_{wv}	f_{qv}	1.0	-1.0
	M_{wv-h}	f_{mh}	0.0	0.0
Accelerations	a_v	f_v	0.5	-0.5
	a_t	f_t	0.0	0.0
	a_{lng}	f_{lng}	-0.6	0.6
Dynamic wave pressure for port side	P_{WL}	f_{WL}	-0.3	0.3
	P_{bilge}	f_{bilge}	-0.3	0.3
	P_{ctr}	f_{ctr}	-0.7	0.7
Dynamic wave pressure for starboard side	P_{WL}	f_{WL}	-0.3	0.3
	P_{bilge}	f_{bilge}	-0.3	0.3
	P_{ctr}	f_{ctr}	-0.7	0.7

Dynamic Load cases (head sea)

Wave direction			Beam sea	
Max response			a_v	
Dynamic Load Case			5a	5b
Global loads	M_{wv}	f_{mv}	0.0	0.0
	Q_{wv}	f_{qv}	0.0	0.0
	M_{wv-h}	f_{mh}	0.0	0.0
Accelerations	a_v	f_v	1.0	1.0
	a_t	f_t	-0.6	0.6
	a_{lng}	f_{lng}	-0.5	-0.5
Dynamic wave pressure for port side	P_{WL}	f_{WL}	1.0	0.4
	P_{bilge}	f_{bilge}	1.0	0.4
	P_{ctr}	f_{ctr}	0.9	0.9
Dynamic wave pressure for starboard side	P_{WL}	f_{WL}	0.4	1.0
	P_{bilge}	f_{bilge}	0.4	1.0
	P_{ctr}	f_{ctr}	0.9	0.9

Loading Conditions

Loading Pattern	Figure	Still Water Loads			Dynamic load cases		
		Draught	% of Perm. SWBM(2)	% of Perm. SWSF(2)	Strength assessment (1a)	Strength assessment against hull girder shear loads (1b)	
					Midship region	Forward region	Midship and aft regions
Design load combination S + D (Sea-going load cases)							
A1		0.9 T_{sc}	100% (sag)	See note 3	1		
			100% (hog)	100% (-ve fwd) See note 4	2, 5a		

Sag SWBM+ Sag WBM = Max B.M.

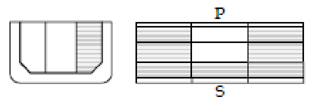
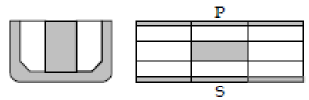
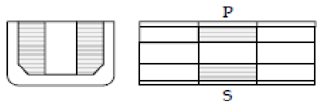
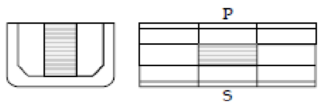
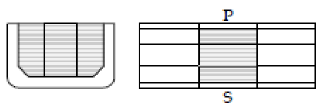
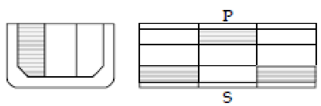
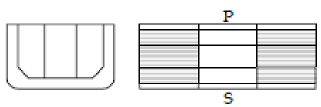
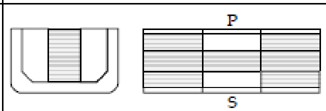
Empty ballast + Beam sea
→ Max. Pressure on Side shell

Hog SWBM+ Hog WBM=Max. B.M.

- **Note 3.** The actual shear force that results from the application of static and dynamic local loads to the FE model are to be used.

- **Note 4.** The actual shear force that results from the application of static and dynamic local loads to the FE model are to be used. Where this shear force exceeds the target SWSF (design load combination S) or target combined SWSF and VWSF, correction vertical loads are to be applied to adjust the shear force down to the required value.

Loading Conditions

Loading Pattern	Figure	Still Water Loads			Dynamic load cases		
		Draught	Perm. SWBM[2]	Perm. SWSF[2]	Strength assessment [1a]	Strength assessment against hull girder shear loads [1b]	
					Midship region	Forward region	Midship and aft regions
A7[8]		T_{LC}	100% (hog)	100% (-ve fwd) See note 4	5a	\	\
A8[9]		$T_{bal\text{-}em}$	100% (sag)	100% (+ve fwd) See note 4	1	\	\
Design load combination S (Harbour and tank testing load cases)							
A9[13]		$\frac{1}{4}T_{sc}$	100% (sag)	100% (+ve fwd) See note 4	Only applicable to strength assessment of midship region (see note 1(a))		
A10[13]		$\frac{1}{4}T_{sc}$	100% (sag)	100% (+ve fwd) See note 4	Only applicable to strength assessment of midship region (see note 1(a))		
A11[12,13]		0.7 T_{sc} see note 12	100% (sag)	100% (+ve fwd) See note 5	Applicable to strength assessment of midship region (see 1(a)) and strength assessment against hull girder shear loads (see 1(b))		
A12[10,13]		1/3T_{sc}	See note 10	See note 10	Only applicable to strength assessment of midship region (see note 1(a))		
A13[11,13]		0.65 T_{sc} see note 11	100% (Hog)	100% (-ve fwd) See note 5	Applicable to strength assessment of midship region (see 1(a)) and strength assessment against hull girder shear loads (see 1(b))		
A14[13]		T_{sc}	100% (Hog)	100% (-ve fwd) See note 4	Only applicable to strength assessment of midship region (see note 1(a))		

Procedure to Adjust Hull Girder Shear Forces and Bending Moments

- Vertical distributed loads + a vertical bending moment applied to the model ends

  = the required vertical shear force at the forward and aft bulkhead

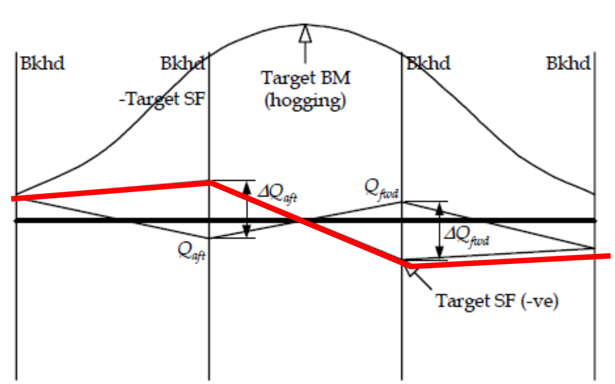
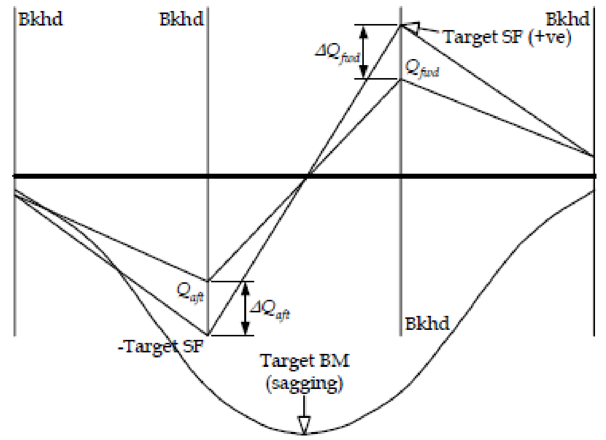
  the required vertical bending moment within the middle tank

- The vertical shear forces generated by the local loads are to be calculated at the transverse bulkhead positions from
  - structural weight distribution,
  - weight of cargo and ballast static sea pressure,
  - dynamic wave pressure, and dynamic tank pressure load.

Procedure to adjust vertical shear force distribution

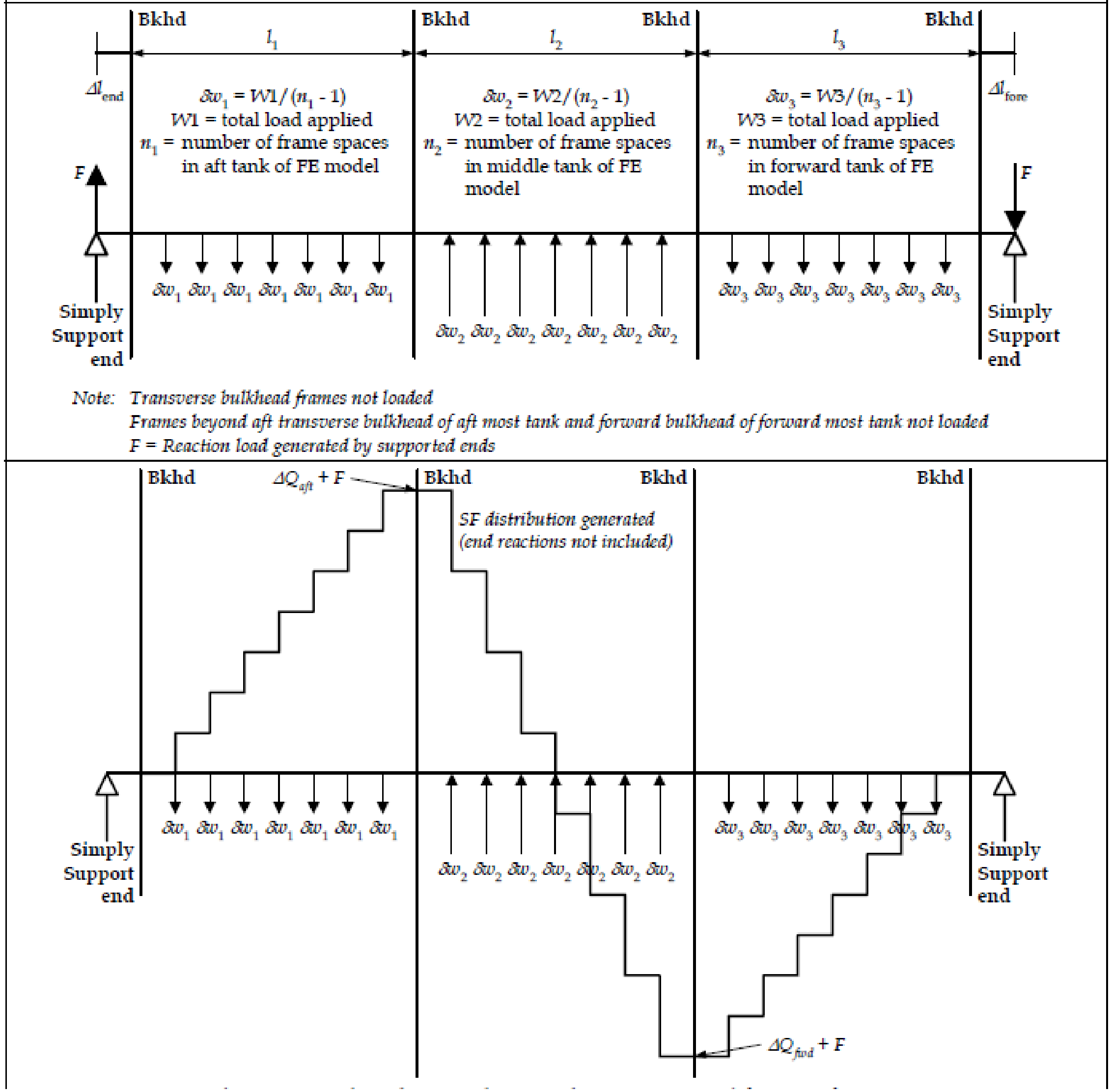
- The maximum absolute shear force at the bulkhead position is to be used to obtain the required adjustment in shear forces at the transverse bulkhead.

Figure B.2.10
Position of Target Shear Force and Required Shear Force Adjustment at Transverse Bulkhead Positions

Condition	Target			Aft Bkhd		Fore Bkhd	
	BM	SF	Bkhd pos	SF	ΔQ_{aft}	SF	ΔQ_{fwd}
	Hog	-ve	Fore	$-Q_{targ}$	$-Q_{targ} - Q_{aft}$	Q_{targ} (-ve)	$Q_{targ} - Q_{fwd}$
	Sag	+ve	Fore	$-Q_{targ}$	$-Q_{targ} - Q_{aft}$	Q_{targ} (+ve)	$Q_{targ} - Q_{fwd}$

Procedure to adjust vertical shear force distribution

Figure B.2.11
Distribution of Adjusting Vertical Force at Frames and Resulting Shear Force Distributions



$$\delta w_1 = \frac{\Delta Q_{aft}(2l - l_2 - l_3) + \Delta Q_{fwd}(l_2 + l_3)}{(n_1 - 1)(2l - l_1 - 2l_2 - l_3)}$$

$$\delta w_2 = \frac{(W1 + W3)}{(n_2 - 1)} = \frac{(\Delta Q_{aft} - \Delta Q_{fwd})}{(n_2 - 1)}$$

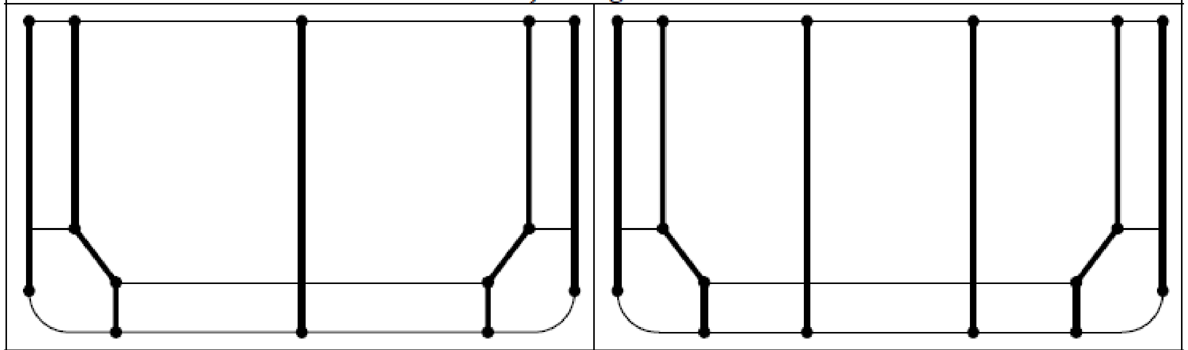
$$\delta w_3 = \frac{-\Delta Q_{fwd}(2l - l_1 - l_2) - \Delta Q_{aft}(l_1 + l_2)}{(n_3 - 1)(2l - l_1 - 2l_2 - l_3)}$$

$$F = 0.5\left(\frac{W1(l_2 + l_1) - W3(l_2 + l_3)}{l}\right)$$

Procedure to adjust vertical shear force distribution

- The amount of adjusting load to be applied to vertical members of of each transverse frame section to generate the vertical load, δw_i. The applied load is proportional to Shear Area and depends on the locations.

Figure B.2.12
Distribution of Adjusting Load on a Transverse Section



Structural member	Applied load F_s
Side Shell	$f \cdot \delta w_i$
Longitudinal bulkhead including bottom girder beneath	$f \cdot \delta w_i$
Inner hull longitudinal bulkhead (vertical part)	$f \cdot \delta w_i \cdot \frac{A_{Ih-net50}}{A_{2-net50}}$
Hopper plate	$f \cdot \delta w_i \cdot \frac{A_{Hp-net50}}{A_{2-net50}}$
Upper slope plating of inner hull	$f \cdot \delta w_i \cdot \frac{A_{Usp-net50}}{A_{2-net50}}$
Outboard girder	$f \cdot \delta w_i \cdot \frac{A_{Og-net50}}{A_{2-net50}}$

$A_{2-net50}$ plate sectional area of individual inner hull longitudinal bulkhead (i.e. on one side), including hopper slope plate, double bottom side girder in way and, where fitted, upper slope plating of inner hull.

Procedure to adjust vertical and horizontal bending moments

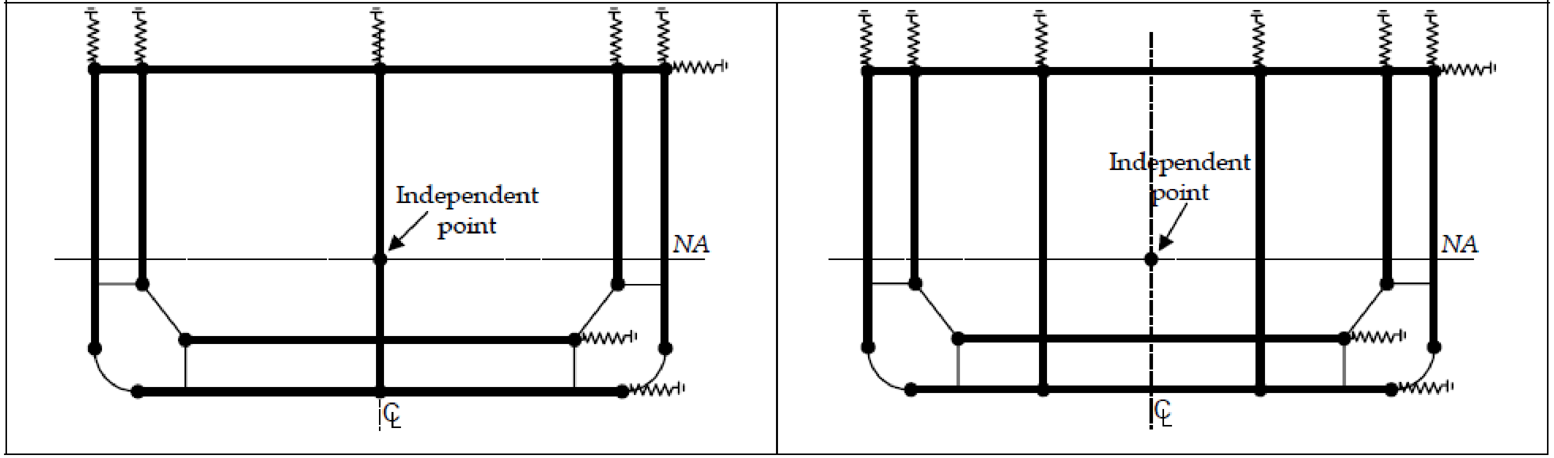
- An additional vertical bending moment is to be applied at both ends of the cargo tank finite element model to generate the required vertical bending moment in the middle tank of the model.
- $M_{v-end} = M_{v-targ} + M_{v-peak}$
- M_{v-end} : additional vertical bending moment to be applied at both ends of finite element model
- M_{v-targ} : required hogging (positive) or sagging (negative) vertical bending moment,
- M_{v-peak} : maximum or minimum bending moment within the length of the middle tank due to the local loads and the additional vertical loads applied to generate the required shear force

Boundary Conditions

- Ground spring elements, (i.e. spring elements with one end constrained in all 6 degrees of freedom), with stiffness in global y degree of freedom are to be applied to the grid points along deck, inner bottom and bottom shell.

- Ground spring elements with stiffness in global z degree of freedom are to be applied to the grid points along the vertical part of the side shells, inner hull longitudinal bulkheads and oil-tight longitudinal bulkheads.

Figure B.2.13
Spring Constraints at Model Ends



Boundary Conditions

Table B.2.9
Boundary Constraints at Model Ends

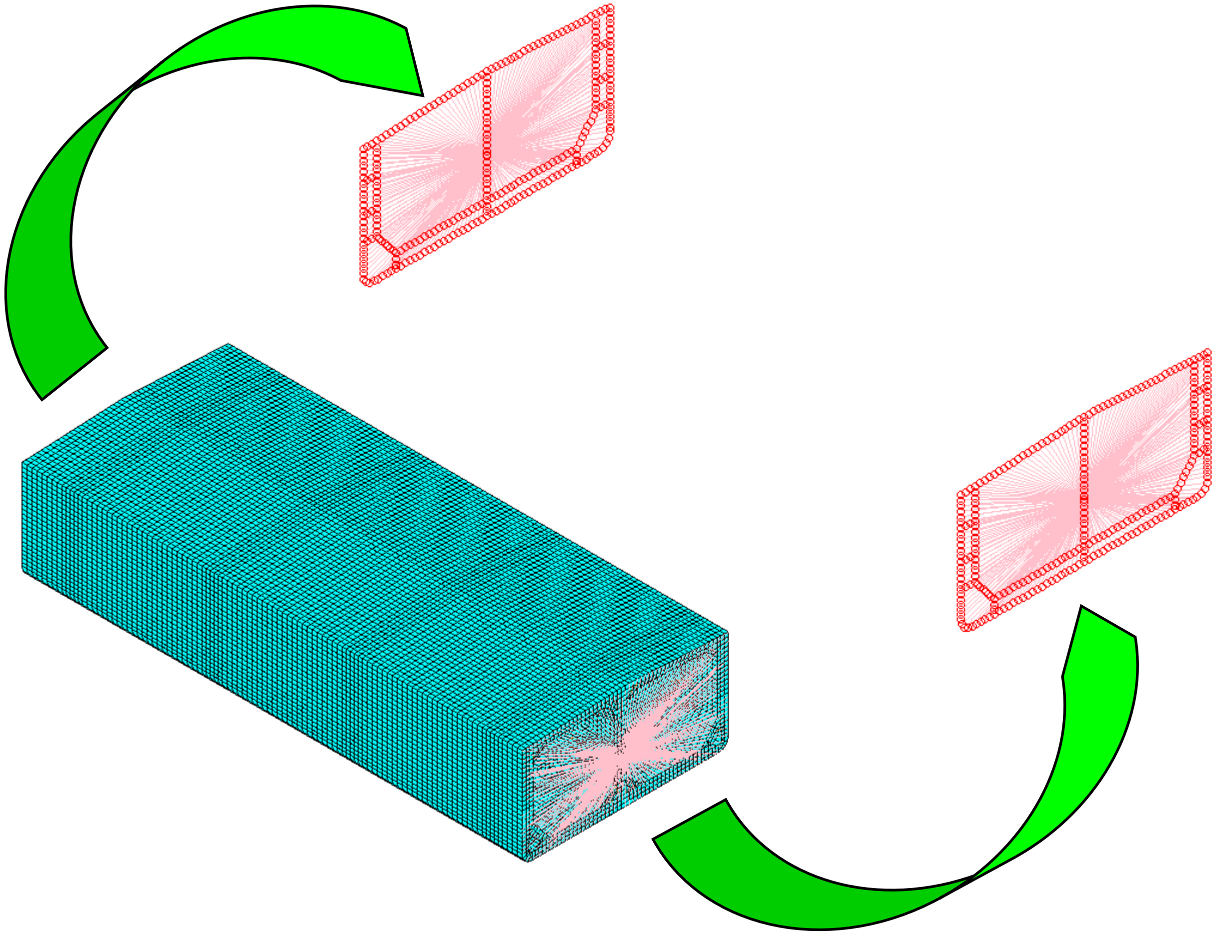
Location	Translation			Rotation		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
Aft End						
Aft end (all longitudinal elements)	*RL*	-	-	-	*RL*	*RL*
Independent Point aft end, see *Figure B.2.13*	Fix	-	-	-	$M_{v\text{-}end}$	$M_{h\text{-}end}$
Deck, inner bottom and outer shell	-	Springs	-	-	-	-
Side, inner skin and longitudinal bulkheads	-	-	Springs	-	-	-
Fore End						
Fore end (all longitudinal elements)	*RL*	-	-	-	*RL*	*RL*
Independent point fore end, see *Figure B.2.13*	-	-	-	-	$M_{v\text{-}end}$	$M_{h\text{-}end}$
Deck, inner bottom and outer shell	-	Springs	-	-	-	-
Side, inner skin and longitudinal bulkheads	-	-	Springs	-	-	-

Where:

- \- no constraint applied (free)
- *RL* nodal points of all longitudinal elements rigidly linked to independent point at neutral axis on centreline

Boundary condition – Rigid Link

- Using Rigid Body Element (RBE) or Rigid Link, section is kept in one plane.

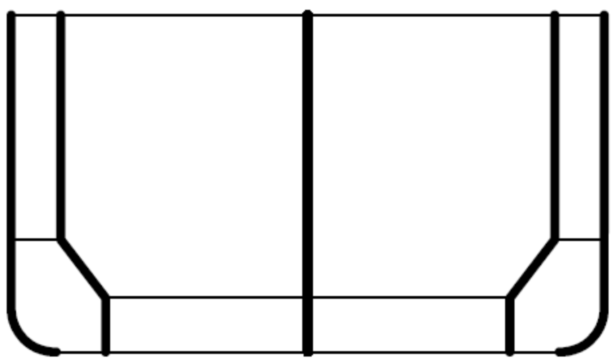
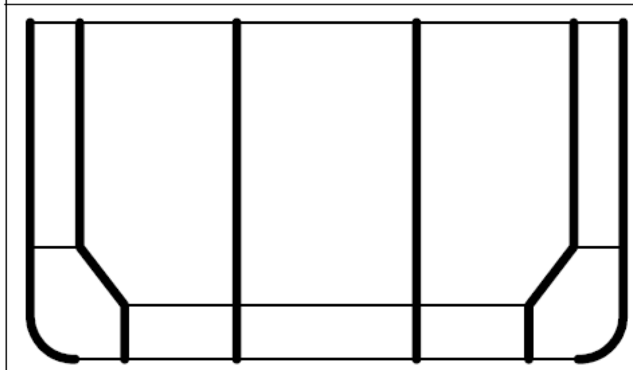


Boundary condition – Spring Stiffness

❖ **Calculation of spring stiffness**

$$c = \left(\frac{E}{1+\nu}\right)\frac{A_{s-net50}}{l_{tk}\ n} = 0.77\ \frac{A_{s-net50}E}{l_{tk}\ n} \qquad \mathrm{N/mm}$$

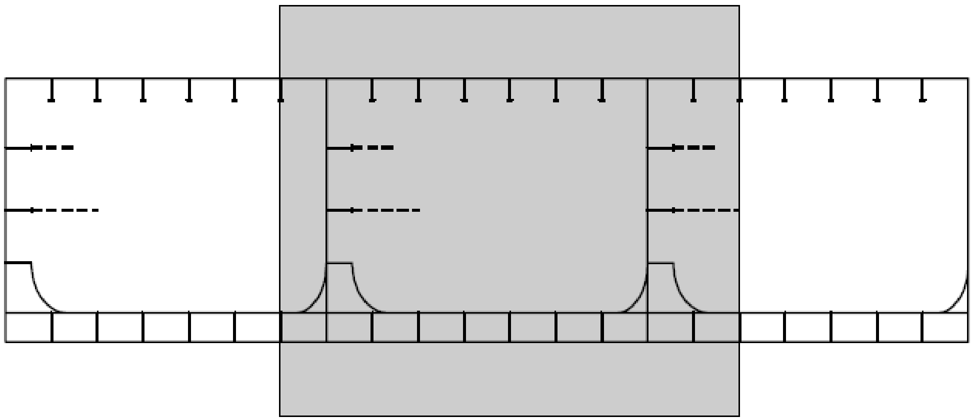
Table B.2.10
Shear Areas to be Considered for the Calculation of Spring Stiffness

Vertical springs		
	Side	Area of side shell plating, including bilge
	Inner hull longitudinal bulkheads	Area of inner skin plating, including hopper slope plate and double bottom side girder in way
	Longitudinal bulkheads	Area of longitudinal bulkhead plating, including double bottom girder in way
	Note Where part of the structural member is not vertical, the area is to be calculated using the projected area in the vertical direction.	

Result Evaluation

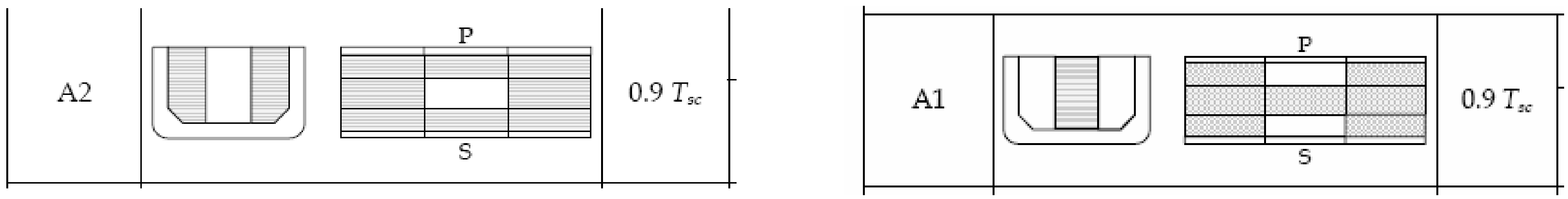
- Verification of result against acceptance criteria is to be carried out for structural members within longitudinal extent shown in *Figure B.2.14.*
- For the strength assessment of tanks in the midship cargo region, stress level and buckling capability of longitudinal hull girder structural members, primary supporting structural members and transverse bulkheads are to be verified

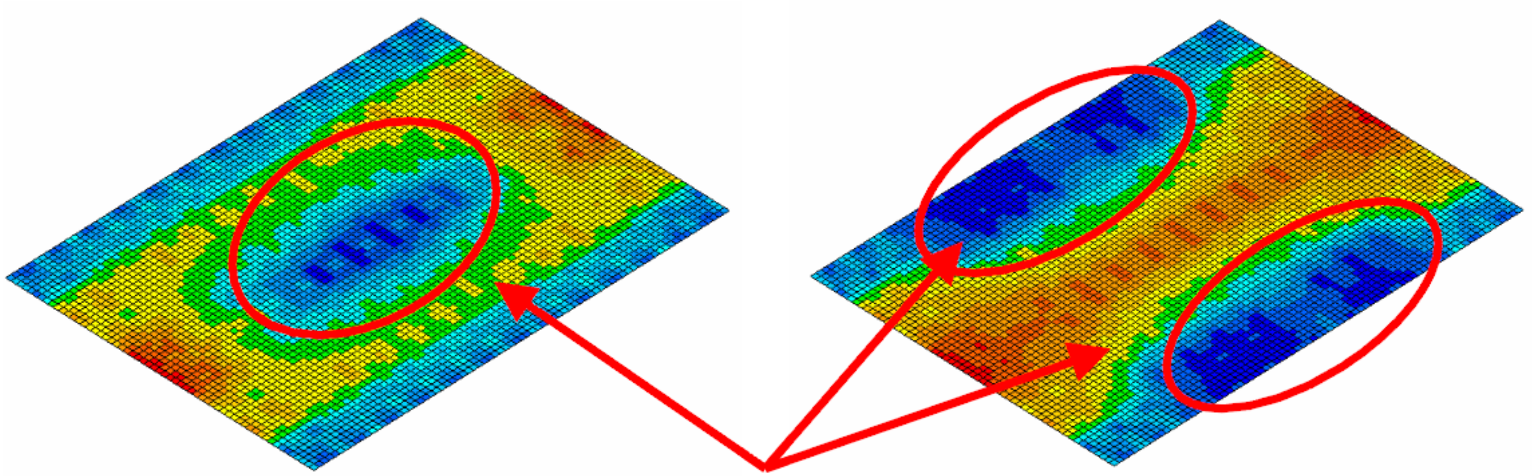
Figure B.2.14
Extent of FE Model for Verification against Acceptance Criteria



Strength Assessment using FEM

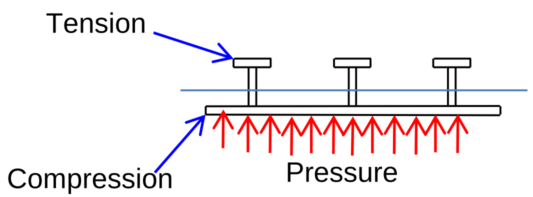
Bottom Plate - Buckling



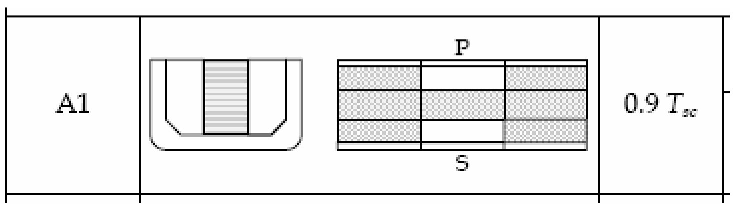


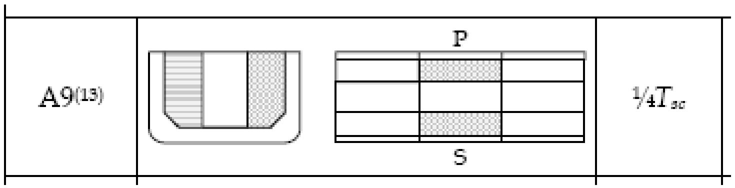
Buckling (Bi-axial)

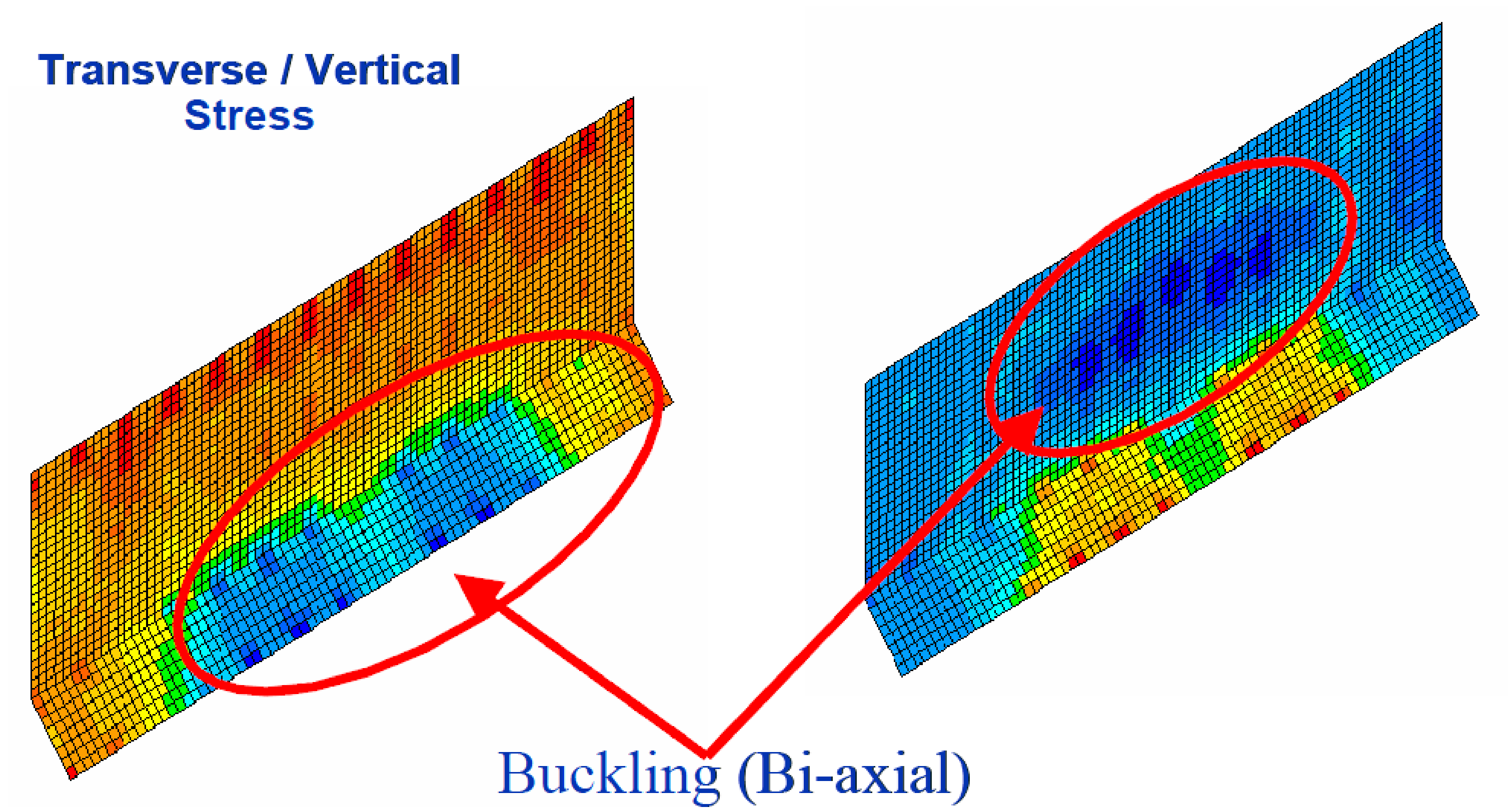
Transverse Stress



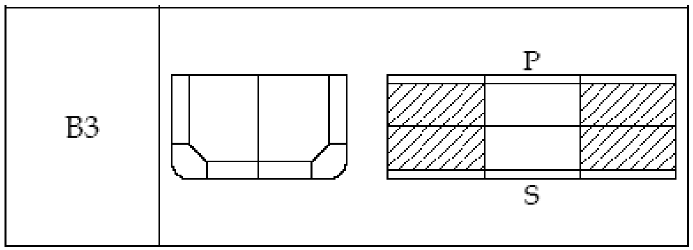
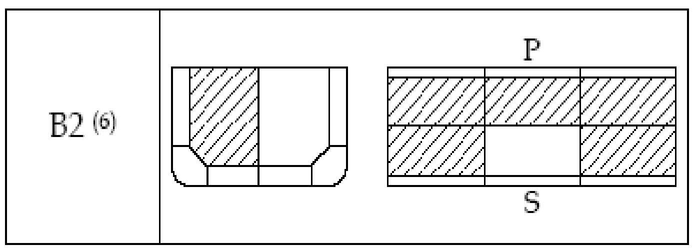
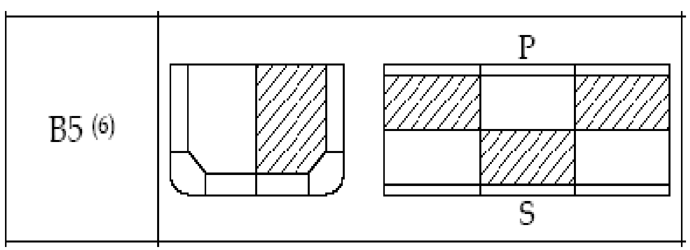
Longitudinal Bulkheads





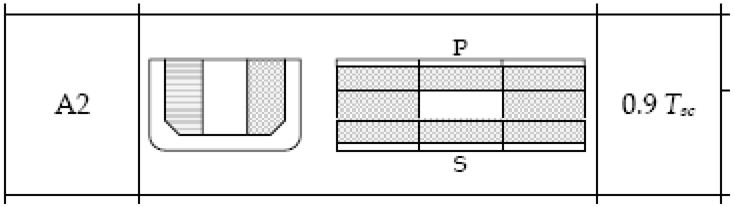


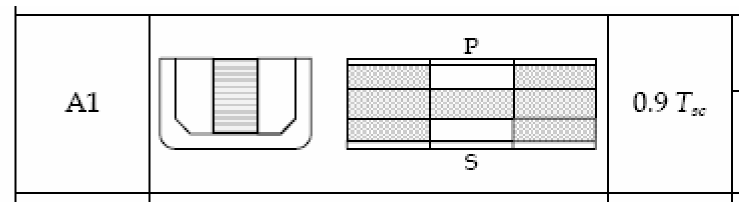
Selection of the most critical load cases w.r.t buckling (Example)

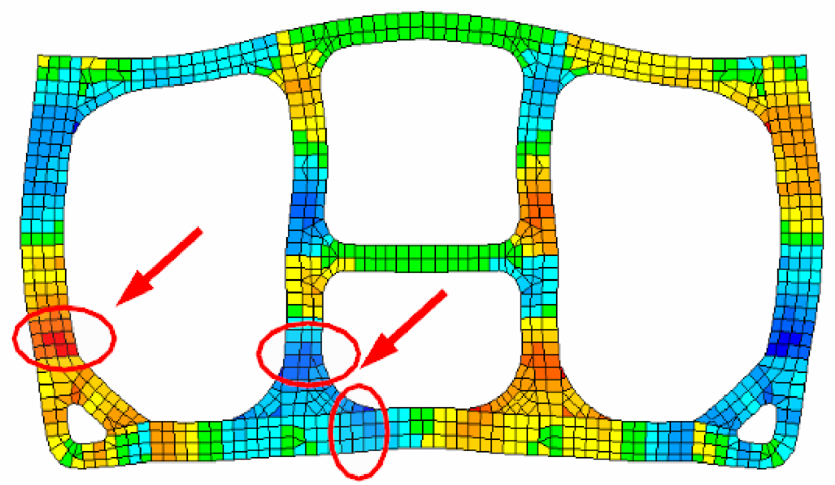
	Internal load	External load
Bottom plate		Head Sea, Hogging condition
Side Shell		Beam Sea, Acceleration toward port side.
Hopper		Beam Sea, Acceleration toward starboard side.

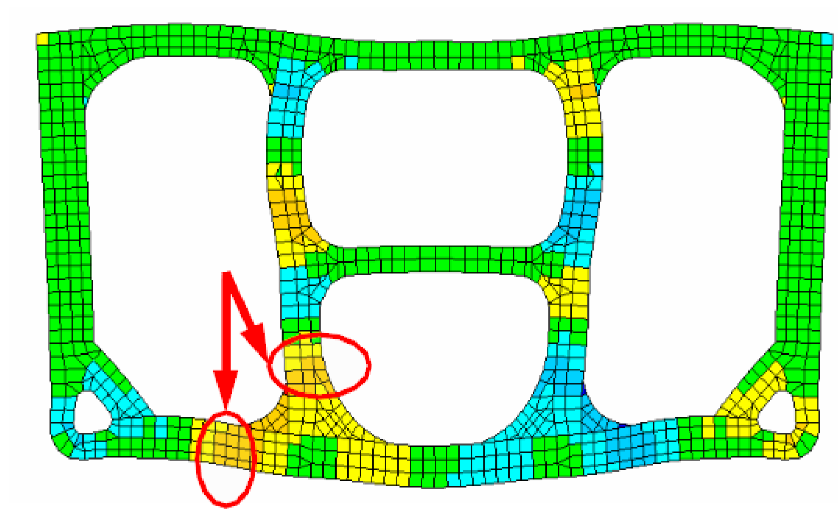
Strength Assessment using FEM

Web section





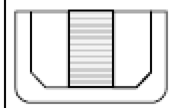
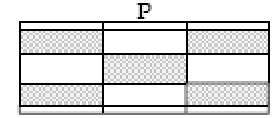


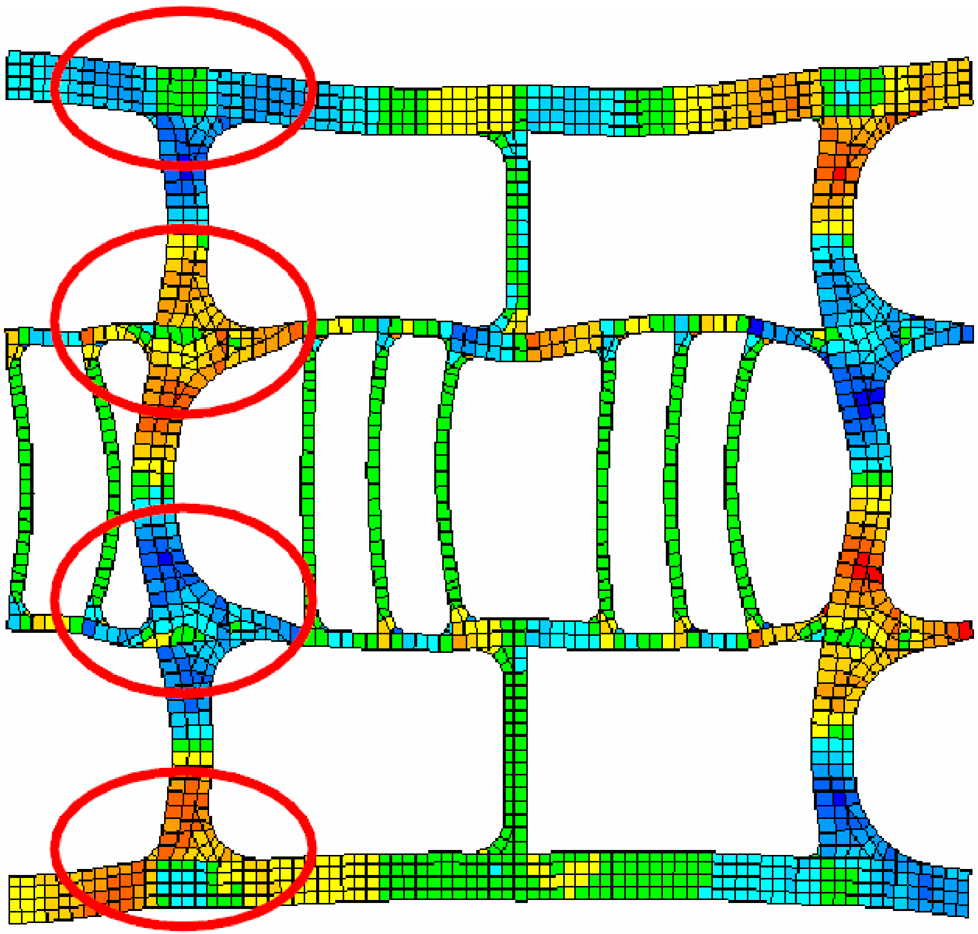


Shear Stress

Strength Assessment using FEM

No. 2 Stringer

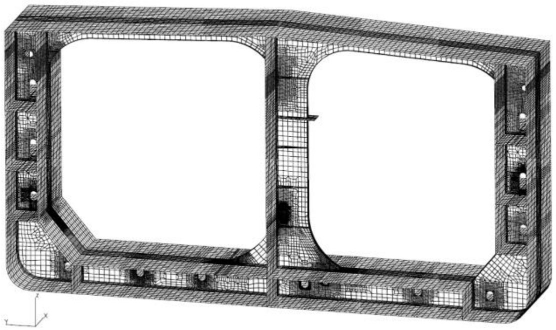
A6			$0.6\ T_{sc}$



Shear Stress

LOCAL FINE MESH STRUCTURAL STRENGTH ANALYSIS

- Mesh size in the fine mesh zones is not to be greater than 50mm x 50mm
- The net thickness with deduction of full corrosion addition, $t_{corr.}$
- The elements outside the first two layers are to be based on the net thickness with a deduction of corrosion addition, $0.5\ t_{corr.}$
- Screening criteria for Fine Mesh Analysis to be used to identify areas that require fine mesh analysis.



A fine mesh finite element analysis is to be carried out where:

$\lambda_y > 1.7$ (load combination S + D)

$\lambda_y > 1.36$ (load combination S)

Where:

λ_y yield utilisation factor

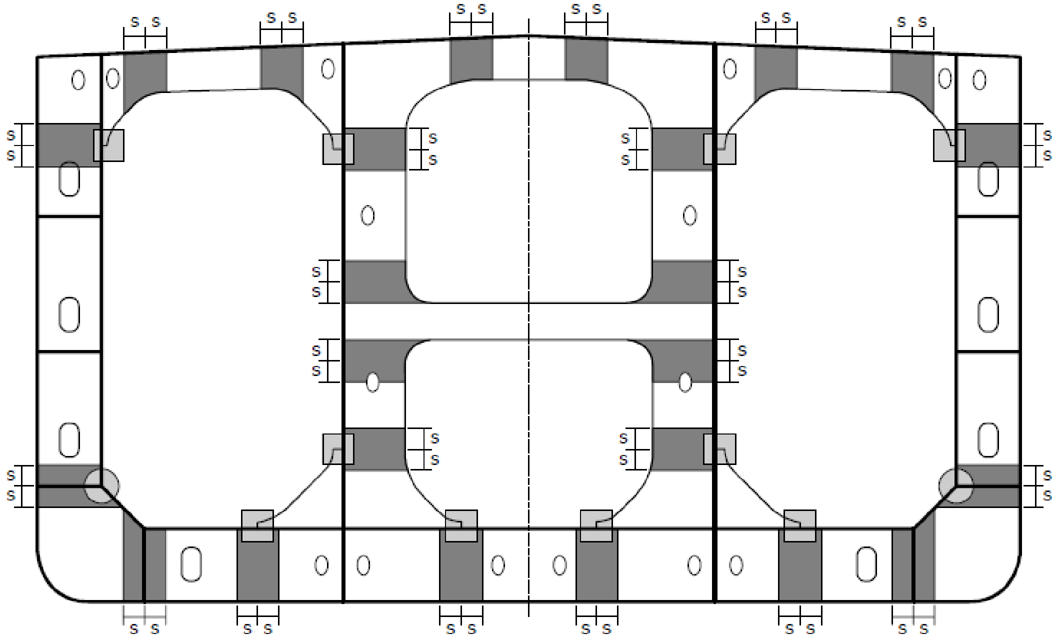
$$= 0.85 C_h \left(\left| \sigma_x + \sigma_y \right| + \left(2 + \left(\frac{l_0}{2r} \right)^{0.74} + \left(\frac{h_0}{2r} \right)^{0.74} \right) \left| \tau_{xy} \right| \right) \frac{k}{235}$$

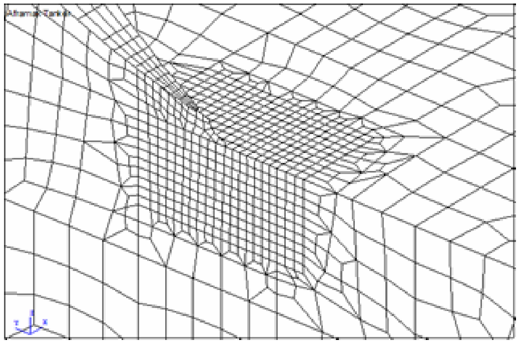
σ_x axial stress in element x direction determined from cargo tank FE analysis according to the coordinate system shown, in N/mm^2

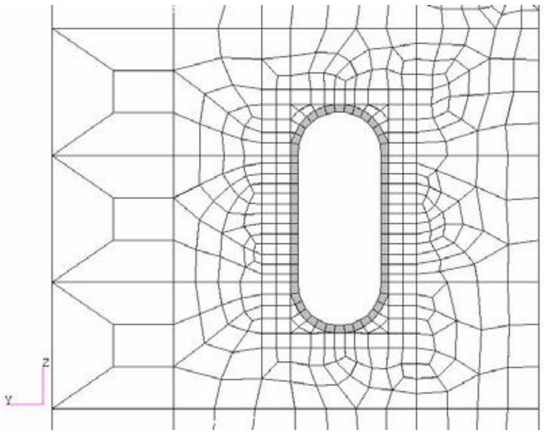
σ_y axial stress in element y direction determined from cargo tank FE analysis according to the coordinate system shown, in N/mm^2

LOCAL FINE MESH STRUCTURAL STRENGTH ANALYSIS

- **Transverse bulkhead**

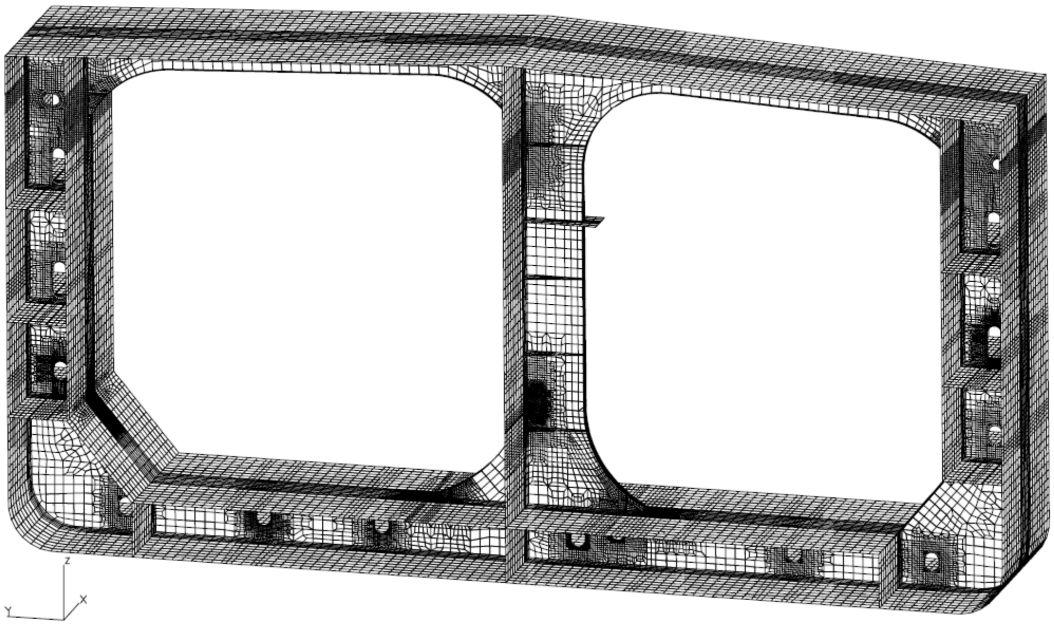


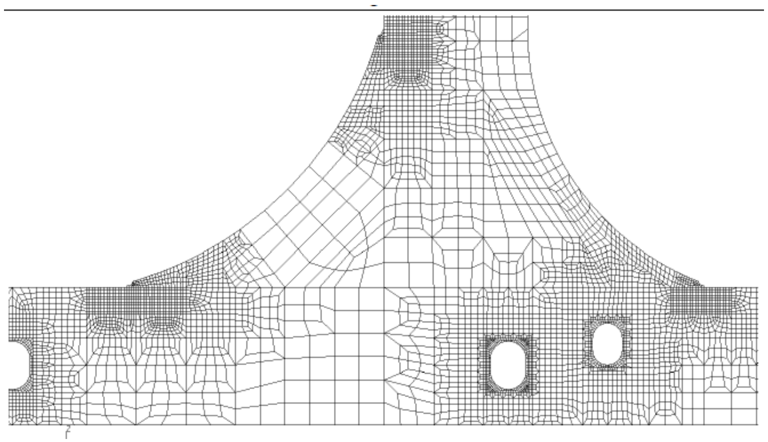


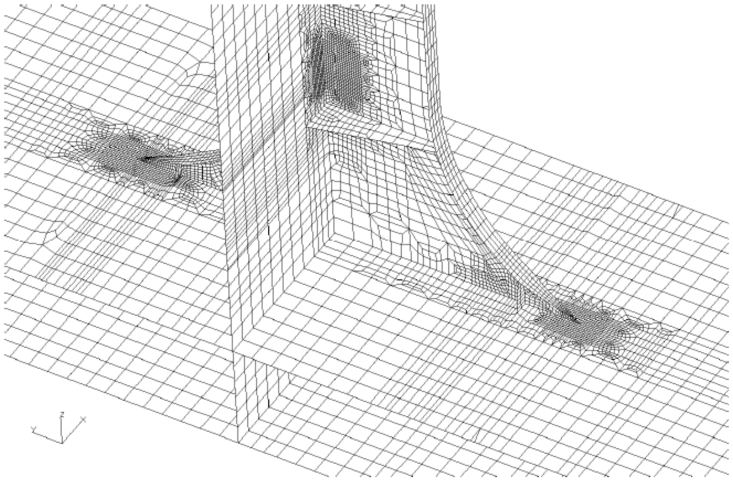


LOCAL FINE MESH STRUCTURAL STRENGTH ANALYSIS

- **Transverse bulkhead**

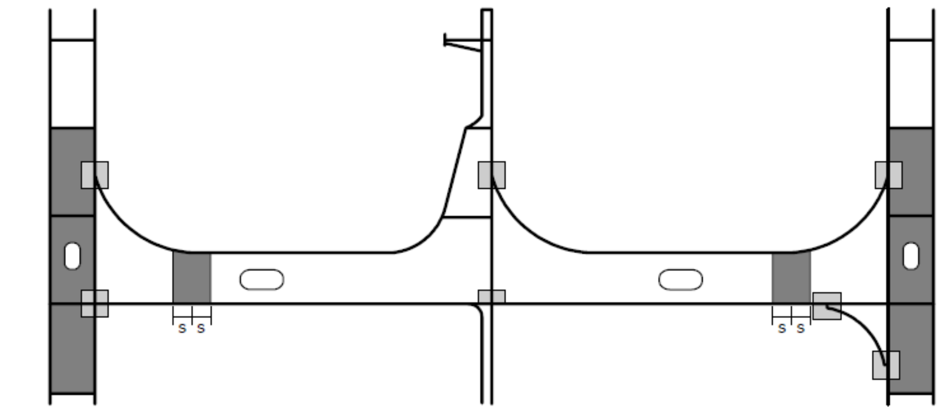


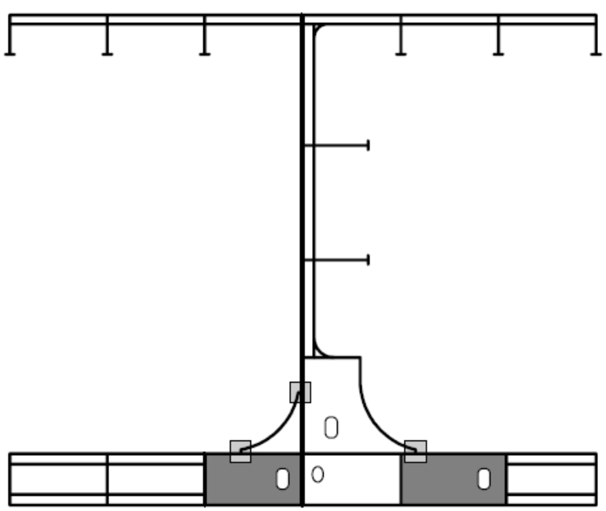


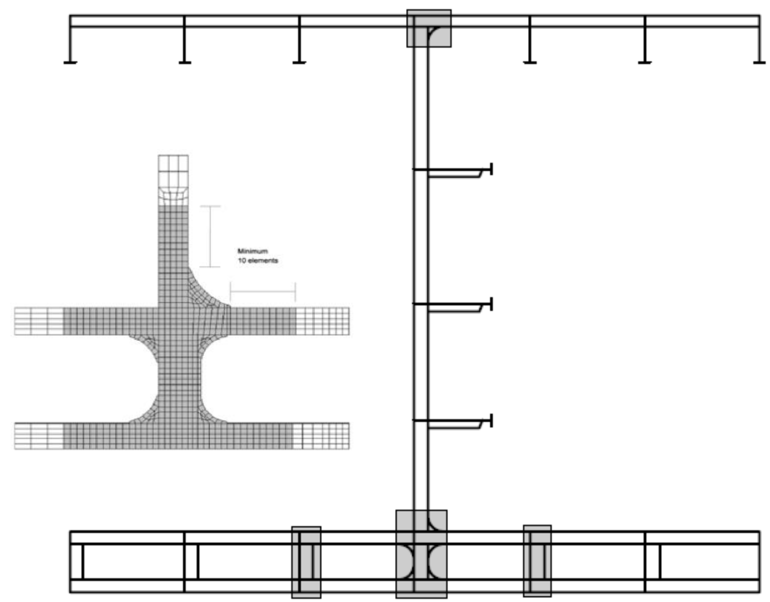


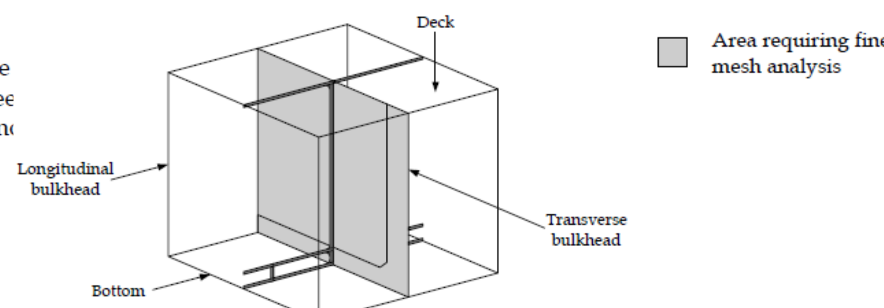
LOCAL FINE MESH STRUCTURAL STRENGTH ANALYSIS

- **Horizontal Stringer and Transverse Bulkhead to Double Bottom Connections**



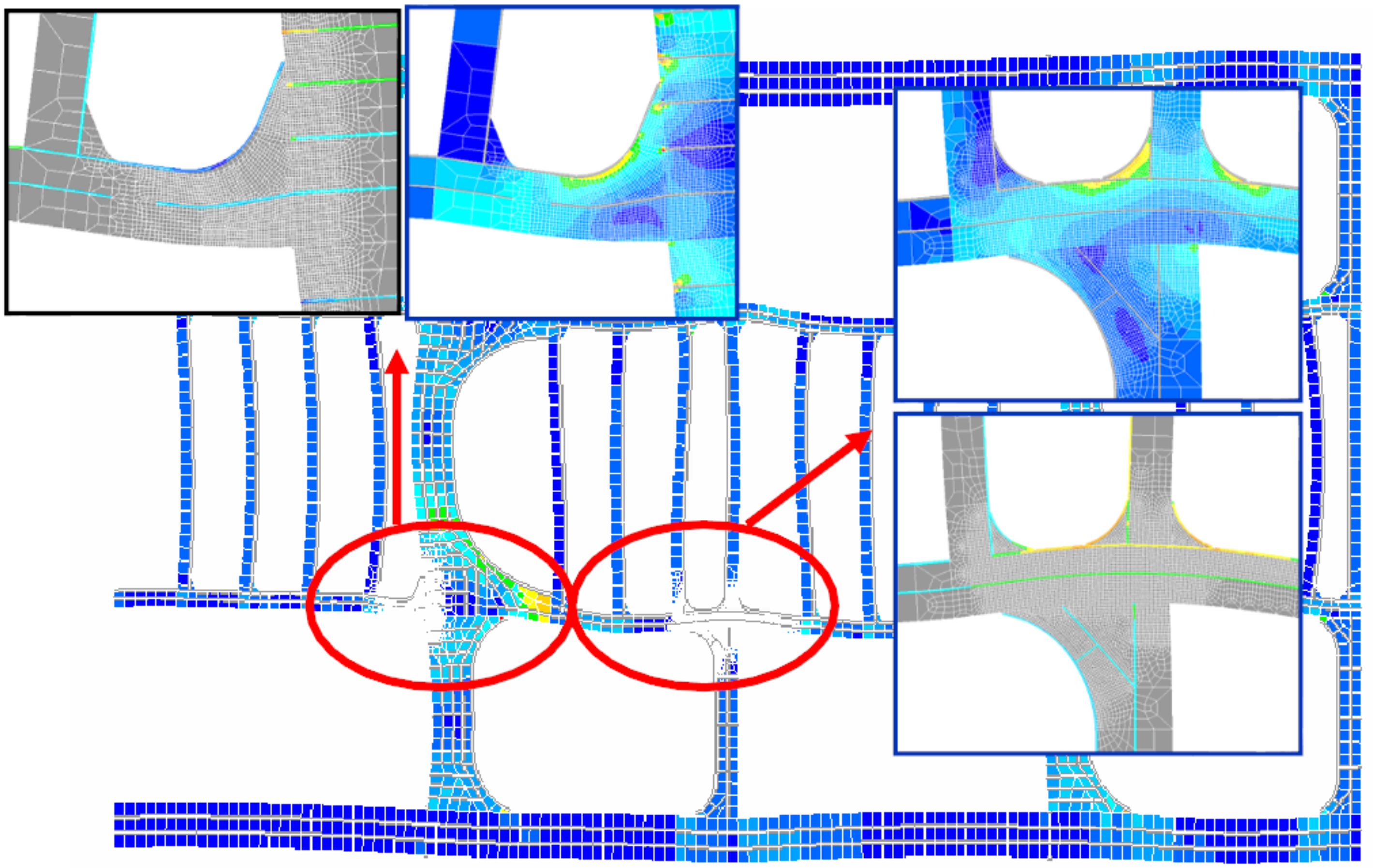






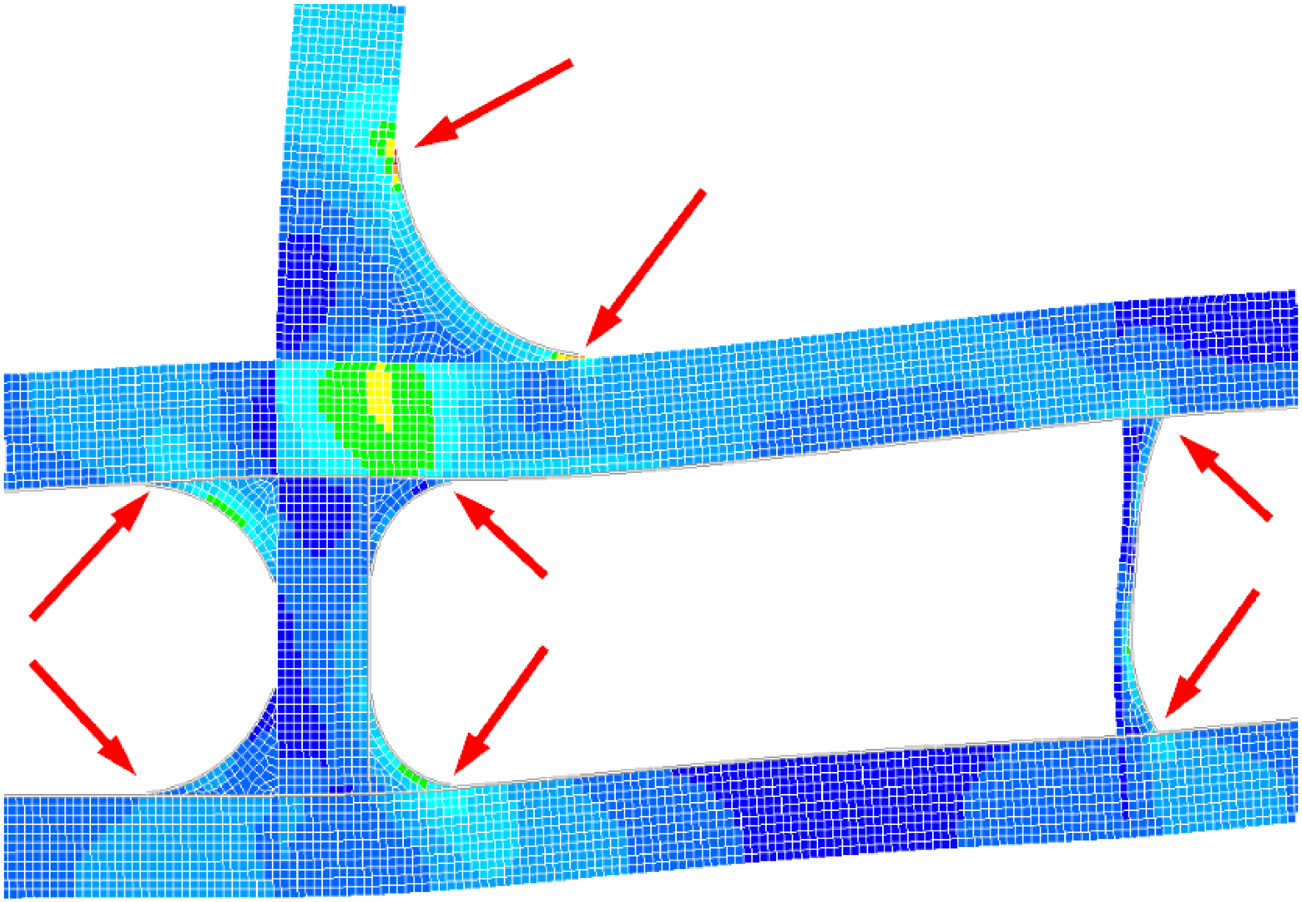
Strength Assessment using FEM

No 2 Stringer (Local Fine Mesh)



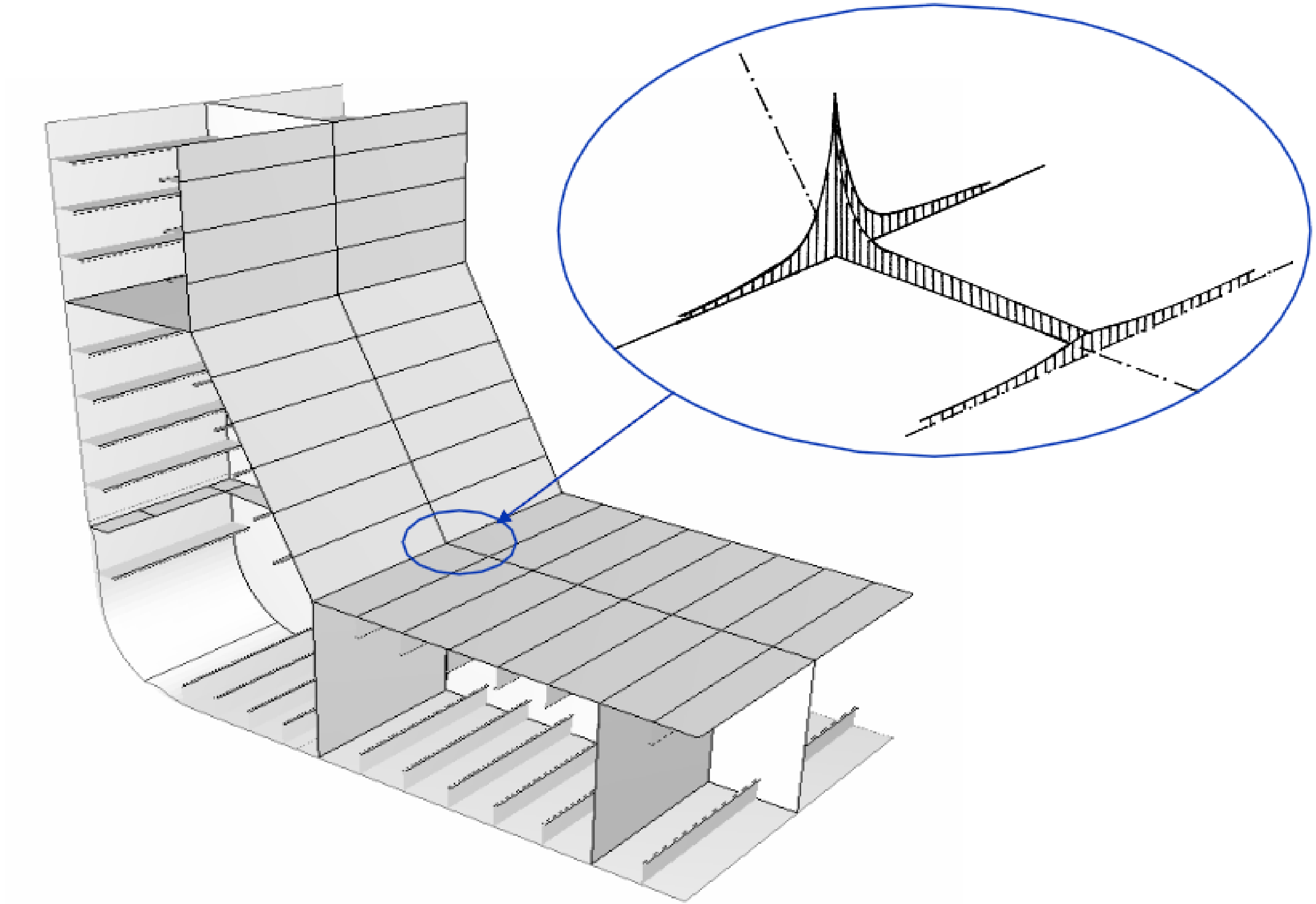
Von-Mises Stress

Double Btm. Longitudinals



Von-Mises Stress

Stress Concentration at Hopper Corner



Max. Permissible Stress

Max. Permissible Stress of Cargo Hold Analysis in CSR

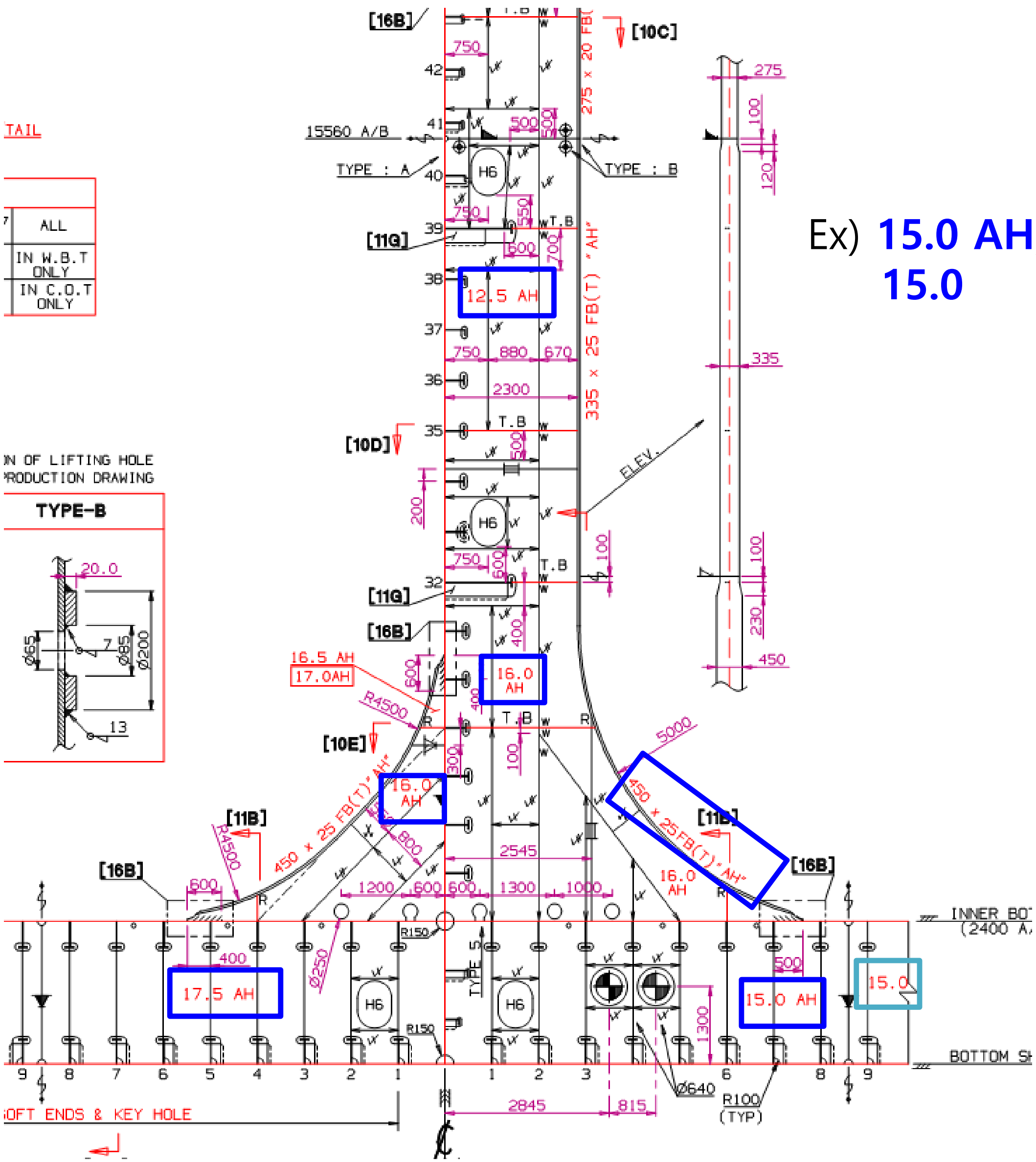
Structural component	Yield utilisation factor
Internal structure in tanks	
Plating of all non-tight structural members including transverse web frame structure, swash bulkheads, internal web, horizontal stringers, floors and girders. Face plate of primary support members modelled using plate or rod elements	$\lambda_y \le 1.0$ (Sea-going load cases, Static + Dynamic Pressure) $\lambda_y \le 0.8$ (Harbour and tank testing load cases, Static Pressure only)
Structure on tank boundaries	
Plating of deck, sides, inner sides, hopper plate, bilge plate, plane and corrugated cargo tank longitudinal bulkheads	$\lambda_y \le 0.9$ (Sea-going load cases) $\lambda_y \le 0.72$ (Harbour and tank testing load cases)
Plating of inner bottom, bottom, plane transverse bulkheads and corrugated bulkheads. Tight floors, girders and webs	$\lambda_y \le 0.8$ (Sea-going load cases) $\lambda_y \le 0.64$ (Harbour and tank testing load cases)

Where:

- λ_y : yield utilisation factor = σ_{vm}/σ_{yd} for plate elements in general
  σ_{rod}/σ_{yd} = for rod elements in general
- σ_{vm} : von Mises stress calculated based on membrane stresses at element's centroid, in N/mm^2
- σ_{rod} : axial stress in rod element, in N/mm^2
- σ_{yd} : specified minimum yield stress of the material, in N/mm^2

Strength Assessment using FEM

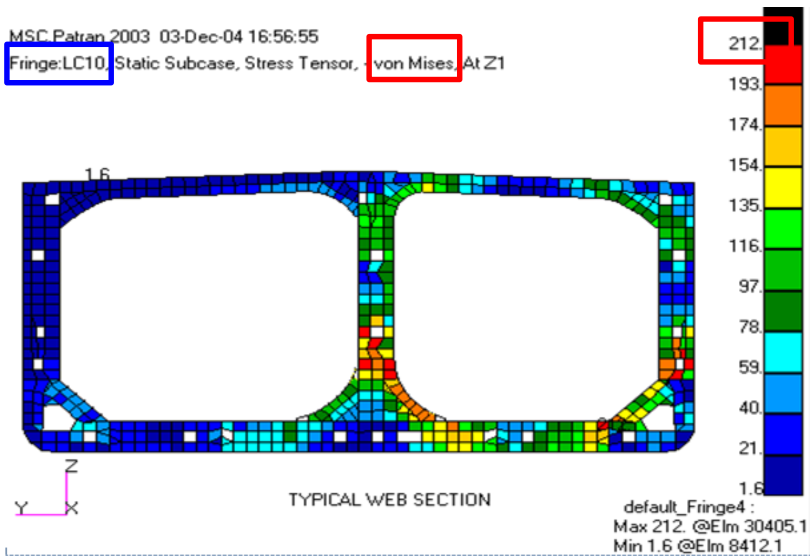
Drawing Example



Ex) **15.0 AH**, High tensile steel, σ_{yd}(=315 MPa)
15.0 , Mild steel, σ_{yd}(=235 MPa)

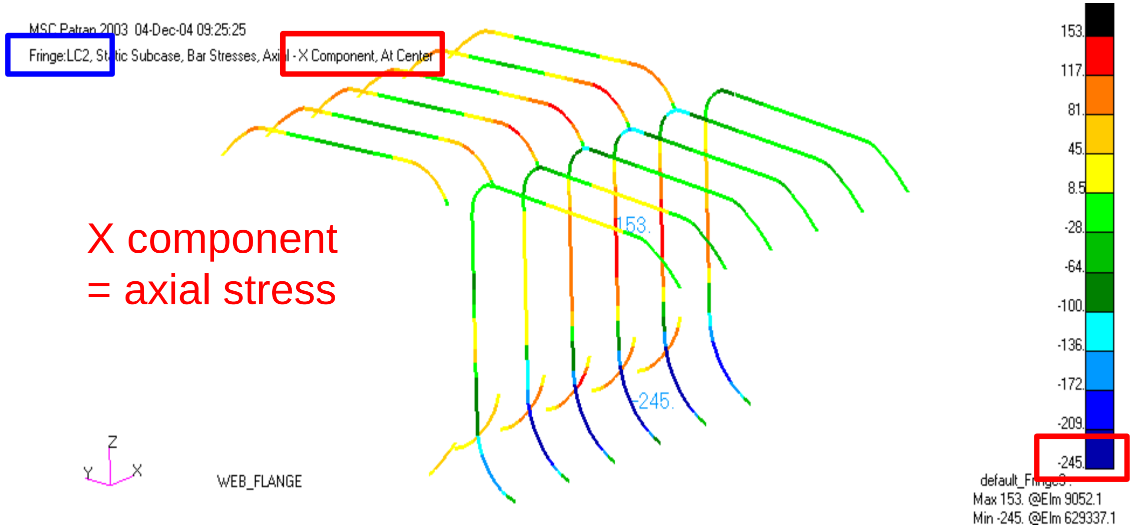
Yield Strength Check

❖ Von Mises stress Distribution, check **Max. stress < Allowable stress**



❖ **Internal structure in tanks**

- Load Case 10
  : Sea going condition
  → $\lambda_y \leq 1.0$
  → $\sigma_{vm} \leq \sigma_{yd}$(=315 AH)
- Max. σ_{vm}(=212 MPa)<315
  Yield strength is satisfied!



X component
= axial stress

❖ **Internal structure in tanks**

- **Load Case 2**
  : Sea going condition
  → $\lambda_y \leq 1.0$
  → $\sigma_{rod} \leq \sigma_{yd}$(=315 AH)
- Max. σ_{rod}(=245 MPa)<315
  Yield strength is satisfied!

Max Permissible Stress of CSR Fine Mesh Analysis

Max. Permissible Stress of Fine Mesh Analysis

Element stress	Yield utilisation factor
Element not adjacent to weld	$\lambda_y \le 1.7$ (Sea-going load cases, Static + Dynamic Pressure) $\lambda_y \le 1.36$ (Harbour and tank testing load cases, Static Pressure only)
Element adjacent to weld	$\lambda_y \le 1.5$ (Sea-going load cases) $\lambda_y \le 1.2$ (Harbour and tank testing load cases)

Where:

λ_y : yield utilisation factor = $k\sigma_{vm}/235$ for plate elements in general

$k\sigma_{rod}/235$ for rod elements in general

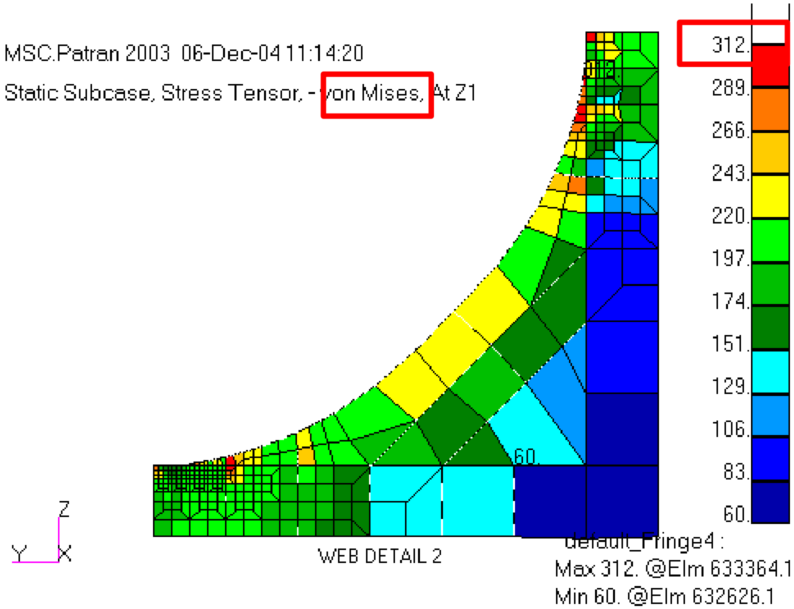
σ_{vm} : von Mises stress calculated based on membrane stresses at element's centroid, in N/mm2

σ_{rod} : axial stress in rod element, in N/mm^2

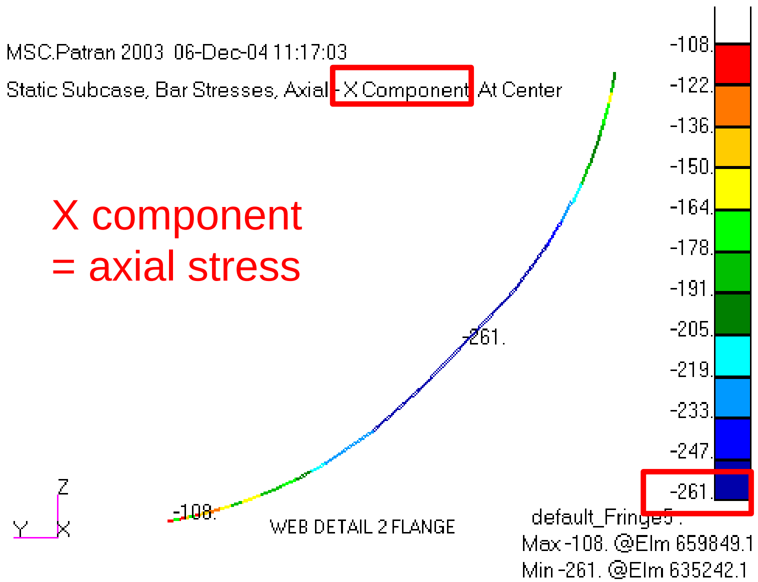
: specified minimum yield stress of the material, in N/mm^2

Specified minimum yield stress, N/mm^2	k
235	1.00
265	0.93
315	0.78
340	0.74
355	0.72
390	0.68

Fine Mesh Analysis



- ❖ **Element adjacent to weld**
  - Sea going condition
    → $\lambda_y \leq 1.5$, σ_{yd}=315 MPa
    → k=0.78
  - $k\ \sigma_{vm}/235$ = 0.78x312/235=1.035
  - Yield strength is satisfied



X component
= axial stress

- ❖ **Element adjacent to weld**
  - Sea going condition
    → $\lambda_y \leq 1.5$, σ_{yd}=315 MPa
    → k=0.78
  - $k\ \sigma_{rod}/235$ = 0.78x261/235=0.866
  - Yield strength is satisfied

Buckling Strength Assessment

❖ Elastic Buckling Analyses and Plasticity correction

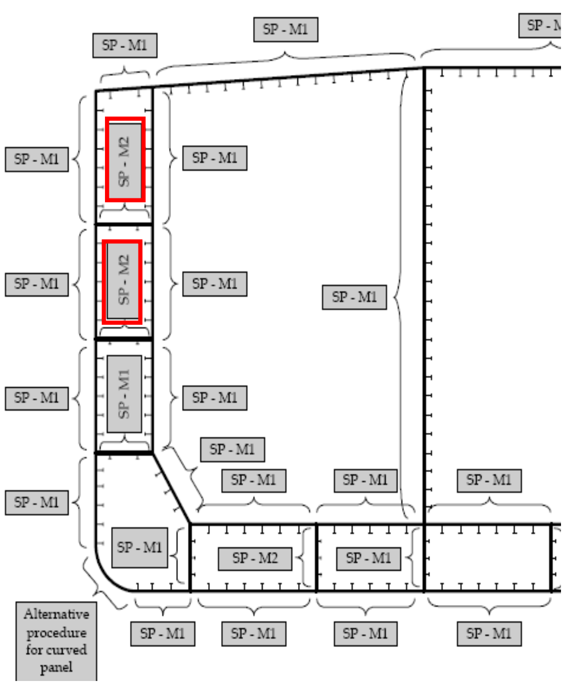
- Uni-axial buckling of plating

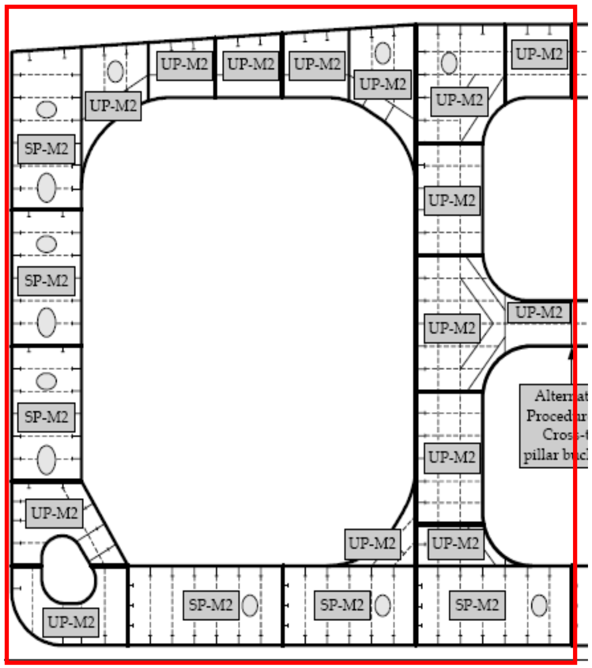
❖ Advanced Buckling Analyses

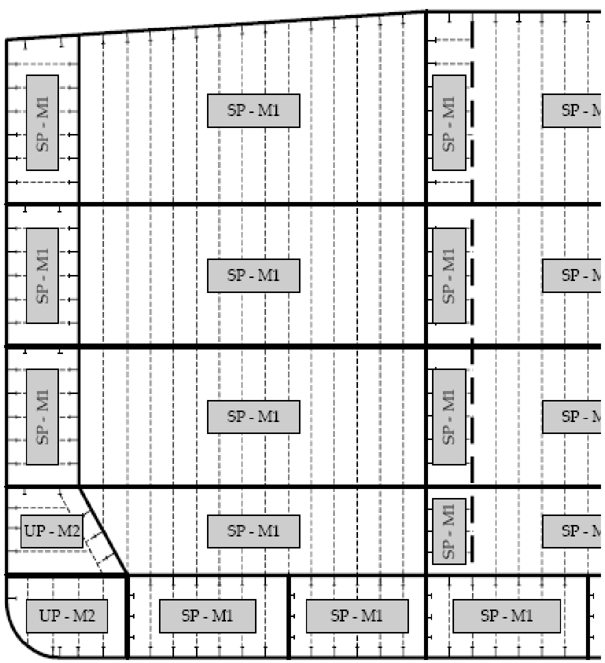
- Geometric nonlinearity
- Material nonlinearity
- initial imperfection
- Welding residual stress
- Interactions between Plate, Stiffener, girders
- Interaction between bi-axial compression, shear lateral pressure
- boundary condition effect

Structural Modeling and Capacity Assessment Method

- SP – M1 : Stiffened panel – Method 1 (with Stress redistribution after local yielding)
- SP – M2 : Stiffened panel – Method 2 (without Stress redistribution after local yielding)
- UP – M2 : Unstiffened panel – Method 2 (without Stress redistribution after local yielding)







PULS – STIFFENED PLATE

❖ STIFFENED PLATE (S3)

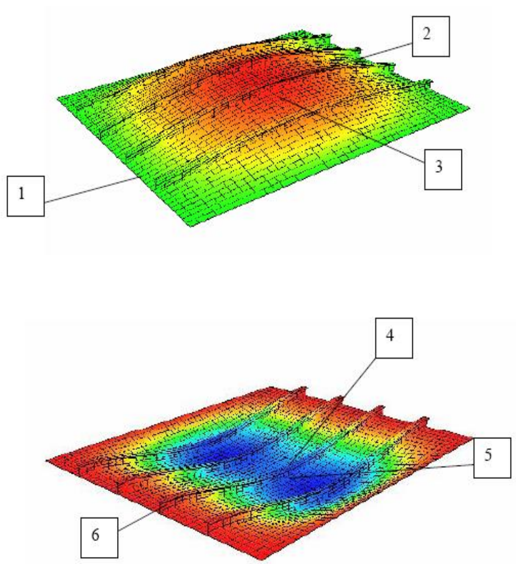
i) Elastic local buckling of a panel is accepted (Local Eigen Value)

- plate buckling, torsional stiffener buckling, stiffener web buckling

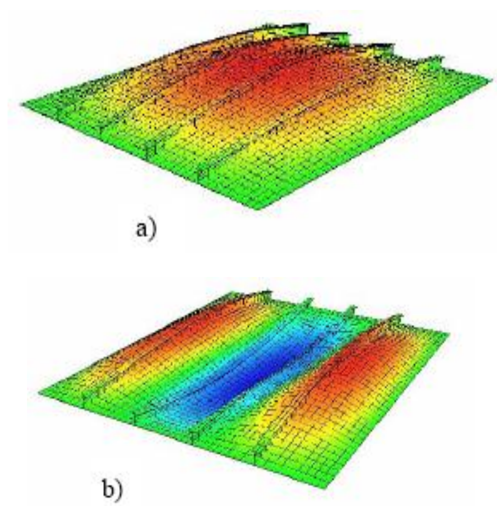
ii) Permanent buckles are not accepted (Ultimate strength evaluation)

- Six limit states

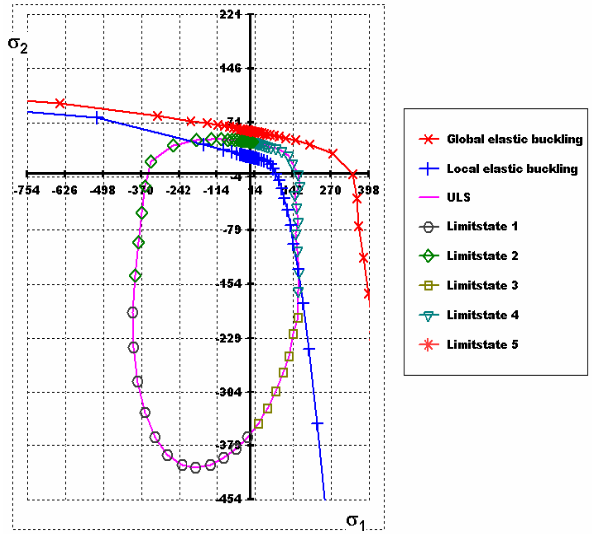
ii) Global buckling is not accepted (Overall Elastic Eigen value)



Ultimate Strength evaluation



Global buckling



Capacity Curve

PULS – UNSTIFFENED PLATE

❖ UNSTIFFENED PLATE (U3)

i) Elastic buckling is accepted

ii) Permanent buckles are not accepted

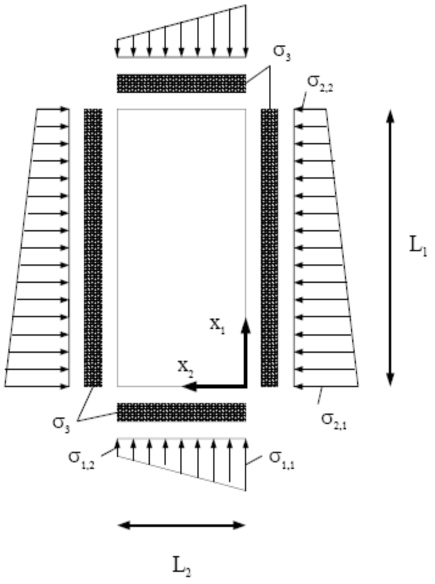
iii) Local eigen value Buckling (LED) calculation

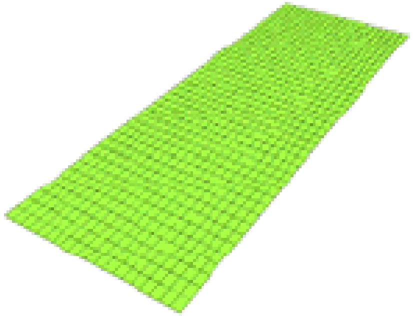
iv) nonlinear postbuckling analysis,

Calculation of Ultimate Capacity (UC)

v) Buckling load = Min. (UC, LED)

vi) Default imperfection to be considered





Selection of Material Grade – Ice Class Ship

❖ **Vessel operated at temperature of -30°C**

Table 1.7 Applications of Material Classes and Grades (Structures Exposed at Low Temperature)

Structural member category	Material class	
	Within 0.4L amidships	Outside 0.4L amidships
<u>SECONDARY:</u> Deck plating exposed to weather, in general Side plating above BWL Transverse bulkheads above BWL	I	I
<u>PRIMARY:</u> Strength deck plating[1] Continuous longitudinal hatch coamings Longitudinal bulkhead above BWL Top wing tank bulkhead above BWL	II	I
<u>SPECIAL:</u> Sheer strake at strength deck[2] Stringer plate n strength deck[2] Deck strake at longitudinal bulkhead[3] Continuous longitudinal hatch coamings[4]	III	II

Selection of Material Grade – Ice Class Ship

❖ **Table 1.8 Material Grade Requirements for Classes, I, II and III at Low Temperature**

Table 1.8 Class I

Plate thickness, in mm	−20/−25℃ MS	−20/−25℃ HT	−26/−35℃ MS	−26/−35℃ HT	−36/−45℃ MS	−36/−45℃ HT	−46/−55℃ MS	−46/−55℃ HT
t ≤ 10	A	AH	B	AH	D	AH	D	AH
10 < t ≤ 15	B	AH	D	DH	D	AH	D	AH
15 < t ≤ 20	B	AH	D	DH	D	AH	E	AH
20 < t ≤ 25	D	DH	D	DH	D	AH	E	AH
25 < t ≤ 30	D	DH	D	DH	E	EH	E	AH
30 < t ≤ 35	D	DH	D	DH	E	EH	E	AH
35 < t ≤ 45	D	DH	E	EH	E	EH	ϕ	AH
45 < t ≤ 50	E	EH	E	EH	ϕ	AH	ϕ	AH

ϕ =Not applicable

Selection of Material Grade – Ice Class Ship

❖ **Material Grade Requirements for Classes, I, II and III at Low Temperature**

Table 1.8 Class II

Plate thickness, in mm	−20/−25℃		−26/−35℃		−36/−45℃		−46/−55℃	
	MS	HT	MS	HT	MS	HT	MS	HT
t ≤ 10	B	AH	D	AH	D	DH	E	EH
10 < t ≤ 20	D	DH	D	DH	E	EH	E	EH
20 < t ≤ 30	D	DH	E	DH	E	EH	ϕ	FH
30 < t ≤ 40	E	EH	E	DH	ϕ	FH	ϕ	FH
40 < t ≤ 45	E	EH	ϕ	FH	ϕ	FH	ϕ	ϕ
45 < t ≤ 50	E	EH	ϕ	FH	ϕ	FH	ϕ	ϕ

ϕ = Not applicable

Selection of Material Grade – Ice Class Ship

❖ **Material Grade Requirements for Classes, I, II and III at Low Temperature**

Table 1.8 Class III

Plate thickness,	−20/−25℃		−26/−35℃		−36/−45℃		−46/−55℃	
in mm	MS	HT	MS	HT	MS	HT	MS	HT
t ≤ 10	D	DH	D	DH	E	EH	E	EH
10 < t ≤ 20	D	DH	E	EH	E	EH	ϕ	FH
20 < t ≤ 25	E	EH	E	EH	ϕ	FH	ϕ	FH
25 < t ≤ 30	E	EH	E	EH	ϕ	FH	ϕ	FH
30 < t ≤ 35	E	EH	ϕ	FH	ϕ	FH	ϕ	ϕ
35 < t ≤ 45	E	EH	ϕ	FH	ϕ	FH	ϕ	ϕ
45 < t ≤ 50	ϕ	FH	ϕ	FH	ϕ	ϕ	ϕ	ϕ

ϕ =Not applicable

Selection of Material Grade – Ice Class Ship

❖ Steel grade of LNGC

- Temperature distribution can be obtained from a heat transfer analysis of LNGC carrying LNGS of -163℃
- Steel grade is determined from the temperature distribution and Table1.7,Table1.8 and IGC Code(Table1.9)

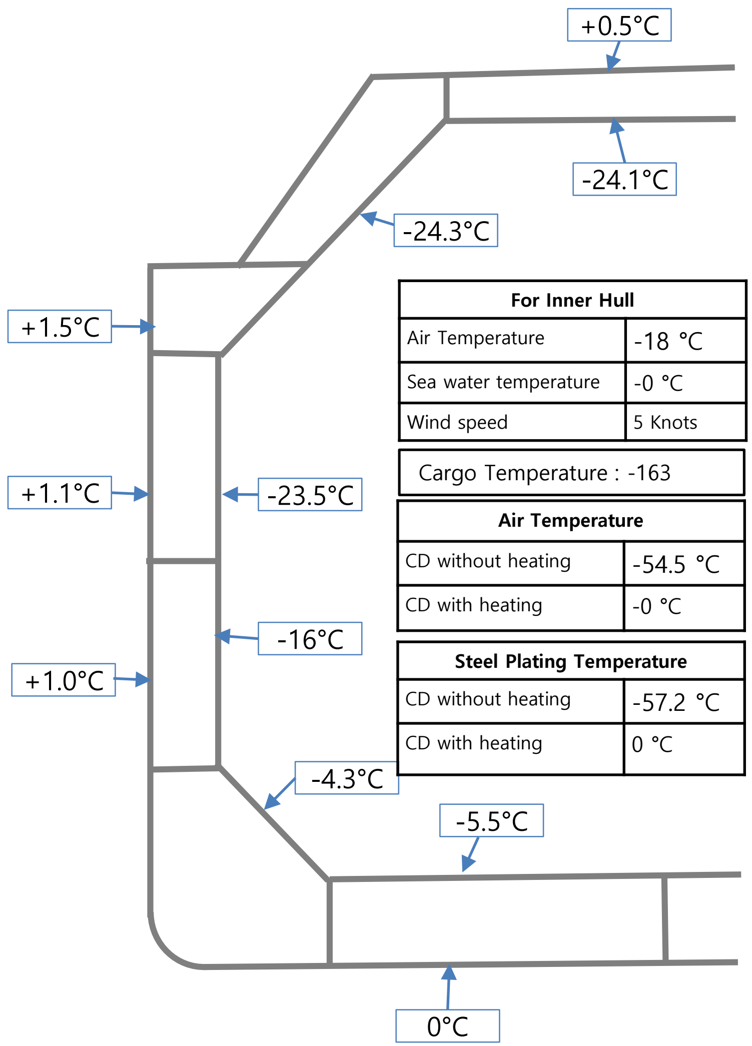
Selection of Material Grade – Ice Class Ship

Plates and Sections for Hull Structures Required by IGC 4.9.1 and 4.9.4

Minimum design temperature of hull structure (°C)	Maximum thickness (mm) for steel grades in accordance with **601. 9**						
	A	B	D	E	AH	DH	EH
0 and above(1) -5 and above(2)	Normal practice						
down to -5	15	25	30	50	25	45	50
down to -10	×	20	25	50	20	40	50
down to -20	×	×	20	50	×	30	50
down to -30	×	×	×	40	×	20	40
Below -30	In accordance with **Table 7.5.4** except that the thickness limitation given in **Table 7.5.4** and in footnote (2) of that table does not apply.						

Notes: "x" means steel grade not to be used.
(1) For the purpose of **409. 4**
(2) For the purpose of **409. 1**

Selection of Material Grade – Ice Class Ship



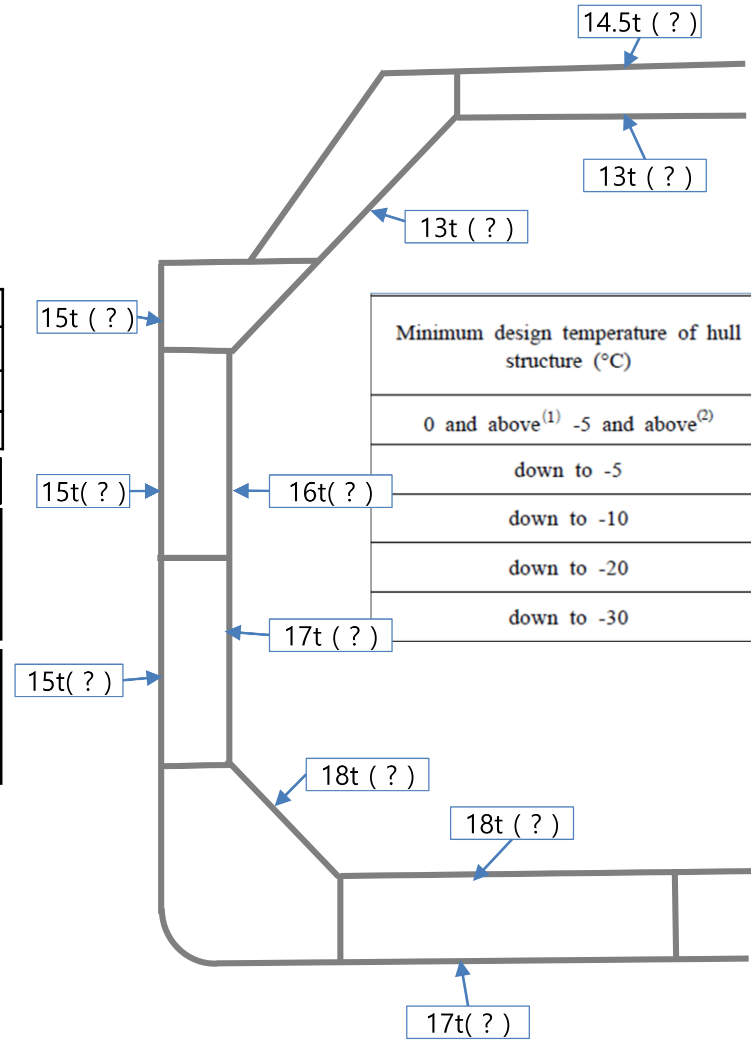
For Inner Hull	
Air Temperature	-18 °C
Sea water temperature	-0 °C
Wind speed	5 Knots

Cargo Temperature : -163

Air Temperature	
CD without heating	-54.5 °C
CD with heating	-0 °C

Steel Plating Temperature	
CD without heating	-57.2 °C
CD with heating	0 °C

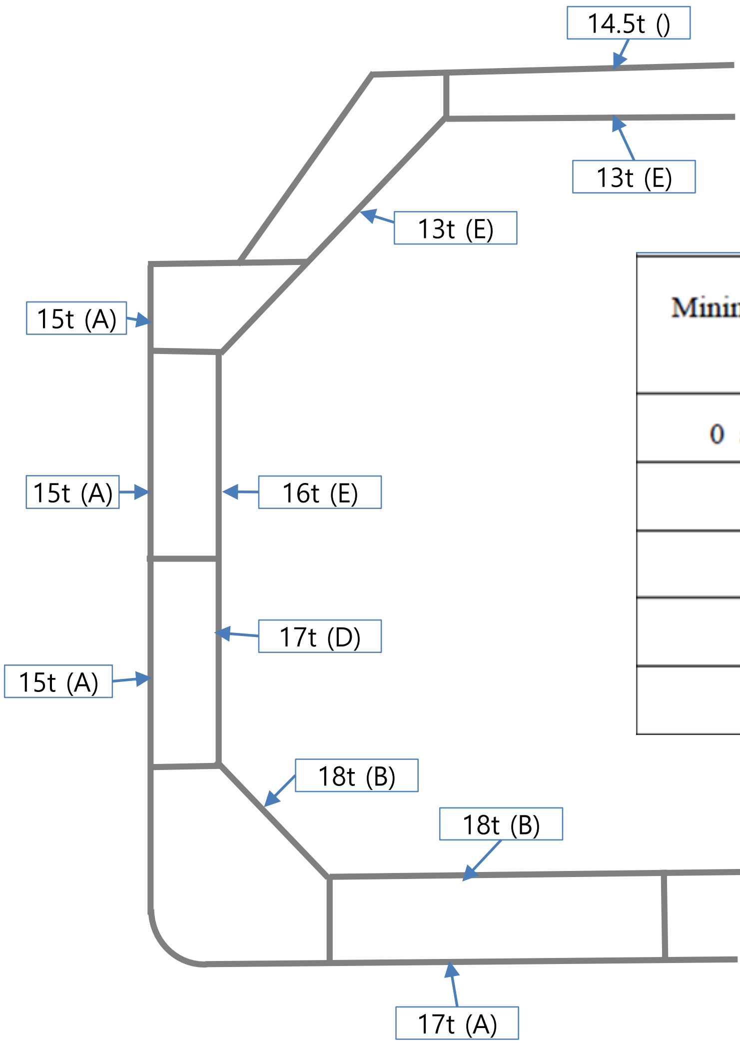
Temperature Distribution from Heat Transfer Analysis



Minimum design temperature of hull structure (°C)	Maximum thickness (mm)			
	A	B	D	E
0 and above[1] -5 and above[2]				
down to -5	15	25	30	50
down to -10	×	20	25	50
down to -20	×	×	20	50
down to -30	×	×	×	40

Material Selection

Selection of Material Grade – Ice Class Ship



Minimum design temperature of hull structure (°C)	Maximum thickness (mm)			
	A	B	D	E
0 and above(1) -5 and above(2)				
down to -5	15	25	30	50
down to -10	×	20	25	50
down to -20	×	×	20	50
down to -30	×	×	×	40