Topics in Ship Structures

04 Low Cycle Fatigue for Welded Joint – Design Rules

Reference : DNV30.7

2017. 9

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OPen INteractive Structural Lab

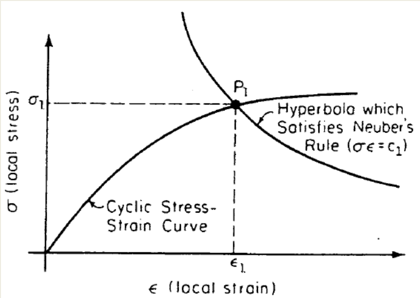
Strain-Life Approach

Applied Load P

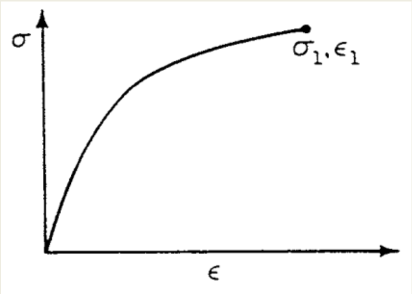
$$S = \frac{P}{A}$$

Nominal Stress range ΔS

Neuber's rule



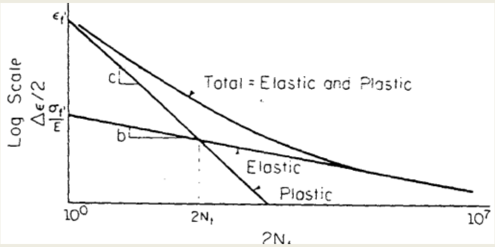
Cyclic Stress-Strain Curve



True Stress range $\Delta\sigma$

True Strain range $\Delta\varepsilon$

Strain-life Curve



N_f : fatigue life

Stress-Life Approach

Linear elastic stress by FEA $\Delta\sigma_{elastic}(=K_t\Delta S)$

⇩

True Stress range $\Delta\sigma_{hs}$

⇩

True Strain range $\Delta\varepsilon_{hs}$

⇩

Pseudo Stress range $\Delta\sigma_{pseudo}(E\Delta\varepsilon_{hs})$

⇩

Stress redistribution factor

⇩

N_f : fatigue life

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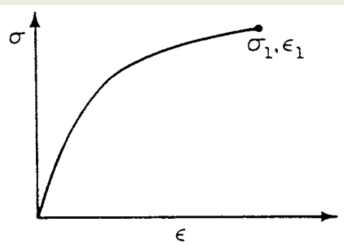
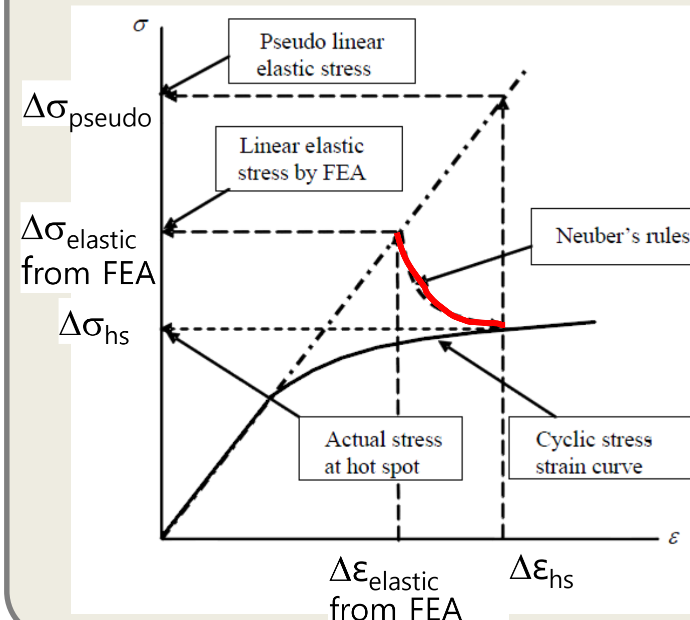


Neuber's rule



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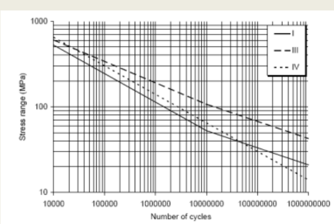
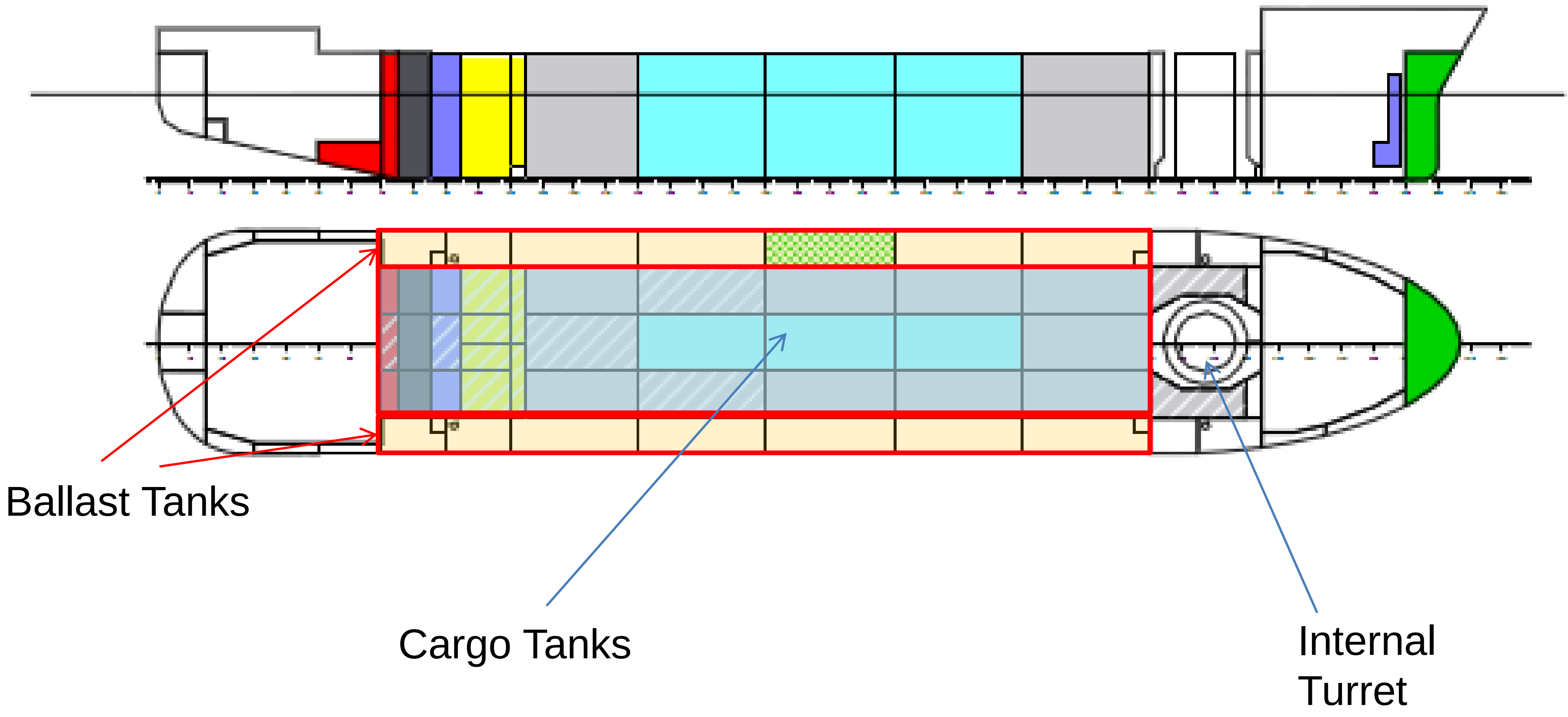
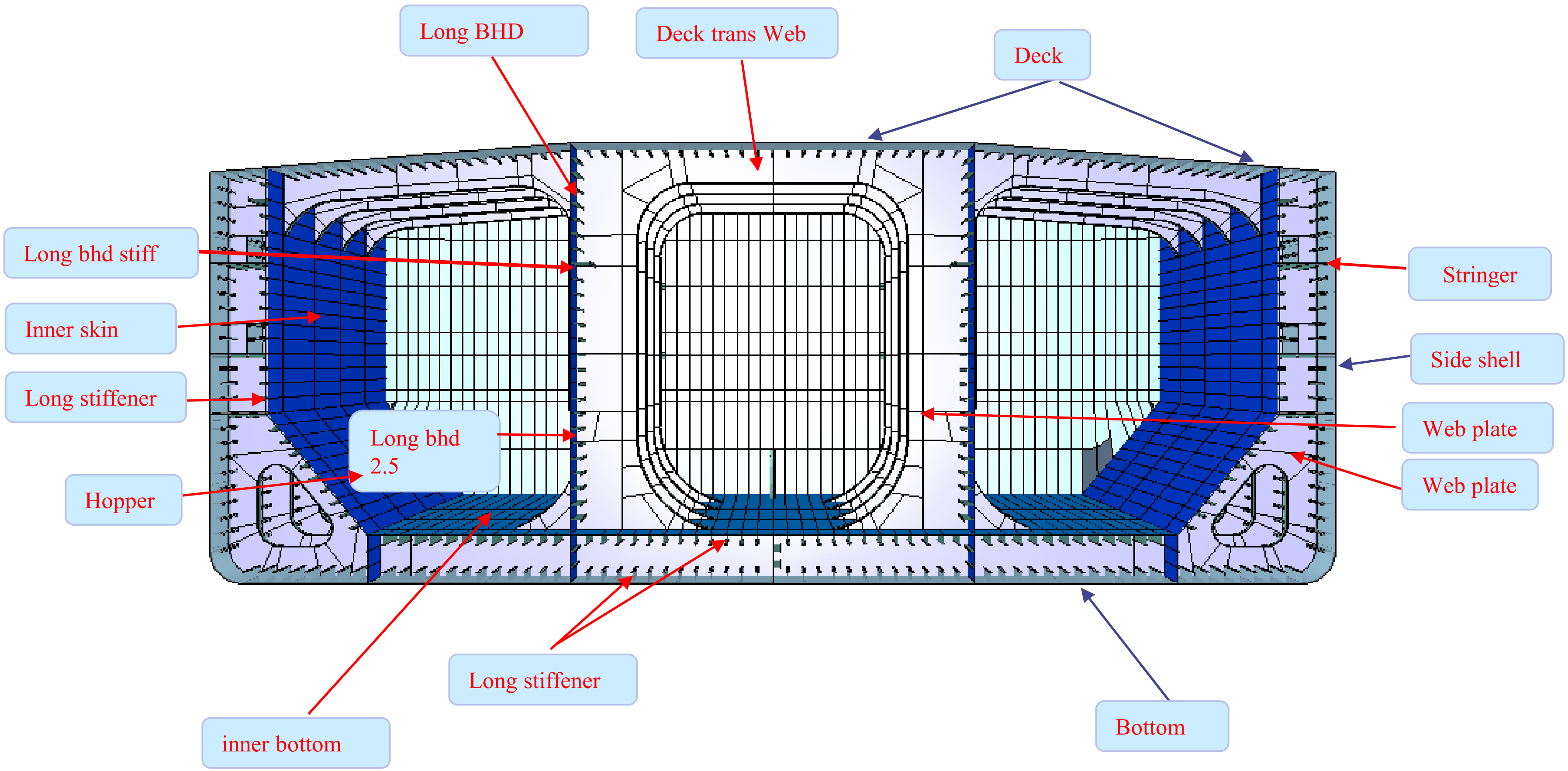


Tank Arrangement



Midship Part



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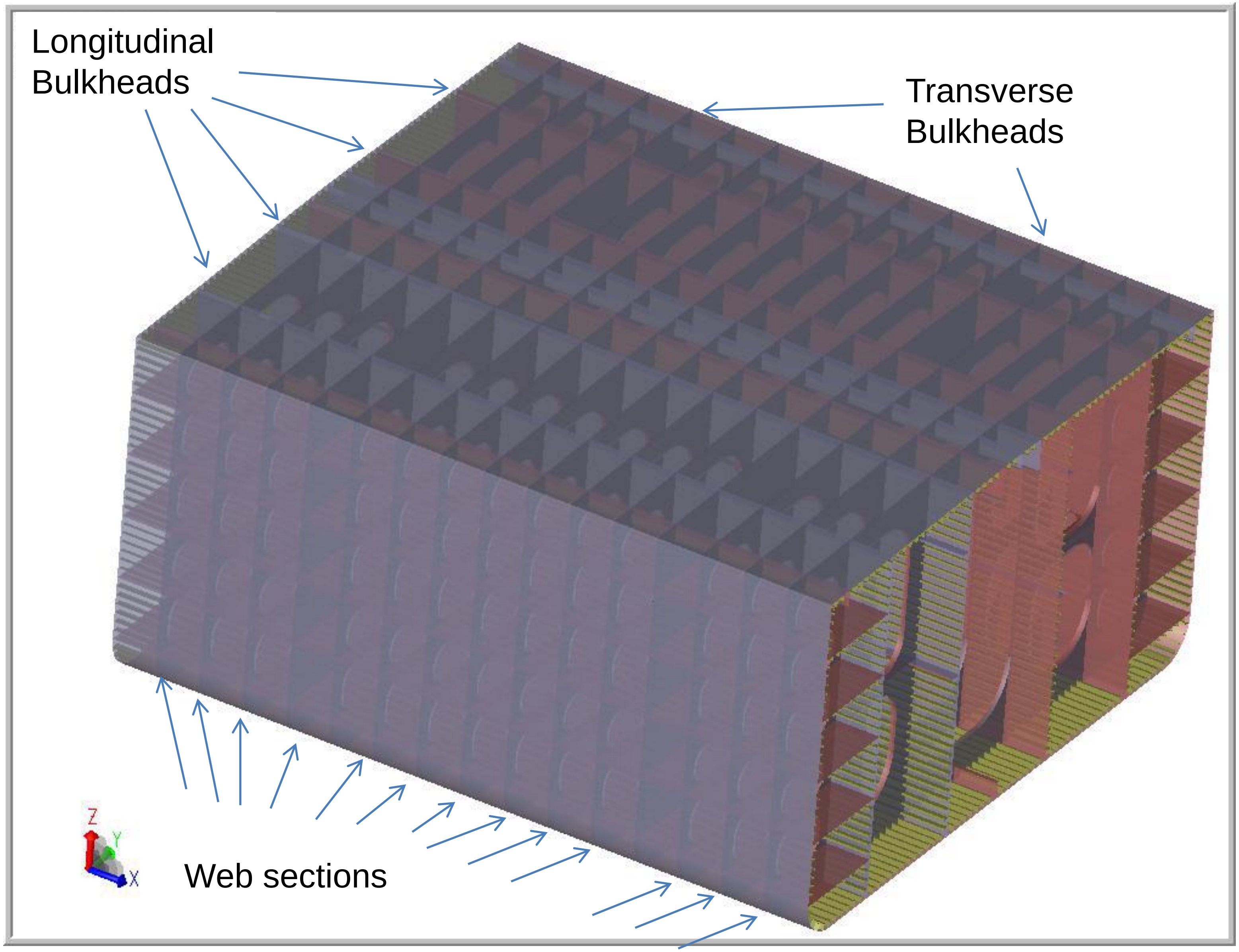

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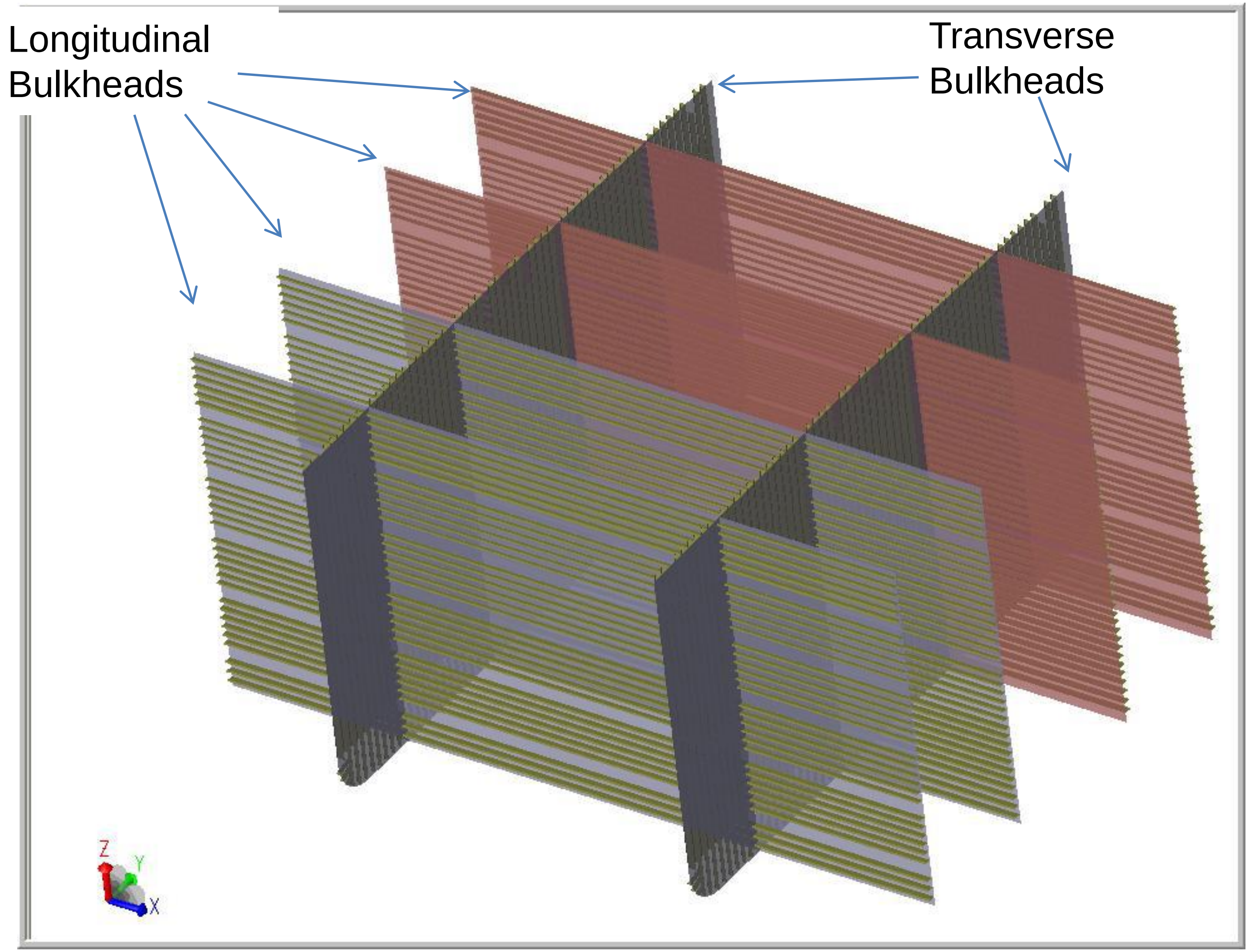
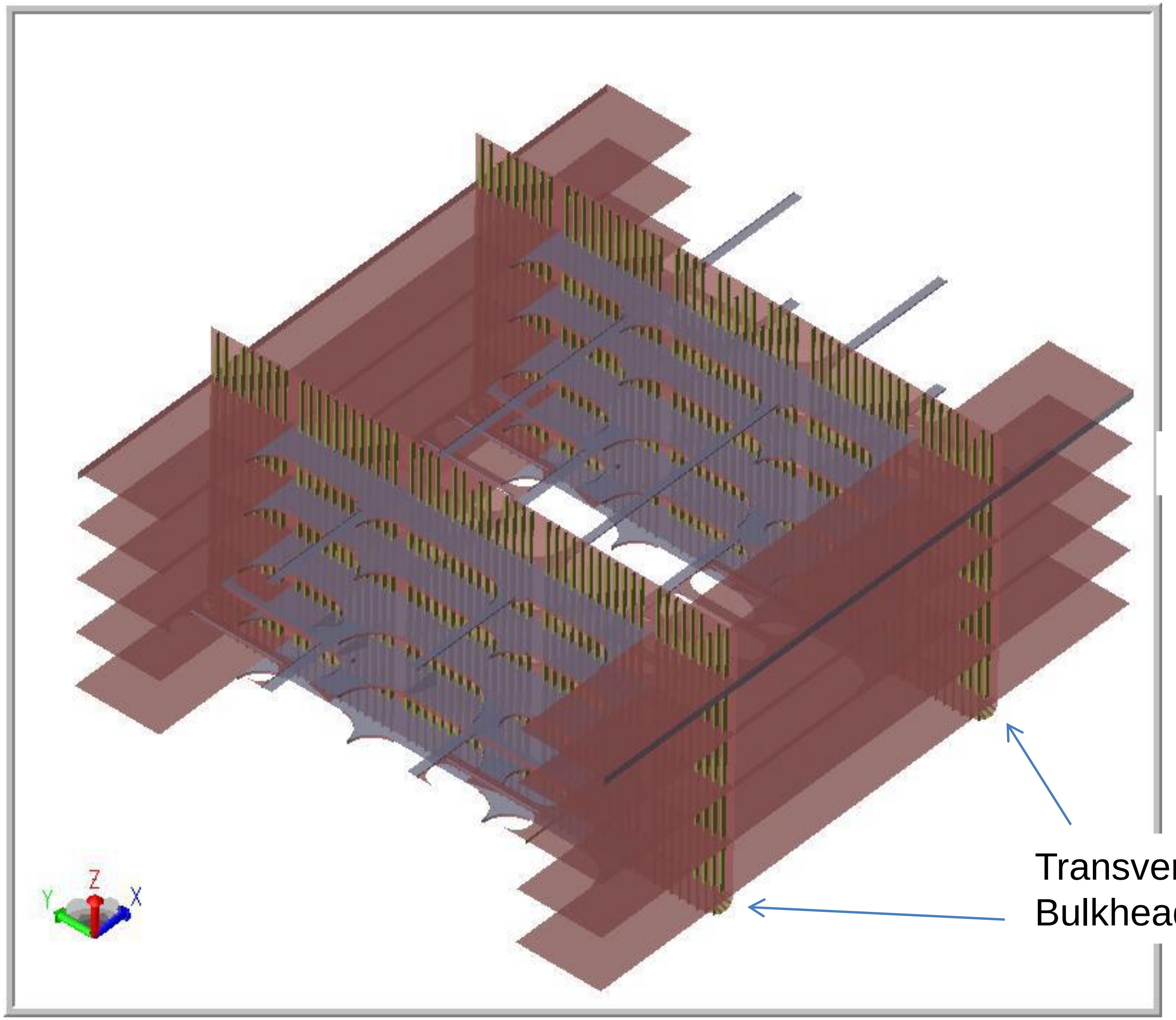


Horizontal Stringers



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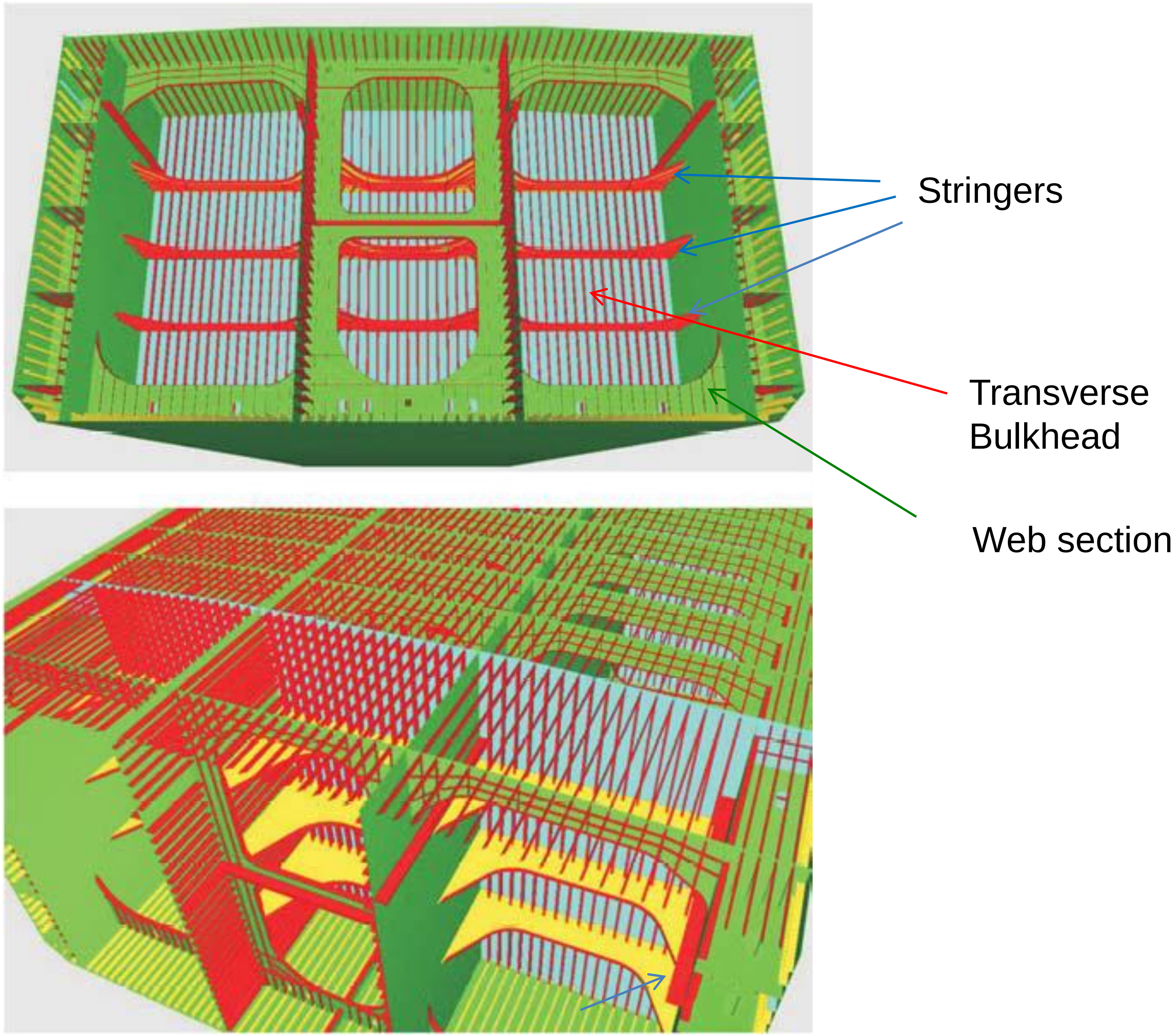
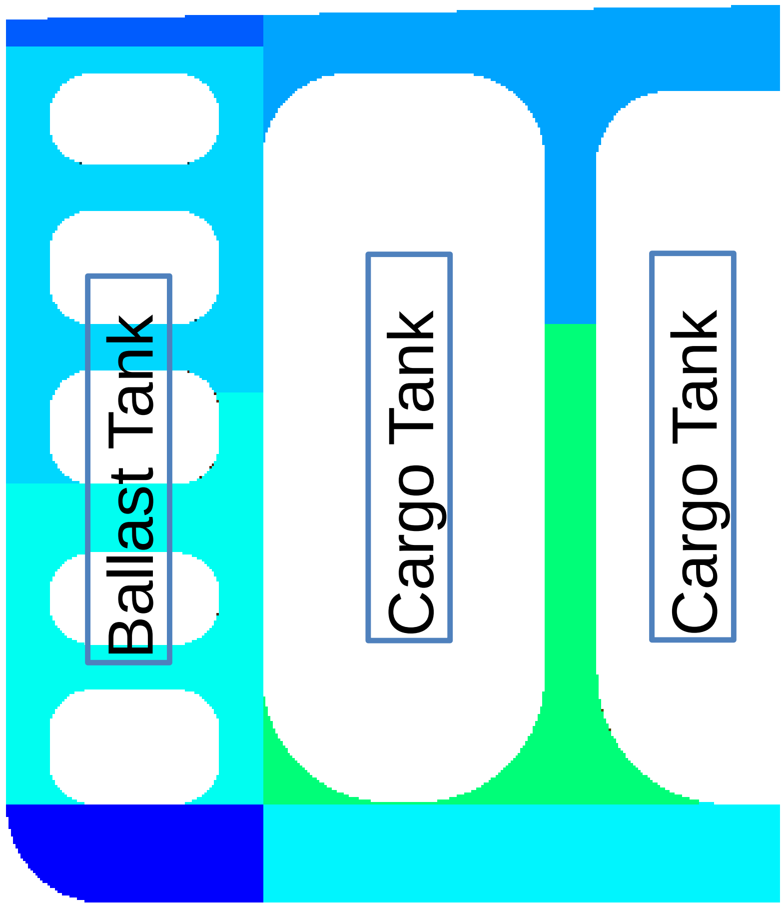
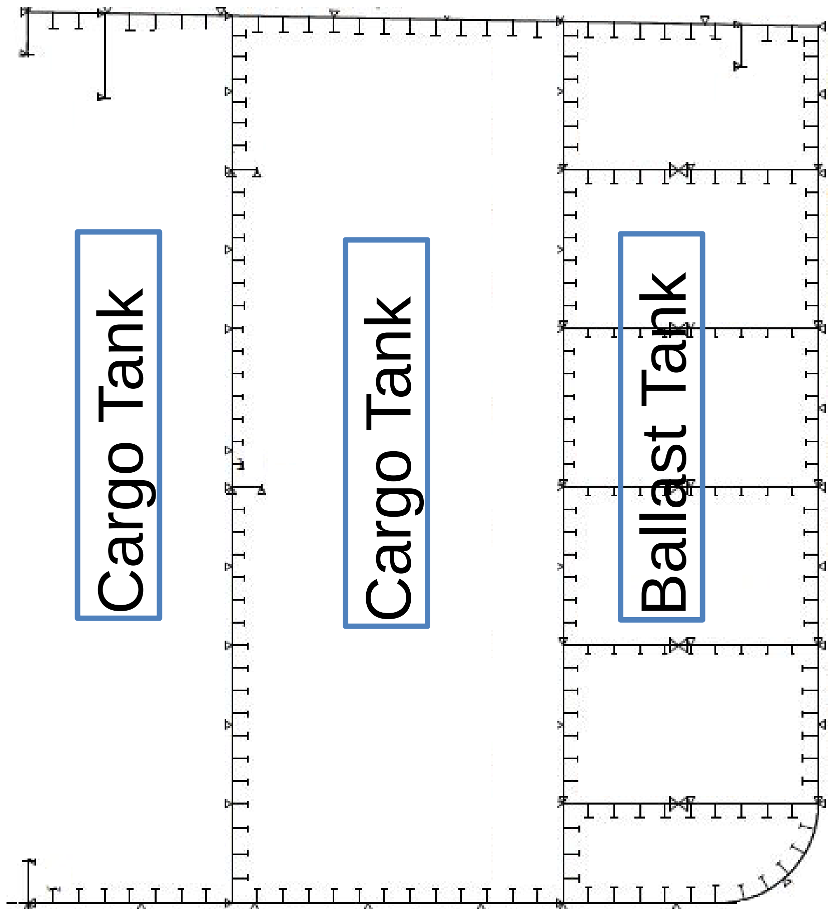


Web Sections

Web Section

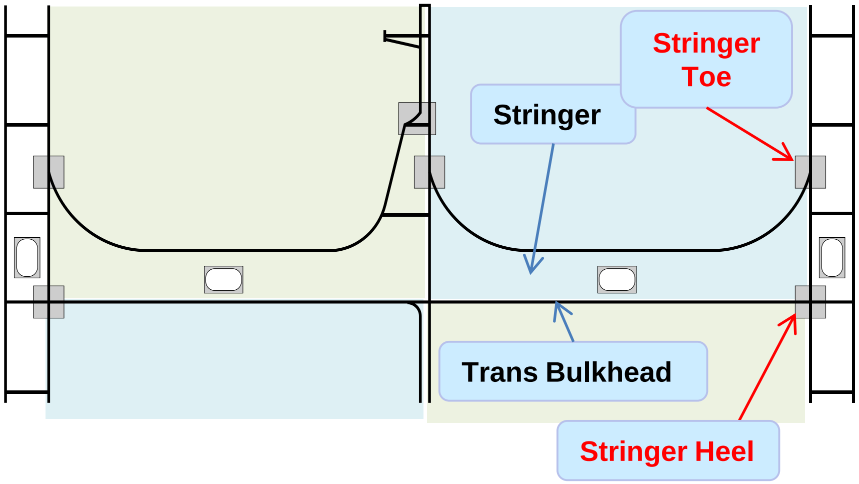


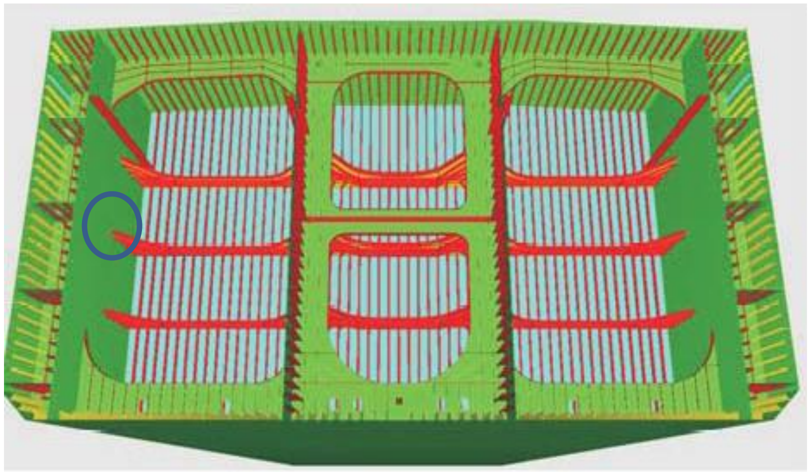
Ordinary Section

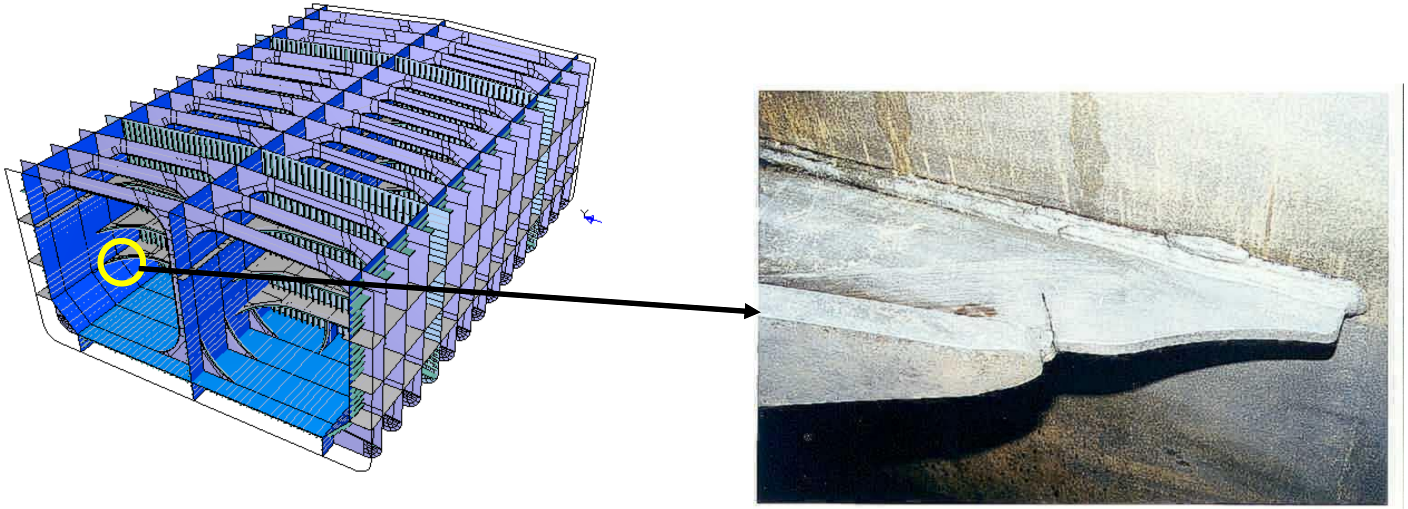


Critical locations for low cycle fatigue

- Heel and toe of horizontal stringer of transverse bulkhead







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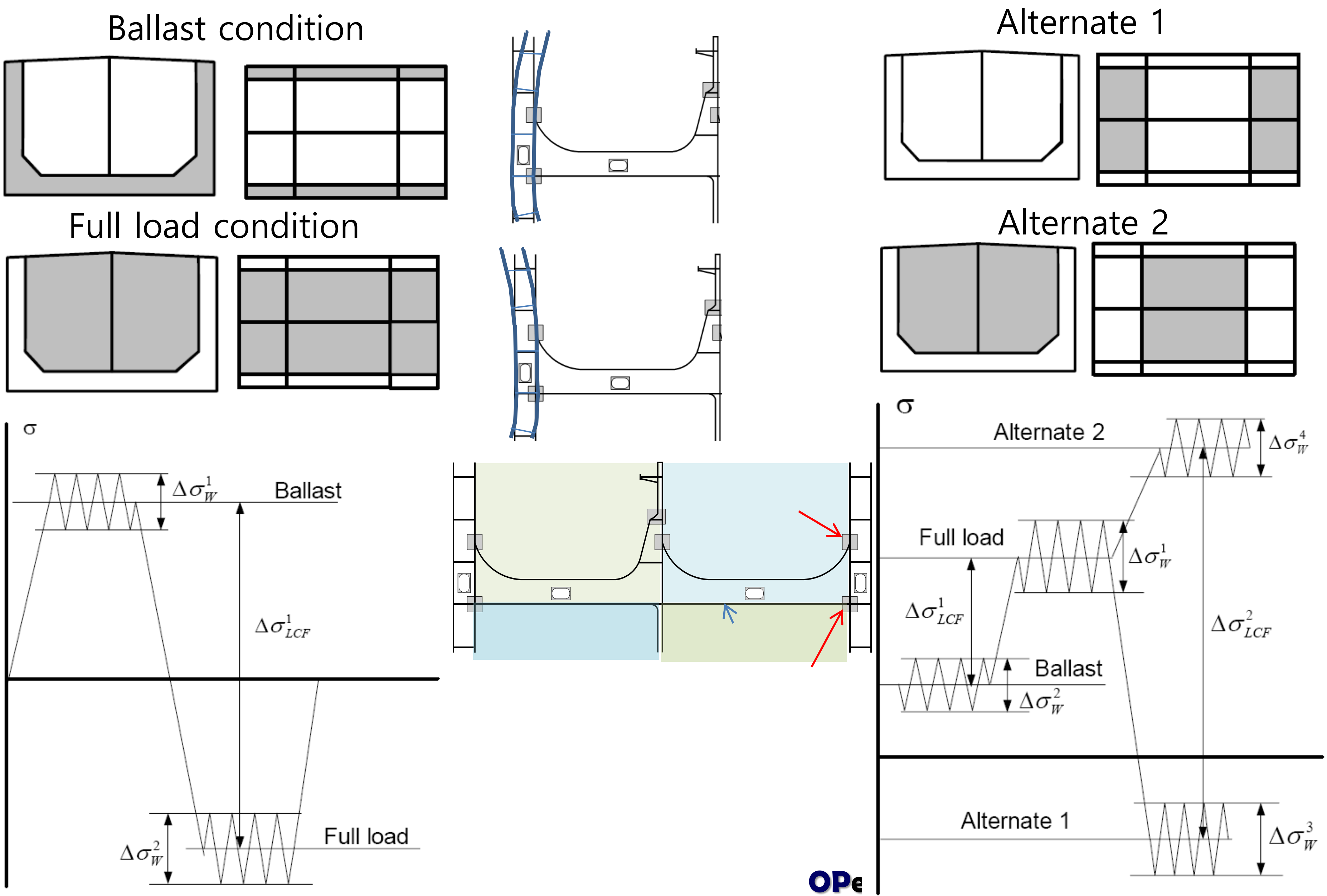
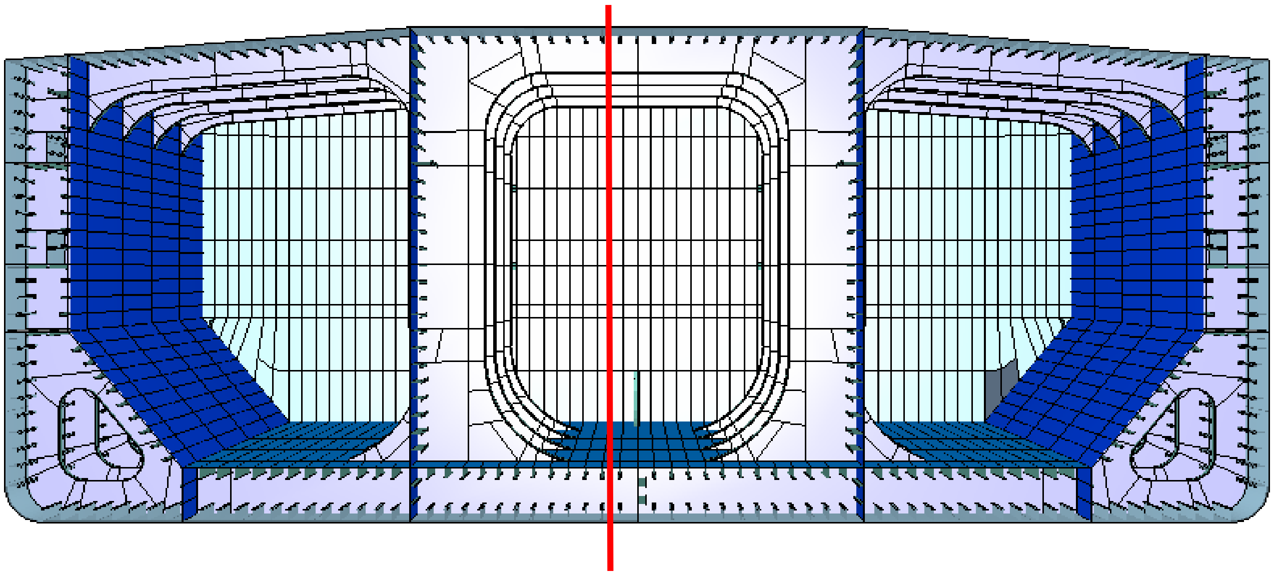
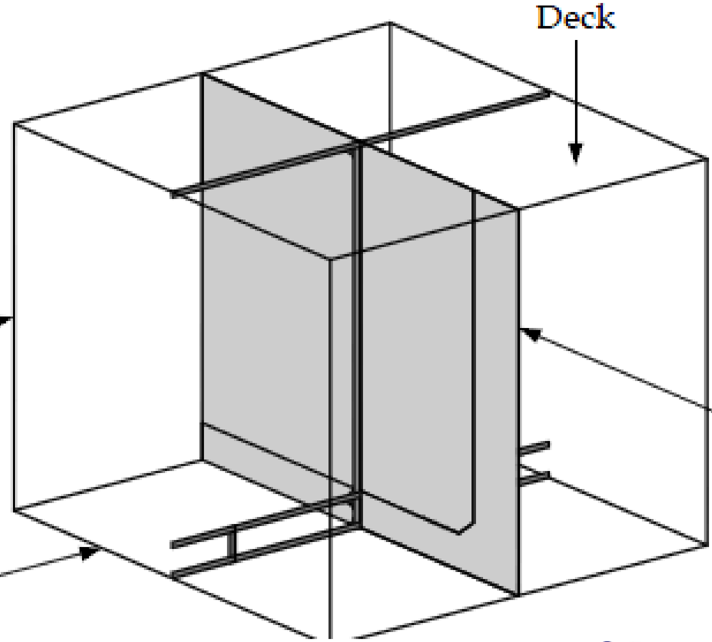


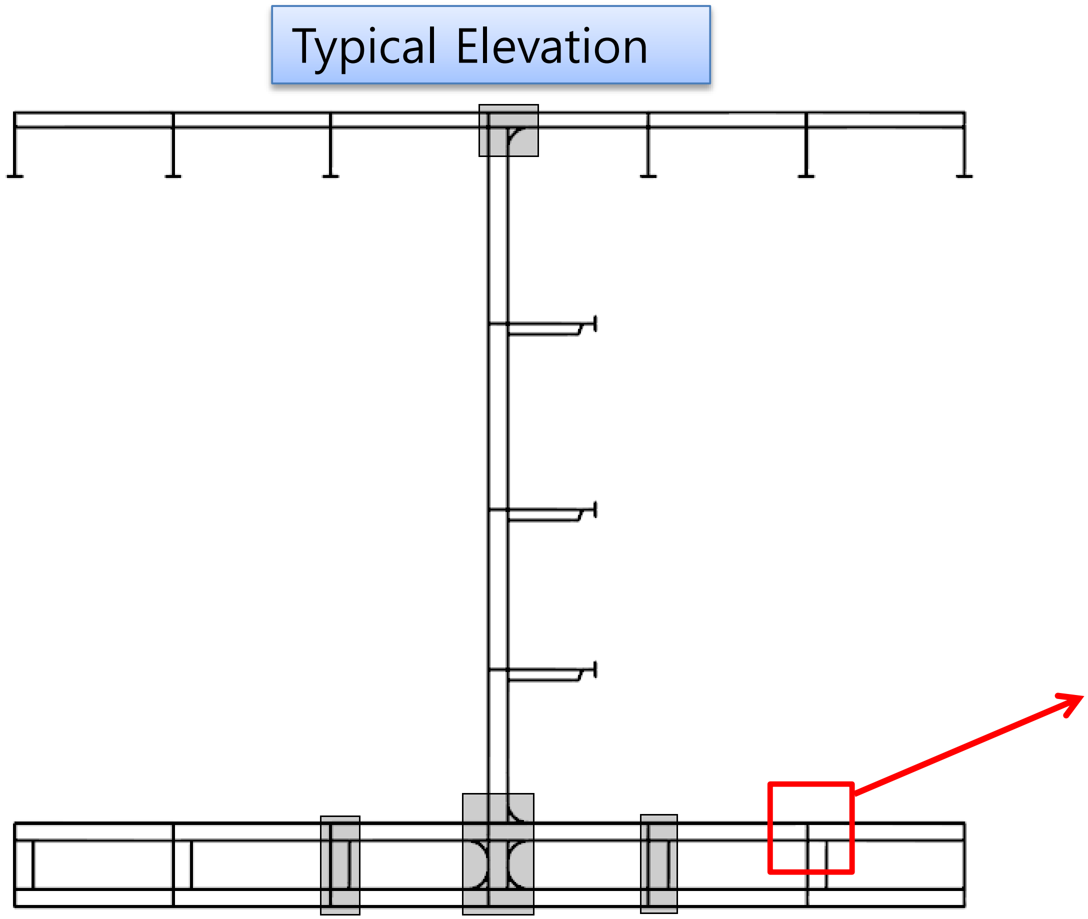
Critical locations for low cycle fatigue

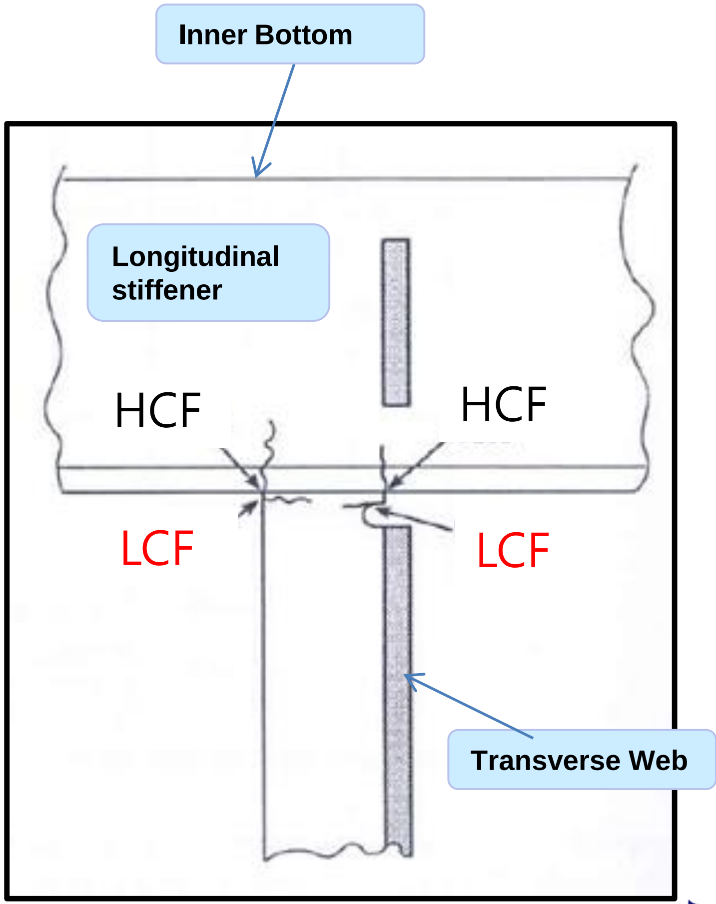




Critical locations for low cycle fatigue

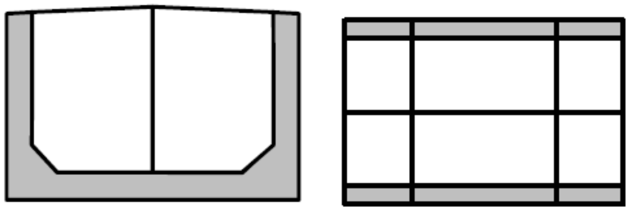
- Web stiffener on top of inner bottom longitudinal.



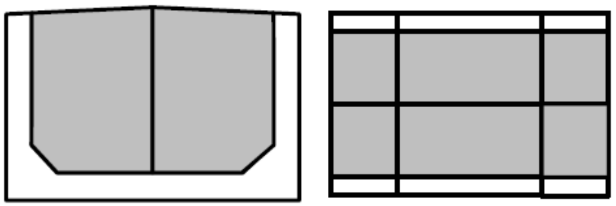


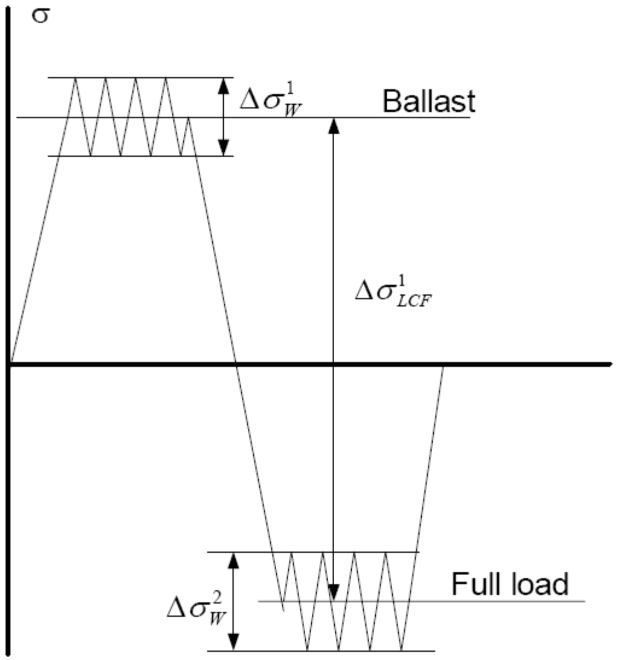
Critical locations for low cycle fatigue

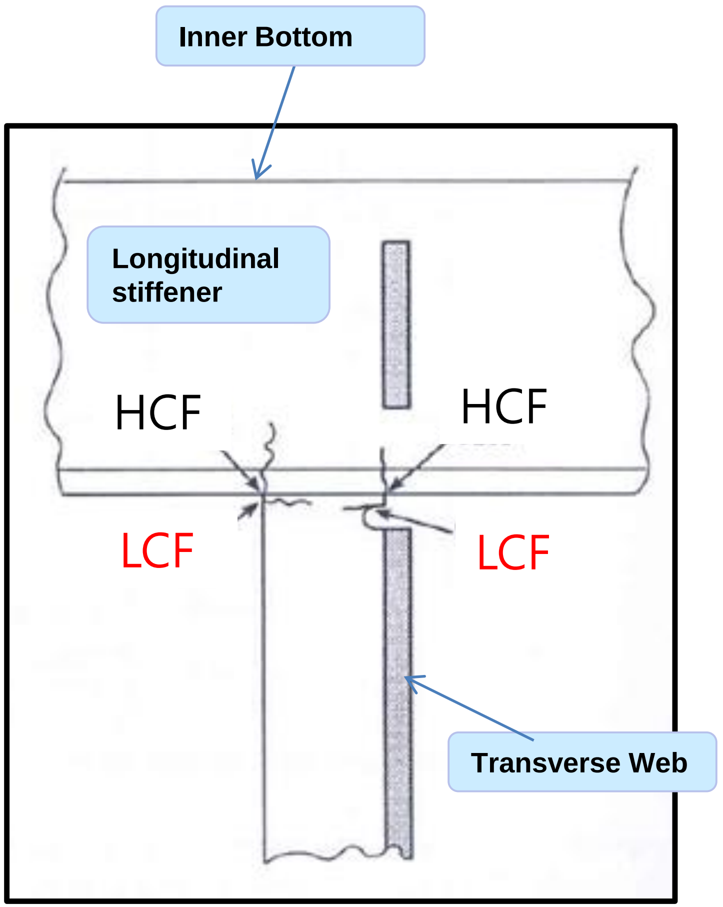
Ballast condition



Full load condition

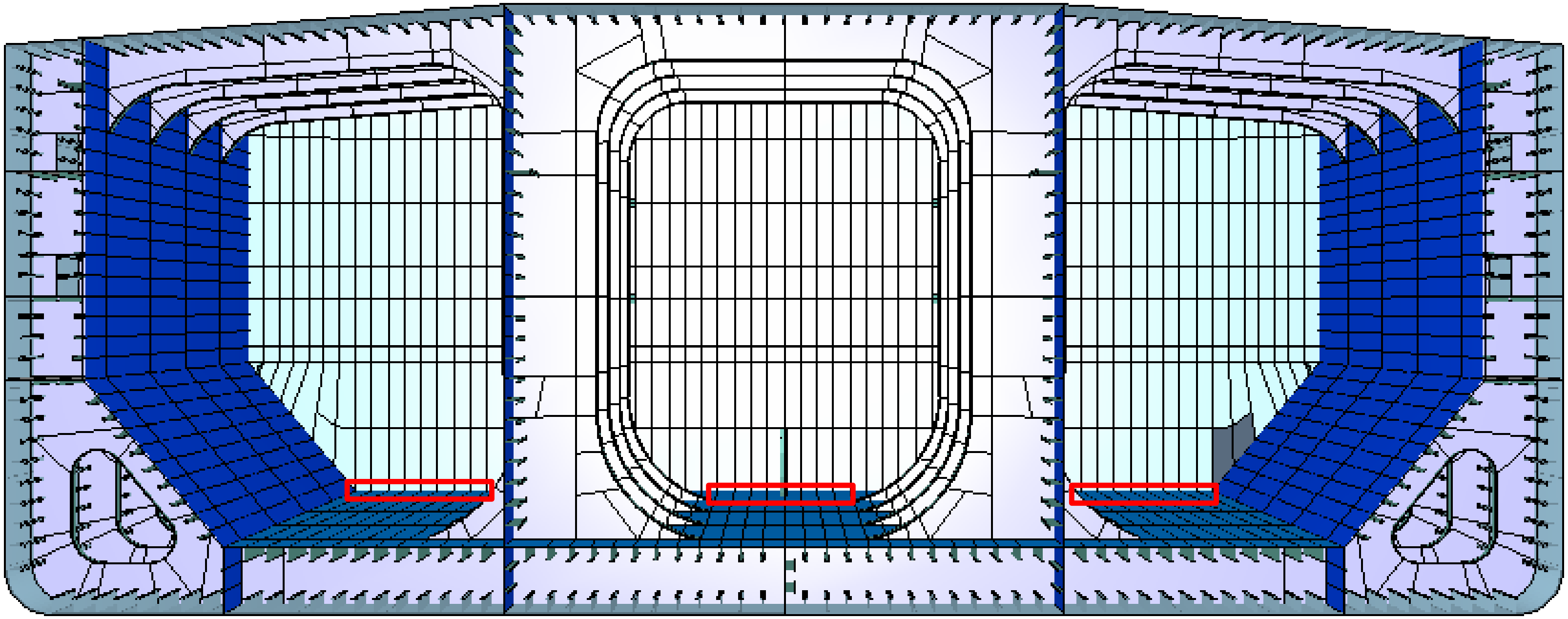




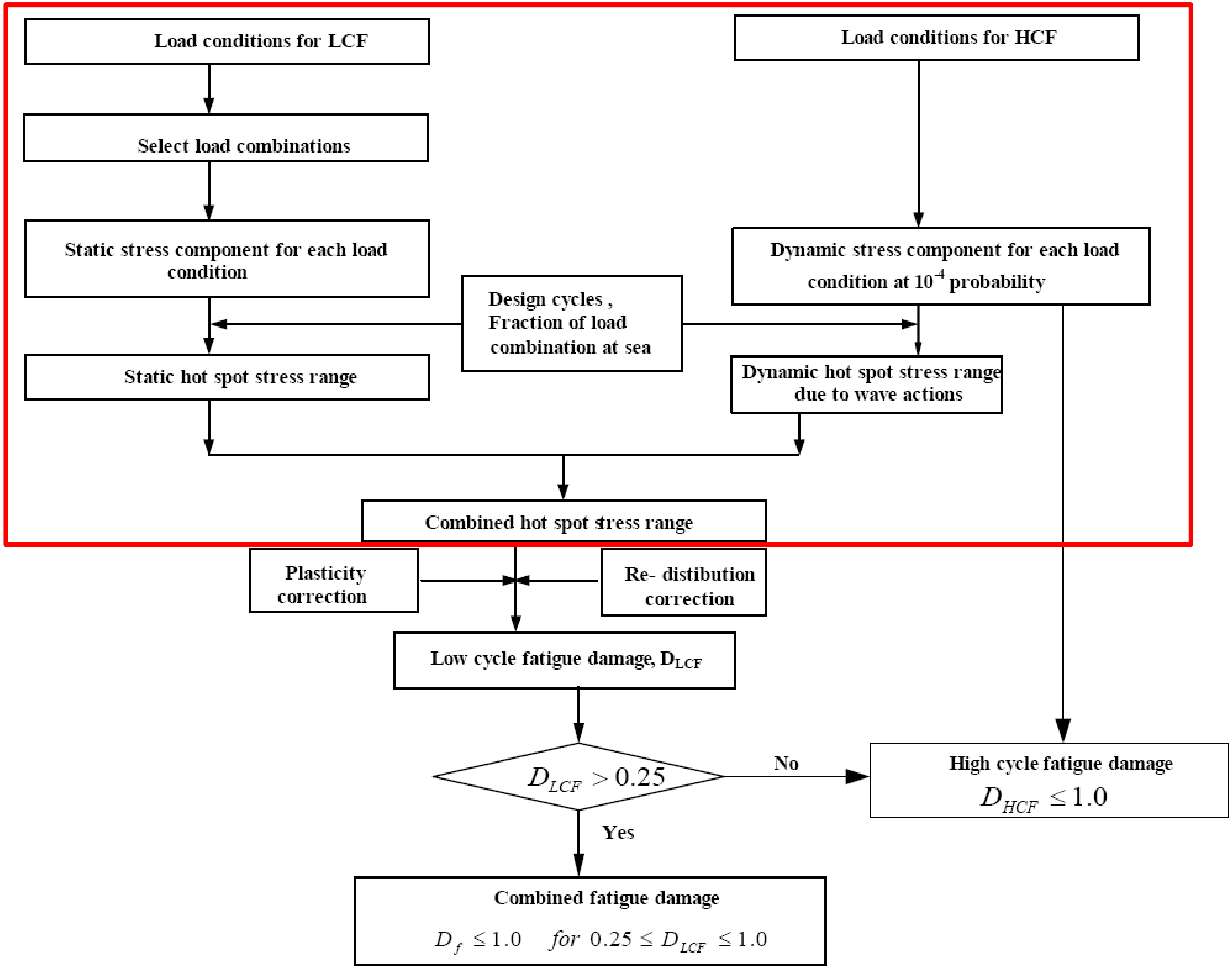


Critical locations for low cycle fatigue

- Inner bottom connection to transverse bulkhead



General



Load conditions for LCF
Select load combinations
Static stress component for each load condition
Static hot spot stress range
Load conditions for HCF
Dynamic stress component for each load condition at 10^{-4} probability
Design cycles , Fraction of load combination at sea
Dynamic hot spot stress range due to wave actions
Combined hot spot stress range
Plasticity correction
Re- distibution correction
Low cycle fatigue damage, D_{LCF}
$D_{LCF} > 0.25$
No
Yes
High cycle fatigue damage
$D_{HCF} \le 1.0$
Combined fatigue damage
$D_f \le 1.0 \quad for\ 0.25 \le D_{LCF} \le 1.0$

Load conditions for assessment

- Low cycle fatigue is mainly due to mainly loading and unloading of cargoes and ballast. Quasi-static load.

  (HCF is caused by Wave loading $n_{HCF}=10^8$, number of waves encountered during 20 years, average period = 7 sec)

- The number of design cycles may vary depending on the ship in operation

Ship Type	Recommended Cycle, n_{LCF}
Tankers over 120,000 TDW	500
Tankers below 120,000 TDW	600
Chemical tankers	1,000
LNG carriers	800
LPG carriers	800
Shuttle tankers	1,200

Hot spot stress range for low cycle fatigue

- Static elastic hot spot stress range for load combination *k* for low cycle fatigue

$$\Delta\sigma_{LCF}^{k} = \left|\sigma_s^i - \sigma_s^j\right|$$

$\Delta\sigma_{LCF}^{k}$ = static hot spot stress range for the *k*-th load combination between two load conditions *i* and *j*

σ_s^i = static hot spot stress amplitude for *i*-th load condition

σ_s^j = static hot spot stress amplitude for *j*-th load condition

Combined hot spot stress range

- A peak to peak stress

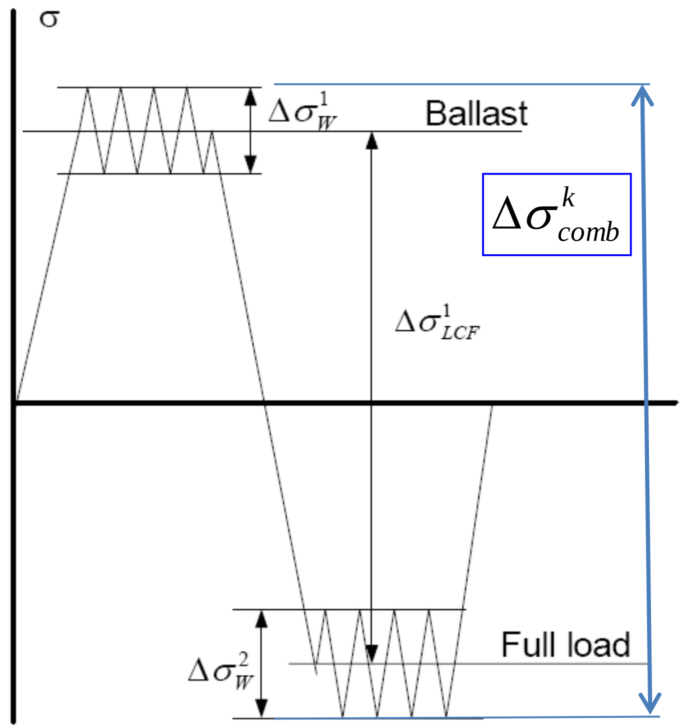
  = static stress induced by static hull girder and static pressure loads during loading and unloading

  + elastic dynamic hot spot stress amplitude at 10^{-4} probability level due to wave actions

$$\Delta\sigma^{k}_{comb} = \Delta\sigma^{k}_{LCF} + 0.5 \cdot \left(\Delta\sigma^{i}_{w} + \Delta\sigma^{j}_{w}\right)$$

$\Delta\sigma^{i}_{w}$ = dynamic stress range at 10^{-4} probability level for the i-th load condition

$\Delta\sigma^{j}_{w}$ = dynamic stress range at 10^{-4} probability level for the j-th load condition



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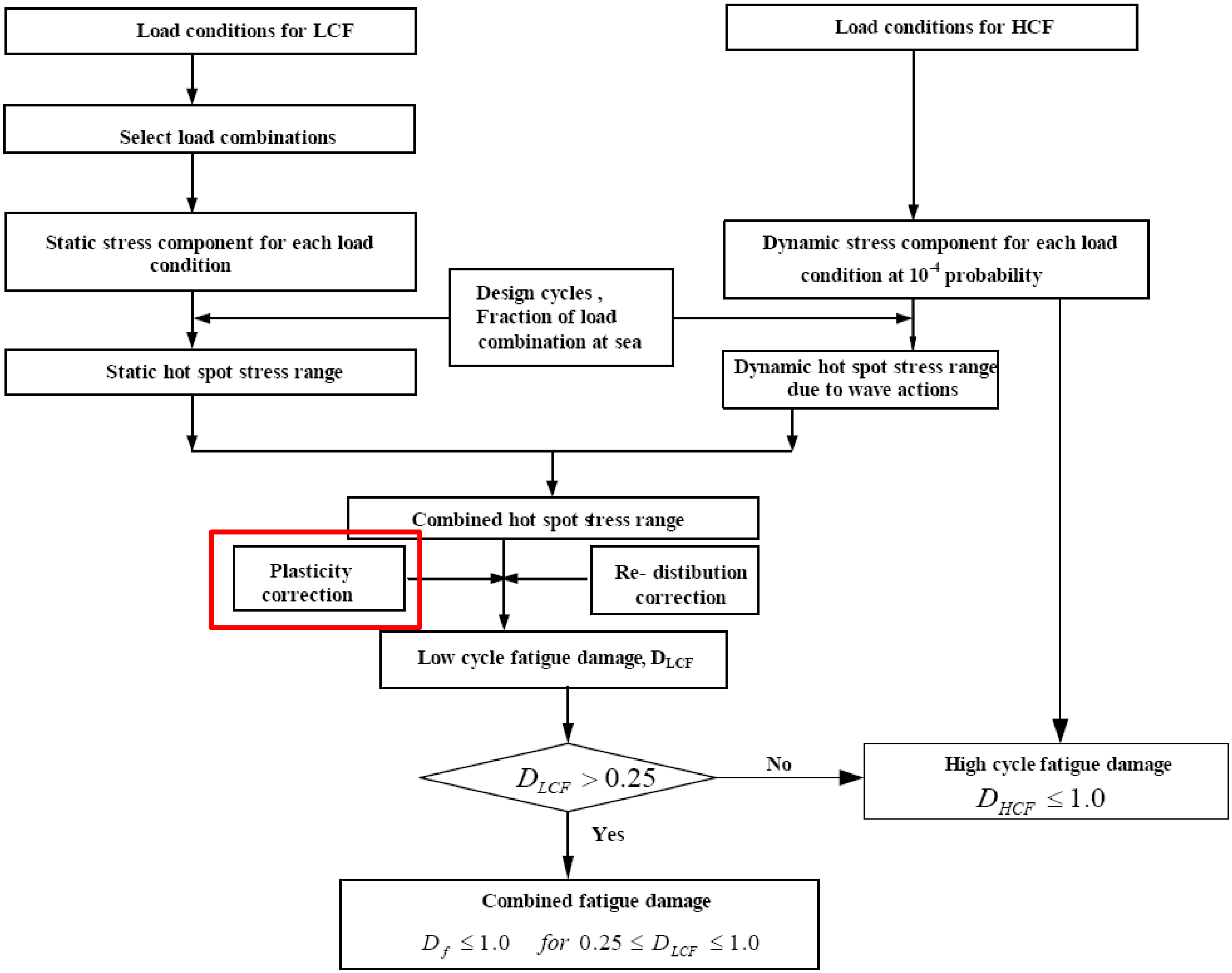
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Plasticity correction factor (K_e)

❖ **Method 1** : from 1) Cyclic stress-strain curve and 2) Neuber's rules

$$\varepsilon_{hs} = \frac{\sigma_{hs}}{E} + \left(\frac{\sigma_{hs}}{K'}\right)^{1/n'}$$

$$\sigma_{hs}\varepsilon_{hs} = \sigma_{elastic}\varepsilon_{elastic} = \text{constant}$$

$$K_t^2 Se = \sigma\varepsilon$$

$$\sigma_{hs}\varepsilon_{hs} = \frac{\sigma_{hs}^2}{E} + \sigma_{hs}\left(\frac{\sigma_{hs}}{K'}\right)^{1/n'}$$

① $$\sigma_{hs}\varepsilon_{hs} = \sigma_{elastic}\varepsilon_{elastic} = \sigma_n\varepsilon_n K^2 = \frac{\sigma_n^2 K^2}{E}$$

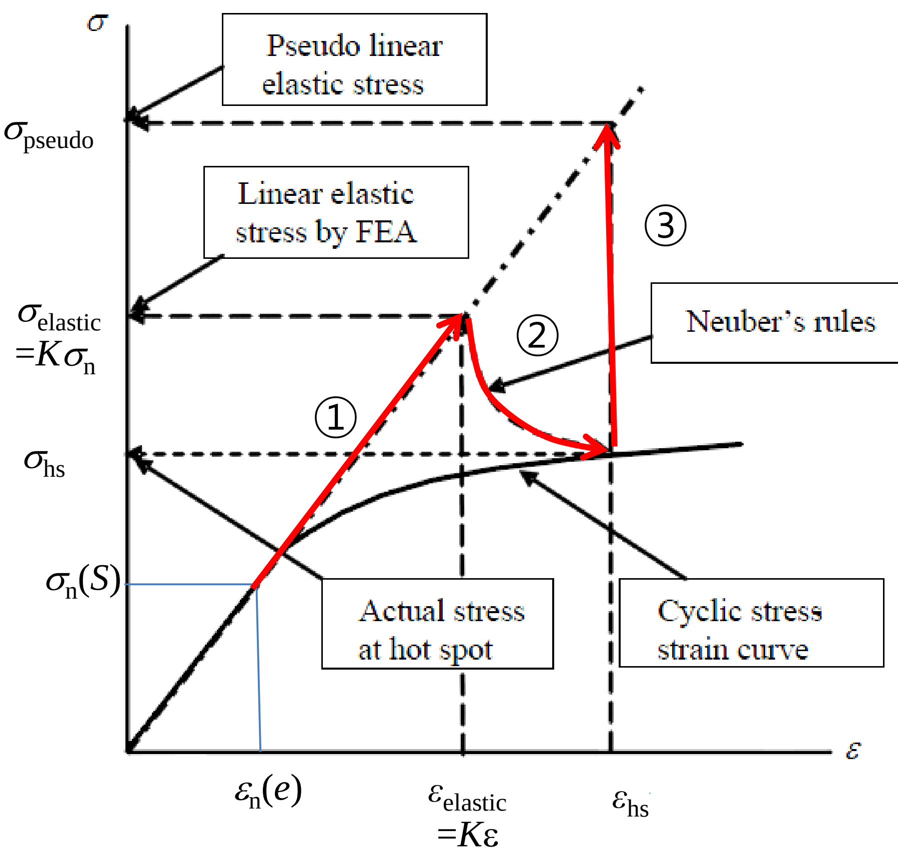
$$\therefore \frac{\sigma_n^2 K^2}{E} = \frac{\sigma_{hs}^2}{E} + \sigma_{hs}\left(\frac{\sigma_{hs}}{K'}\right)^{1/n'}$$

② σ_{hs} can be obtained from an iterative way.

$$\varepsilon_{hs} = \frac{\sigma_{hs}}{E} + \left(\frac{\sigma_{hs}}{K'}\right)^{1/n'}$$

③ $\sigma_{pseudo} = E\varepsilon_{hs}$ ➡ $K_e = \dfrac{\sigma_{pseudo}}{\sigma_{elastic}}$

Material	*Mild*	*NV32*	*NV36*
K', (N/mm²)	602.8	678.3	689.4
n	0.117	0.111	0.115



Plasticity correction factor

- $K(\approx K_t)$ = theoretical stress concentration factor
- σ_{hs}, ε_{hs} = actual hot spot stress and strain in hot spot
- $\sigma_{elastic}$, $\varepsilon_{elastic}$ = linear elastic hot spot stress and strain by FEA
- σ_n $(=S)$ = nominal stress
- E = *Young's modulus*
- n', K' = *material coefficients*
- σ_{pseudo} = Pseudo linear elastic hot spot stress=$E\varepsilon_{hs}$

Plasticity correction factor

❖ **Method 2** : from an empirical formula

- Plasticity correction factor is proportional to $\Delta\sigma_{comp}$. If $\Delta\sigma_{comp}$ is below 2.0 σ_Y, the factor =1 since it remains within elastic limit.

K_e : plasticity correction factor

$$= 1.0 \quad \text{for } \frac{\Delta\sigma_{\text{comb}}}{\sigma_Y} \leq 2.0$$

$$= \max\begin{cases} 1.0 \\ a \cdot \Delta\sigma_{\text{comb}} \cdot 10^{-3} + b \end{cases} \quad \text{for } \frac{\Delta\sigma_{\text{comb}}}{\sigma_Y} > 2.0$$

σ_Y : yield stress

Stress range	$\frac{\Delta\sigma_{comb}}{\sigma_f}$ **>2.0**
Mild steel	a = 1.16 b = 0.524
NV-32 and NV-36 steels	a = 1.0 b = 0.53

Plasticity correction factor

❖ **Method 3** : a non-linear finite element analysis

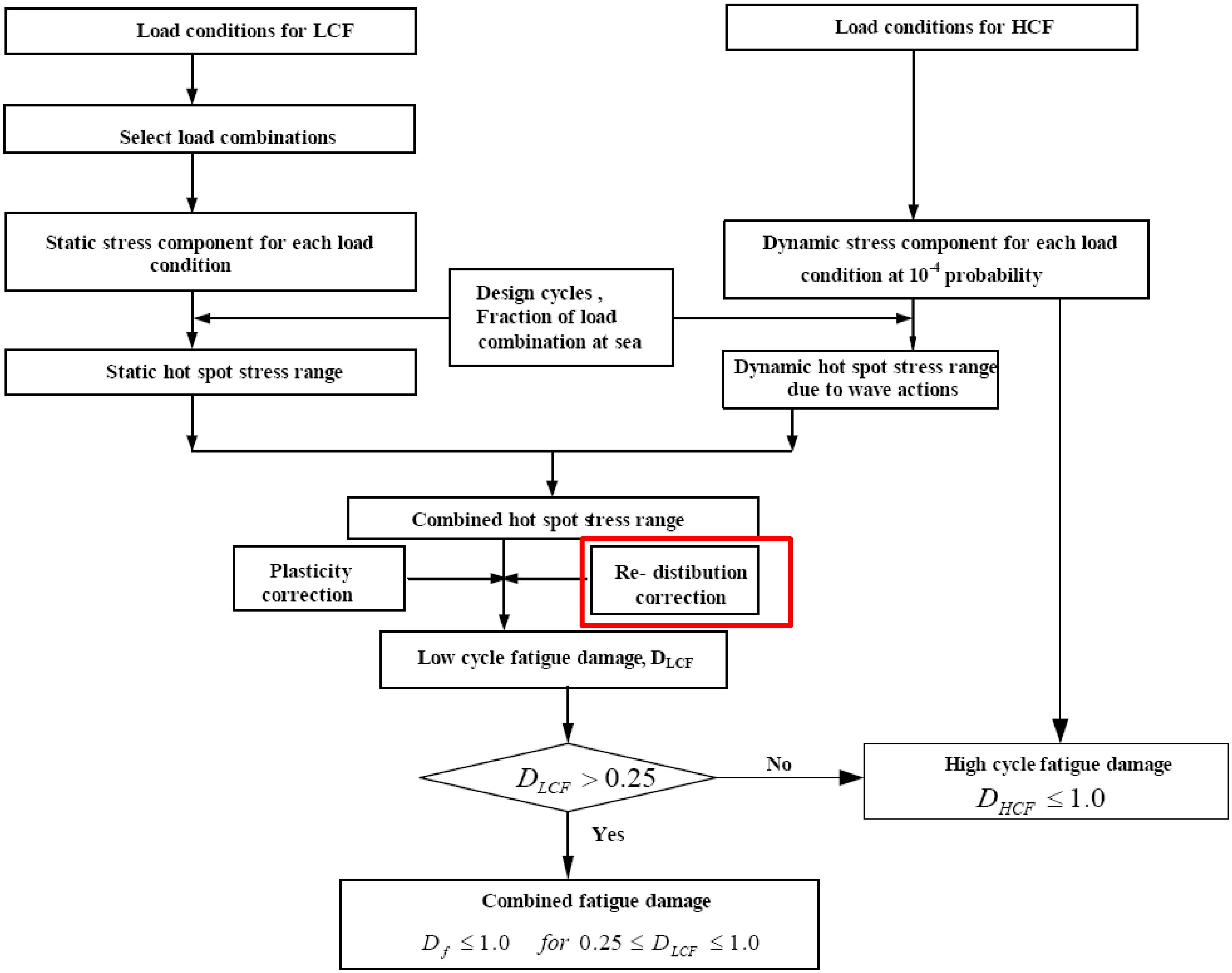
- ε_{hs} can be directly obtained form a non-linear FE analysis.
- Cyclic stress-strain curve should be provided to non-linear FE analysis.
- $\sigma_{elastic}$ can be linear elastic hot spot stress and strain by FEA.

$$\sigma_{pseudo} = E\varepsilon_{hs}$$

⇓

$$K_e = \frac{\sigma_{pseudo}}{\sigma_{elastic}}$$

General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Effective pseudo stress range

❖ Factor due to stress redistribution.

- Stress redistribution factor is applied when $\Delta\sigma_{comp}$ goes beyond elastic limit.

Ψ : Factor due to stress redistribution

$$= 1.0 \quad \text{if } \frac{\Delta\sigma_{\text{comb}}}{\sigma_{\text{Y}}} \le 2.0$$

$$= 0.9 \quad \text{for mild steel} \quad \text{if } \frac{\Delta\sigma_{\text{comb}}}{\sigma_{\text{Y}}} > 2.0$$

$$= 0.8 \quad \text{for NV32 or NV36 steel} \quad \text{if } \frac{\Delta\sigma_{\text{comb}}}{\sigma_{\text{Y}}} > 2.0$$

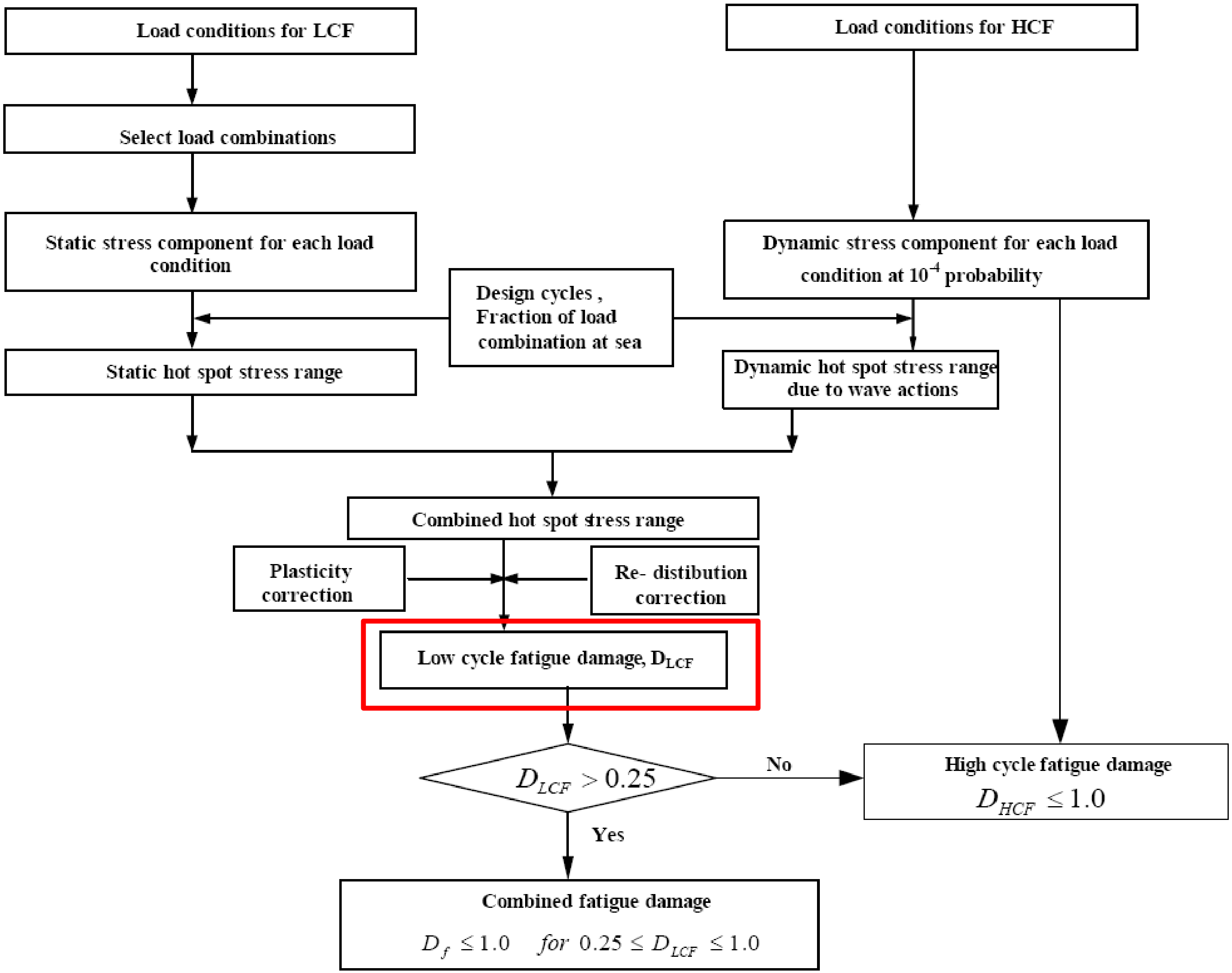
NV : High tensile steel.
NV32 : yield stress =315MPa
NV32 : yield stress = 355 MPa

❖ Effective pseudo stress range

$$\lambda : \text{non-linearity correction factor} = \text{K}_{\text{e}} \cdot \Psi$$

$$\Delta\sigma_{eff}^{k} = \lambda \cdot \Delta\sigma_{comb}^{k}$$

General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Fatigue damage calculations for LCF

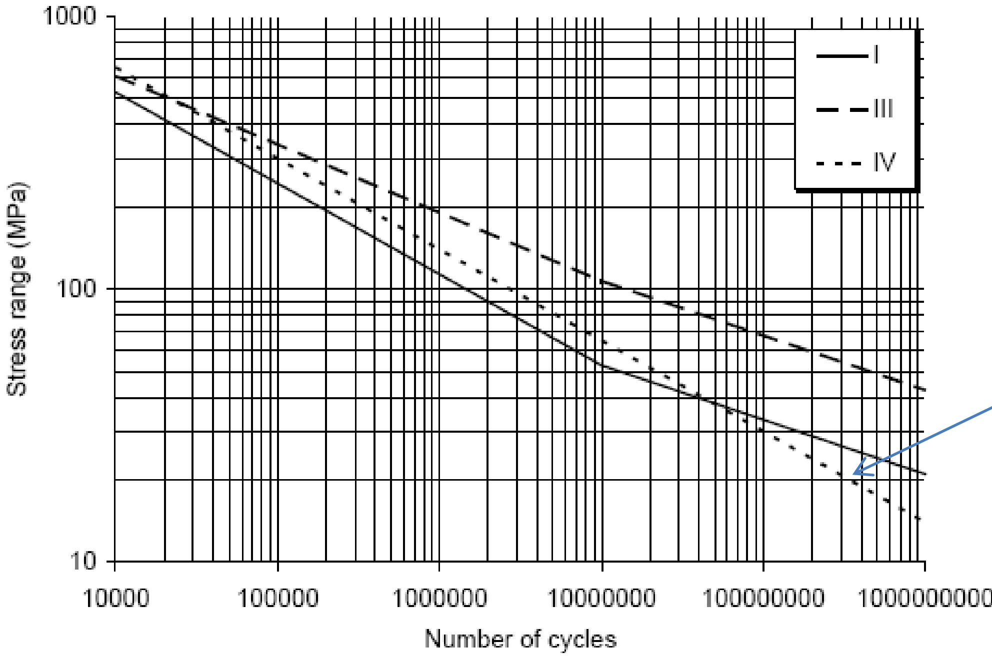
- One-slope S-N curve for low cycle fatigue strength

$$\log N_k = \log \bar{a} - m \cdot Log\Delta\sigma_{eff}^{k}$$

N_k : number of cycles to failure for low cycle fatigue stress range

σ^{k}_{eff} : effective stress range for the k-th load combination

- This design curve is applicable to both welded joints and base metal for LCF region.



Welded joint with cathodic protection

$10^2 \le N < 10^4$	
$\log \bar{a}$	m
12.164	3.0

Fatigue damage calculations for LCF

- The damage due to low cycle fatigue is calculated as follows,

$$D_{LCF} = \sum_{1}^{n_{LC}} L_k D_{LCF}^{k} = \sum_{1}^{n_{LC}} L_k \frac{n_{LCF}}{N_k}$$

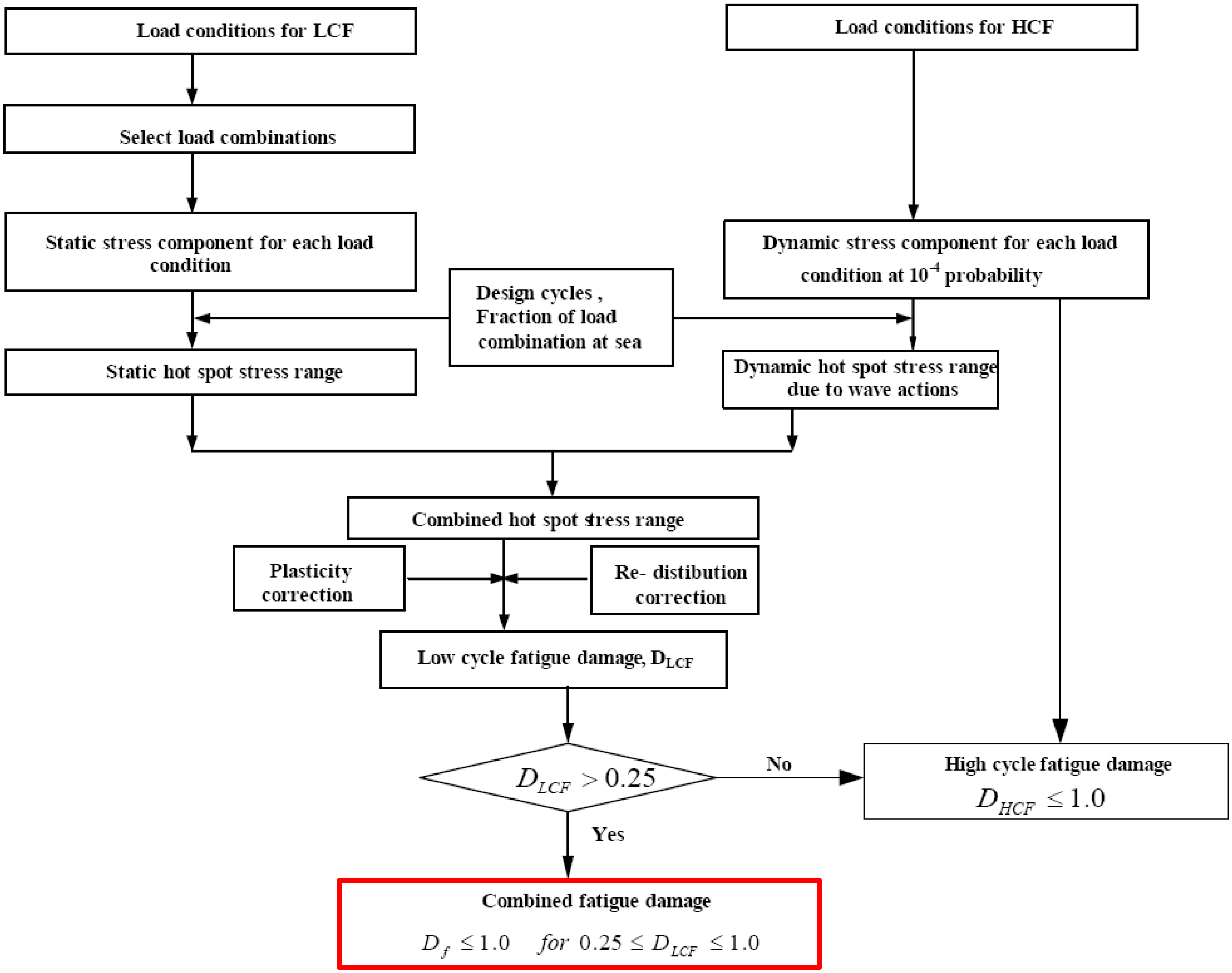
n_{LC} : total number of design load condition

L_k : fraction of load combinations

Low Cycle Fatigue Factors

- **Thickness effect :** not accounted
- **Mean stress effect :** not accounted
- **Environmental reduction factor :** not considered
- **Weld Improvement :** Benefit of weld improvement methods like grinding, hammer peening and TIG-dressing should not be applied
- **Fabrication tolerance :** are assumed applicable.

General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Combined fatigue damage due to HCF and LCF

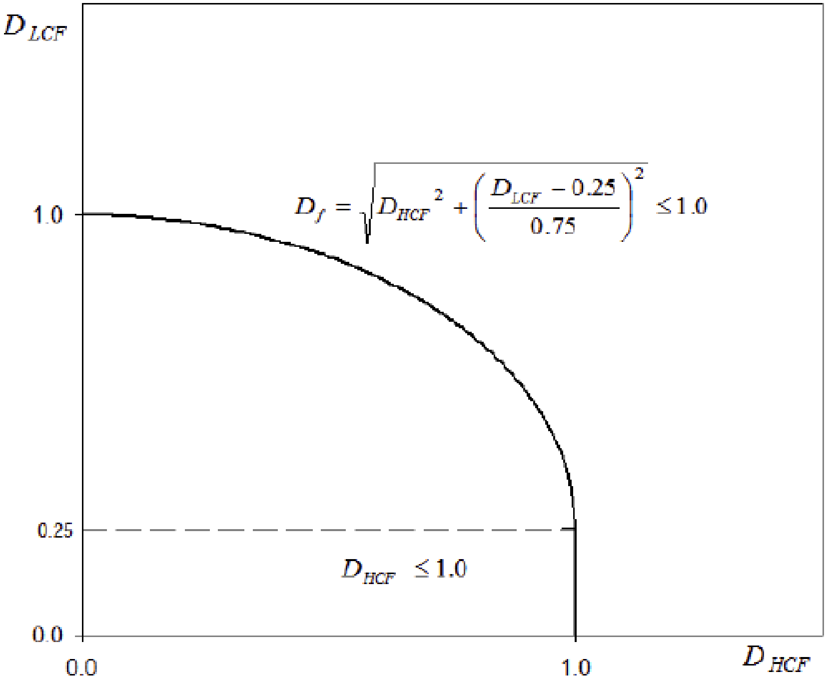
- Combined damage ratio due to high cycle fatigue and low cycle fatigue shall be satisfied when $D_{LCF} \geq 0.25$.

$$D_f = \sqrt{D_{HCF}^2 + \left(\frac{D_{HCF} - 0.25}{0.75}\right)^2} \leq 1.0 \quad for\ 0.25 \leq D_{LCF} \leq 1.0$$

D_{HCF} = damage due to high cycle fatigue based on design life
D_{LCF} = damage due to low cycle fatigue based on the design cycles

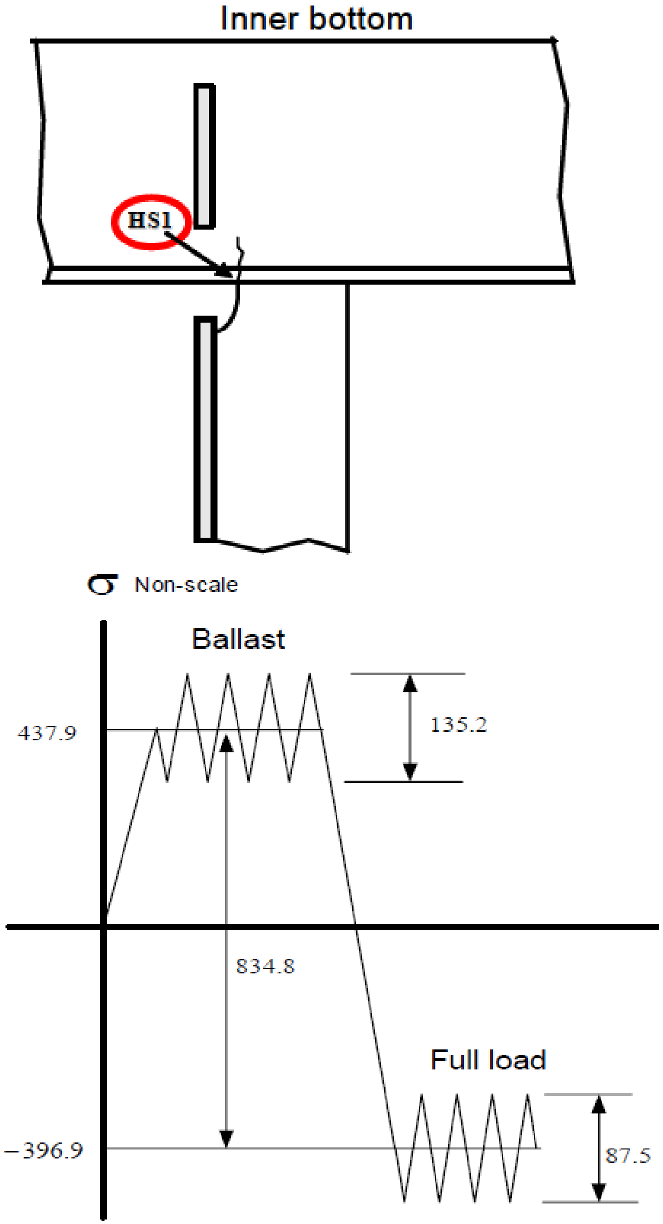
- For low cycle fatigue damage below 0.25, fatigue damage due to HCF shall be satisfied.

$$D_{HCF} \leq 1\ for\ D_{LCF} \leq 0.25$$



The combined fatigue criteria

Example



Location to be checked

Item	*Requirements*	*Remark*
Design cycle, n_{LCF}	600 cycles	From Table 21.1
Dimension of longitudinal	645 x 12 + 175 x 20 mm (T), NV-32 steel	Net scantling

Hot spot stress components at HS1, N/mm²

Stress components	*Full load*	*Ballast*
Hot spot stress amplitude due to still water vertical bending moment	-126.9	126.9
Hot spot stress amplitude due to local bending of stiffener	-270	311.0
Total static hot spot stress amplitude, σ^i_s	-396.9	437.9
Dynamic stress range at 10^{-4} probability level, σ^i_{HCF}	64.7	100.6
Dynamic stress range due to wave actions, $\Delta\sigma^i_w$	87.5	135.2

Combined stress range for low cycle fatigue strength assessment, N/mm²

Stress component	*Full load-Ballast*
Static hot spot stress range for low cycle fatigue, $\Delta\sigma^k_{LCF}$	437.9 – (-396.9) = 834.8
Combined stress range, $\Delta\sigma^k_{Comb}$	834.8+ 0.5 (87.5+135.2) = 946.2

Example

Low cycle fatigue strength assessment

	Full load-Ballast
Plasticity correction k_e,	$1.0 \cdot 946.2 \cdot 10^{-3} + 0.53 = 1.48$
Effective pseudo stress range, $\Delta\sigma^k_{eff}$, N/mm²	$0.8 \cdot 1.48 \cdot 946.2 = 1\ 120.3$
The number of cycles, N_k	$10^{12.164 - 3\mathrm{Log}1120.3} = 1\ 038$
Damage ratio due to high cycle fatigue, D_{HCF}	0.24
Damage ratio due to low cycle fatigue, D_{LCF}	$\frac{600}{1038} = 0.58$

K_e : plasticity correction factor

$$= 1.0 \quad \text{for } \frac{\Delta\sigma_{comb}}{\sigma_Y} \le 2.0$$

$$= \max\begin{cases} 1.0 \\ a \cdot \Delta\sigma_{comb} \cdot 10^{-3} + b \end{cases} \quad \text{for } \frac{\Delta\sigma_{comb}}{\sigma_Y} > 2.0$$

NV-32 and NV-36 steels	a = 1.0 b = 0.53

Ψ : Factor due to stress redistribution

$$= 1.0 \quad \text{if } \frac{\Delta\sigma_{comb}}{\sigma_Y} \le 2.0$$

$$= 0.9 \quad \text{for mild steel if } \frac{\Delta\sigma_{comb}}{\sigma_Y} > 2.0$$

$$= 0.8 \quad \text{for NV32 or NV36 steel if } \frac{\Delta\sigma_{comb}}{\sigma_Y} > 2.0$$

$$D_f = \sqrt{D_{HCF}^2 + \left(\frac{D_{LCF} - 0.25}{0.75}\right)^2} =$$

$$\sqrt{0.24^2 + 0.44^2} = 0.50 \le 1.0$$