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

Lecture 01 Introduction

Professor: Jang, Beom Seon
E-mail : seanjang@snu.ac.kr
Homepage : openlab.snu.ac.kr
Tel : 880-8380
Office : 34-202

Materials

- Mechanics of Material, 7th Edition by James M. Gere
- Ship Structural Design by Owen F. Hughes
- Ultimate Limit State Design of Steel-Plated Structure by Paik
- DNV Rule for Classification of Ships Part 3 Chapter 1, Section 13
- Common Structural Rule

Evaluation

❖ Homework

- Exercises, FE calculations and so on.

❖ Evaluation

- Examination : Open book & Close book

Attendance	Task	Medium	Final	Total
10%	20%	35%	35%	100%

❖ Board

- ETL to be utilized

Lecture Plan

Week	Lecture Contents	Remarks
1 Week	Ultimate Limit State, Material behavior of Steel Structures	
2 Week	Column Buckling	No class due to ISSC on 10th and 12th September
3 Week	Plate Bending, Orthotropic Plate Bending	
4 Week	Understanding of Structural Behavior of COT in CSR Cargo Hold Analysis	
5 Week	Buckling and Ultimate Strength of Beam-Column	
6 Week	Buckling and Ultimate Strength of Plates	
7 Week	Mid Examination	
8 Week	Global Strength Assessment of Offshore Structure and Understanding of Structural Behavior	
9 Week	Elastic and Inelastic Buckling of Stiffened Panels	
10 Week	Ultimate Strength of Stiffened Panels	
11 Week	Ultimate Strength of Hull	
12 Week	Buckling and Ultimate Strength in CSR	
13 Week	Buckling check using Classification rule	
14 Week	Nonlinear Finite Element Analysis	
15 Week	Final Examination	

Purpose of Course

- ❖ **Understanding of buckling and ultimate strength, one of the most important subjects in the assessment of ship and offshore structure.**

- ❖ **Understanding of a basic plate & buckling theory, semi-analytical approaches for ultimate strength and practical method to assess ultimate strength using nonlinear FE analysis.**

- ❖ **Understanding of structural behavior of vessels and offshore structures under environmental load.**

- ❖ **Understanding buckling and ultimate strength in terms of the structural behavior.**

- ❖ **Practice of buckling check and ultimate strength assessment using FE analysis**

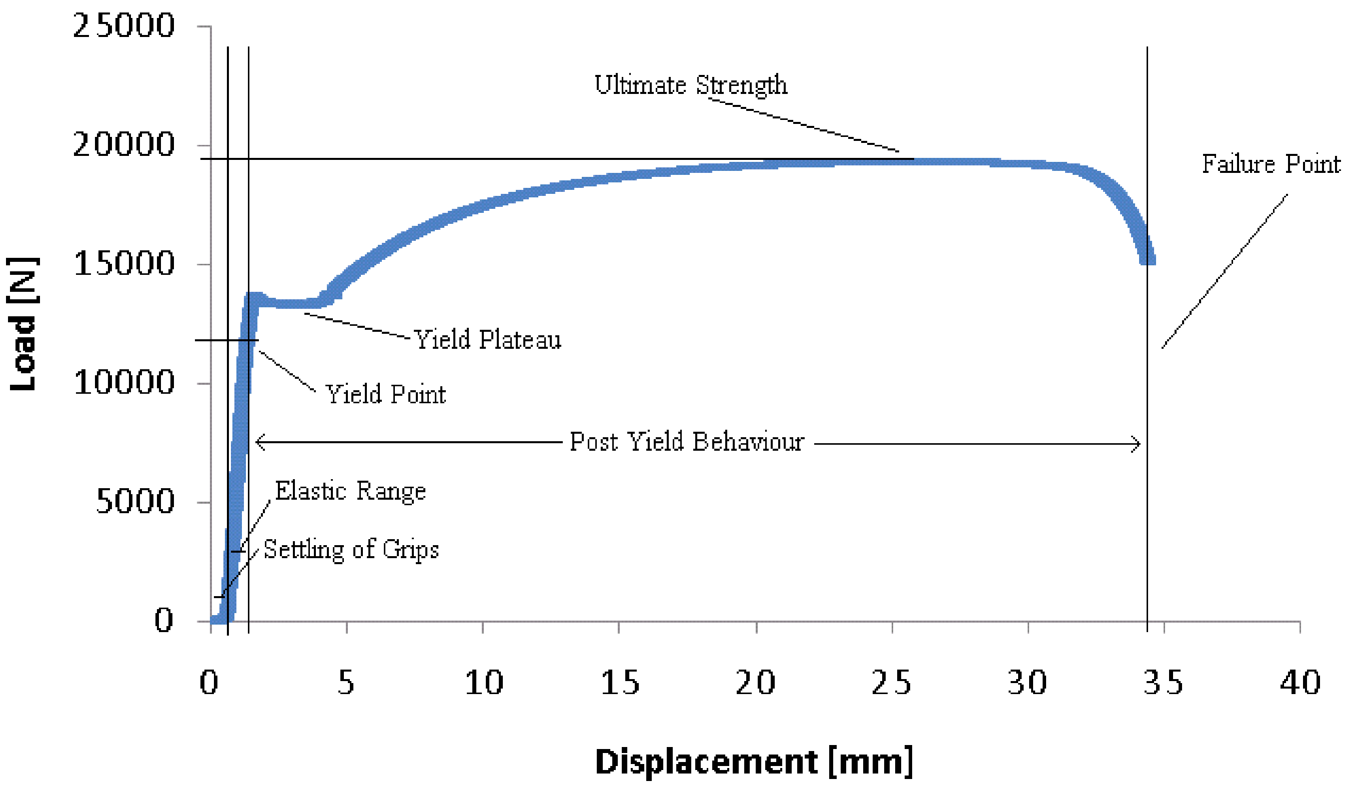
Contents

- General
- Concept of Buckling, Post buckling, Ultimate Strength
- Types of Buckling and Ultimate Strength in a Vessel
- Principles of Limit State Design
- Material Behavior of Structural Steels

General

General – Material Yield

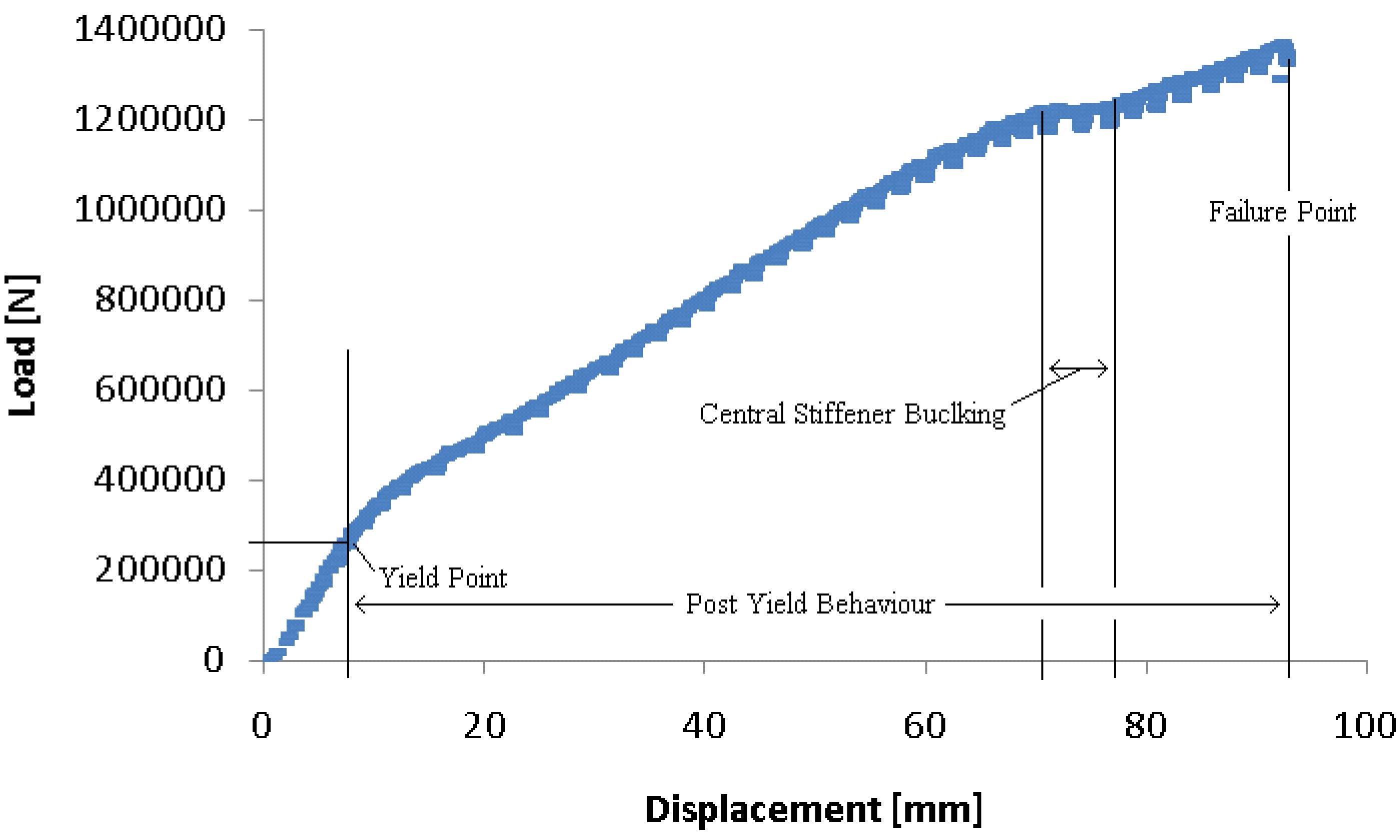
❖ **Material load v.s. Deflection curve**



General - Structural Yield

❖ Structural load v.s. Deflection plot

: structural load and deflection parameters are generally gross parameters :e.g. the deflection at the centre of a grillage vs. the load applied to the whole grillage.



General

❖ **A general load-deflection curve for a ductile steel structure**

- Yielding takes place partly.
- Redistribution of stress occurs as the plastic strain field grows.
- The linear potion of the curve ends when the strain field can redistribute no more and a mechanism (eg. hinge) is formed.
- After this the structure may continue to support further load increase, now in a new way (e.g. by membrane behavior).
- Start a new redistribution process and lead to another mechanism

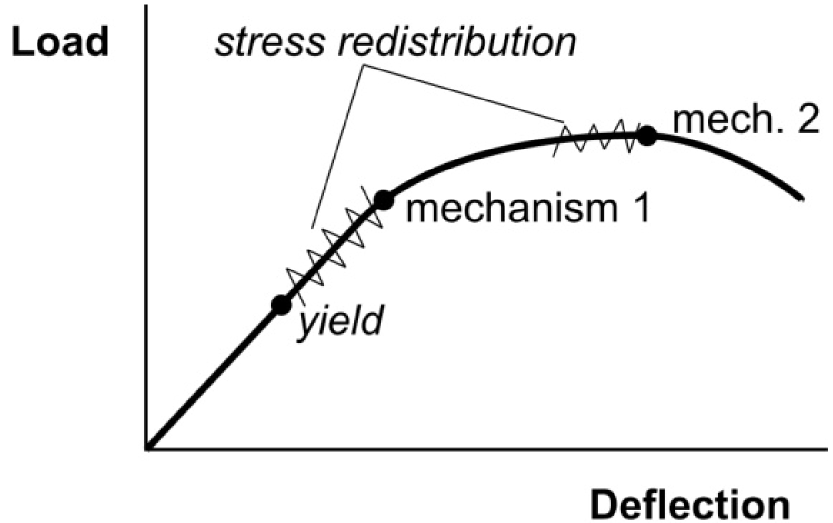


Figure 1 (alternate)

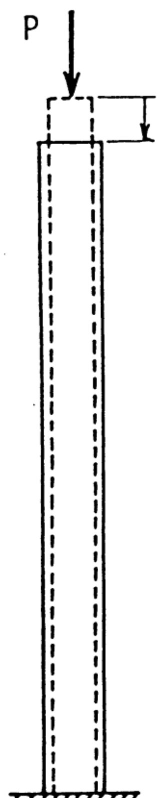
Concept of Buckling, Post buckling, Ultimate Strength

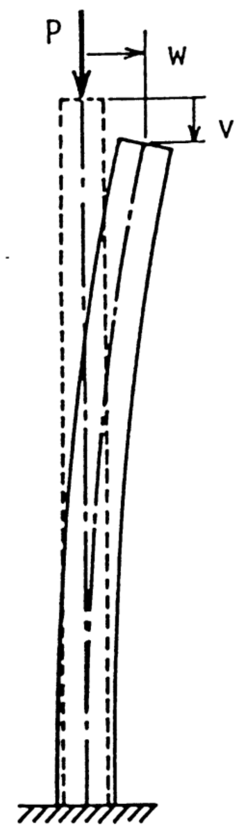
General - Occurrence of Buckling

When compressive stress reaches critical value

Occurrence of Buckling

Axial def. **Axial def.+ Bending def.**





Concept of Buckling

❖ Buckling in a strict sense

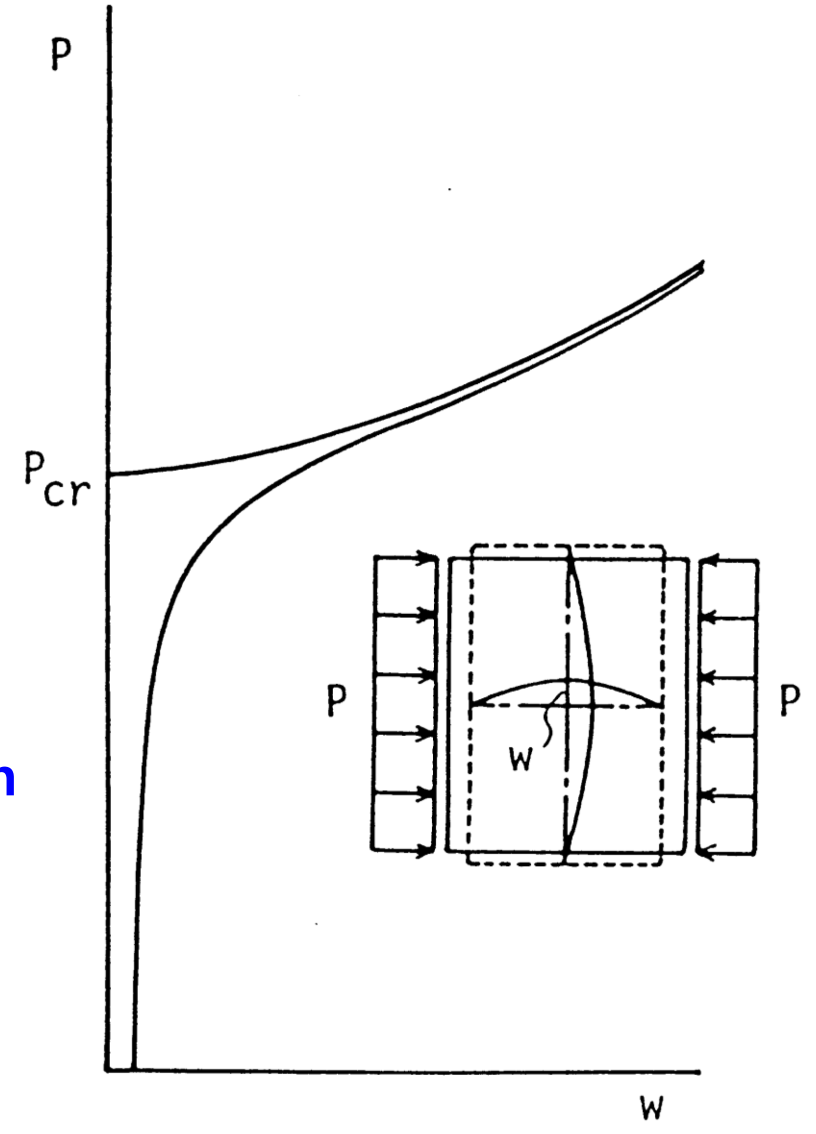
Axial def.

⇩

Bifurcation point

⇩

Axial def. + Bending def.



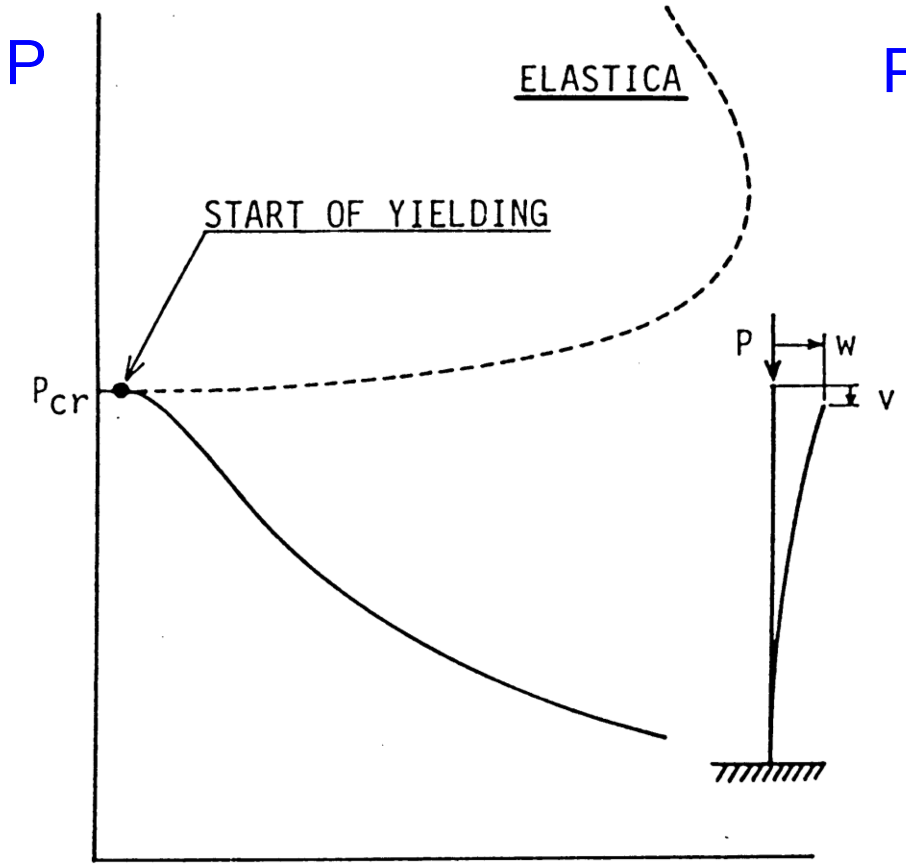
❖ Buckling in a wide sense

(When initial deflection is accompanied)

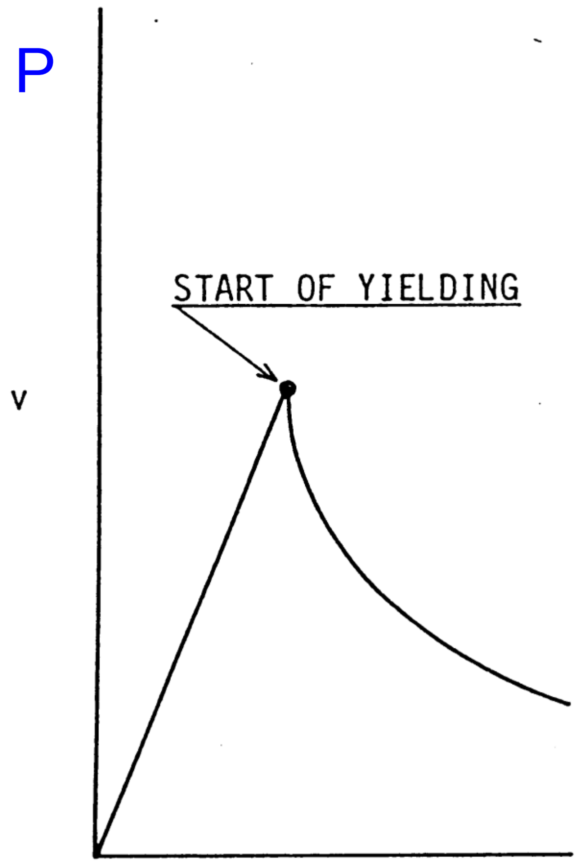
- Strictly saying, no bifurcation
- deflection rapidly increases as th e load approaches buckling load when initial deflection is small.

Post-buckling Behaviour

❖ One-dimensional member: Axially compressed column



Stress-deflection w

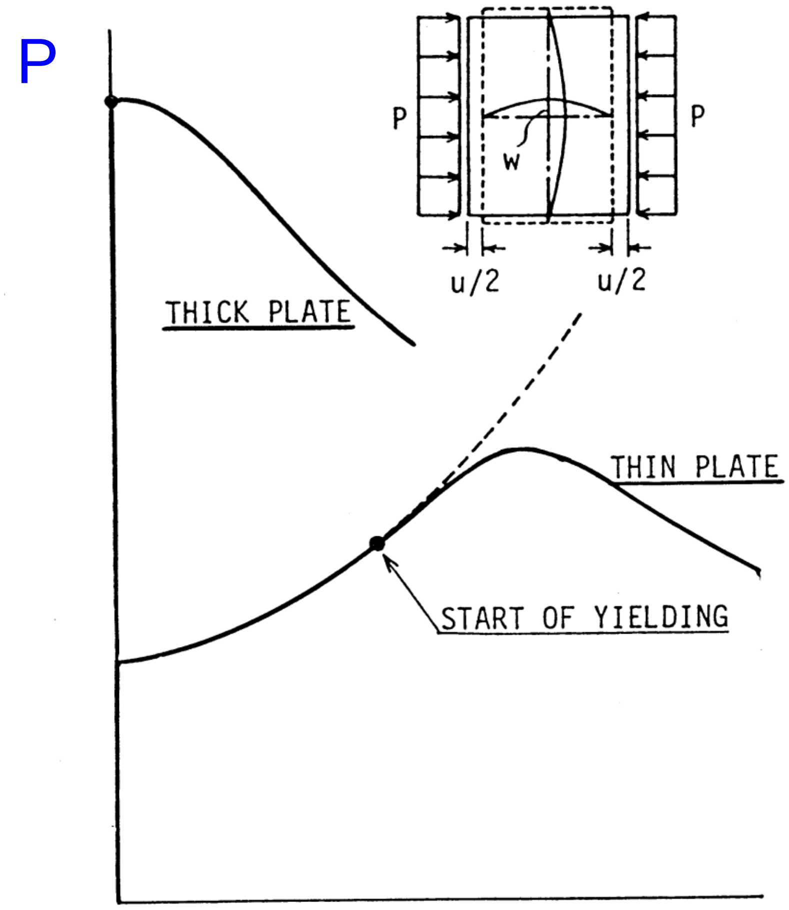


Stress-strain v

Post-buckling Behaviour

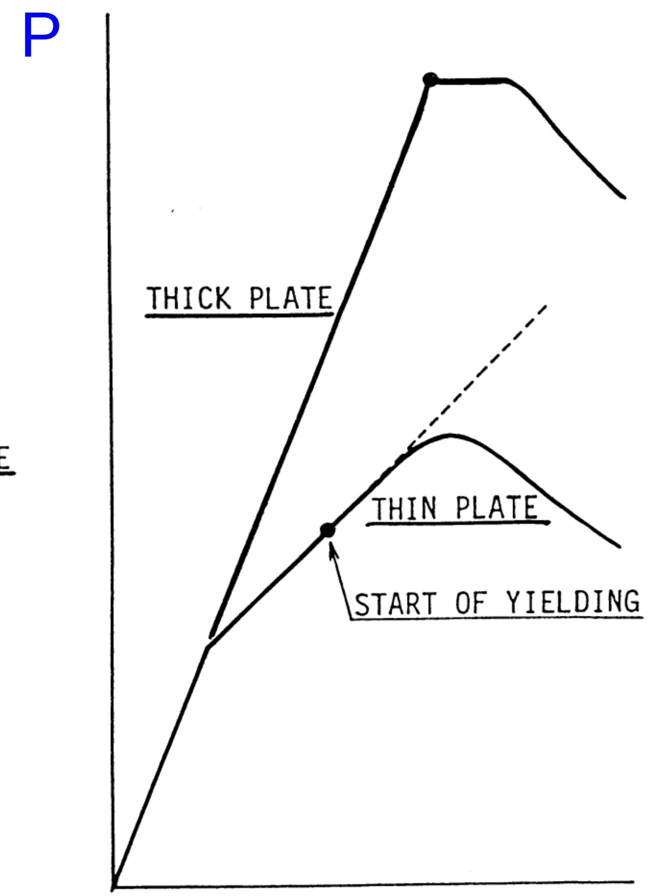
❖ **Two-dimensional member: Rectangular plate under thrust**

Q : deflection v.s. strain ?



Stress-deflection

w



Stress-strain

u

Buckling/plastic collapse behavior of stiffened plate subjected to thrust

❖ Case A:

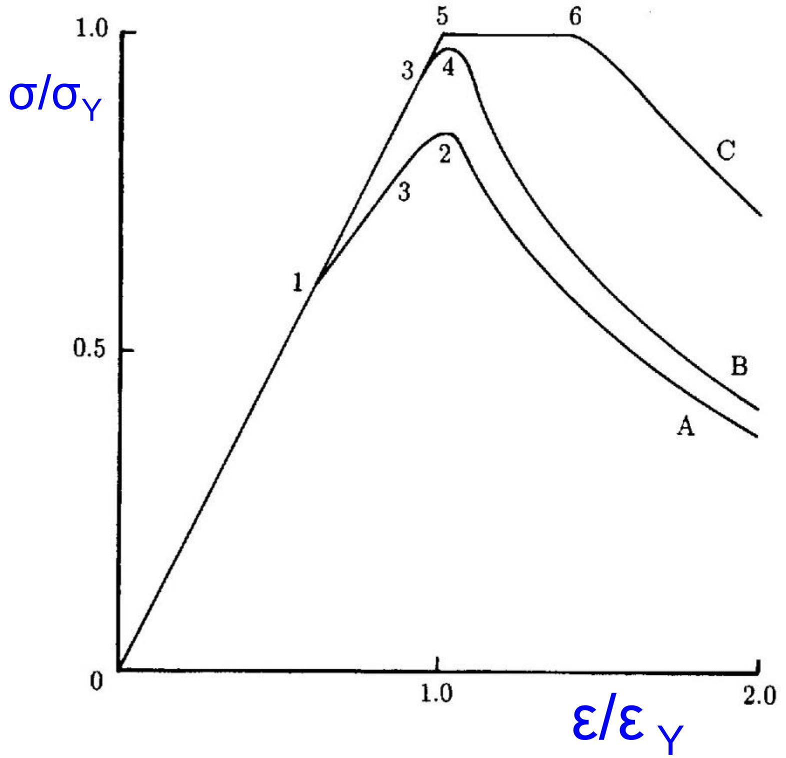
- Overall collapse by elastic buckling after elastic panel buckling

❖ Case B:

- Overall collapse by elasto-plastic buckling after elasto-plastic panel buckling

❖ Case C:

- Overall collapse by plastic buckling after general yielding

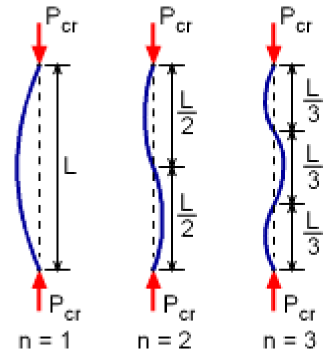


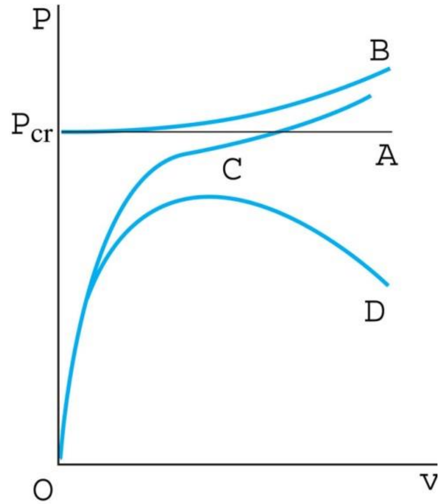
Types of Buckling and Ultimate Strength in a Vessel

Buckling & Ultimate Strength I

❖ Column buckling

- Elastic buckling
- Inelastic buckling



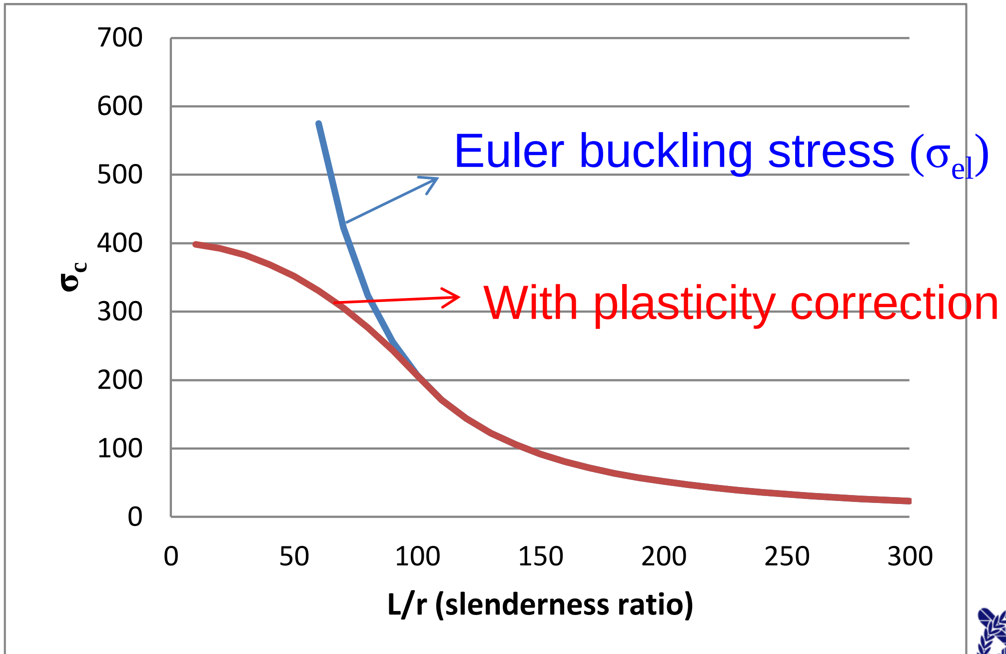


Classification Rule

$$\sigma_c = \sigma_{el} \quad \text{when} \quad \sigma_{el} < \frac{\sigma_f}{2}$$

$$= \sigma_f \left(1 - \frac{\sigma_f}{4\sigma_{el}}\right) \quad \text{when} \quad \sigma_{el} > \frac{\sigma_f}{2}$$

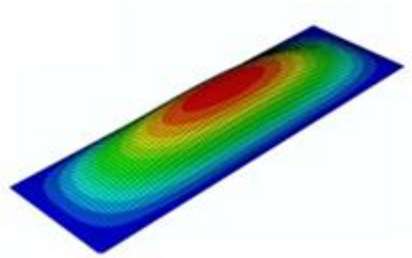
$$\boxed{\sigma_{el} = \frac{\pi^2 E I_A}{A L^2} = \frac{\pi^2 E}{(L/r)^2}}$$

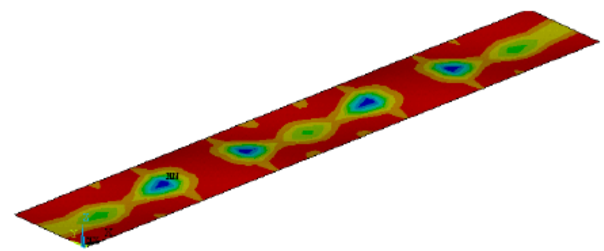


Buckling & Ultimate Strength II

❖ Unstiffened Plate (Plating between stiffeners)

- Elastic and Inelastic Buckling
- Post-Buckling and Ultimate strength





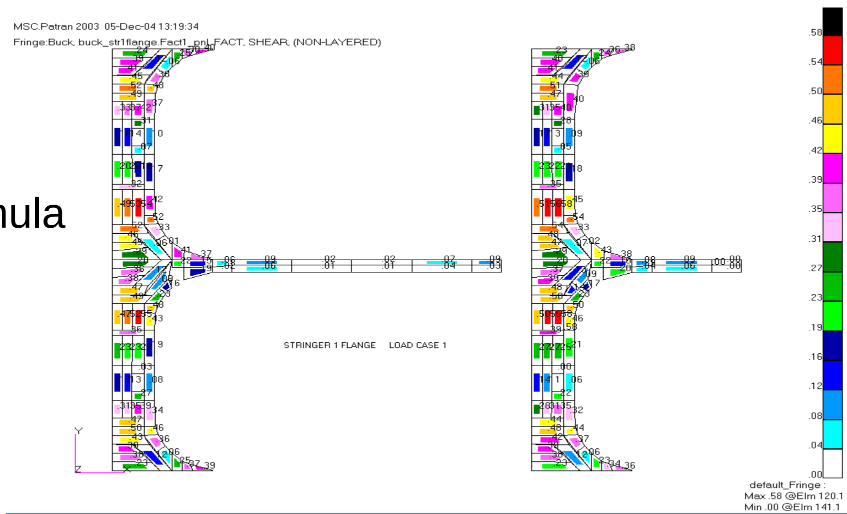
Classification Rule

Johnson-Ostenfeld plasticity correction formula

$$\sigma_c = \sigma_{el} \quad \text{when} \quad \sigma_{el} < \frac{\sigma_f}{2}$$

$$= \sigma_f \left(1 - \frac{\sigma_f}{4\sigma_{el}}\right) \quad \text{when} \quad \sigma_{el} > \frac{\sigma_f}{2}$$

$$\sigma_{el} = 0.9\mathrm{kE}\left(\frac{t-t_k}{1000s}\right)^2 \ (N/mm^2)$$

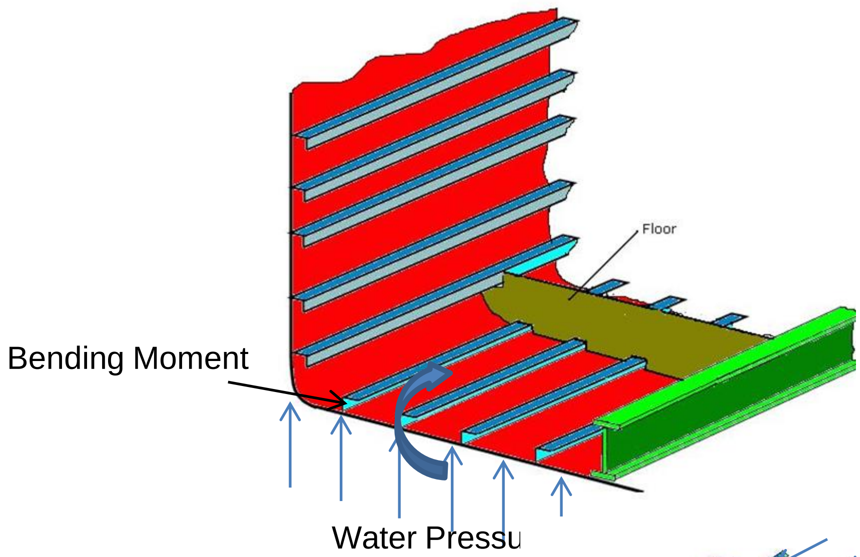


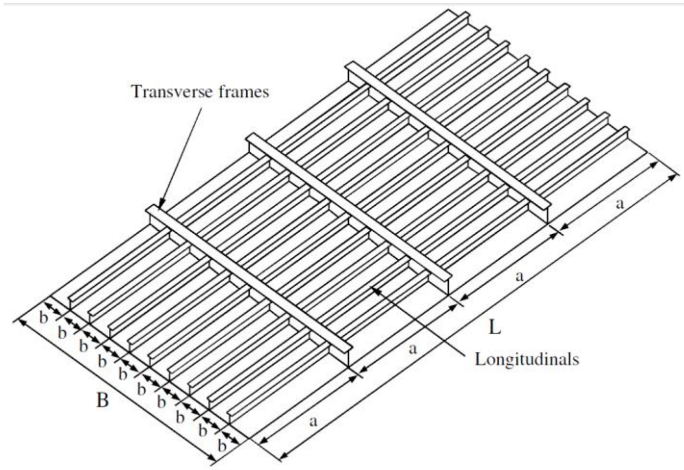
Example of Buckling check in accordance with Classification Rule

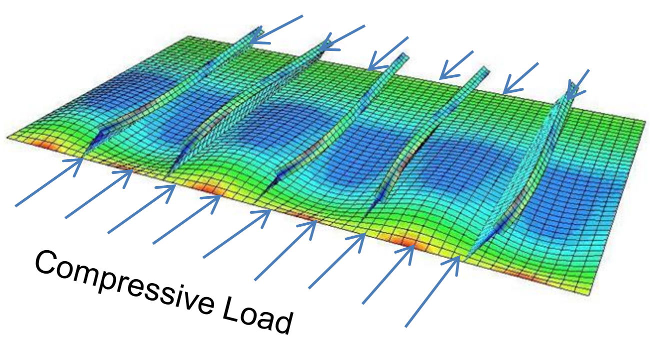
Stiffened Plate in Hull Structure

❖ Resist against bending moment induced by out-of-plane pressure

❖ Resist against in-plane compressive load



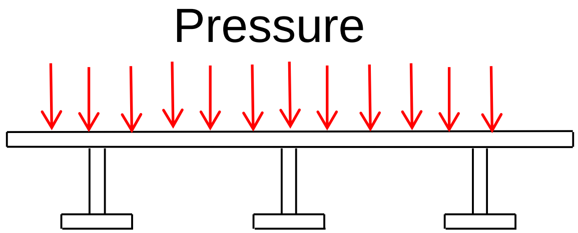


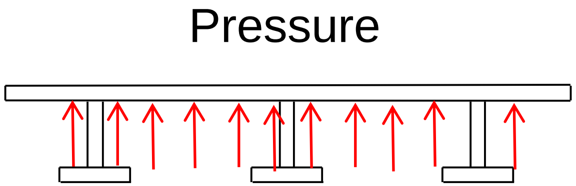


Buckling of Stiffened plate

Cargo Hold Example - Question?

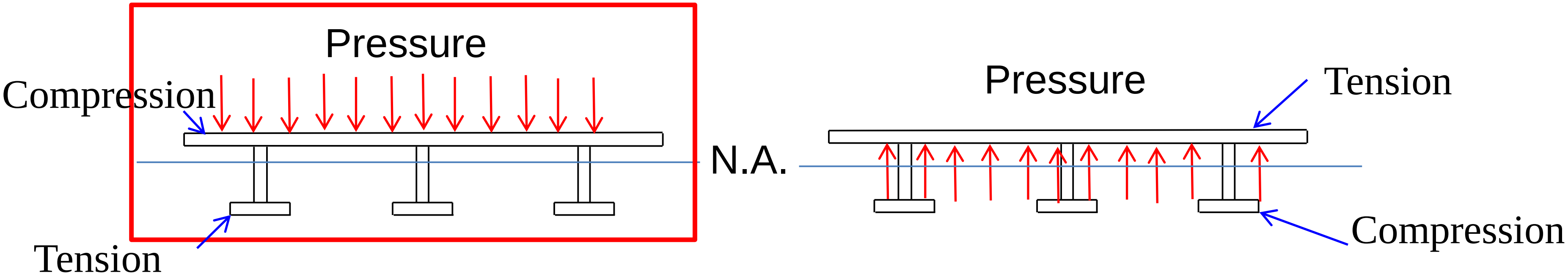
❖ **Which pressure induce buckling of plating?**



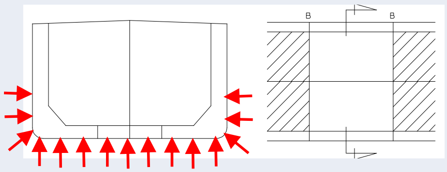


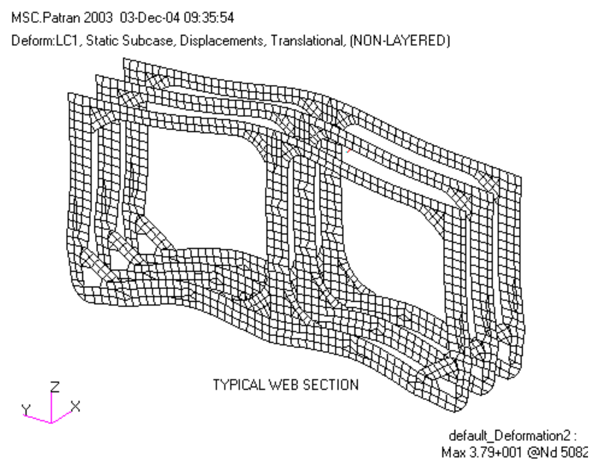
Cargo Hold Example - Answer

❖ Which pressure induce buckling of plating?



Cargo Hold Example

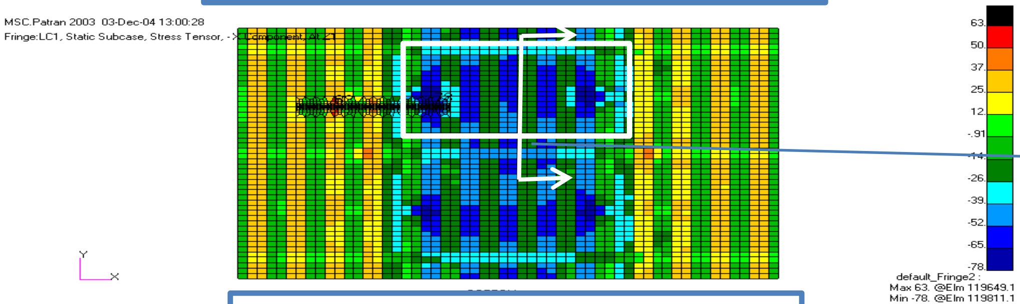
Loading	Draught	Ext. Press	Int. Press
	T_{scant}	Dynamic	Static

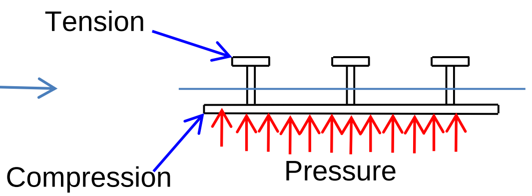


Cargo Hold Example - Result

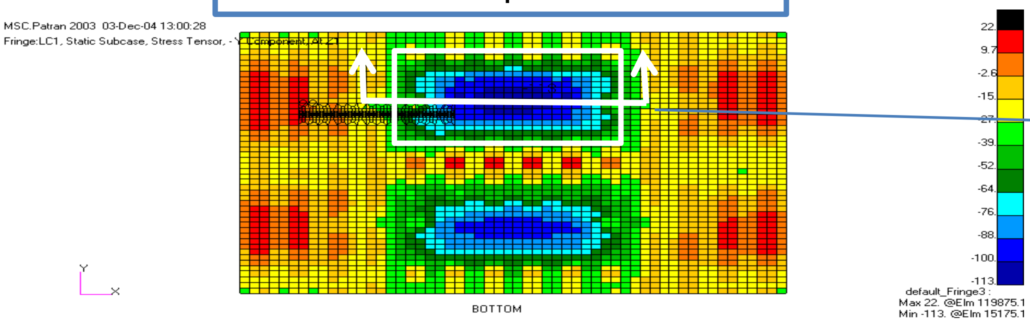
Bottom Plate

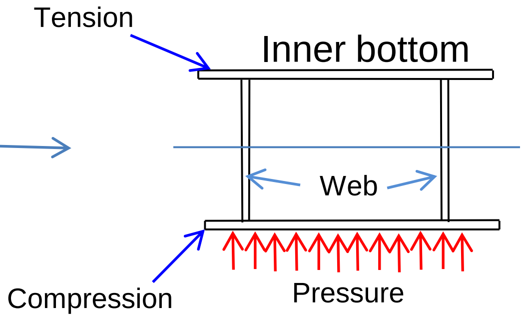
Longitudinal compressive stress

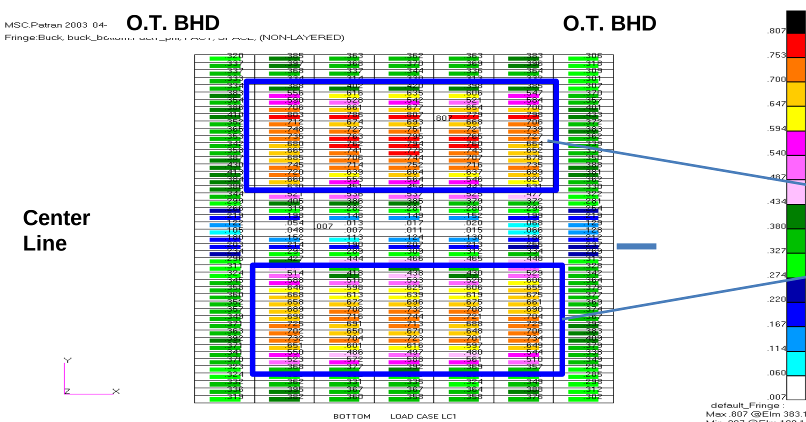




Transvers Compressive stress







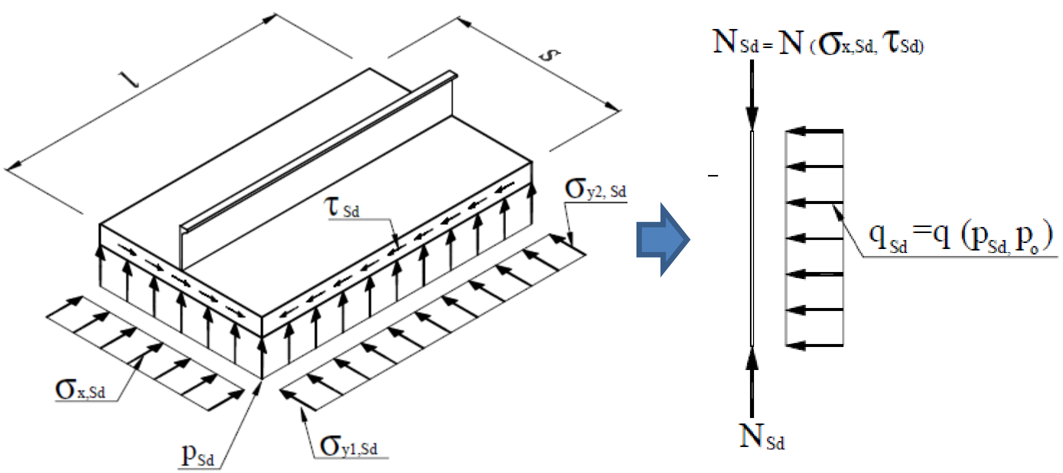
High compressive stress

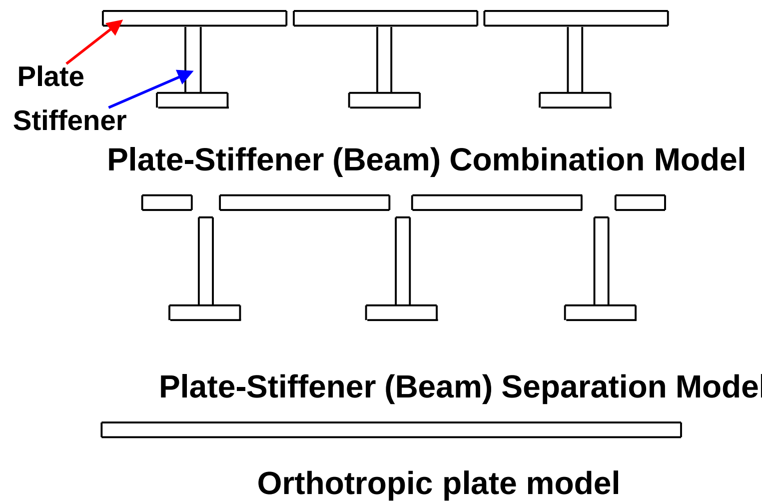
→ High Buckling factor

Buckling & Ultimate Strength III

❖ Buckling of Plate-Stiffener Combination (DNV RP C201)

- Stiffener with associated effective plate flange
- Effective width of plate flange accounts for biaxial compression or compression-tension
- Transverse stress and shear gives added lateral pressure

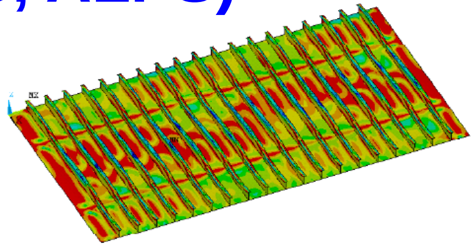




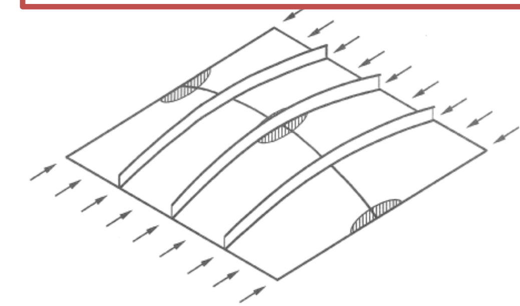
Buckling & Ultimate Strength III

❖ Buckling of Stiffened Plate (DNV PULS, ALPS)

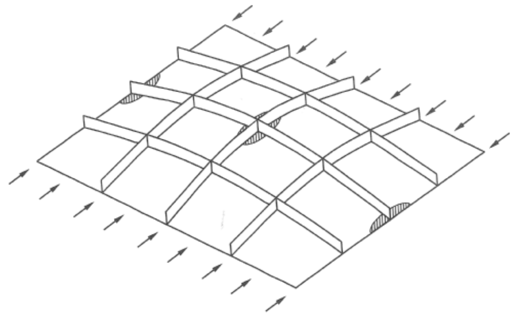
- Elastic and Inelastic buckling
- Post –buckling and Ultimate strength



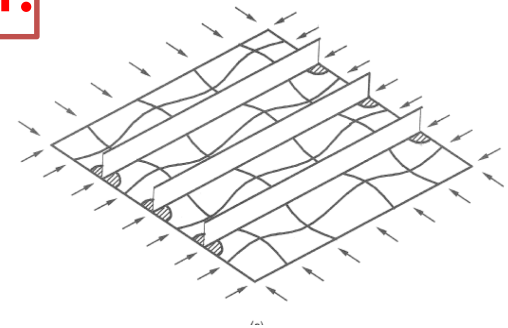
Q: Which one is the most common?



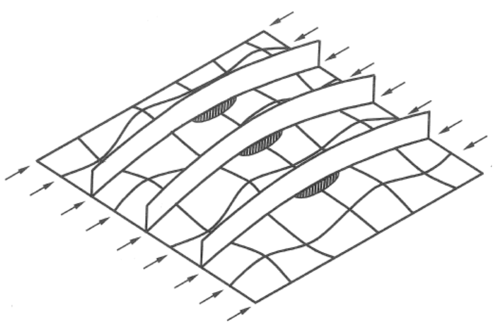
Mode I-1: Overall collapse of a uniaxially stiffened panel



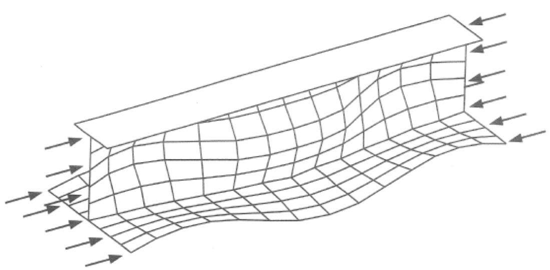
Mode I-2: Overall collapse of a cross-stiffened panel



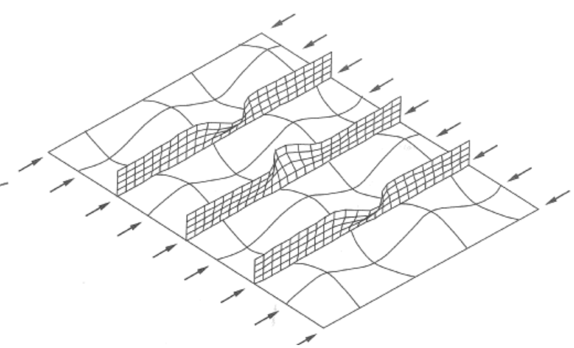
Mode II: Plate induced failure - yielding at the corners of plating between stiffeners



Mode III: Plate induced failure - yielding of plate-stiffener combination at mid-span



Mode IV: Stiffener induced failure - local buckling of the stiffener web



Mode V: Stiffener induced failure - lateral-torsional buckling of stiffener

Buckling & Ultimate Strength IV

❖ Ultimate strength of Hull (CSR Rule, MAESTRO)

Progressive buckling/plastic collapse

Decrease in rigidity of buckled members

⬇

Increase in stress in un-buckled members due to stress re-distribution

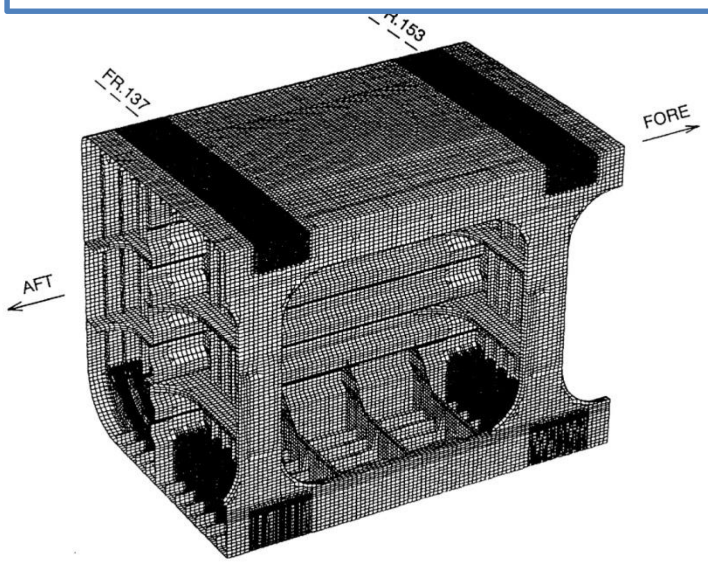
⬇

Progressive occurrence of buckling/plastic collapse in structural members

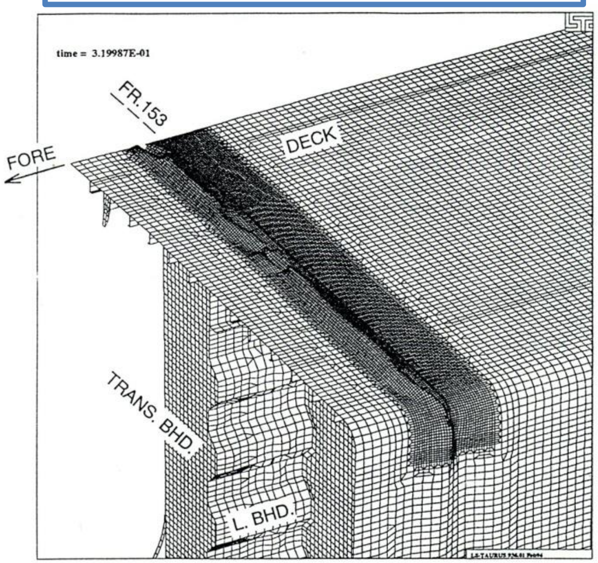
⬇

Buckling/plastic collapse of whole structure

Nonlinear FE analysis considering both Buckling and Yielding



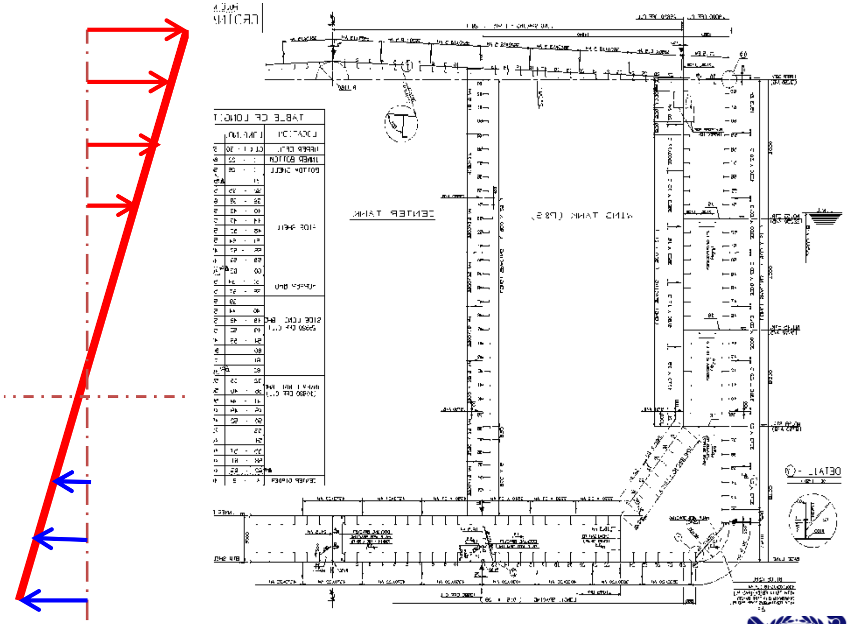
Buckling at deck plating under sagging moment



Progressive Failure of Crude Oil Tank

- **Section modulus of upper deck is smaller than bottom**
- **High compressive stress occurs when sagging**
- **Stiffened plate is prone to buckling subjected to compressive stress**
- **Progressive failure**

High compressive stress at Upper Deck



Principles of Limit State Design

Reference : Ultimate Limit State Design of Steel-Plated Structures
Ch.1 Principles of Limit State Design

1.1 Design Philosophies for Steel Structures

❖ Allowable stress design

- ✓ to keep actual stresses under a certain working level that is based on successful similar past experience (e.g. 85% of yield stress)

❖ Limit state design

- ✓ based on explicit consideration of the various considerations under which the structure ceases to fulfill its intended function.
- ✓ more refined computations such as nonlinear elastic-plastic large-deformation FE analyses.
- ✓ appropriate modeling related to geometric/material properties, initial imperfections, boundary condition, load application, etc.
- ✓ Ultimate Limit State (ULS)
- ✓ Fatigue Limit State (FLS)
- ✓ Accidental Limit State (ALS)

Q: material nonlinear v.s. geometric nonlinear?

1.1 Design Philosophies for Steel Structures

❖ **The partial safety factor (γ_{fi}, γ_0, γ_m, γ_c) based design criterion for a structure**

- **Demand (≈Load) < Capacity (≈ strength)**

$$D_d < C_d \quad \text{or} \quad \text{safety measure} = C_d / D_d > 1$$

$$D_\mathrm{d} = \underline{\gamma_0} \sum_i \underline{D_{\mathrm{k}i}} (\underline{F_{\mathrm{k}i}} , \underline{\gamma_{\mathrm{f}i}})$$

- γ_{fi}: Uncertainties related to loads
- F_{ki}: Characteristic measure of load
- D_{ki}: Characteristic measure of demand
- γ_0: The seriousness of economical and social consequences

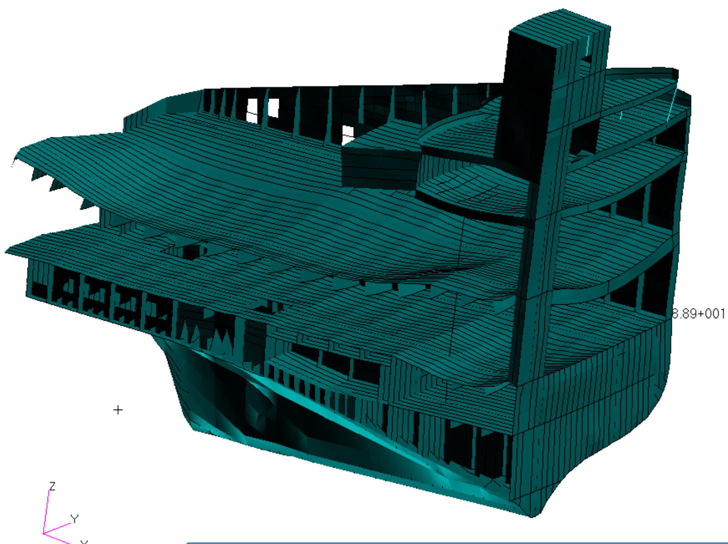
$$C_\mathrm{d} = \underline{C_\mathrm{k}} / \underline{\gamma_\mathrm{m}} \underline{\gamma_\mathrm{c}}$$

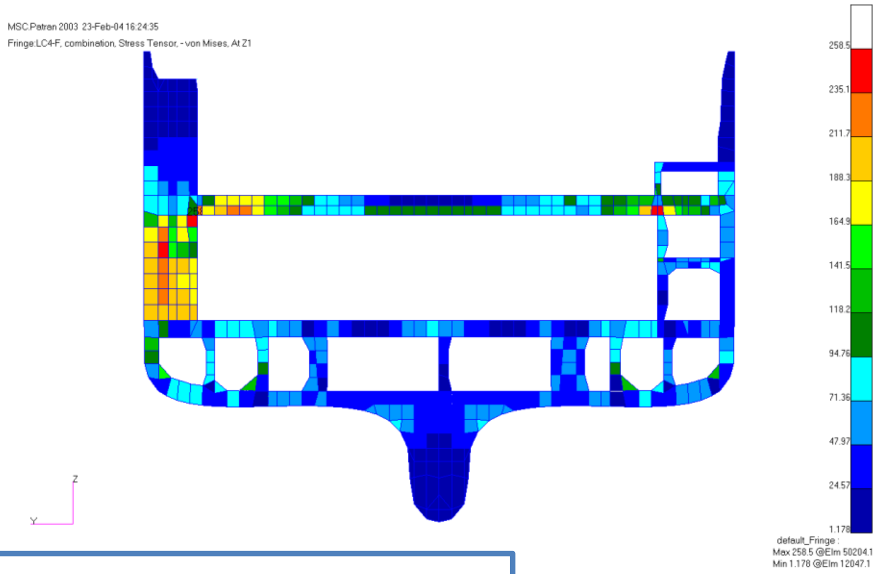
- γ_c: The uncertainties on the capacity of structure
- γ_m: Uncertainties in material property
- C_k: Characteristic measure of capacity

1.1 Design Philosophies for Steel Structures

❖ Serviceability limit state (SLS)

- Local damage which reduces the durability of the structure
- Unacceptable deformations causing discomfort or affect the proper function of equipment
- Deformation and deflection spoiling the aesthetic appearance



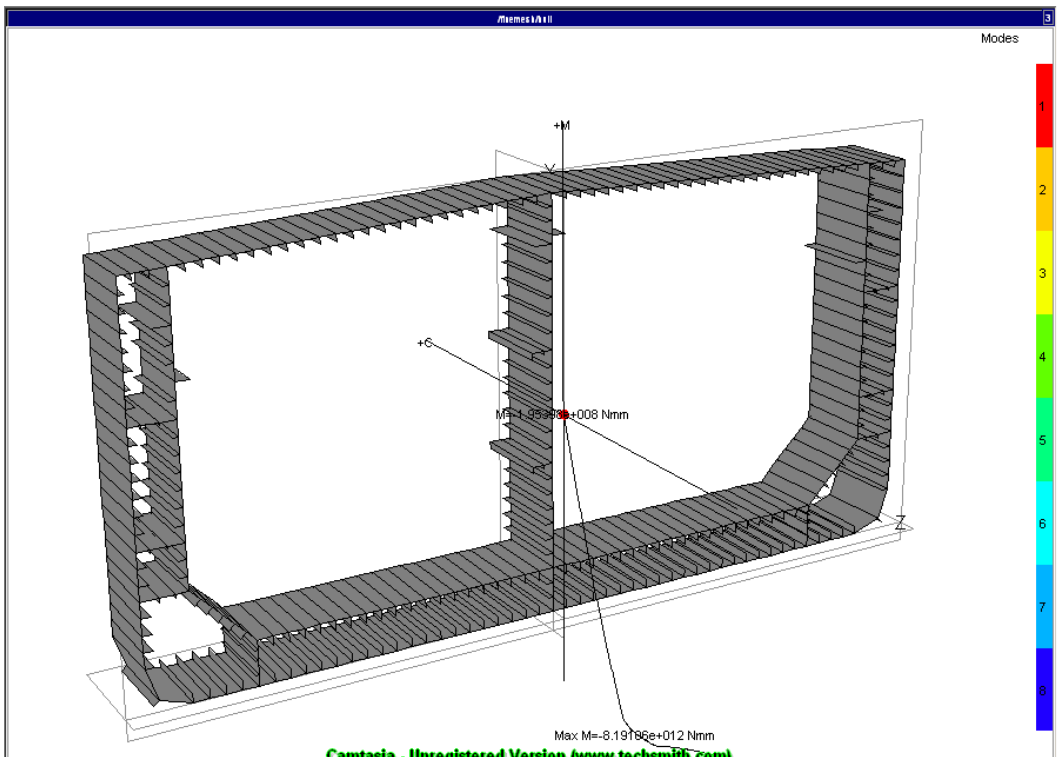


Ropax (Ro-Ro & Passenger ship) example

1.1 Design Philosophies for Steel Structures

❖ Ultimate Limit State (ULS)

- Loss of equilibrium in part or of entire structure
- Attainment of the maximum resistance of structural regions
- Instability in part or of the entire structure resulting from buckling and plastic collapse of plating, stiffened panels and support members.
- elastic-plastic buckling collapse

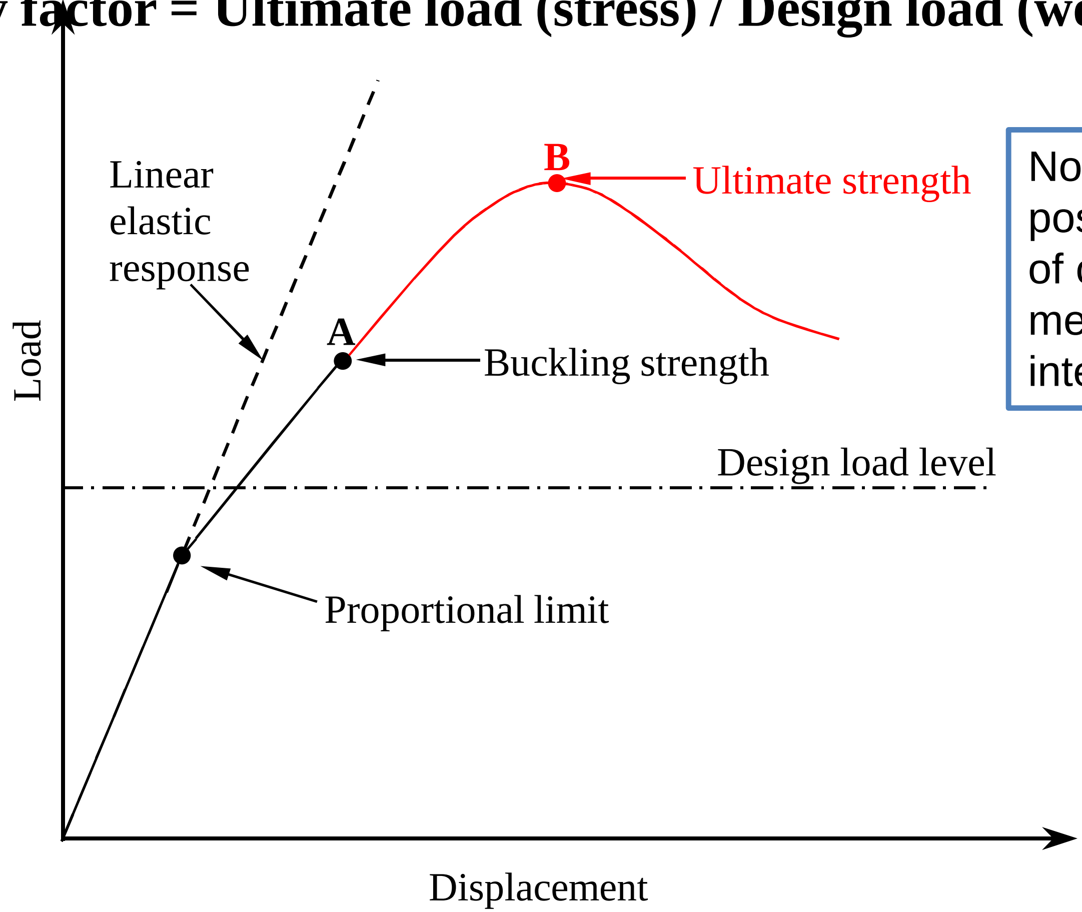


1.2 Considerations in Limit State Design

❖ Necessity of Ultimate State

- Point A : Elastic buckling strength with plasticity correction
- Point B : Ultimate strength considering post-buckling behavior

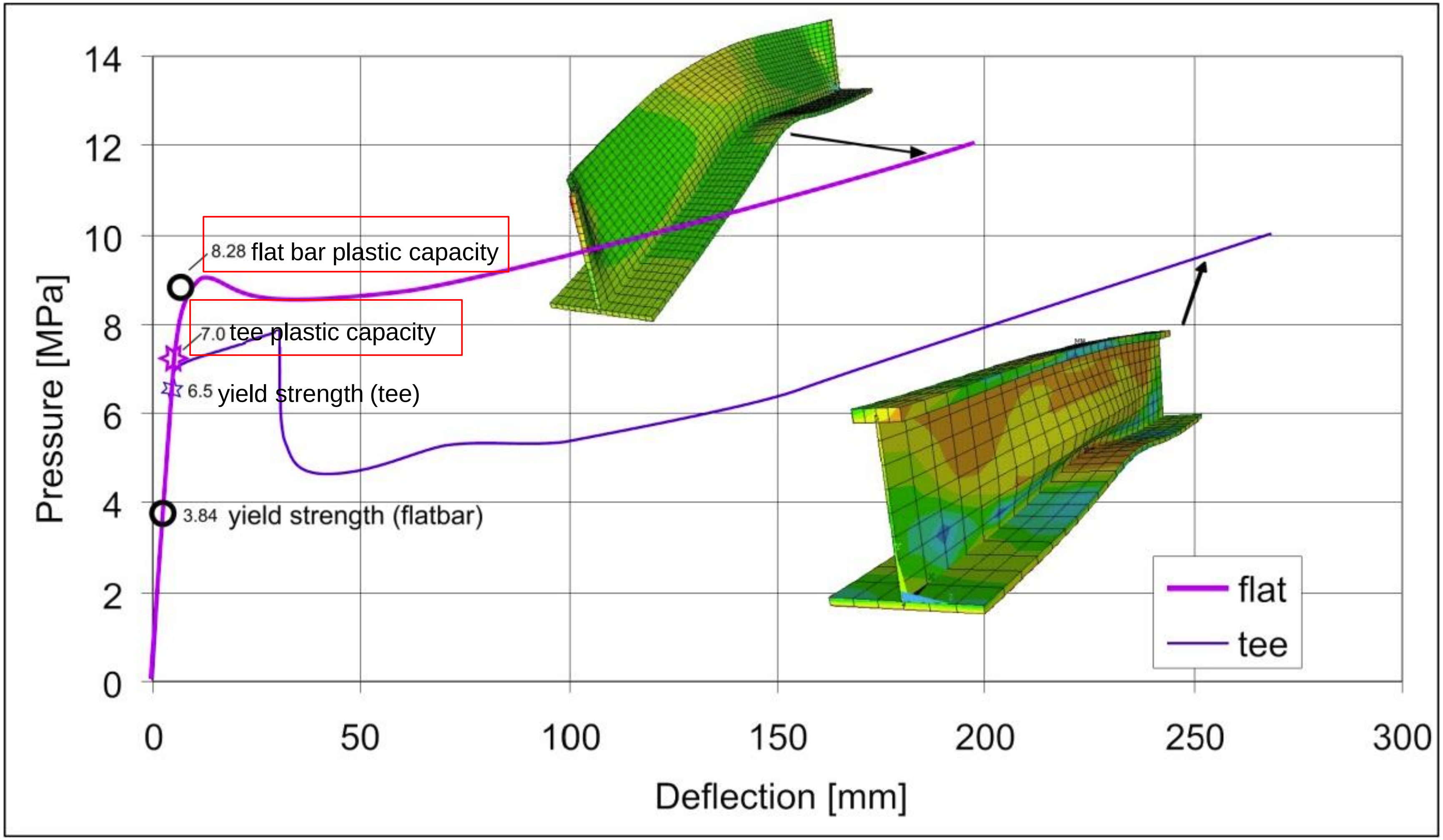
Safety factor = Ultimate load (stress) / Design load (working stress)



No information on the post buckling behavior of component members and their interaction.

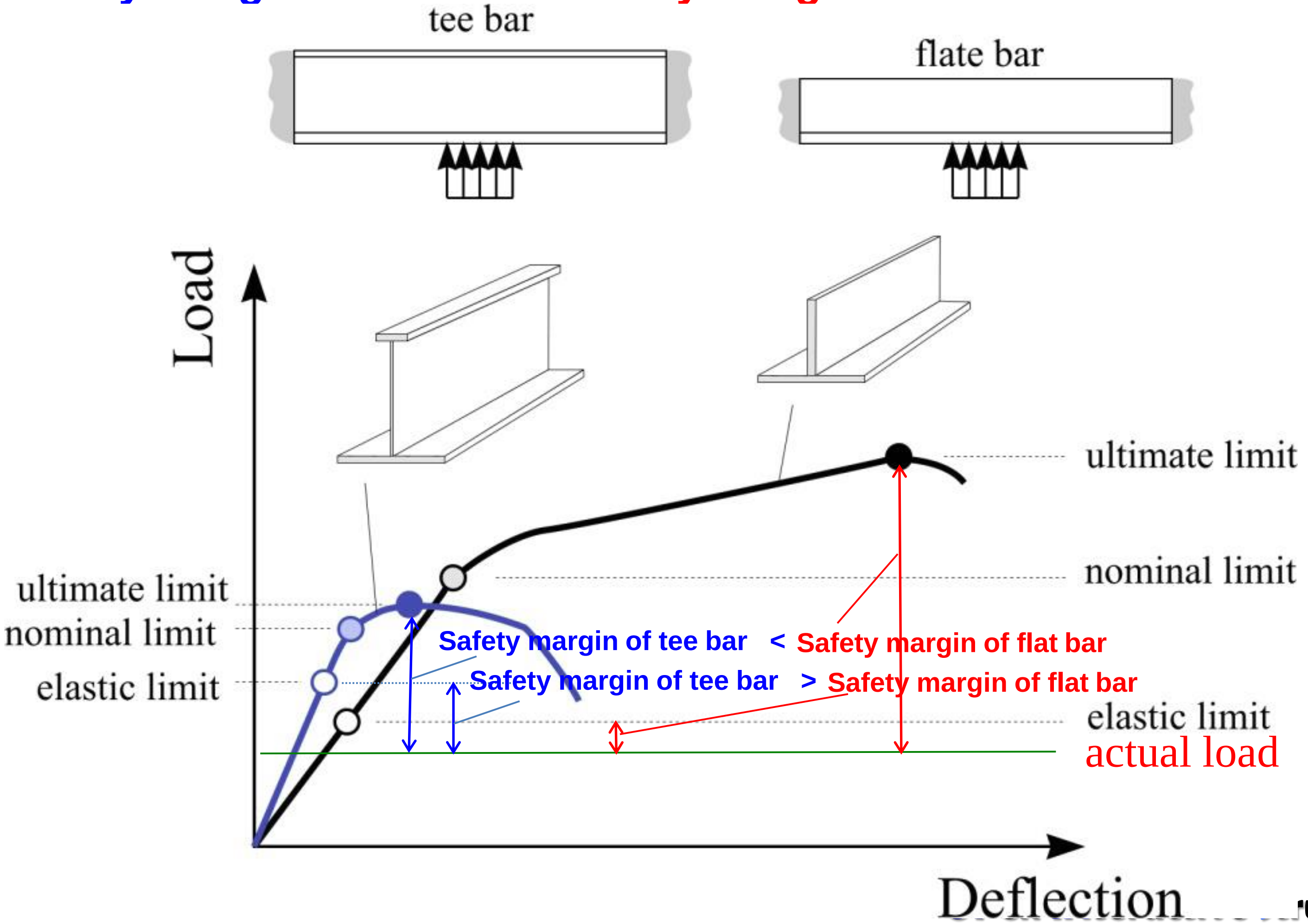
Illustrating example I

❖ Flat bar v.s. tee bar stiffener



Illustrating example II

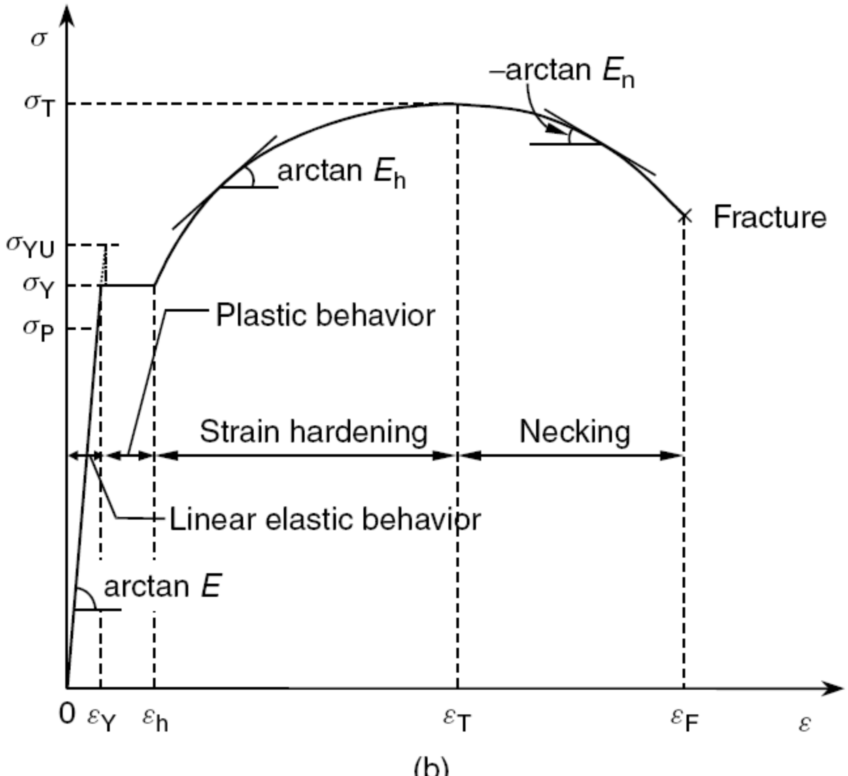
- Tee bar is optimized in terms of elastic limit
  ⇒ Safety margin of tee bar > Safety margin of flat bar
- However, in terms of ultimate limit
  Safety margin of tee bar < Safety margin of flat bar



Material Behavior of Structural Steel

1.3.1 Monotonic Tensile Stress-Strain Curve

❖ Typical schematic relationships between stress and strain



Idealized monotonic stress-strain relationship for structural steel

- Young's modulus (or modulus of elasticity), E
- proportional limit, σ_P
- upper yield point, σ_{YU}
- lower yield point, σ_{YL} ($\approx\sigma_Y$)
- yield strength, σ_Y
- yield strain, $\varepsilon_Y=\sigma_Y/E$
- strain-hardening strain, ε_h
- strain-hardening tangent modulus, E_h (5~15% of Young's modulus)
- ultimate tensile strength, σ_T (must be 1.2 times σ_Y)
- ultimate tensile strain, ε_T (20 times ε_Y)
- necking tangent modulus, E_n
- fracture strain, ε_F (about 20%, must be > 15%)
- Poisson's ratio, ν
- Elastic Shear Modulus, G $G=\dfrac{E}{2(1+\nu)}$

1.3.1 Monotonic Tensile Stress-Strain Curve

❖ A schematic of stress-strain curve and offset yield stress for heat-treated higher tensile steel

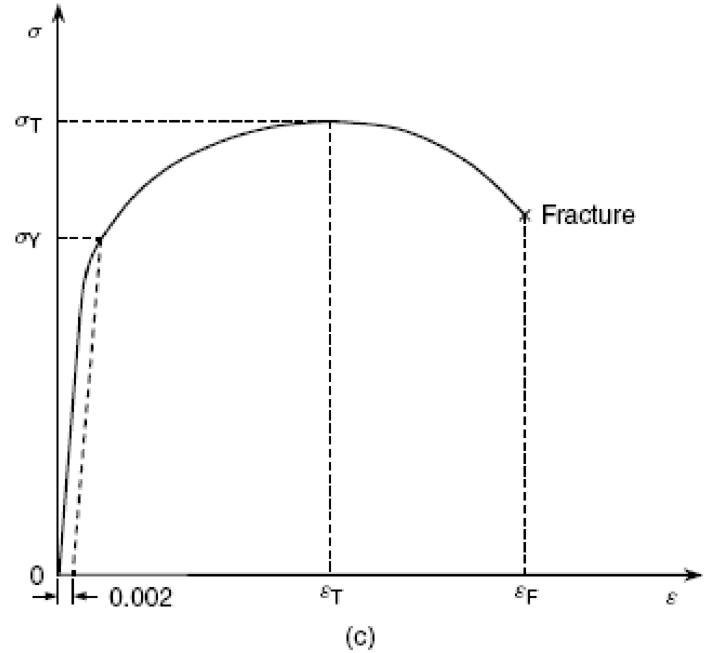
- The yield strength of a steel is increased by the heat treatments or cold forming.
- The stress versus strain monotonically increases until its maximum.

- Yield strength = intersection point of stress-strain curve and a straight line passing through an offset point strain $(\sigma,\varepsilon)=(0, 0.002)$
- Classification steels

  Mild steel = 235 MPa

  AH32 = 315 MPa

  AH36 = 355 MPa

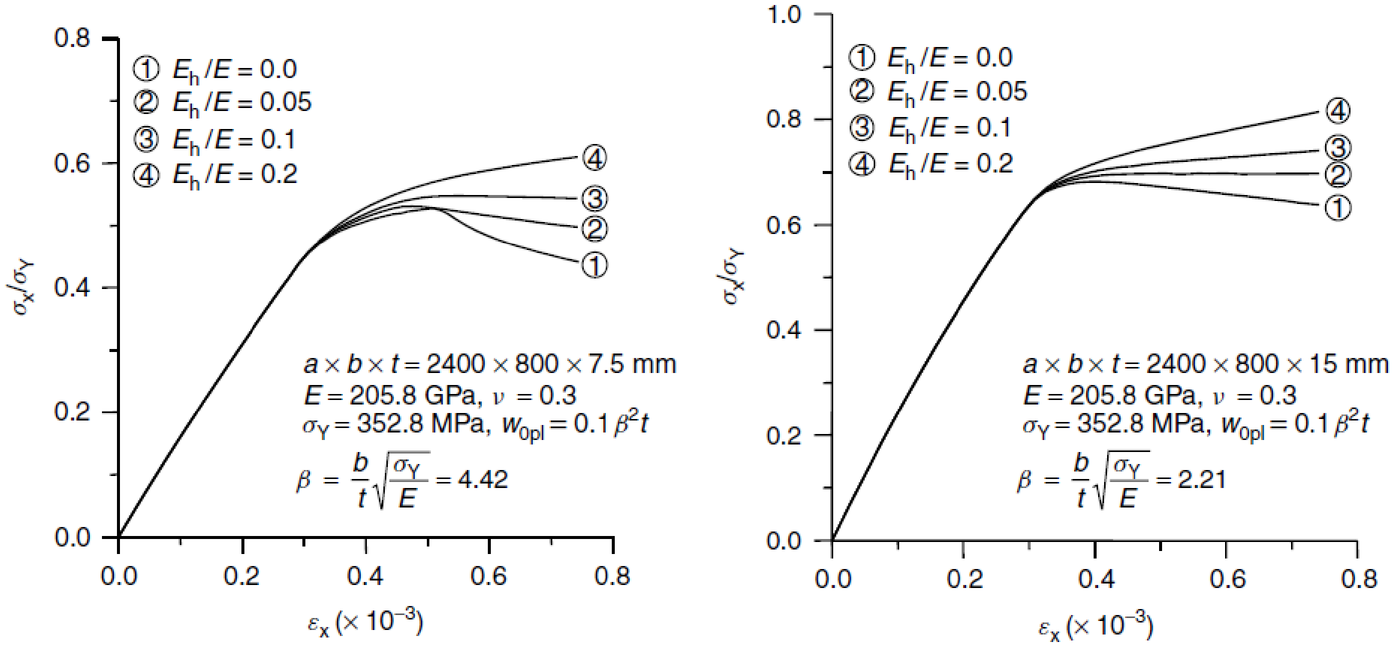


A schematic of stress-strain curve and offset yield stress for heat-treated higher tensile steels

1.3.1 Monotonic Tensile Stress-Strain Curve

❖ Effect of Strain Hardening on Ultimate Strength

- Elastic-plastic large deflection behavior of a steel rectangular plate under uniaxial compressive loads in nonlinear FE analysis.
- The strain-hardening has an effect on increasing ultimate strength to a degree.
- Elastic and perfectly plastic material model is considered sufficient.



The effect of strain hardening on the ultimate strength of a steel plate under axial compression

1.3.2 Yield Condition under Multiple Stress Components

- For 1 D structural member : uniaxial tension test is used to check the state of yielding → Simple.
- Plate element subjected to a combination of biaxial tension/compression (σ_x, σ_y) and shear stress (τ_{xy}) → plane stress state.

Q: Plane stress v.s. Plane strain?

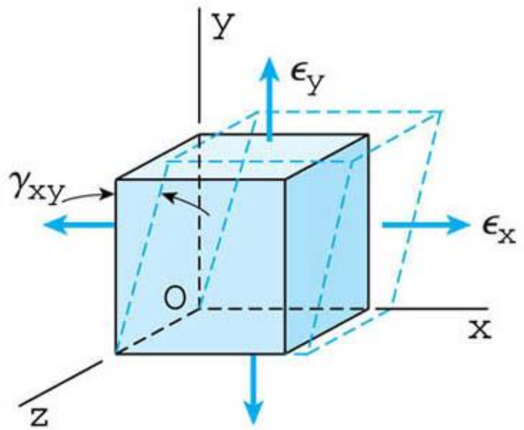
- For an isotropic 2-dimensional steel member (e.g plate), the following three yield criteria are presented.

1. Maximum principal stress based criterion

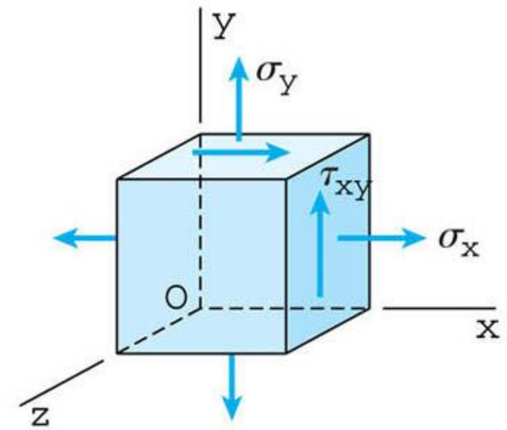
$$\max\left(|\sigma_1|, |\sigma_2|\right) = \sigma_Y$$

- Relevant for brittle materials

Plane stress v.s. Plane strain?



	Plane strain
Stresses	$\boxed{\tau_{xz}=0 \qquad \tau_{yz}=0}$ σ_x, σ_y, σ_z, and τ_{xy} may have nonzero values
Strains	$\boxed{\epsilon_z=0}$ $\boxed{\gamma_{xz}=0 \qquad \gamma_{yz}=0}$ ϵ_x, ϵ_y, and γ_{xy} may have nonzero values



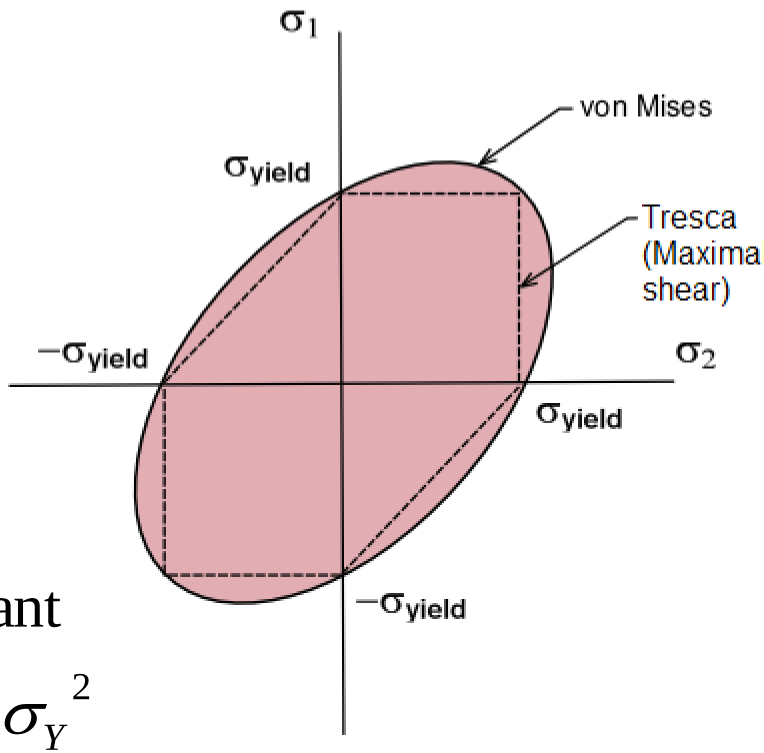
	Plane stress
Stresses	$\boxed{\sigma_z=0}$ $\boxed{\tau_{xz}=0 \qquad \tau_{yz}=0}$ σ_x, σ_y, and τ_{xy} may have nonzero values
Strains	$\boxed{\gamma_{xz}=0 \qquad \gamma_{yz}=0}$ ϵ_x, ϵ_y, ϵ_z, and γ_{xy} may have nonzero values

1.3.2 Yield Condition under Multiple Stress Components

2. Maximum shear-stress-based criterion (Tresca criterion)

$$\tau_{max} = \left| \frac{\sigma_1 - \sigma_2}{2} \right| = \frac{\sigma_Y}{2}$$

- Relevant for ductile materials



3. Von-Mises Criterion is applicable for ductile materials

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = \text{constant}$$

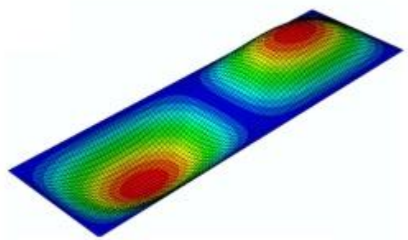
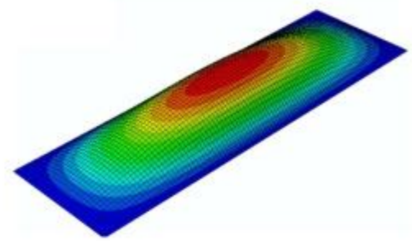
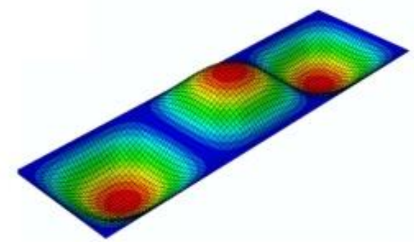
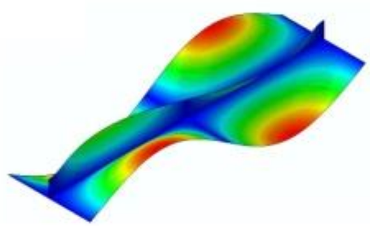
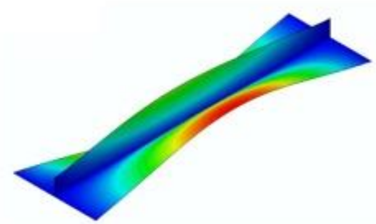
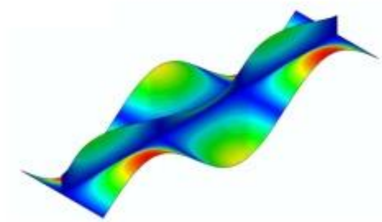
$$\sigma_3 = 0 \Rightarrow \quad (\sigma_1 - \sigma_2)^2 + (\sigma_2)^2 + (\sigma_1)^2 = 2\sigma_Y{}^2$$

$$\sigma_{eq} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} = \sigma_Y$$

$$\boxed{from, \quad \sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{(\frac{\sigma_x - \sigma_y}{2})^2 + \tau_{xy}^2}}$$

$$\sigma_{eq} = \sqrt{\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2} = \sigma_Y$$

Q: Linear or not?

	1st Eigenmode	2nd Eigenmode	3rd Eigenmode
Simply Supported Plate			
Simply Supported PSC			
Simply Supported Panel