Ph. D. Thesis Presentation

Hydro-elastoplastic analysis of floating plate structures

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Mechanical Engineering
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KAIST

CMSS
Computational Mechanics and Structural Systems.

Contents

Introduction

- Introduction to hydrodynamic analysis
- Brief history
- Methods for hydroelastic analysis
- Related problems and studies
- Research problems

Introduction to hydrodynamic analysis

Figure source : google image

❖ **Offshore market demands**

- **Resources**
- **Space**

↑

❖ **Design of floating structures**

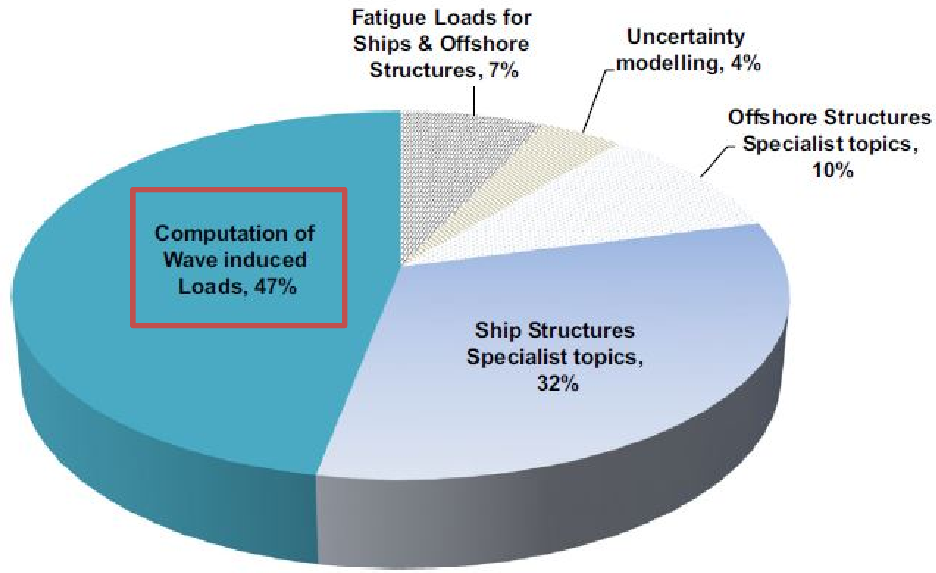
- **Complexity**
- **Size**
- **Risk**

↑

Importance of hydrodynamic analysis of floating structures has been increasing

Introduction to hydrodynamic analysis

Video source : YouTube



Research development activities (2009~2012)

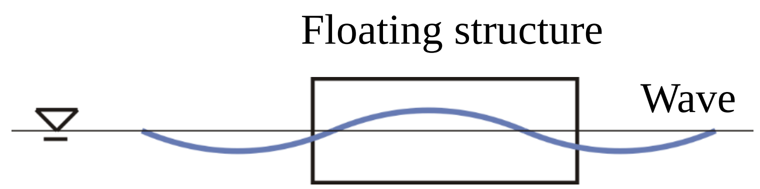
Hirdaris et al., *Loads for use in the design of ships and offshore structures. Ocean Eng 2014;78:131-74.*

Floating structure - wave interaction is a key topic

Introduction to hydrodynamic analysis

❖ Problems of the interaction

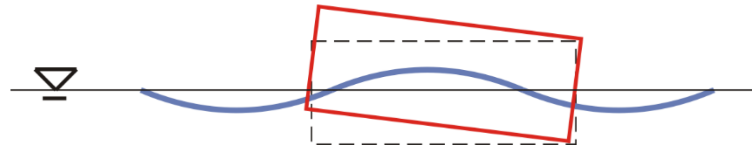
- Be coupled together
- Need to be solved simultaneously



Assumption : Static equilibrium state

Problem 1. Structural dynamics

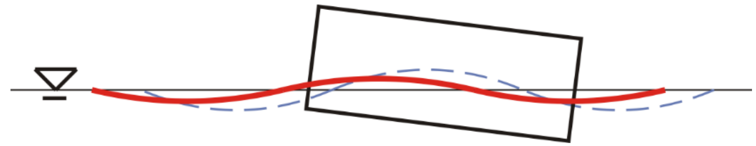
- Motions of floating structures responding to wave-induced forces



Problem 3. Coupling

Problem 2. Hydrodynamics

- Waves responding to motions of the wetted surface of the structures



Brief history

❖ Events in the hydrodynamic analysis of floating structure – wave interaction

1980s

1990s

2000s

Rigid - body motion analysis

- Pioneering works on the motion of floating rigid bodies in frequency and time domain
- Dealing with various problems of potential flows and hydrodynamics
- Lamb(1945), John (1950), Stoker(1956), Wehausen (1960), Cummins(1962), Newman(1977), …

- Development of numerical methods for rigid body - wave interactions in frequency domain
- WAMIT - WaveAnalayisMIT(MIT, 1987)

- Development of numerical methods for rigid body - wave interactions in time domain
- TiMIT(MIT,1999)

- Improve numerical algorithms for complex structure – nonlinear wave interactions

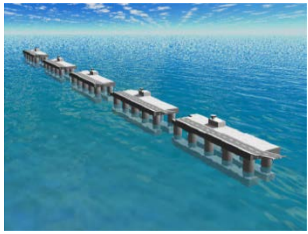
Hydroelastic analysis

- 2D hydroelastic analysis of **ships** in frequency domain developed by Bishop (1979)

- 3D hydroelastic analysis of **ships** extended by Wu (1984)

Mega-float

- Research projects for very large floating structures(VLFS)
- Mega-float(Japan, 1995-2001)
- MOB - Mobile Offshore Base(USA, 1997-2000)



MOB

- Development of numerical methods for hydroelastic analysis of VLFS in frequency and time domain
- Kashiwagi(2000), Khabakhpasheva(2002), Taylor(2007), …
- 3D floating structures – wave interactions in frequency domain
- HYDRAN(Riggs, 2003)
- PADO(CMSS, 2013)

Methods for hydroelastic analysis

❖ Floating elastic plate structure – wave interactions

Floating Airport

Floating Bridge

Features of pontoon-type VLFSs

- Huge horizontal size compared to the wavelengths
- Relatively small bending rigidity

Considerations in the analysis

- Elastic deformations are more important than rigid body motions
- Hydroelastic analyses should be performed to accurately predict the bending moment and deflection
- The VLFSs have mainly been modeled as thin elastic plate structures

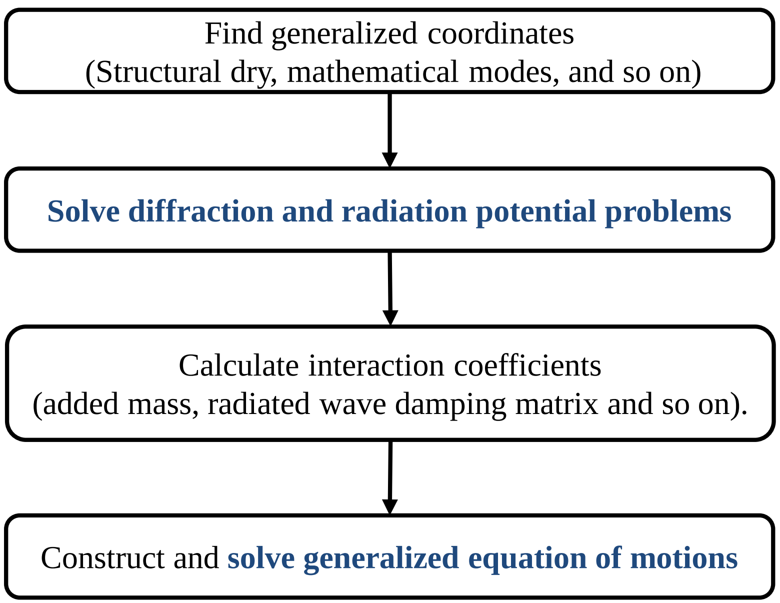
Methods for hydroelastic analysis

❖ Frequency-domain analysis

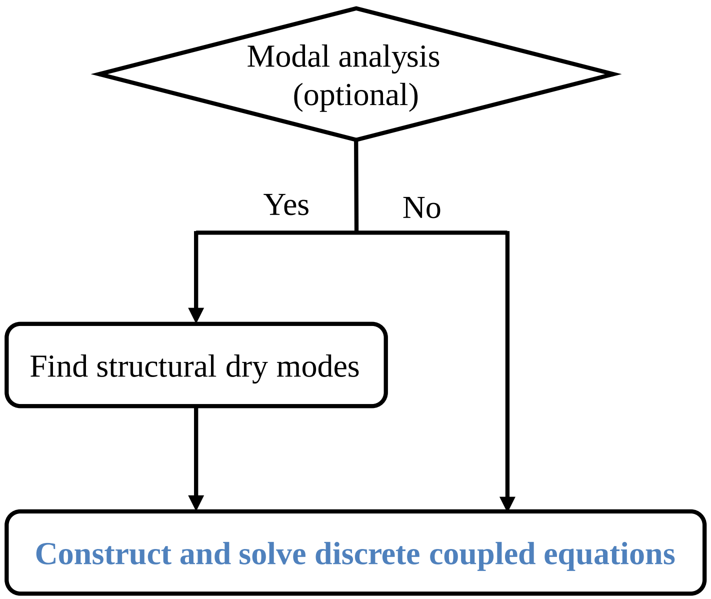
		Descriptions	
Structural dynamics	Modal Expansion Method	▪ **Modal functions** as dry modes or simple mathematical modes of a structure	▪ Free-free beam modes(Maeda 1995, Ohmatsu 1998) ▪ 2D polynomial functions(Wang 2001) ▪ Eigenvectors(PADO 2013)
	Direct Method	▪ Solving **directly** structural dynamic problems without any help of modal functions	▪ FEM(Yago 1996, Kim 2007, HYDRAN 2003, PADO 2013) ▪ B-spline Galerkin scheme(Kashiwagi 1998)
Hydro-dynamics (based BEM)	Free-surface Green Function Method	▪ Discretizing **only wetted surface** of structures in boundary integral equations	▪ CPM-Constant panel method(HYDRAN 2003) ▪ BEM(Yago 1996, PADO 2013) ▪ B-spline(Kashiwagi 1998)
	Rankine Panel Method	▪ Discretizing **all boundary surfaces** in boundary integral equations	▪ HOBEM-Higher Order BEM(Kim 2007)
Coupling (Solution procedure)	Conventional Method	▪ Solving **step by step** potential problems and structural dynamic problems	▪ In most studies ▪ HYDRAN
	$\boxed{\text{Direct Coupling Method}}$	▪ Solving **simultaneously** coupled structural and fluid equations	▪ Floating beam structure (Khabakhpasheva 2002) ▪ Floating plate structure(Taylor 2007) ▪ 3D floating structure(PADO 2013)

Methods for hydroelastic analysis

Conventional method



Direct coupling method



K.T. Kim, P.S. Lee and K.C. Park , A direct coupling method for 3D hydroelastic analysis of floating structures, Int J Numer Meth Eng 2013:96:842-66

Methods for hydroelastic analysis

❖ Time-domain analysis

		Descriptions	
Hydro-dynamics	Direct Integral Method	▪ Solving time-dependent structure and fluid equations by a **direct integration**	▪ FEM-CPM(Liu 2002) ▪ FEM(Qiu 2005, Kyoung 2006) ▪ Green-Naghdi theory – FDM(Ertekin 2014)
	Cummins Method	▪ Deriving time-dependent hydrodynamic forces by the **convolution integral and impulse response functions**	▪ Modal Expansion Method - BEM (Kashiwagi 2000) ▪ FEM - HOBEM(Lee 2003)

❖ Convolution integral

Arbitrary time dependent input → LTI system (Impulse response $irf(t)$) → Corresponding response

$ip(t)$ → $rp(t)$

By the convolution integral, the response to the input $ip(t)$ is given by:

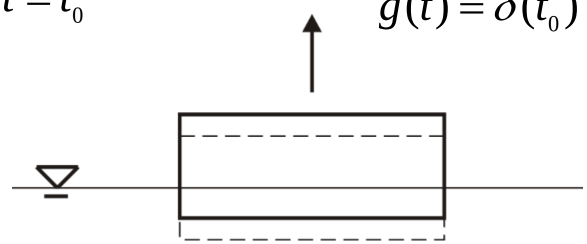
$$\boxed{rp(t) = \int_{-\infty}^{\infty} irf(t-\tau)\, ip(\tau)\, d\tau}$$

Methods for hydroelastic analysis

❖ Concepts of the Cummins method

- **Impulsive velocity of floating structures**

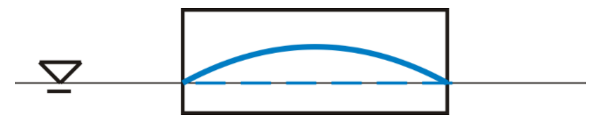
$t = t_0$ $\quad$ $\dot{g}(t) = \delta(t_0)$



μg	: Heave motion
μ	: Heave mode
$g(t)$	: Magnitude of heave mode

Impulse response functions

$t = t_0$



Added mass at infinite frequency $[A]$

$t > t_0$

Memory function $[B(t)]$

- **Impulsive wave elevation**

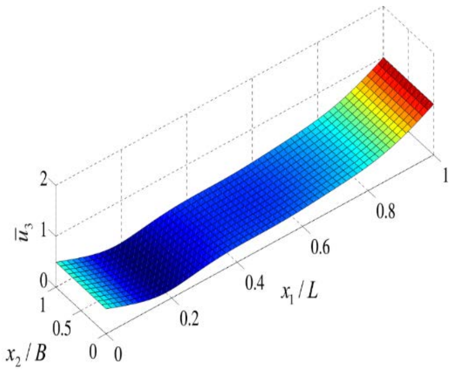
$\eta(t) = \delta(t)$ $\quad$ Diffraction impulse – function $[D(t)]$

By the **convolution integral**, the hydrodynamic forces at time t are given by:

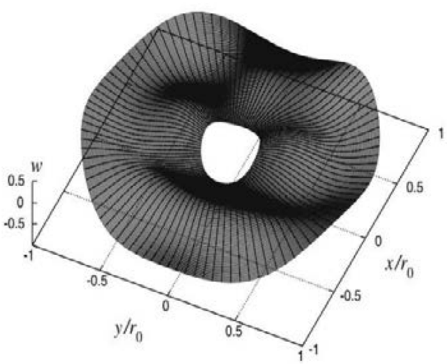
$$R_{HF}(t) = A\ddot{g}(t) + \int_{-\infty}^{t} B(t-\tau)\dot{g}(\tau)d\tau + \int_{-\infty}^{\infty} D(t-\tau)\eta(\tau)d\tau$$

Related problems and studies - Frequency-domain analysis

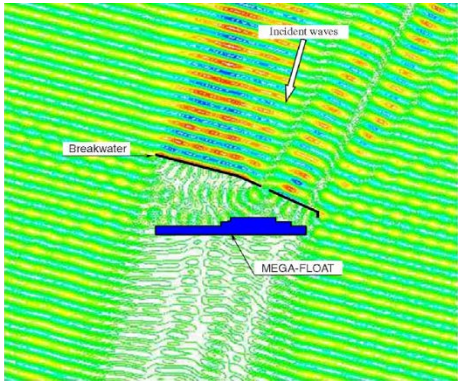
❖ Hydroelastic responses of VLFS considering various conditions



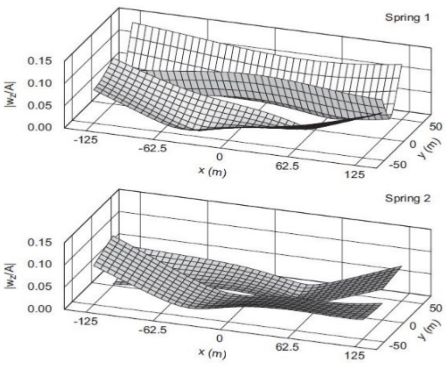
J.S.Yoon, et al., Mar Struct. 2014;36;65-87



A.I.Andrianov, J Eng Math. 2006;54;31-48

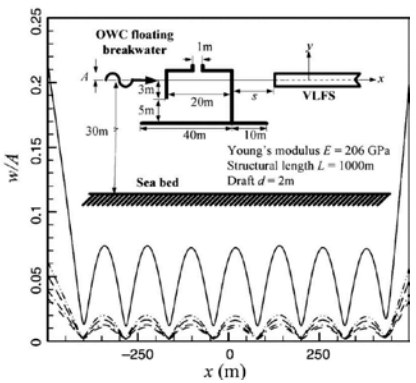


H.Seto, et al., Mar Struct. 2005;18;181-2000

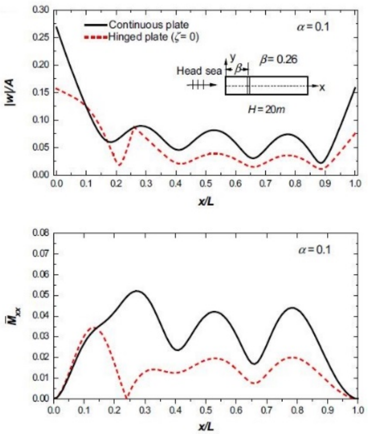


B.W.Kim, et al., Ocean Eng. 2007;34;1668-1679

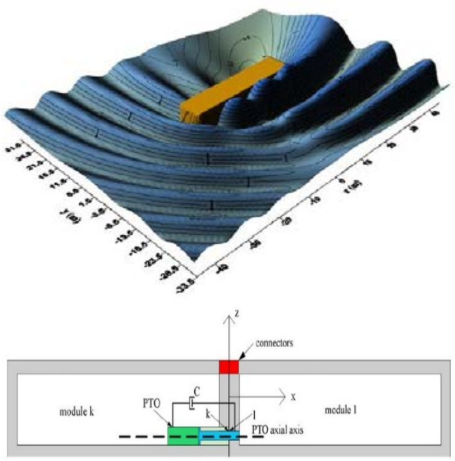
❖ Mitigation of hydroelastic responses ❖ Wave energy extraction ❖ Ice – wave interactions



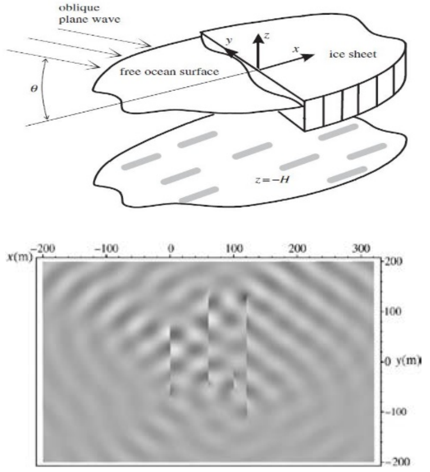
D.C.Hong, et al., Ocean Eng. 2007;34;696-708



R.P.Gao, et al., Ocean Eng. 2011;38;1957-1966



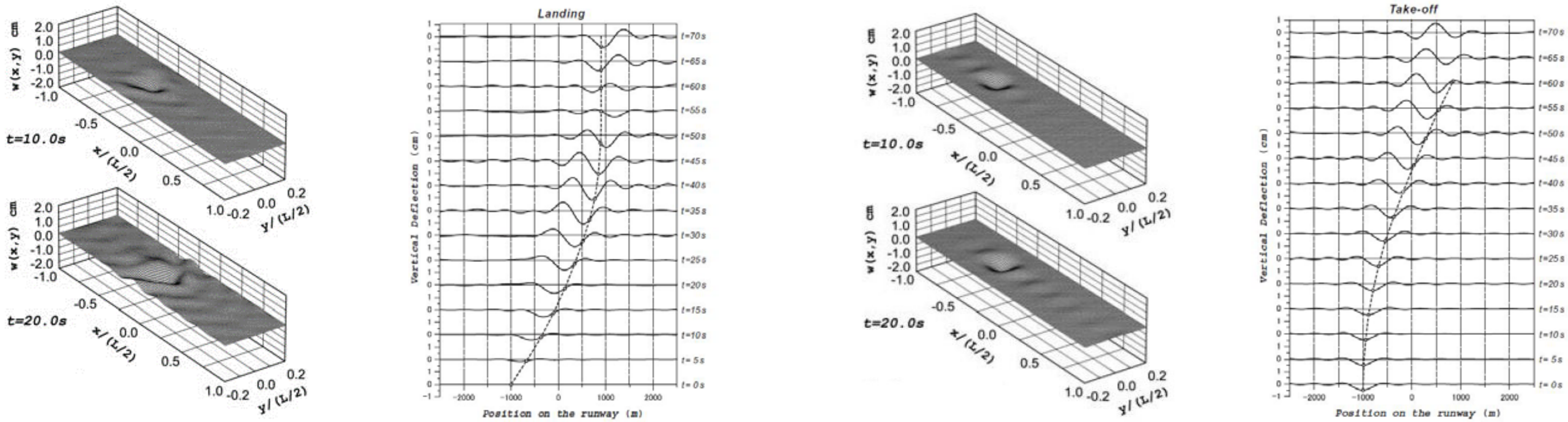
E.Loukogeorgaki, et al., J Fluids Struct. 2012;31;103-124



V.A.Squire, Cold Reg Sci Technol. 2007;49;110-133

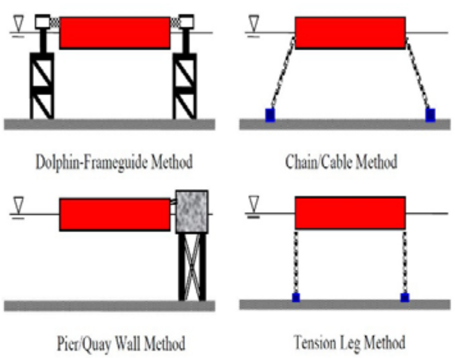
Related problems and studies - Time-domain analysis

❖ Effect of aircraft landing on and taking off from VLFS

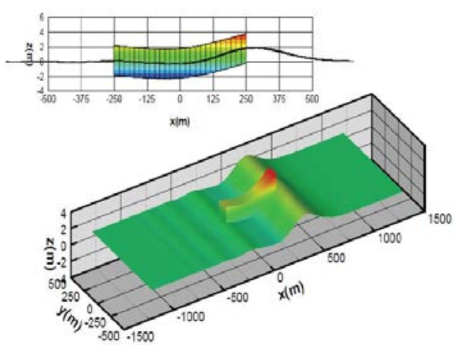


M.Kashiwagi, J Mar Sci Technol. 2004;9;14-23

❖ Nonlinear effects of a mooring system or nonlinear waves

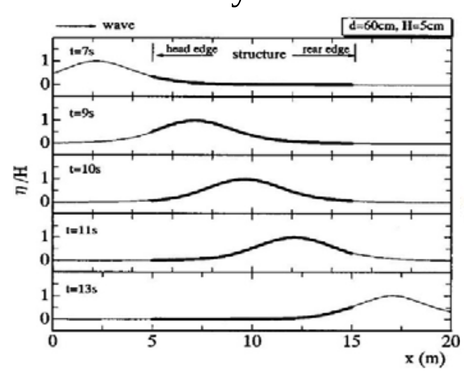


E.Watanabe, et al., Eng Struct. 2004;26;245-256



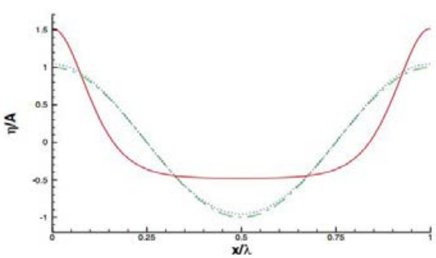
J.H.Kyoung, et al., 17th ISOPE. 2007;1;231-236

Solitary wave



X.Liu, et al., J Eng Mech. 2002;128;48-56

Cnoidal wave

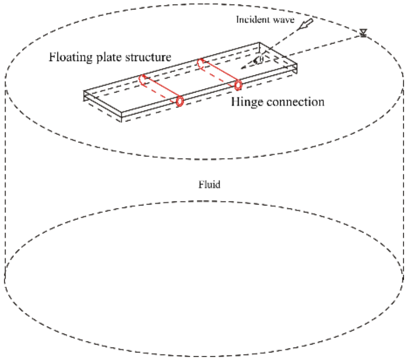


R.C.Ertekin, et al., Phys Fluids. 2014;26;027101

Research problems

Problem 1. Mitigation or enhancement of hydroelastic responses

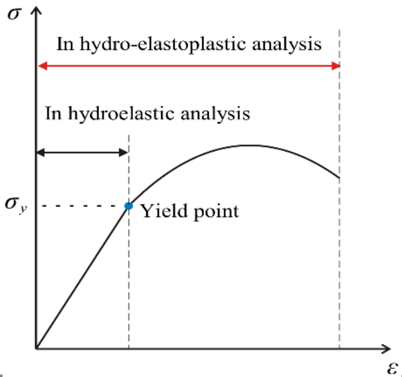
- Hydroelastic analysis of floating plate structures
- Bending moment reduced by hinge connections
- Modeling hinge connections



Hydroelastic analysis of floating plate structures with multiple hinge connections

Problem 2. Hydrodynamic responses beyond the elastic limit

- Nonlinear structural behaviors under severe external loads
- Modeling plastic behaviors in hydrodynamic analysis
- Employing the Cummins method

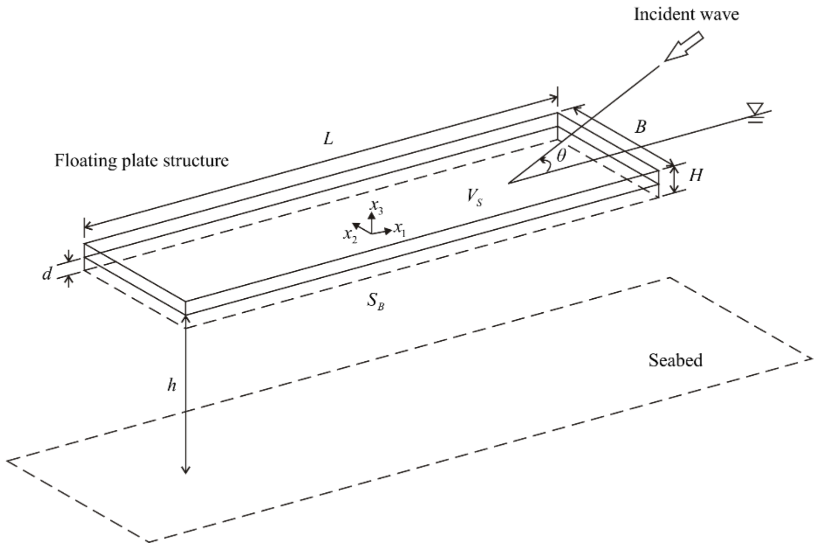


Hydro-elastoplastic analysis of floating plate structures

Hydroelastic analysis of floating plate structures

- Formulation of floating plate structures
- Formulation of fluid
- Matrix formulation of coupled equations

Formulation of floating plate structures



❖ Assumptions

- Homogeneous, isotropic, linear-elastic material
- Displacement and strain are infinitesimally small

❖ Governing equations

$$\frac{\partial \sigma_{ij}}{\partial x_j} - \rho_s g \delta_{i3} - \rho_s \ddot{u}_i = 0 \qquad \text{in} \quad V_S$$

$$\sigma_{ij} n_j = -p n_i \qquad \text{on} \quad S_B$$

❖ Principle of virtual work

$$\int_{V_S} \rho_s \ddot{u}_i \delta u_i dV + \int_{V_S} C_{ijkl} e_{kl} \delta e_{ij} dV - \int_{S_B} p \delta u_3 \mathrm{d}S = 0$$

❖ Structural equations for the steady state

$$-\omega^2 \int_{V_S} \rho_s \tilde{u}_i \delta \tilde{u}_i \mathrm{d}V + \int_{V_S} C_{ijkl} \tilde{e}_{kl} \delta \tilde{e}_{ij} \mathrm{d}V - \int_{S_B} \tilde{p} \delta \tilde{u}_3 \mathrm{d}S = 0$$

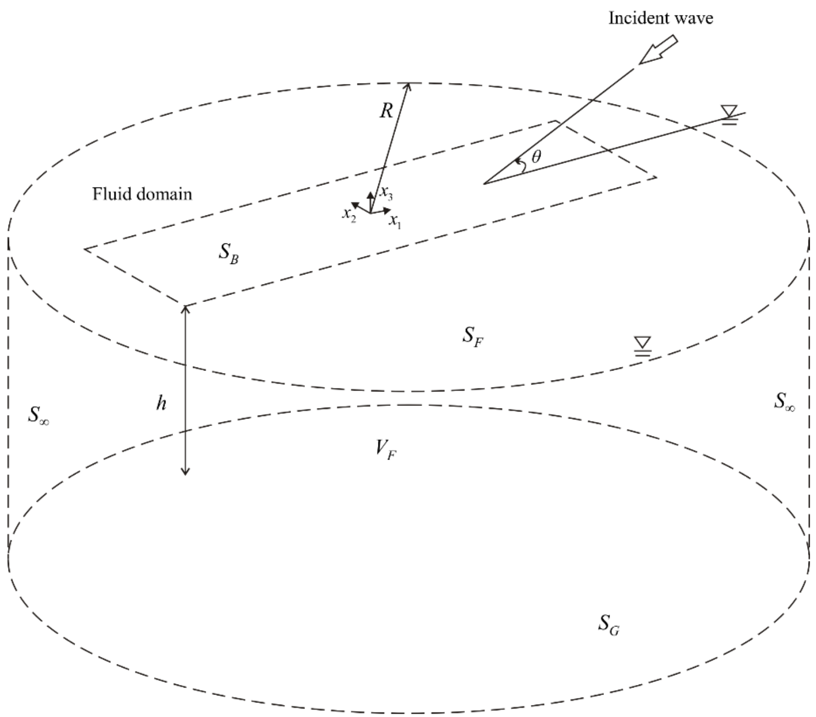
$$u_i(\mathbf{x};t) = \mathrm{Re}\left\{ \tilde{u}_i(\mathbf{x}) e^{jwt} \right\}$$

u_i	Displacement vector
σ_{ij}	Cauchy stress tensor
C_{ijkl}	Elastic stress-strain relation tensor
e_{ij}	Linear strain tensor
n_i	Unit normal vector
p	Elastic stress-strain relation tensor
ω	Angular frequency
j	Imaginary number

Formulation of fluid

❖ Assumptions

- Incompressible, inviscid and irrotational flow
- Amplitude is small
- Draft is zero



❖ Governing equations

$$\phi(\mathbf{x};t) = \mathrm{Re}\left\{\tilde{\phi}(\mathbf{x})e^{j\omega t}\right\}$$

$$\nabla^2\tilde{\phi} = 0 \qquad \text{in } V_S$$

$$\frac{\partial\tilde{\phi}}{\partial x_3} = \frac{\omega^2}{g}\tilde{\phi} \qquad \text{for } x_3 = 0 \qquad \text{on } S_F$$

$$\frac{\partial\tilde{\phi}}{\partial x_3} = 0 \qquad \text{on } S_G$$

$$\sqrt{R}\left(\frac{\partial}{\partial R} + jk\right)\left(\tilde{\phi} - \tilde{\phi}_I\right) = 0 \qquad \text{on } S_\infty (R \to \infty)$$

$$\frac{\partial\tilde{\phi}}{\partial n} = -j\omega u_3 \qquad \text{on } S_B$$

ϕ	Velocity potential
ϕ_I	Incident wave potential
∇^2	Laplace operator
k	Wave number

Formulation of fluid

❖ Boundary integral equations

- Employing Green's theorem and the free-surface Green's function $\nabla^2 G = -4\pi\delta(x_1-\xi_1)\delta(x_2-\xi_2)\delta(x_3-\xi_3)$

$$\int_{V_F}\left(\nabla^2 G(\mathbf{x};\boldsymbol{\xi})\tilde{\phi}(\mathbf{x}) - G(\mathbf{x};\boldsymbol{\xi})\nabla^2\tilde{\phi}(\mathbf{x})\right)dV = \int_S \left(G(\mathbf{x};\boldsymbol{\xi})\frac{\partial\tilde{\phi}(\mathbf{x})}{\partial n(\mathbf{x})} - \frac{\partial G(\boldsymbol{\xi})}{\partial n(\boldsymbol{\xi})}\tilde{\phi}(\mathbf{x})\right)\mathrm{d}S$$

$$4\pi\tilde{\phi}(\mathbf{x}) + p.v.\int_{S_B}\left(\tilde{\phi}(\boldsymbol{\xi})\frac{\omega^2}{\mathrm{g}} + \frac{\partial\tilde{\phi}(\boldsymbol{\xi})}{\partial n(\boldsymbol{\xi})}\right)G(\mathbf{x};\boldsymbol{\xi})\mathrm{d}S_\xi = 4\pi\tilde{\phi}_I(\mathbf{x}) \qquad \text{for } \mathbf{x} \text{ on } S_B$$

$\boldsymbol{\xi}$: Source point vector $p.v.$: Cauchy principal value

- Using body boundary condition and linearized Bernoulli equation

$$-u_3 - \frac{p}{\rho_w g} - \frac{\omega^2}{4\pi\rho_w g^2}\, p.v.\int_{S_B} pG\,\mathrm{d}S_\xi = j\frac{\omega}{g}\tilde{\phi}_I \qquad \text{for } \mathbf{x} \text{ on } S_B$$

❖ Fluid equations for the steady state

$$-\int_{S_B}\tilde{u}_3\,\delta\tilde{p}\,\mathrm{d}S - \frac{1}{\rho_w g}\int_{S_B}\tilde{p}\,\delta\tilde{p}\,\mathrm{d}S - \frac{\omega^2}{4\pi\rho_w g^2}\int_{S_B} p.v.\int_{S_B}\tilde{p}G\,\mathrm{d}S_\xi\,\delta\tilde{p}\,\mathrm{d}S_x = j\frac{\omega}{g}\int_{S_B}\tilde{\phi}_I\,\delta\tilde{p}\,\mathrm{d}S \qquad \text{on } S_B$$

Matrix formulation of coupled equations

❖ **Coupled equations**

$$-\omega^2\int_{V_S}\rho_s\tilde{u}_i\delta\tilde{u}_i\mathrm{d}V+\int_{V_S}C_{ijkl}\tilde{e}_{kl}\delta\tilde{e}_{ij}\mathrm{d}V-\int_{S_B}\tilde{p}\,\delta\tilde{u}_3\mathrm{d}S=0$$

$$-\int_{S_B}\tilde{u}_3\,\delta\tilde{p}\,\mathrm{d}S-\frac{1}{\rho_w g}\int_{S_B}\tilde{p}\,\delta\tilde{p}\,\mathrm{d}S-\frac{\omega^2}{4\pi\rho_w g^2}\int_{S_B}p.v.\int_{S_B}\tilde{p}G\,\mathrm{d}S_\xi\,\delta\tilde{p}\,\mathrm{d}S_x=j\frac{\omega}{g}\int_{S_B}\tilde{\phi}_I\,\delta\tilde{p}\,\mathrm{d}S$$

❖ **Matrix formulation for a hydroelasitc analysis in frequency domain**

- Discretization of the structural and fluid equations by FEM and BEM
- 4-node MITC plate finite element
- 4-node quadrilateral boundary element

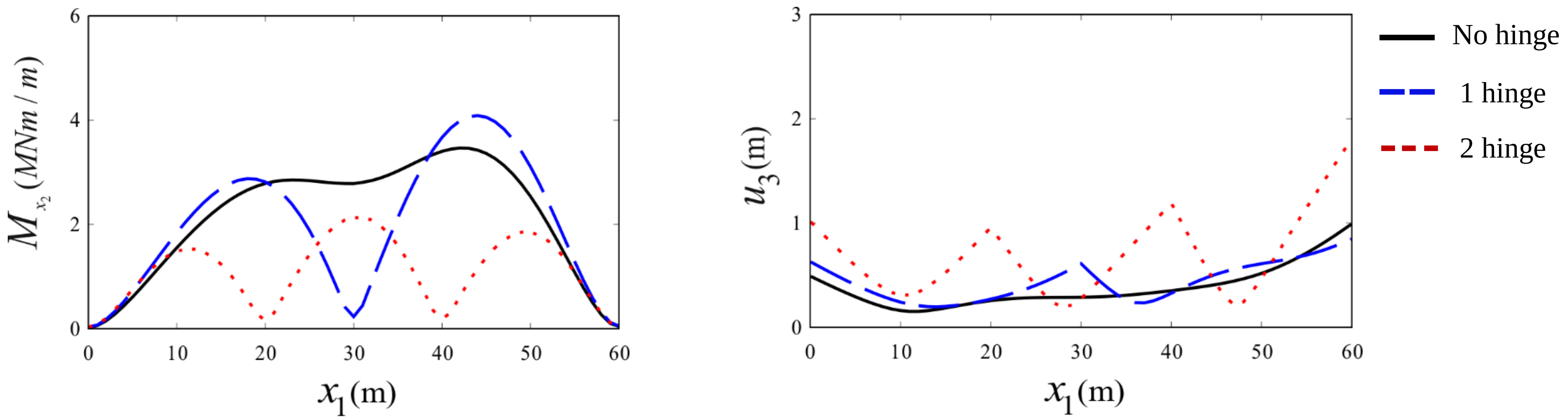
$$\begin{bmatrix}-\omega^2\,\mathbf{S}_M+\mathbf{S}_K & -\mathbf{C}_{up}\\ -\mathbf{C}_{up}{}^T & -\mathbf{F}_M-\mathbf{F}_G\end{bmatrix}\begin{bmatrix}\hat{\mathbf{u}}\\ \hat{\mathbf{p}}\end{bmatrix}=\begin{bmatrix}\mathbf{0}\\ \hat{\mathbf{R}}_{\mathbf{I}}\end{bmatrix}$$

Consideration of multiple hinge connections

- Motivation
- Previous studies
- Research description
- Modeling hinge connections
- Dimensionless quantities
- Validation
- Numerical analyses
- Closure

Motivation

❖ **Hydroelastic responses of floating plate structures with multiple hinge connections**



❖ **When using more hinge connections**,

the bending moment of cross sections can be effectively **reduced**.

However, the deflection could be **increased**, and **vice versa**.

❖ For the design of a floating airport or an wave energy converter**,**

hinge connections can be helpful or harmful.

Previous studies

❖ **Development of modeling methods of hinge connections in the conventional method**

- **Hinge deflection modes**

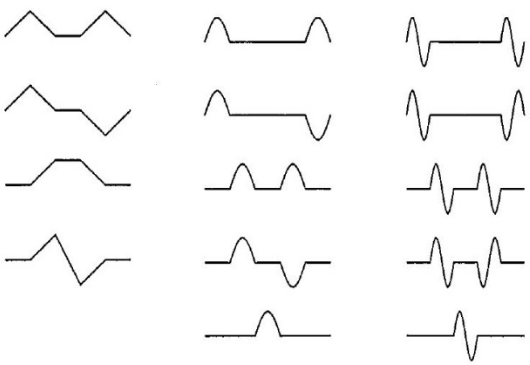
  Analytically evaluation for simple problems
  C.H. Lee, J.N. Newman, J Fluid Struct, 2000;14;957-70
  J.N. Newman, Mar Struct, 2005;16; 169-180

  Numerically evaluation for complicated problems
  S. Fu et al., Ocean. Eng. 2007;34;1516-31
  R.P. Gao et al, Ocean. Eng. 2011; 38 1957-66
  E. Loukogeorgaki et al., J Fluid Struct, 2012;31;103-24

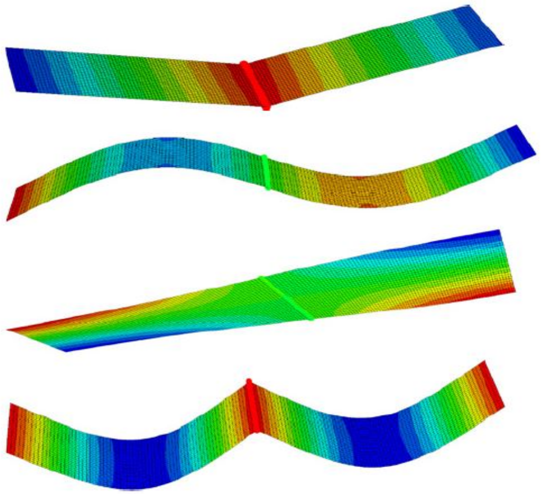
- **Constraints enforced by penalty technique**

  Modification of the equation of motion
  B.W. Kim et al., 15th ISOPE, 2005; 210-17

Hinge deflection modes



C.H. Lee, J.N. Newman



S. Fu et al

❖ **The effect of the number of hinge connections** has not been studied well

- **Reducing hydroelastic responses**

  Gao(2011) – **1 hinge**, position, wave angle, length and depth, plate's aspect ratio
  Kim(2005) – **2 hinges**, hinge-linked stiffness and shape of breakwaters, wave length

- **Enhancing hydroelastic responses**

  Loukogeorgaki(2012) – **1hinge**, position, wave angle and length

Research descriptions

❖ **To study effects of multiple hinge connections** on hydroelastic responses of floating plate structures subjected to regular waves,

we propose **a numerical procedure to effectively model hinge connections**

- ✓ Assuming linear elastic material and potential flow
- ✓ Based on the **direct coupling method** in frequency domain
- ✓ Using a **dynamic condensation method**
- ✓ **Validation** through comparison with previous experimental and numerical results

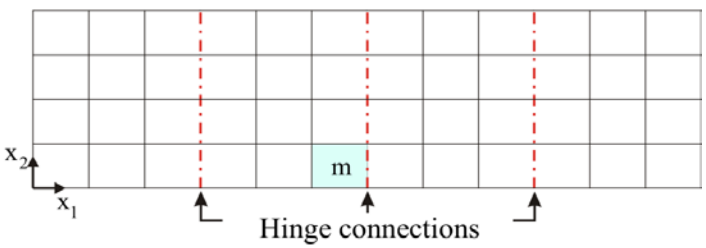
and investigate the maximum bending moment and deflection through numerical analyses

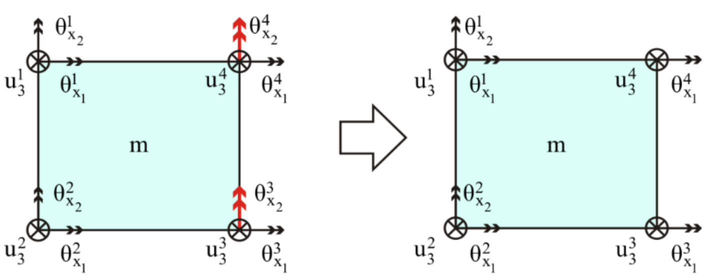
- ✓ Using **dimensionless quantities**
- ✓ Considering **the number of hinge connections, several structural and wave conditions**

Modeling hinge connections

❖ Since **the bending moments are zero** at hinge connections, we **release rotational DOFs** associated with the bending moments at the element local nodes

$\theta_{x_2}^3$ and $\theta_{x_2}^4$ can be released by **the dynamic condensation method**





Step 1. Divide retained $(\hat{\mathbf{u}}_a)$ and condensed $(\hat{\mathbf{u}}_c)$ DOFs in the element matrix

$$\begin{bmatrix} -\omega^2\mathbf{S}_M^{aa}+\mathbf{S}_K^{aa} & -\mathbf{C}_{up}^{ap} & -\omega^2\mathbf{S}_M^{ac}+\mathbf{S}_K^{ac} \\ -\mathbf{C}_{up}^{ap\,T} & -\mathbf{F}_M-\mathbf{F}_G & -\mathbf{C}_{up}^{cp\,T} \\ -\omega^2\mathbf{S}_M^{ca}+\mathbf{S}_K^{ca} & -\mathbf{C}_{up}^{cp} & -\omega^2\mathbf{S}_M^{cc}+\mathbf{S}_K^{cc} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{u}}_a \\ \hat{\mathbf{p}} \\ \hat{\mathbf{u}}_c \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \hat{\mathbf{R}}_{\mathbf{I}} \\ \mathbf{0} \end{bmatrix}$$

Step 2. From the third matrix equation

$$\hat{\mathbf{u}}_c = -\left(\omega^2\mathbf{S}_M^{cc}+\mathbf{S}_K^{cc}\right)^{-1}\left(-\omega^2\mathbf{S}_M^{ca}+\mathbf{S}_K^{ca}\right)\hat{\mathbf{u}}_a + \left(-\omega^2\mathbf{S}_M^{cc}+\mathbf{S}_K^{cc}\right)^{-1}\mathbf{C}_{up}^{cp}\hat{\mathbf{p}}$$

Step 3. Substitute for $\hat{\mathbf{u}}_c$ into first matrix and obtain the condensed element matrix

$$\begin{bmatrix} \mathbf{S}^{aa} & \mathbf{C}^{ap} \\ \mathbf{C}^{ap\,T} & \mathbf{F}^{pp} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{u}}_a \\ \hat{\mathbf{p}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \hat{\mathbf{R}}_{\mathbf{I}} \end{bmatrix}$$

Dimensionless quantities

❖ Related parameters

1. **Aspect ratio**

$$L_r = \frac{L}{B}$$

2. **Dimensionless bending stiffness**

$$S = \frac{EI}{\rho_w g L^5}$$

3. **Dimensionless wave length**

$$\alpha = \frac{\lambda}{L}$$

❖ Related responses

1. **RAO of deflection**

$$\bar{u}_3 = \frac{|u_3|}{a}$$

2. **Dimensionless bending moment**

$$\overline{M}_{x_2x_2} = \frac{|M_{x_2x_2}|}{\rho_w g L^2}$$

3. **Maximum deflection ratio**

$$R_{u_3} = \frac{|u_3|_{\max}}{|u_3|_{\max}^{\text{no hinge}}}$$

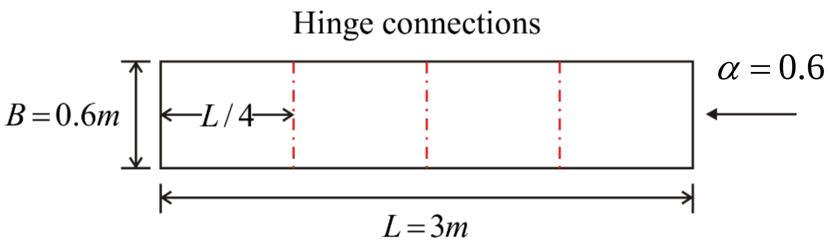
4. **Maximum bending moment ratio**

$$R_M = \frac{\overline{M}_{\max}}{\overline{M}_{\max}^{\text{no hinge}}}$$

Validation

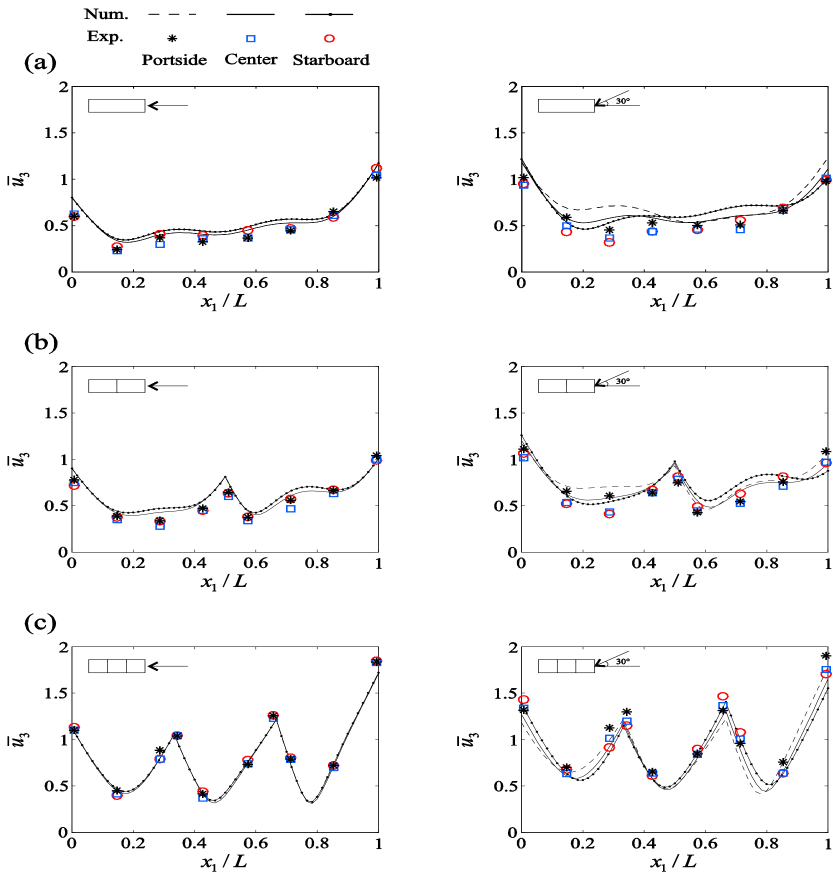
❖ Comparison with previous experimental results conducted by S.P. Cho (2013)

- Experimental model



Parameter	Value
Length(L)	3m
Width(B)	0.6m
Thickness(H)	0.4m
Draft(d)	0.11m
Bending stiffness(EI)	30.385Nm^2
Dimensionless bending stiffness(S)	1.244×10^{-5}

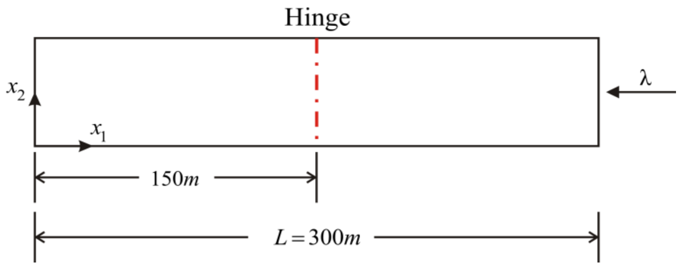
- RAOs of deflection



Validation

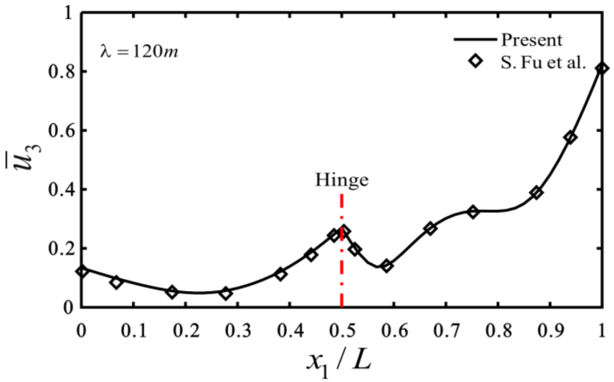
❖ Comparison with previous numerical results conducted by S. Fu (2007)

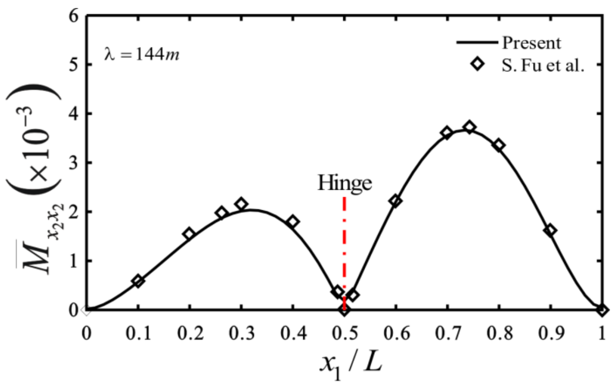
- Numerical model



Parameter	Value
Width(B)	60m
Thickness(H)	2m
Draft(d)	0.5m
Bending stiffness(EI)	$4.77\times 10^{11}\,\text{Nm}^2$
Dimensionless bending stiffness(S)	1.954×10^{-5}

- Hydroelastic responses

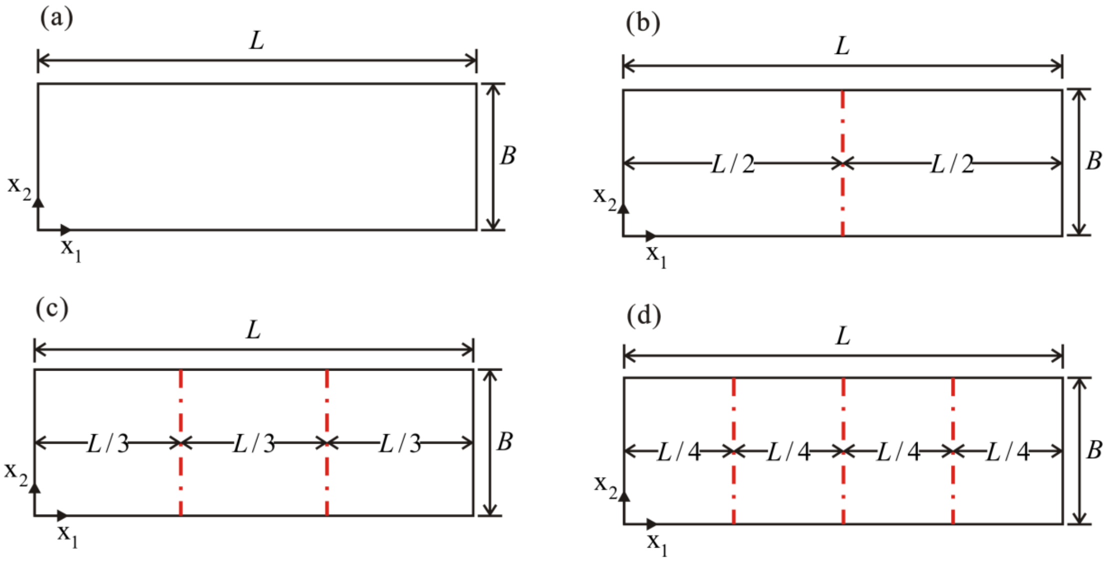




Numerical analyses

❖ Effects of multiple hinge connections under several structural and wave conditions

- Numerical models



- Cases of problem

➢ **Related floating plate structures**

$$L_r = 1.0,\ 5.0$$

$$S = 3.04\times10^{-4},\ 3.04\times10^{-5},\ 3.04\times10^{-6}$$

➢ **Related incident waves**

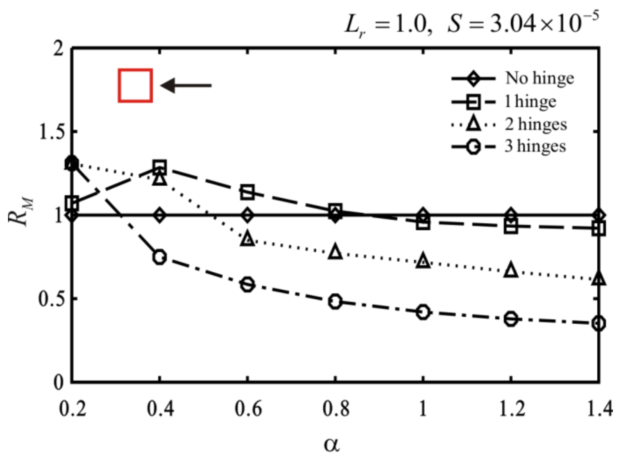
$$\alpha = 0.2,\ 0.4,\ 0.6,\ 0.8,\ 1.0,\ 1.2,\ 1.4$$

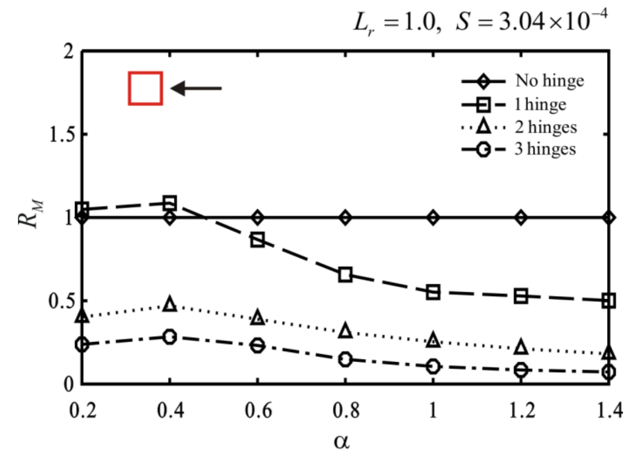
$$\theta = 0^0$$

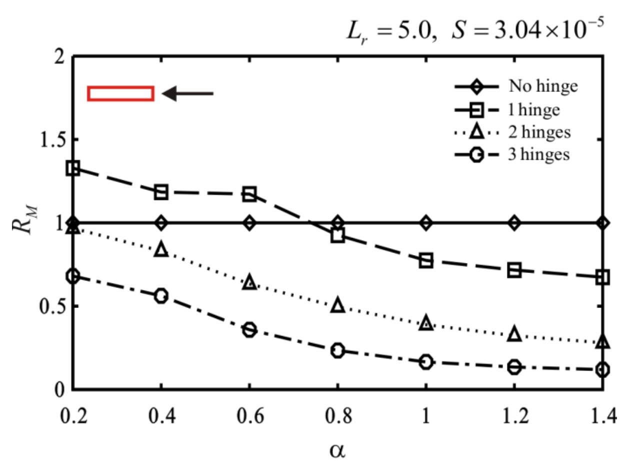
Numerical analyses

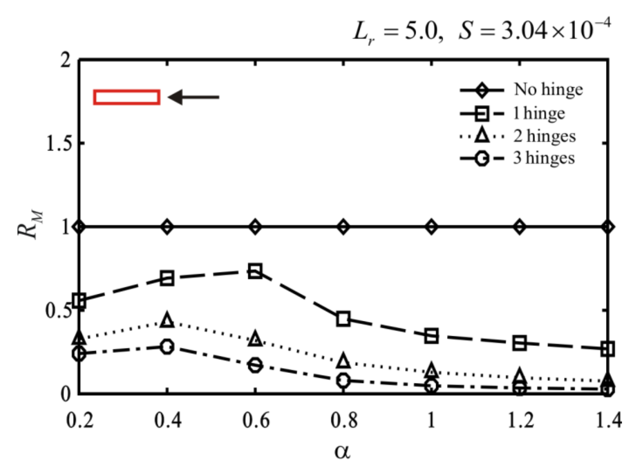
❖ Effects on the maximum bending moment

- Maximum bending moment ratio R_M





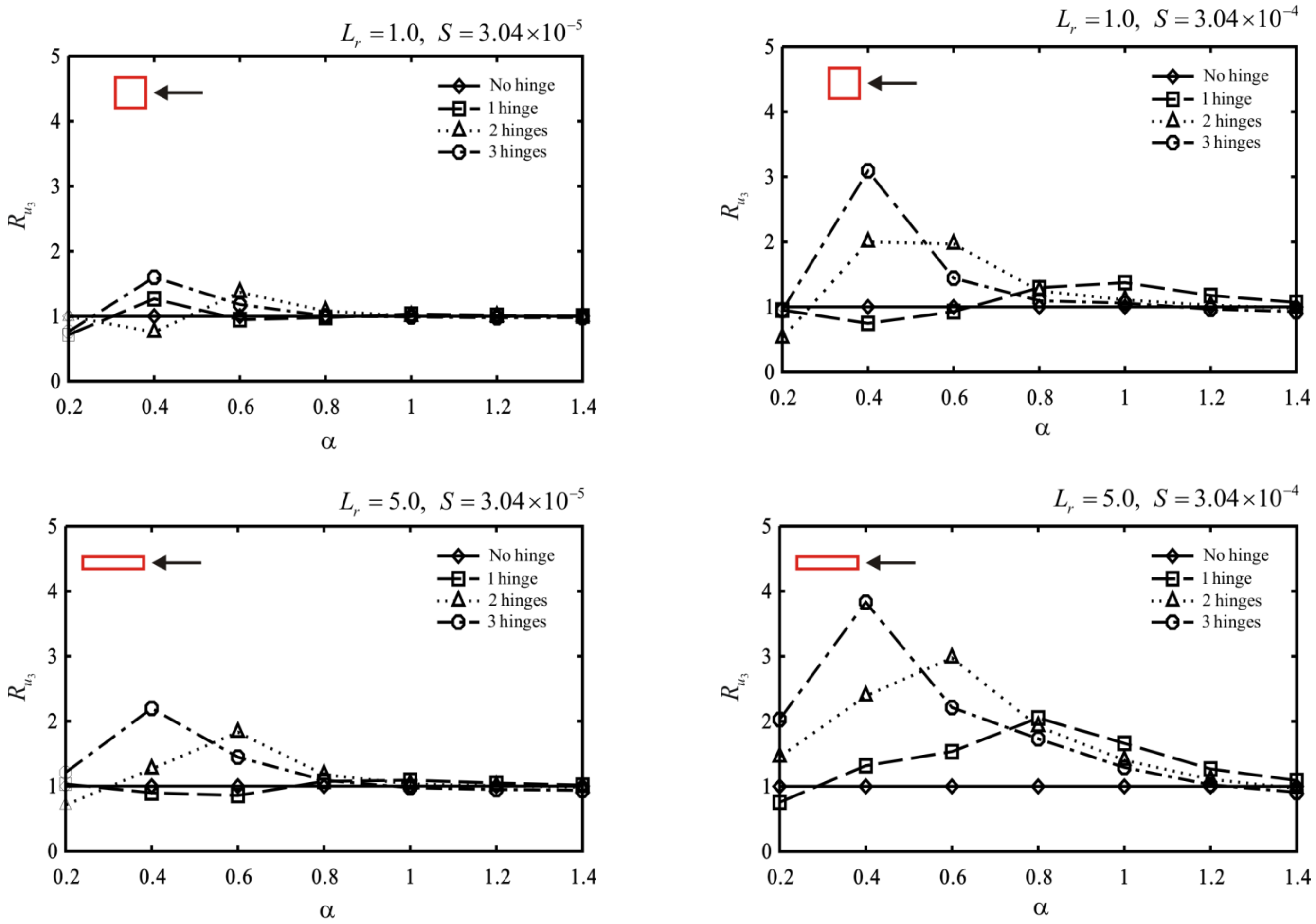




Numerical analyses

❖ Effects on the maximum deflection

- Maximum deflection ratio R_{u_3}



Numerical analyses

❖ **Summary for effect of the number of hinge connections**

	Aspect ratio $L_r = \frac{L}{B}$	Dimensionless bending stiffness $S = \frac{EI}{\rho_w g L^5}$	Dimensionless Wavelength $\alpha = \frac{\lambda}{L}$
Reducing the maximum bending moment	Larger	Stiffer	**Longer**
Enhancing the maximum deflection	Larger	Stiffer	**Shorter**

✓ **When the floating plate structure is very flexible**, the use of hinge connections is not effective

Hydro-elastoplastic analysis of floating plate structures

- Motivation
- Previous studies
- Research descriptions
- Structural dynamics associated with material nonlinearity
- Hydrodynamics in the time domain
- Floating plate structure – wave interactions
- Numerical procedure
- Validation
- Numerical examples

Motivation

❖ **When severe external loads applied**,

nonlinear behaviors of floating structures (ex. yielding, buckling, and fracturing) can occur.

❖ For **safer and more economically effective designs,**

it is essential to accurately predict **hydrodynamic responses beyond elastic limit.**

Figure source : google image

Previous studies

❖ **To analyze ship – wave interactions considering plastic deformations few numerical methods have been developed.**

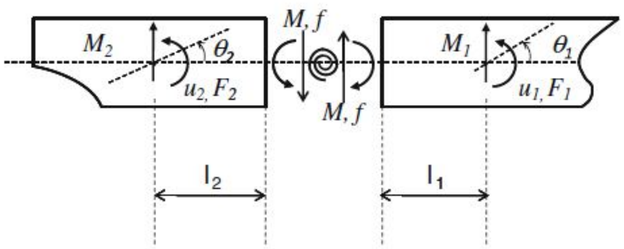
1. K. Iijima et al. (2011) – Dynamic collapse behavior of a ship's hull girder in waves

- Structural dynamics

  Modeled as two rigid body with a **nonlinear rotational spring**

- Hydrodynamics

  A nonlinear strip theory
  Considering **plastic deformations of the spring**



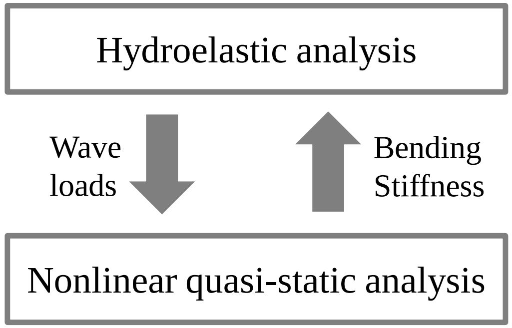
2. W. Liu et al. (2015) – 2D hydroelastoplasticity method of a ship in extreme waves

- Structural dynamics

  Modeled as Euler-Bernoulli beam
  Calculation of **plasticity by a quasi-static method**

- Hydrodynamics

  A nonlinear strip theory
  Considering only **elastic deformations by a hydroelastic analysis**



Previous studies

❖ **Few researches related to nonlinear behaviors of VLFS have been conducted.**

M. Fujikubo (2005) – Structural analysis for the design of VLFS

- Structural analysis is performed by two-step approach

  Step 1. **Hydroelastic analysis**

  Step 2. Nonlinear quasi-static analysis

  considering the calculated hydroelastic responses

Hydroelastic analysis

↓ Wave loads

Nonlinear quasi-static analysis

➡ **It is difficult to accurately predict hydro-elastoplastic responses for floating plate structures in waves through previous methods**

Research descriptions

To develop a effective numerical procedure of 3D hydro-elastoplastic analysis for floating plate structure in waves

Problem I. Structural dynamics associated with material nonlinearity

- ✓ Using **incremental equilibrium equations** in the nonlinear finite element analysis
- ✓ Considering **the 3D von Mises plasticity model**
- ✓ Adopting implicit return mapping algorithm to simulate the plastic behaviors

Problem II. Hydrodynamics in the time domain

- ✓ Based on the **Cummins method**
- ✓ Using the boundary element method for frequency-domain analysis

Problem III. Floating plate structure – wave interactions

- ✓ Constructing **the convolution integral of IRFs with nodal incremental displacements**
- ✓ Formulating **a time-domain incremental coupled equations of motion**

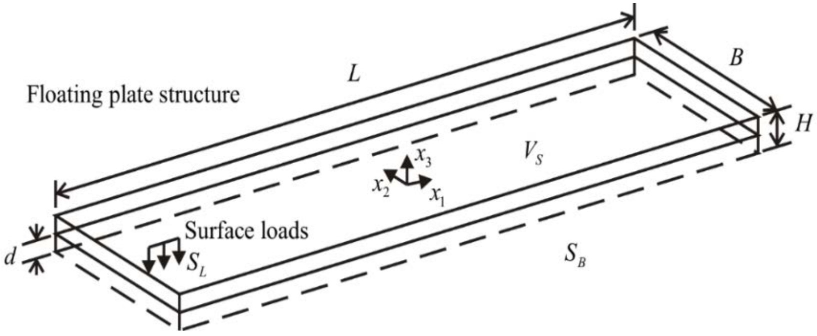
Structural dynamics associated with material nonlinearity

❖ **Governing equations at time t+Δt**

$$\frac{\partial \sigma_{ij}}{\partial x_j} - \rho_s g \delta_{i3} - \rho_s \ddot{u}_i = 0 \quad \text{in } V_S$$

$$\sigma_{ij} n_j = -\, p n_i \quad \text{on } S_B$$

$$\sigma_{ij} n_j = -\, f_i^{S_L} n_i \quad \text{on } S_L$$



❖ **Linearization of the internal virtual work**

$$\int_{V_S} \sigma_{ij}(\mathbf{x};t+\Delta t)\delta e_{ij} dV \approx \int_{V_S} C_{ijkl}^{EP}(\mathbf{x};t) e_{ij} \delta e_{ij} dV + \int_{V_S} \sigma_{ij}(\mathbf{x};t)\delta e_{ij} dV$$

❖ **Incremental equilibrium equations**

$$\int_{V_S} \rho_s \ddot{u}_i(\mathbf{x};t+\Delta t)\delta u_i dV + \int_{V_S} C_{ijkl}^{EP}(\mathbf{x};t) e_{kl} \delta e_{ij} dV - \int_{S_B} \rho_w g \Delta u_3 n_i \delta u_i dS =$$

$$-\int_{S_B} p_d(\mathbf{x};t+\Delta t) n_i \delta u_i dS + \int_{S_L} f_i^{S_L}(\mathbf{x};t+\Delta t) n_i \delta u_i dS + \int_{S_B} \rho_w g u_3(\mathbf{x};t) n_i \delta u_i dS - \int_{V_S} \sigma_{ij}(\mathbf{x};t)\delta e_{ij} dV$$

❖ **Matrix form by finite element discretization**

$$\mathbf{M}\ddot{\mathbf{U}}(t+\Delta t) + \left(\mathbf{K}(t) + \mathbf{C}\right)\Delta\mathbf{U} = \boxed{\mathbf{R}_{HF}(t+\Delta t)} + \mathbf{R}_{S_L}(t+\Delta t) - \mathbf{C}\mathbf{U}(t) - \mathbf{F}(t)$$

Structural dynamics associated with material nonlinearity

❖ Von Mises plastic model with isotropic hardening

- Yield condition

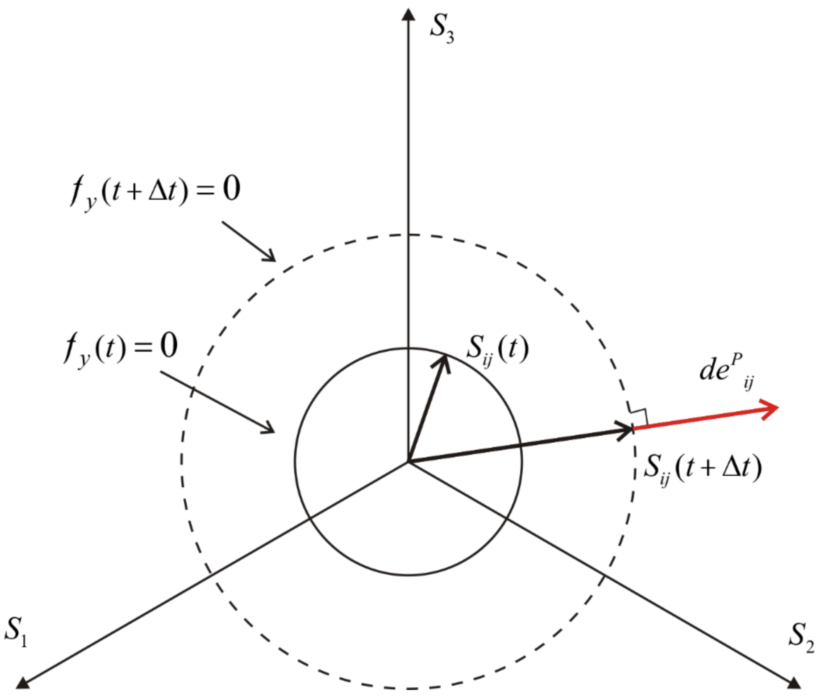
$$f_y = \frac{1}{2} S_{ij} S_{ij} - \frac{1}{3} \sigma_y^2$$

- Flow rule (Prandtl-Reuss equation)

$$de_{ij}^P = d\lambda \frac{\partial f_y}{\partial \sigma_{ij}} = d\lambda S_{ij}$$

- Isotropic hardening

$$\sigma_y = \sigma_y\left(\bar{e}^P\right) \qquad d\bar{e}^P = \sqrt{\frac{2}{3} de_{ij}^P de_{ij}^P}$$



Hydrodynamics in the time domain

❖ **Governing equations**

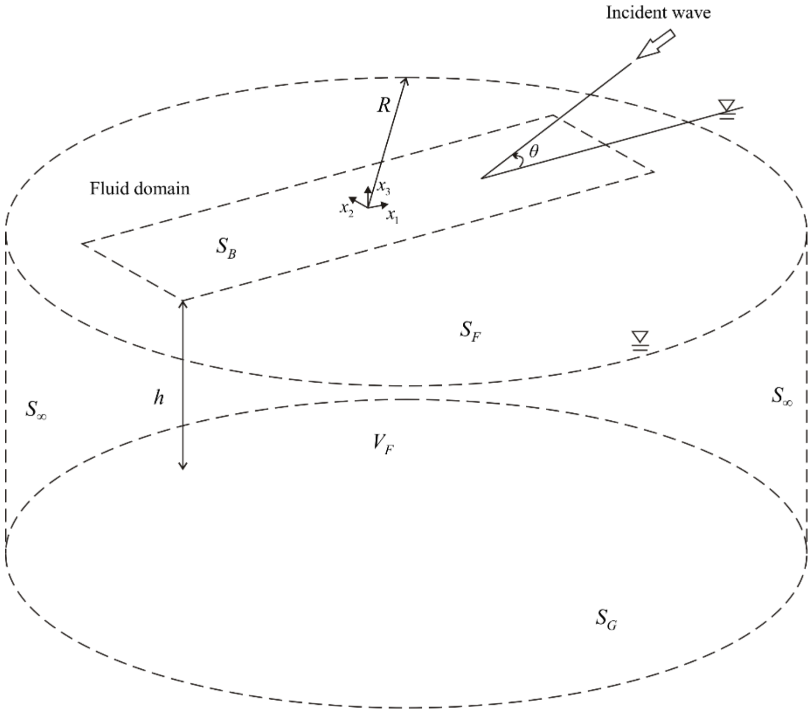
$$\nabla^2\phi(\mathbf{x};t)=0 \qquad \text{in} \quad V_S$$

$$\ddot{\phi}+g\frac{\partial\phi}{\partial x_3}=0 \qquad \text{for} \quad x_3=0 \quad \text{on} \quad S_F$$

$$\frac{\partial\phi}{\partial x_3}=0 \qquad \text{on} \quad S_G$$

$$\nabla\phi\to 0 \qquad \text{on} \quad S_\infty(R\to\infty)$$

$$\frac{\partial\phi}{\partial n}=\dot{u}_i n_i \qquad \text{on} \quad S_B$$



❖ **Initial conditions at time** $t=0$

$$\phi(\mathbf{x};t)=0 \qquad \text{for} \quad x_3 \quad \text{on} \quad S_F$$

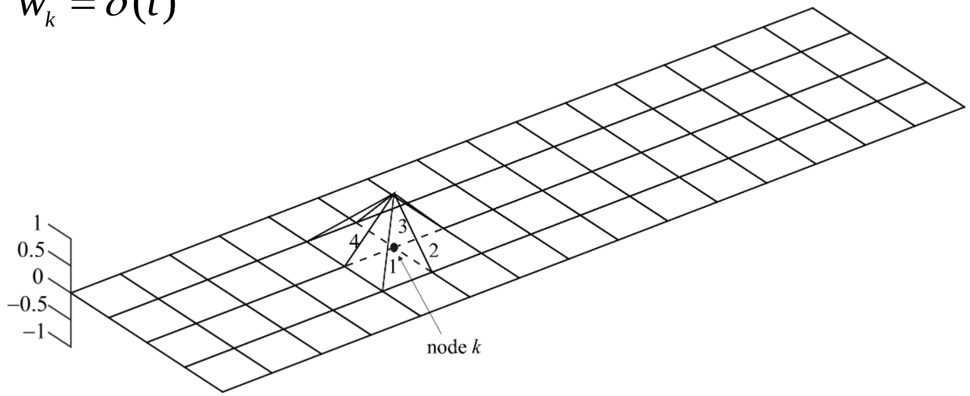
$$\dot{\phi}(\mathbf{x};t)=0 \qquad \text{for} \quad x_3 \quad \text{on} \quad S_F$$

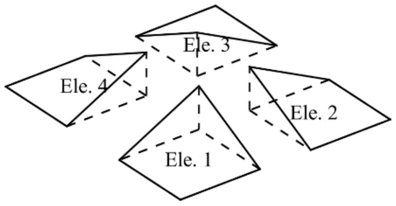
Hydrodynamics in the time domain

❖ **IRFs associated with finite element model**

- Impulsive velocity in transverse direction at node k

$$\dot{w}_k = \delta(t)$$





- Finite element basis functions

Employing **a set of piecewise linear functions** constructed by the shape functions of the finite elements sharing the node

❖ **Hydrodynamic forces at time** $t+\Delta t$

$$\boxed{\mathbf{R}_{HF}(t+\Delta t) = -\mathbf{A}\ddot{\mathbf{U}}(t+\Delta t) - \int_{-\infty}^{t+\Delta t} \mathbf{B}(t+\Delta t-\tau)\dot{\mathbf{U}}(\tau)d\tau + \int_{-\infty}^{\infty} \mathbf{D}(t+\Delta t-\tau)\eta(\tau)d\tau}$$

Floating plate structure – wave interactions

❖ **Time-domain incremental coupled equations of motion**

$$(\mathbf{M}+\mathbf{A})\ddot{\mathbf{U}}(t+\Delta t)+\int_{-\infty}^{t+\Delta t}\mathbf{B}(t+\Delta t-\tau)\dot{\mathbf{U}}(\tau)d\tau+\left(\mathbf{K}(t)+\mathbf{C}\right)\Delta\mathbf{U}$$

$$=\mathbf{R}_{S_L}(t+\Delta t)+\int_{-\infty}^{\infty}\mathbf{D}(t+\Delta t-\tau)\eta(\tau)d\tau-\mathbf{C}\mathbf{U}(t)-\mathbf{F}(t)$$

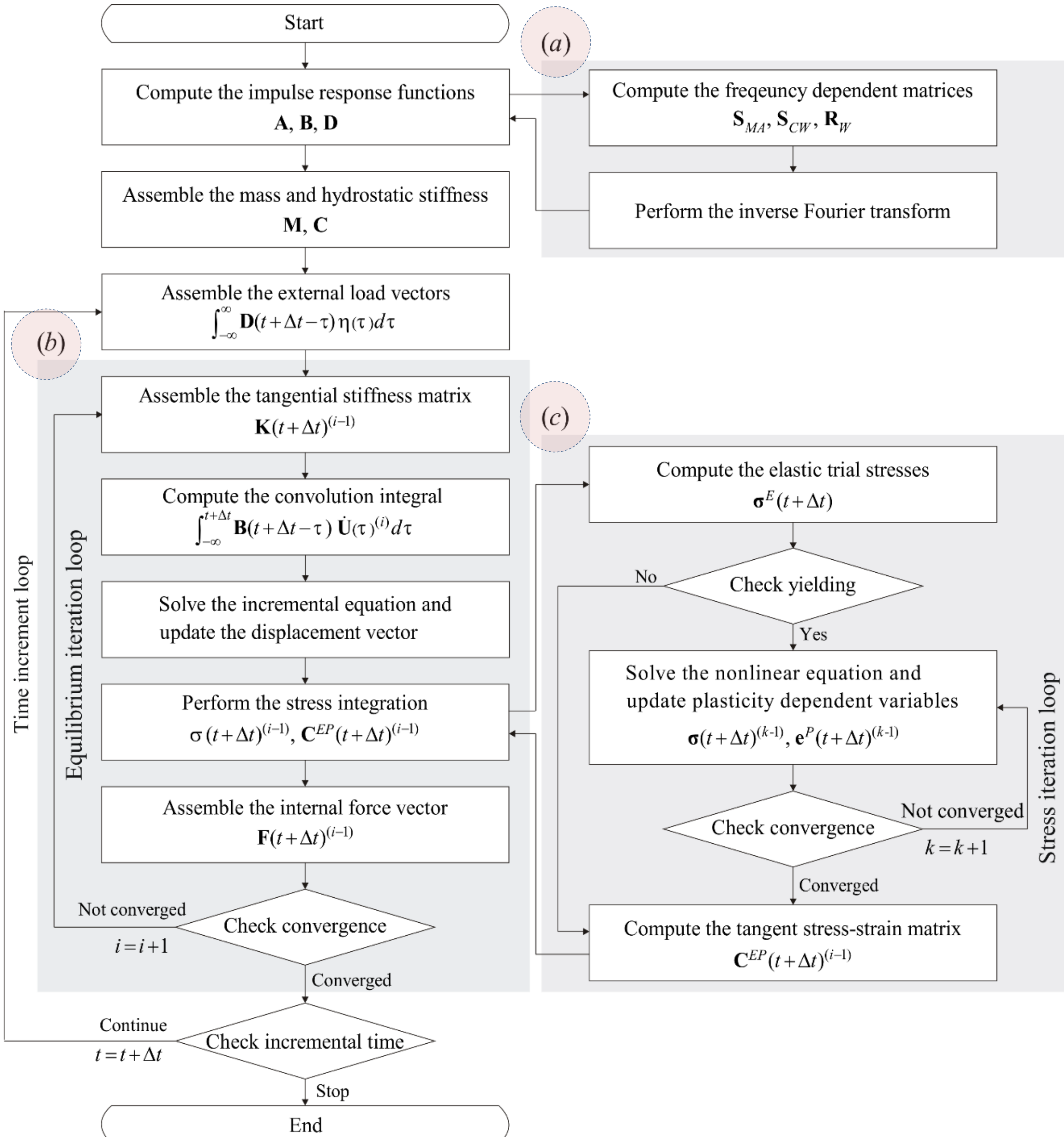
❖ **Evaluation of IRFs using the Fourier transform**

$$\mathbf{B}(t)=\frac{2}{\pi}\int_0^{\infty}\mathbf{b}(\omega)\cos(\omega t)d\omega$$

$$\mathbf{A}=\mathbf{a}(\omega)+\frac{1}{\omega}\int_0^{\infty}\mathbf{B}(\tau)\sin(\omega\tau)d\tau$$

$$\mathbf{D}(t)=\frac{1}{\pi}\int_0^{\infty}\left[\mathrm{Re}\left(\mathbf{R}_W(\omega)\right)\cos(\omega t)-\mathrm{Im}\left(\mathbf{R}_W(\omega)\right)\sin(\omega t)\right]d\omega$$

Nonlinear solution procedure



(a) Evaluation of the IRFs

- Direct coupling method
- 4-node MITC plate finite element
- 4-node quadrilateral boundary element
- Filon quadrature

(b) Equilibrium iteration loop

- Full Newton-Raphson method
- Newmark method

(c) Stress integration

- Implicit return mapping algorithm
- Newton-Raphson method

Validation

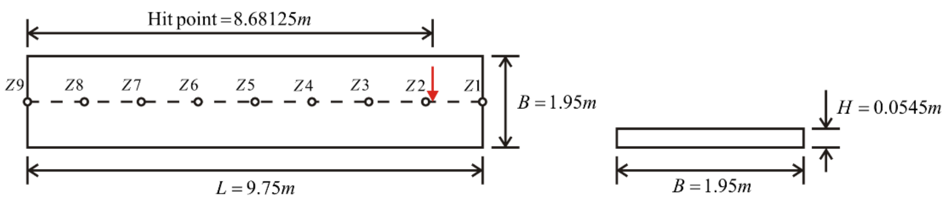
❖ **Comparison with results of a hydroelastic experiment conducted by Endo (1996)**

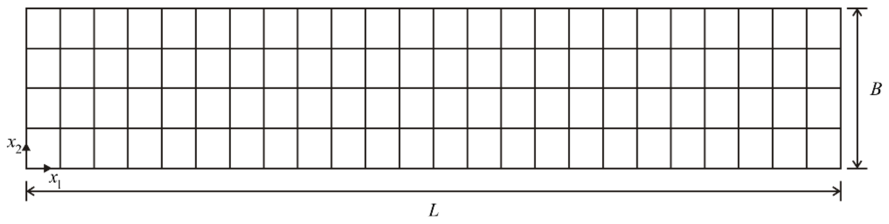
- Problem description

$E = 0.6661 Gpa$ $\quad EI = 17.52 kNm^2$

$\rho_s = 299.083 kg/m^3$ $\quad h = 1.9m$

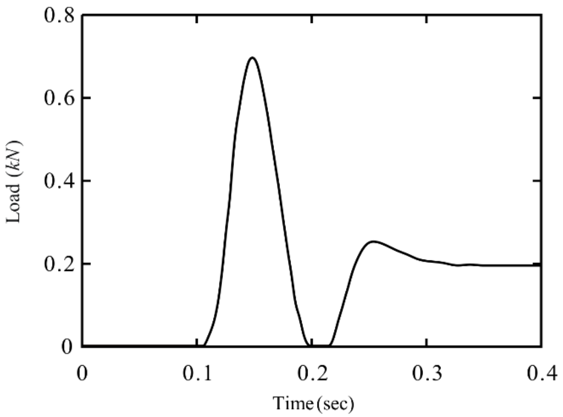
Plate elements – 24×4





Total time – 2.5s

Time step size – 0.001s



< Impact load curve >

H. Endo, K. Yago. Tim history response of a large floating structure subjected to dynamic load. J Soc Nav Archit Jpn 1996;186;369-76.

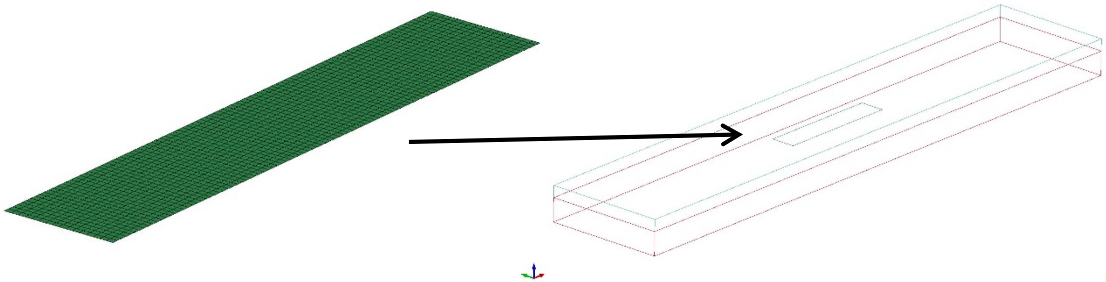
Validation

❖ Numerical modeling in LS-DYNA

- Floating plate structure

  Dimension – 9.75×1.95×0.545

  Shell elements – 48×8



- Fluid modeling by MMALE(Multi-Material Arbitrary Lagrangian Eulerian)

  ✓ Air

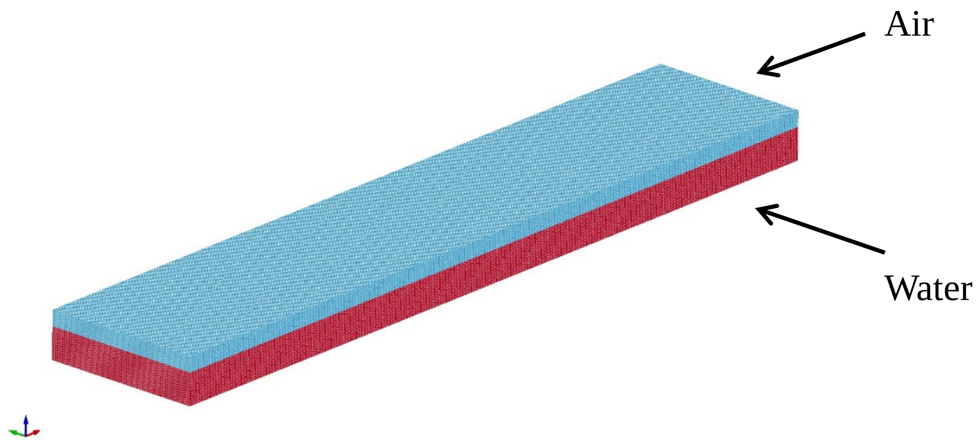
  Dimension – 48.75×9.75×0.95

  3D solid elements – 480×80×24

  ✓ Water

  Dimension – 48.75×9.75×1.9

  3D solid elements – 480×80×48

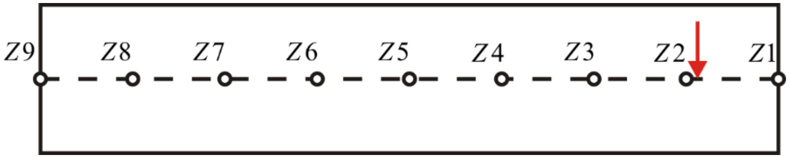


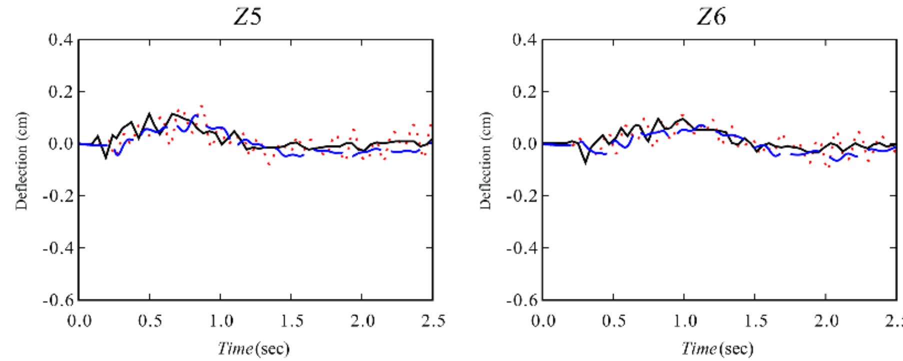
- FSI modeled by “Constrained Lagrange in Solid”

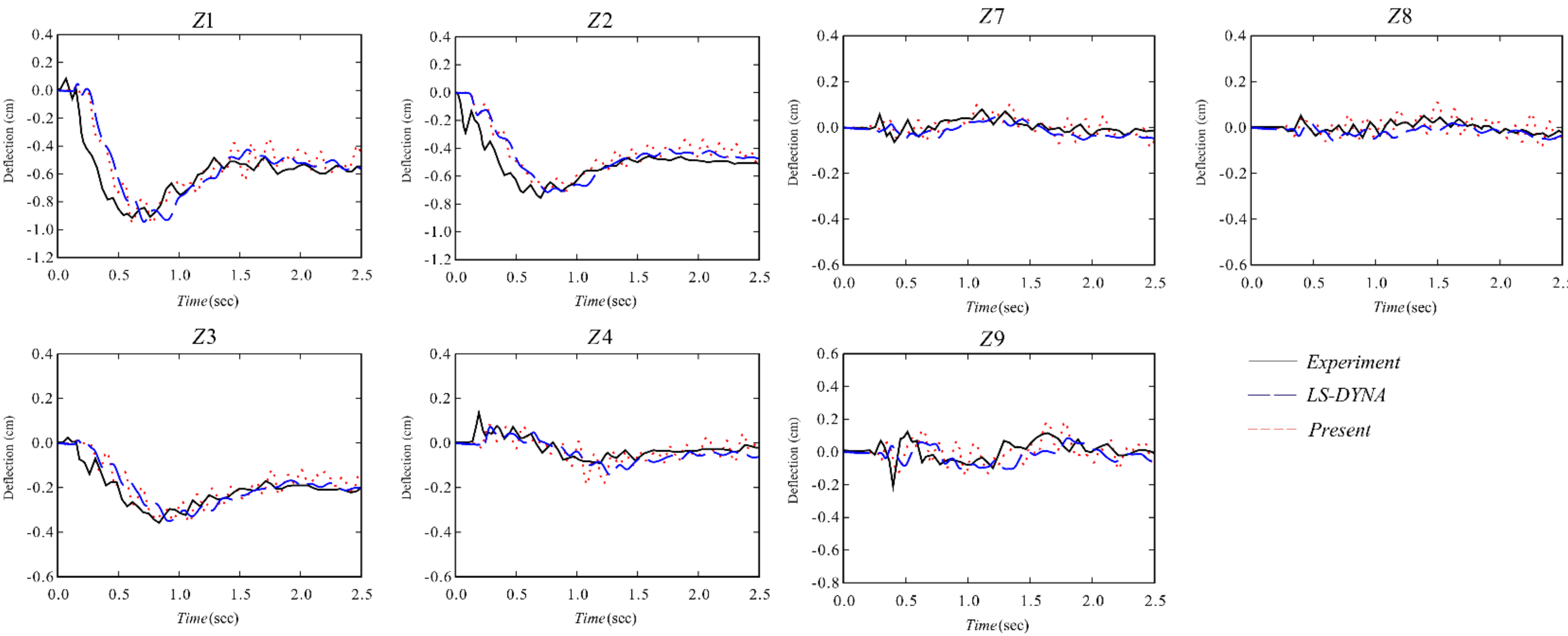
  Computing coupling forces by a penalty method

Validation

❖ **Time histories of deflections**







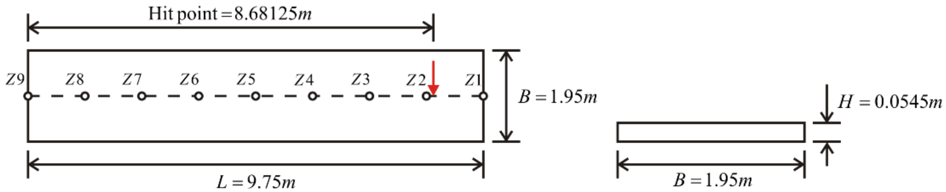
Validation

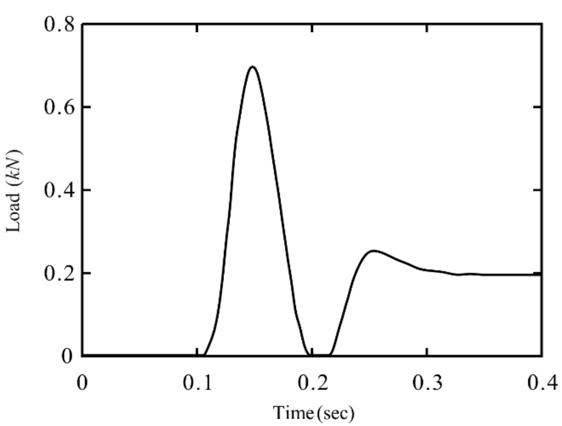
❖ Comparison with LS-DYNA for results of hydro-elastoplastic problem

- Problem description
  - ✓ Considering elastic-perfectly-plastic material

$$\boxed{\sigma_y = 30kpa} \qquad E = 0.6661Gpa$$

$$\rho_s = 299.083kg/m^3 \qquad h = 1.9m$$

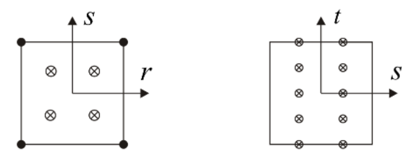




< Impact load curve >

✓ Present

Plate element – 48×8



Horizontal plane Cross-section

• : Node point
⊗ : Integration point

Total time – 2.5s

Time step size – 0.001s

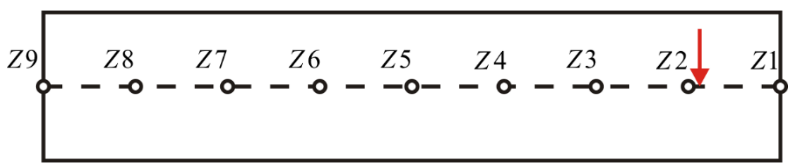
✓ LS-DYNA

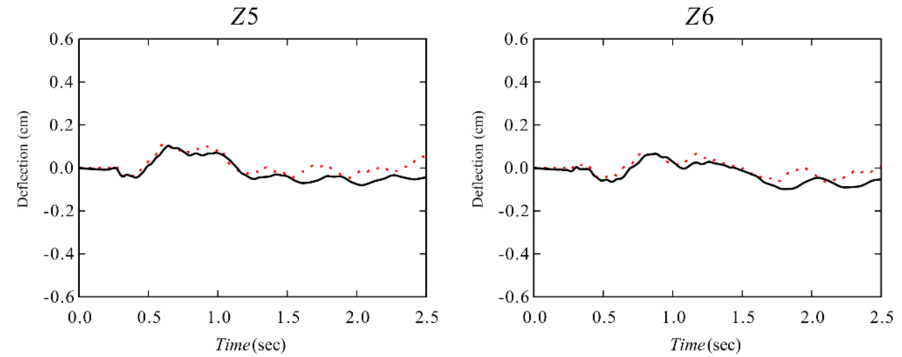
Shell element – 48×8

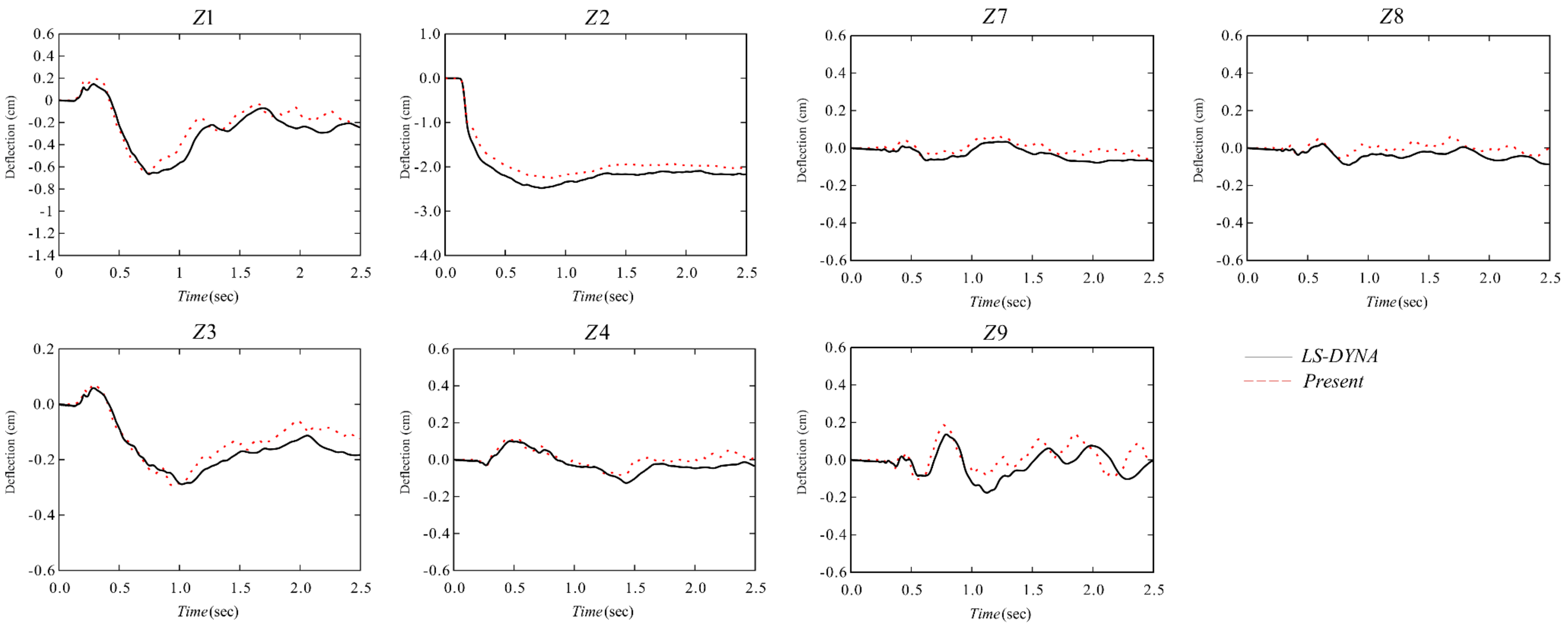
5-point Lobatto integration

Validation

❖ **Time histories of deflections**



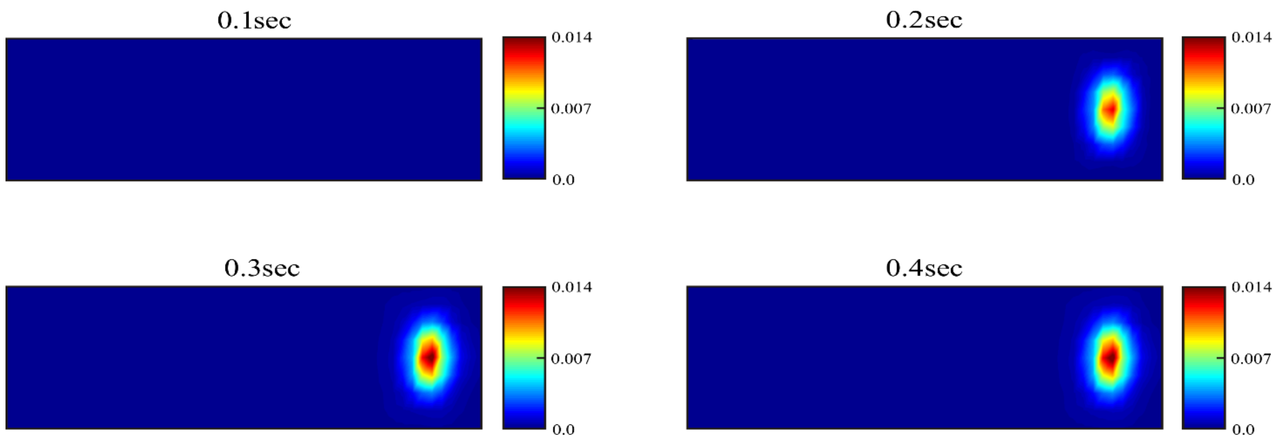




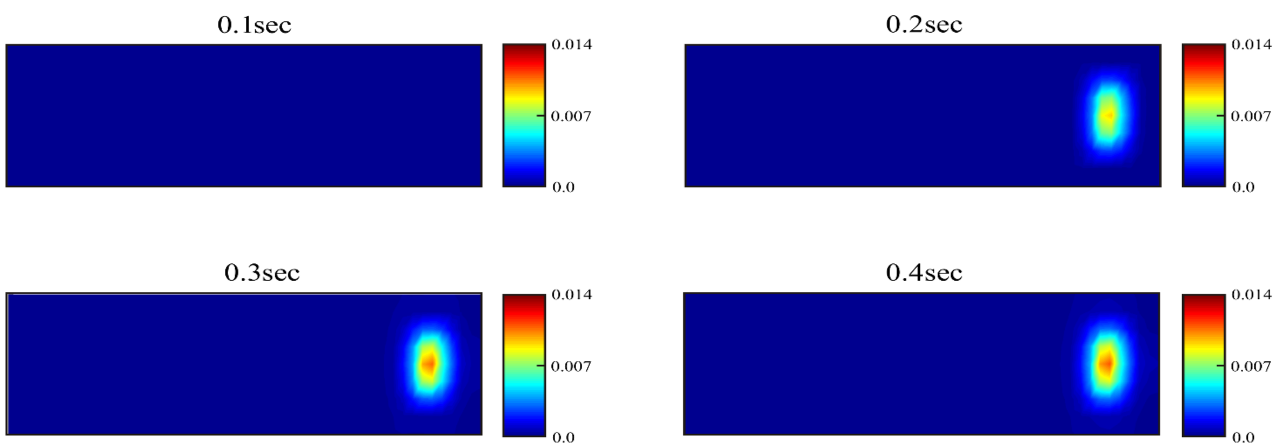
Validation

❖ **Effective plastic strain**

Present



LS-DYNA



Validation

❖ **Computational times**

	Items	[hr]	Ratio [%]
Present (performed in PC)	Evaluation of impulse response functions	1.252	43.7
	Performance of the time increment loop	1.614	56.3
	Total	$\boxed{2.866}$	100.0
LS-DYNA (performed in a high performance computer)		15.375	536.5

Present - Intel (R) core (TM) i7-2600 3.40GHz CPU, 16 GB RAM

LS-DYNA - 5.3TFLOPS, 248 CPUs - Intel Xeon 2.60GHz, 2TB RAM,
16CPUs, Massively parallel processing(MPP)

Numerical examples

❖ Floating double plate structure considering two load cases

- Problem description

✓ Based on the **phase – I Mega-float model**

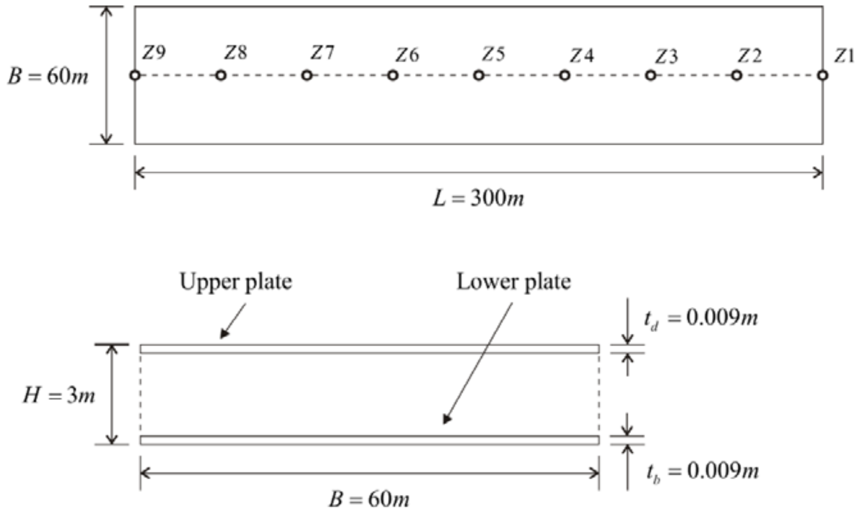
✓ Considering bilinear isotropic hardening plastic model

$$E = 206Gpa \qquad \sigma_y = 238Mpa$$

$$\rho_s = 7800kg/m^3 \qquad E_P = 0.05E$$

✓ Load I : **An impact load**

✓ Load II : **A dead load and an incident wave**



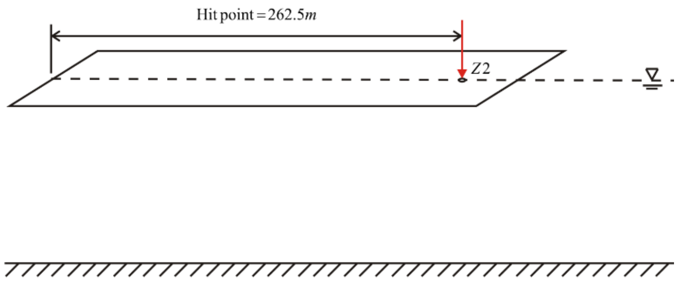
H. Suzuki. Overview of Megafloat: Concept, design criteria, analysis, and design. Mar Struct 2005;18;111-32.

Numerical examples

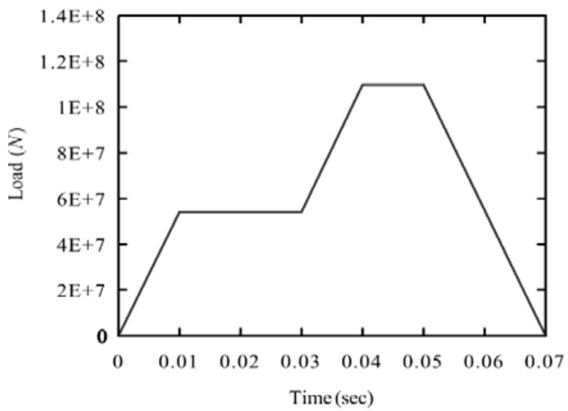
❖ Load Case I : An impact load

- Crash of a Phantom RF-4E aircraft

✓ Hit point



✓ Impact load curve



F.O. Henkel, D. Klein. Variants of the load case airplane crash. Transactions SMiRT 19 Toronto 2007; J03/2.

✓ Numerical model

Plate elements – 48×8

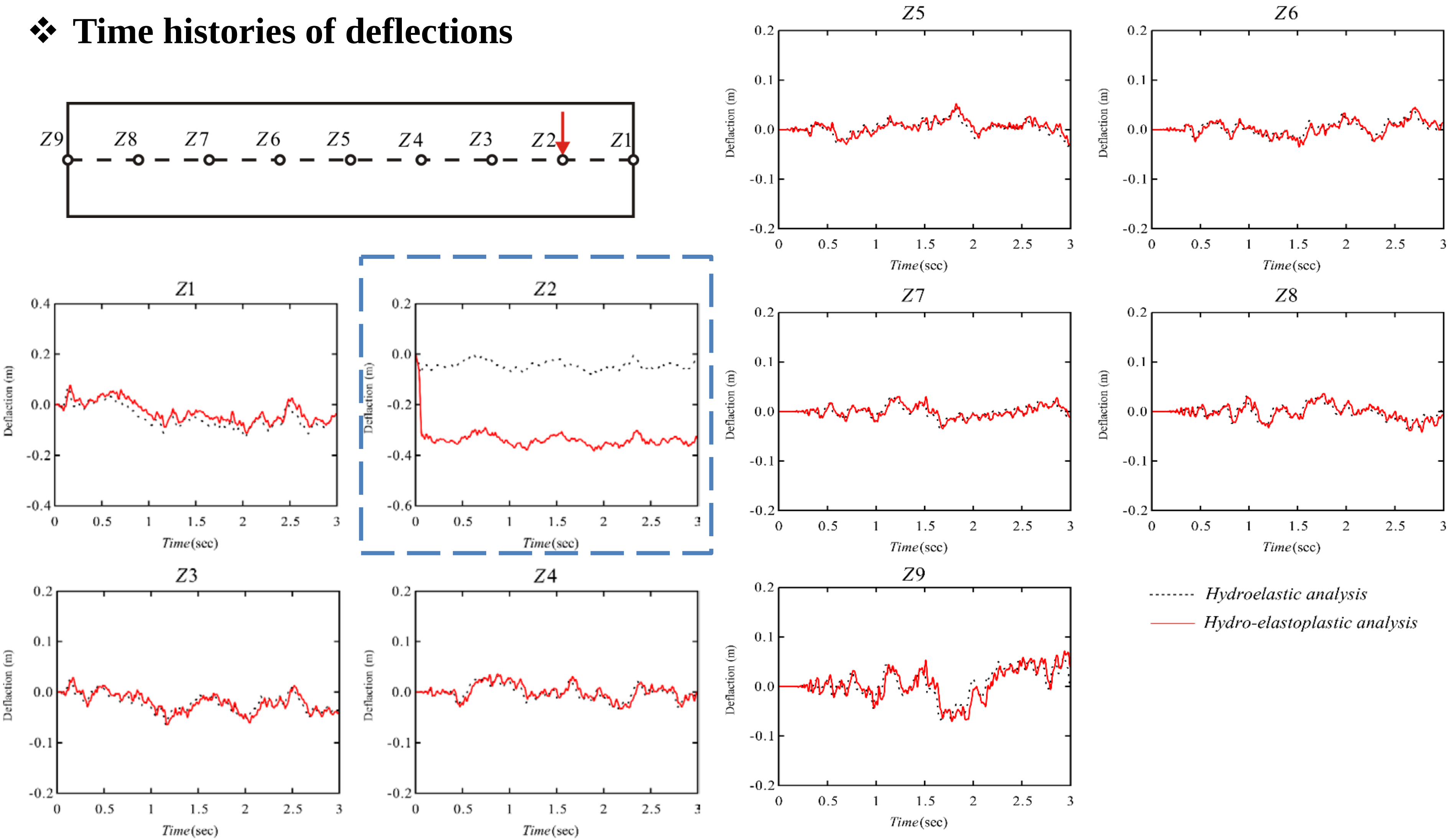
5-point Newton-Cotes integration for the upper and lower layers

Total time – 3s

Time step size – 0.001s

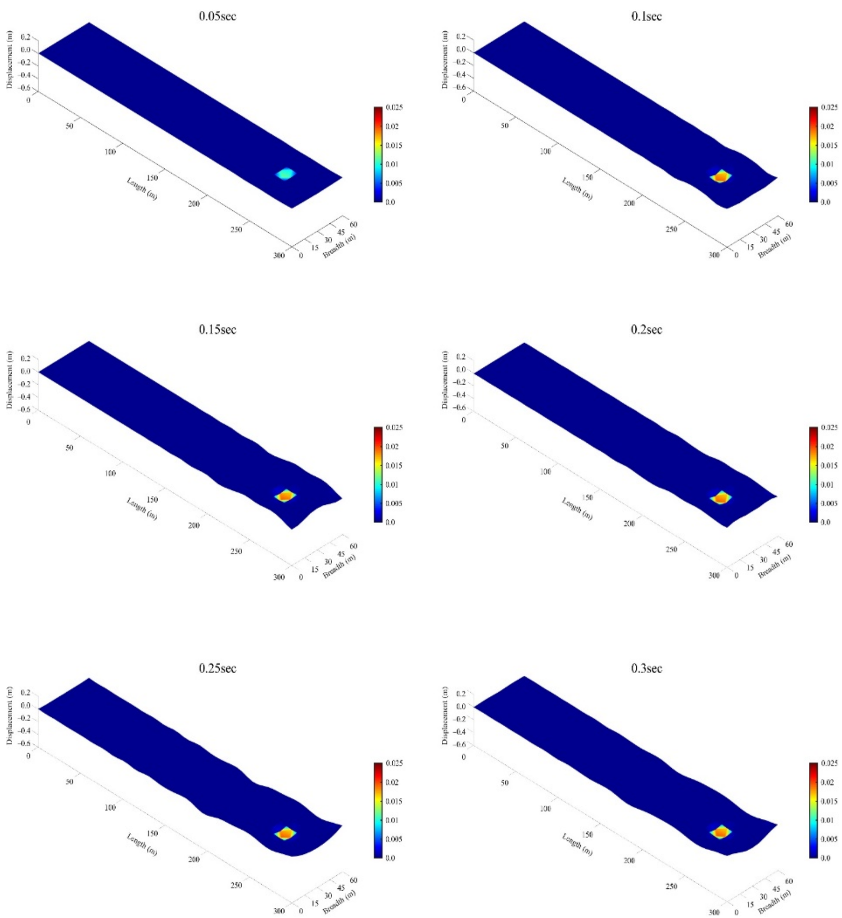
Numerical examples

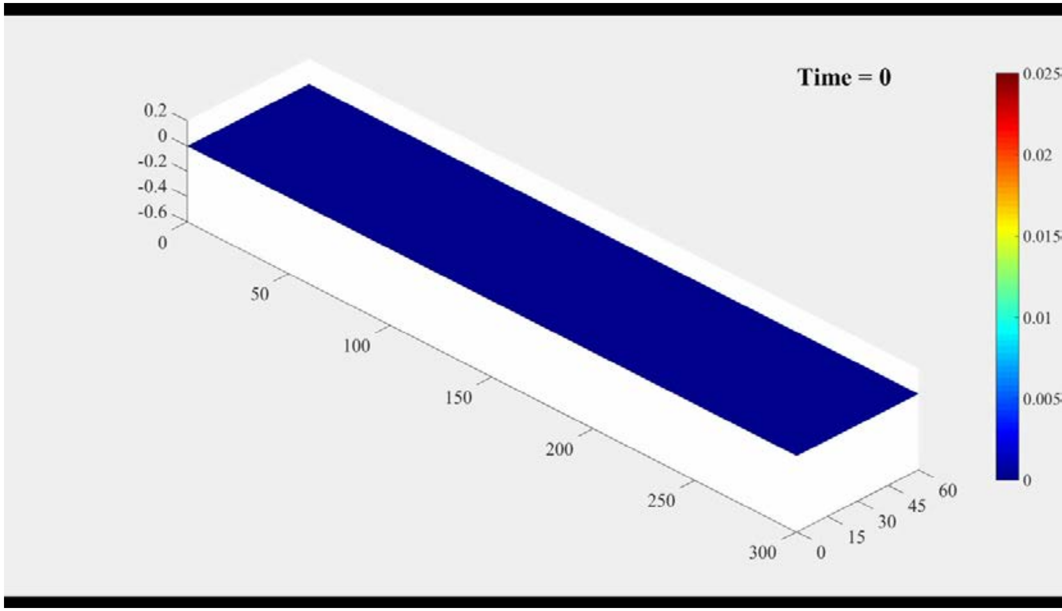
❖ Time histories of deflections



Numerical examples

❖ **Effective plastic strain**





Numerical examples

❖ Load Case II : An impact load a dead load and an incident wave

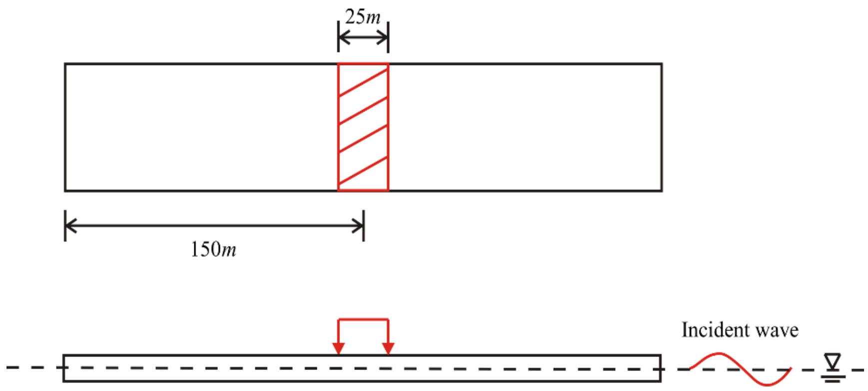
- Problem description

  ✓ Dead load

  $$4000kg/m^2$$

  ✓ A linear regular wave

  $$A = 0.8m \qquad \lambda = 240m \qquad \theta = 0°$$



  ✓ Numerical model

  Plate elements – 48×8

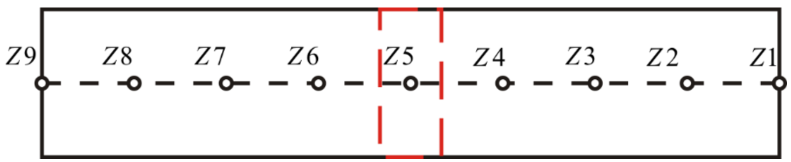
  5-point Newton-Cotes integration for the upper and lower layers

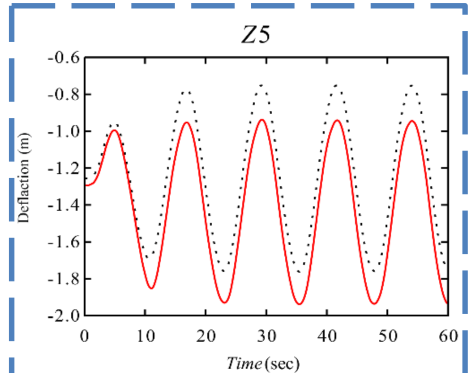
  Total time – 60s

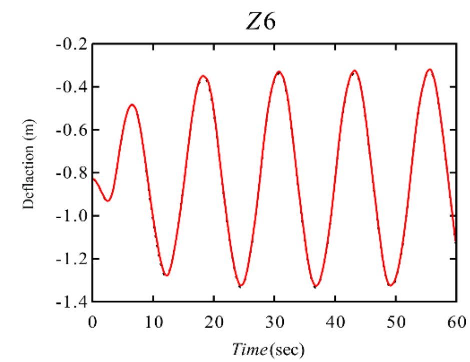
  Time step size – 0.002s

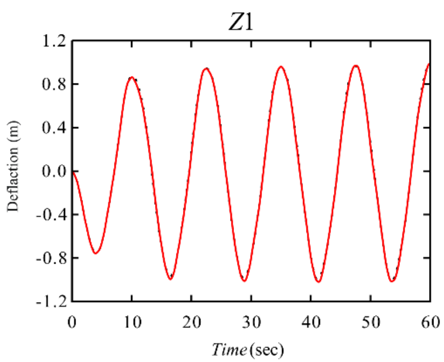
Numerical examples

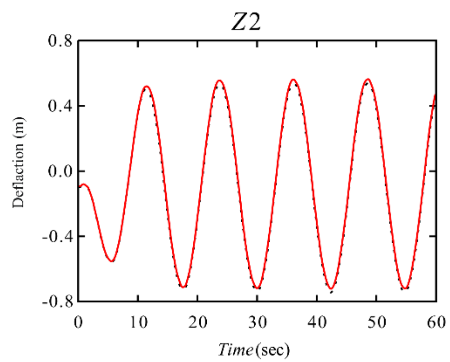
❖ **Time histories of deflections**

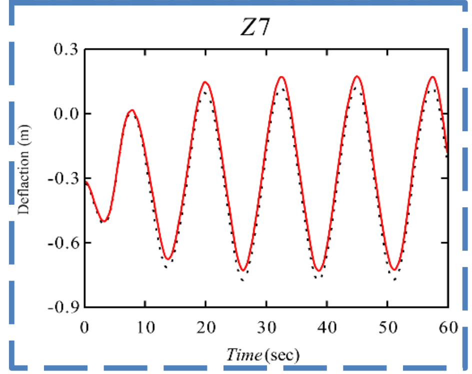


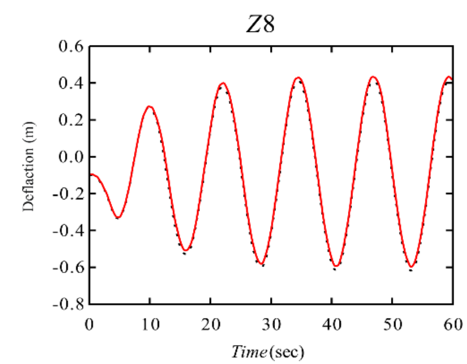


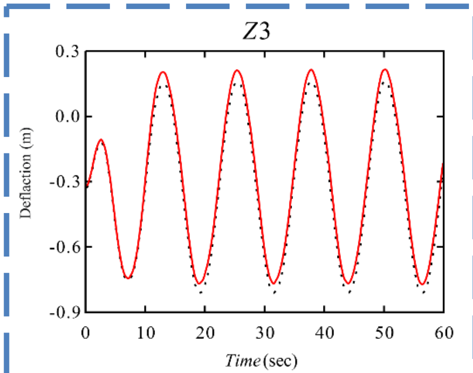


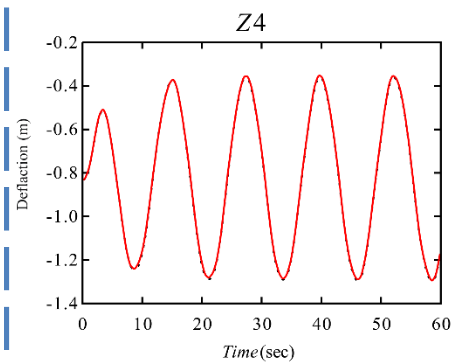


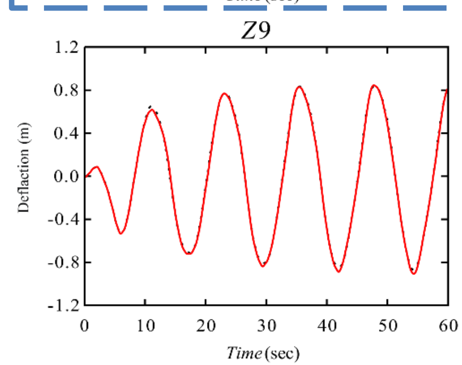








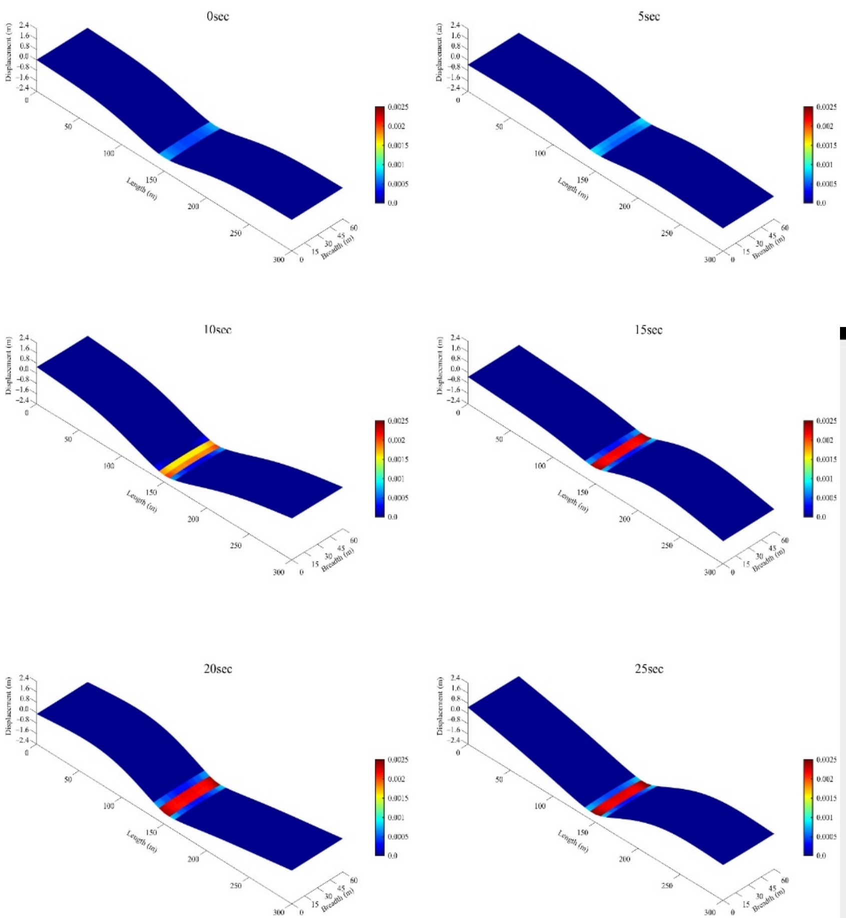


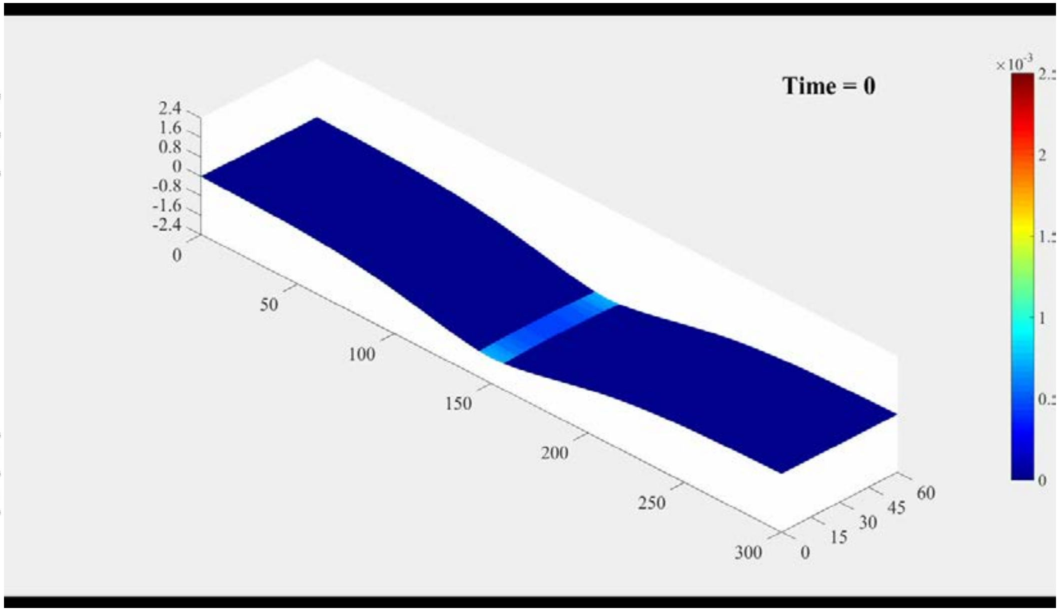


Hydroelastic analysis
Hydro-elastoplastic analysis

Numerical examples

❖ **Effective plastic strain**





Conclusion & Future works

Conclusion

1. A numerical procedure for a **hydroelastic analysis of floating plate structure** with multiple hinge connections is proposed

2. We investigated **the effect of the number of hinge connections** on the maximum bending moment and deflection in floating plate structures.

3. We developed a nonlinear procedure for a **hydro-elastoplastic analysis** considering elastoplastic behaviors and linear waves

4. **The hydro-elastoplastic problems of floating plate structures** subjected to an impact load or an incident wave under a dead load are solved

Future works

- ❖ **Experimental studies** for verification of the proposed procedure and understanding of hydro-elastoplastic behaviors of floating plate structures
  - ✓ Experimental set-up
  - ✓ Dimensional analysis

- ❖ **Improvement of the proposed method**
  - ✓ Computation efficiency through modal analysis or modification of the convolutions
  - ✓ Hydro-elastoplastic analysis of 3D ships or offshore platforms
  - ✓ Nonlinear behaviors of structure and fluid

Thank you