Very Large Floating Structures for the future
NTNU, Oct 28-29, 2004

Structural Analysis for Design of VLFS

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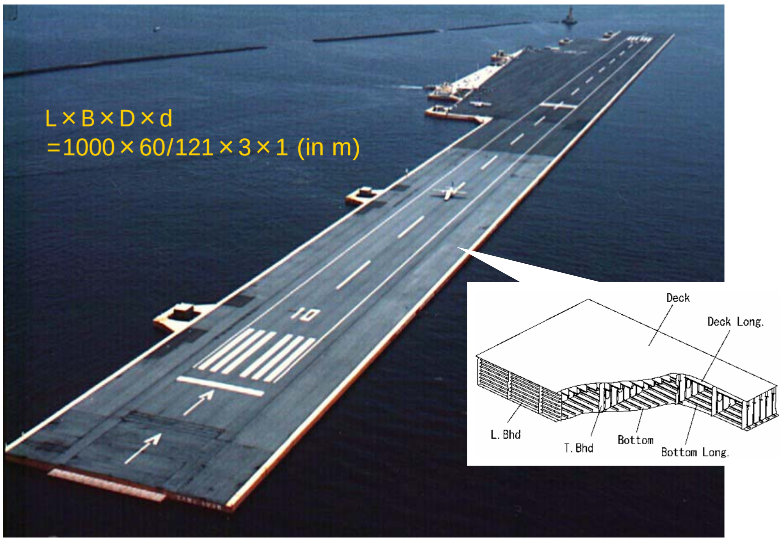
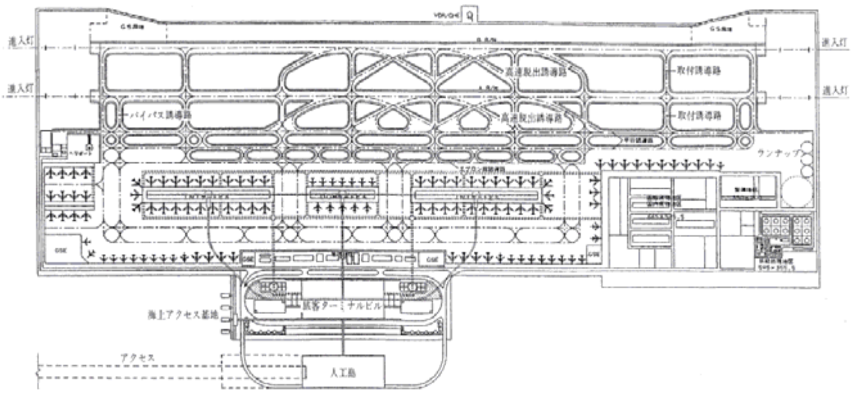
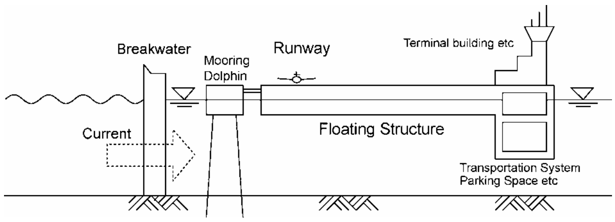
1000m Floating Airport Model

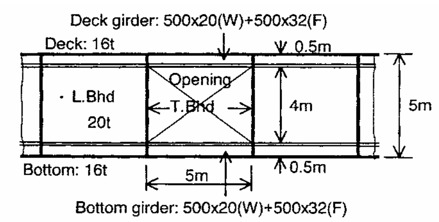


5000m Floating Airport Model

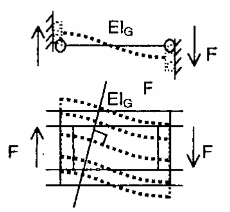


Use of internal space





Opening of bulkhead



Shear bending

Analysis necessary for structural design

- Global hydroelastic response analysis
- Stress analysis of local structures and members
  - Structural modeling technique
  - Hierarchical system of analysis
- Nonlinear collapse analysis
  - Estimate of damages
  - Estimate of ultimate collapse mode and failure scenario

Outline of Presentation

1. Design Limit States
2. Structural modeling for global analysis
3. Stress analysis of local structures
4. Collapse analysis
   - Damage due to accidents
   - Collapse in waves
5. Overall safety evaluation

Strength Limit States

Limit states	Definition	Remark
Allowable strength limit state	A state in which a structure or principal structural member reaches a strength limit state, where a slight damage that will not hinder the use of the structure may occur.	ULS (Ultimate Limit State) check, in more conventional term, for component level based on global elastic response analysis
Ultimate strength limit state	A state in which a structure or a principal structural member reaches a full collapse state, where a structural damage dangerous to human lives, a sinking or a drifting occurs.	PLS (Progressive collapse Limit State) check for system level when subjected to abnormal load effects
Fatigue limit state	A state in which cracks initiate and propagate due to fatigue caused by a repeated load and the load bearing capacity of the member starts to decrease.	
State after partial damage	A state in which load redistribution due to some damage makes the other sound structural members or structure damaged.	PLS check for system level when subjected to damages or accidental load effects

Characteristic Loads and Load Combinations for Strength Limit States

Limit state	Dead load	Live load	Environmental loads	
			Case A	Case B
Allowable strength limit state	Mean	Max/Min values	Class 1	
				Class 1
Ultimate strength limit state	Mean	Max/Min values	Class 2	
				Class 2
Fatigue limit state	Mean	Max or load frequency	Expected load frequency	-
State after partial damage	Mean	Max/Min values	Class 0	-

Case A: wave, wind, current and others excluding Case B
Case B: earthquake, seaquake, tsunami and storm surge

Class 0: Return period of 2 years
Class 1: Return period of at least 2 times service years
Class 2: Return period of at least 100 times service years

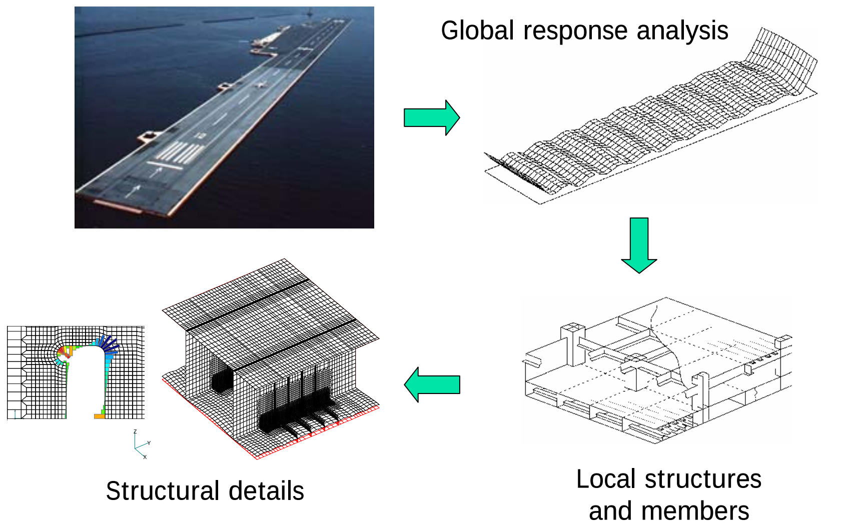
Functionality Limit States

- Limit state corresponding to the criteria applicable to normal use
- Typical example for a floating airport:

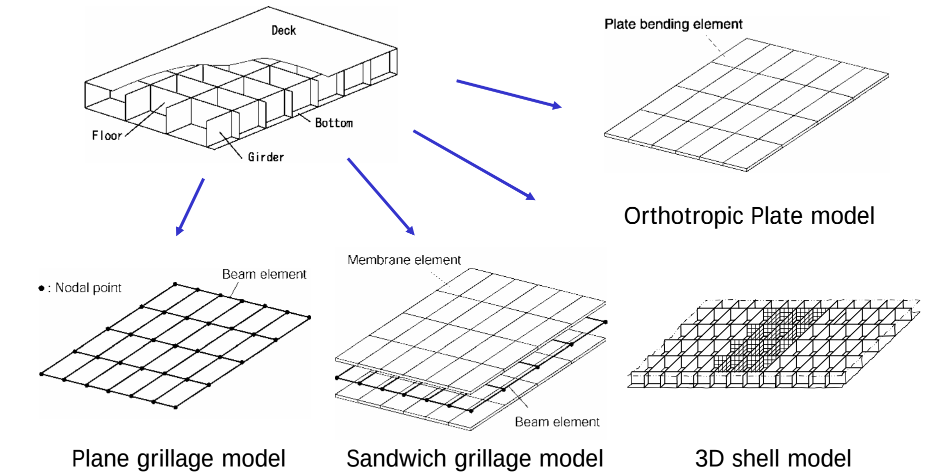
  Radius of curvature of runway > 30000 m

- Class-0 environmental loads are considered.
- Functionality requirements are generally severe in VLFS that is used for a foundation of upper structure.

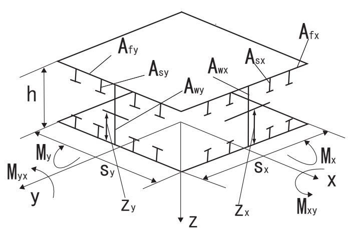
Hierarchical System of Analysis

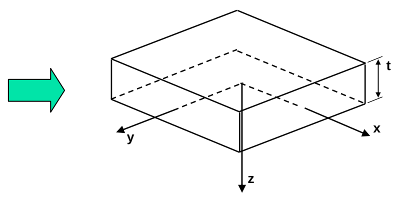


Model for Global Response Analysis



Orthotropic Plate Model





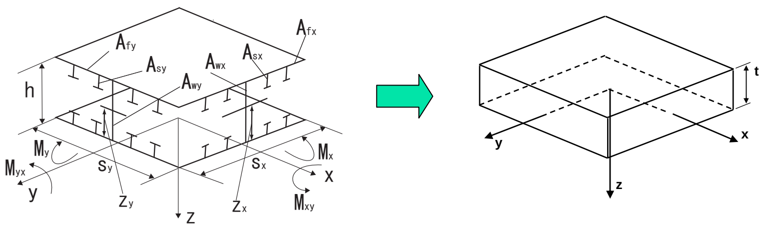
$$\begin{Bmatrix} M_x \\ M_x \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} D_x & D_{xy} & 0 \\ D_{yx} & D_y & 0 \\ 0 & 0 & G_{xy} \end{bmatrix} \begin{Bmatrix} -\frac{\partial^2 w}{\partial x^2} \\ -\frac{\partial^2 w}{\partial y^2} \\ -2\frac{\partial^2 w}{\partial x \partial y} \end{Bmatrix}$$

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \frac{t^3}{12} \begin{bmatrix} \frac{E_1}{1-\nu_{12}\nu_{21}} & \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & \frac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \begin{Bmatrix} -\frac{\partial^2 w}{\partial x^2} \\ -\frac{\partial^2 w}{\partial y^2} \\ -2\frac{\partial^2 w}{\partial x \partial y} \end{Bmatrix}$$

$$D_x s_x = \frac{E}{1-\nu^2} I_{fx} + E\left(I_{sx} + I_{wx}\right) \qquad D_y s_y = \frac{E}{1-\nu^2} I_{fy} + E\left(I_{sy} + I_{wy}\right)$$

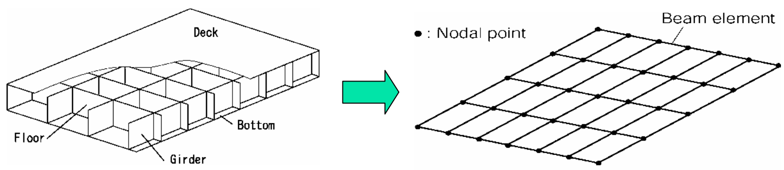
$$D_{xy} = D_{yx} = \frac{E\nu}{1-\nu^2} I_{fx} / s_x \qquad G_{xy} = \frac{E}{2(1+\nu)} I_{fx} / s_x$$

Orthotropic Plate Model



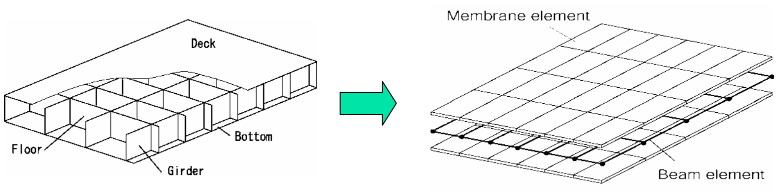
- Both bending and shear stiffness can be made equivalent.
- Applicable to both analytical and FEA approaches.
- Local structural configuration like a web opening cannot be modelled.

Plane Grillage Model



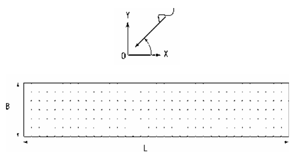
- Beam-element model
- Deck and bottom panels are considered as an effective flange of beam elements.
- Equivalent torsional stiffness based on the equivalence of strain energy (Fujikubo, 2001)
- Effect of web opening can be considered in beam stiffness.
- Poisson's effect cannot be considered.

Sandwich Grillage Model



- Girders and floors: Beam elements
- Deck and bottom plate panels: Membrane elements
- Deck and bottom longitudinals: included in beam elements
- D.O.F.s of membrane elements are expressed as a function of those of beam elements based on Kirchihoff-Love hypothesis.
- Effect of web opening can be considered.
- Poisson's effect and torsional stiffness can be considered.

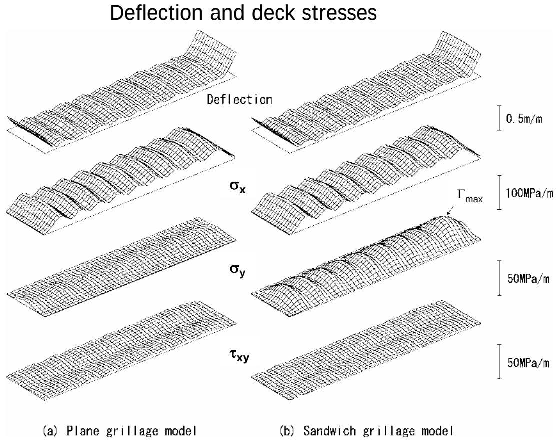
Comparison of Two Grillage Models



LxBxDxd=
1200x240x4.5x1.0 (m)

λ/L=0.08, θ=0deg

Deflection and deck stresses



Neglect of Poisson's effect in plane grillage model leads to a significant error in the estimate of stresses in VLFS. Hence, orthotropic plate model or sandwich grillage model is recommended.

Stress Analysis of Local Structures

One step method

- Local structural configurations are considered in global hydroelastic response analysis.
- The stress of local members is directly obtained.

Two step method

- Simplified structural model is employed in global hydroelastic response analysis.
- The results, e.g. external-force or cross-sectional force distributions, obtained by the first-step analysis are applied to more detailed structural models quasi-statically.

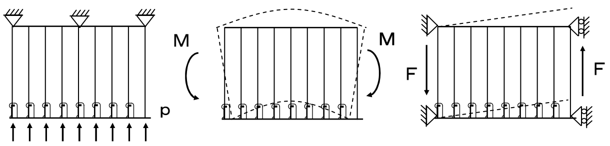
$$[K_2]\{d\} = \{F_{W1}\} - [M_1]\{\ddot{d}_1\} - [N_1]\{\dot{d}_1\}$$ (1: first step, 2: second step)

Stress Analysis of Local Structures

For further structural details, zooming analysis is performed.

Stress factor method to consider combined load effects (Inoue, 2002)

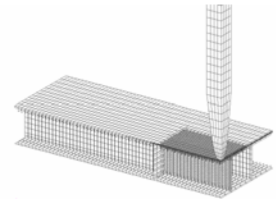
$$\sigma = (\sigma_{0p} \times p) + (\sigma_{0M} \times M) + (\sigma_{0Q} \times Q)$$



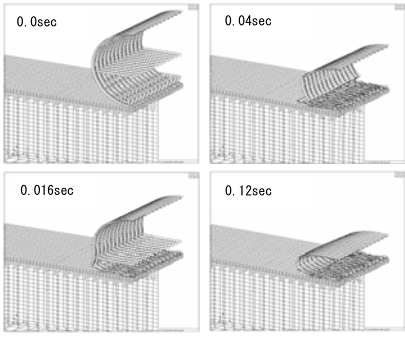
Local pressure   Transverse bending moment   Vertical shear

Stress factors that represent the local stress due to unit load components (pressure, moment, shear etc.) are calculated by zooming model with appropriate boundary conditions. The contributions of each load components are summed up considering their amplitude and phase obtained by the global analysis.

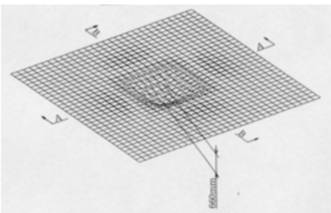
Analysis of Accidental Damages



Airplane crash (Vertical fall)



Airplane crash (Body landing)



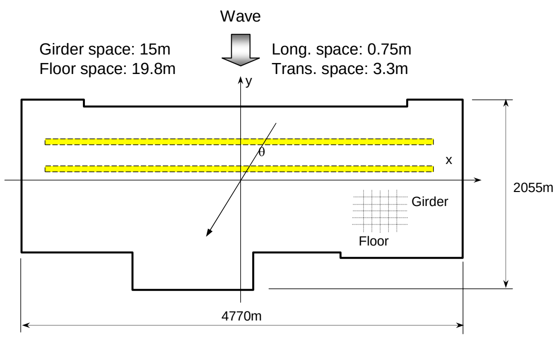
Flooding

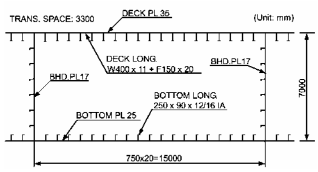
Analysis of global collapse in waves

Objectives

- To develop a method of progressive collapse analysis of VLFS
- To examine the collapse behavior of a pontoon-type VLFS in abnormal waves as a part of the Ultimate Strength Limit State Check

Floating Airport Model

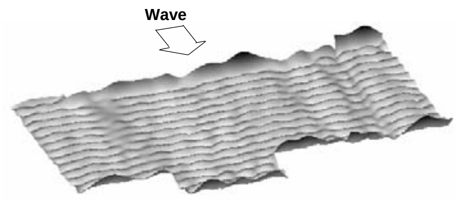




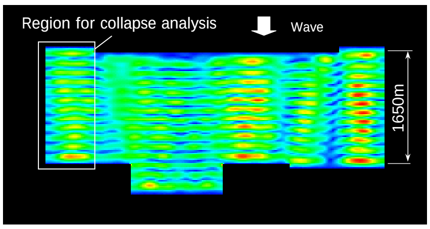
Hydroelastic Global Response Analysis

Hydroelastic response analysis: 3D detailed method by Prof. Seto

Structural model: Equivalent orthotropic model



Deflection amplitude



Bending stress amplitude

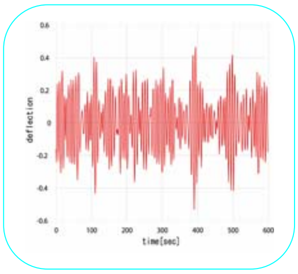
in transverse regular wave（T_w=7sec)

Quasi-static Collapse Analysis

Two step method

1st step:

Analysis of hydroelastic global response
Generation of time history of external loads distributions in irregular waves



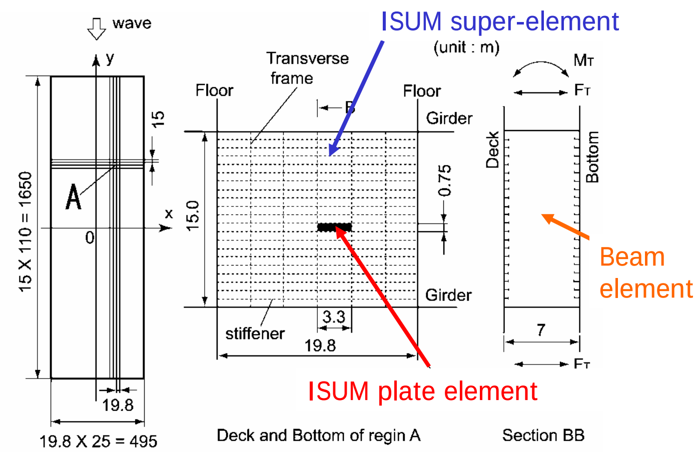
2nd step:

Quasi-static collapse analysis of VLFS mounted on elastic buoyancy spring using Idealized Structural Unit Method (ISUM) (Fujikubo and Kaeding, 2002)

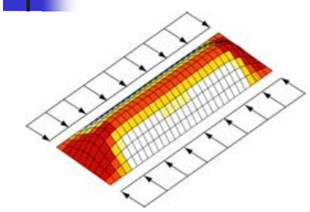
$$[K_{ISUM}^{NL}]\{d\} = \{F_{ext}(t)\}_{hydroelasic\_response\_analysis}$$

Structural Modeling for Collapse Analysis

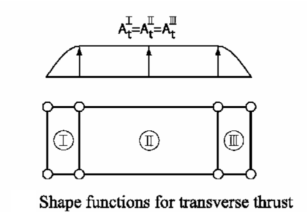
Sandwich grillage model with both bending and in-plane D.O.F.s is used to allow a shift of neutral axis due to buckling/yielding.



Idealized Structural Unit Method



Collapse mode under transverse thrust



ISUM Plate element

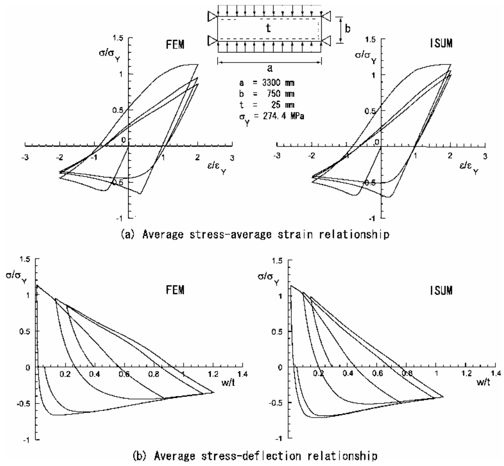
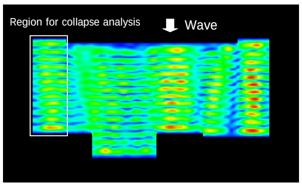
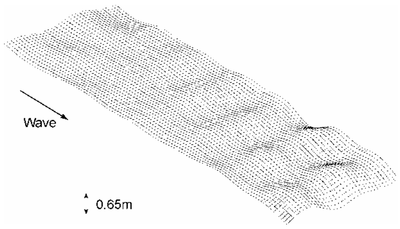


Plate under cyclic in-plane load

Collapse Behavior in Irregular Waves

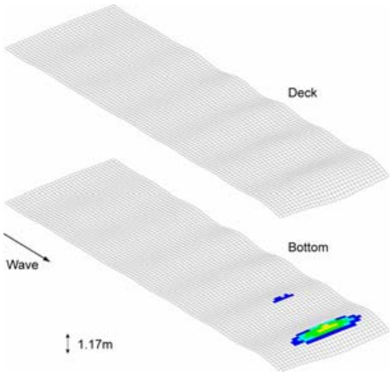


Bending stress amplitude



Multi-directional irregular wave

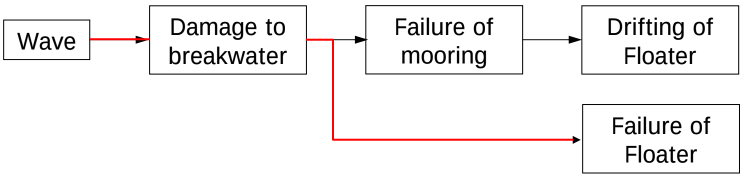
Spread of collapse region



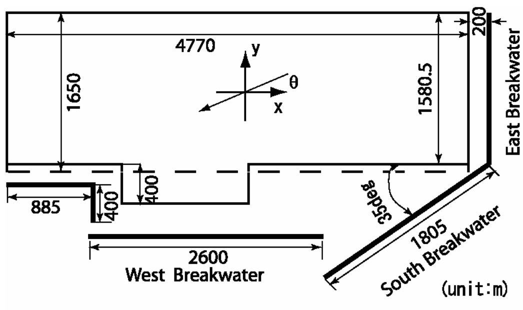
Assumed uni-directional irregular wave

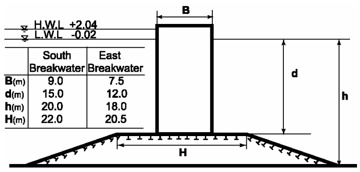
Structural Safety Assessment of a Pontoon-Type VLFS Considering Damage to the Breakwater

As a part of risk-based safety assessment of VLFS



Objective Structure

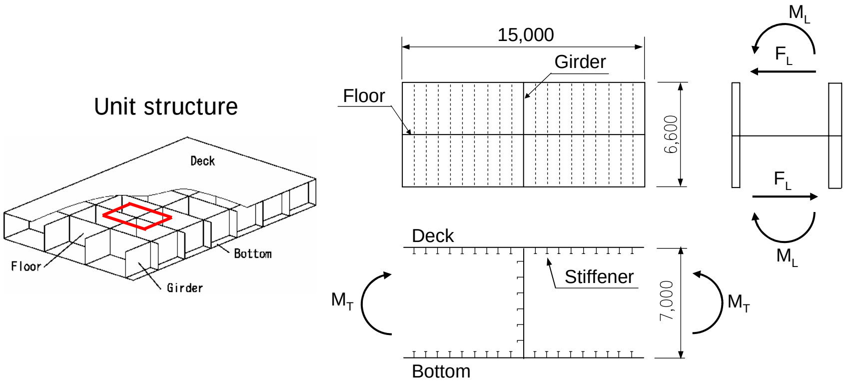




	South Breakwater	East Breakwater
B(m)	9.0	7.5
d(m)	15.0	12.0
h(m)	20.0	18.0
H(m)	22.0	20.5

Failure modes

Breakwater: Overturning
VLFS: Bending and shear collapses of a unit structure

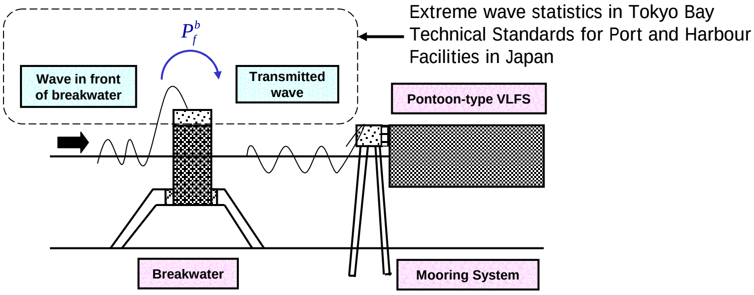


Probability of Structural Failure

$$P_f = (1 - P_{fb}) P_{f\_intact} + P_{fb} P_{f\_damaged}$$

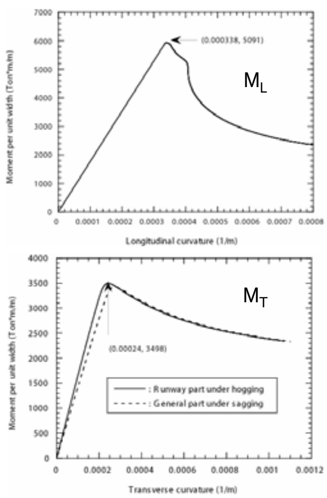
P_{fb} : Probability of overturning of breakwater

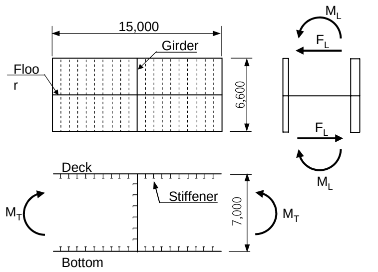
P_{f_intact}, $P_{f\_damaged}$: Conditional probability of structural failure in intact and damaged conditions of breakwater



Ultimate strength and failure function

Bending Moment – Curvature Relationship of Unit Structure (ISUM)





Ultimate strength Hydroelastic response

$$Z_M = M_u(E,\sigma_Y) - M_w \le 0$$
$$Z_F = F_u(E,\sigma_Y) - F_w \le 0$$

FOSM

P_{f_cond}

Annual Probability of Structural Failure Considering Damage to Breakwater

Longitudinal waves

	Bending Collapse		Shear Collapse	
P_{f_cond}	P_{f_intact}	$P_{f\_damaged}$	P_{f_intact}	$P_{f\_damaged}$
	$<1.0\times10^{-25}$	1.8×10^{-6}	$<1.0\times10^{-25}$	6.3×10^{-6}
P_f	1.0×10^{-9}		3.6×10^{-8}	

Transverse waves

	Bending Collapse		Shear Collapse	
P_{f_cond}	P_{f_intact}	$P_{f\_damaged}$	P_{f_intact}	$P_{f\_damaged}$
	$<1.0\times10^{-25}$	7.4×10^{-3}	$<1.0\times10^{-25}$	1.0×10^{-11}
P_f	3.2×10^{-7}		4.6×10^{-16}	

$P_f < 1\times10^{-6}$ (Target level proposed by Prof. Suzuki)