Lloyd's Register Educational Trust

UNIVERSITY OF Southampton

# Ultimate Strength of Plates and Stiffened Panels

by

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The LRET Research Collegium
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# Ultimate Strength of Plates and Stiffened Panels

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# Overview

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- Theory of the ALPS/ULSAP Method
  - Ultimate Strength of Plates
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  - Target Structure: Stiffened panel
  - Nonlinear FEA Modeling
  - Ultimate Strength of Stiffened Panels
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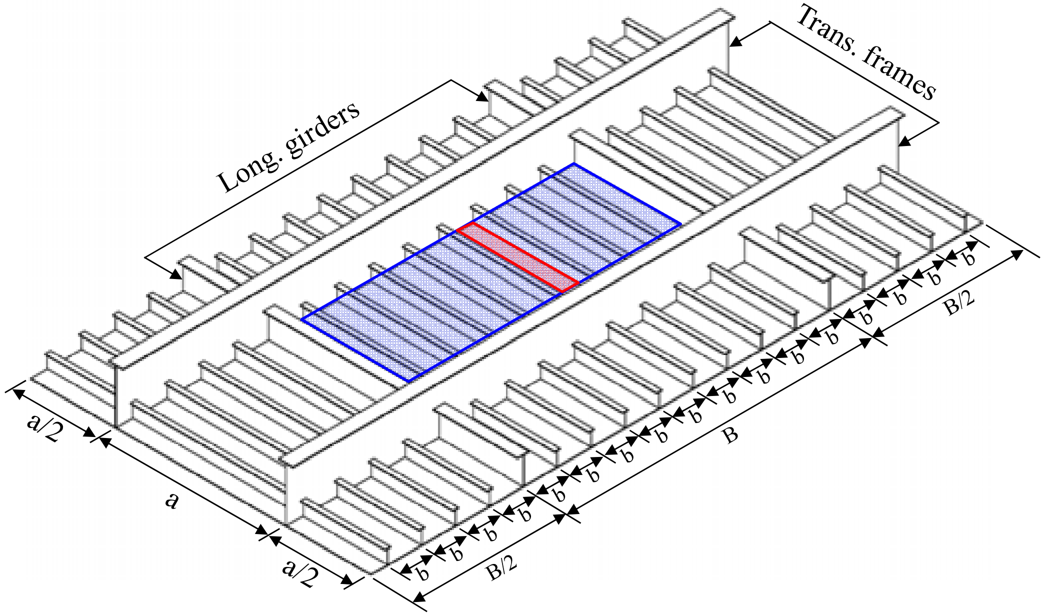
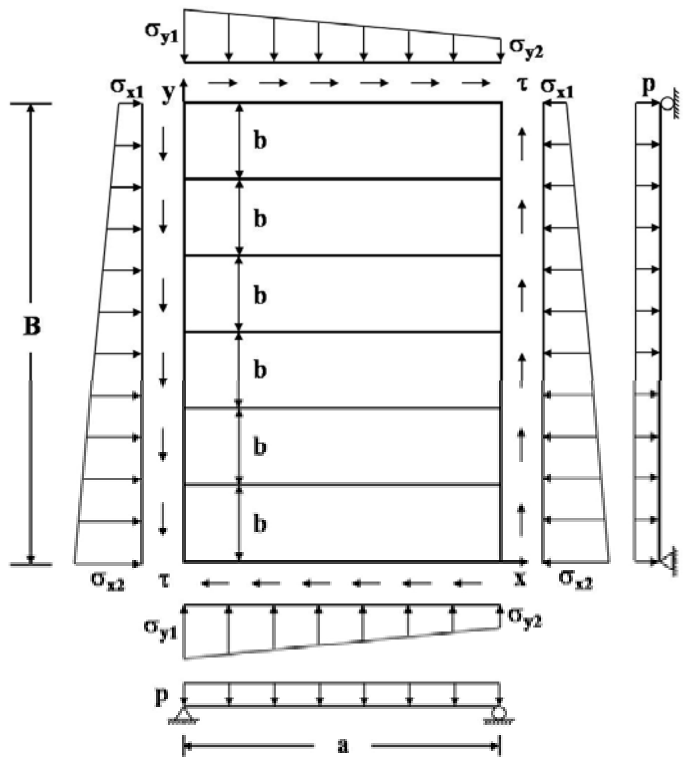
# Aims and Scope



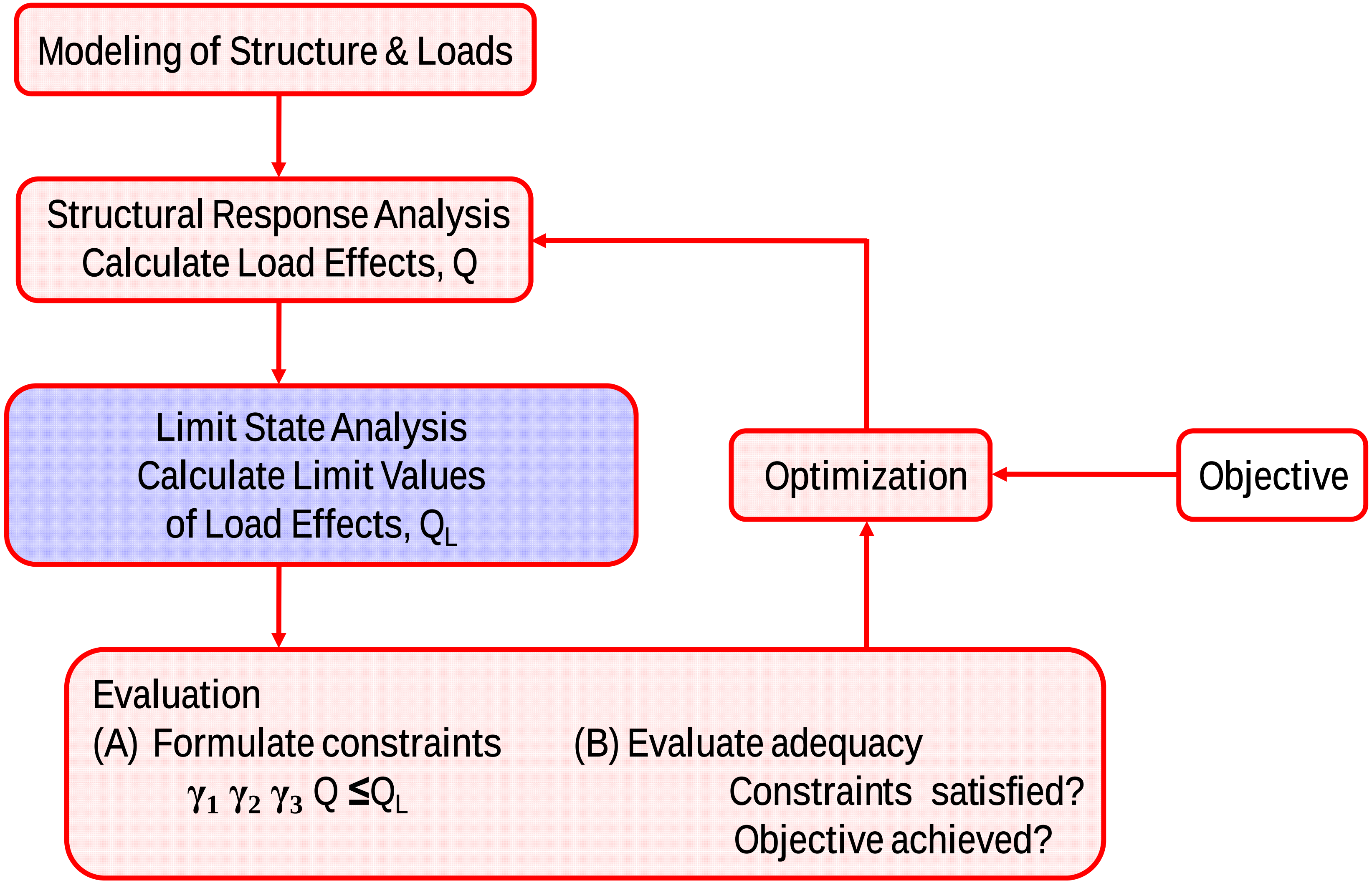

Stiffened panel structure




Stiffened panel subject to a combined in-plane and lateral pressure load

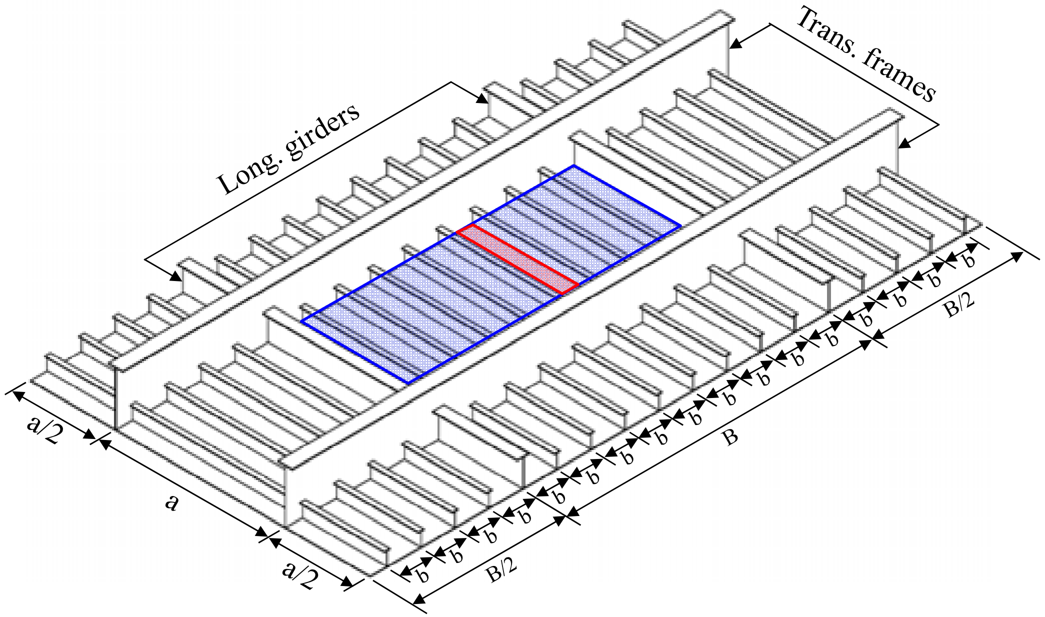
# Rationally-Based Structural Design

(Optimum structural design procedure based on ultimate limit state)



# Methods Used for Benchmark Study

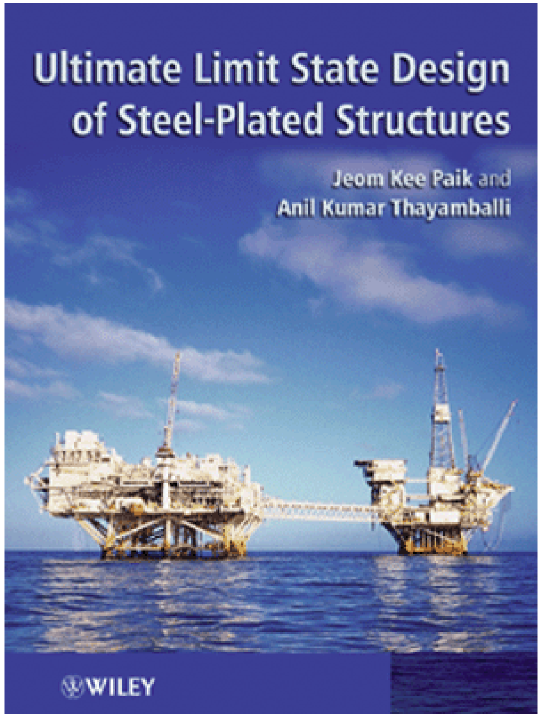
- Candidate methods
  - Nonlinear finite element method (ANSYS, MSC/MARC, Abaqus)
  - ALPS/ULSAP method
  - DNV/PULS method



# Theory of the ALPS/ULSAP Method

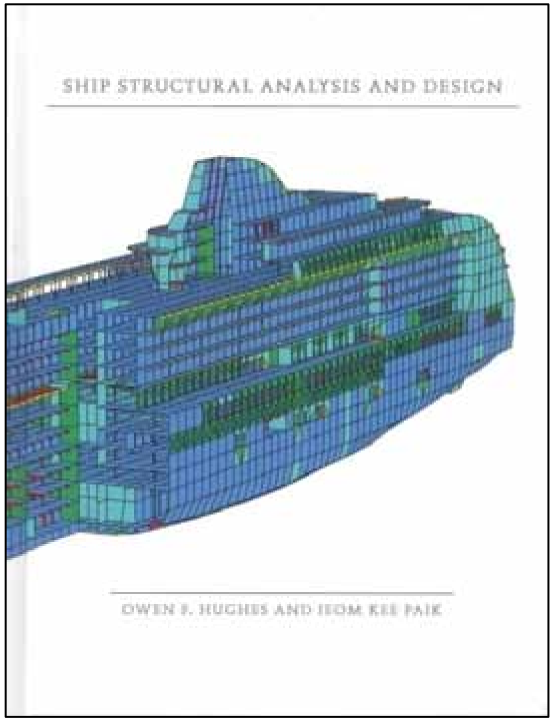
# Theory of the ALPS/ULSAP Method

- ALPS/ULSAP (Analysis of Large Plated Structures / Ultimate Limit State Assessment Program), developed by Prof. J.K.Paik, Pusan National University




Ultimate Limit State Design of Steel-Plated Structures (2003)

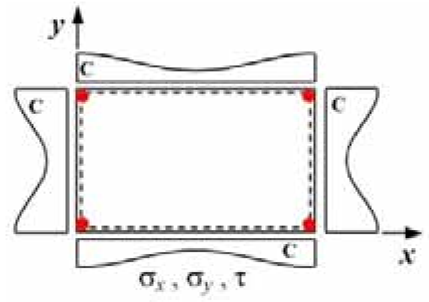
Paik & Thayamballi




Ship Structural Analysis and Design (2010)

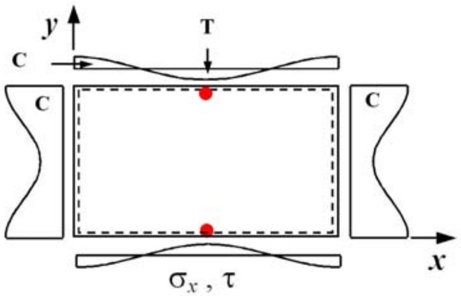
Hughes & Paik

# Ultimate Strength of Plates: $\sigma_u = \min.(\sigma_{u1}, \sigma_{u2}, \sigma_{u3})$



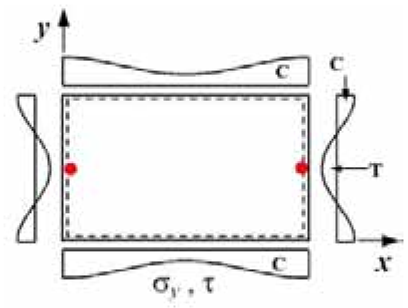

$$\sigma_{eq1} = \sqrt{\sigma_{x\max}^2 - \sigma_{x\max}\sigma_{y\max} + \sigma_{y\max}^2 + 3\tau^2} = \sigma_Y$$

(a) Plasticity at the corners




$$\sigma_{eq2} = \sqrt{\sigma_{x\max}^2 - \sigma_{x\max}\sigma_{y\min} + \sigma_{y\min}^2 + 3\tau^2} = \sigma_Y$$

(b) Plasticity at the longitudinal mid-edges



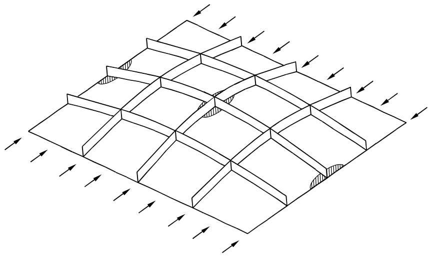

$$\sigma_{eq3} = \sqrt{\sigma_{x\min}^2 - \sigma_{x\min}\sigma_{y\max} + \sigma_{y\max}^2 + 3\tau^2} = \sigma_Y$$

(c) Plasticity at the transverse mid-edges

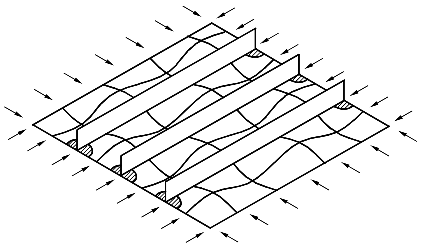
• : Expected plasticity location
T: Tension
C: Compression

# Ultimate Strength of Stiffened Panels: 6 Types of Collapse Modes

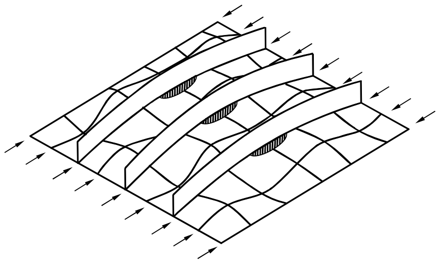
$$\sigma_u = \min.(\sigma_u^{I}, \sigma_u^{II}, \sigma_u^{III}, \sigma_u^{IV}, \sigma_u^{V}, \sigma_u^{VI})$$



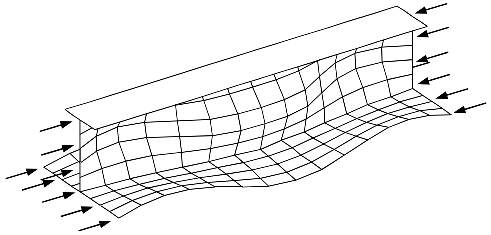
Mode I – overall collapse



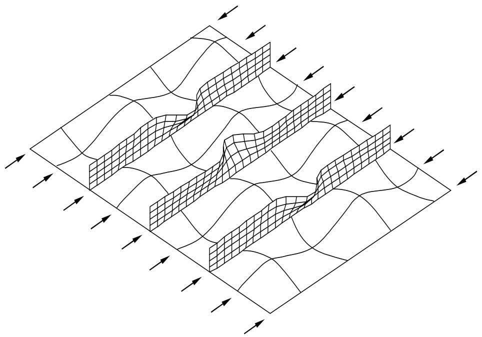
Mode II – plate-induced collapse




Mode III – stiffener-induced collapse by beam-column type collapse



Mode IV – stiffener-induced collapse by web buckling




Mode V – stiffener-induced collapse by tripping

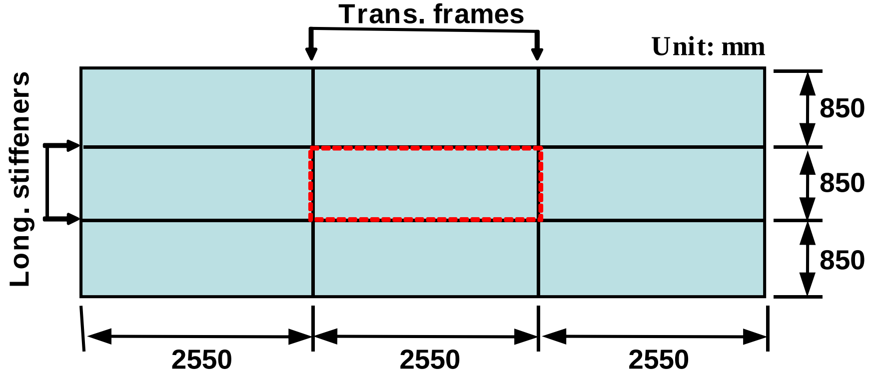
Mode VI: Gross yielding

# Benchmark Study

- Candidate methods
  - Nonlinear finite element method (ANSYS, MSC/MARC, Abaqus)
  - ALPS/ULSAP method
  - DNV/PULS method

# Target Structure: Unstiffened Panel

- Material and Geometric Properties
  - Yield stress of plate, $\boldsymbol{\sigma}_{Yp}$ = 313.6 N/mm$^2$
  - Yield stress of stiffener, $\boldsymbol{\sigma}_{Ys}$ = 313.6 N/mm$^2$
  - Elastic modulus, E = 205800 N/mm$^2$
  - Poisson's ratio, $\boldsymbol{\nu}$ = 0.3
  - Plate length, a = 2550 mm
  - Plate breath, b = 850 mm
  - Plate thickness, $t_p$ = 11, 16, 22, 33 mm
  - Under biaxial compressive loads
  - All edges simply supported
  - No residual stress
  - No lateral pressure



# Unstiffened Plates under Biaxial Compression (1/3)

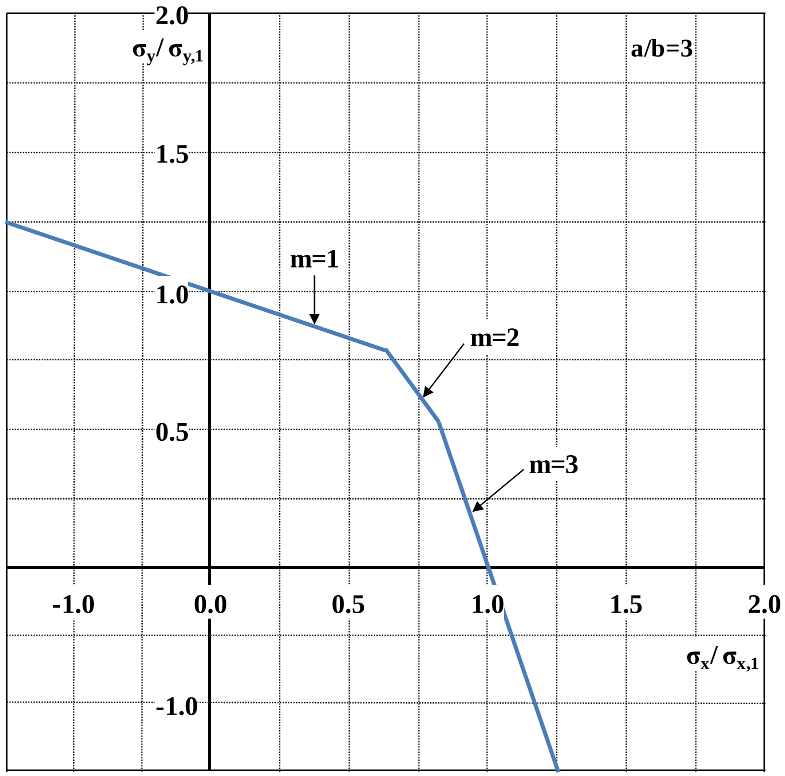
- Buckling half-wave number

$$\frac{(m^2/a^2 + 1/b^2)^2}{m^2/a^2 + c/b^2} \le \frac{[(m+1)^2/a^2 + 1/b^2]^2}{(m+1)^2/a^2 + c/b^2}$$

**where,** $c = \sigma_y / \sigma_x$

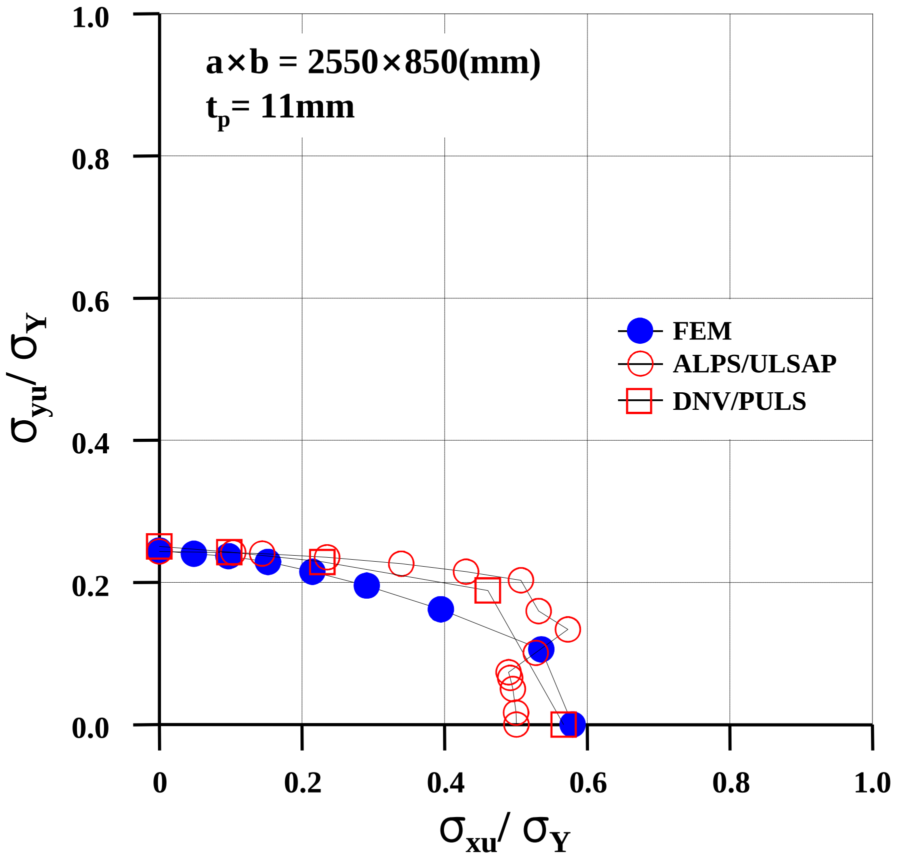
$\sigma_x$ and $\sigma_y$ are the component of the longitudinal and transverse axial buckling stress of the plate under combined biaxial loading.

$\sigma_{x,1}$ and $\sigma_{y,1}$ are the component of the longitudinal or transverse axial buckling stress of the plate under uniaxial loading.

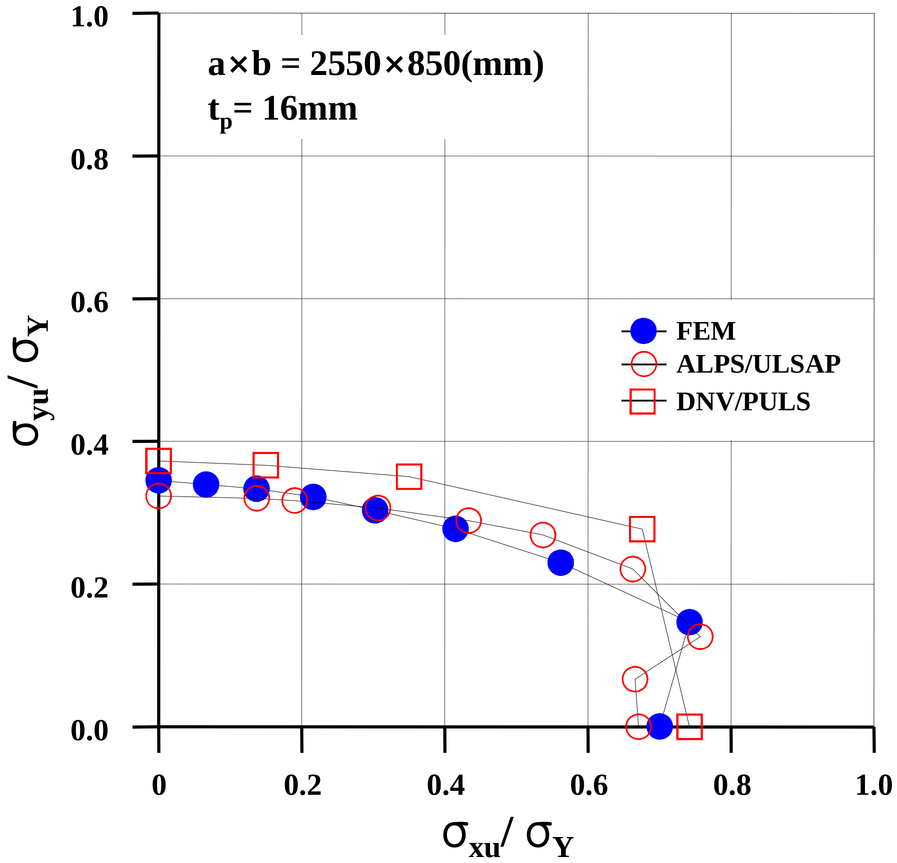


# Unstiffened Plates under Biaxial Compression (2/3)

$t_p$=11mm

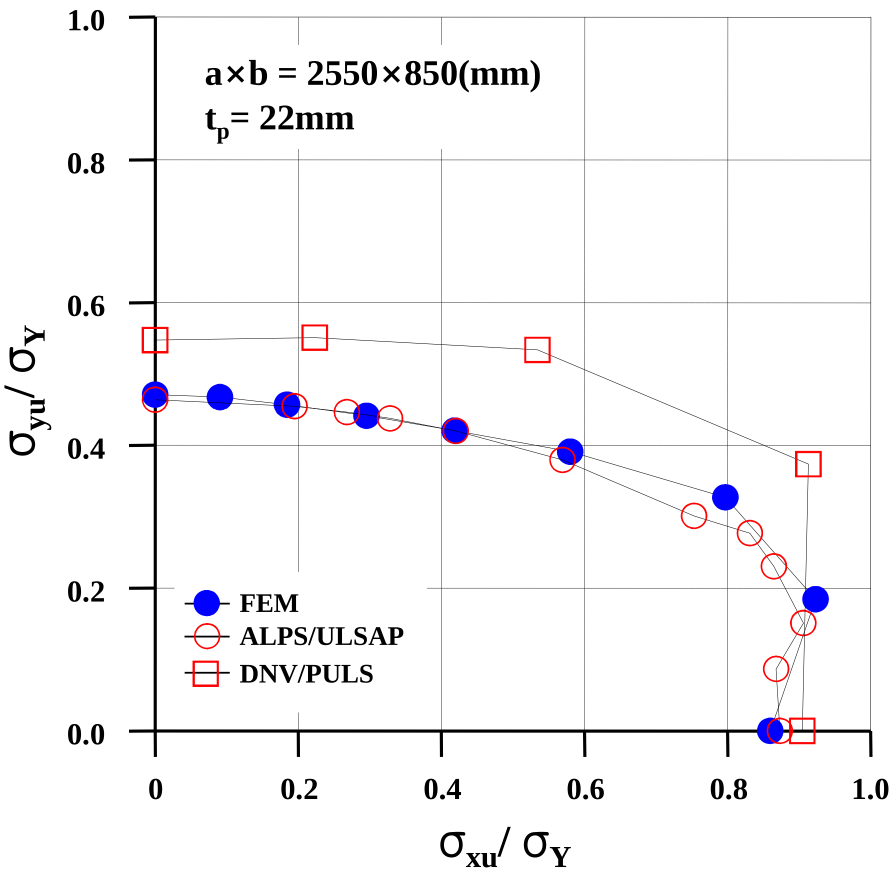



$t_p$=16mm

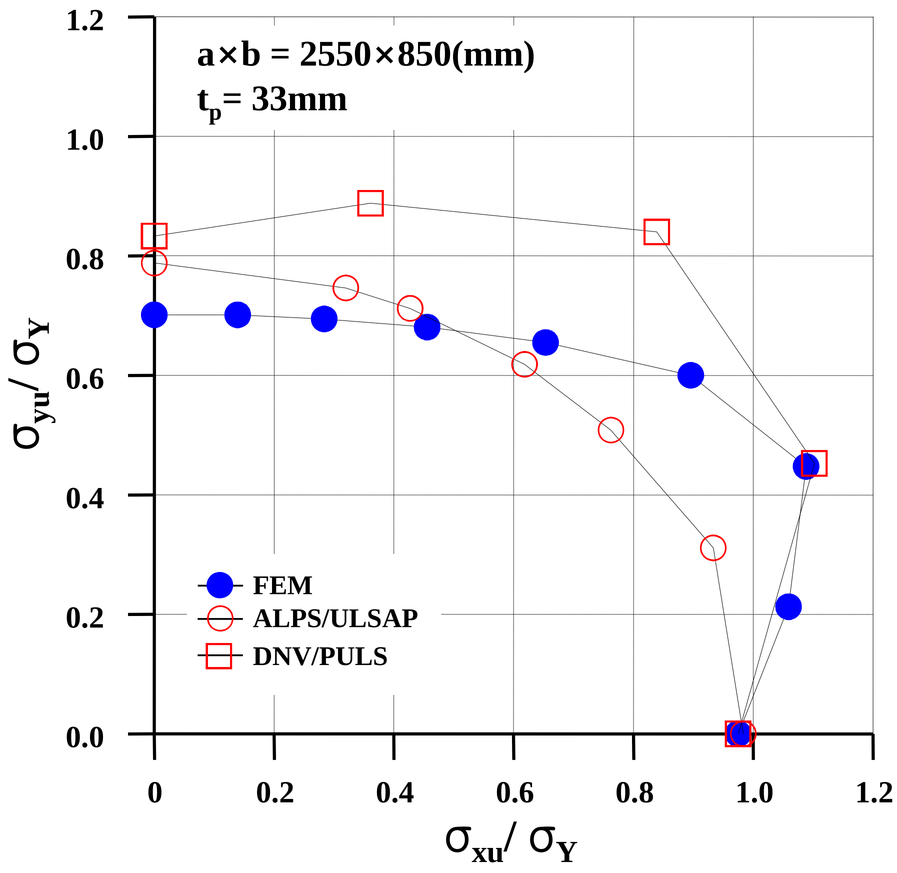


# Unstiffened Plates under Biaxial Compression (3/3)

$t_p$=22mm

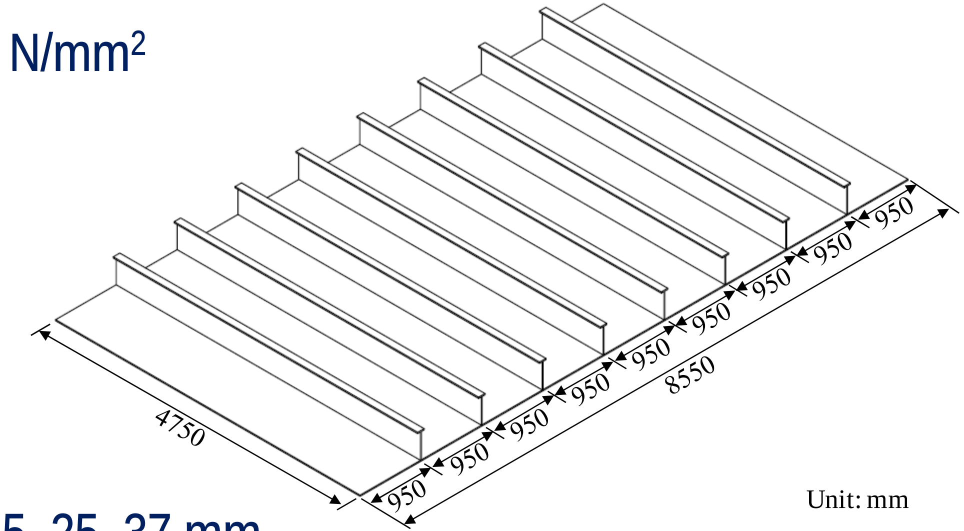



$t_p$=33mm



# Target Structure: Stiffened Panel (1/2)

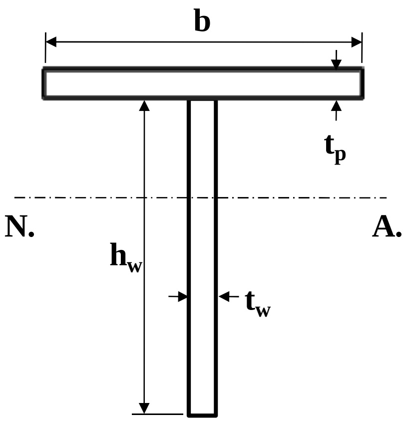
- Material and Geometric Properties
  - Yield stress of plate, $\boldsymbol{\sigma}_{Yp}$ = 313.6 N/mm$^2$
  - Yield stress of stiffener, $\boldsymbol{\sigma}_{Ys}$ = 313.6 N/mm$^2$
  - Elastic modulus, E = 205800 N/mm$^2$
  - Poisson's ratio, $\boldsymbol{\nu}$ = 0.3
  - Plate length, a = 4750 mm
  - Plate breath, b = 950 mm
  - Plate thickness, $t_p$ = 11, 12.5, 15, 18.5, 25, 37 mm
  - Number of the stiffeners: 8 stiffeners in a panel
  - No residual stress



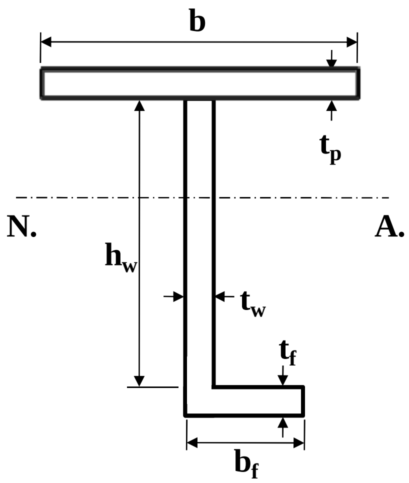
# Target Structure: Stiffened Panel (2/2)

- Dimensions of the Stiffeners

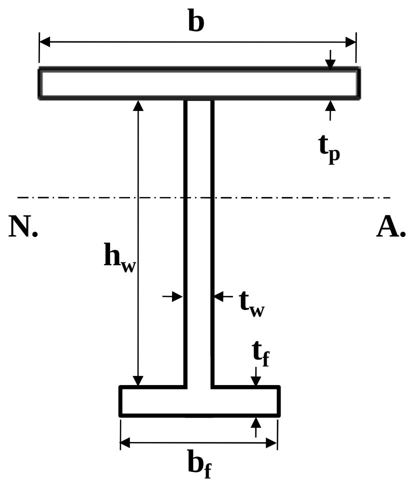
| | Flat bar ($h_w x t_w$) | Angle bar ($h_w x b_f x t_w/t_f$) | Tee bar ($h_w x b_f x t_w/t_f$) |
|---|---|---|---|
| Size 1 | 150x17 | 138x90x9/12 | 138x90x9/12 |
| Size 2 | 250x25 | 235x90x10/15 | 235x90x10/15 |
| Size 3 | 350x35 | 383x100x12/17 | 383x100x12/17 |
| Size 4 | 550x35 | 580x150x15/20 | 580x150x15/20 |



Flat bar



Angle bar

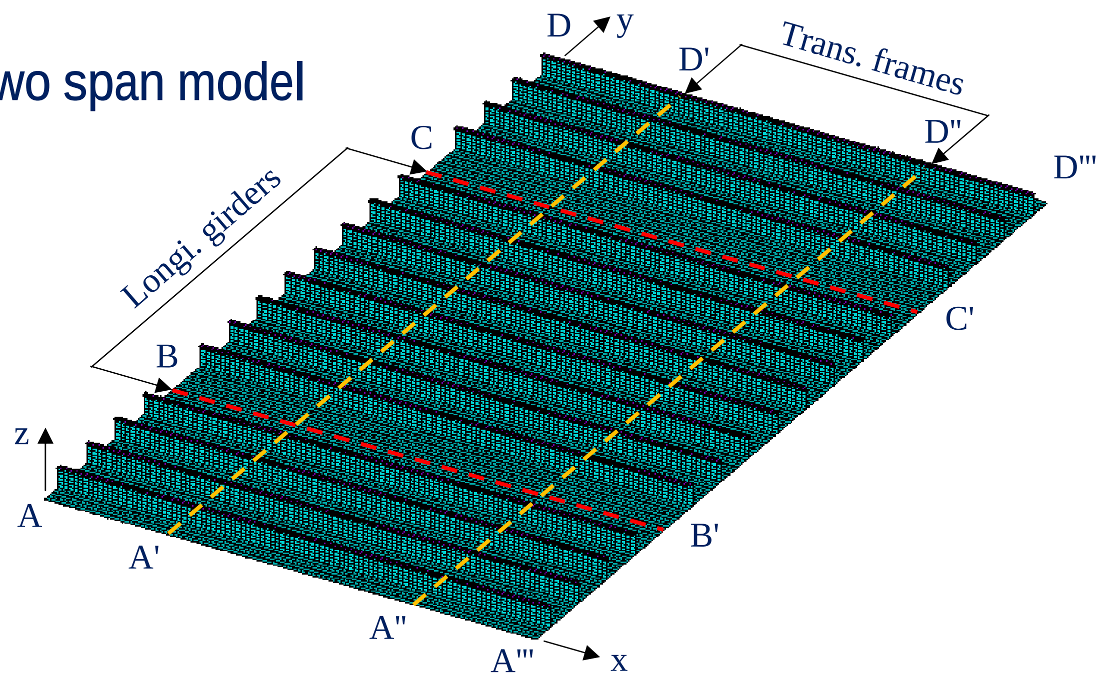


Tee bar

*N.A. = neutral axis

# ANSYS Nonlinear FEA Modeling (1/2)

- Extent of Analysis: Two bay/two span model

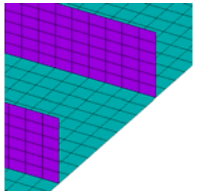
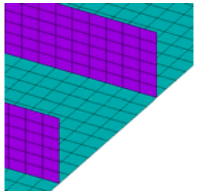
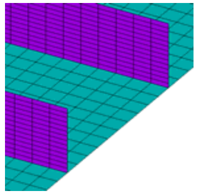
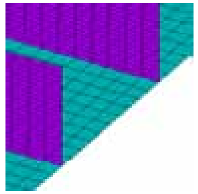
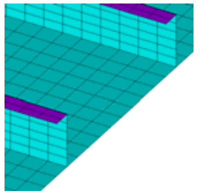
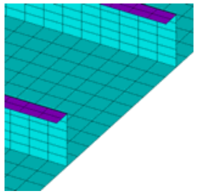
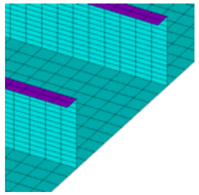
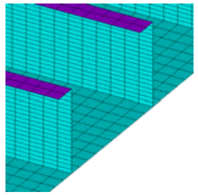
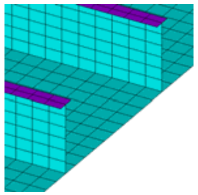
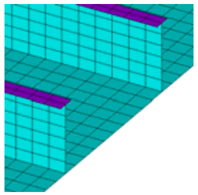
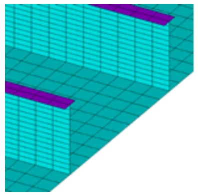
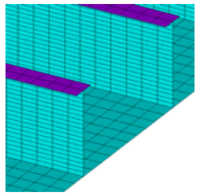



- Boundary Conditions

| Boundary | Description |
|---|---|
| **A-A''' and D-D'''** | Symmetric condition with $R_x$=$R_z$=0 and<br>uniform displacement in the y direction ($U_y$=uniform),<br>coupled the plate part |
| **A-D and A'''-D'''** | Symmetric condition with $R_y$=$R_z$=0 and<br>uniform displacement in the x direction ($U_x$=uniform),<br>coupled with longitudinal stiffeners |
| **A'-D', A''-D'',<br>B-B' and C-C'** | $U_z$=0 |

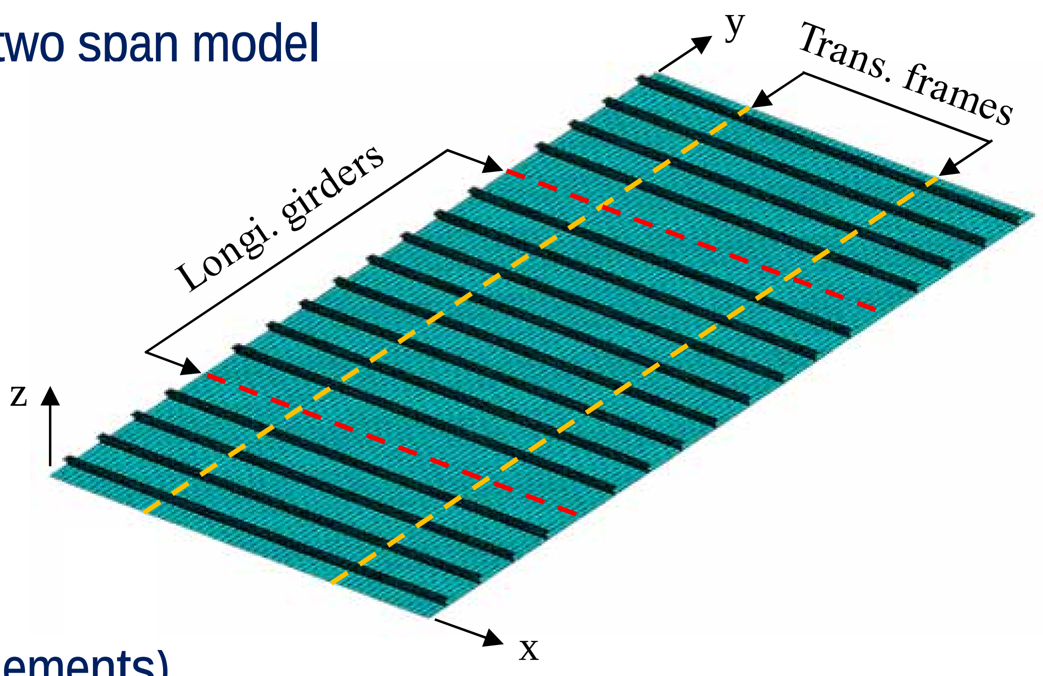
# ANSYS Nonlinear FEA Modeling (2/2)

- Mesh Sizes Applied

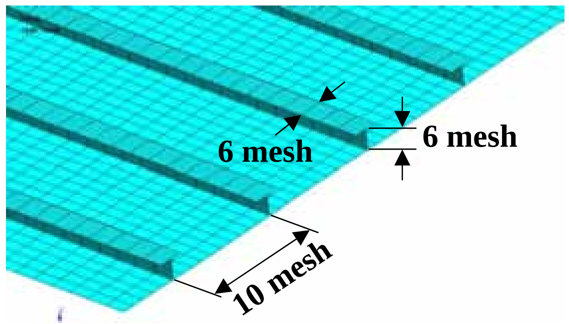
| | Size 1 | Size 2 | Size 3 | Size 4 |
|---|---|---|---|---|
| **Flat type** **($h_w \times t_w$)** |  |  |  |  |
| | **150×17(mm)** | **250×25(mm)** | **350×35(mm)** | **550×35(mm)** |
| | **27600 elements** | **27600 elements** | **40400 elements** | **50000 elements** |
| **Angle type** **($h_w \times b_f \times t_w/t_f$)** |  |  |  |  |
| | **138×90×9/12(mm)** | **235×90×10/15(mm)** | **383×100×12/17(mm)** | **580×150×15/20(mm)** |
| | **30800 elements** | **30800 elements** | **43600 elements** | **53200 elements** |
| **Tee type** **($h_w \times b_f \times t_w/t_f$)** |  |  |  |  |
| | **138×90×9/12(mm)** | **235×90×10/15(mm)** | **383×100×12/17(mm)** | **580×150×15/20(mm)** |
| | **30800 elements** | **30800 elements** | **43600 elements** | **53200 elements** |

# MSC/MARC Nonlinear FEA Modeling by Prof. M. Fujikubo, Osaka University

- Extent of Analysis: Two bay/two span model

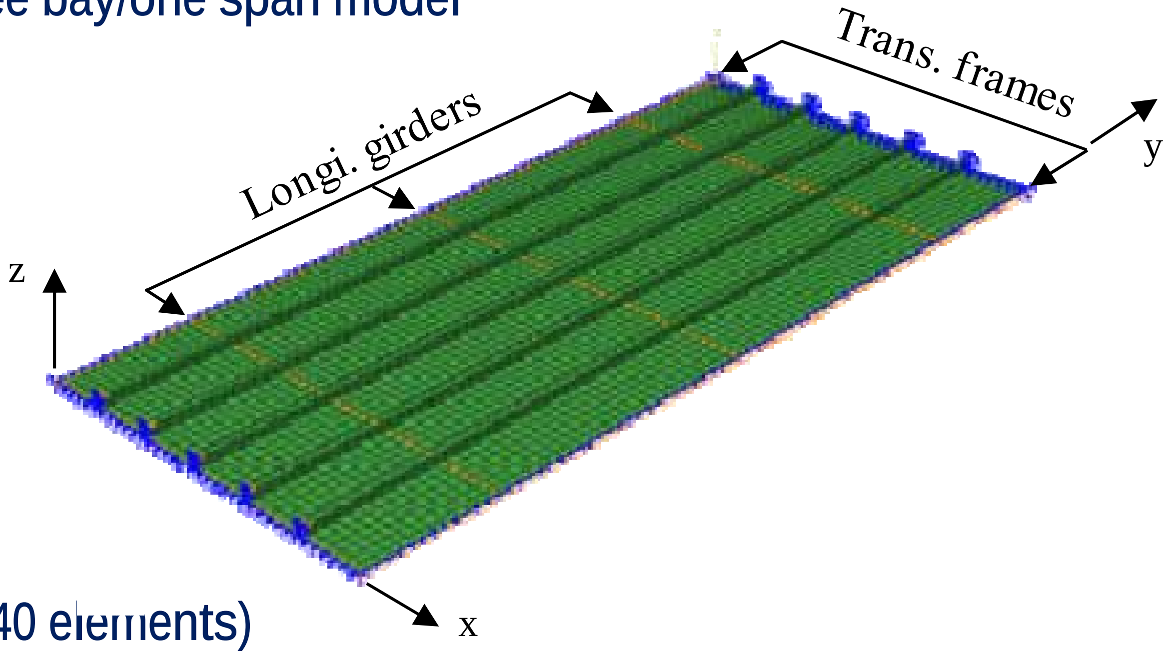



- Mesh Sizes Applied (22753 elements)

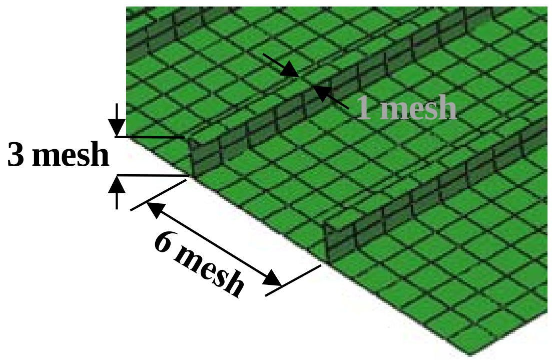


# Abaqus Nonlinear FEA Modeling by Dr. Amlashi Hadi, DNV

- Extent of Analysis: Three bay/one span model

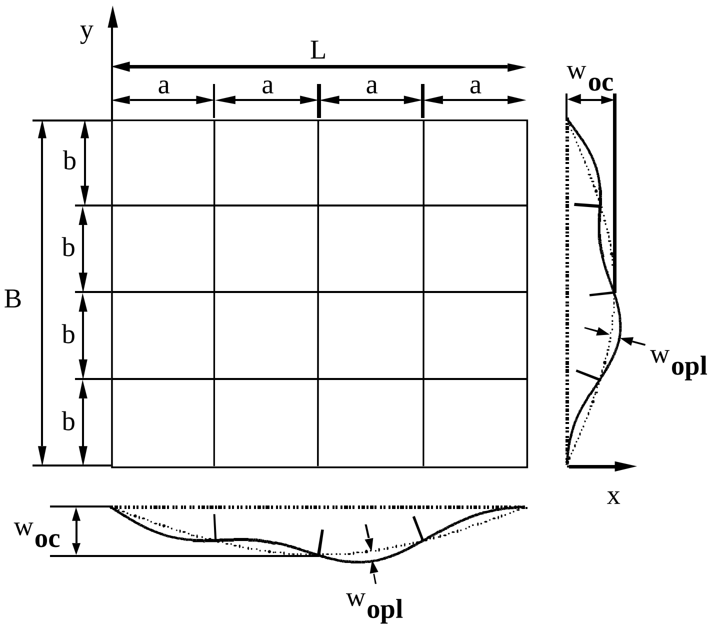



- Mesh Sizes Applied (7740 elements)



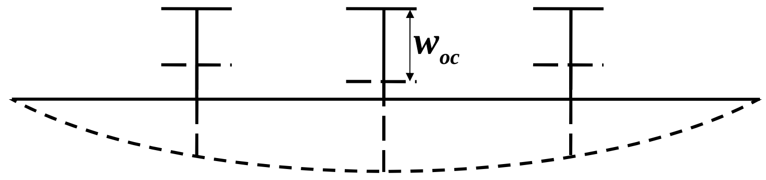
# Nonlinear FEA Modeling for ANSYS and MSC/MARC

- Plate Initial Deflection



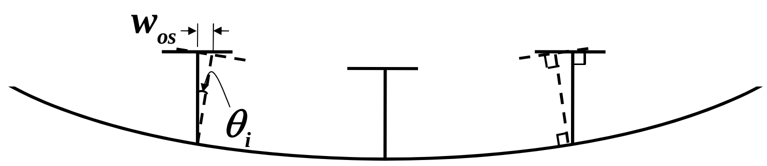

$$w_{opl} = A_o \sin\frac{m\pi x}{a}\sin\frac{\pi y}{b}$$

- Column Type Initial Distortion of Stiffener




$$w_{oc} = B_o \sin\frac{\pi x}{a}\sin\frac{\pi y}{B}$$

- Sideways Initial Distortion of Stiffener

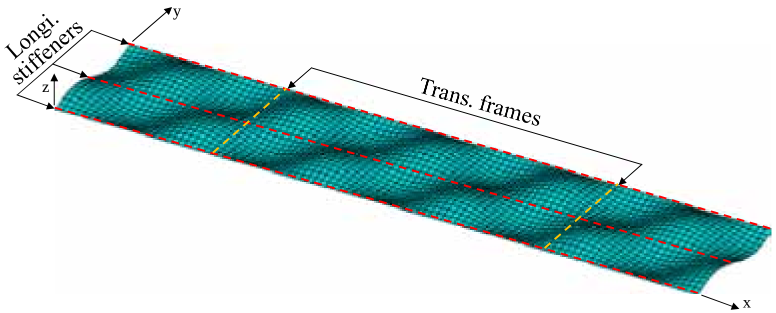



$$w_{os} = C_0 \frac{z}{h_w}\sin\frac{\pi x}{a}$$

$$A_o = 0.1\beta^2 t_p;\quad B_o = C_o = 0.0015a;\quad \beta = \frac{b}{t_p}\sqrt{\frac{\sigma_{Yp}}{E}}$$

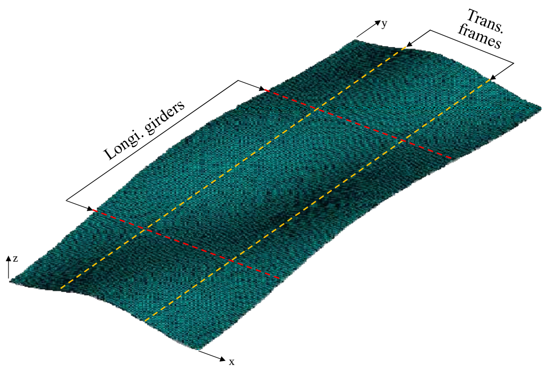
# Nonlinear FEA Modeling for ANSYS and MSC/MARC

- Plate Initial Deflection



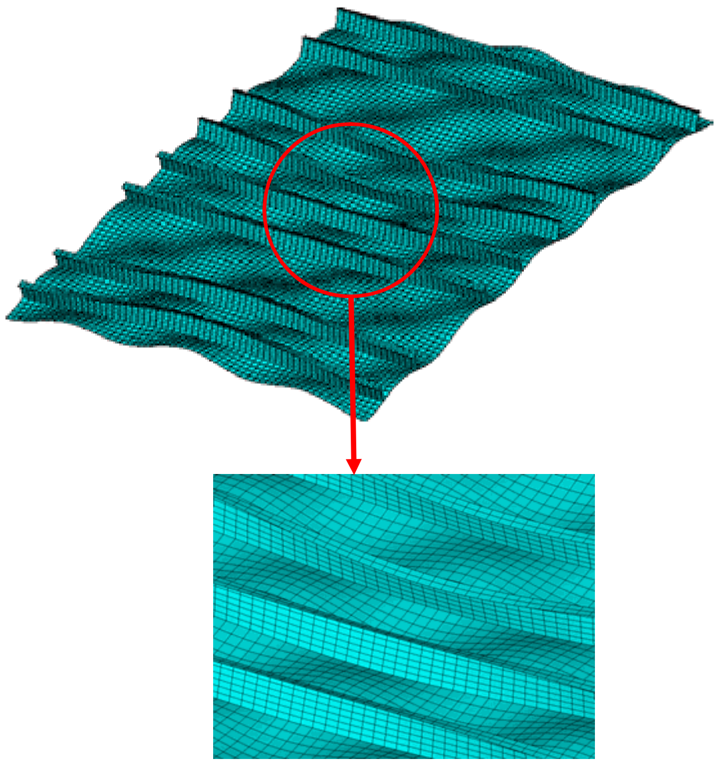

Local deflection with amplification factor of 20

- Column Type Initial Distortion of Stiffener




Overall deflection with amplification factor of 50

- Sideways Initial Distortion of Stiffener

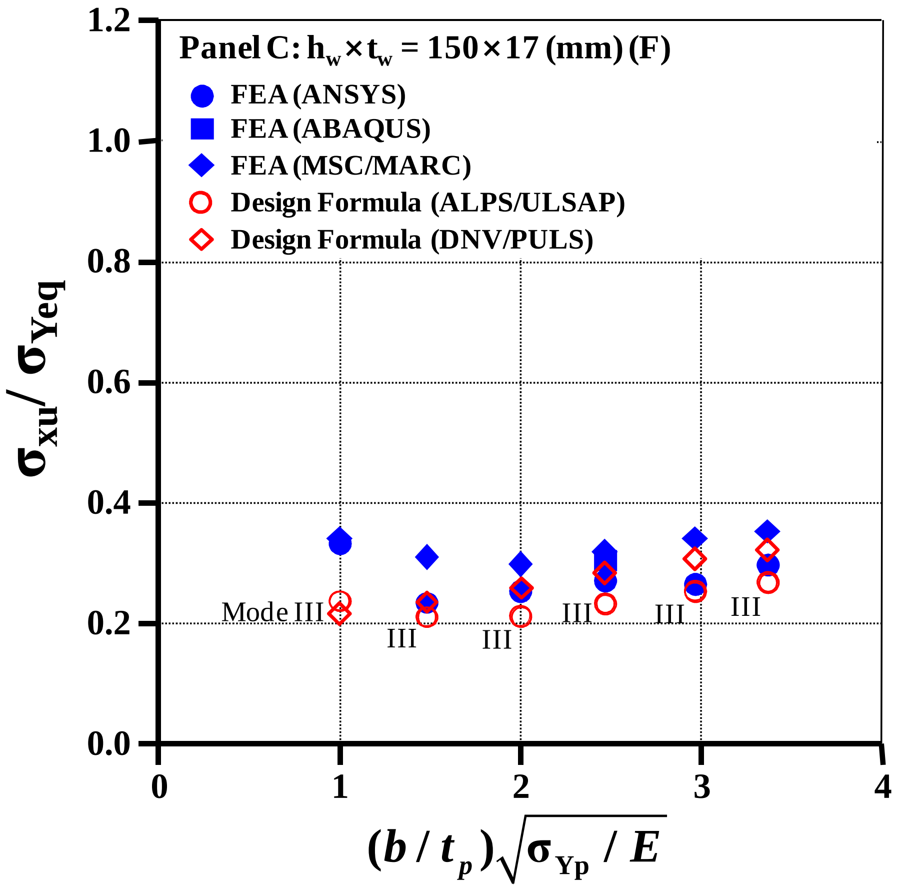


Initial deflection with amplification factor of 20

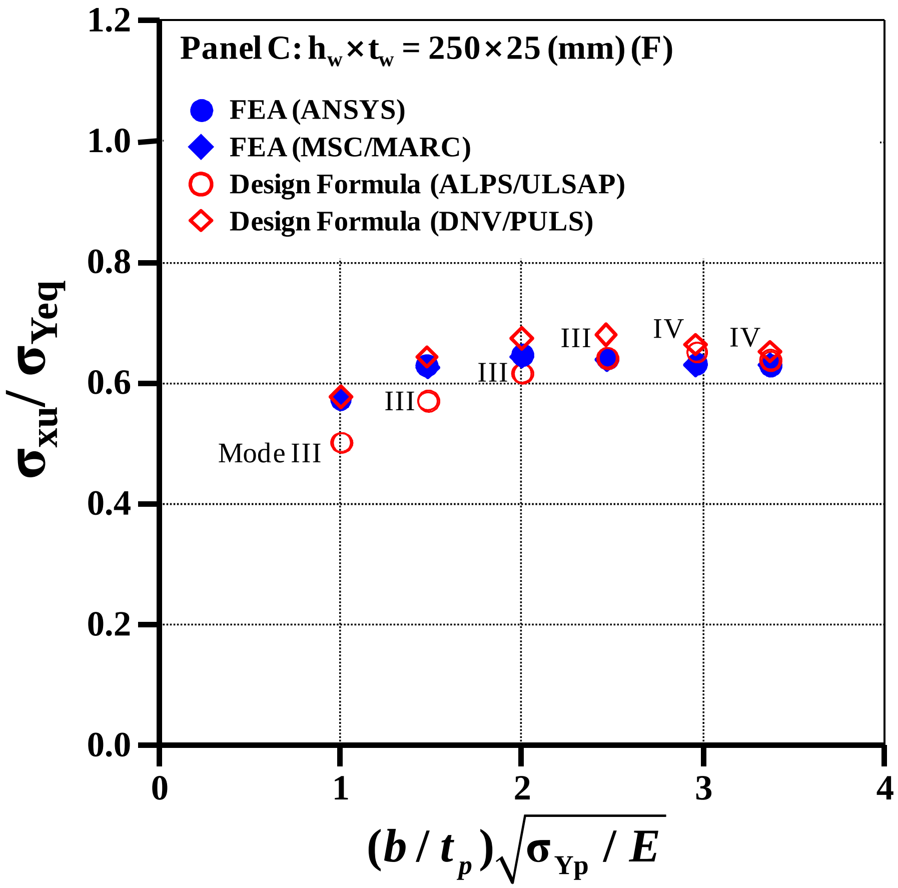
# Ultimate Strength of Stiffened Panels (1/26)

- Flat Bar Under Longitudinal Uniaxial Compression

Size 1



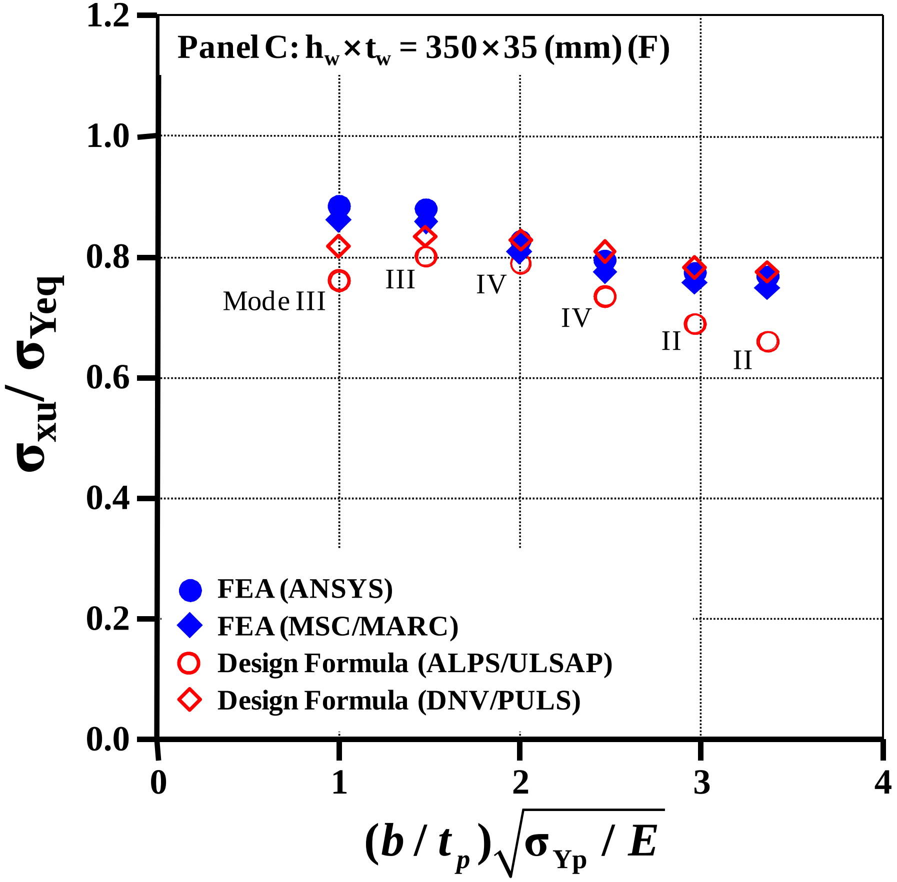

Size 2



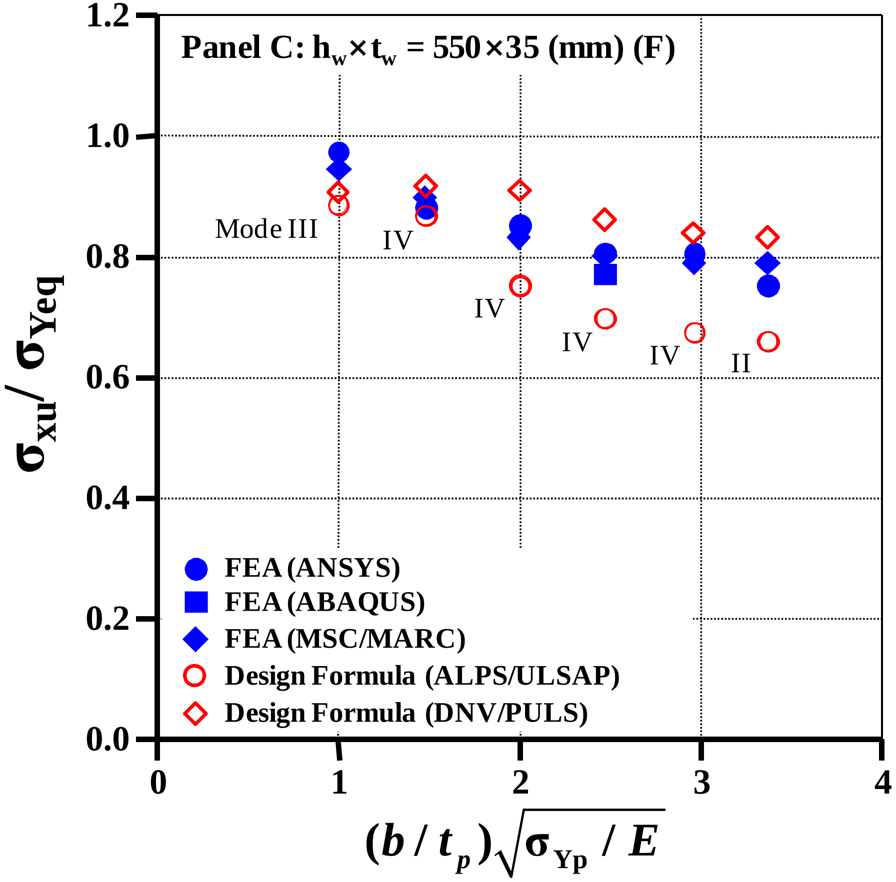
# Ultimate Strength of Stiffened Panels (2/26)

- Flat Bar Under Longitudinal Uniaxial Compression

Size 3



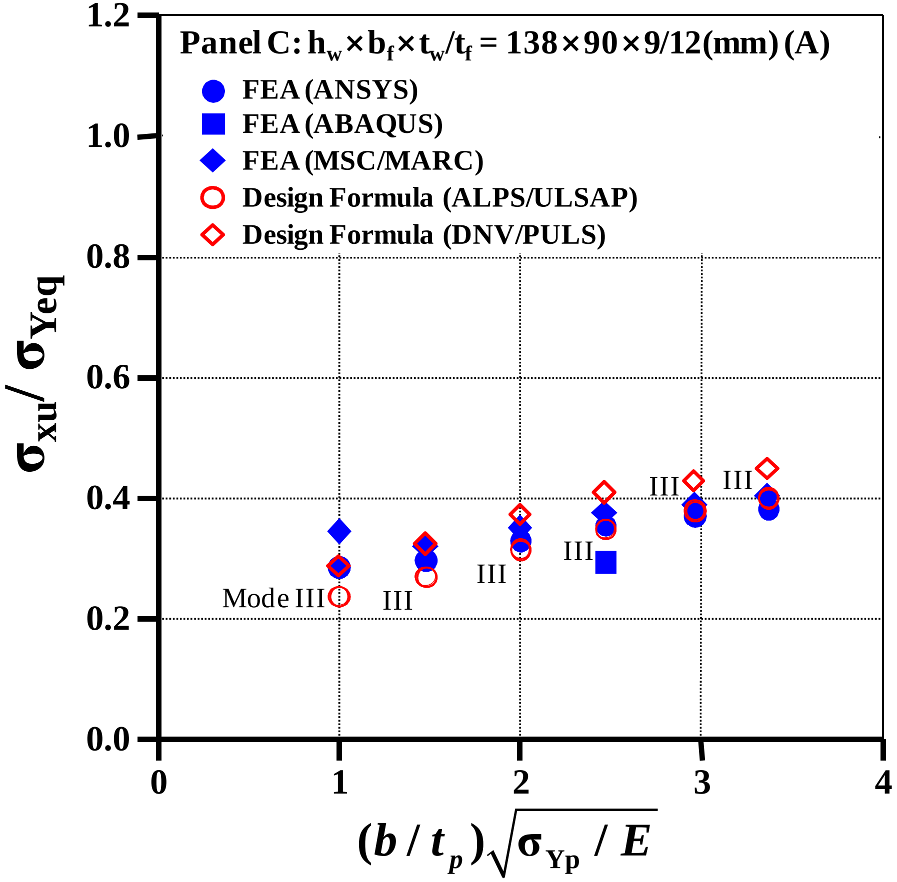

Size 4



# Ultimate Strength of Stiffened Panels (3/26)

- Angle Bar Under Longitudinal Uniaxial Compression

Size 1

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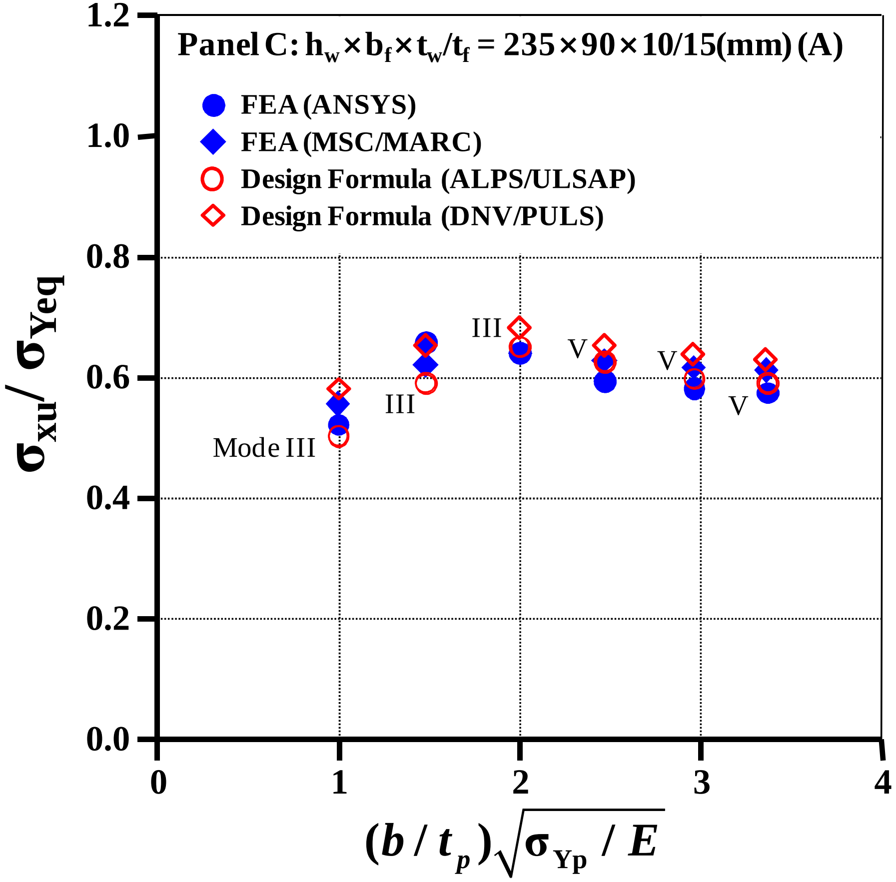
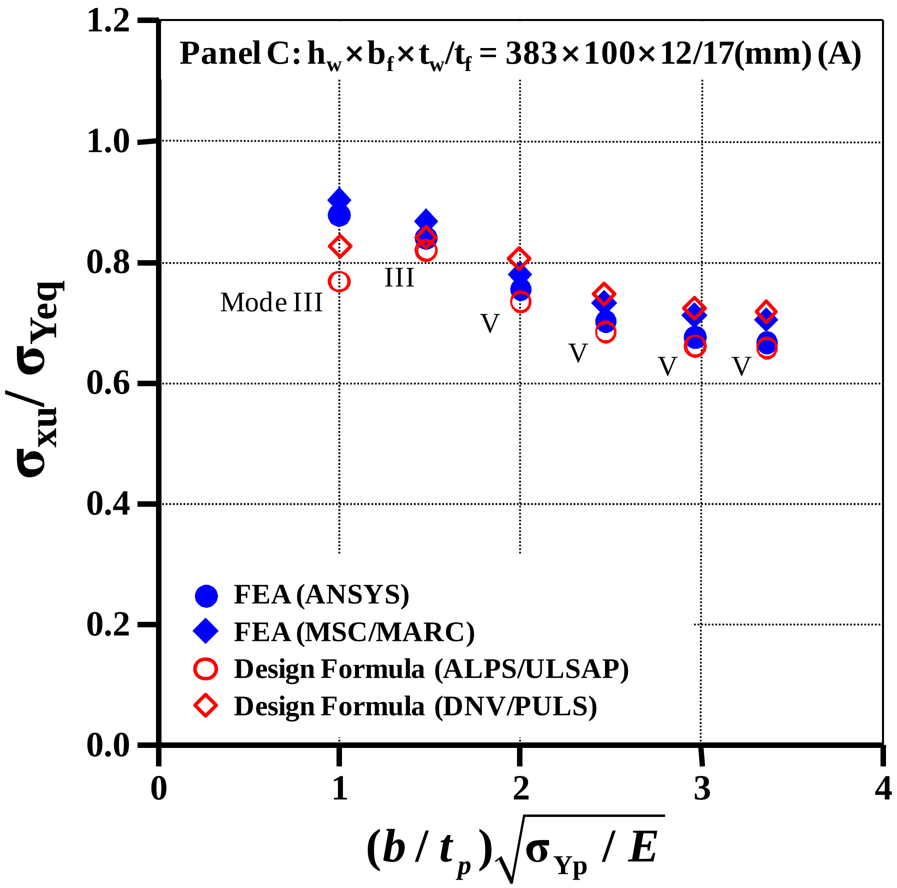


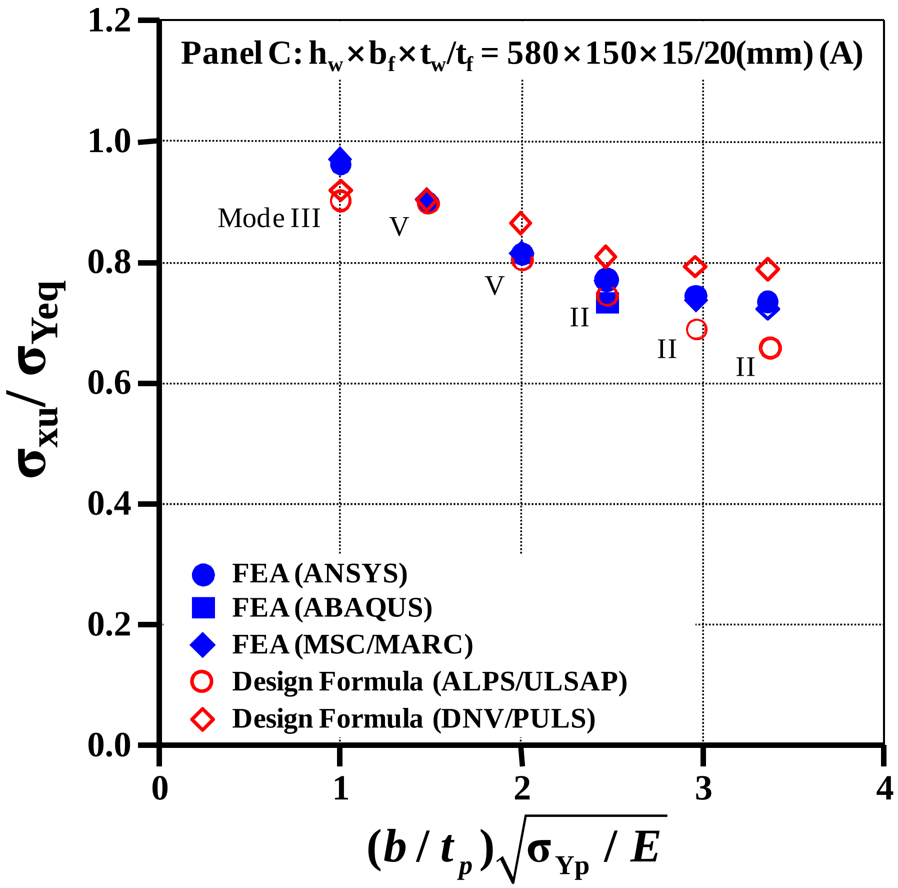
# Ultimate Strength of Stiffened Panels (4/26)

- Angle Bar Under Longitudinal Uniaxial Compression

Size 3



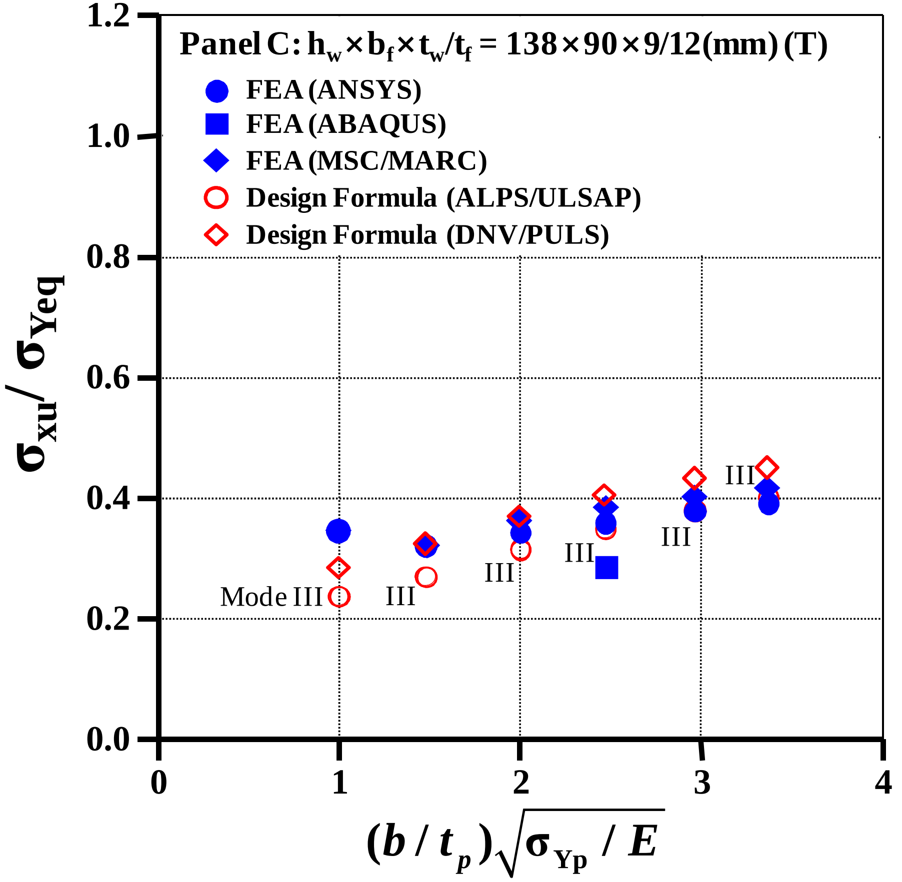

Size 4



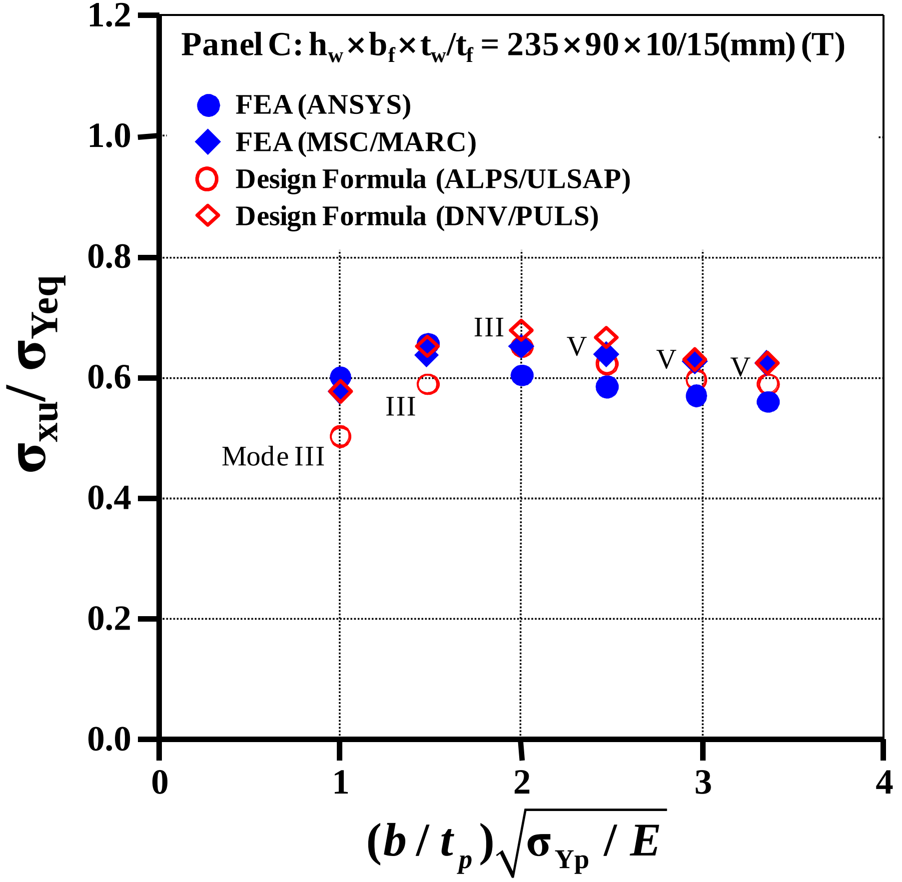
# Ultimate Strength of Stiffened Panels (5/26)

- Tee Bar Under Longitudinal Uniaxial Compression

## Size 1



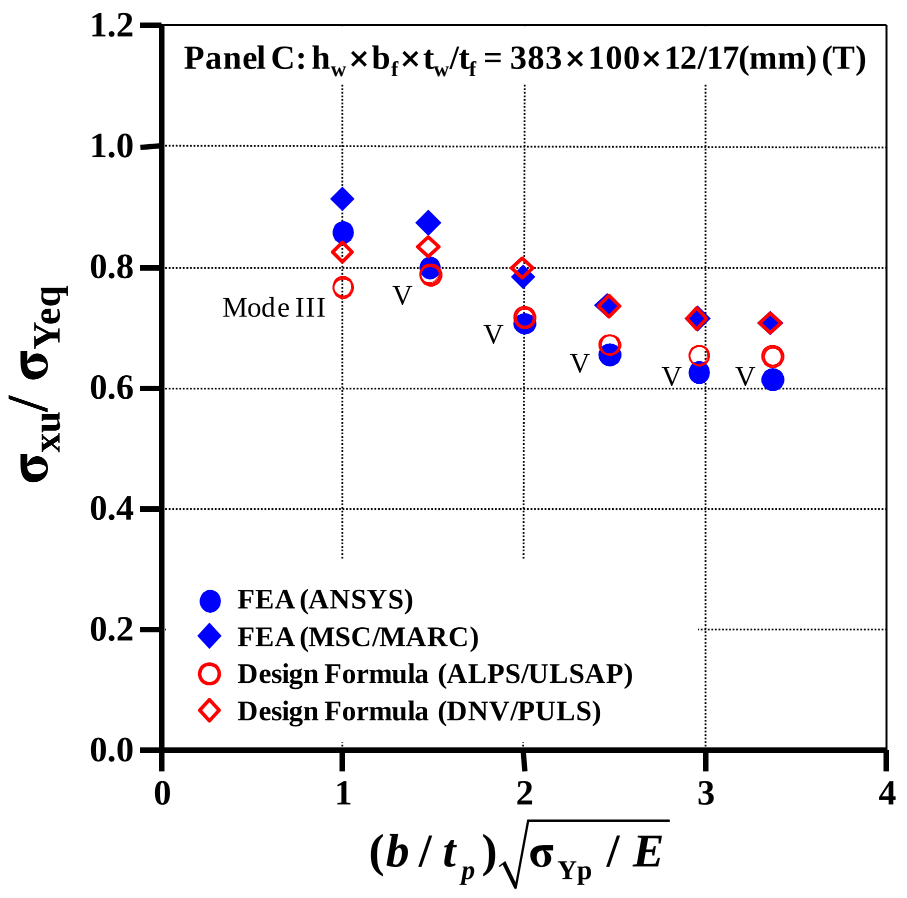

## Size 2



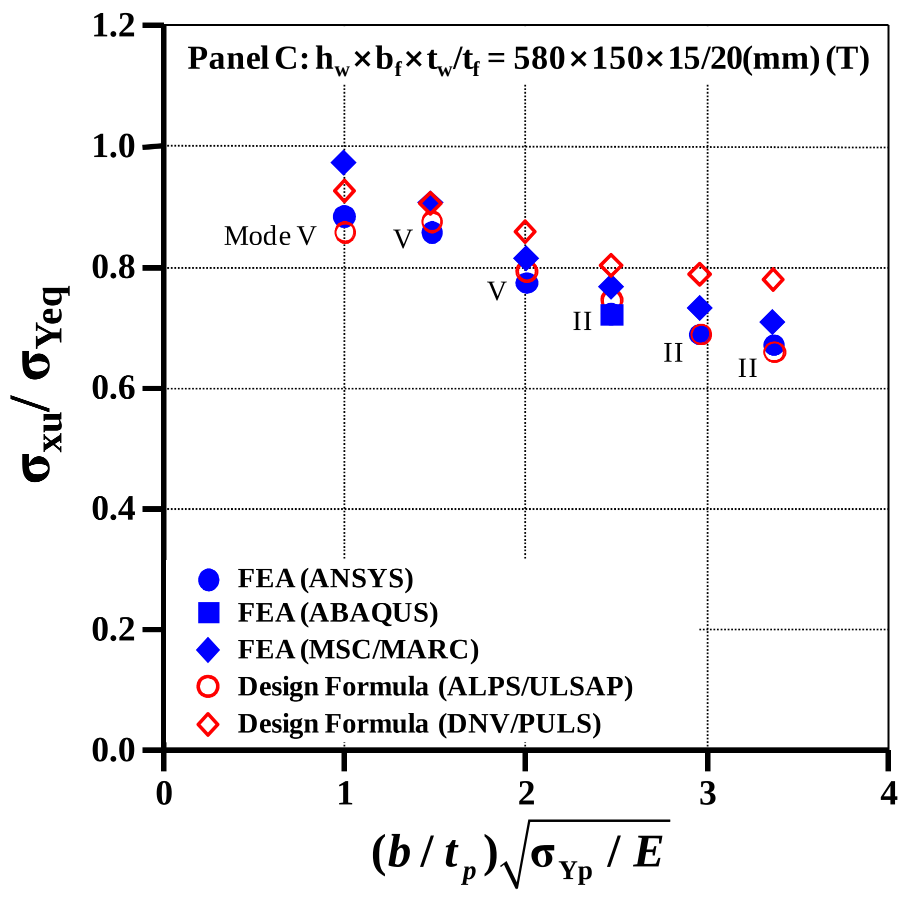
# Ultimate Strength of Stiffened Panels (6/26)

- Tee Bar Under Longitudinal Uniaxial Compression

Size 3



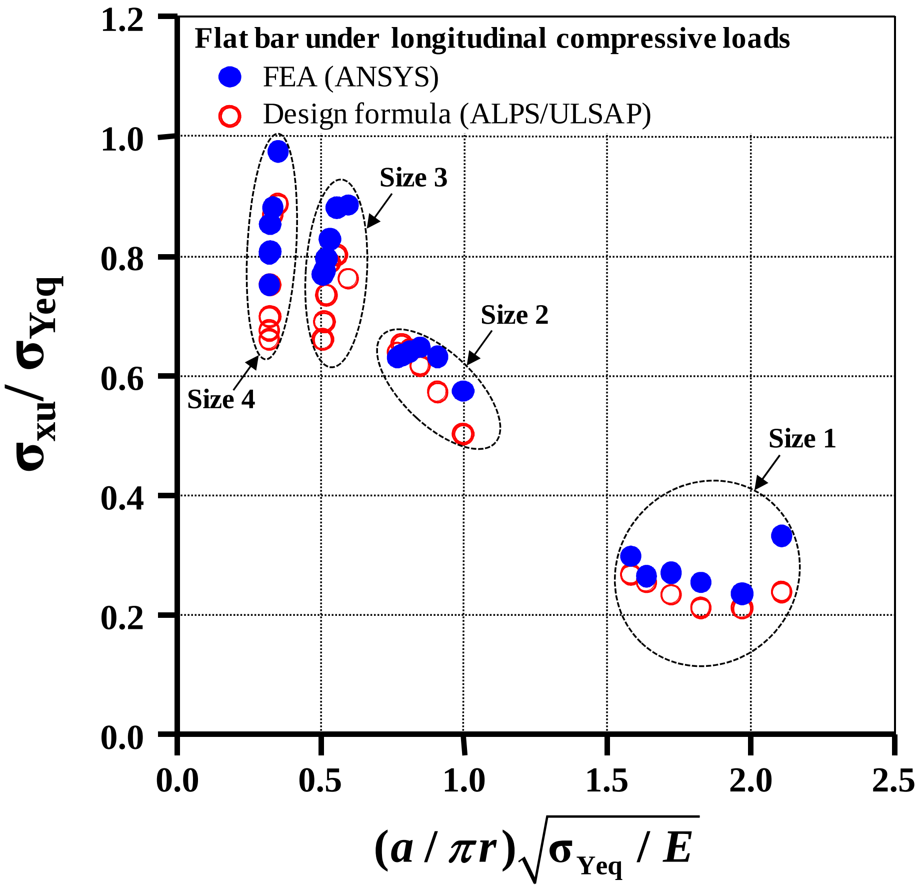

Size 4



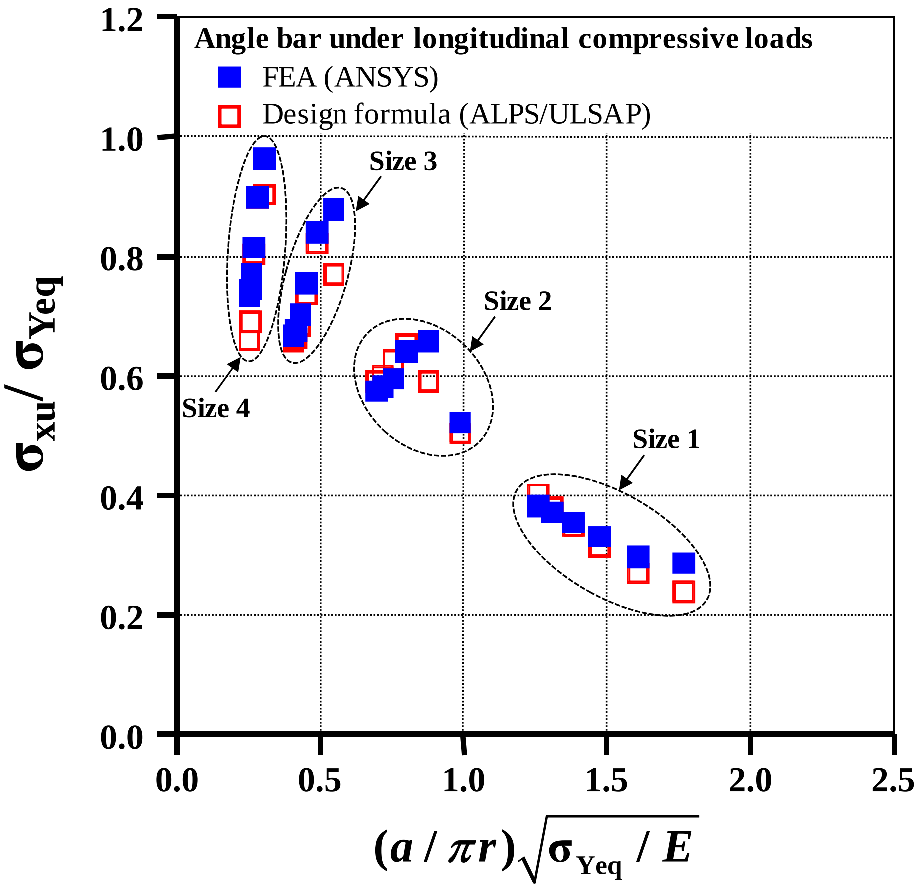
# Ultimate Strength of Stiffened Panels (7/26)

- Under Longitudinal Uniaxial Compression

Flat bar



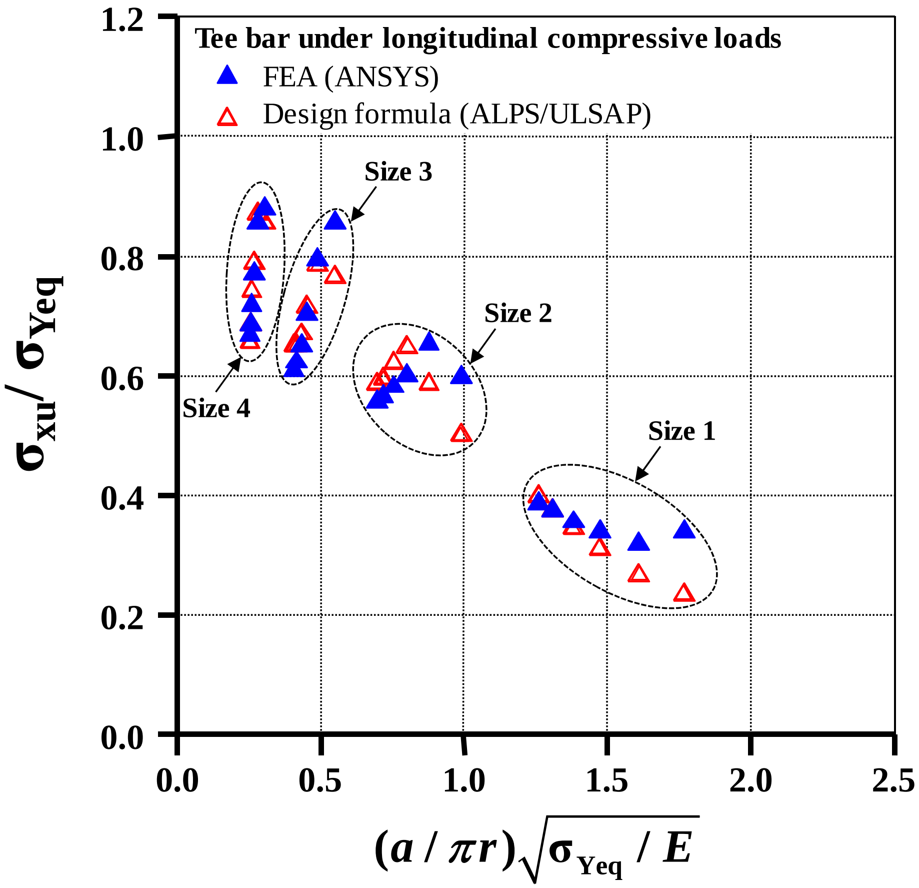

Angle bar



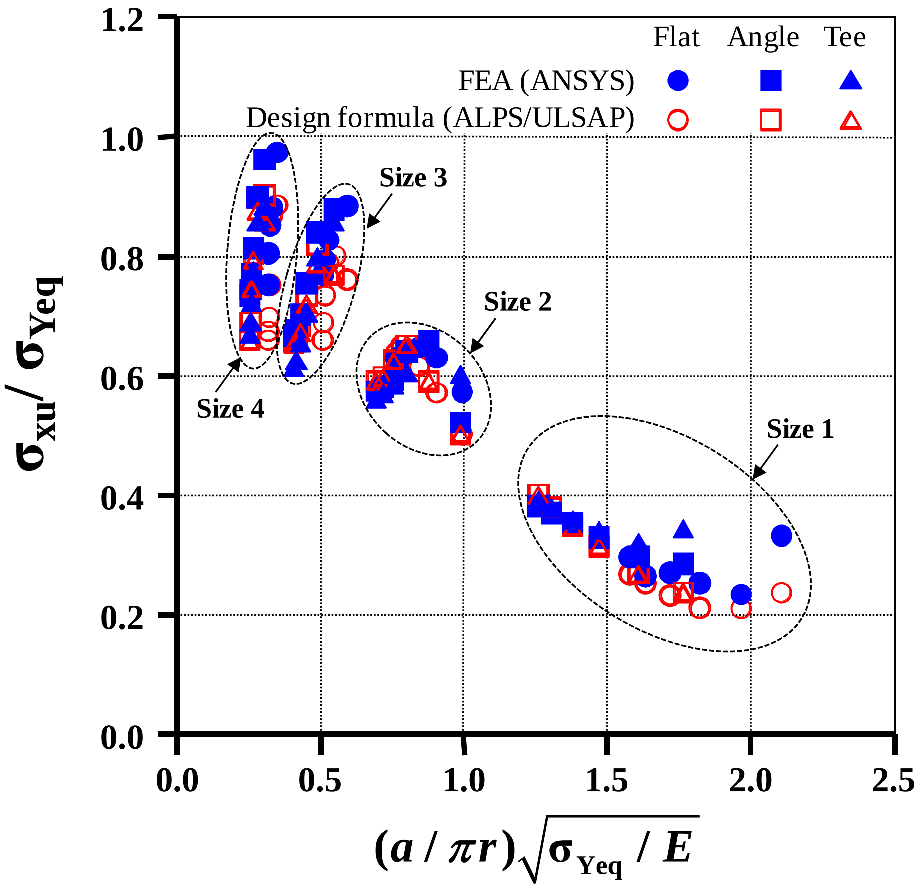
# Ultimate Strength of Stiffened Panels (8/26)

- Under Longitudinal Uniaxial Compression

## Tee bar

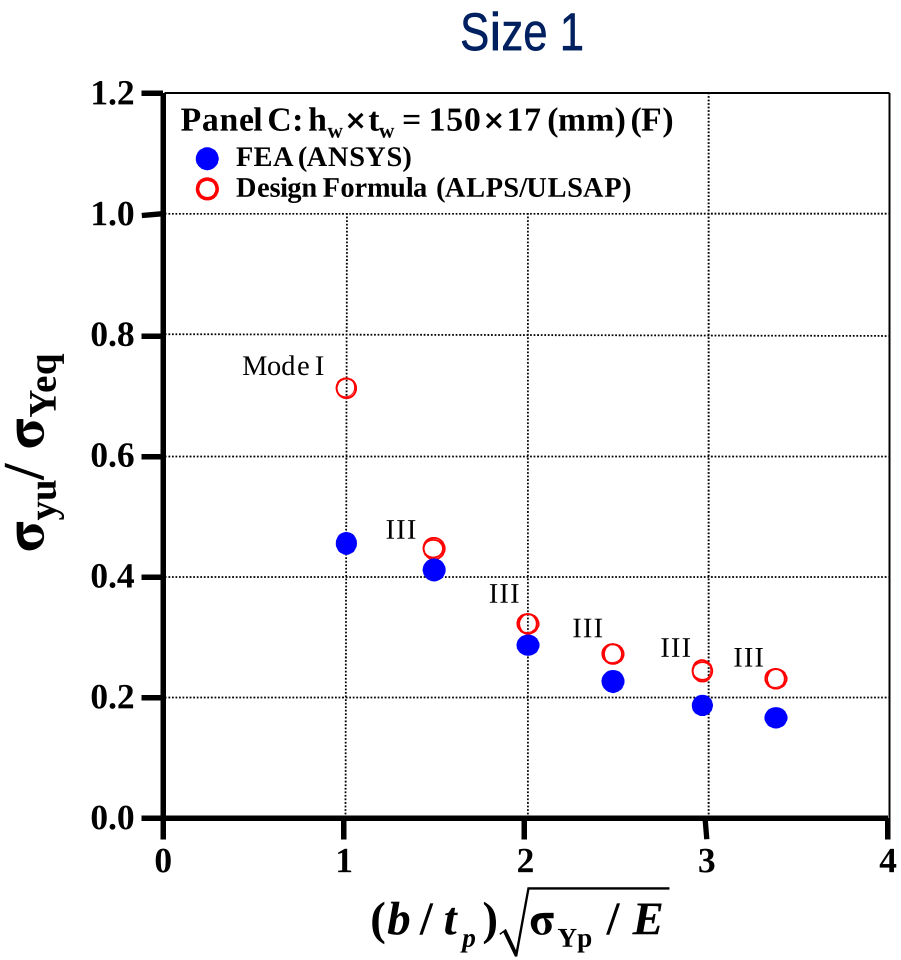


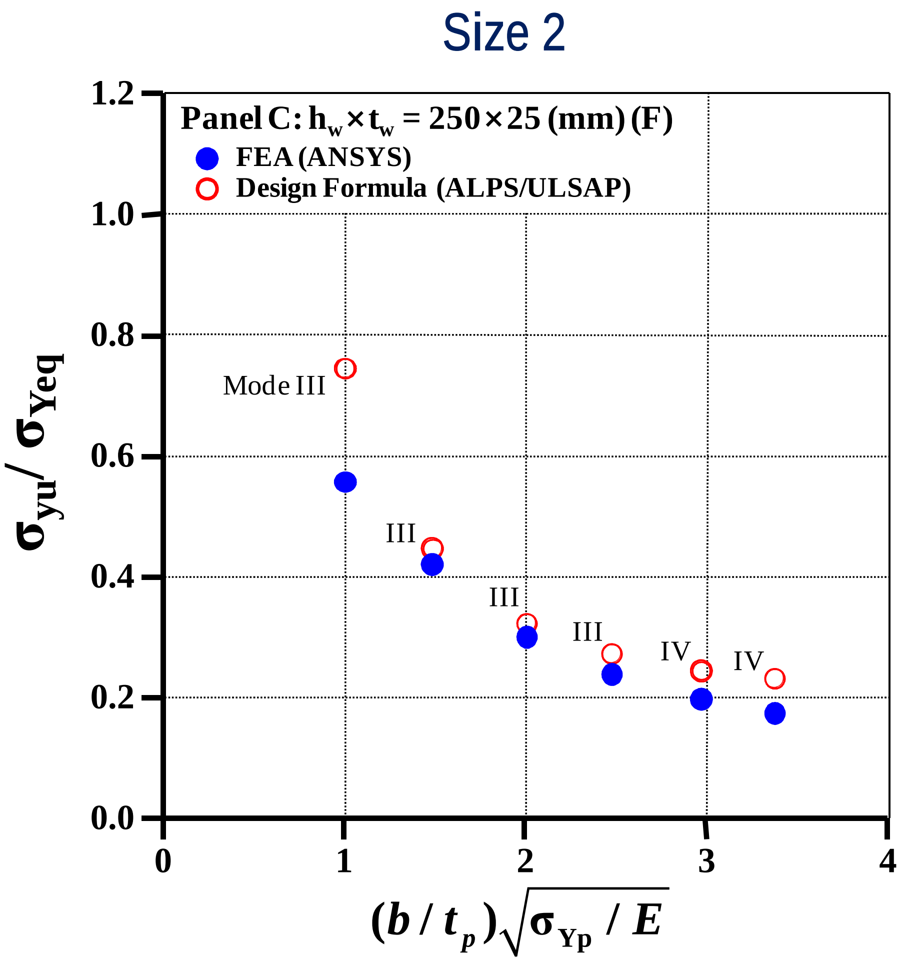

## All stiffener types



# Ultimate Strength of Stiffened Panels (9/26)

- Flat Bar Under Transverse Uniaxial Compression

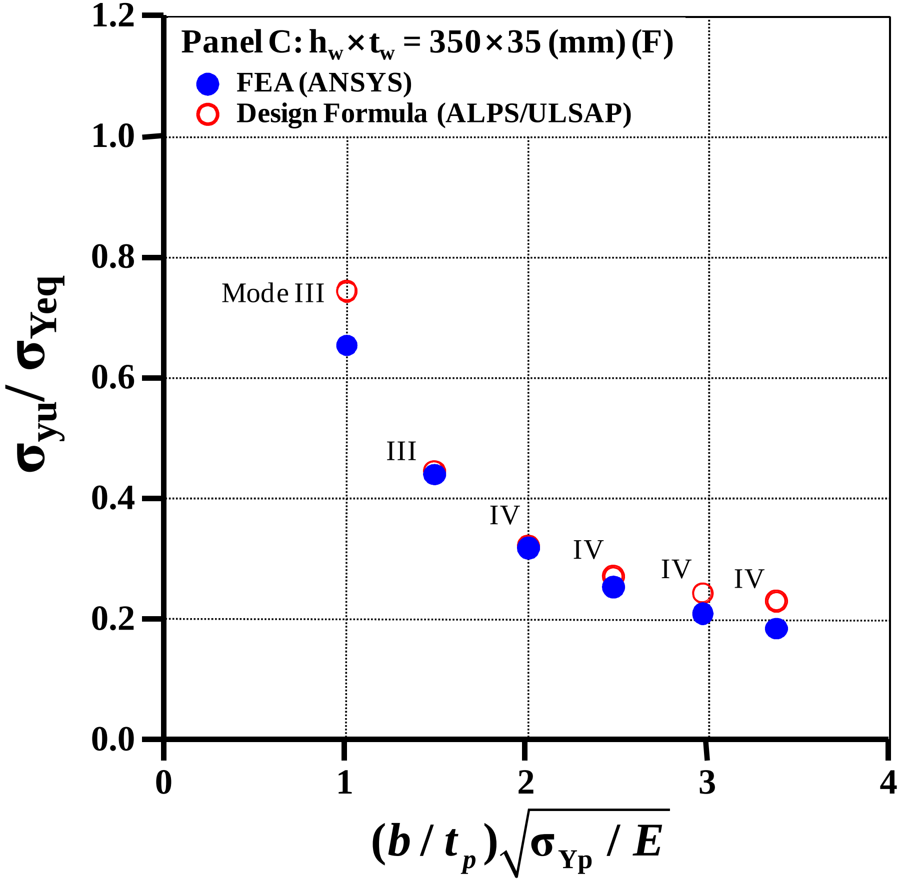


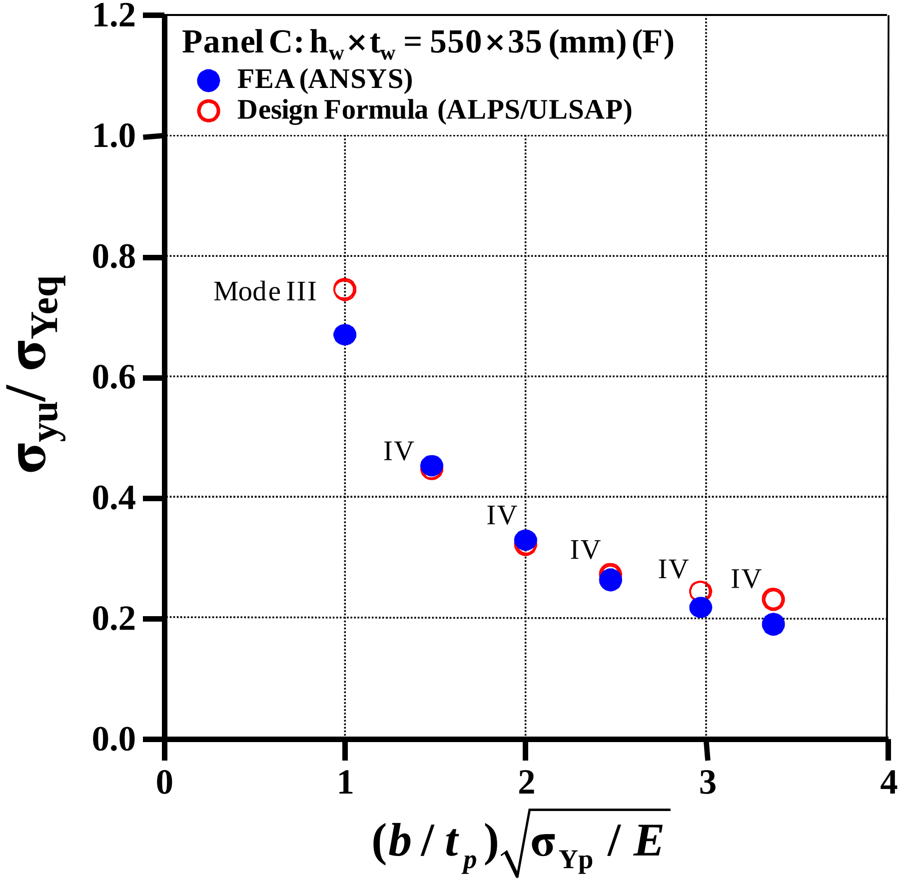
# Ultimate Strength of Stiffened Panels (10/26)

- Flat Bar Under Transverse Uniaxial Compression

Size 3



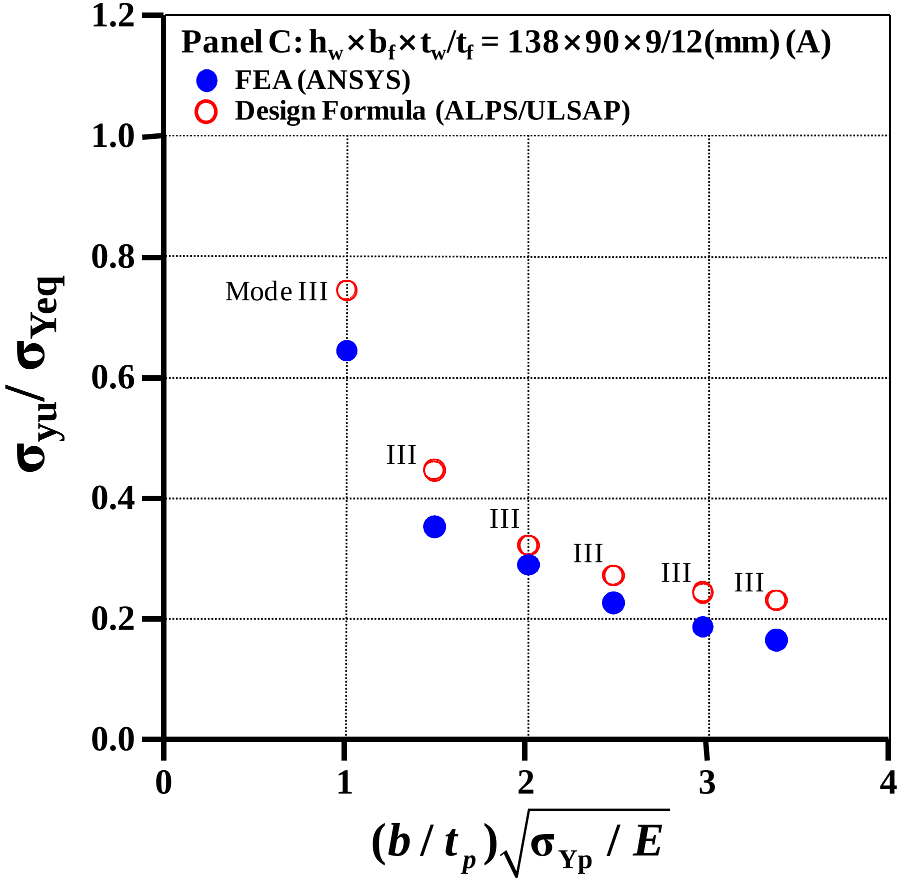

Size 4



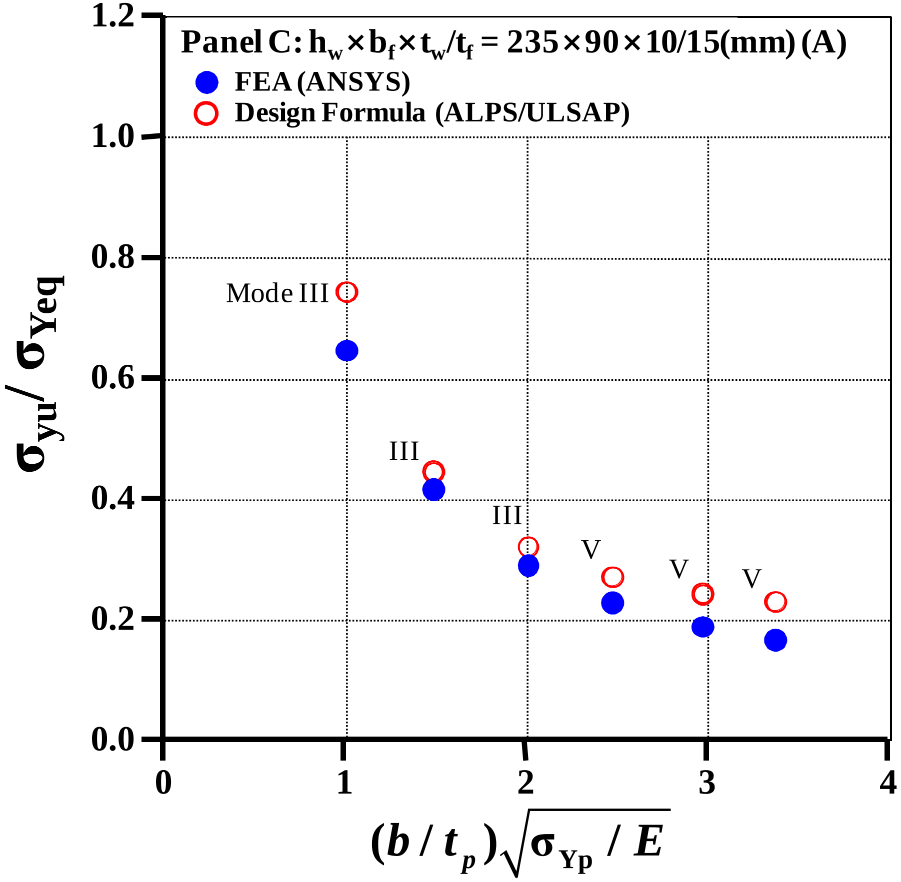
# Ultimate Strength of Stiffened Panels (11/26)

- Angle Bar Under Transverse Uniaxial Compression

Size 1



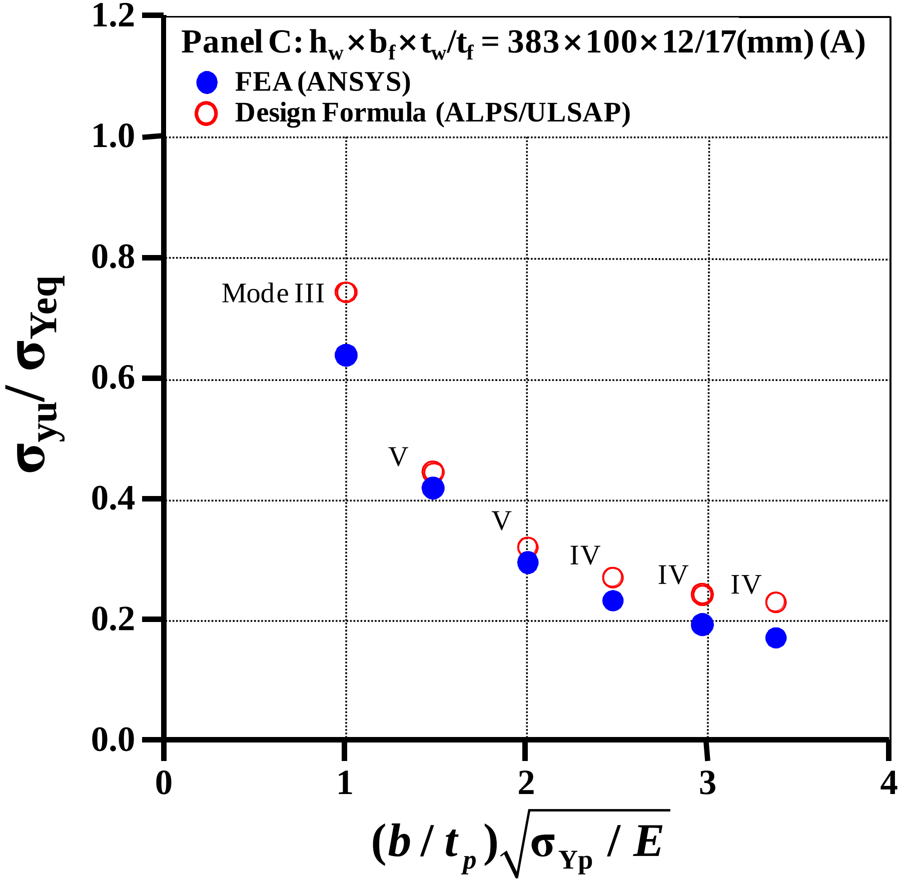

Size 2



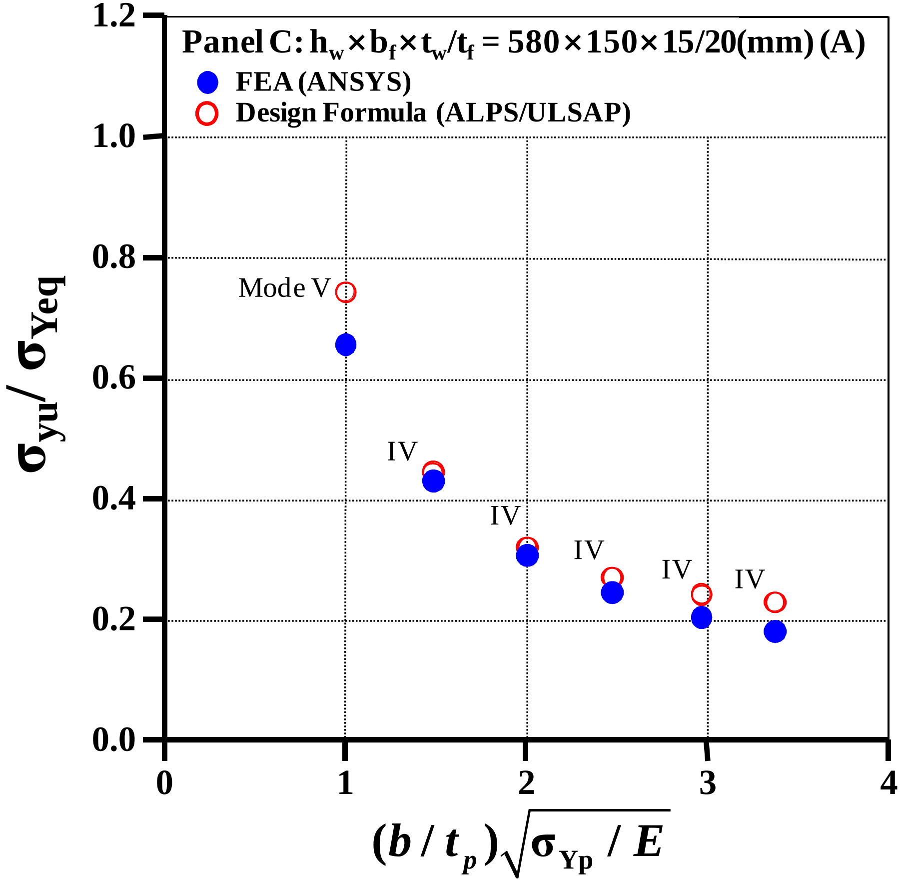
# Ultimate Strength of Stiffened Panels (12/26)

- Angle Bar Under Transverse Uniaxial Compression

Size 3



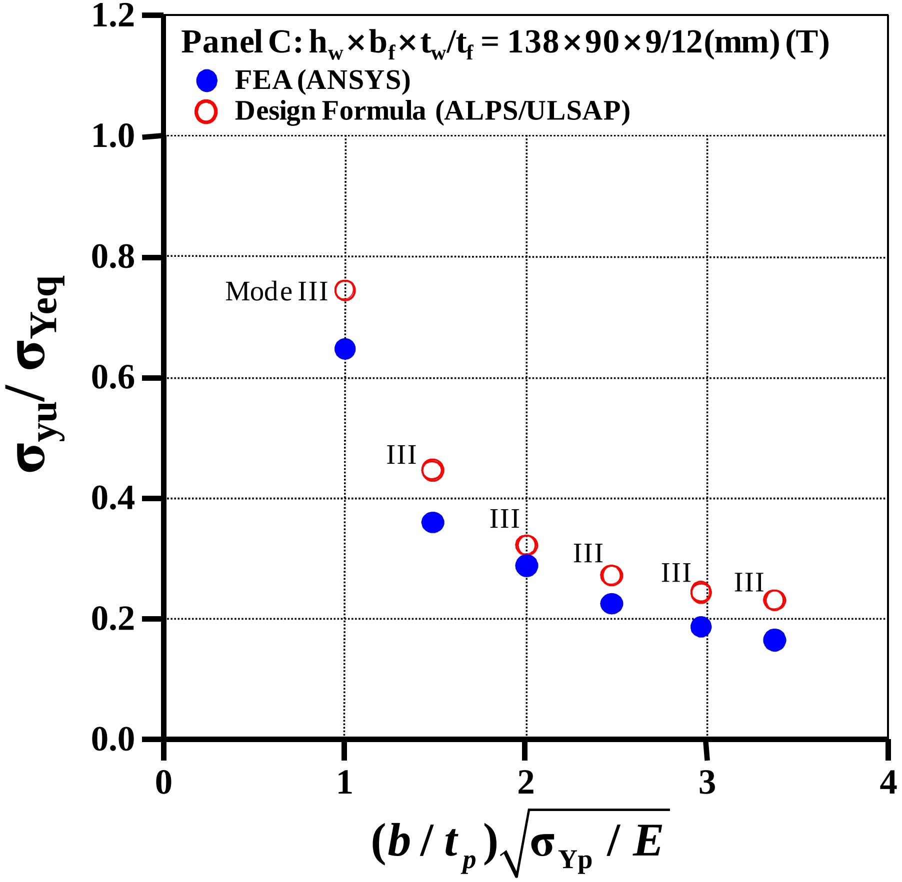

Size 4



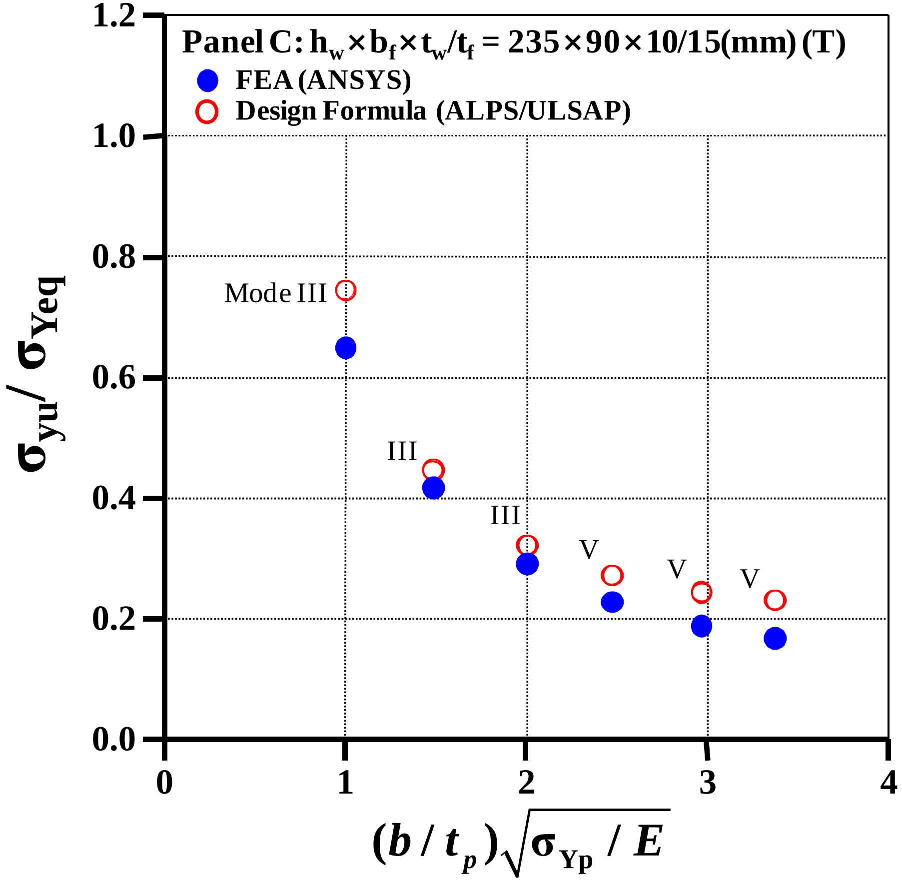
# Ultimate Strength of Stiffened Panels (13/26)

- Tee Bar Under Transverse Uniaxial Compression

Size 1



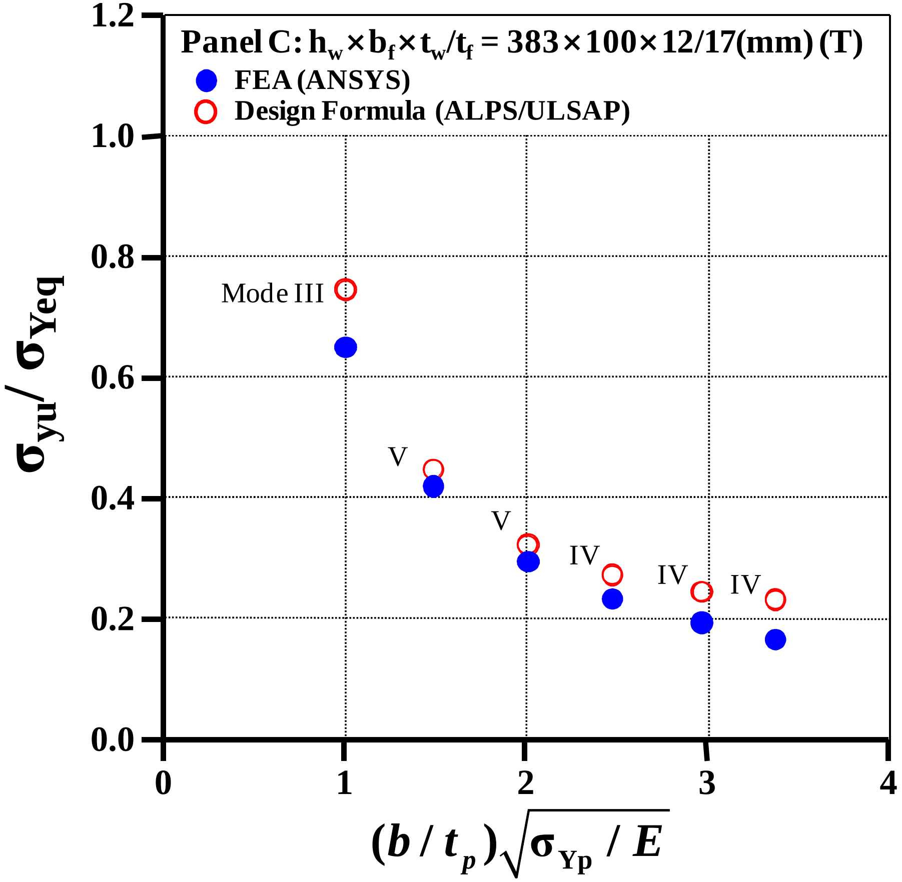

Size 2



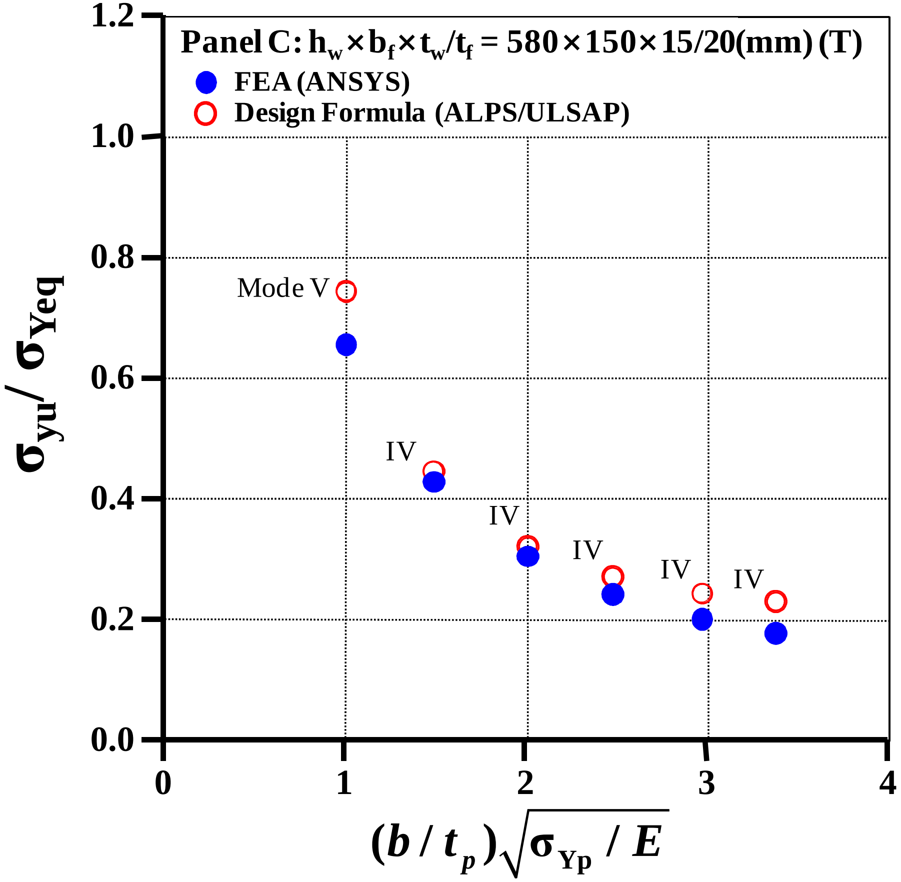
# Ultimate Strength of Stiffened Panels (14/26)

- Tee Bar Under Transverse Uniaxial Compression

Size 3



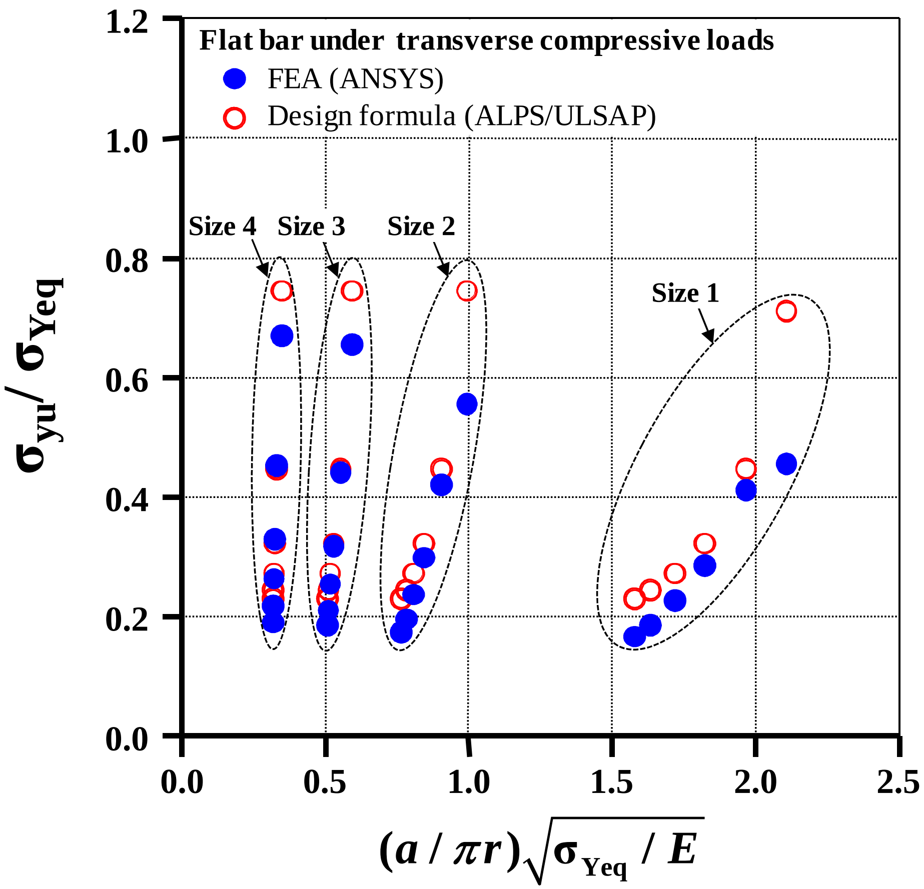

Size4



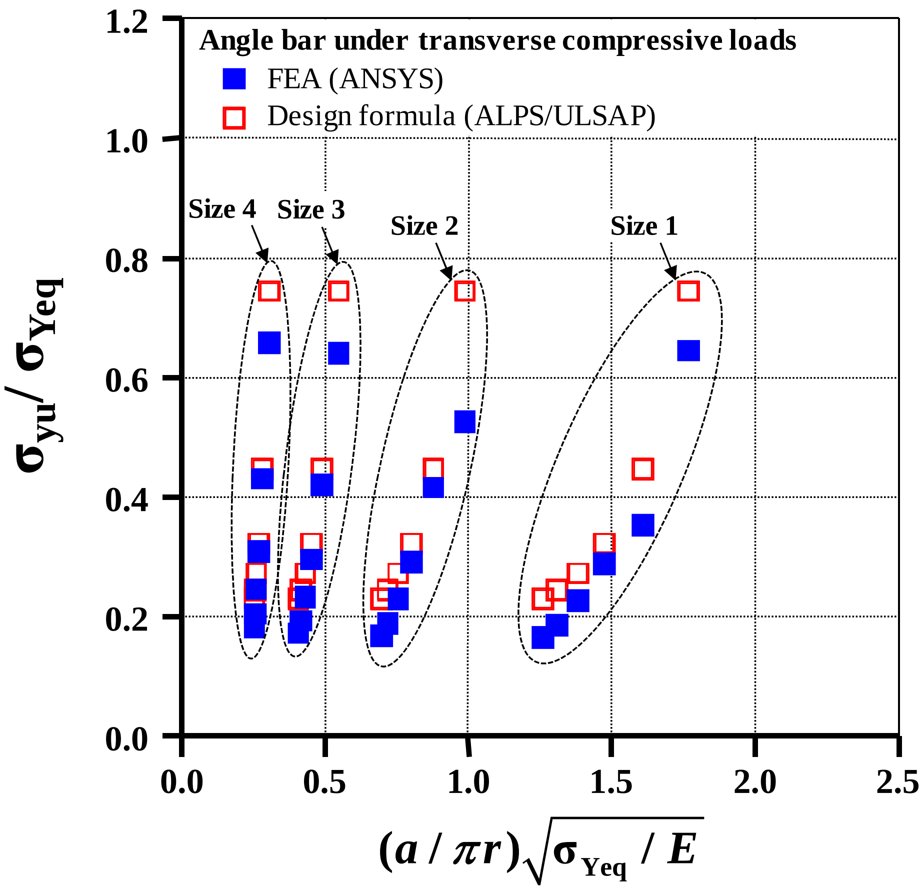
# Ultimate Strength of Stiffened Panels (15/26)

- Under Transverse Uniaxial Compression

Flat bar



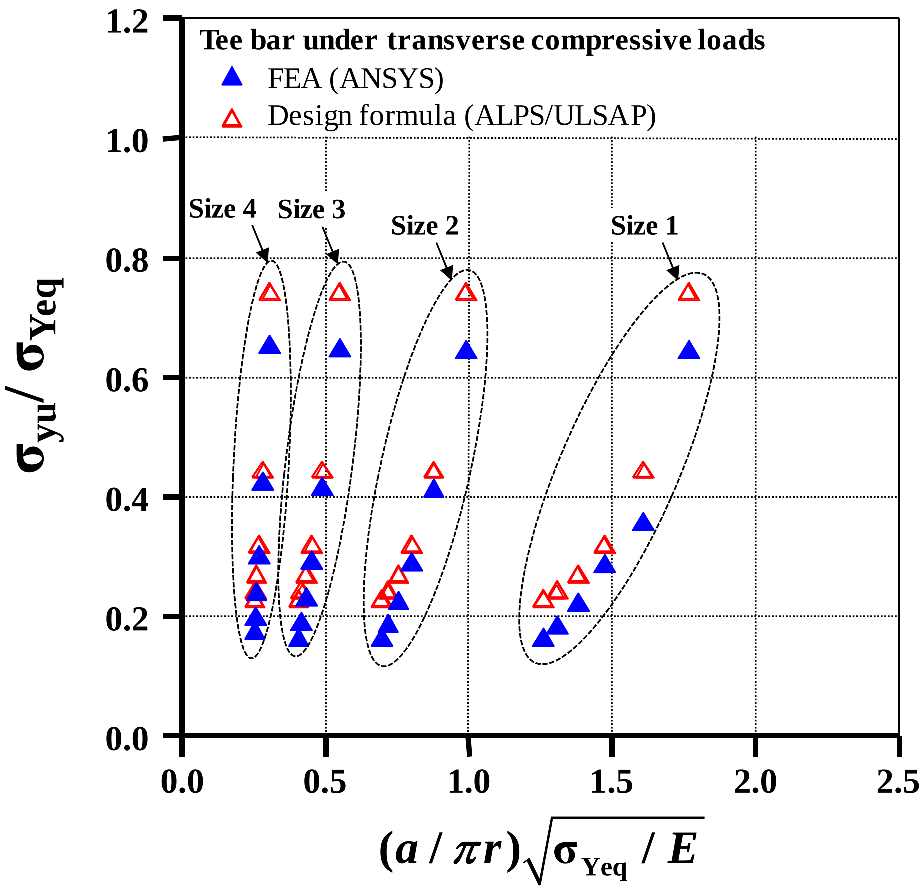

Angle bar



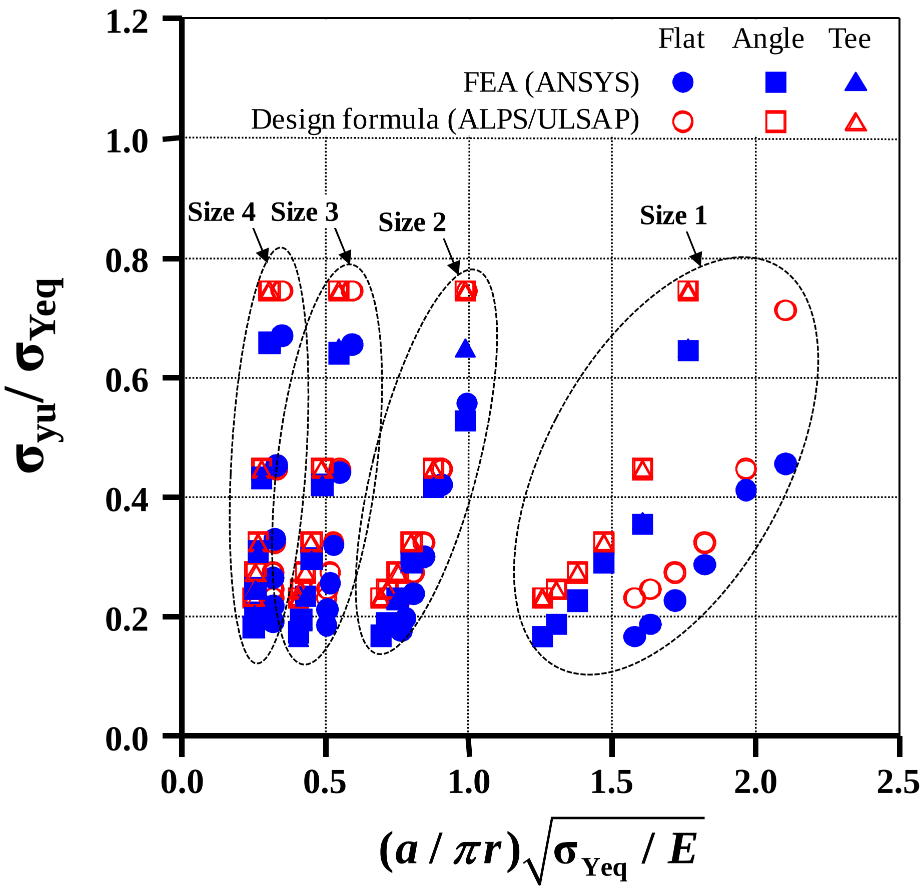
# Ultimate Strength of Stiffened Panels (16/26)

- Under Transverse Uniaxial Compression

Tee bar




All stiffener types



# Ultimate Strength of Stiffened Panels (17/26)

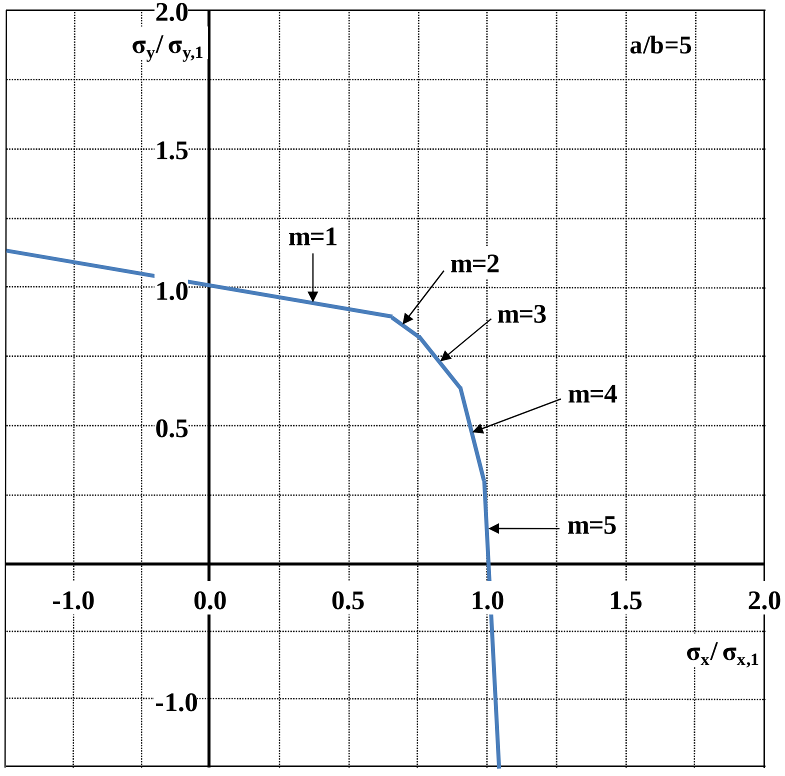
- Buckling half-wave number

$$\frac{(m^2/a^2+1/b^2)^2}{m^2/a^2+c/b^2} \le \frac{[(m+1)^2/a^2+1/b^2]^2}{(m+1)^2/a^2+c/b^2}$$

**where,** $c = \sigma_y / \sigma_x$

$\sigma_x$ and $\sigma_y$ are the component of the longitudinal and transverse axial buckling stress of the plate under combined biaxial loading.

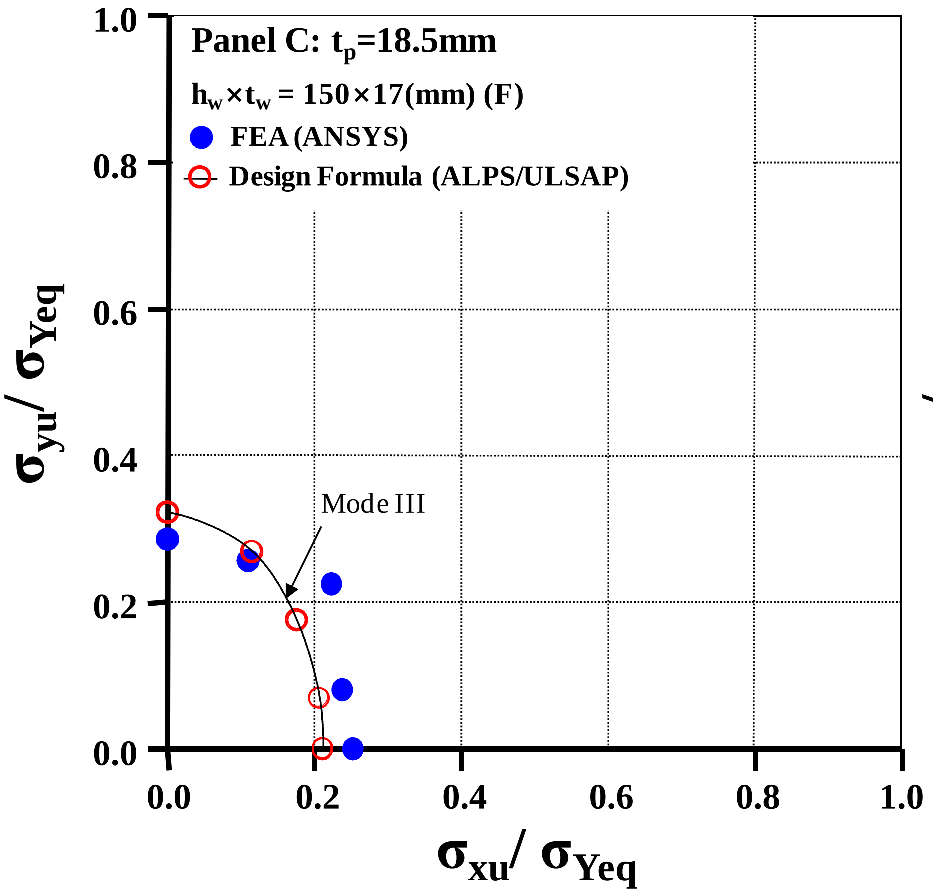
$\sigma_{x,1}$ and $\sigma_{y,1}$ are the component of the longitudinal or transverse axial buckling stress of the plate under uniaxial loading.



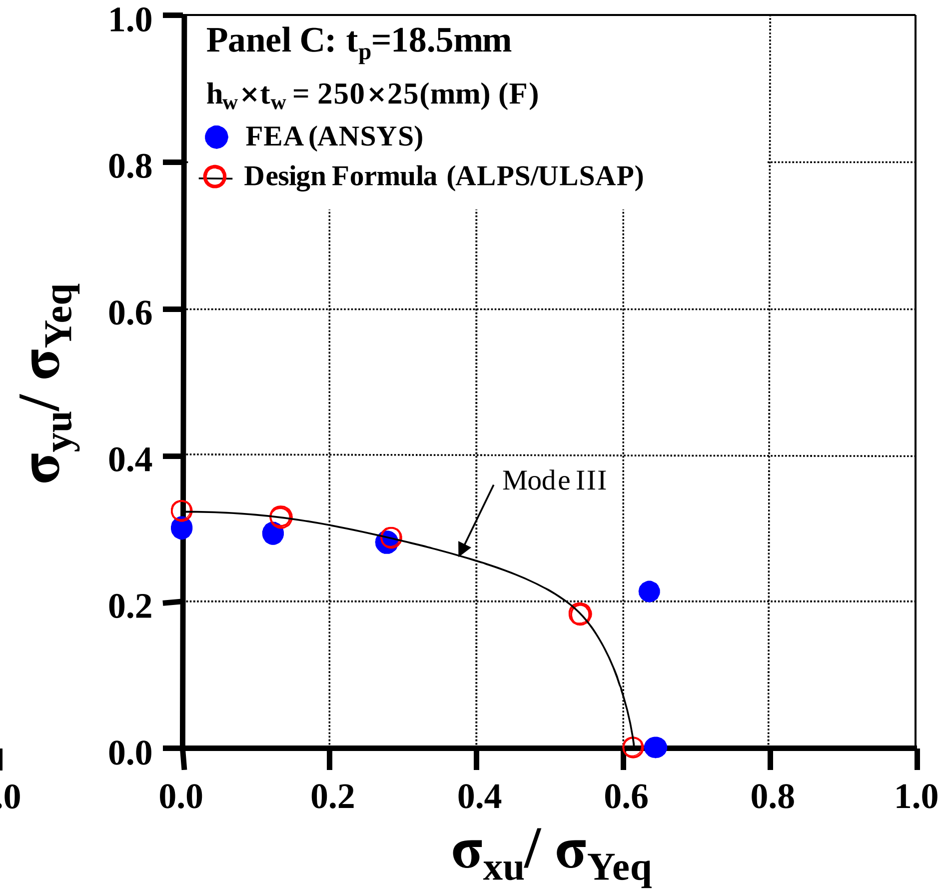
# Ultimate Strength of Stiffened Panels (18/26)

- Under Biaxial Compression (Flat Bar, $t_p$=18.5mm)

Size 1



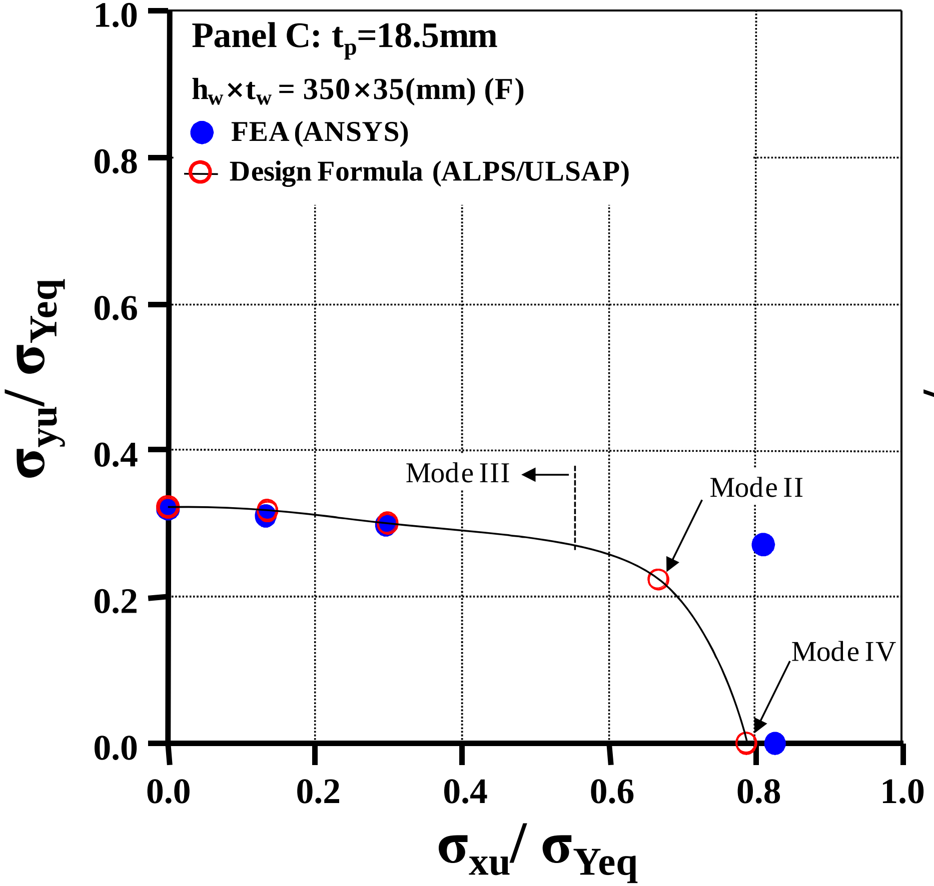

Size 2



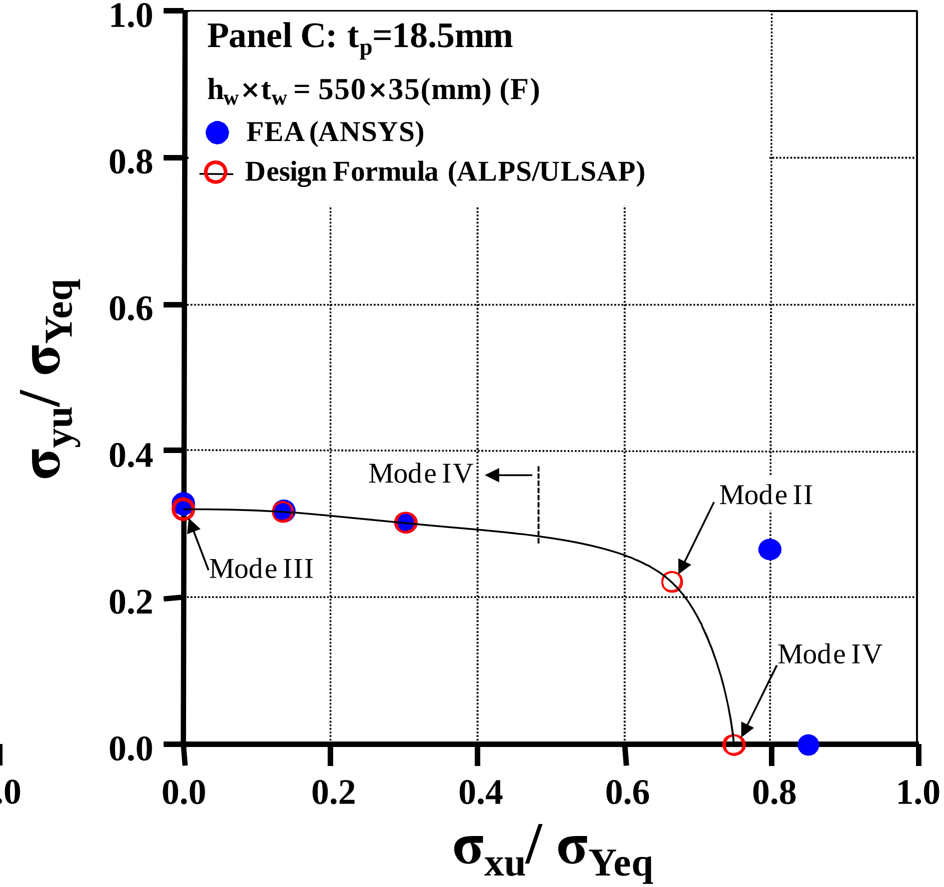
# Ultimate Strength of Stiffened Panels (19/26)

- Under Biaxial Compression (Flat Bar, $t_p$=18.5mm)

Size 3



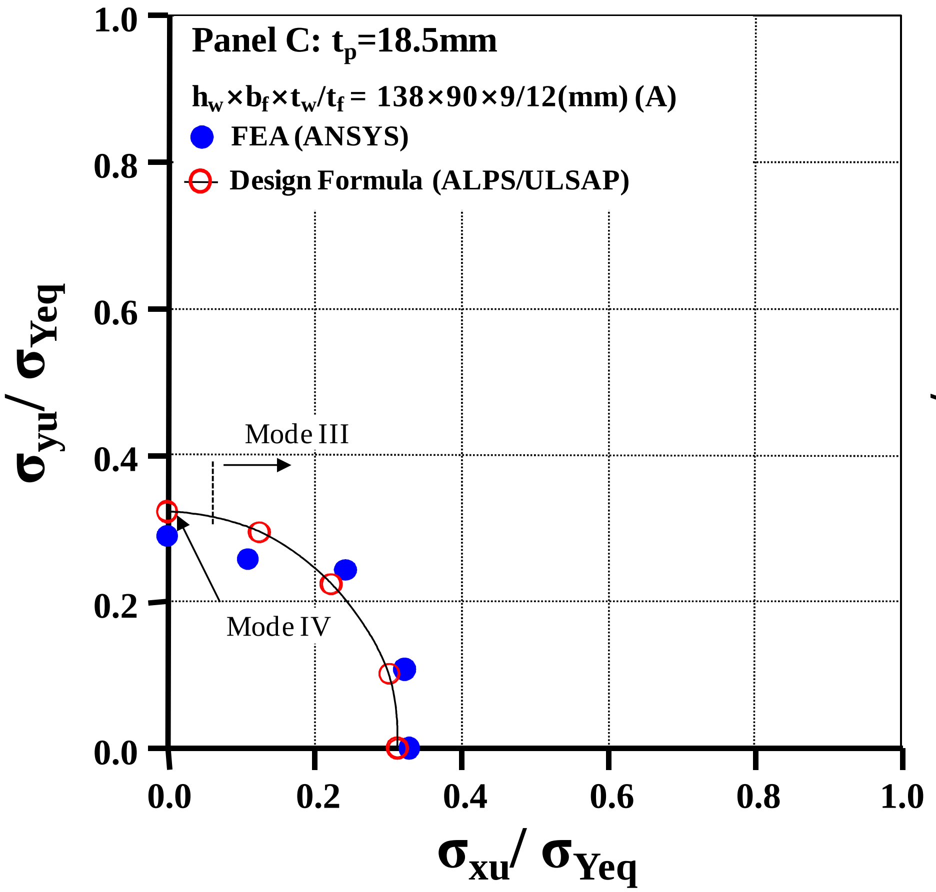

Size 4



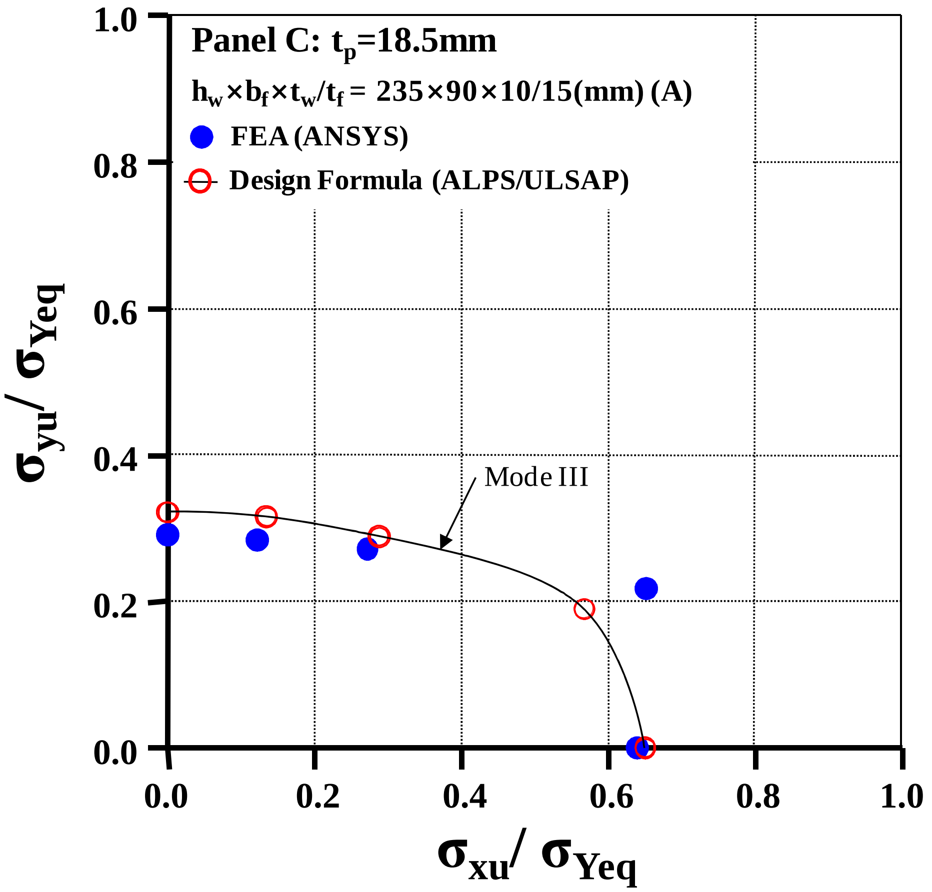
# Ultimate Strength of Stiffened Panels (20/26)

- Under Biaxial Compression (Angle Bar, $t_p$=18.5mm)

## Size 1



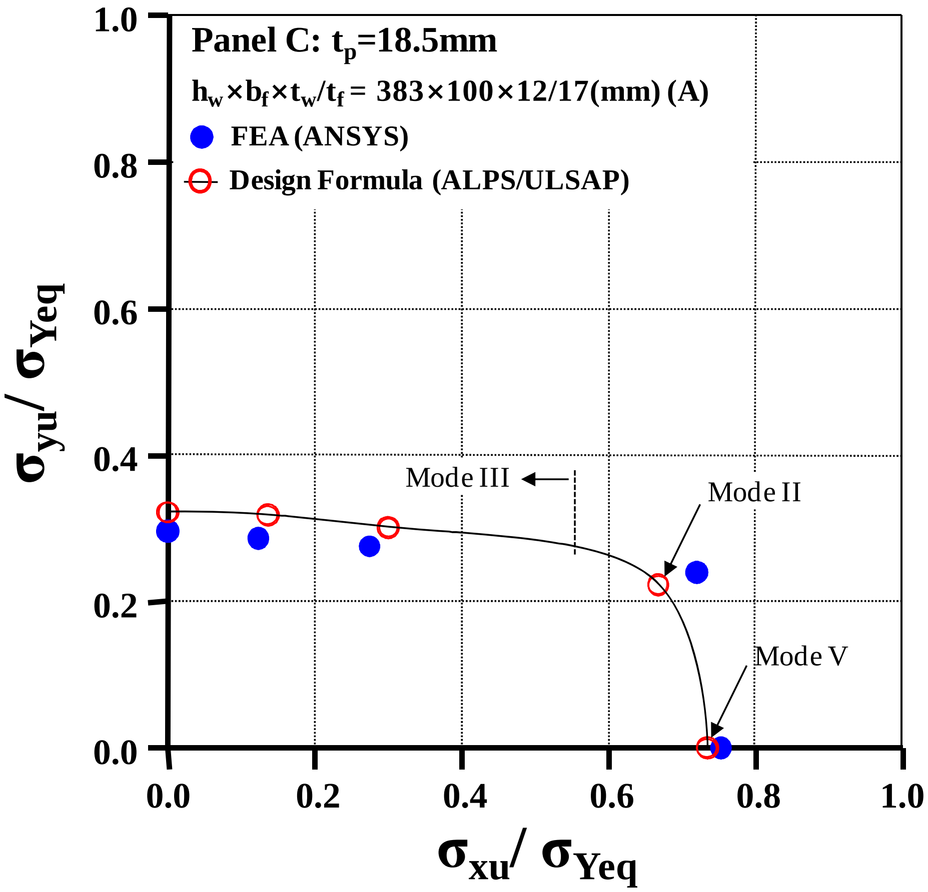

## Size 2



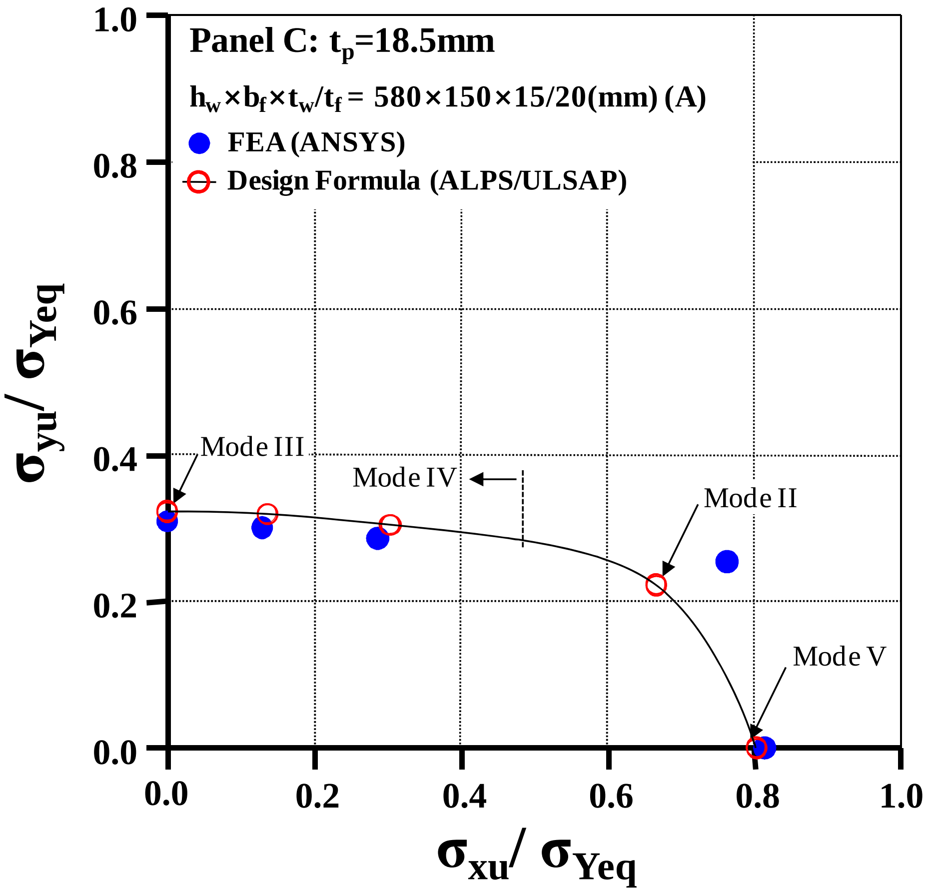
# Ultimate Strength of Stiffened Panels (21/26)

- Under Biaxial Compression (Angle Bar, $t_p$=18.5mm)

Size 3



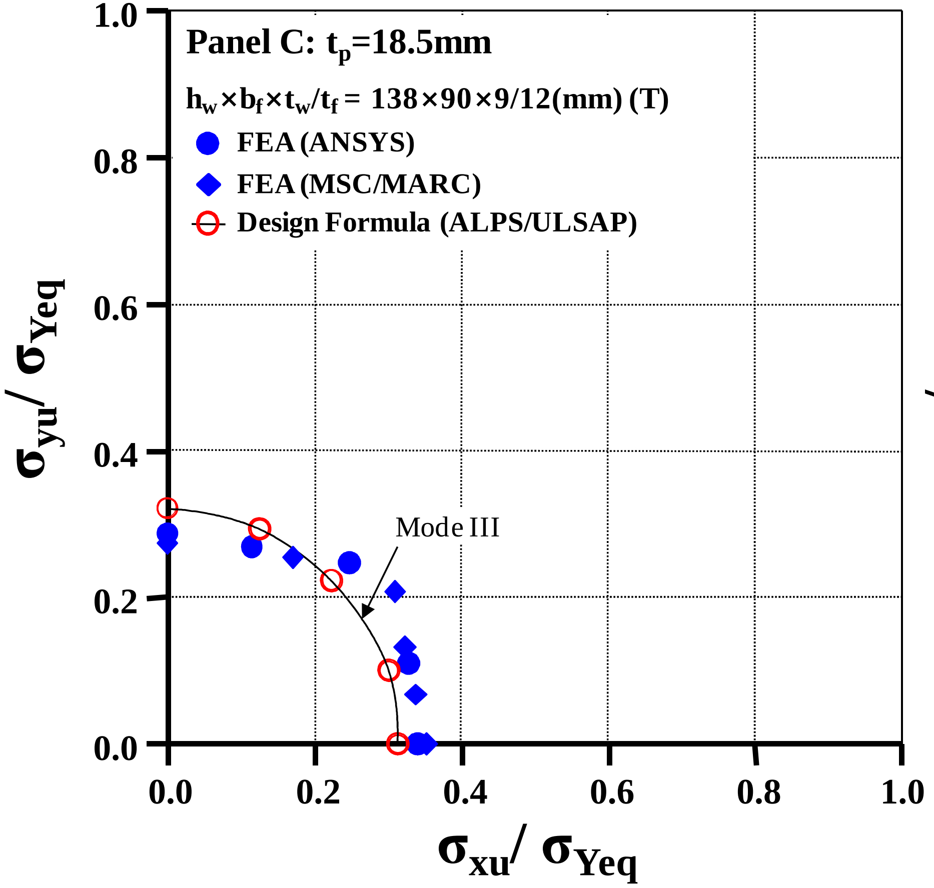

Size 4



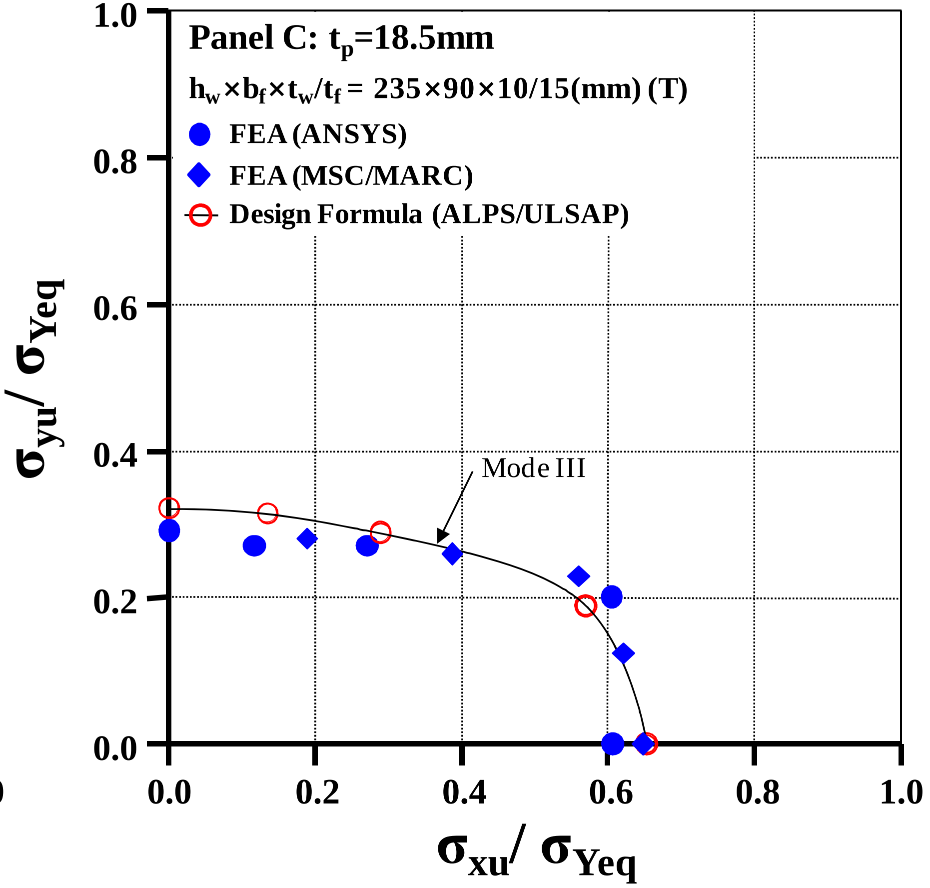
# Ultimate Strength of Stiffened Panels (22/26)

- Under Biaxial Compression (Tee Bar, $t_p$=18.5mm)

Size 1



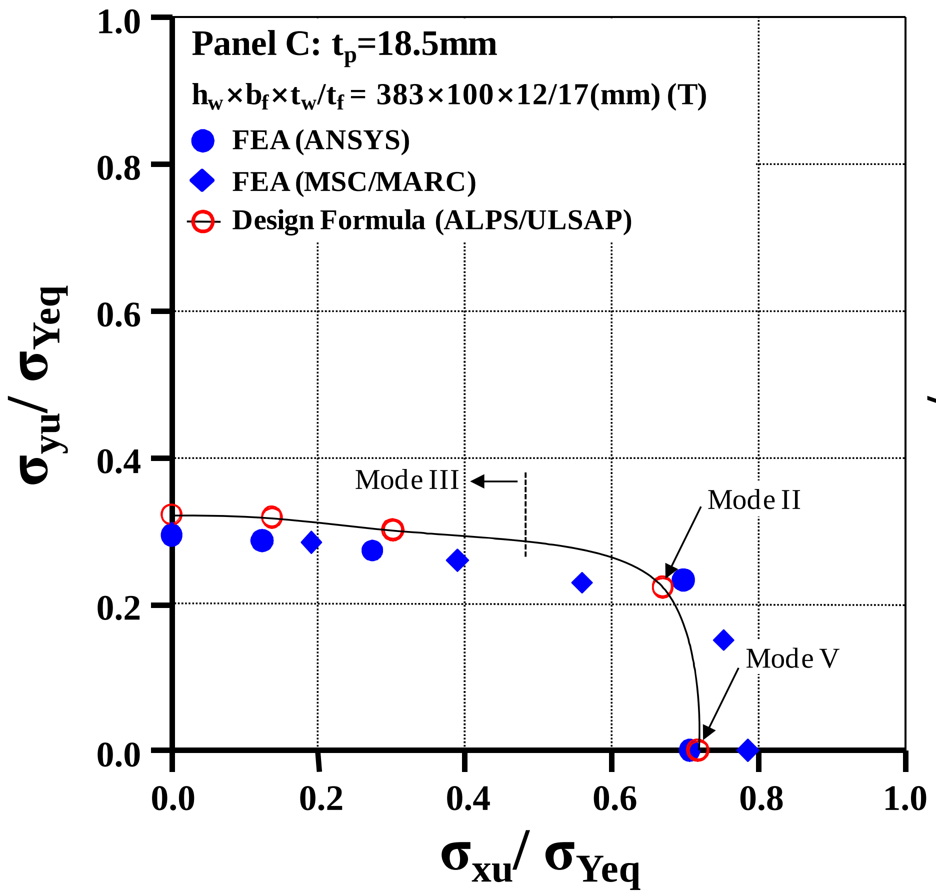

Size 2



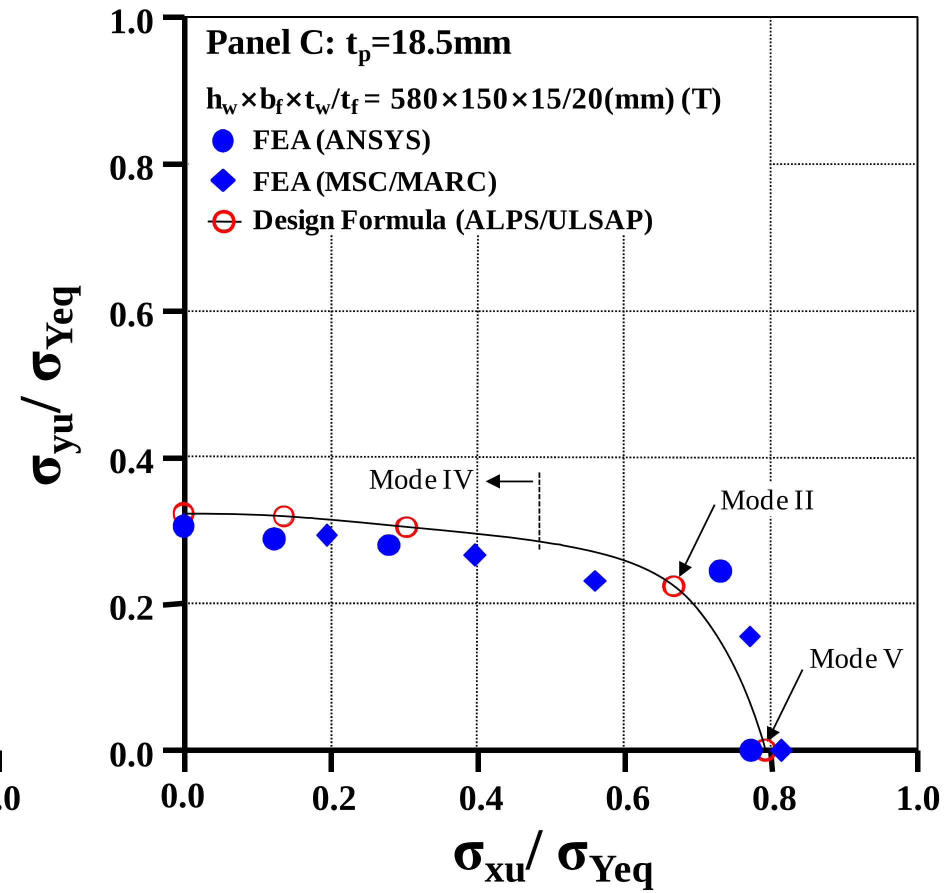
# Ultimate Strength of Stiffened Panels (23/26)

- Under Biaxial Compression (Tee Bar, $t_p$=18.5mm)

Size 3

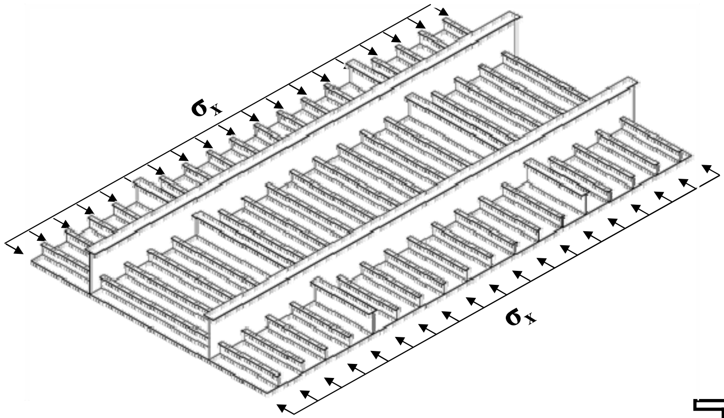


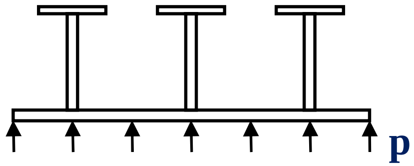

Size 4



# Ultimate Strength of Stiffened Panels (24/26)

- Under Combined Longitudinal Compression and Lateral Pressure Loads



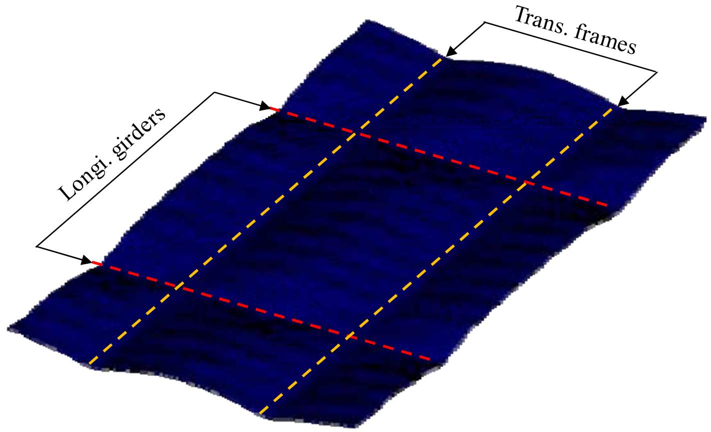
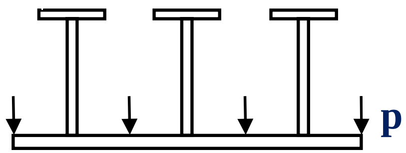
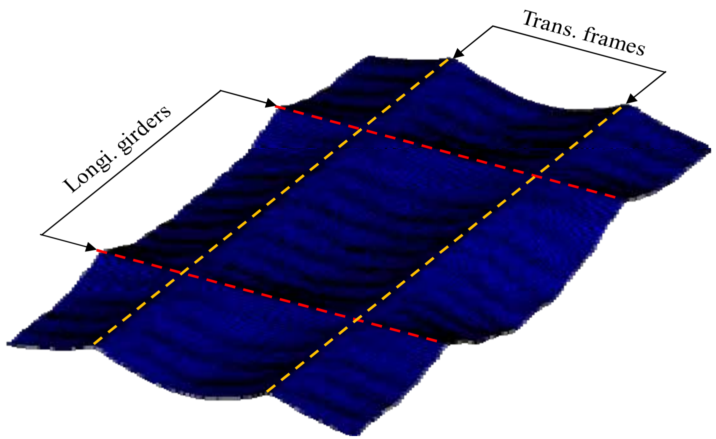




Plate-sided Pressure




Stiffener-sided Pressure

# Ultimate Strength of Stiffened Panels (25/26)

- Under Combined Longitudinal Compression and Lateral Pressure Loads

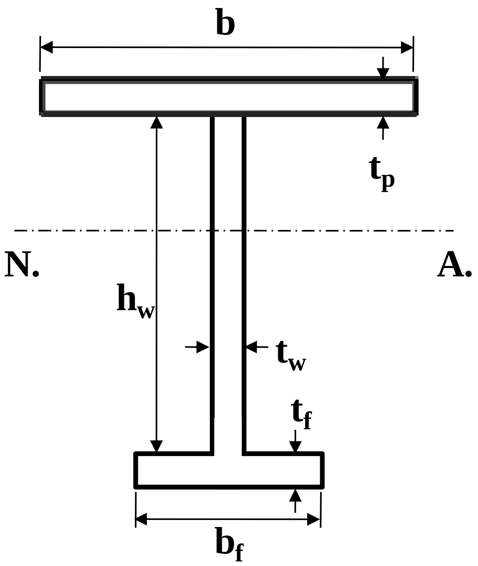
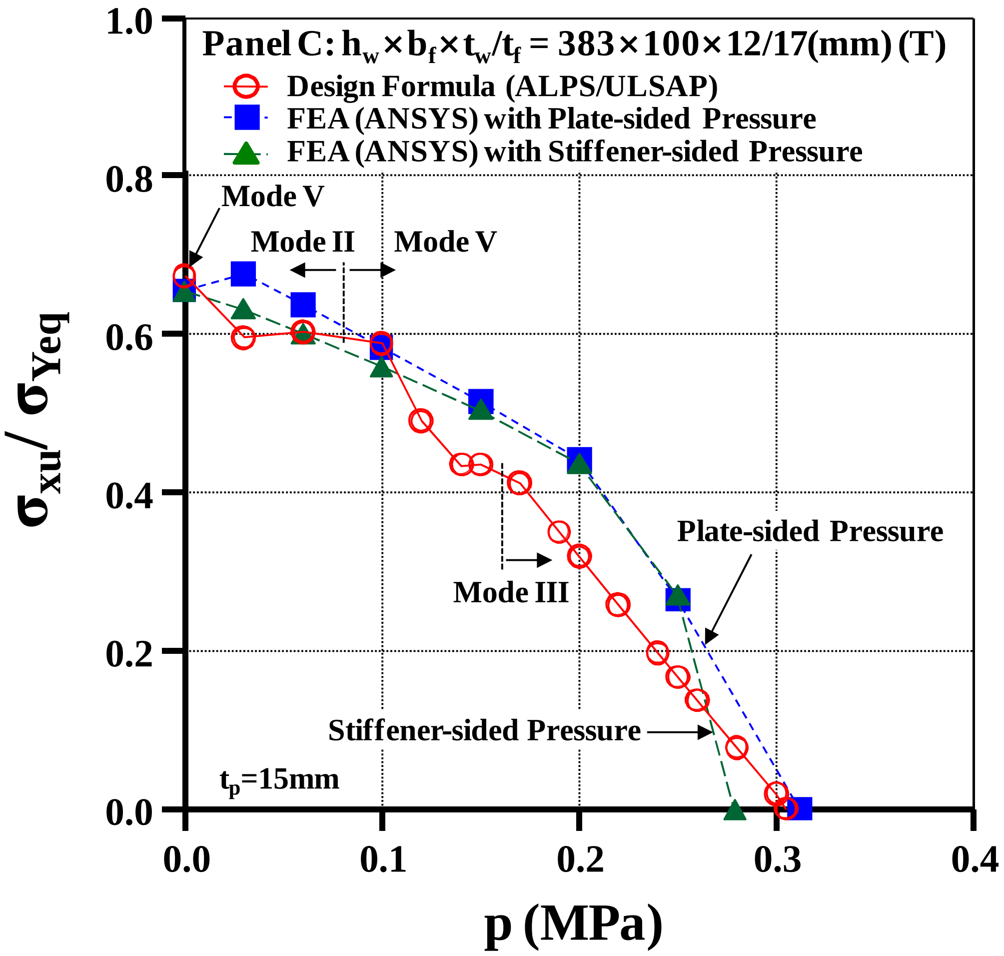



Plate thickness, $t_p$ = 15 mm

$h_w \times b_f \times t_w/t_f$ = 383×100×12/17(mm) (T)



# Ultimate Strength of Stiffened Panels (26/26)

- Under Combined Longitudinal Compression and Lateral Pressure Loads

Plate thickness, $t_p$ = 15 mm

$h_w \times b_f \times t_w / t_f$ = 383×100×12/17(mm) (T)

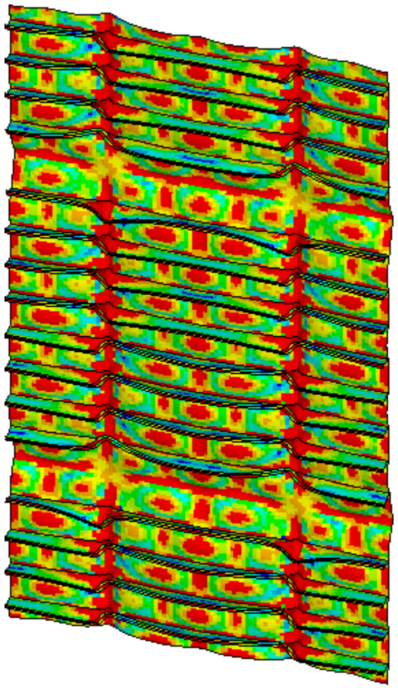
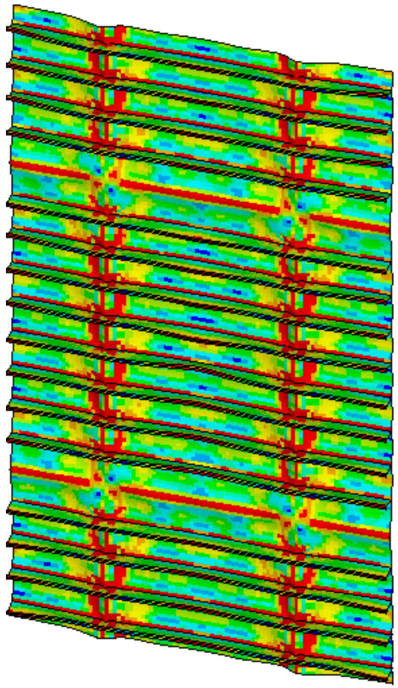


Plate-sided Pressure

(with p=0.25 MPa, amplification factor of 10)



Stiffener-sided Pressure

(with p=-0.25 MPa, amplification factor of 10)

# Concluding Remarks

## Concluding Remarks

- The dimension and material properties of a real ship panel was selected as a standard panel and a wider range of plating and stiffener dimensions were considered by varying the panel's properties.

- The objective of the benchmark study reported in this paper was to check the accuracy of the ALPS/ULSAP method's use to calculate the ultimate strength of plate and stiffened panel, compared with nonlinear finite element method.

- The ALPS/ULSAP method was found in a good agreement with the nonlinear finite element method computations through a wide range of panel dimensions and different loading conditions.

- The ALPS/ULSAP method is based on design formulations, the computational time required is extremely short compared to the nonlinear finite element method. So, this will be of great advantage in the structures design and safety assessment of ship structures comprising a large number of plate and panels.

# Ultimate Strength of Hull Girders

Prof. Jeom Kee Paik, Director

The LRET Research Centre of Excellence

at Pusan National University, Korea

# Overview

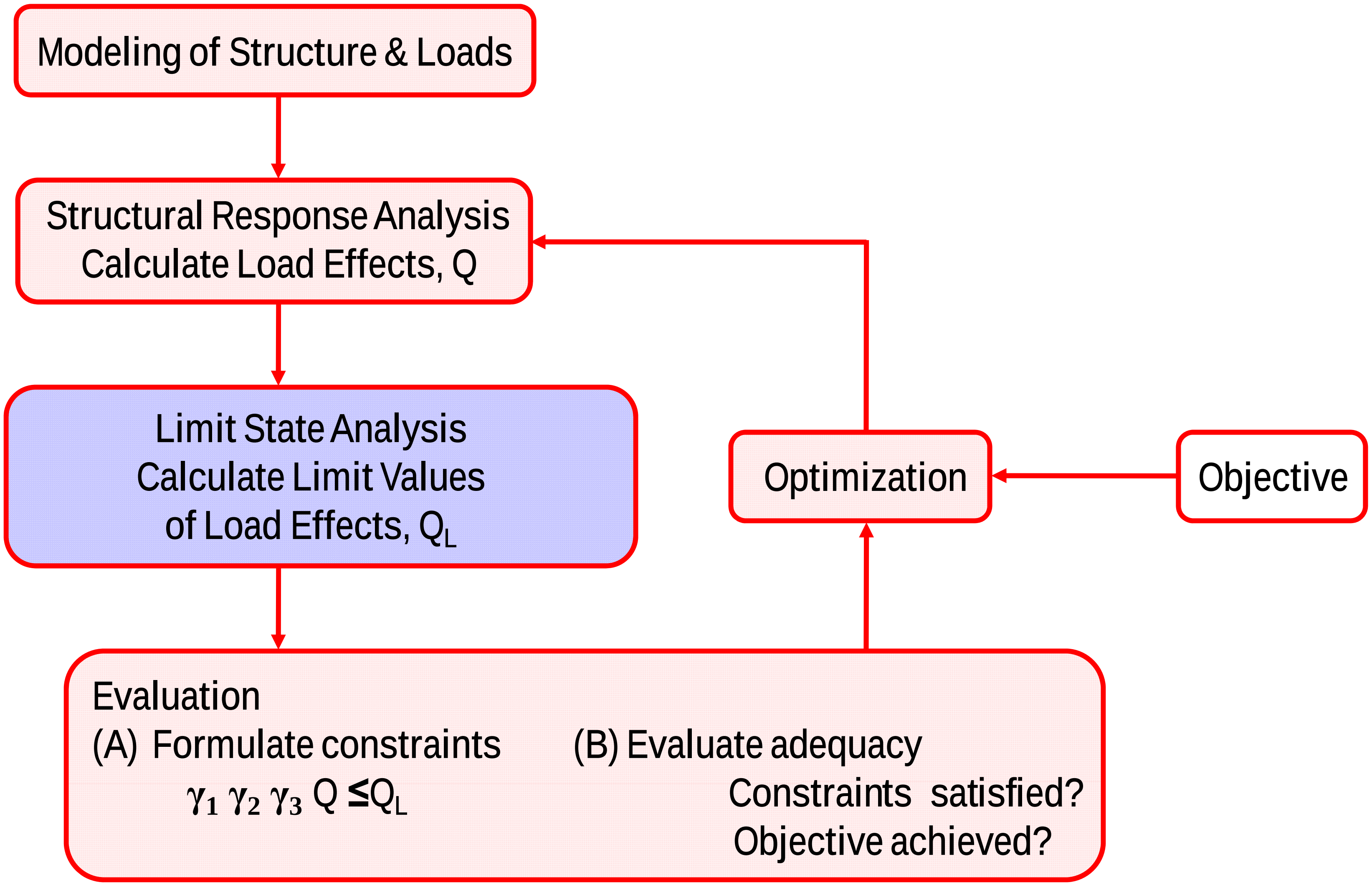
1. Background
2. Rationally-based structural design
3. Presumed stress distribution-based method
4. Methods applied for the ultimate hull strength analysis
5. Analysis results
6. Statistical analysis
7. Concluding remarks

# Background

- To develop the modified Paik-Mansour formula method for the ultimate strength calculations of ship hulls subject to vertical bending moments.
- To validate the accuracy and applicability of modified Paik-Mansour formula method by comparing with more refined other methods.

# Rationally-based structural design

(Optimum structural design procedure based on ultimate limit state)

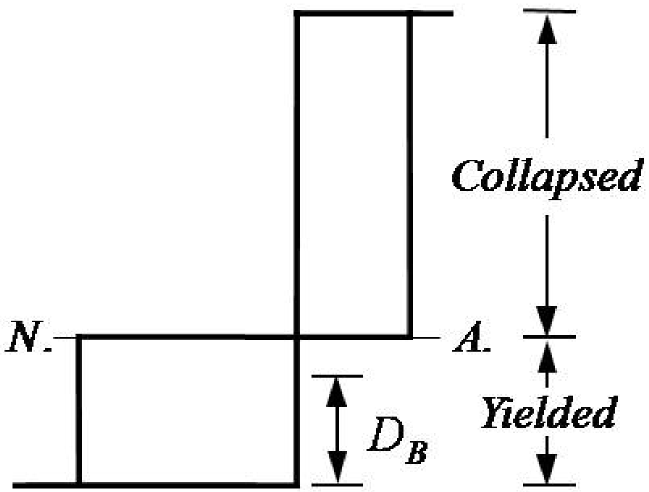


# Methods for the ultimate hull strength analysis

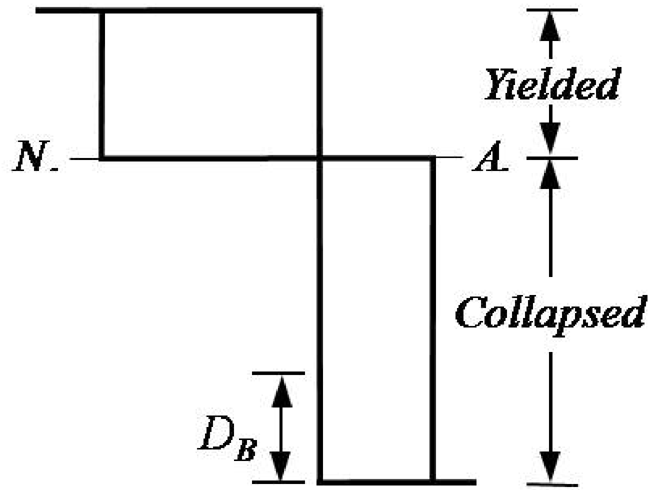
- Numerical
  - Nonlinear FEM
  - Intelligent supersize FEM
  - Idealized structural unit method
- Analytical
  - Design formula
- Experimental

# Presumed stress distribution-based method (1/8)

## Caldwell's original formula method (1965)




Sagging



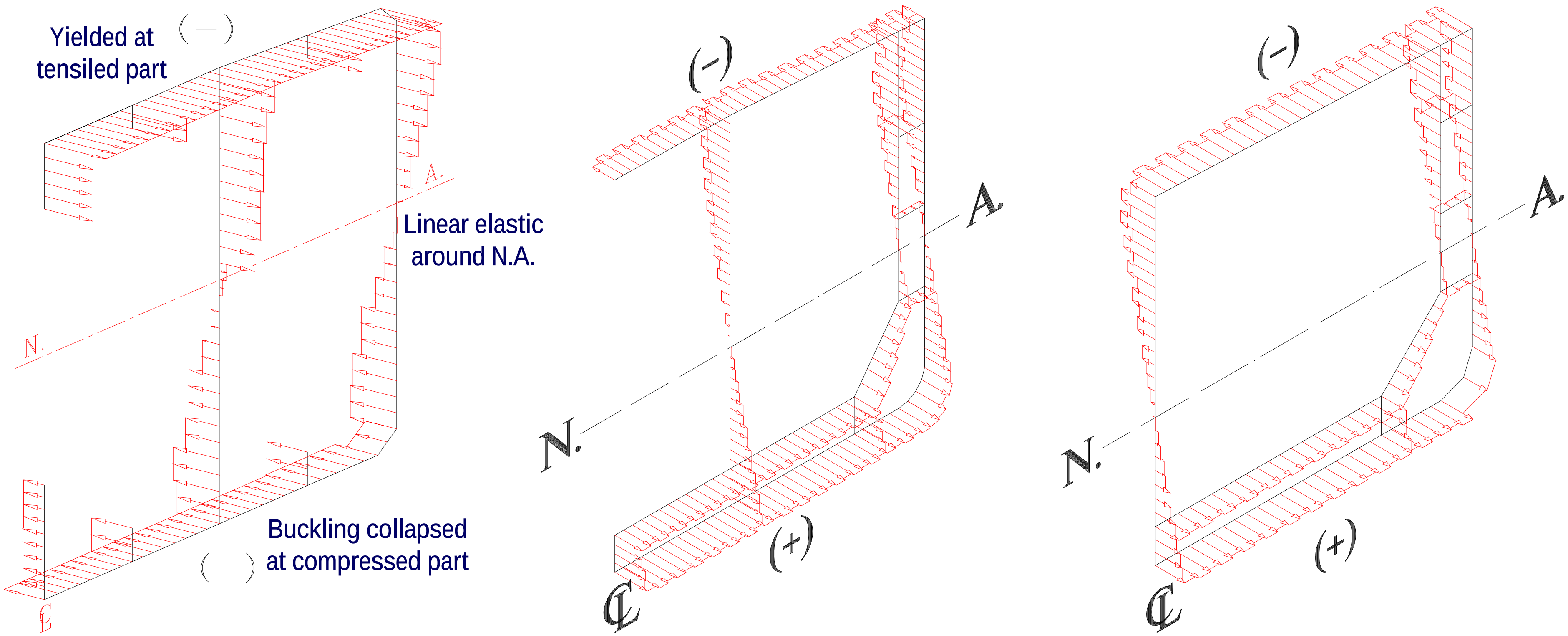

Hogging

$$\int \sigma_x dA = 0$$

$$g_u = \frac{\sum_{i=1}^{n} |\sigma_{xi}| a_i z_i}{\sum_{i=1}^{n} |\sigma_{xi}| a_i}$$

$$M_u^v = \sum_{i=1}^{n} \sigma_{xi} a_i \left( z_i - g_u \right)$$

# Presumed stress distribution-based method (2/8)



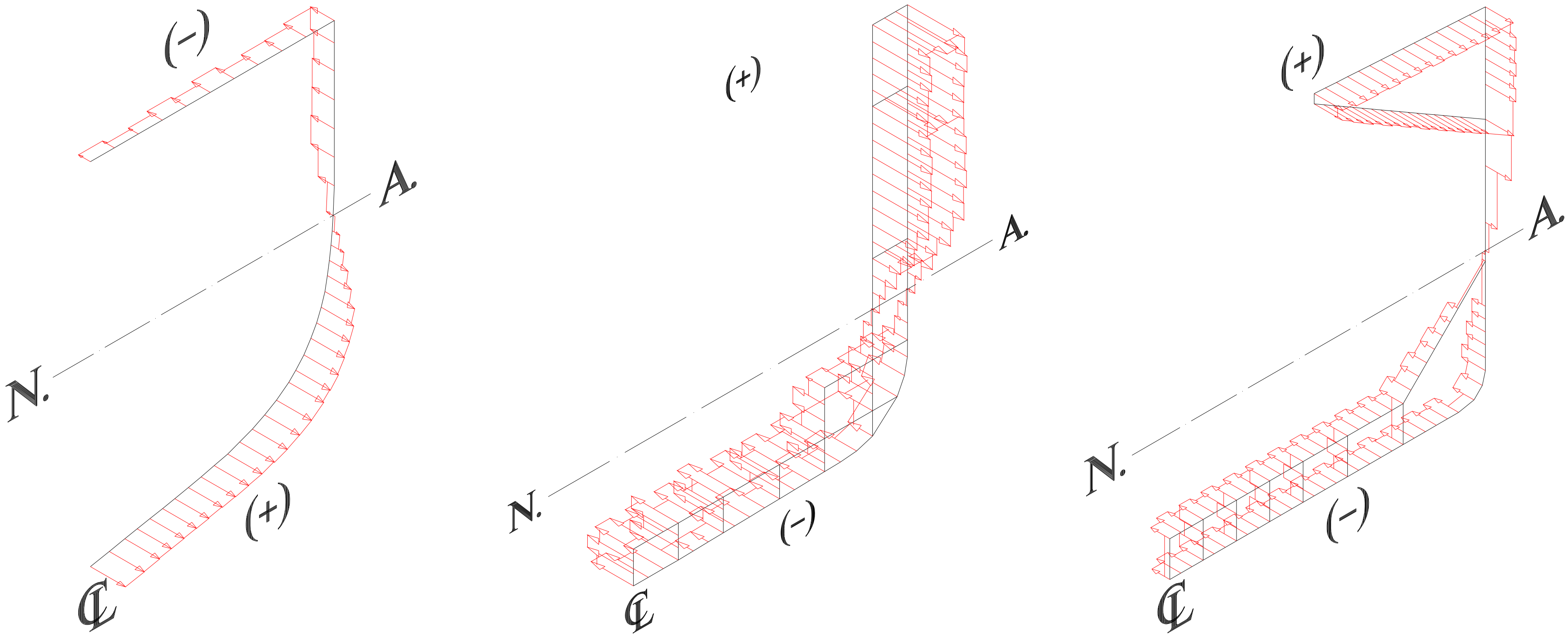

Single hull VLCC
in hogging

Double hull VLCC
in sagging

Suezmax-class double hull
VLCC in sagging

Longitudinal bending stress distribution of tanker hull
at ULS obtained by Nonlinear FEA

# Presumed stress distribution-based method (3/8)




Dow's frigate test hull
in sagging

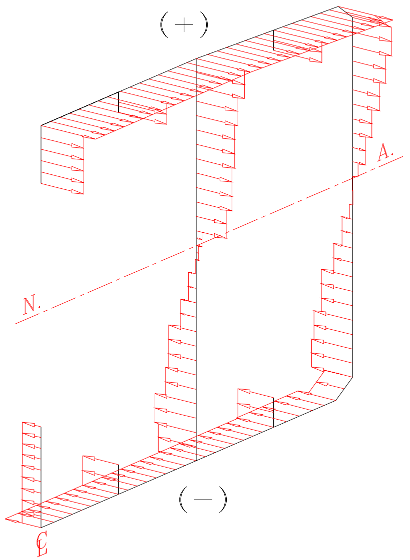
Container ship
in hogging

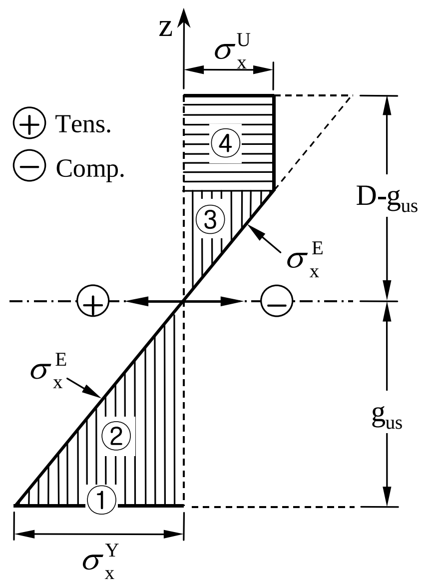
Bulk carrier
in hogging

Longitudinal bending stress distribution of ship hull
at ULS obtained by Nonlinear FEA

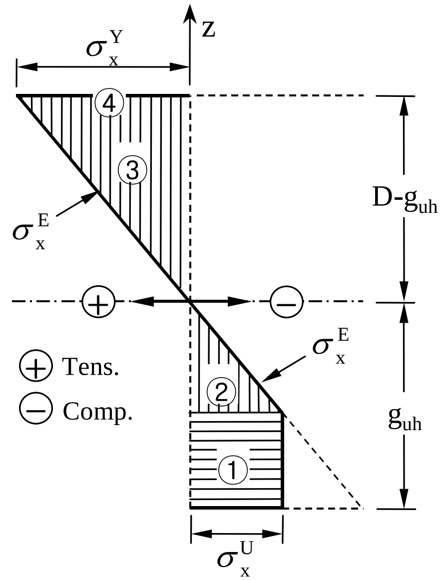
# Presumed stress distribution-based method (4/8)

## Original Paik-Mansour formula method (1995)




Sagging




Hogging

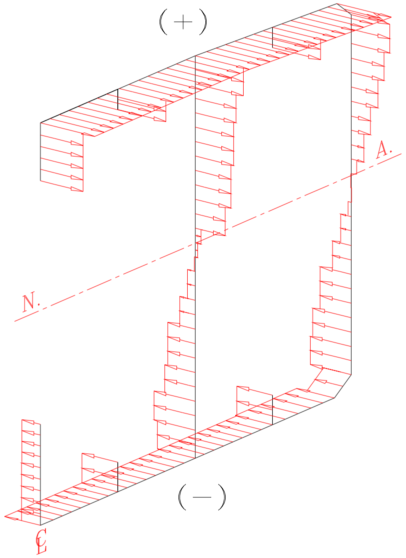
$$\int \sigma_x dA = 0$$

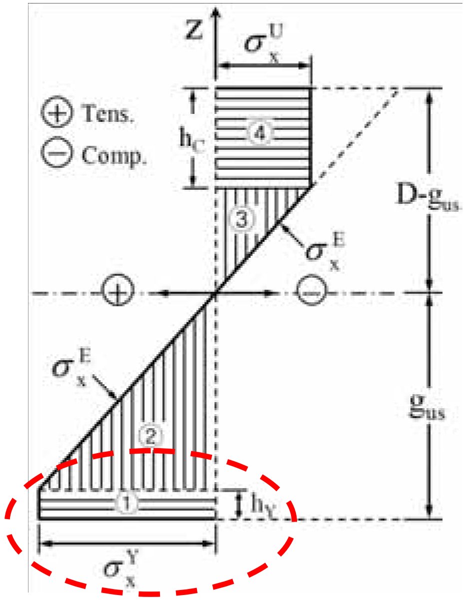
$$g_u = \frac{\sum_{i=1}^{n} \left|\sigma_{xi}\right| a_i z_i}{\sum_{i=1}^{n} \left|\sigma_{xi}\right| a_i}$$

$$M_u^v = \sum_{i=1}^{n} \sigma_{xi} a_i \left( z_i - g_u \right)$$

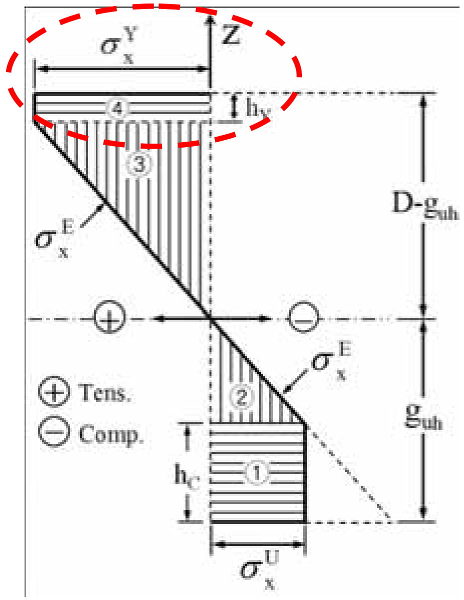
# Presumed stress distribution-based method (5/8)

## Modified Paik-Mansour formula method




Sagging



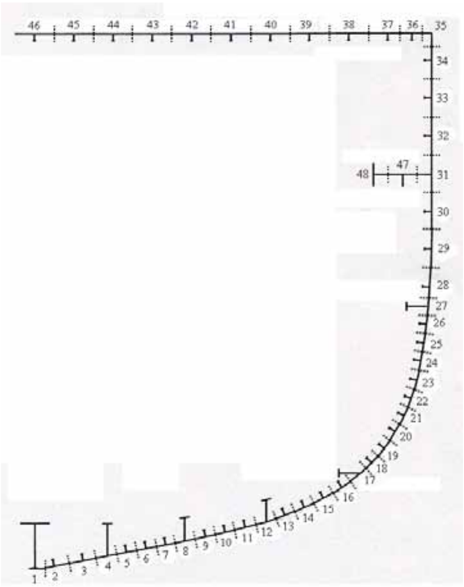

Hogging

$$\int \sigma_x dA = 0$$

$$g_u = \frac{\sum_{i=1}^{n} |\sigma_{xi}| a_i z_i}{\sum_{i=1}^{n} |\sigma_{xi}| a_i}$$

$$M_u^v = \sum_{i=1}^{n} \sigma_{xi} a_i \left( z_i - g_u \right)$$

# Presumed stress distribution-based method (6/8)



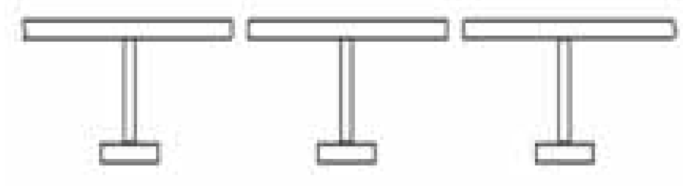


Plate-stiffener combination element (PSC)

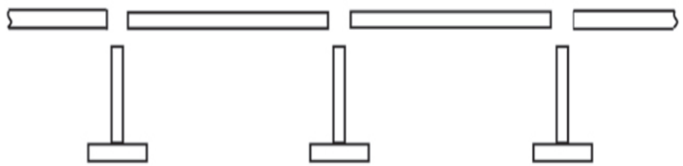


Plate-stiffener separation element (PSS)

$$\frac{\sigma_{xu}}{\sigma_{Yeq}} = \frac{1}{\sqrt{0.995 + 0.936\lambda^2 + 0.170\beta^2 + 0.188\lambda^2\beta^2 - 0.067\lambda^4}}$$

$$\lambda = \frac{a}{\pi r}\sqrt{\frac{\sigma_{Yeq}}{E}} \qquad \beta = \frac{b}{t}\sqrt{\frac{\sigma_{Yp}}{E}} \qquad r = \sqrt{\frac{I}{A_s}}$$

(Paik and Thayamballi, 1997)

# Presumed stress distribution-based method (7/8)

Plate element: a/b≥1 (Paik at al. 2004)

$$\frac{\sigma_{xu}}{\sigma_{Yp}} = \begin{cases} -0.032\beta^4 + 0.002\beta^2 + 1.0 & \text{for } \beta \le 1.5 \\ 1.274/\beta & \text{for } 1.5 < \beta \le 3.0 \\ 1.248/\beta^2 + 0.283 & \text{for } \beta > 3.0 \end{cases}$$

$$\beta = \frac{b}{t}\sqrt{\frac{\sigma_{Yp}}{E}}$$

Plate element: a/b<1 (Paik at al. 2004)

$$\frac{\sigma_{xu}}{\sigma_{Yp}} = \frac{a}{b}\frac{\sigma^*_{xu}}{\sigma_{Yp}} + \frac{0.475}{\alpha^2}\left(1 - \frac{a}{b}\right)$$

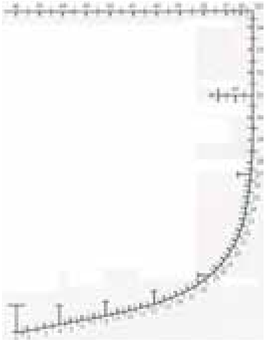
$$\frac{\sigma^*_{xu}}{\sigma_{Yp}} = \begin{cases} -0.032\alpha^4 + 0.002\alpha^2 + 1.0 & \text{for } \alpha \le 1.5 \\ 1.274/\alpha & \text{for } 1.5 < \alpha \le 3.0 \\ 1.248/\alpha^2 + 0.283 & \text{for } \alpha > 3.0 \end{cases}$$

$$\alpha = \frac{a}{t}\sqrt{\frac{\sigma_{Yp}}{E}}$$

# Presumed stress distribution-based method (8/8)

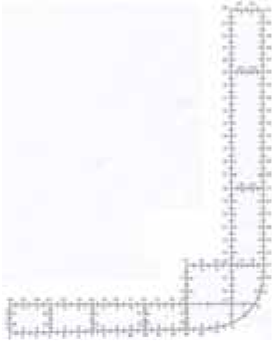
## Modeling: Modified Paik-Mansour formula method

### Dow's Test Hull



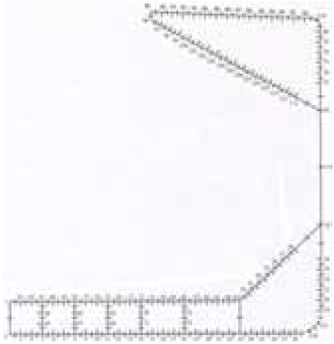
PSC model

### Container Ship



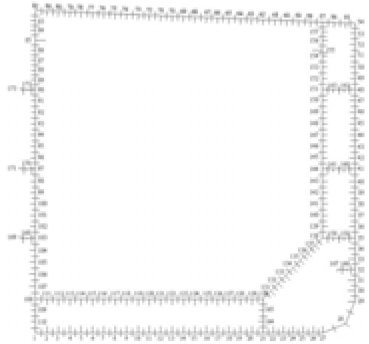
PSC model

### Bulk Carrier

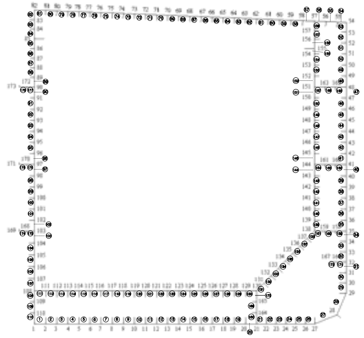


PSC model

### D/H Suezmax

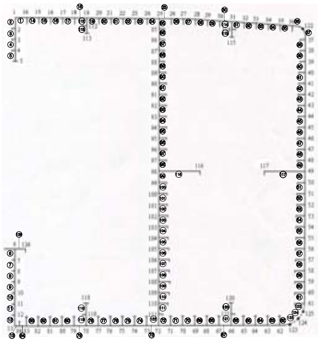


PSC model for hogging



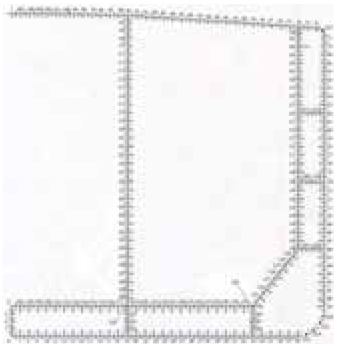
PSS model for sagging

### S/H VLCC

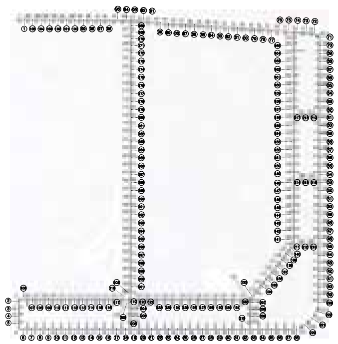


PSS model

### D/H VLCC



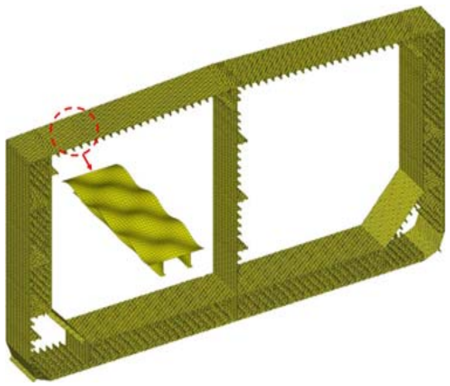
PSC model for hogging



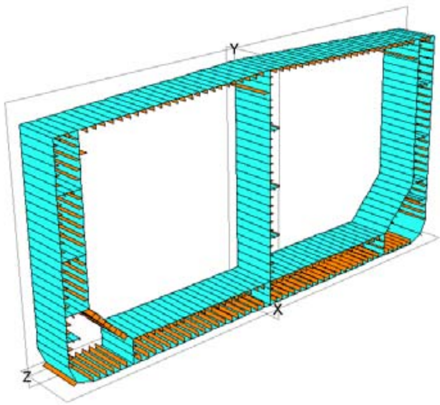
PSS model for sagging

# Methods applied
# for the ultimate hull strength analysis (1/5)

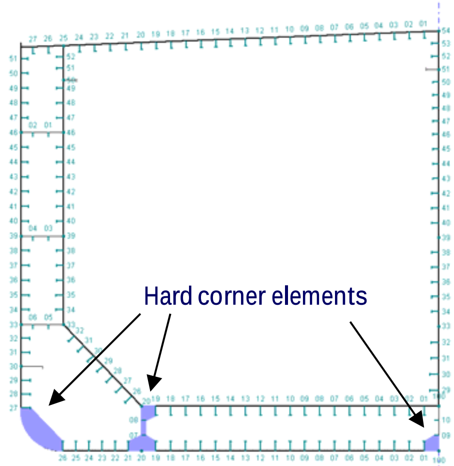
- Nonlinear FEM: ANSYS
- Intelligent supersize FEM: ALPS/HULL
- Idealized structural unit method (Smith method): IACS CSR by Dr. C.H. Huang (China Corporation Register of Shipping)
- Modified Paik-Mansour formula method



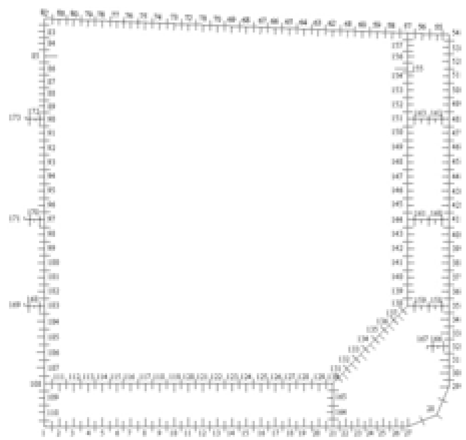
NLFEM model



ISFEM model

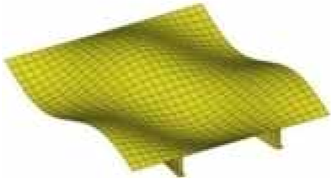
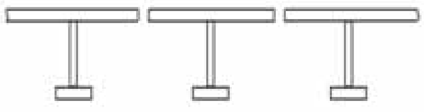
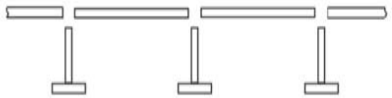



ISUM model



Modified
P-M method

# Methods applied
# for the ultimate hull strength analysis (2/5)

| | NLFEM (ANSYS) | ISUM/Smith Method (IACS CSR) | ISFEM (ALPS/HULL) |
|---|---|---|---|
| **Geometric modeling** |  **Finite element model** |  **Plate-stiffener combination model** |  **Plate-stiffener separation model** |
| **Formulation technique** | $\sigma = \int [B]^T [D][B] d\mathrm{vol}$ **: Numerical formulation** **[D]: Numerical formulation** | $\sigma = \Phi \sigma_Y$ **:Closed-form solution** $\Phi = edge\ function$ $= \begin{cases} -1 & for\ \ \varepsilon < -1 \\ \varepsilon & for\ -1 < \varepsilon < 1 \\ 1 & for\ \varepsilon > 1 \end{cases}$ | $\sigma = \int [B]^T [D][B] d\mathrm{vol}$ **: Numerical formulation** **[D]: Closed-form solution** |
| **Computational cost** | **Expensive** | **Cheap** | **Cheap** |
| **Feature (1)** | **2 and 3-dimensional** | **2-dimensional** | **2 and 3-dimensional** |
| **Feature (2)** | **Can deal with interaction between local and global failures** | **Can not deal with interaction between local and global failures** | **Can deal with interaction between local and global failures** |

# Methods applied for the ultimate hull strength analysis (3/5)

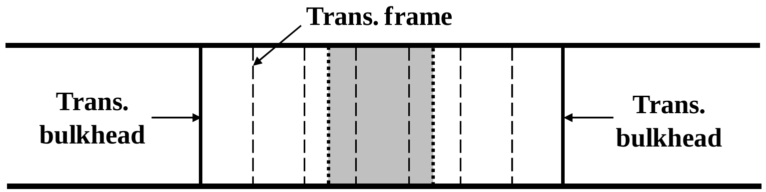
## Extent of the analysis

(a) The entire hull model

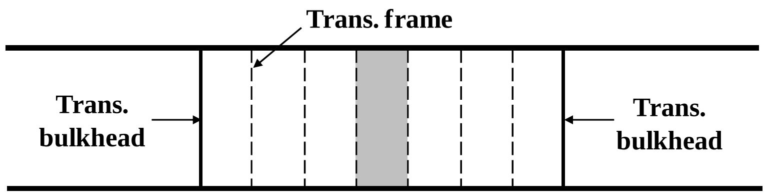
(b) The three cargo hold model

(c) The two cargo hold model

(d) The one cargo hold model



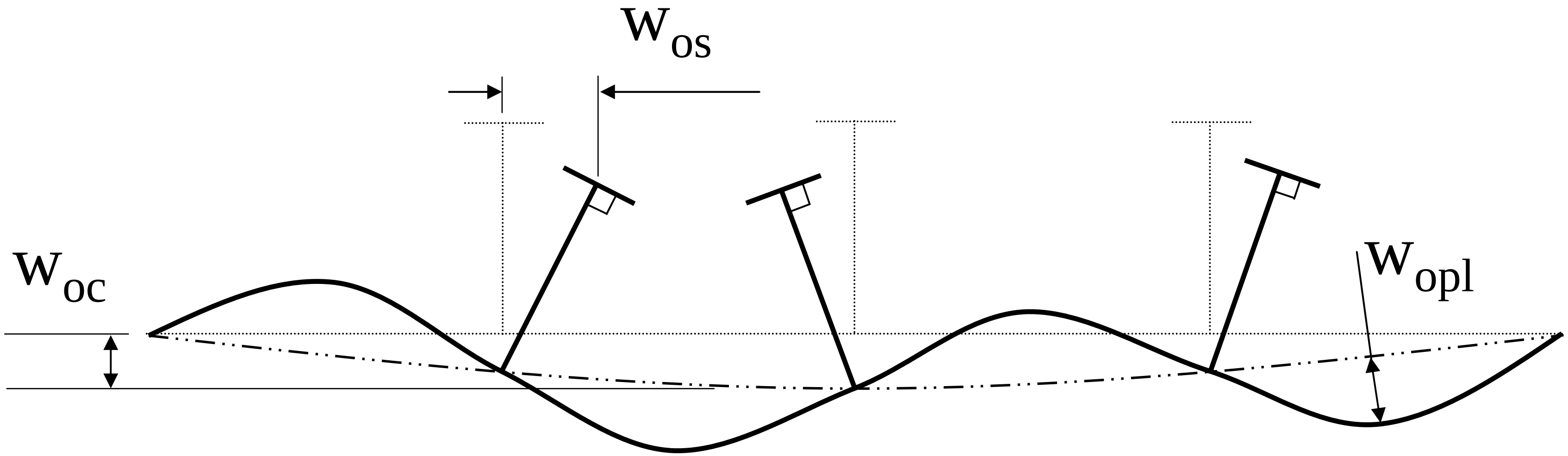

(e) The two-bay sliced hull cross-section model




(f) The one-bay sliced hull cross-section model

# Methods applied
# for the ultimate hull strength analysis (4/5)

## Initial imperfections



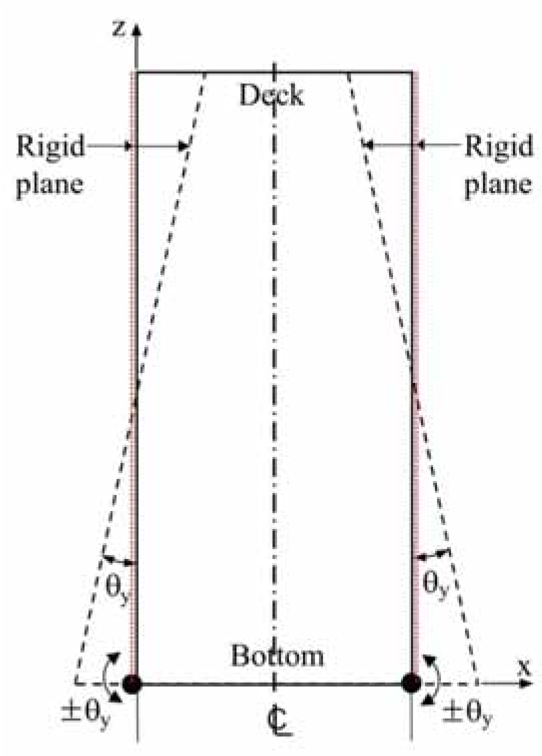

$$w_{opl} = A_o \sin\frac{m\pi x}{a}\sin\frac{\pi y}{b}$$

$$w_{oc} = B_o \sin\frac{\pi x}{a}\sin\frac{\pi y}{B} \qquad \text{where,} \quad A_o = 0.1\beta^2 t_p; \quad B_o = C_o = 0.0015a; \quad \beta = \frac{b}{t_p}\sqrt{\frac{\sigma_{Yp}}{E}}$$

$$w_{os} = C_0 \frac{z}{h_w}\sin\frac{\pi x}{a}$$

# Methods applied
# for the ultimate hull strength analysis (5/5)

## Displacement control with neutral axis changes



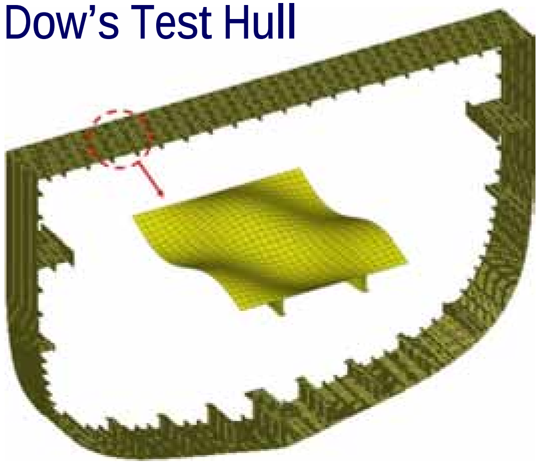

Application of vertical bending moments keeping the hull cross-section plane

$$g = \frac{\sum_{i=1}^{n} |\sigma_{xi}| a_i z_i}{\sum_{i=1}^{n} |\sigma_{xi}| a_i}$$

- $g$ = neutral axis position from the baseline
- $z_i$ = distance from the ship's baseline (reference position) to the horizontal neutral axis of the $i^{th}$ structural component
- $\sigma_{xi}$ = longitudinal stress of the $i^{th}$ structural component following the presumed stress distribution
- $a_i$ = cross-sectional area of the $i^{th}$ structural component
- $n$ = total number of structural components

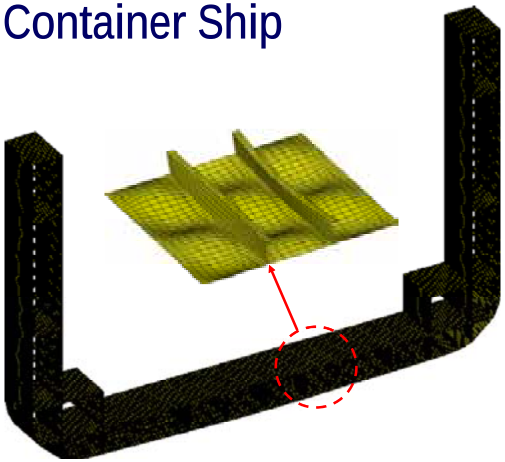
# NLFEM (ANSYS) Modeling

## Dow's Test Hull



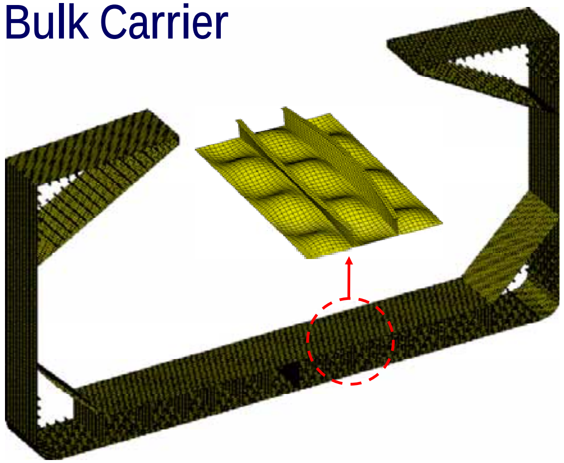
Total number of elements: 36,432
Elements distribution:
Plate: 10 Web: 4 Flange: 2

## Container Ship



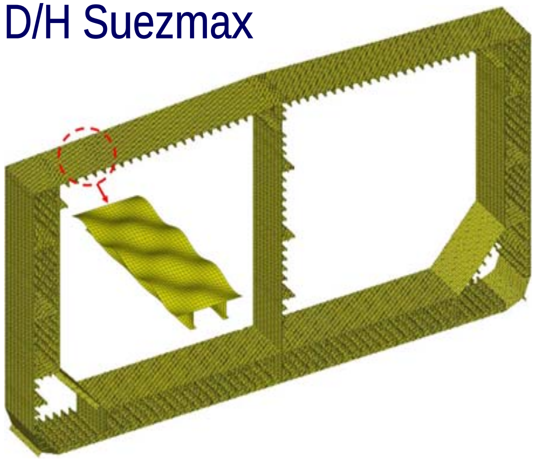
Total number of elements: 76,992
Elements distribution:
Plate: 8 Web: 4 Flange: 1

## Bulk Carrier



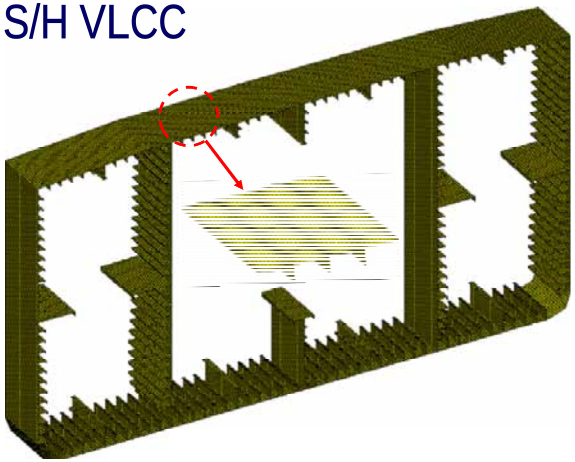
Total number of elements: 271,680
Elements distribution:
Plate: 10 Web: 8 Flange: 2

## D/H Suezmax



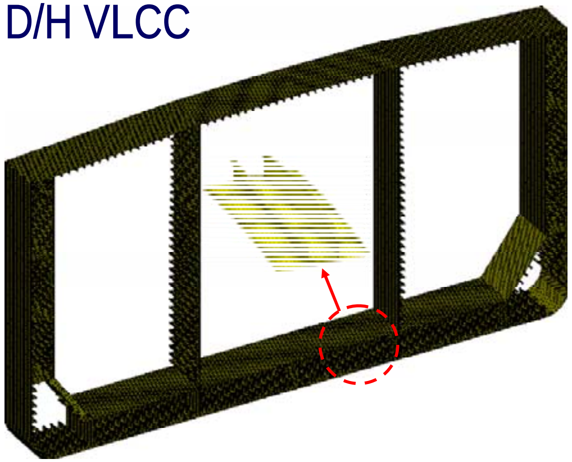
Total number of elements: 262,630
Elements distribution:
Plate: 10 Web: 6 Flange: 2

## S/H VLCC



Total number of elements: 222,858
Elements distibution:
Plate: 10 Web: 6 Flange: 1

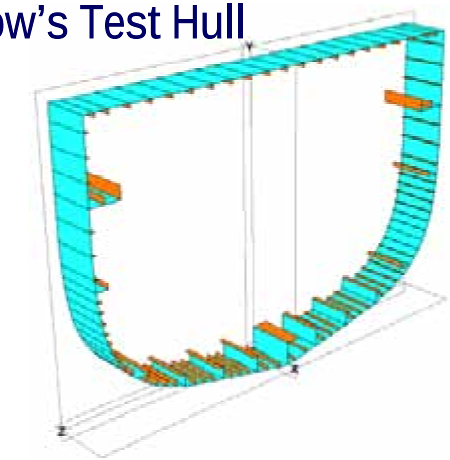
## D/H VLCC



Total number of elements: 297,888
Elements distribution:
Plate: 8 Web: 6 Flange: 2

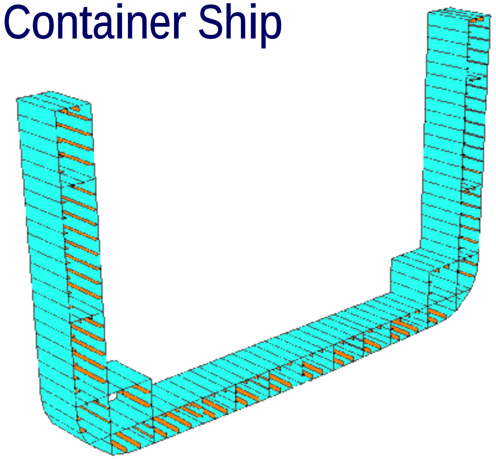
# ISFEM (ALPS/HULL) Modeling

## Dow's Test Hull



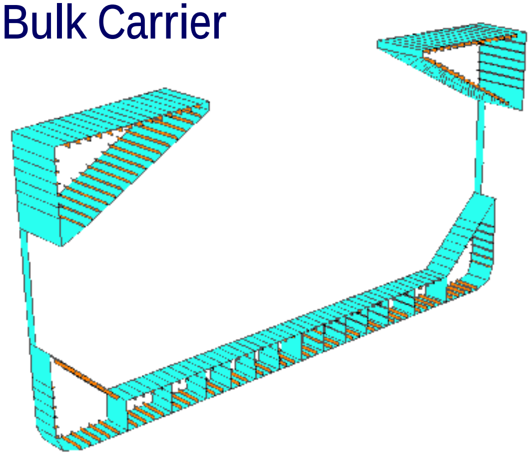
Total number of elements: 196
Plate: 106 elements
Beam-column: 90 elements

## Container Ship



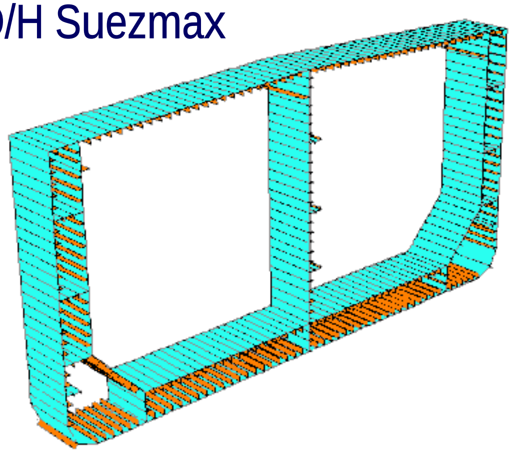
Total number of elements: 389
Plate: 231 elements
Beam-column: 158 elements

## Bulk Carrier



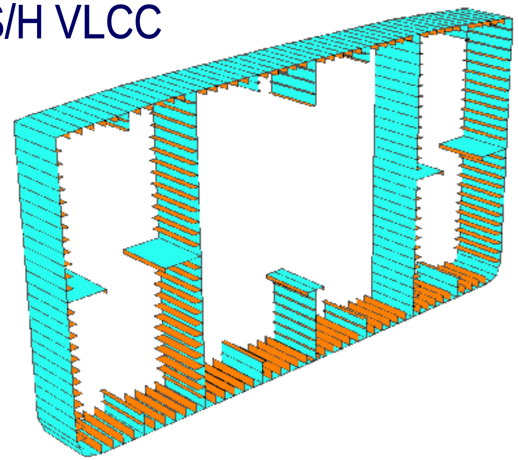
Total number of elements: 431
Plate: 243 elements
Beam-column: 188 elements

## D/H Suezmax



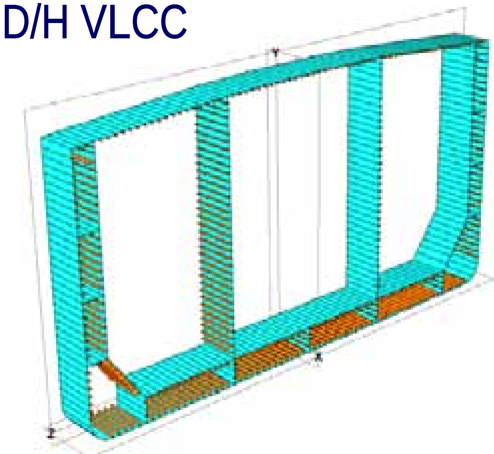
Total number of elements: 605
Plate: 367 elements
Beam-column: 238 elements

## S/H VLCC



Total number of elements: 453
Plate: 341 elements
Beam-column: 112 elements

## D/H VLCC

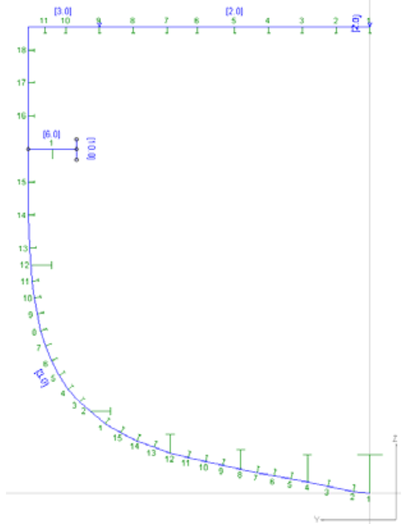


Total number of elements: 834
Plate: 442 elements
Beam-column: 392 elements

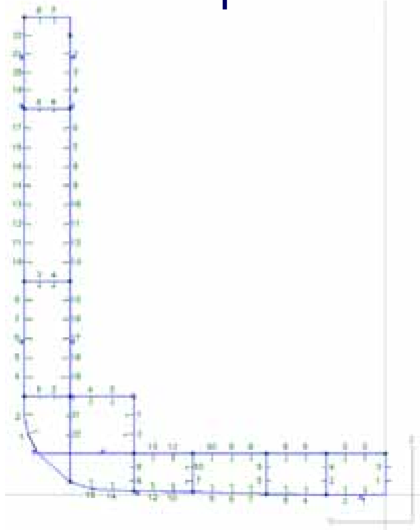
# ISUM (CSR) Modeling by Dr. C. H. Huang

## (China Corporation Register of Shipping, Taiwan)

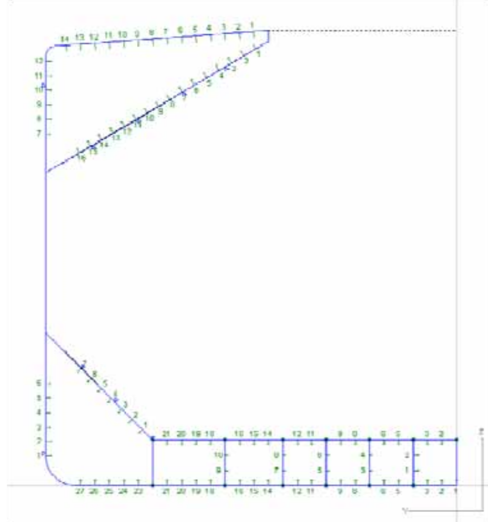
Dow's Test Hull



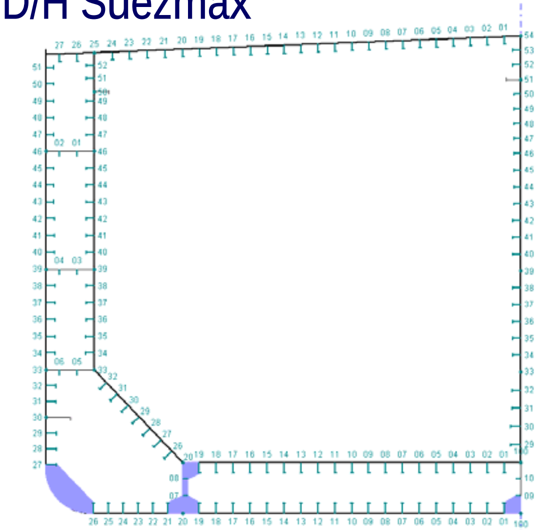
Container Ship



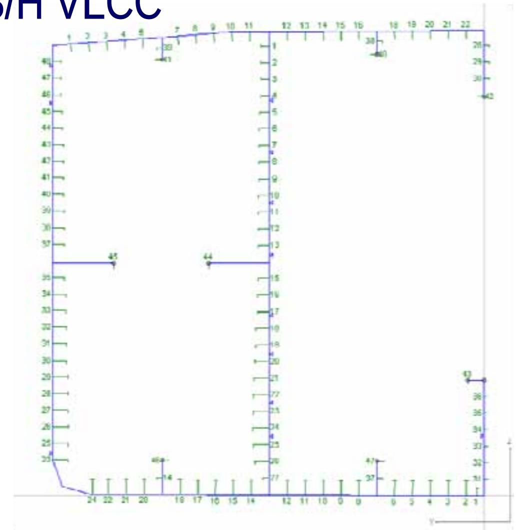
Bulk Carrier



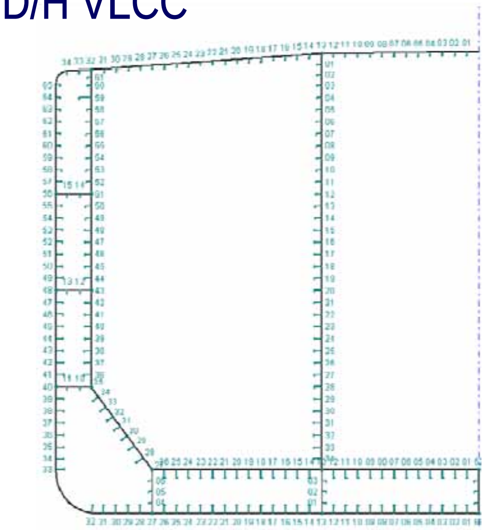
D/H Suezmax



S/H VLCC

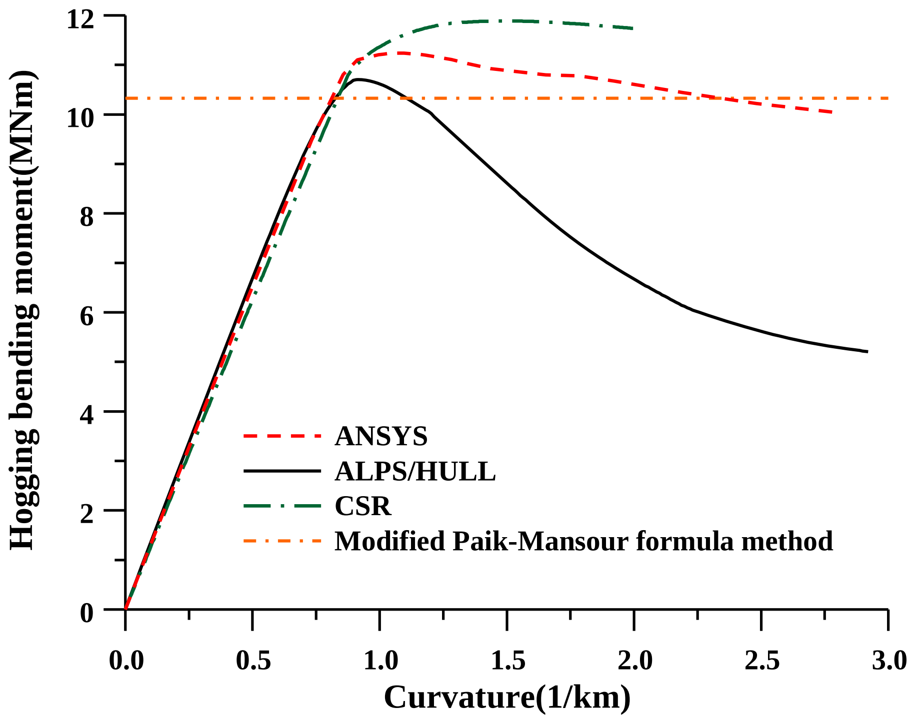


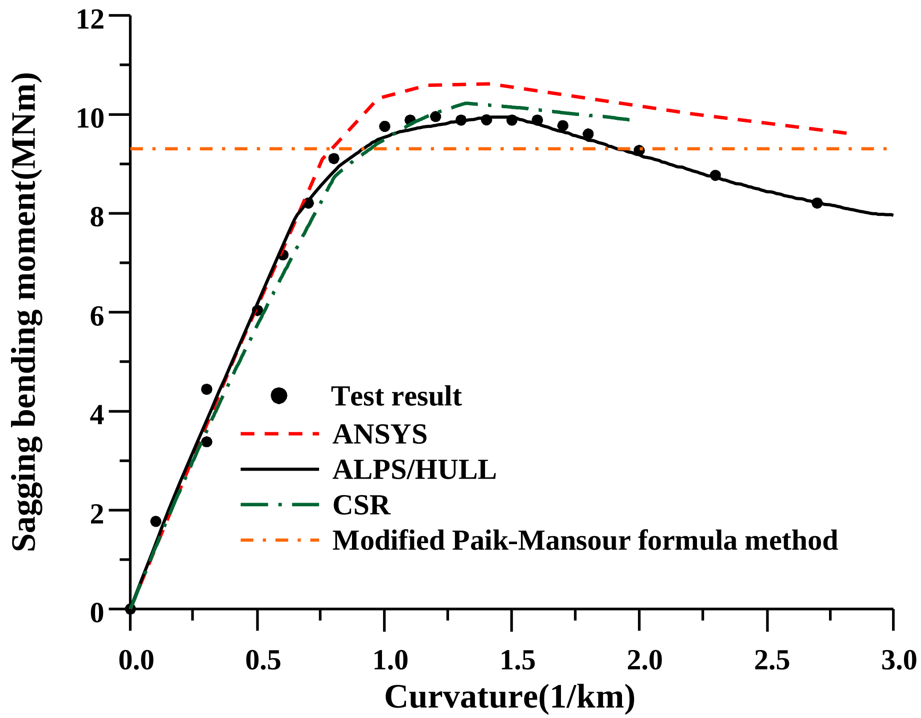
D/H VLCC



# Result - Case I: Dow's Test Hull (1/6)

## Curvature versus vertical bending moments



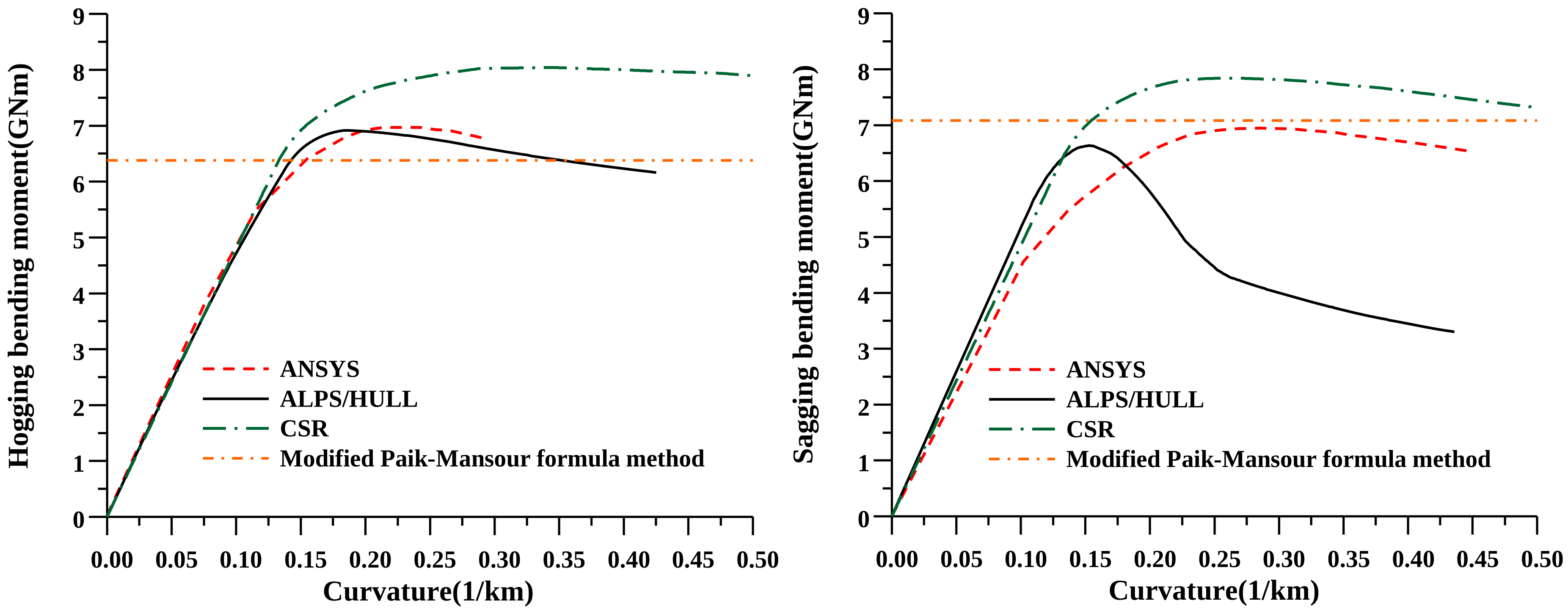




| Dow's test hull | Design formula method | | | | | $M_u$ ANSYS (MNm) | $M_u$ ALPS/HULL (MNm) | $M_u$ CSR (MNm) |
|---|---|---|---|---|---|---|---|---|
| | $M_u$ (MNm) | Original P-M | | Modified P-M | | | | |
| | | $h_C$(mm) | $h_Y$(mm) | $h_C$(mm) | $h_Y$(mm) | | | |
| Hogging | 10.338 | 210.000 | 0.000 | 210.000 | 0.000 | 11.235 | 10.698 | 11.889 |
| Sagging | 9.329 | 760.200 | 0.000 | 760.200 | 0.000 | 10.618 | 9.940 | 10.224 |

Note: $M_u$ = ultimate moment, $h_C$ = height of collapsed hull part, $h_Y$ = height of yielded hull part.

# Result - Case II: Container Ship (2/6)

## Curvature versus vertical bending moments

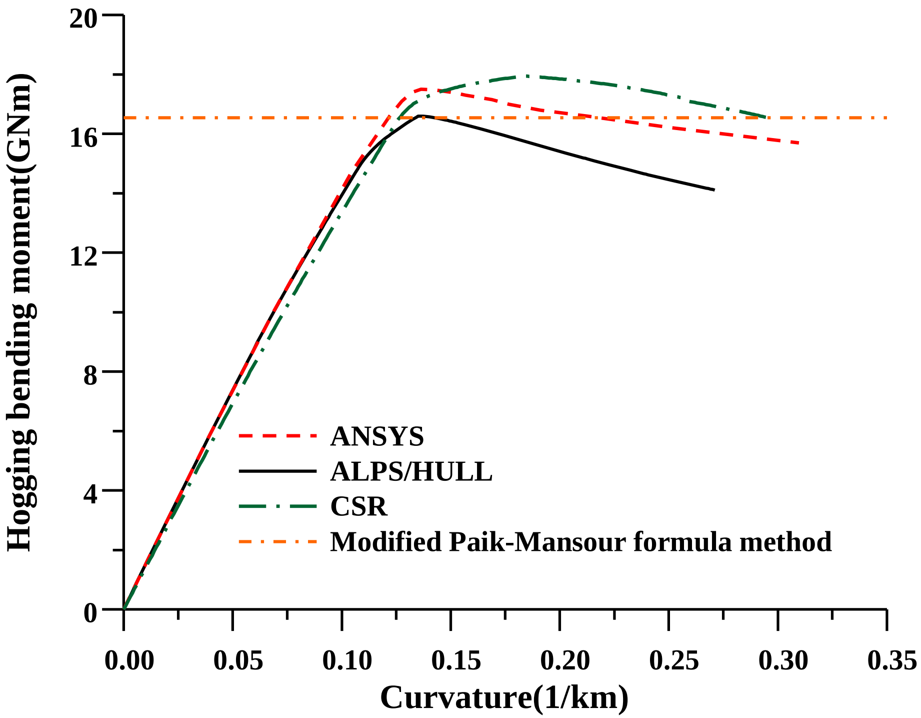


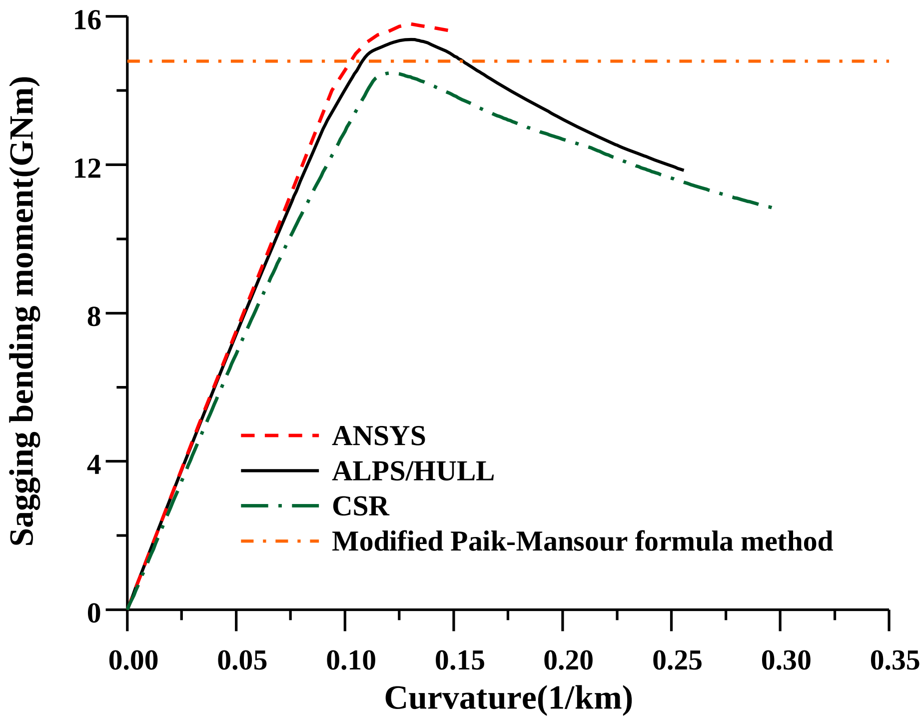

| Container ship | Design formula method | | | | | $M_u$ ANSYS (GNm) | $M_u$ ALPS/HULL (GNm) | $M_u$ CSR (GNm) |
|---|---|---|---|---|---|---|---|---|
| | $M_u$ (GNm) | Original P-M | | Modified P-M | | | | |
| | | $h_C$(mm) | $h_Y$(mm) | $h_C$(mm) | $h_Y$(mm) | | | |
| Hogging | 6.400 | 698.800 | 0.000 | 698.800 | 0.000 | 6.969 | 6.916 | 8.040 |
| Sagging | 7.077 | 10330.800 | 0.000 | 10330.800 | 0.000 | 6.951 | 6.635 | 7.843 |

Note: $M_u$ = ultimate moment, $h_C$ = height of collapsed hull part, $h_Y$ = height of yielded hull part.

# Result - Case III: Bulk Carrier (3/6)

## Curvature versus vertical bending moments



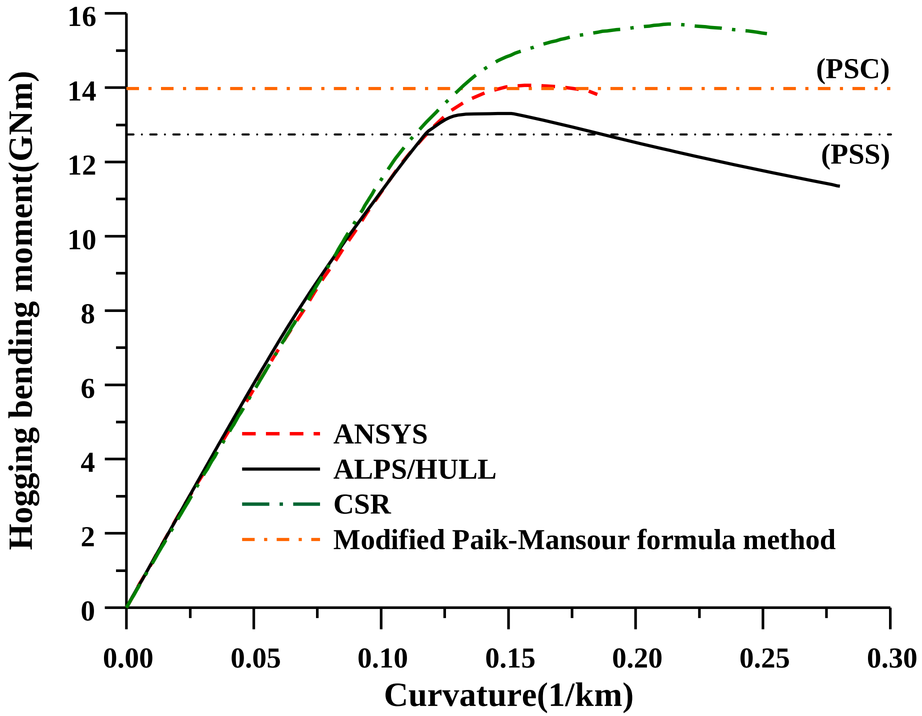



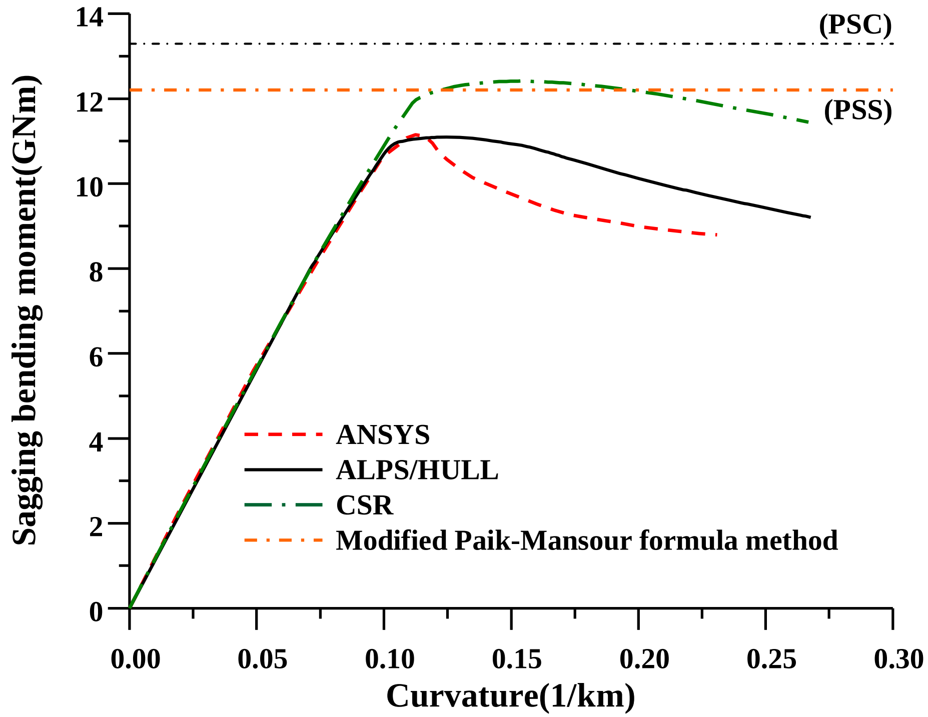

| Bulk carrier | Design formula method | | | | | $M_u$ ANSYS (GNm) | $M_u$ ALPS/HULL (GNm) | $M_u$ CSR (GNm) |
|---|---|---|---|---|---|---|---|---|
| | $M_u$ (GNm) | Original P-M | | Modified P-M | | | | |
| | | $h_C$(mm) | $h_Y$(mm) | $h_C$(mm) | $h_Y$(mm) | | | |
| Hogging | 16.576 | - | - | 1654.100 | 13.700 | 17.500 | 16.602 | 17.941 |
| Sagging | 14.798 | 17935.000 | 0.000 | 17935.000 | 0.000 | 15.800 | 15.380 | 14.475 |

Note: $M_u$ = ultimate moment, $h_C$ = height of collapsed hull part, $h_Y$ = height of yielded hull part.

# Result - Case IV: Double Hull Suezmax Class Tanker (4/6)

## Curvature versus vertical bending moments



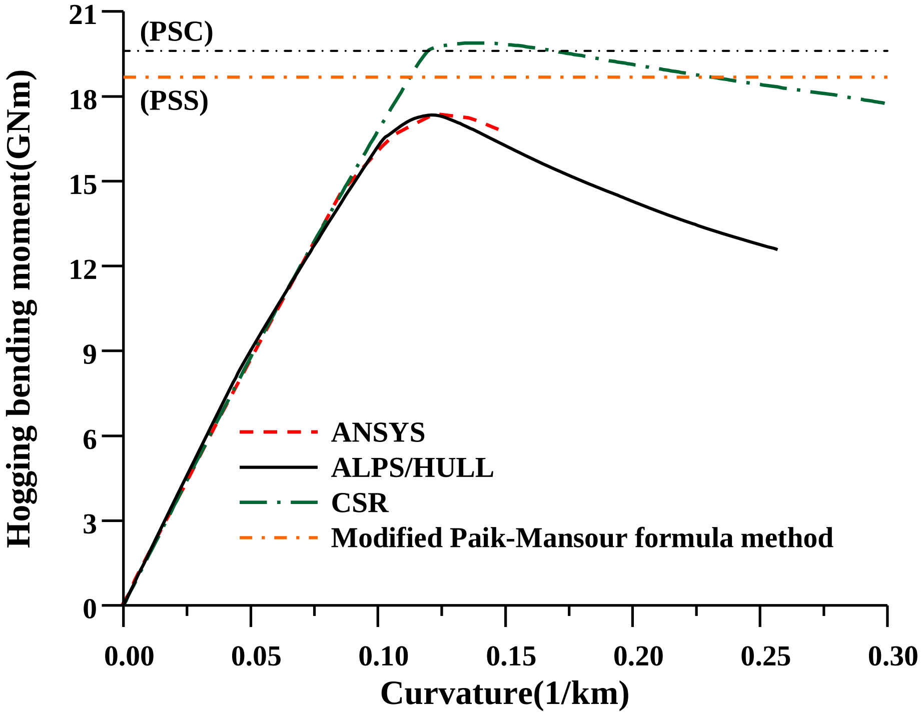



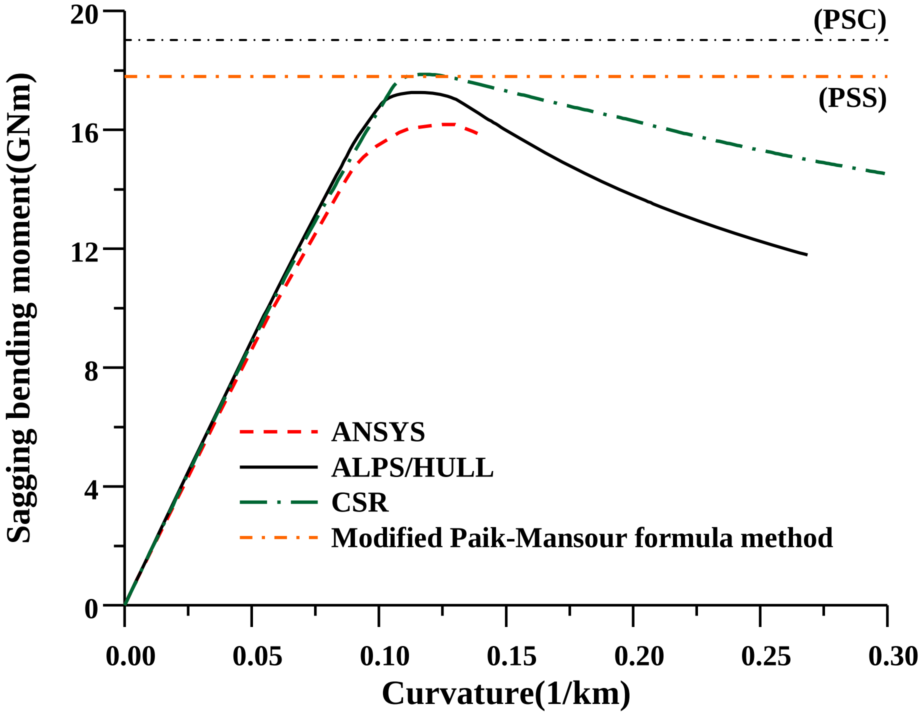

| Double hull Suezmax tanker | Design formula method | | | | | $M_u$ ANSYS (GNm) | $M_u$ ALPS/HULL (GNm) | $M_u$ CSR (GNm) |
|---|---|---|---|---|---|---|---|---|
| | $M_u$ (GNm) | Original P-M | | Modified P-M | | | | |
| | | $h_C$(mm) | $h_Y$(mm) | $h_C$(mm) | $h_Y$(mm) | | | |
| Hogging | 13.965 | - | - | 12.100 | 2210.600 | 14.066 | 13.308 | 15.714 |
| Sagging | 12.213 | 16078.500 | 0.000 | 16078.500 | 0.000 | 11.151 | 11.097 | 12.420 |

Note: $M_u$ = ultimate moment, $h_C$ = height of collapsed hull part, $h_Y$ = height of yielded hull part.

# Result - Case V: Single Hull VLCC Class Tanker (5/6)

## Curvature versus vertical bending moments



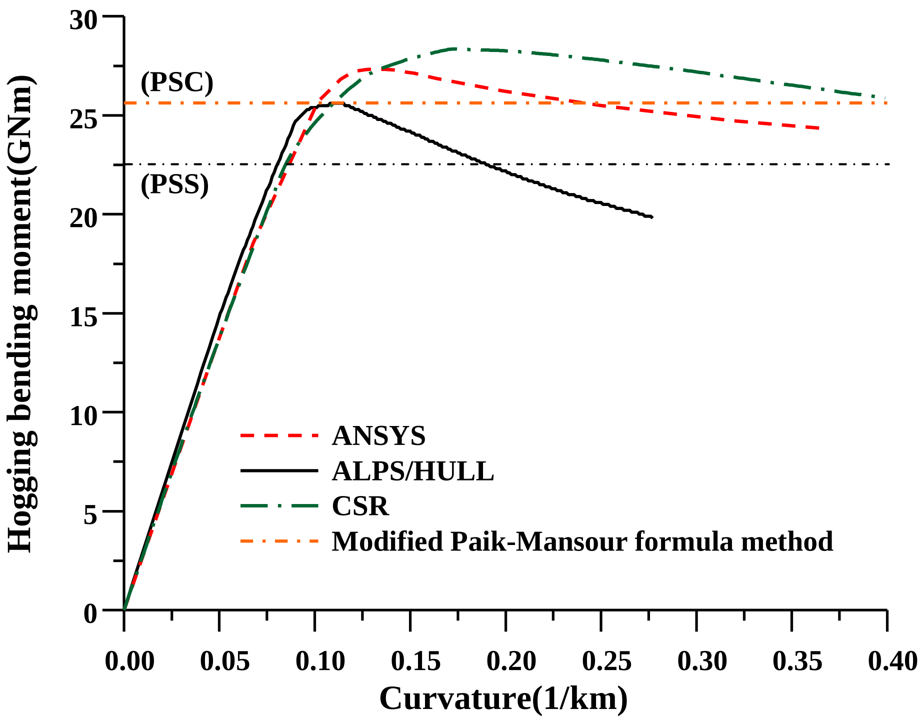



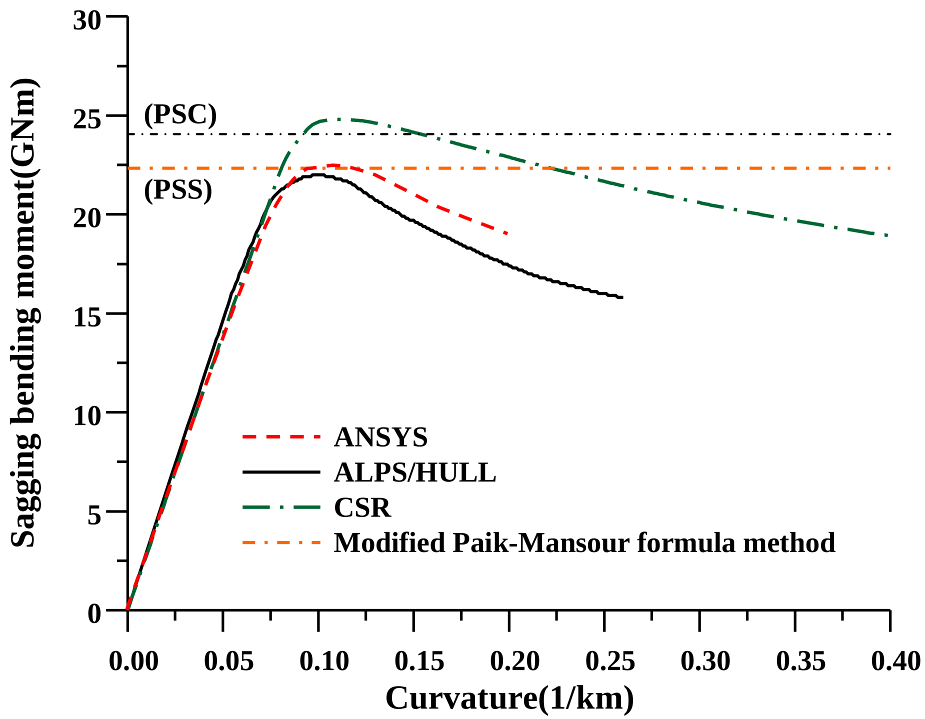

| Single hull VLCC tanker | Design formula method | | | | | $M_u$ ANSYS (GNm) | $M_u$ ALPS/HULL (GNm) | $M_u$ CSR (GNm) |
|---|---|---|---|---|---|---|---|---|
| | $M_u$ (GNm) | Original P-M | | Modified P-M | | | | |
| | | $h_C$(mm) | $h_Y$(mm) | $h_C$(mm) | $h_Y$(mm) | | | |
| Hogging | 18.701 | 7035.200 | 0.000 | 7035.200 | 0.000 | 17.355 | 17.335 | 19.889 |
| Sagging | 17.825 | 15225.500 | 0.000 | 15225.500 | 0.000 | 16.179 | 17.263 | 17.868 |

Note: $M_u$ = ultimate moment, $h_C$ = height of collapsed hull part, $h_Y$ = height of yielded hull part.

# Result - Case VI: Double Hull VLCC Class Tanker (6/6)

## Curvature versus vertical bending moments

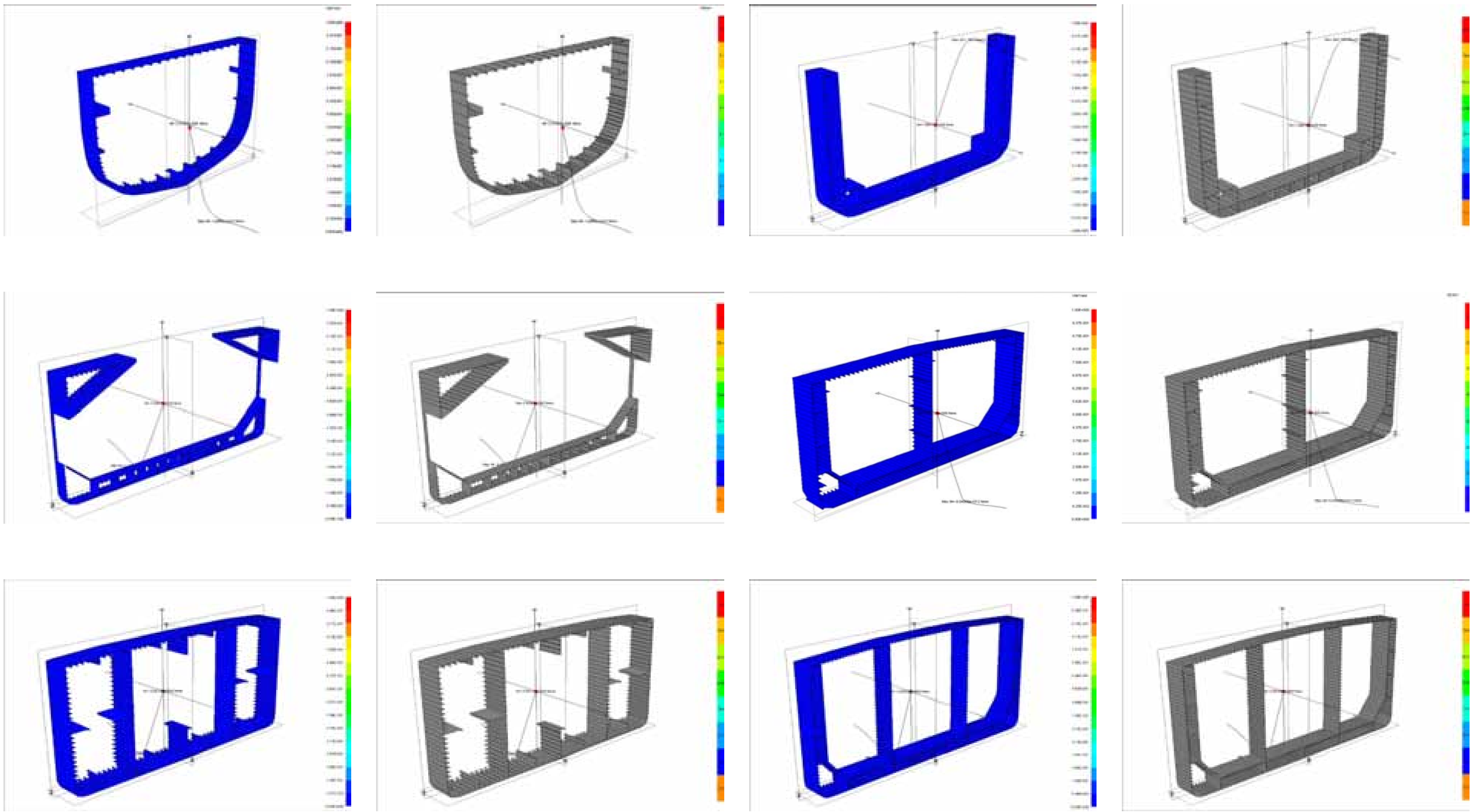



| Double hull VLCC tanker | Design formula method | | | | | $M_u$ ANSYS (GNm) | $M_u$ ALPS/HULL (GNm) | $M_u$ CSR (GNm) |
|---|---|---|---|---|---|---|---|---|
| | $M_u$ (GNm) | Original P-M | | Modified P-M | | | | |
| | | $h_C$(mm) | $h_Y$(mm) | $h_C$(mm) | $h_Y$(mm) | | | |
| Hogging | 25.667 | - | - | 15.900 | 3816.000 | 27.335 | 25.600 | 28.352 |
| Sagging | 22.390 | 20240.700 | 0.000 | 20240.700 | 0.000 | 22.495 | 22.000 | 24.798 |

Note: $M_u$ = ultimate moment, $h_C$ = height of collapsed hull part, $h_Y$ = height of yielded hull part.

# Result: Analysis Video



# Statistical analysis - Mean and COV (1/12)

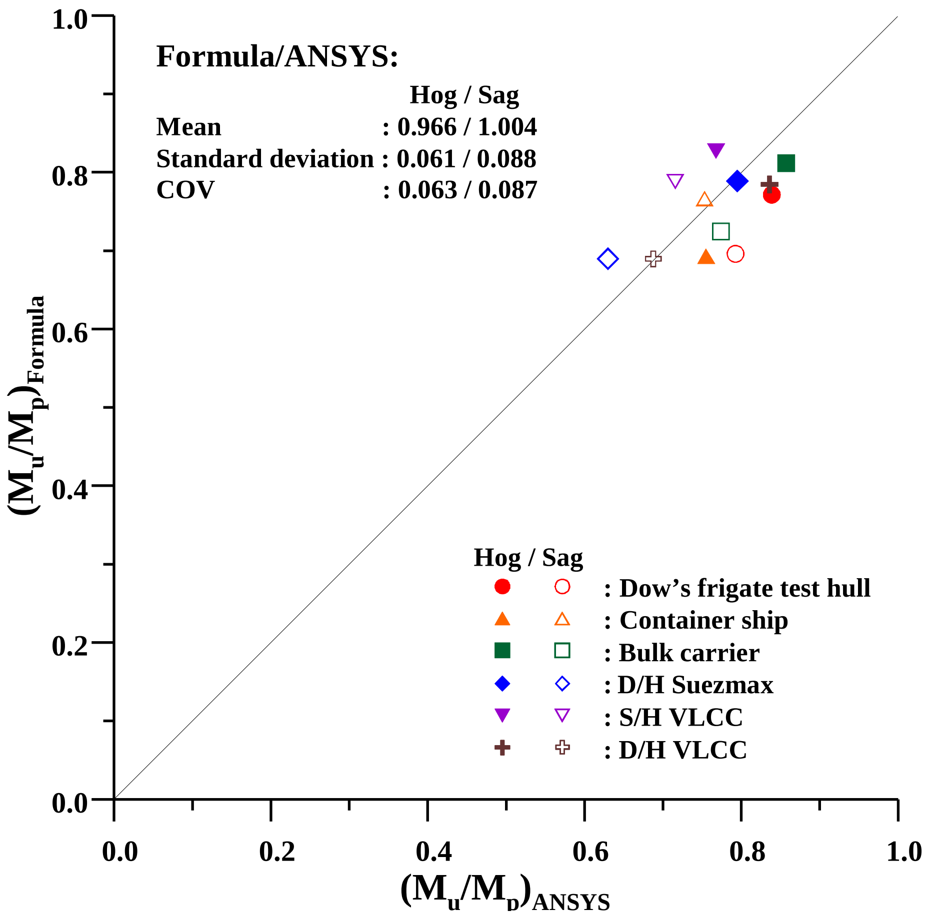
## Modified P-M Formula Method versus ANSYS Nonlinear FEA (1/2)

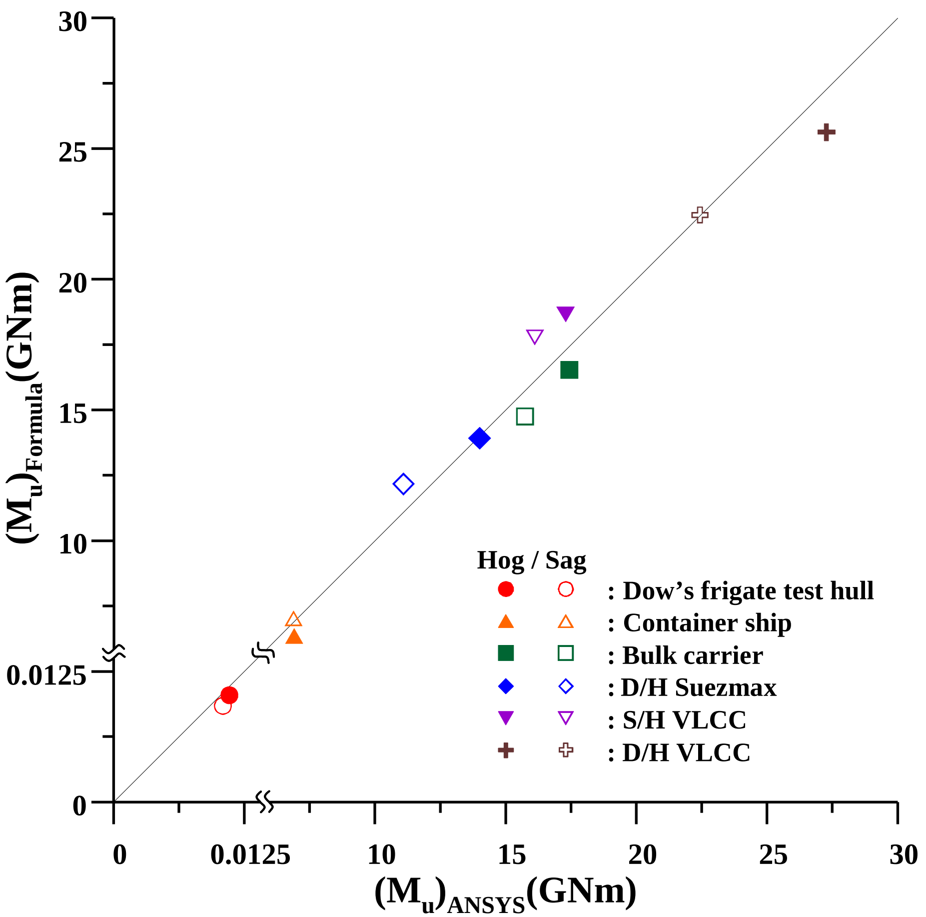
| Ship | $M_p$ (GNm) | Hogging | | | | | Sagging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Formula | | ANSYS | | Formula/ ANSYS | Formula | | ANSYS | | Formula/ ANSYS |
| | | $M_{uh}$ (GNm) | $M_{uh}/M_p$ | $M_{uh}$ (GNm) | $M_{uh}/M_p$ | | $M_{us}$ (GNm) | $M_{us}/M_p$ | $M_{us}$ (GNm) | $M_{us}/M_p$ | |
| **Dow's test hull** | 0.013 | 0.010 | 0.772 | 0.011 | 0.840 | 0.920 | 0.009 | 0.697 | 0.011 | 0.793 | 0.879 |
| **Container ship** | 9.220 | 6.400 | 0.694 | 6.969 | 0.756 | 0.918 | 7.077 | 0.768 | 6.951 | 0.754 | 1.018 |
| **Bulk carrier** | 20.394 | 16.576 | 0.813 | 17.500 | 0.858 | 0.947 | 14.798 | 0.726 | 15.800 | 0.775 | 0.937 |
| **D/H Suezmax** | 17.677 | 13.965 | 0.790 | 14.066 | 0.796 | 0.993 | 12.213 | 0.691 | 11.151 | 0.631 | 1.095 |
| **S/H VLCC** | 22.578 | 18.701 | 0.828 | 17.355 | 0.769 | 1.078 | 17.825 | 0.789 | 16.179 | 0.717 | 1.102 |
| **D/H VLCC** | 32.667 | 25.667 | 0.786 | 27.335 | 0.837 | 0.939 | 22.390 | 0.685 | 22.495 | 0.689 | 0.995 |
| **Mean** | | | | | | 0.966 | | | | | 1.004 |
| **S-D** | | | | | | 0.061 | | | | | 0.088 |
| **COV** | | | | | | 0.063 | | | | | 0.087 |

Note: $M_p$ = fully plastic bending capacity , $M_{uh}$ = ultimate hogging moment, $M_{us}$ = ultimate sagging moment,
S-D = standard deviation, COV = coefficient of variation

# Statistical analysis - Mean and COV (2/12)

## Modified P-M Formula Method versus ANSYS Nonlinear FEA (2/2)



# Statistical analysis - Mean and COV (3/12)

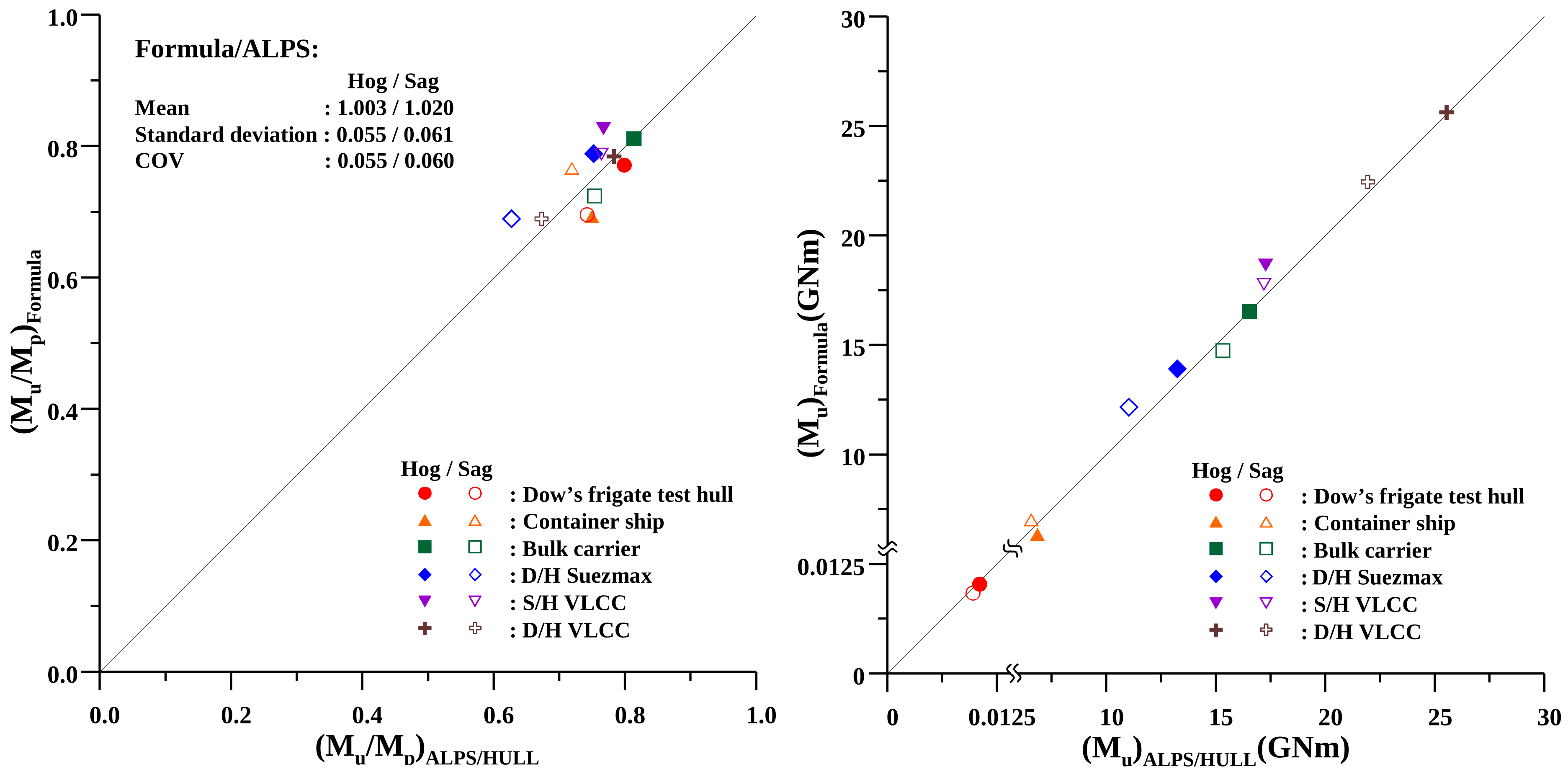
## Modified P-M Formula Method versus ALPS/HULL ISFEM (1/2)

| Ship | $M_p$ (GNm) | Hogging | | | | | Sagging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Formula | | ALPS | | Formula/ ALPS | Formula | | ALPS | | Formula/ ALPS |
| | | $M_{uh}$ (GNm) | $M_{uh}/M_p$ | $M_{uh}$ (GNm) | $M_{uh}/M_p$ | | $M_{us}$ (GNm) | $M_{us}/M_p$ | $M_{us}$ (GNm) | $M_{us}/M_p$ | |
| Dow's test hull | 0.013 | 0.010 | 0.772 | 0.011 | 0.799 | 0.966 | 0.009 | 0.697 | 0.010 | 0.743 | 0.939 |
| Container ship | 9.220 | 6.400 | 0.694 | 6.916 | 0.750 | 0.925 | 7.077 | 0.768 | 6.635 | 0.720 | 1.067 |
| Bulk carrier | 20.394 | 16.576 | 0.813 | 16.602 | 0.814 | 0.998 | 14.798 | 0.726 | 15.380 | 0.754 | 0.962 |
| D/H Suezmax | 17.677 | 13.965 | 0.790 | 13.308 | 0.753 | 1.049 | 12.213 | 0.691 | 11.097 | 0.628 | 1.101 |
| S/H VLCC | 22.578 | 18.701 | 0.828 | 17.335 | 0.768 | 1.079 | 17.825 | 0.789 | 17.263 | 0.765 | 1.033 |
| D/H VLCC | 32.667 | 25.667 | 0.786 | 25.600 | 0.784 | 1.003 | 22.390 | 0.685 | 22.000 | 0.673 | 1.018 |
| Mean | | | | | | 1.003 | | | | | 1.020 |
| S-D | | | | | | 0.055 | | | | | 0.061 |
| COV | | | | | | 0.055 | | | | | 0.060 |

Note: $M_p$ = fully plastic bending capacity , $M_{uh}$ = ultimate hogging moment, $M_{us}$ = ultimate sagging moment,
S-D = standard deviation, COV = coefficient of variation

# Statistical analysis - Mean and COV (4/12)

## Modified P-M Formula Method versus ALPS/HULL ISFEM (2/2)



# Statistical analysis - Mean and COV (5/12)

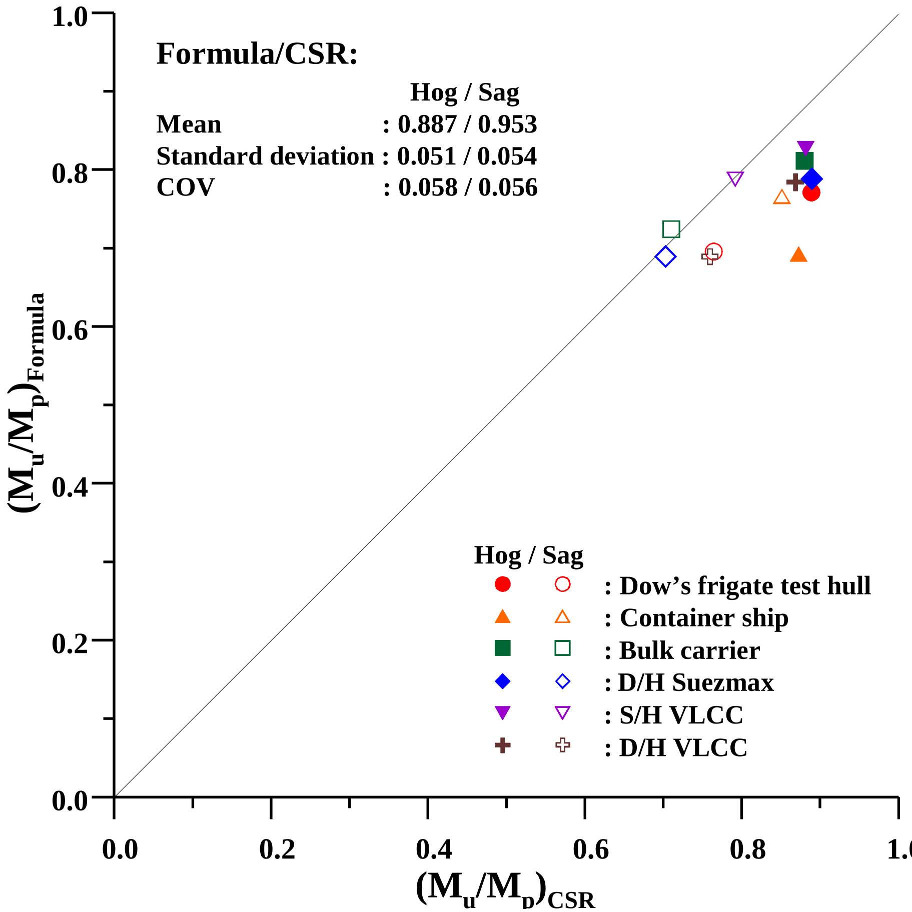
## Modified P-M Formula Method versus CSR ISUM (1/2)

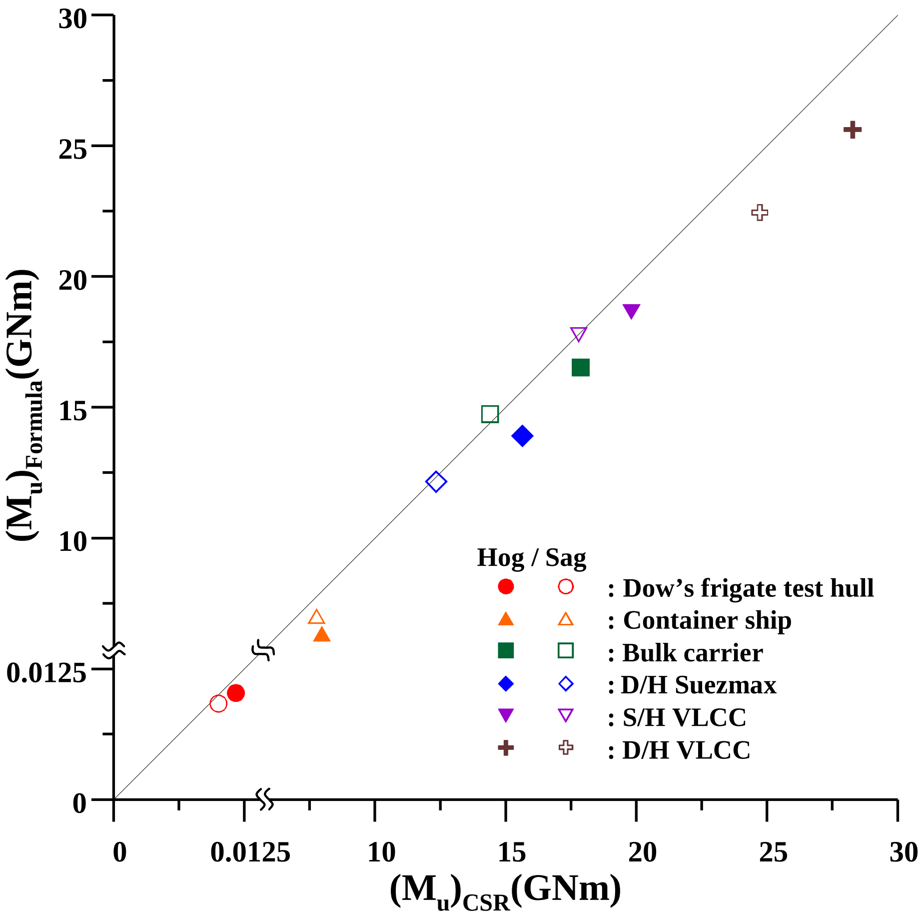
| Ship | $M_p$ (GNm) | Hogging | | | | | Sagging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Formula | | CSR | | Formula/ CSR | Formula | | CSR | | Formula/ CSR |
| | | $M_{uh}$ (GNm) | $M_{uh}$/ $M_p$ | $M_{uh}$ (GNm) | $M_{uh}$/ $M_p$ | | $M_{us}$ (GNm) | $M_{us}$/ $M_p$ | $M_{us}$ (GNm) | $M_{us}$/ $M_p$ | |
| **Dow's test hull** | 0.013 | 0.010 | 0.772 | 0.012 | 0.888 | 0.870 | 0.009 | 0.697 | 0.010 | 0.764 | 0.912 |
| **Container ship** | 9.220 | 6.400 | 0.694 | 8.040 | 0.872 | 0.796 | 7.077 | 0.768 | 7.843 | 0.851 | 0.902 |
| **Bulk carrier** | 20.394 | 16.576 | 0.813 | 17.941 | 0.880 | 0.924 | 14.798 | 0.726 | 14.475 | 0.710 | 1.022 |
| **D/H Suezmax** | 17.677 | 13.965 | 0.790 | 15.714 | 0.889 | 0.889 | 12.213 | 0.691 | 12.420 | 0.703 | 0.983 |
| **S/H VLCC** | 22.578 | 18.701 | 0.828 | 19.889 | 0.881 | 0.940 | 17.825 | 0.789 | 17.868 | 0.791 | 0.998 |
| **D/H VLCC** | 32.667 | 25.667 | 0.786 | 28.352 | 0.868 | 0.905 | 22.390 | 0.685 | 24.798 | 0.759 | 0.903 |
| **Mean** | | | | | | 0.887 | | | | | 0.953 |
| **S-D** | | | | | | 0.051 | | | | | 0.054 |
| **COV** | | | | | | 0.058 | | | | | 0.056 |

Note: $M_p$ = fully plastic bending capacity , $M_{uh}$ = ultimate hogging moment, $M_{us}$ = ultimate sagging moment,
S-D = standard deviation, COV = coefficient of variation

# Statistical analysis - Mean and COV (6/12)

## Modified P-M Formula Method versus CSR ISUM (2/2)



# Statistical analysis - Mean and COV (7/12)

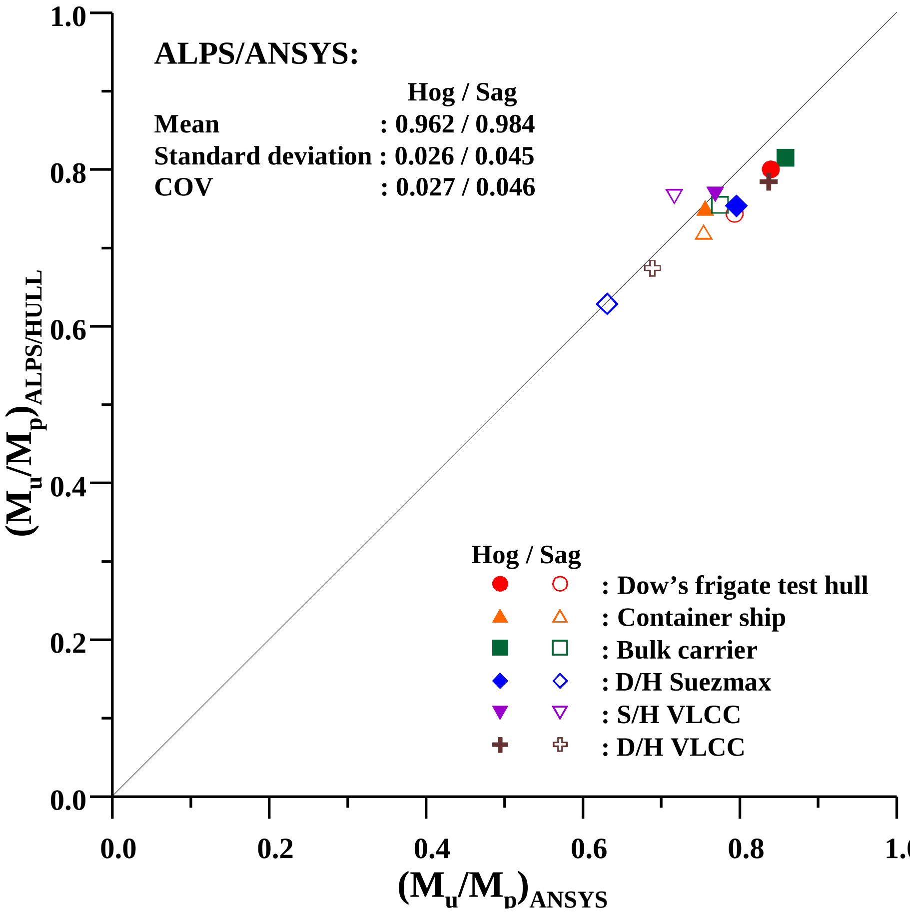
## ANSYS Nonlinear FEA versus ALPS/HULL ISFEM (1/2)

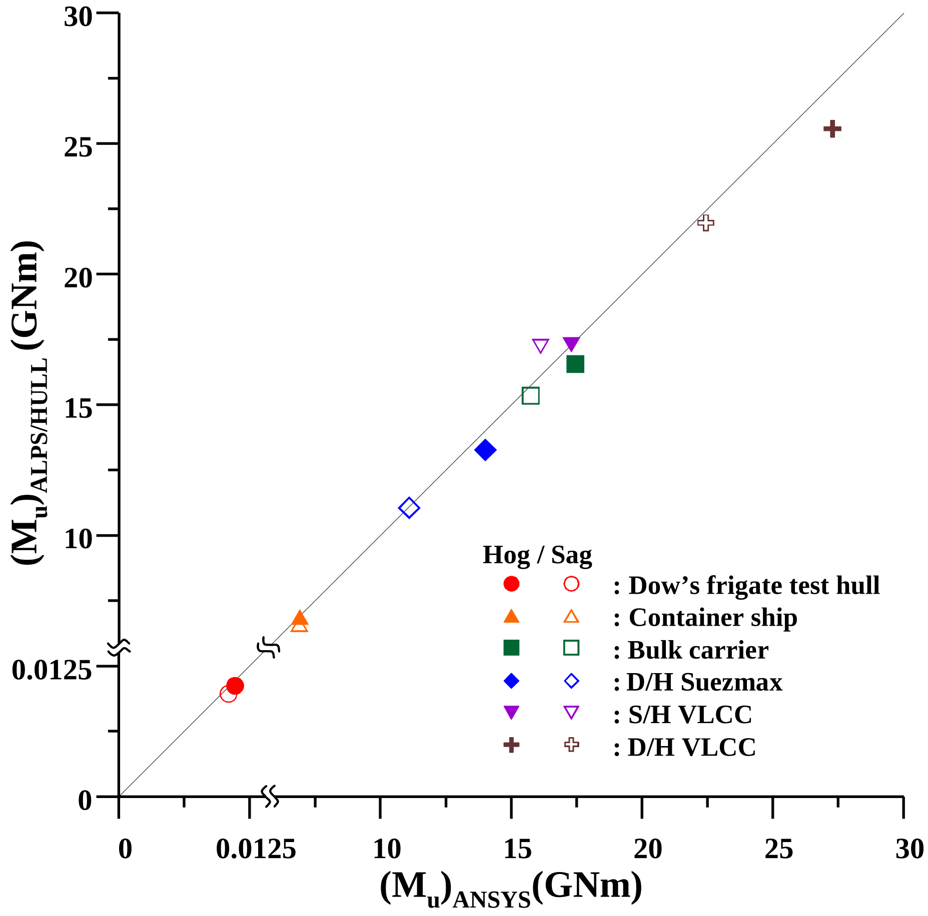
| Ship | $M_p$ (GNm) | Hogging | | | | | Sagging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ANSYS | | ALPS | | ALPS / ANSYS | ANSYS | | ALPS | | ALPS / ANSYS |
| | | $M_{uh}$ (GNm) | $M_{uh}$/ $M_p$ | $M_{uh}$ (GNm) | $M_{uh}$/ $M_p$ | | $M_{us}$ (GNm) | $M_{us}$/ $M_p$ | $M_{us}$ (GNm) | $M_{us}$/ $M_p$ | |
| **Dow's test hull** | 0.013 | 0.011 | 0.840 | 0.011 | 0.799 | 0.952 | 0.011 | 0.793 | 0.010 | 0.743 | 0.936 |
| **Container ship** | 9.220 | 6.969 | 0.756 | 6.916 | 0.750 | 0.992 | 6.951 | 0.754 | 6.635 | 0.720 | 0.955 |
| **Bulk carrier** | 20.394 | 17.500 | 0.858 | 16.602 | 0.814 | 0.949 | 15.800 | 0.775 | 15.380 | 0.754 | 0.973 |
| **D/H Suezmax** | 17.677 | 14.066 | 0.796 | 13.308 | 0.753 | 0.946 | 11.151 | 0.631 | 11.097 | 0.628 | 0.995 |
| **S/H VLCC** | 22.578 | 17.355 | 0.769 | 17.335 | 0.768 | 0.999 | 16.179 | 0.717 | 17.263 | 0.765 | 1.067 |
| **D/H VLCC** | 32.667 | 27.335 | 0.837 | 25.600 | 0.784 | 0.937 | 22.495 | 0.689 | 22.000 | 0.673 | 0.978 |
| **Mean** | | | | | | 0.962 | | | | | 0.984 |
| **S-D** | | | | | | 0.026 | | | | | 0.045 |
| **COV** | | | | | | 0.027 | | | | | 0.046 |

Note: $M_p$ = fully plastic bending capacity , $M_{uh}$ = ultimate hogging moment, $M_{us}$ = ultimate sagging moment,
S-D = standard deviation, COV = coefficient of variation

# Statistical analysis - Mean and COV (8/12)

## ANSYS Nonlinear FEA versus ALPS/HULL ISFEM (2/2)



# Statistical analysis - Mean and COV (9/12)

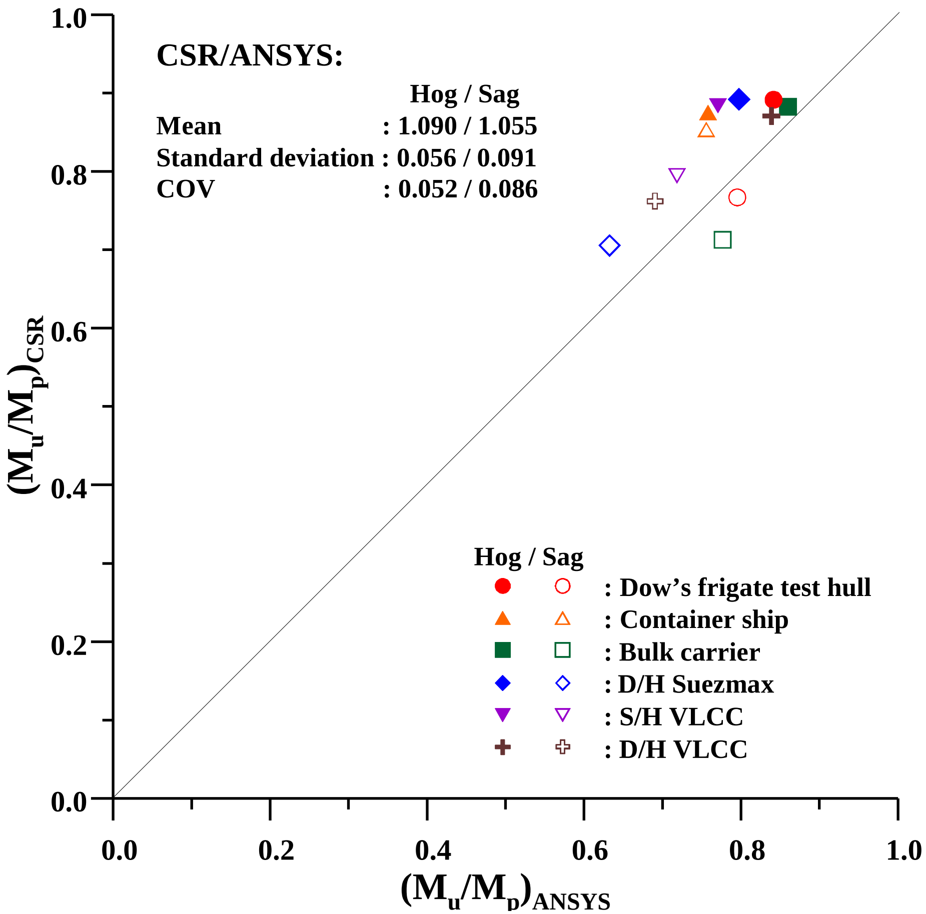
## ANSYS Nonlinear FEA versus CSR ISUM (1/2)

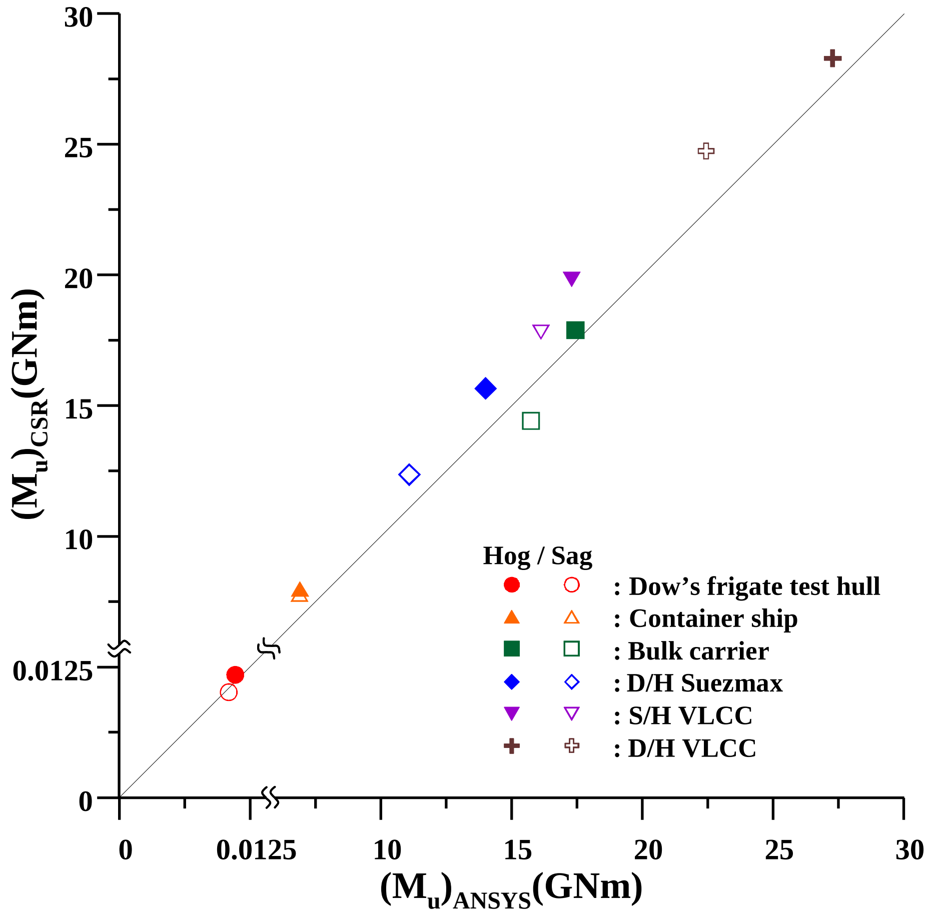
| Ship | $M_p$ (GNm) | Hogging | | | | | Sagging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ANSYS | | CSR | | CSR/ ANSYS | ANSYS | | CSR | | CSR/ ANSYS |
| | | $M_{uh}$ (GNm) | $M_{uh}$/ $M_p$ | $M_{uh}$ (GNm) | $M_{uh}$/ $M_p$ | | $M_{us}$ (GNm) | $M_{us}$/ $M_p$ | $M_{us}$ (GNm) | $M_{us}$/ $M_p$ | |
| **Dow's test hull** | 0.013 | 0.011 | 0.840 | 0.012 | 0.888 | 1.058 | 0.011 | 0.793 | 0.010 | 0.764 | 0.963 |
| **Container ship** | 9.220 | 6.969 | 0.756 | 8.040 | 0.872 | 1.154 | 6.951 | 0.754 | 7.843 | 0.851 | 1.128 |
| **Bulk carrier** | 20.394 | 17.500 | 0.858 | 17.941 | 0.880 | 1.025 | 15.800 | 0.775 | 14.475 | 0.710 | 0.916 |
| **D/H Suezmax** | 17.677 | 14.066 | 0.796 | 15.714 | 0.889 | 1.117 | 11.151 | 0.631 | 12.420 | 0.703 | 1.114 |
| **S/H VLCC** | 22.578 | 17.355 | 0.769 | 19.889 | 0.881 | 1.146 | 16.179 | 0.717 | 17.868 | 0.791 | 1.104 |
| **D/H VLCC** | 32.667 | 27.335 | 0.837 | 28.352 | 0.868 | 1.037 | 22.495 | 0.689 | 24.798 | 0.759 | 1.102 |
| **Mean** | | | | | | 1.090 | | | | | 1.055 |
| **S-D** | | | | | | 0.056 | | | | | 0.091 |
| **COV** | | | | | | 0.052 | | | | | 0.086 |

Note: $M_p$ = fully plastic bending capacity , $M_{uh}$ = ultimate hogging moment, $M_{us}$ = ultimate sagging moment,
S-D = standard deviation, COV = coefficient of variation

# Statistical analysis - Mean and COV (10/12)

## ANSYS Nonlinear FEA versus CSR ISUM (2/2)



# Statistical analysis - Mean and COV (11/12)

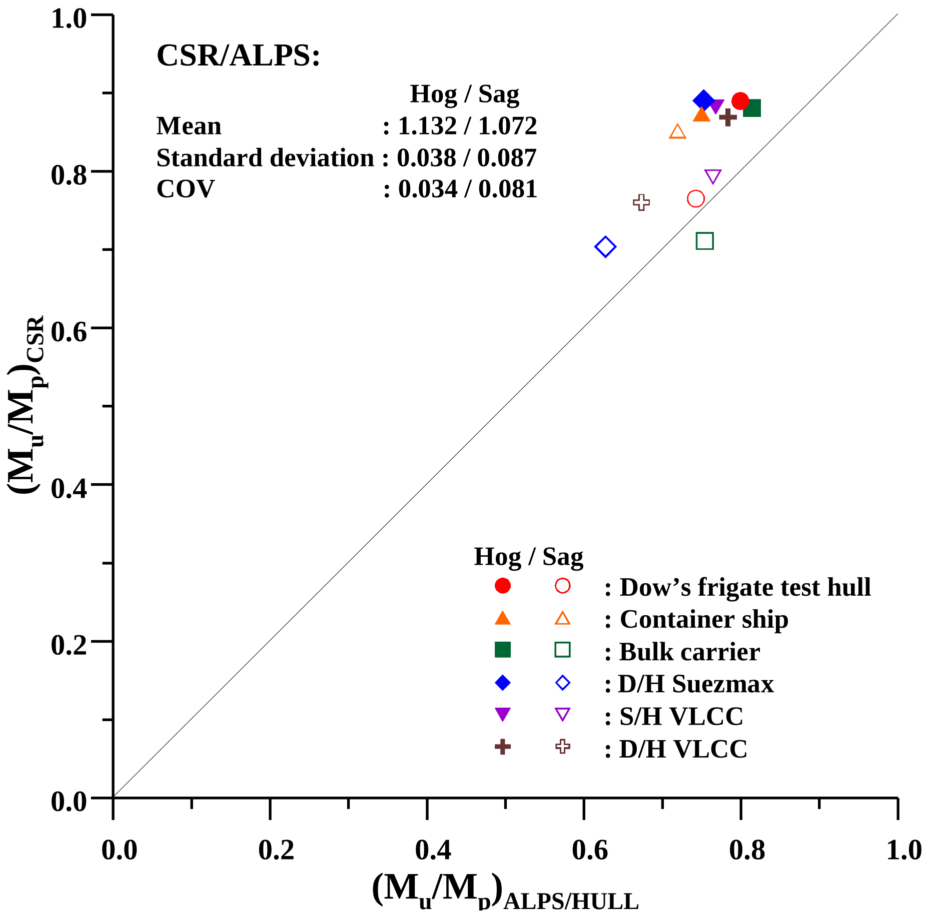
## ALPS/HULL ISFEM versus CSR ISUM (1/2)

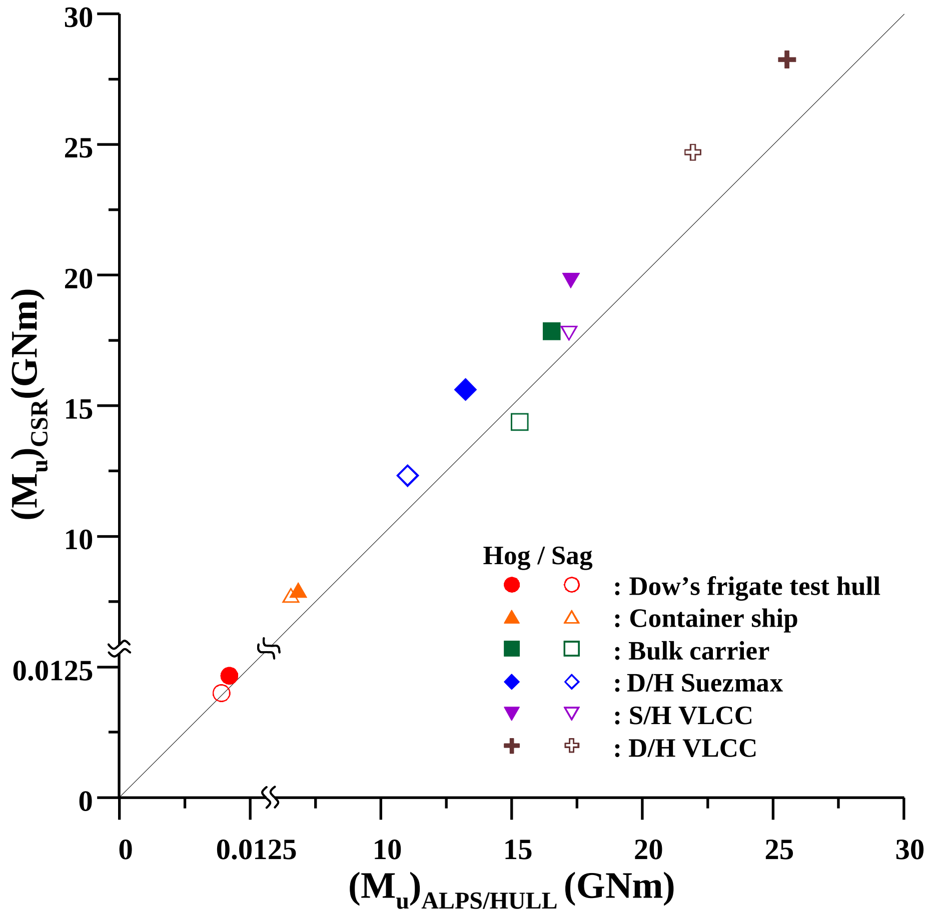
| Ship | $M_p$ (GNm) | Hogging | | | | | Sagging | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ALPS | | CSR | | CSR/ ALPS | ALPS | | CSR | | CSR/ ALPS |
| | | $M_{uh}$ (GNm) | $M_{uh}/M_p$ | $M_{uh}$ (GNm) | $M_{uh}/M_p$ | | $M_{us}$ (GNm) | $M_{us}/M_p$ | $M_{us}$ (GNm) | $M_{us}/M_p$ | |
| **Dow's test hull** | 0.013 | 0.011 | 0.799 | 0.012 | 0.888 | 1.111 | 0.010 | 0.743 | 0.010 | 0.764 | 1.029 |
| **Container ship** | 9.220 | 6.916 | 0.750 | 8.040 | 0.872 | 1.163 | 6.635 | 0.720 | 7.843 | 0.851 | 1.182 |
| **Bulk carrier** | 20.394 | 16.602 | 0.814 | 17.941 | 0.880 | 1.081 | 15.380 | 0.754 | 14.475 | 0.710 | 0.941 |
| **D/H Suezmax** | 17.677 | 13.308 | 0.753 | 15.714 | 0.889 | 1.181 | 11.097 | 0.628 | 12.420 | 0.703 | 1.119 |
| **S/H VLCC** | 22.578 | 17.335 | 0.768 | 19.889 | 0.881 | 1.147 | 17.263 | 0.765 | 17.868 | 0.791 | 1.035 |
| **D/H VLCC** | 32.667 | 25.600 | 0.784 | 28.352 | 0.868 | 1.108 | 22.000 | 0.673 | 24.798 | 0.759 | 1.127 |
| **Mean** | | | | | | 1.132 | | | | | 1.072 |
| **S-D** | | | | | | 0.038 | | | | | 0.087 |
| **COV** | | | | | | 0.034 | | | | | 0.081 |

Note: $M_p$ = fully plastic bending capacity , $M_{uh}$ = ultimate hogging moment, $M_{us}$ = ultimate sagging moment,
S-D = standard deviation, COV = coefficient of variation

# Statistical analysis - Mean and COV (12/12)

## ALPS/HULL ISFEM versus CSR ISUM (2/2)



# Concluding Remarks(1/2)

- Four methods, namely NLFEM (ANSYS), ISFEM(ALPS/HULL), ISUM(CSR method), and Modified P-M formula method have been considered.

- Modified P-M formula method calculations are in good agreement with ANSYS nonlinear FEA and ALPS/HULL progressive collapse simulations.

# Concluding Remarks(2/2)

- Statistical analysis of the hull girder ultimate strength based on comparisons among the various computation is carried out in terms of their mean values and coefficient of variation.

| Ship | Formula/ ANSYS | | Formula/ ALPS | | Formula/ CSR | | ALPS/ ANSYS | | CSR/ ANSYS | | CSR/ ALPS | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hog | Sag | Hog | Sag | Hog | Sag | Hog | Sag | Hog | Sag | Hog | Sag |
| Dow's test hull | 0.920 | 0.879 | 0.966 | 0.939 | 0.870 | 0.912 | 0.952 | 0.936 | 1.058 | 0.963 | 1.111 | 1.029 |
| Container ship | 0.918 | 1.018 | 0.925 | 1.067 | 0.796 | 0.902 | 0.992 | 0.955 | 1.154 | 1.128 | 1.163 | 1.182 |
| Bulk carrier | 0.947 | 0.937 | 0.998 | 0.962 | 0.924 | 1.022 | 0.949 | 0.973 | 1.025 | 0.916 | 1.081 | 0.941 |
| D/H Suezmax | 0.993 | 1.095 | 1.049 | 1.101 | 0.889 | 0.983 | 0.946 | 0.995 | 1.117 | 1.114 | 1.181 | 1.119 |
| S/H VLCC | 1.078 | 1.102 | 1.079 | 1.033 | 0.940 | 0.998 | 0.999 | 1.067 | 1.146 | 1.104 | 1.147 | 1.035 |
| D/H VLCC | 0.939 | 0.995 | 1.003 | 1.018 | 0.905 | 0.903 | 0.937 | 0.978 | 1.037 | 1.102 | 1.108 | 1.127 |
| Mean | 0.966 | 1.004 | 1.003 | 1.020 | 0.887 | 0.953 | 0.962 | 0.984 | 1.090 | 1.055 | 1.132 | 1.072 |
| S-D | 0.061 | 0.088 | 0.055 | 0.061 | 0.051 | 0.054 | 0.026 | 0.045 | 0.056 | 0.091 | 0.038 | 0.087 |
| COV | 0.063 | 0.087 | 0.055 | 0.060 | 0.058 | 0.056 | 0.027 | 0.046 | 0.052 | 0.086 | 0.034 | 0.081 |