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

Lecture 9 Ultimate Strength of Ship Hulls

Reference: CSR Rule
Ultimate Limit State Design of Steel-Plated Structures Ch. 8

NAOE
Jang, Beom Seon
1. General

- **Hull girder bending moment capacity**
  - The hull girder ultimate bending moment capacity, $M_U$, is the maximum sagging bending capacity of the hull girder beyond which the hull will collapse.
  - Hull girder failure is controlled by buckling, ultimate strength and yielding of longitudinal structural elements.
  - The maximum value on the static non-linear bending moment-curvature relationship $M-\kappa$. The curve represents the *progressive collapse behavior* of hull girder under vertical bending.

![Bending Moment - Curvature Curve M-κ](image)
1. General

- The curvature of the critical inter-frame section, $\kappa$, is defined as
  \[ \kappa = \frac{\theta}{l} \]
  
  Where:
  - $\theta$: the relative angle rotation of the two neighboring cross-sections at transverse frame positions
  - $l$: the transverse frame spacing, i.e. span of longitudinal

- The critical failure mode: Inter-frame buckling failure in sagging

- Only **vertical bending is considered**. The effects of shear force, torsional loading, horizontal bending moment and lateral pressure are neglected
2. Single Step Ultimate Capacity Method

\[ A_{\text{net50}}: \text{net area of the stiffened deck plate} \]
\[ A_{\text{eff}}: \text{effective net area after buckling} \]

\[ \sigma_{\text{Top}} \Rightarrow \sigma_U: \text{buckling capacity} \]

\[ \sigma_U \]

\[ \sigma_{\text{Bot}} \]

\[ Z_{\text{dk-mean}} \]

\[ N.A. \]

\[ Z_{\text{NA}} \]

\[ I \]

\[ Z = \frac{Z_{\text{dk-mean}} - Z_{\text{NA}}}{Z_{\text{NA}}} \] \text{at upper Deck}

\[ Z_{\text{red}} = \frac{I_{\text{red}}}{Z_{\text{dk-mean}} - Z_{\text{NA}} \text{red}} \]

\[ \sigma_Y \]

\[ \text{Failure of stiffened deck plate} \]

\[ \sigma_{\text{Top}} \Rightarrow \sigma_U \]

\[ \sigma_{\text{Bot}} \]

\[ Z_{\text{dk-mean}} - Z_{\text{NA-red}} \]

\[ N.A. - \text{Reduced} \]

\[ Z_{\text{NA-red}} \]

\[ I_{\text{red}} \]

\[ \sigma_Y \]

\[ Z_{\text{red}} = \frac{I_{\text{red}}}{Z_{\text{dk-mean}} - Z_{\text{NA-red}}} \]

\[ \text{Ultimate hull girder capacity} \]

\[ M_u = Z_{\text{red}} \sigma_{\text{yd}} \]

\[ M_u < \sigma_{\text{yd}} \frac{I_{\text{red}}}{Z_{\text{NA-red}}} \] : B.M. when yield stress occurs on reduced upper deck
CSR – Calculation of hull girder ultimate capacity

2. Single Step Ultimate Capacity Method

\[ \sigma = E \varepsilon = -\frac{E \gamma}{\rho} = -E \kappa \]

Moment – Curvature of Hull Girder Single Step Procedure
2. Single Step Ultimate Capacity Method

- **Single Step Ultimate Capacity Method**
  - The assumption: that the ultimate sagging capacity of tankers is the point at which the ultimate capacity of the stiffened deck panels is reached.

  The single step procedure for calculation of the sagging hull girder ultimate bending capacity is a simplified method based on a reduced hull girder bending stiffness accounting for buckling of the deck.

\[ M_U = Z_{red} \sigma_{yd} \cdot 10^3 \text{kNm} \]

- **\( Z_{red} \):** reduced section modulus of deck
  \[ Z_{red} = \frac{I_{red}}{z_{dk-mean} - z_{NA-red}} \text{m}^3 \]

- **\( I_{red} \):** reduced hull girder moment of inertia using
  - a hull girder net thickness of \( t_{net50} \) for all longitudinally
  - effective members the effective net area after buckling of each stiffened panel of the deck, \( A_{eff} \).
2. Single Step Ultimate Capacity Method

- \( A_{\text{eff}} \): effective net area after buckling of the stiffened deck panel. The effective area is the proportion of stiffened deck panel that is effectively able to be stressed to yield:

\[
A_{\text{eff}} = \frac{\sigma_U}{\sigma_{yd}} A_{\text{net50}} \text{ m}^2
\]

- \( \sigma_U \): buckling capacity of stiffened deck panel. To be calculated for each stiffened panel using:
  - the advanced buckling analysis method
  - the net thickness \( t_{\text{net50}} \)

- \( \sigma_{yd} \): specified minimum yield stress of the material

- \( z_{dk\text{-mean}} \): vertical distance to the mean deck height, taken as the mean of the deck at side and the deck at centreline, measured from the baseline.

- \( z_{NA\text{-mean}} \): vertical distance to the neutral axis of the reduced section measured from the baseline.
2. Single Step Ultimate Capacity Method

- $M_U$, does not give stresses exceeding the specified minimum yield stress of the material, $\sigma_{yd}$, in the bottom shell plating. $M_U$ is not to be greater than

$$M_U = \sigma_{yd} \frac{I_{\text{red}}}{Z_{\text{NA-red}}} \times 10^3 \text{ kNm}$$

- Moment – Curvature of Hull Girder Single Step Procedure

$$\sigma = E \varepsilon = -\frac{E_y}{\rho}$$
2. Single Step Ultimate Capacity Method

- Vertical hull girder ultimate bending capacity

\[ \gamma_S M_{sw} + \gamma_W M_{wv-sag} \leq \frac{M_U}{\gamma_R} \]

- \( M_{sw} \): sagging still water bending moment
- \( M_{wv-sag} \): sagging vertical wave bending moment
- \( M_U \): sagging vertical hull girder ultimate bending capacity
- \( \gamma_S \): partial safety factor for the sagging still water bending moment
- \( \gamma_W \): partial safety factor for the sagging vertical wave bending moment
- \( \gamma_R \): partial safety factor for the sagging vertical hull girder bending capacity covering material, geometric and strength prediction uncertainties

<table>
<thead>
<tr>
<th>Design load combination</th>
<th>Definition of Still Water Bending Moment, Msw</th>
<th>( \gamma_S )</th>
<th>( \gamma_W )</th>
<th>( \gamma_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>Permissible sagging still water bending moment, ( M_{sw-perm-sea} ), Maximum sagging still water bending moment for operational seagoing homogeneous full load condition, ( M_{sw-full} ) (&lt;( M_{sw-perm-sea} ))</td>
<td>1.0</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>b)</td>
<td></td>
<td>1.0</td>
<td>1.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>
3. Simplified Method Based on an Incremental-iterative Approach

- Ultimate hull girder bending moment capacity $M_U$ is defined as the peak value of the curve with vertical bending moment $M$ versus the curvature $\kappa$.

- The curve $M$-$\kappa$ is obtained by means of an incremental-iterative approach; The expected maximum required curvature, $\kappa_F$,

\[
\kappa_F = 3 \frac{M_{yd}}{EI_{v-net50}} \times 10^{-3} \text{ m}^{-1}
\]

- $M_{yd}$: vertical bending moment given by a linear elastic bending stress of yield in the deck or keel. To be taken as the greater of:

\[
\begin{align*}
Z_{v-net50-dk}\sigma_{yd} \\
Z_{v-net50-kl}\sigma_{yd}
\end{align*}
\]

$Z_{v-net50-dk}, Z_{v-net50-kl}$: section modulus at deck or bottom,
Assumptions and modeling of the hull girder cross-section

Assumptions

(a) The ultimate strength is calculated at a **hull girder transverse section** between two adjacent transverse webs.
(b) The hull girder transverse section **remains plane** during each curvature increment.
(c) The material properties of steel are assumed to be **elastic, perfectly plastic**.
(d) The hull girder transverse section can be divided into a set of elements which **act independently** of each other.

The elements making up the hull girder transverse section are:

(a) longitudinal stiffeners with attached plating
(b) transversely stiffened plate panels
(c) hard corners
**CSR – Calculation of hull girder ultimate capacity**

**Overall Procedure**

- **Start**
- Calculate elastic section modulus and position of the neutral axis, $z_{na}$
- Initialize curvature $\kappa_i = \Delta \kappa$
  - Derive maximum curvature $\kappa_F$

- **For all structural elements (index = $j$)**
  - Calculate the strain $\varepsilon_{ij}$ induced on each structural element by the curvature $\kappa_i$ about the neutral axis position $z_{na-i}$
  - Derive maximum curvature $\kappa_F$
  - For each structural element calculate the stress $\sigma_j$ relevant to the strain $\varepsilon$
  - Derive the total force on the transverse section $F_i = \Sigma \sigma_j A_j$
  - Adjust the position of the neutral axis based on $F_i$
  - Exit loop when the adjustment of the neutral axis is less than 0.0001
  - Calculation of the bending moment $M_i$ relevant to the curvature $\kappa_i$, summing the contribution of each structural element stress

- Increase curvature
  - $i = i + 1$
  - $\kappa_i = \kappa_{i-1} + \Delta \kappa$
  - $z_{NA-i} = z_{NA-i+1}$

- Curve $M - \kappa$
- The ultimate capacity is the peak value, $Mu$, from the $M - \kappa$ curve
CSR – Calculation of hull girder ultimate capacity
Simplified Method Based on an Incremental-iterative Approach

Calculate the strain $\varepsilon_{ij}$ induced on each structural element by the curvature $\kappa_i$ about the neutral axis position $z_{na-i}$.

For each structural element calculate the stress $\sigma_j$ relevant to the strain $\varepsilon$.

Stress strain curve $\sigma$-$\varepsilon$ for elastic, perfectly plastic failure of a hard corner.

Typical stress strain curve $\sigma$-$\varepsilon$ for elasto-plastic failure of a stiffener.
CSR – Calculation of hull girder ultimate capacity

Simplified Method Based on an Incremental-iterative Approach

Derive the total force on the transverse section \( F_i = \sum \sigma_j A_j \)

For each structural element calculate the stress \( \sigma_j \) relevant to the strain \( \varepsilon \)

Calculate the strain \( \varepsilon_{ij} \) induced on each structural element by the curvature \( \kappa_i \) about the neutral axis position \( z_{NA-i} \)

Exit loop when the adjustment of the neutral axis is less than 0.0001
CSR – Calculation of hull girder ultimate capacity
Simplified Method Based on an Incremental-iterative Approach

- Neutral axis above base line

\[
g_{us} = \frac{\sum_{i} \sigma_{xi}^Y A_i z_i + \sum_{j} \sigma_{xj}^E A_j z_j + \sum_{k} \sigma_{xk}^E A_{ek} z_k + \sum_{l} \sigma_{xl}^U A_{el} z_l}{\sum_{i} \sigma_{xi}^Y A_i + \sum_{j} \sigma_{xj}^E A_j + \sum_{k} \sigma_{xk}^E A_{ek} + \sum_{l} \sigma_{xl}^U A_{el}}
\]

- Ultimate hull girder moment

\[
M_{us} = -\sum_{i} \sigma_{xi}^Y A_i (g_{us} - z_i) - \sum_{j} \sigma_{xj}^E A_j (g_{us} - z_j) + \sum_{k} \sigma_{xk}^E A_{ek} (z_k - g_{us}) + \sum_{l} \sigma_{xl}^U A_{el} (z_l - g_{us})
\]

\begin{align*}
\sum_{i} \sigma_{xi}^Y A_i & : \text{yield region} \\
\sum_{j} \sigma_{xj}^E A_j & : \text{elastic tension region} \\
\sum_{k} \sigma_{xk}^E A_{ek} & : \text{elastic compression region} \\
\sum_{l} \sigma_{xl}^U A_{el} & : \text{collapsed compression region}
\end{align*}
CSR – Calculation of hull girder ultimate capacity
Simplified Method Based on an Incremental-iterative Approach

Exit loop when the adjustment of the neutral axis is less than 0.0001

Yes

Calculation of the bending moment $M_i$ relevant to the curvature $\kappa_i$, summing the contribution of each structural element stress

No

$\kappa = \kappa_F$

Yes

The ultimate capacity is the peak value, $M_u$, from the $M - \kappa$ curve

Increase curvature

$i = i+1$

$\kappa_i = \kappa_{i-1} + \Delta\kappa$

$Z_{NA-i} = Z_{NA-i+1}$
CSR – Calculation of hull girder ultimate capacity

Stress-strain Curves $\sigma$-$\varepsilon$ (or Load-end Shortening Curves)

- Plate panels and stiffeners
  - Plate panels and stiffeners are assumed to fail according to one of the modes of failure
  - The relevant stress-strain curve $\sigma$-$\varepsilon$ is to be obtained for lengthening and shortening strains

<table>
<thead>
<tr>
<th>Element</th>
<th>Mode of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lengthened transversely framed plate panels or stiffeners</strong></td>
<td>Elastic, perfectly plastic failure</td>
</tr>
<tr>
<td><strong>Shortened stiffeners</strong></td>
<td>Beam column buckling</td>
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<td></td>
<td>Torsional buckling</td>
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<td></td>
<td>Web local buckling of flanged profiles</td>
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<tr>
<td></td>
<td>Web local buckling of flat bars</td>
</tr>
<tr>
<td><strong>Shortened transversely framed plate panels</strong></td>
<td>Plate buckling</td>
</tr>
</tbody>
</table>

![Stress-strain curve diagram](image)
CSR – Calculation of hull girder ultimate capacity

Stress-strain Curves $\sigma$-$\varepsilon$ (or Load-end Shortening Curves)

- Hard Corners
  - Hard corners are sturdier elements which are assumed to buckle and fail in an elastic, perfectly plastic manner.

![Stress-strain Curves Diagram]
**CSR – Calculation of hull girder ultimate capacity**

**Stress-strain Curves σ-ε (or Load-end Shortening Curves)**

- Elasto-plastic failure of structural elements

![Stress-strain Curves](image)

- Beam column buckling
  - Euler buckling with plasticity correction

\[ \sigma_{C1} = \frac{\sigma_{E1}}{\varepsilon} \]

for \( \sigma_{E1} \leq \frac{\sigma_{ydB}}{2} \cdot \varepsilon \)

\[ \sigma_{C1} = \sigma_{ydB} \left( 1 - \frac{\sigma_{ydB} \varepsilon}{4 \sigma_{E1}} \right) \]

for \( \sigma_{E1} > \frac{\sigma_{ydB}}{2} \cdot \varepsilon \)

\[ \varepsilon \text{ relative strain defined in 2.3.3.1} \]

\[ \sigma_{E1} \text{ Euler column buckling stress, in N/mm}^2: \]

\[ \sigma_{E1} = \pi^2 E \frac{I_{E-net50}}{A_{E-net50}^2 \cdot L_{eff}} \times 10^{-4} \]
Stress-strain Curves $\sigma$-$\varepsilon$ (or Load-end Shortening Curves)

- **Torsional buckling of stiffeners**
  - Euler torsional buckling with plasticity correction
    
    $\sigma_{C2}$ critical stress, in N/mm$^2$:
    
    $$\sigma_{C2} = \frac{\sigma_{E2}}{\varepsilon} \quad \text{for} \quad \sigma_{E2} \leq \frac{\sigma_{yds}}{2} \varepsilon$$
    
    $$\sigma_{C2} = \sigma_{yds} \left(1 - \frac{\sigma_{yds} \varepsilon}{4\sigma_{E2}}\right) \quad \text{for} \quad \sigma_{E2} > \frac{\sigma_{yds}}{2} \varepsilon$$
    
    $\sigma_{E2}$ Euler torsional buckling stress, in N/mm$^2$
    
    $\sigma_{E2} = \sigma_{ET}$

- **Web local buckling of stiffeners with flanged profiles**
  - Effective breadth concept
    
    $$\sigma_{CR3} = \Phi \frac{b_{eff-p} t_{net50} \sigma_{ydp} + (d_{w-eff} t_{w-net50} + b_f t_f - net50) \sigma_{yds}}{st_{net50} + d_w t_{w-net50} + b_f t_f - net50}$$
    
    $d_{w-eff}$ effective depth of the web, in mm:
    
    $$d_{w-eff} = \left(\frac{2.25}{\beta_w} - 1.25\right) d_w \quad \text{for} \quad \beta_w > 1.25$$
    
    $$d_{w-eff} = d_w \quad \text{for} \quad \beta_w \leq 1.25$$
    
    $$\beta_w \frac{d_w}{t_{w-net50}} \sqrt{\frac{\varepsilon \sigma_{yds}}{E}}$$
CSR – Calculation of hull girder ultimate capacity

Stress-strain Curves $\sigma$-$\varepsilon$ (or Load-end Shortening Curves)

- Web local buckling of flat bar stiffeners
  - Euler torsional buckling with plasticity correction
    
    \[
    \sigma_{C4} = \frac{\sigma_{E4}}{\varepsilon}
    \]
    \[
    \text{for } \sigma_{E4} \leq \frac{\sigma_{yds}}{2} \varepsilon
    \]
    \[
    \sigma_{C4} = \sigma_{yds} \left(1 - \frac{\sigma_{yds} \varepsilon}{4\sigma_{E4}}\right)
    \]
    \[
    \text{for } \sigma_{E4} > \frac{\sigma_{yds}}{2} \varepsilon
    \]

    $\sigma_{E4}$ Euler buckling stress, in N/mm$^2$:
    
    \[
    \sigma_{E4} = 160000 \left(\frac{t_{w-net}}{d_{w}}\right)^2
    \]

- Web local buckling of flat bar stiffeners

\[
\sigma_{CR5} = \min\left\{ \Phi \sigma_{ydp} \left[ \frac{s}{1000l_{stf}} \left( \frac{2.25}{\beta_p} - \frac{1.25}{\beta_p^2} \right) + 0.1 \left(1 - \frac{s}{1000l_{stf}}\right) \left(1 + \frac{1}{\beta_p^2}\right) \right] \right\} \sigma_{ydp} \Phi
\]

N/mm$^2$
4. Alternative Methods

- Considerations for alternative models
  - The bending moment-curvature relationship, $M-\kappa$, may be established by alternative methods. Such models are to consider all the relevant effects important to the non-linear response with due considerations of:
    - a. non-linear geometrical behaviour
    - b. inelastic material behaviour
    - c. geometrical imperfections and residual stresses (geometrical out-of-flatness of plate and stiffeners)
    - d. simultaneously acting loads:
      - e. bi-axial compression
      - f. bi-axial tension
      - g. shear and lateral pressure
      - h. boundary conditions
      - i. interactions between buckling modes
      - j. interactions between structural elements such as plates, stiffeners, girders etc.
      - k. post-buckling capacity.
4. Alternative Methods

- Non-linear finite element analysis
  - FE models are to consider the relevant effects important to the non-linear responses with due consideration of the items listed in.
  - Particular attention is to be given to modeling the shape and size of geometrical imperfections. It is to be ensured that the shape and size of geometrical imperfections trigger the most critical failure modes.
Nonlinear FE analysis

5. Nonlinear FE analysis

- Non-linear finite element analysis
  - 50% corrosion margin
  - Initial deflection of plating of plating ($w_{opl}$) and stiffener web ($w_{ow}$), elastic buckling mode
    
    \[
    w_{opl} = \frac{b}{200}, \quad w_{ow} = \frac{h_w}{200}
    \]
    
    - the fabrication related initial distortions of stiffeners
  
  \[
  w_{oc} = w_{os} = \frac{a}{1000}
  \]

- buckling collapse may take place in vertical members of the hull structure until the hull girder reaches the ultimate limit state → fine mesh modeling for vertical member
- Changing neutral axis of the hull cross-section due to the progressive collapse of individual structural components is to be considered.
CSR – Calculation of hull girder ultimate capacity

5. Nonlinear FE analysis

Deformed shape of the hull at the ultimate limit state under sagging moment
CSR – Calculation of hull girder ultimate capacity
FE analysis results

Nonlinear FEA:
- CSR structure deducting 50% corrosion margin
- Pre-CSR structure deducting 100% corrosion margin

ALPS/HULL:
- CSR structure deducting 50% corrosion margin

Curvature (1/m)

Vertical bending moment (Nm)
ISUM Modeling strategy

- Ueda & Rashed (1974, 1984) suggested
- Idealized Structural Unit Method (ISUM)
- Several different types of ISUM units
  - the beam-column unit
  - the rectangular plate unit
  - the stiffened panel unit

When stiffeners are relatively weak and strong,
- Plate → the rectangular plate unit
- Stiffeners without attached plating → beam-column unit

A typical steel plated structure
Plate-stiffener combination units
Plate-stiffener Separation units
Assembly of stiffened panels
ISUM Method

ISUM Units Development Procedure

- ISUM units (elements) are used within the framework of the nonlinear matrix displacement procedure, by applying the incremental method, much like in the case of conventional FEM.

Selection of relevant large part of the structure as an idealized unit for modeling

Boundary conditions — Loadings

A detailed investigation of nonlinear behavior of the unit component members under the specified boundary conditions and loading

Idealization of the actual nonlinear behavior of the unit

Formation of the unit behavior in incremental matrix form until after the limit state is reached

Procedure for the development of an idealized structural unit

“The behavior will differ depending on User’s insight and knowledge”
ISUM Beam-Column Unit

- Four nodes, three translational DOF

\[
\{\Delta R\} = \{\Delta R_{x1} \; \Delta R_{y1} \; \Delta R_{z1} \; \Delta R_{x2} \; \Delta R_{y2} \; \Delta R_{z2}\}^T
\]

\[
\{\Delta U\} = \{\Delta u_1 \; \Delta v_2 \; \Delta w_1 \; \Delta u_2 \; \Delta v_2 \; \Delta w_2\}^T
\]

\[
\{\Delta R\} = [K]\{\Delta U\}
\]

\{\Delta R\} = \text{nodal force increment vector}

\{\Delta U\} = \text{nodal displacement increment vector}

[K] : \text{tangent stiffness matrix}
ISUM Rectangular Plate Unit

The ISUM Method refers to a method in structural analysis. The ISUM rectangular plate unit is an idealized structural element used in the analysis of plate structures. The idealized structural behavior of the ISUM rectangular unit is given by:

\[
\{ \Delta R \} = [K] \{ \Delta U \}
\]

Where:
- \( \{ \Delta R \} \) is the nodal force increment vector
- \( \{ \Delta U \} \) is the nodal displacement increment vector
- \([K]\) is the tangent stiffness matrix

The equation describes the linear relationship between the nodal force increments and the nodal displacement increments for the ISUM rectangular plate unit.
ISUM Method

Modeling using **Beam-Column Unit** and **Rectangular Plate Unit**
Double Hull Tanker Example

- The collapse of the compression flange of the tanker hulls takes place prior to the yielding of the tension flange as in design of usual ship structures.

**ISUM Method**

**Double Hull Tanker Example**

- The collapse of the compression flange of the tanker hulls takes place prior to the yielding of the tension flange as in design of usual ship structures.

**For sagging:**

11. Buckling collapse of upper inner side shell longl.*
12. Buckling collapse of lower longitudinal bulkhead longl.*
13. Buckling collapse of deck girder longl.
14. Buckling collapse of upper outer shell longl.
15. Buckling collapse of upper inner side shell longl. & deck plates*
16. Buckling collapse of deck plates & longitudinal bulkhead plates*
17. Buckling collapse of deck plates & upper inner/outer shell plates* (Ultimate limit state)

Note: * denotes that the related failure event starts.
Double Hull Tanker Example

For Hogging:
1. Buckling collapse of outer bottom longl.*
2. Buckling collapse of center girder longl.*
3. Buckling collapse of center girder longl. & inner bottom longl.*
4. Buckling collapse of bottom girder longl. & lower side shell longl.*
5. Buckling collapse of lower sloping tank longl.* & lower longitudinal bulkhead longl.*
6. Buckling collapse of bottom girder plates* & yielding of deck longl.*
7. Buckling collapse of outer bottom plates*, yielding of deck plates* & upper longitudinal bulkhead plates*
8. Buckling collapse of outer bottom plates & yielding of deck longl.
9. Buckling collapse of bottom girder plates, yielding of deck plates & yielding of upper side
10. Buckling collapse of inner

Note: * denotes that the related failure event starts.

Level of initial imperfections:
①: Slight
②: Average

313,000 DWT double hull tanker
ISUM Method

Other Examples

254,000 DWT single hull tanker

L = 313.0 m  
B = 48.2 m  
D = 25.2 m  
F.S. = 5.1 m

105,000 DWT double hull tanker

L = 233.0 m  
B = 42.0 m  
D = 21.3 m  
F.S. = 4.12 m

Sagging

Sagging
ISUM Method

Other Examples

169,000 DWT double sided bulk carrier

L = 273.0 m
B = 44.5 m
D = 23.0 m
F.S.
Deck = 5.16 m
Side shell = 0.86 m
Bottom = 2.58 m

9,000 TEU container

L = 305.0 m
B = 45.3 m
D = 27.0 m
F.S. = 3.27 m