Study on the Risk-Based Methodology for Ship Structural Design

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Contents

1.

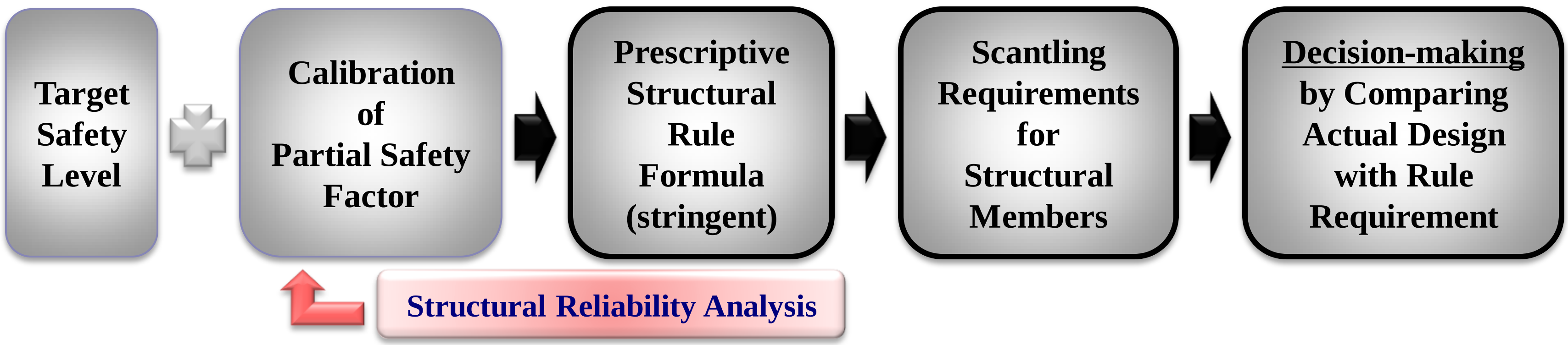
Safety Level Based Hull Scantling Assessment

1. Safety Level Based Assessment

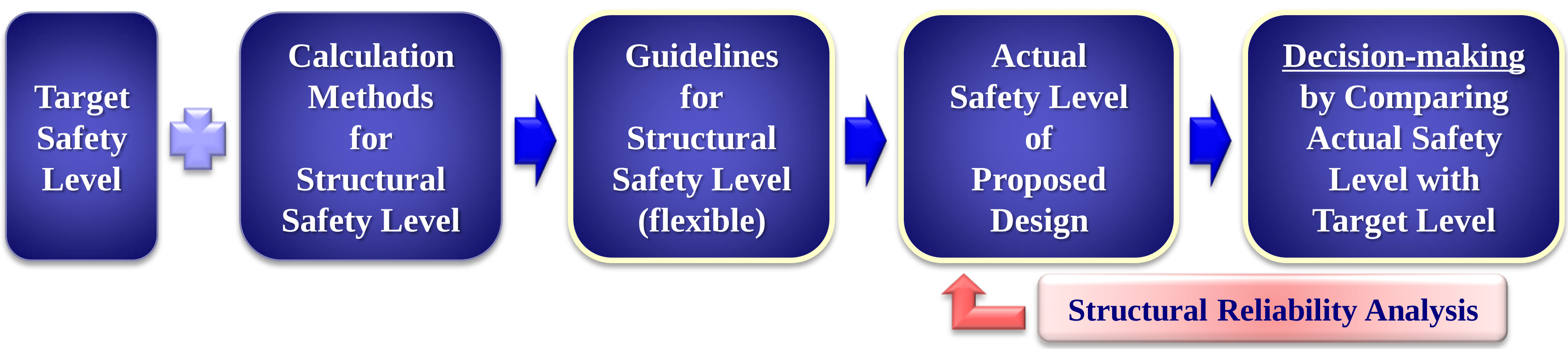
- Risk-Based Design/Approval of Ship
  - New design paradigm based on the risk assessment
  - This stands on probabilistic approach, not deterministic
  - Safety level approach is one of the key methodology for RBD/A
  - Activities to apply RBD/A into ship design/approval (e.g. IMO GBS)

1. Safety Level Based Assessment

- RBD/A for Ship Structure
  - Rule based assessment on structural safety (currently underway)

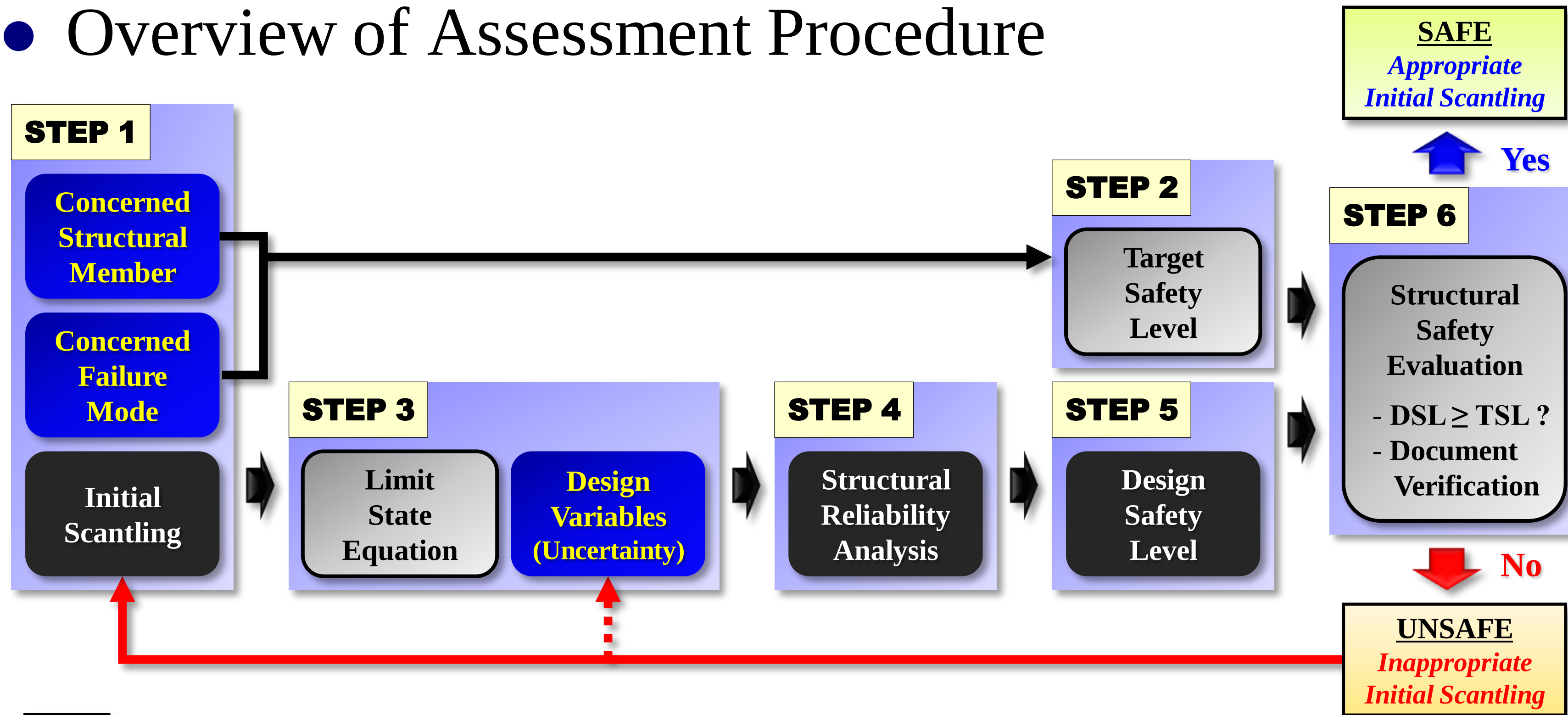


  - Safety level based assessment on structural safety (this study)



1. Safety Level Based Assessment

- Overview of Assessment Procedure



- (light grey box) To be defined obviously by the SLA-based Procedure and/or conducted by Approver
- (dark box) To be determined and/or conducted by Ship Structure Designer
- (blue box) To be determined by Ship Structure Designer in accordance with the guideline in the SLA-based Procedure

1. Safety Level Based Assessment

- Step 1. Design Scope
  - To select initial scantling and concerned failure mode
    - Dimension, location, material, corrosion, configuration, etc.
    - Yielding, buckling, fatigue, impact, etc.
- Step 2. Target Safety Level
  - Safety goal, i.e. the smallest allowable level securing safety
  - Considering member type, failure mode and damage consequence
- Step 3-1. Limit State Equation
  - Design criteria: $Z = R - L$ (R & L: resistance & load factor)
  - $Z = 0$: boundary between safe and fail
  - Probability of failure is the likelihood that $Z < 0$ occurs

1. Safety Level Based Assessment

- Step 3-2. Design Variables
  - Probabilistic modeling is necessary
  - Categorization of design variables
    - Related to loads acting on hull
    - Related to materials
    - Related to uncertainties in fabrication
    - Related to uncertainties in structural modeling and mechanics
- Step 4. Structural Reliability Analysis
  - There are various techniques established well at present
    - Monte-Carlo simulation, FOSM, SOSM and so forth
  - From the SRA, probability of failure can be produced

1. Safety Level Based Assessment

- Step 5. Design Safety Level
  - Quantitative safety inherent in the structural member
  - The actual safety level ensured by the structural design proposed
  - It could be estimated considering failure probability and operation plan
- Step 6. Structural Safety Evaluation
  - First, document verification is necessary
    - All the works done by designer should be verified to be reasonable
  - Second, comparing the DSL with the TSL is necessary
    - If DSL is not less than the TSL, current design is safe enough
    - Otherwise, current design is to be amended to make its structural safety level higher

2.

Safety Level of LSM

(Local Supporting Member)

2. Safety Level of LSM

- Formulation of Limit State Equation

$$Z = R - L = \sigma_{LMT} - \sigma_{Working}$$

$$\sigma_{Working} = \left(P_{WK-Stat} + P_{WK-Dyn}\right)\frac{s\ell^2}{f_{bend}\, z_{stiff}} + \left(M_{WK-Stat} + C_{Scale} M_{WK-Dyn}\right)\frac{0.001 d_{vert}}{I_{HG-vert}}$$

- Failure mode concerned
  - ✓ Yielding failure of local stiffener, due to local bending
- Load type concerned
  - ✓ Local loads: lateral pressure from external sea and internal ballast/cargo
  - ✓ Global loads: vertical wave bending moment
- Resistance factor (R) = yield stress capacity of the material used
- Load factor (L) = working stress on the stiffener considered
- Background
  - ✓ Beam theory (both ends fixed)
  - ✓ Scantling formulas in IACS CSR for double hull oil tanker
  - ✓ Net scantling approach

2. Safety Level of LSM

- Consideration on Design Variables

$$Z = R - L = \sigma_{LMT} - \sigma_{Working}$$

$$\sigma_{Working} = \left(P_{WK-Stat} + P_{WK-Dyn}\right)\frac{s\ell^2}{f_{bend}\, z_{stiff}} + \left(M_{WK-Stat} + C_{Scale}\, M_{WK-Dyn}\right)\frac{0.001\, d_{vert}}{I_{HG-vert}}$$

- σ_{LMT}: Nominal yield stress of material
- $s\ell^2$: Spacing & bending span of stiffener
- $I_{HG-vert}$: Net vertical hull girder moment of inertia
- d_{vert}: Vertical distance from N.A. to stiffener
- $P_{WK-Stat}$: Local pressure acting on stiffener (static)
- P_{WK-Dyn}: Local pressure acting on stiffener (dynamic)
- f_{bend}: Bending moment factor
- z_{stiff}: Net section modulus of stiffener
- $M_{WK-Stat}$: Still water bending moment
- C_{Scale}: Correction factor (for IACS UR 11)
- M_{WK-Dyn}: Vertical wave bending moment

2. Safety Level of LSM

- Calculation of Design Safety Level
  - Direct Load Analysis
    - is considered as more reasonable than simplified formulas that are based on plenty of assumption and idealization
    - is essential to probabilistic modeling of dynamic loads
  - Probability of failure can be produced by using
    - SRA (Structural Reliability Analysis), established well at present
  - Design safety level
    - For estimating DSL, HPP (Homogeneous Poisson Process) was used
    - to model occurrences of a specific event within a given time period
    - Assumptions
      - ✓ Ship experiences a wave repeatedly & independently during its lifetime
      - ✓ Event: occurrence of structural failure while ship goes through a wave
      - ✓ DSL equivalent to no occurrence of the event throughout ship's lifetime

2. Safety Level of LSM

- Calculation of Design Safety Level

To calculate Failure Probability (P_f)
, when the vessel experiences a wave having a specific direction (heading angle) in a given loading condition.

To combine the Probabilities calculated
, in case one wave approaches the vessel
, considering all the possible loading conditions and wave directions.

To estimate Design Safety Level
, that means the probability of no structural failure occurrence throughout the vessel's lifetime.

$$P_{f-LC,\,angle} = \int_{Z<0} Z(LC, angle)$$

$$P_{f-LC} = \sum_{angle} r_{angle} P_{f-LC,\,angle}$$

$$P_{f-one\ wave} = \sum_{LC} r_{LC} P_{f-LC}$$

$$P_{Safe-Design} = P(n=0, T) = e^{-P_{f-one\ wave} T}$$

LC – a given loading condition
angle – a given wave direction (heading angle)
r_{angle} – ratio of each wave direction to 360^{O}
r_{LC} – ratio of each loading condition to lifetime
T – vessel's lifetime (design life)
n – number of occurrence of specific failure event

Homogeneous Poisson Process

$$P(n,T) = \frac{(\lambda T)^n}{n!} e^{-\lambda T} \quad for\ n = 0, 1, 2, \ldots$$

3.

Case Study

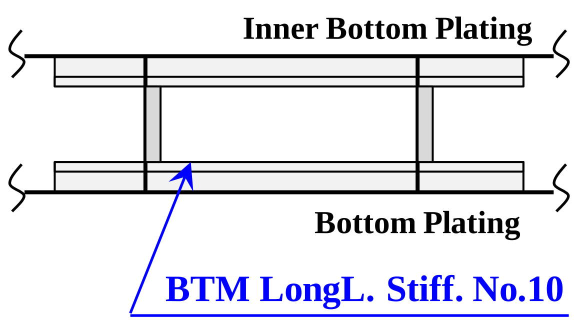
3. Case Study

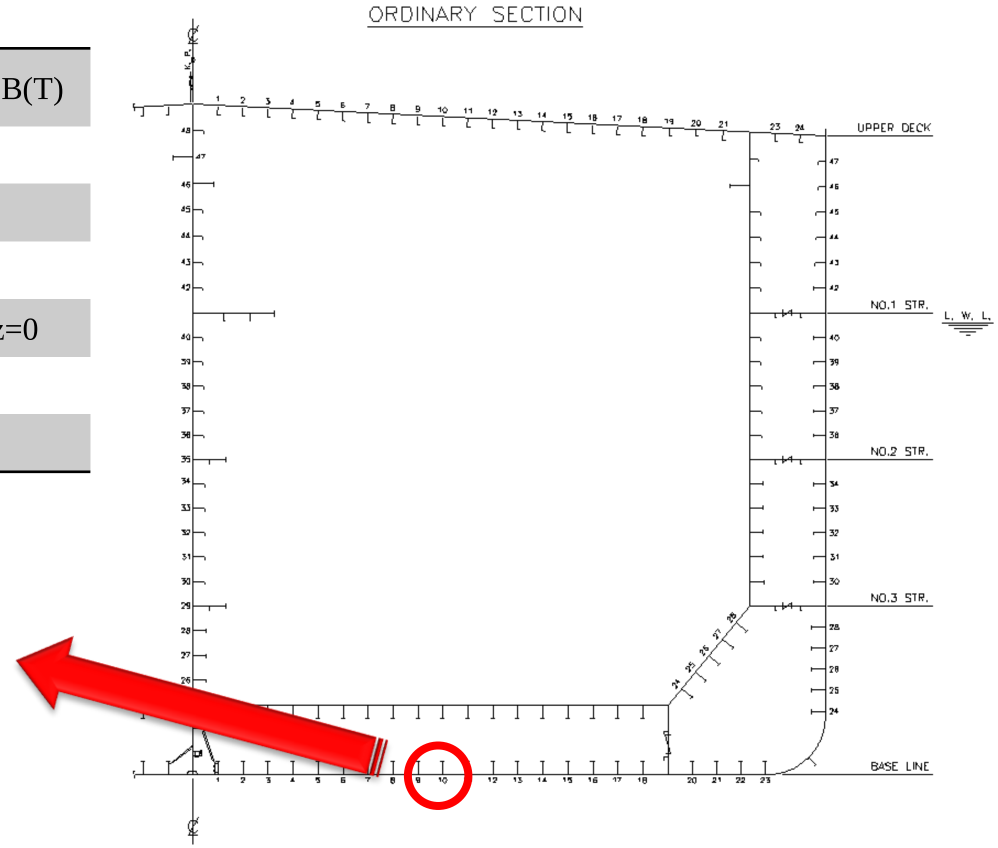
- Step 1. Design Scope (1/3)
  - Subject vessel
    - Type : Double hull oil tanker (AFRAMAX class)
    - Dead weight : 105,000 Ton
    - Principle dimension : 234m (LBP) x 42m (B) x 21.2m (D)
    - Draught : 15m
    - Applied rule : IACS CSR-Oil Tanker, RCN No.1
    - Delivery : September 2008
  - Structural member concerned
    - A bottom longitudinal stiffener located at midship
    - A kind of LSM (local supporting member)
  - Failure mode concerned
    - Yield strength resisting local bending due to both lateral pressure and vertical wave bending moment

3. Case Study

- Step 1. Design Scope (2/3)

Details of Structural Member	
Scantling (gross)	450x11+150x22 F.B(T)
Corrosion addition	3.0 mm
Section modulus (100% net)	1,762.9 cm^3
Material	HT32 (A-grade)
Load calculation point (m)	x=118.34/ y=8.3/ z=0
Stiffener spacing	830 mm
Effective bending span	4.030 m





3. Case Study

- Step 1. Design Scope (3/3)

Design Conditions Assumed

Nominal design life	• 25 years
External environment	• Operating in North Atlantic wave environment for its entire life • Effects of wind, current, ice, low temperature ignored
Internal environment	• Identical to those defined in IACS CSR-Oil Tanker
Loading condition	• Operating for 85% of the design life (non-operating for 15% of the design life) • Full loading condition for 45% of the design life • Normal ballast condition for 40% of the design life
Wave spectrum	• 2-parameter Pierson-Moskowitz spectrum

3. Case Study

- Step 2. Target Safety Level
  - For example, MSC 79/6/15 was considered

Target annual failure probabilities and corresponding reliability indices			
Failure development	Failure consequences		
	Not serious	Serious	Very serious
Ductile failure with reserve strength capacity	$P_f = 10^{-3}, \beta = 3.09$	$P_f = 10^{-4}, \beta = 3.71$	$P_f = 10^{-5}, \beta = 4.26$
Ductile failure with no reserve capacity	$P_f = 10^{-4}, \beta = 3.71$	$P_f = 10^{-5}, \beta = 4.26$	$P_f = 10^{-6}, \beta = 4.75$
Brittle behavior in terms of fracture of instability	$P_f = 10^{-5}, \beta = 4.26$	$P_f = 10^{-6}, \beta = 4.75$	$P_f = 10^{-7}, \beta = 5.20$
$\beta = -\Phi^{-1}(P_f)$, where Φ is the standard normal distribution			

Target Failure Level

= 10^{-4} x 25 years
= 2.5 x 10^{-3} for design life

Target Safety Level
(for entire design life)

$P_{Safe\text{-}Target}$ = 1 – 2.5 x 10^{-3}
= 0.9975

3. Case Study

- Step 3-1. Limit State Equation
  - Structural member
    - Longitudinal ordinary stiffener
  - Failure mode
    - Yield failure of local stiffener, due to local bending
  - Loads
    - Local load - lateral pressure
    - Global load - vertical wave bending moment

$$Z = R - L = \sigma_{LMT} - \sigma_{Working}$$

$$\sigma_{Working} = \left(P_{WK-Stat} + P_{WK-Dyn}\right)\frac{s\ell^2}{f_{bend} z_{stiff}} + \left(M_{WK-Stat} + C_{Scale} M_{WK-Dyn}\right)\frac{0.001 d_{vert}}{I_{HG-vert}}$$

3. Case Study

- Step 3-2. Design Variables (1/3)
  - Stochastic modeling of the design variables

Design Variables	Unit	Distribution Type	Distribution Parameters	Reference
σ_{LMT}	N/mm²	Lognormal	Mean=348/ CoV=0.06	MSC 81/INF.6
$P_{WK\text{-}Stat}$	kN/m²	Constant	150.829 for full loading 69.884 for normal ballast	IACS CSR-Oil Tanker
$P_{WK\text{-}Dyn}$	kN/m²	Weibull	Refer to the next slide	DLA (Direct Load Analysis)
$M_{WK\text{-}Stat}$	kN-m	Normal	Mean=1,950,228/ CoV=0.2857	MSC 81/INF.6 (70% of permissible moment considered for the example)
$M_{WK\text{-}Dyn}$	kN-m	Weibull	Refer to the next slide	DLA (Direct Load Analysis)
s, ℓ	mm, n	Normal	Mean=830, 4.03/ CoV=0.04	SSS-93
f_{bend}	-	Constant	12 for both ends fixed	IACS CSR-Oil Tanker
z_{stiff}	cm³	Normal	Mean=1762.9/ CoV=0.04	SSS-93
C_{Scale}	-	Constant	Refer to the next slide	DLA & IACS UR S11
d_{vert}	m	Normal	Mean=8.845/ CoV=0.04	SSS-93
$I_{HG\text{-}vert}$	m⁴	Normal	Mean=354.492/ CoV=0.04	SSS-93

3. Case Study

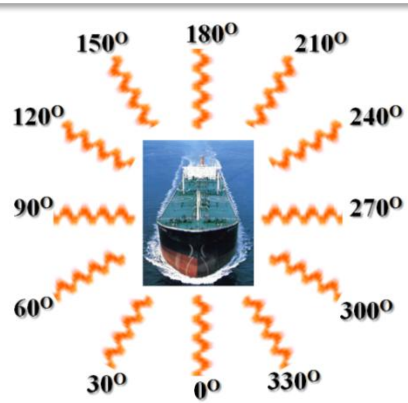
- Step 3-2. Design Variables (2/3)
  - Stochastic modeling of dynamic lateral pressure

Weibull Distribution

- Lower bound = 0
- h: shape parameter
- q: scale parameter

$$P_{WK-Dyn} = F(x) = 1 - e^{-\left(\frac{x}{q}\right)^{h}}$$

[kN/m²]



Heading Angle (degree)	Full Loading Condition		Normal Ballast Condition	
	Shape Parameter	Scale Parameter	Shape Parameter	Scale Parameter
0	1.03737	1.68135	1.04434	1.73038
30	1.03464	1.98516	1.04854	1.70500
60	1.03056	2.38922	1.05558	1.59753
90	1.02734	2.70590	1.05422	1.47172
120	1.02567	2.48912	1.05489	1.49974
150	1.02644	1.88106	1.05284	1.63043
180	1.04162	1.43410	1.05308	1.67741
210	1.02964	2.77332	1.05512	2.52563
240	1.02707	3.67518	1.05519	2.85417
270	1.02720	4.26562	1.05403	3.16280
300	1.03519	3.63436	1.05661	2.69334
330	1.03740	2.72686	1.05540	2.33878

It is assumed the occurrence probability of each heading angle is 0.0833 (=1/12).

3. Case Study

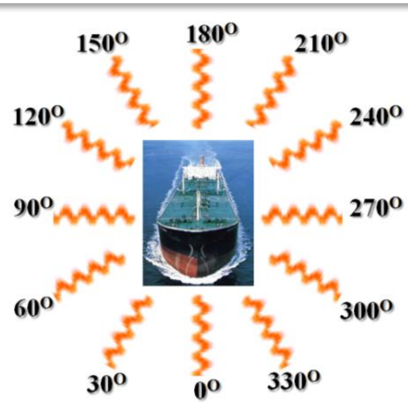
- Step 3-2. Design Variables (3/3)
  - Stochastic modeling of vertical wave bending moment

Weibull Distribution

- Lower bound = 0
- h: shape parameter
- q: scale parameter

$$M_{WK-Dyn} = F(x) = 1 - e^{-\left(\frac{x}{q}\right)^{h}}$$

[kN-m]



Heading Angle (degree)	Full Loading Condition			Normal Ballast Condition		
	Shape Para.	Scale Para.	C_{Scale}	Shape Para.	Scale Para.	C_{Scale}
0	1.02534	270034	0.826	1.03677	229781	1.000
30	1.03145	254465	0.891	1.04077	212142	1.000
60	1.05452	231936	1.000	1.05602	173345	1.000
90	1.05484	203519	1.000	1.05810	153381	1.000
120	1.04259	223626	1.000	1.05848	195326	1.000
150	1.02804	265590	0.846	1.05055	239661	0.993
180	1.02294	282137	0.785	1.04797	256419	0.923
210	1.03145	254465	0.891	1.04077	212142	1.000
240	1.05452	231936	1.000	1.05602	173345	1.000
270	1.05484	203519	1.000	1.05810	153381	1.000
300	1.04259	223626	1.000	1.05848	195326	1.000
330	1.02804	265590	0.846	1.05055	239661	0.993

It is assumed the occurrence probability of each heading angle is 0.0833 (=1/12).

3. Case Study

- Step 4. Structural Reliability Analysis
  - By MC simulation & AFOSM (Advanced First Order Second Moment)

Heading Angle (degree)	Probability of Failure	
	Full Loading $P_{f\text{-full, angle}}$	Normal Ballast $P_{f\text{-ballast, angle}}$
0	8.79 x 10^{-12}	2.82 x 10^{-16}
30	9.26 x 10^{-12}	2.85 x 10^{-17}
60	6.25 x 10^{-12}	6.04 x 10^{-20}
90	1.22 x 10^{-12}	2.93 x 10^{-21}
120	5.65 x 10^{-12}	9.58 x 10^{-19}
150	9.07 x 10^{-12}	2.46 x 10^{-16}
180	8.42 x 10^{-12}	2.59 x 10^{-16}
210	1.03 x 10^{-11}	3.15 x 10^{-17}
240	7.69 x 10^{-12}	7.56 x 10^{-20}
270	1.77 x 10^{-12}	4.26 x 10^{-21}
300	6.79 x 10^{-12}	1.14 x 10^{-18}
330	1.01 x 10^{-11}	2.66 x 10^{-16}

$$P_{f-ballast} = \sum_{angle} r_{angle} P_{f-ballast,\ angle}$$

$$P_{f-full} = \sum_{angle} r_{angle} P_{f-full,\ angle}$$

- r_{angle}
  : it is assumed to be 0.083 (equally).

$$P_{f-one\ wave} = r_{full} P_{f-full} + r_{ballast} P_{f-ballast}$$

- r_{full} = 0.45 (ratio of full loading cond.)
- $r_{ballast}$ = 0.40 (ratio of normal ballast cond.)

Therefore,

$$P_{f-one\ wave} = 3.199 \times 10^{-12}$$

3. Case Study

- Step 5. Design Safety Level
  - Design safety level ($P_{Safe\text{-}Design}$) was estimated
    - on the basis of HPP (Homogeneous Poisson Process)

$$P(n)_{T=total\ number\ of\ waves} = \frac{(\lambda T)^n}{n!} e^{-\lambda T} \quad for\ n = 0, 1, 2, \ldots$$

• It means, within the time interval (T), a specific event having the intensity of λ could occur n-times independently with the probability of P(n).

$$P_{Safe-Design} = P(0)_{T=10^8} = \frac{(P_{f-one\ wave}10^8)^0}{0!} e^{-P_{f-one\ wave}10^8} = e^{-P_{f-one\ wave}10^8}$$

• Structural failure when the vessel experiences one wave is defined as the event

• T is defined as 10^8 , based on the assumption that one wave approaches the vessel every 10 seconds

• $P_{Safe\text{-}Design}$ means the probability of no event occurrence throughout the design life of 25 years

➔ $n = 0$ & $\lambda = P_{f\text{-}one\ wave}$

• Therefore,

$$P_{Safe-Design} = P(0)_{T=10^8} = e^{-(3.199\times10^{-12})\times10^8} = 0.9997$$

3. Case Study

- Step 6. Structural Safety Evaluation
  - Current design of the stiffener is safe enough both
    - From a viewpoint of "safety level approach"
      - ✓ Calculated DSL is larger than the TSL defined
      - ✓ $P_{Safe\text{-}Design} = 0.9997 > P_{Safe\text{-}Target} = 0.9975$
    - From a viewpoint of "deterministic approach"
      - ✓ Actual S.M. is larger than the required S.M. by IACS CSR
      - ✓ $S.M_{net\text{-}Actual} = 1762.9\ cm^3 > S.M_{net\text{-}Req} = 1317.98\ cm^3$
  - Further examination on design modification

Case	Dimension	Actual net S.M. (cm^3)	Design safety level	Assessment based on: Deterministic approach (IACS CSR)	Assessment based on: Safety level approach
Original	450x11 + 150x22 F.B(T) HT32	1762.9	0.9997	**SAFE**	**SAFE**
Revision 1	450x11 + 150x20 F.B(T) HT32	1675.5	0.9990	**SAFE**	**SAFE**
Revision 2	450x11 + 150x18 F.B(T) HT32	1507.8	0.9877	**SAFE**	**FAIL**

4.

Conclusion

4. Conclusion

- In this study,
  - Necessity of Risk-based design/approval for ship was mentioned
  - Safety level based procedure for scantling assessment was proposed
  - Regarding yield strength of LSM (e.g. longitudinal stiffener),
    - limit state equation was formulated
    - stochastic modeling of dynamic loads by using DLA was attempted
    - design safety level calculation based on failure probability was invented
  - And, calculation of one example case was carried out
- As a result,
  - It has been found that specific safety level of a given structural design could be quantified in consideration of;
    - ship's operating scheme (i.e. time dependent safety level) as well as
    - deviation, that is potential while constructing, from the intended design

4. Conclusion

- Consideration on Applicability
  - Target safety levels for ship structural members are to be established,
    - on the basis of agreement among various maritime stakeholders
  - Regarding design variables, the followings are needed;
    - Loads – more active utilization of direct load analysis
    - Material – statistical analysis of measured data on material properties
    - Fabrication – investigation on the quality control capacity of ship-yards
    - Modeling – theoretical research on related mechanics
  - Calculation tools should be provided to users;
    - S/W for DLA – several S/Ws were developed well and are being used
    - S/W for Statistical analysis of DLA results – further development necessary
    - S/W for SRA – several S/Ws were developed well and are being used
    - S/W for GUI – possible to use the scantling S/W with slight modification

THANK YOU FOR YOUR ATTENTION!