3.155J/6.152J Lecture 13: MEMS Lab Testing

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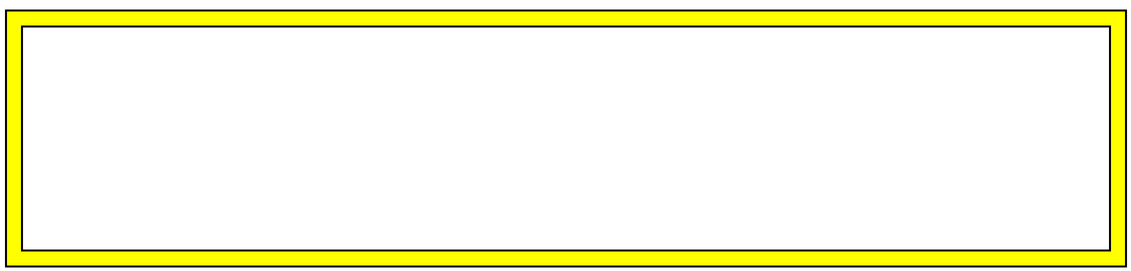
Outline

- Review of the Process and Testing
- Mechanics
  - Cantilever
  - Fixed-Fixed Beam
  - Second-order effects
    - Residual stress
    - Support compliance
- References
    - Senturia, Microsystems Design, Kluwer

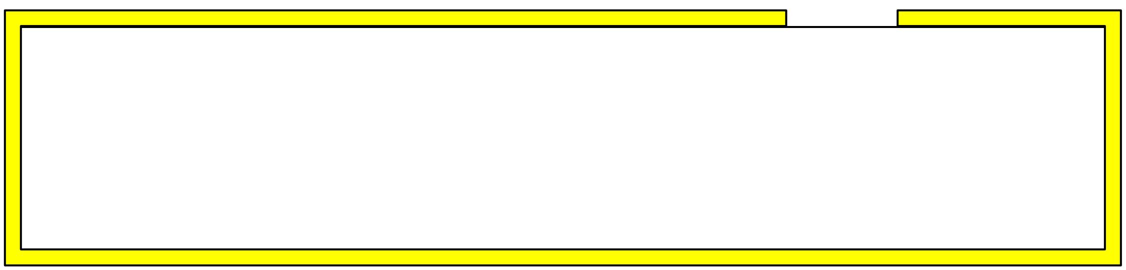
The Process – Lab 1

- Grow 1.0μm of Si-Rich Silicon Nitride (SiN_x)
  - LPCVD Process (details to follow)
  - Characterize (UV1280)
    - Thickness
    - Refractive index



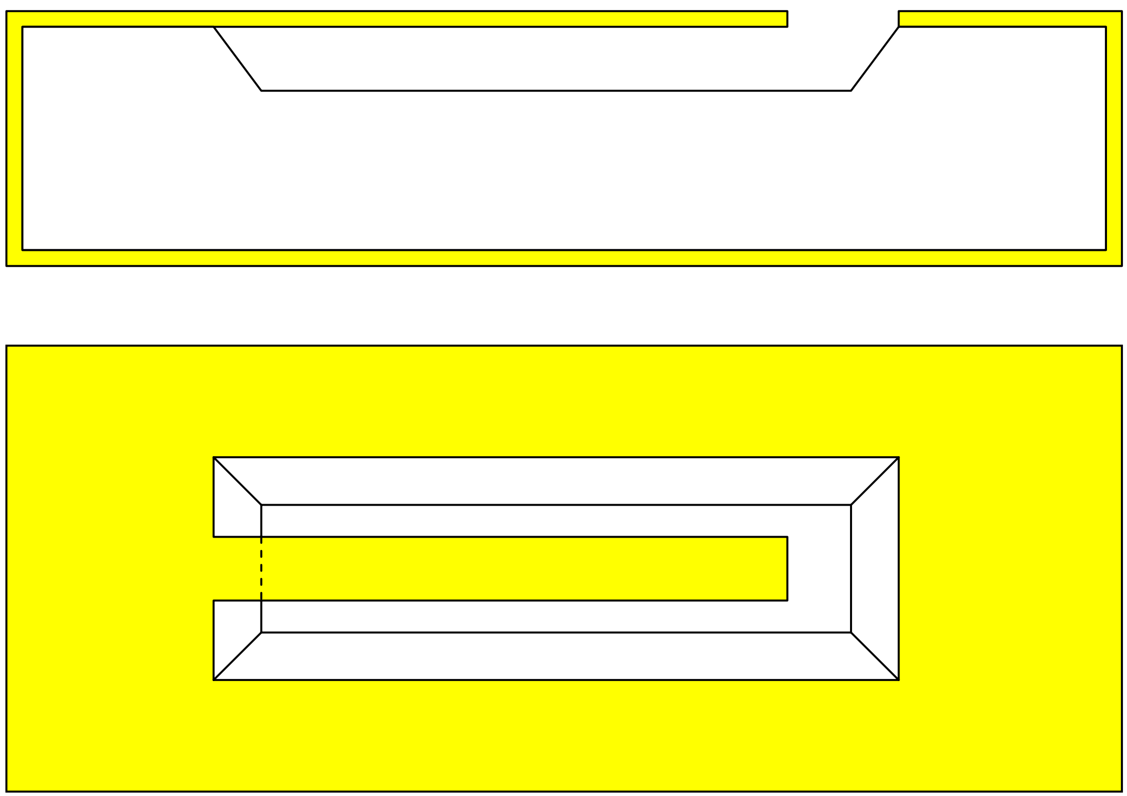
The Process – Lab 1

- Pattern Transfer
  - Deposit photoresist
  - Expose on contact aligner
  - Plasma etch using SF_6 chemistry
  - Strip resist



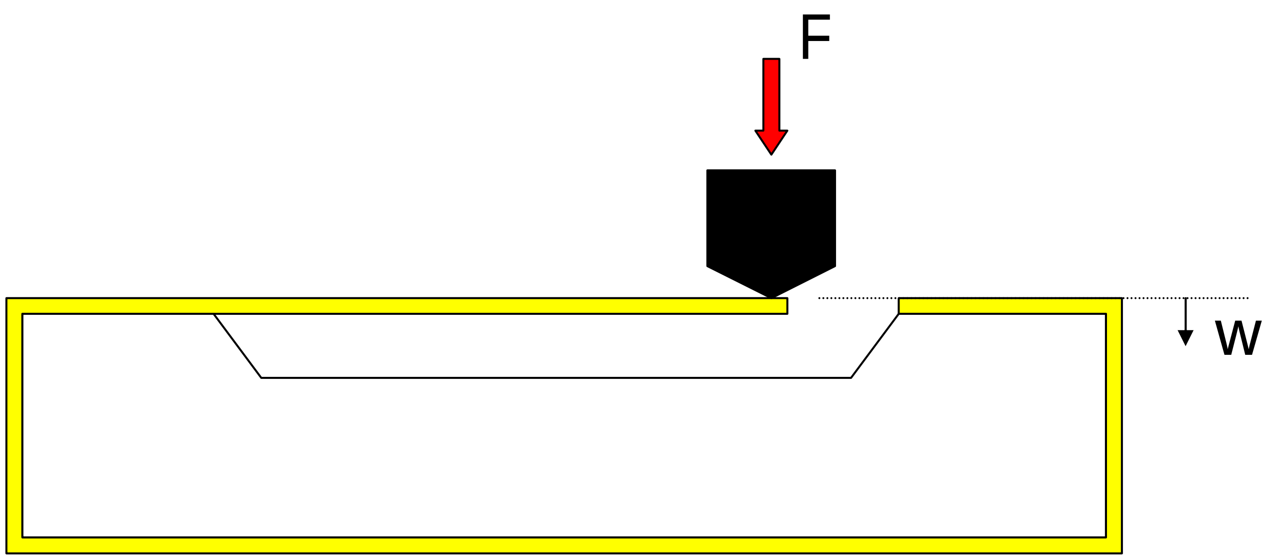
The Process – Lab 2

- KOH Undercut Etch
  - 20%, 80C



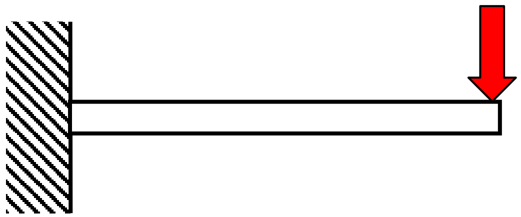
The Process – Lab 3

- Break the wafer into die
- Mount the die on a metal plate
- Test using the Hysitron Nanoindenter

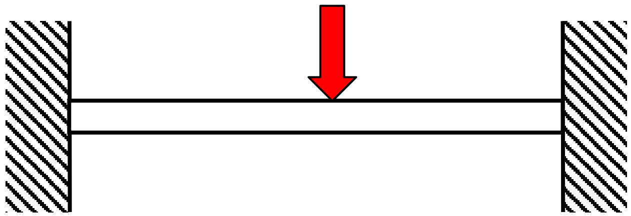


Testing

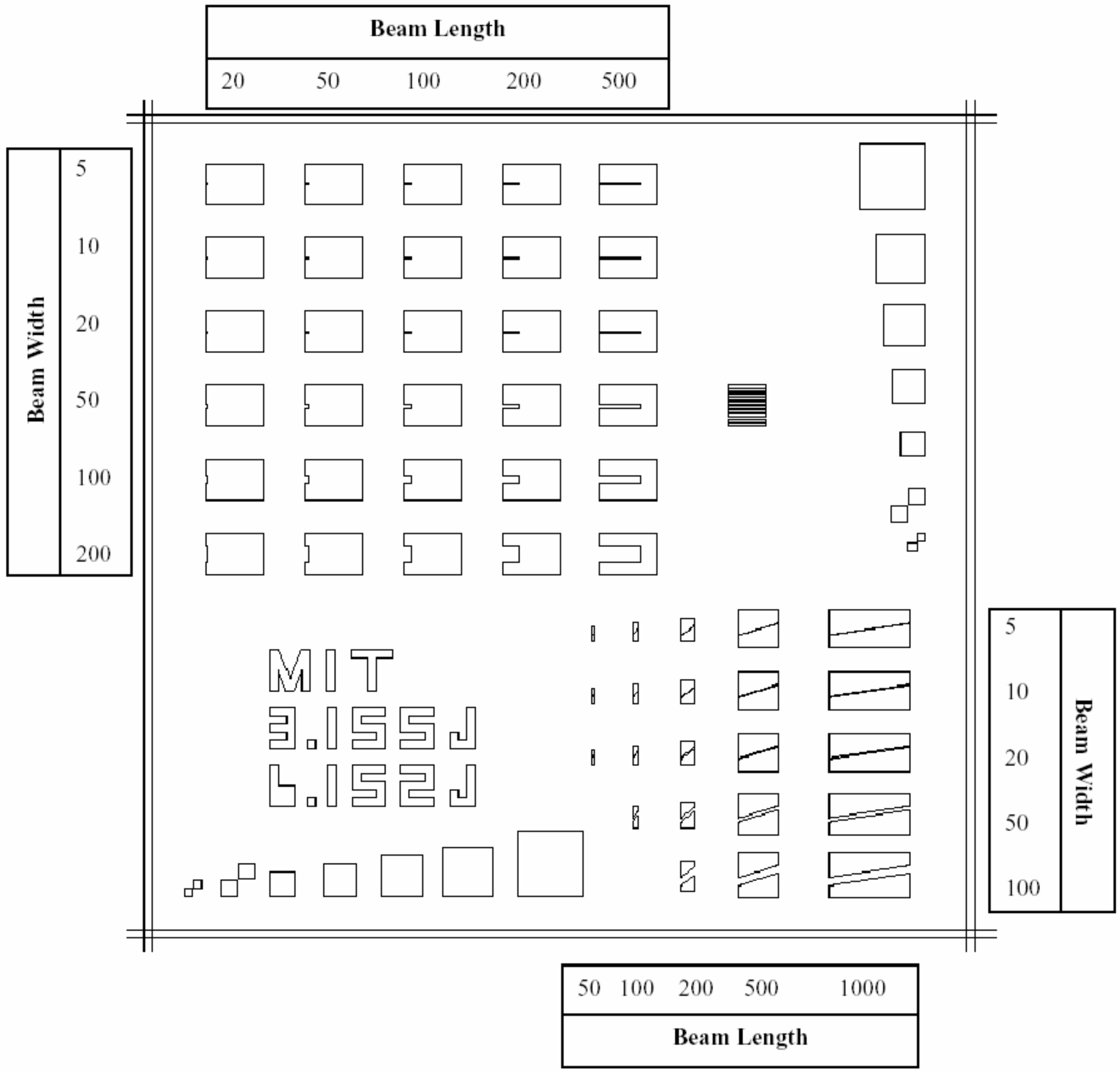
- Cantilever
  - Young's Modulus



- Fixed-Fixed Beams
  - Young's Modulus
  - Residual Stress

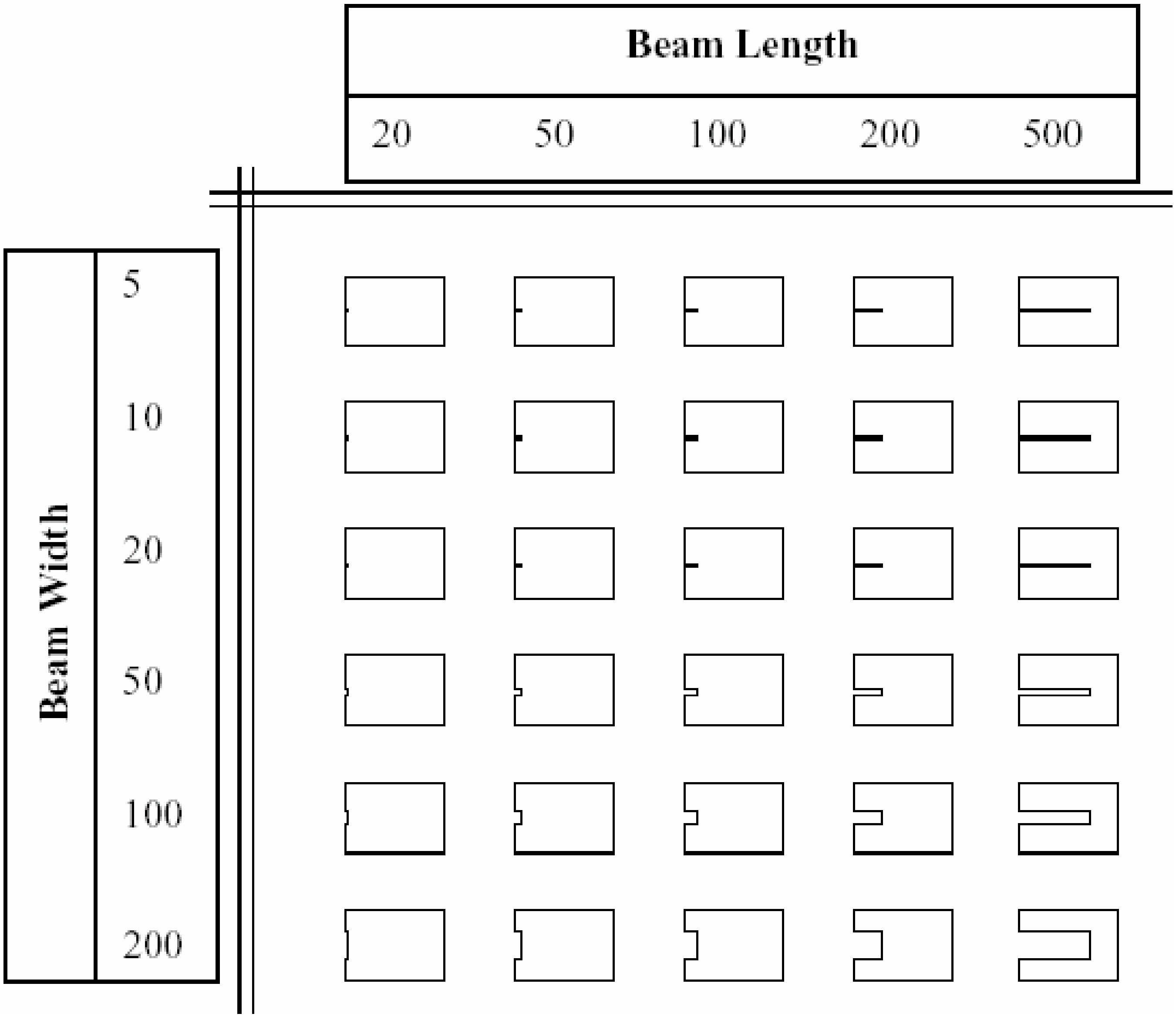


The Mask

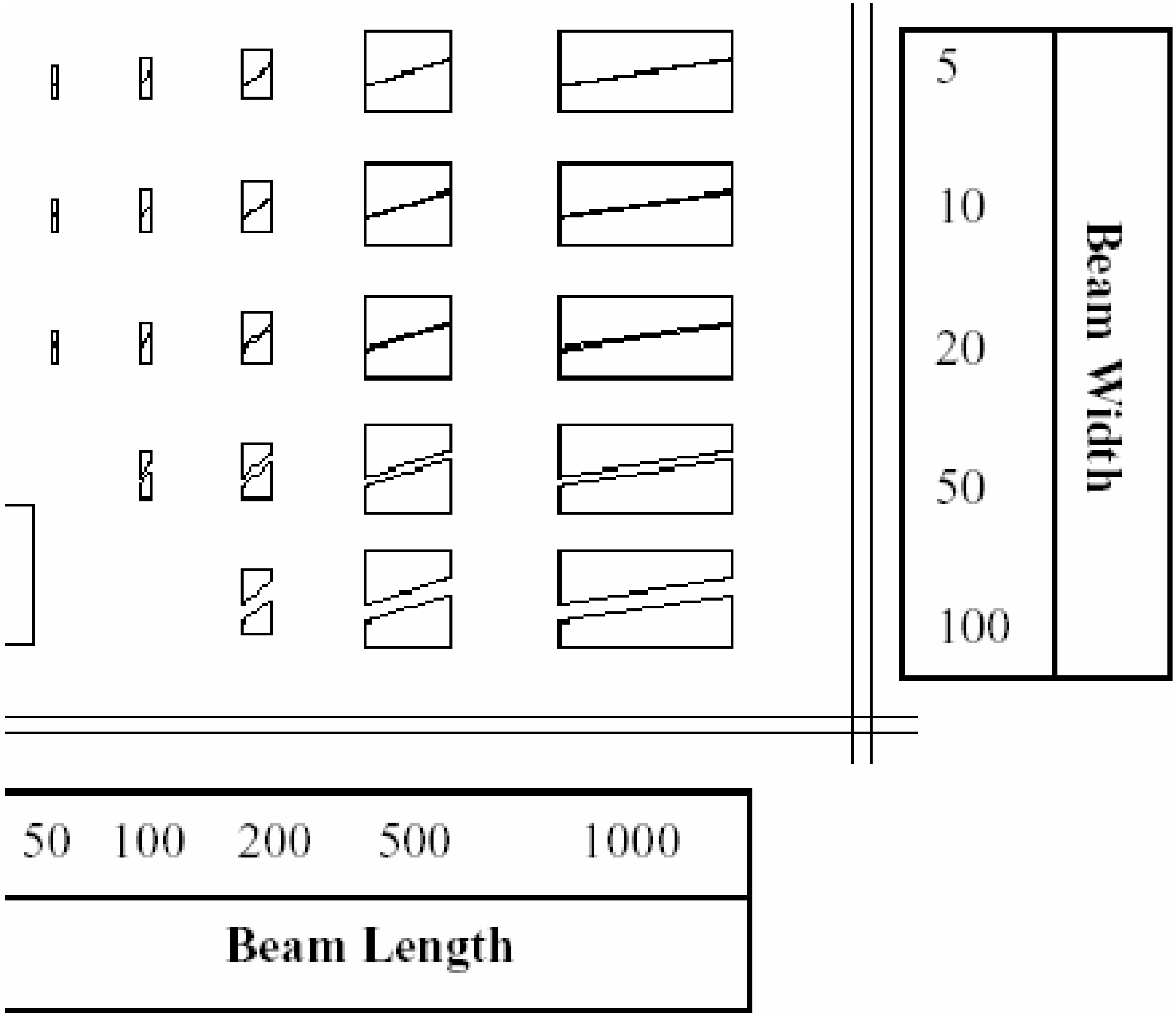


Beam Length
20 50 100 200 500
Beam Width
5
10
20
50
100
200
MIT
3.155J
6.152J
5
10
20
50
100
Beam Width
50 100 200 500 1000
Beam Length

The Mask - Cantilevers

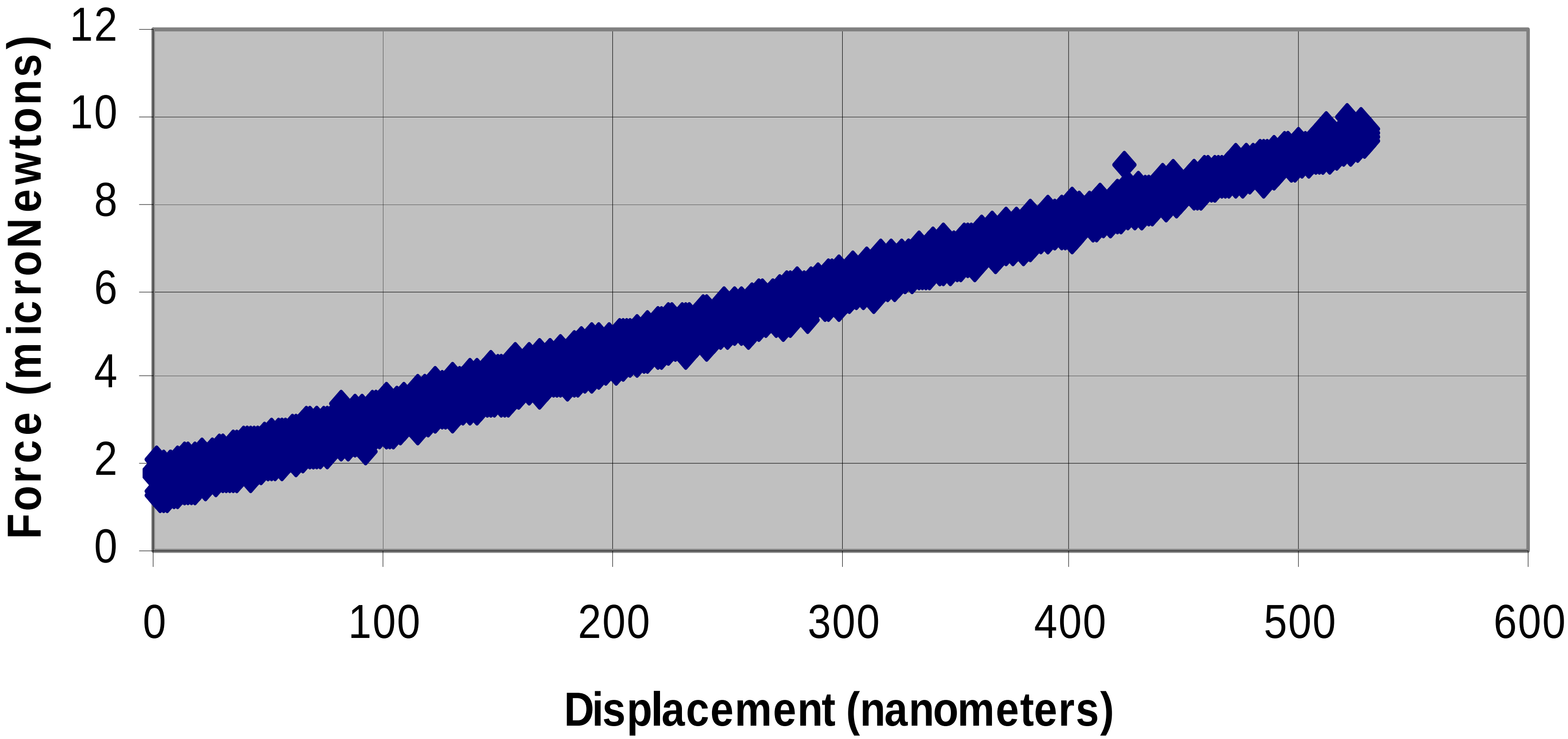


The Mask – Fixed-Fixed Beams



Cantilever Data

$$F = k\,x$$



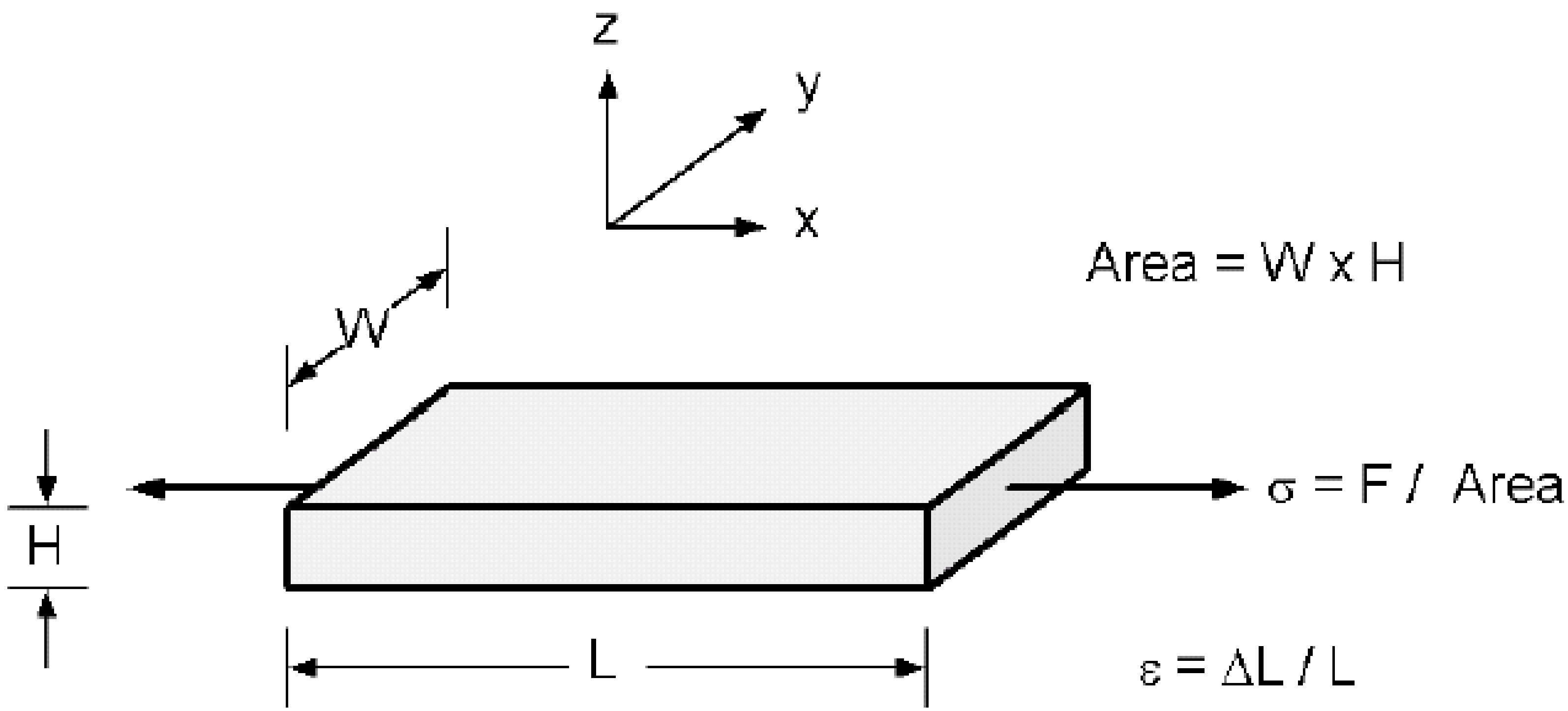
Force on a Beam

σ = stress = F / area (N/m², Pa, J/m³)

ε = strain = ΔL / L (unitless)

E = Young's Modulus (N/m², Pa, J/m³, ~160 GPa for Si)

$$\sigma = E\,\varepsilon$$



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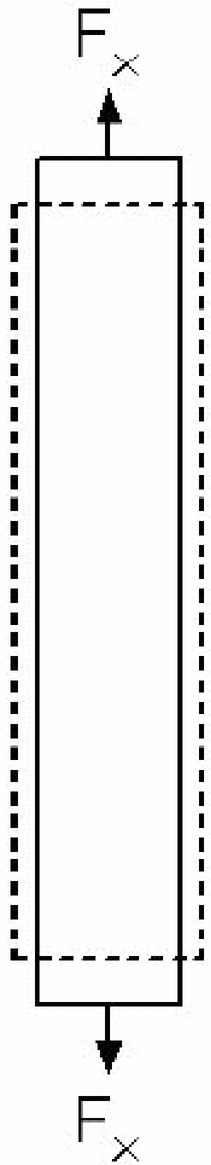
Uniaxial Stress



F_x = Force

σ = Force / (Normal Area)

$\varepsilon = \Delta L/L$

$\sigma = E\,\varepsilon$

E = Young's Modulus

ν = Poisson's ratio

$$\nu = -\frac{\text{transverse strain}}{\text{axial strain}} = -\frac{\varepsilon_y}{\varepsilon_x}$$

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Material Properties: Elastic/Plastic

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Material Properties: Brittle

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Differential Equation of Bending

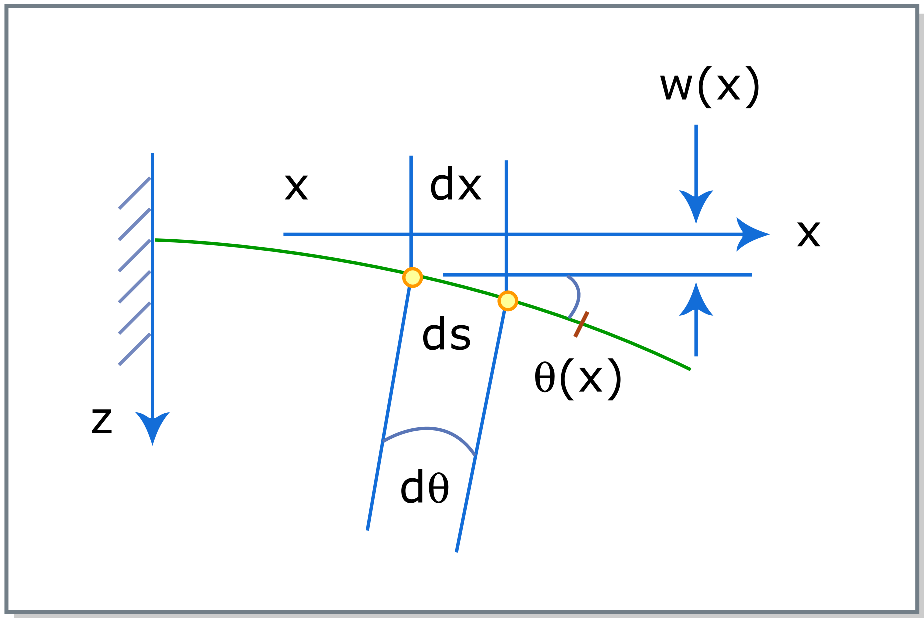

Figure by MIT OCW.

H = thickness
W = width

$$\frac{d^2w}{dx^2} = -\frac{M}{EI}$$

$$I = \left(\frac{1}{12}WH^3\right)$$

Reference: Senturia, S.D. *Microsystems Design*. Norwell, MA: Kluwer Academic Publisher, 2001.

Deflection of a Cantilever - 1

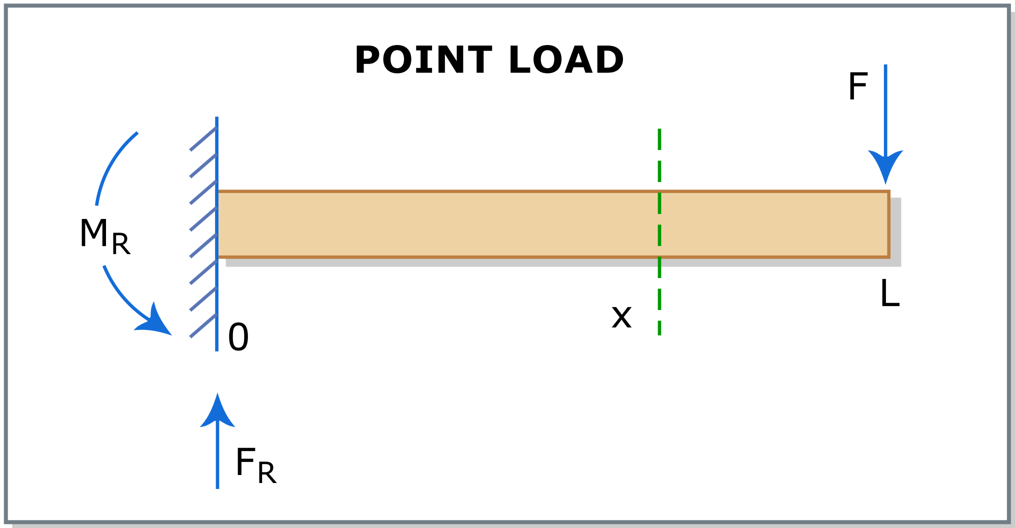

Figure by MIT OCW.

a point load F is applied at the end of a cantilever of length L.

The applied moment $M_{applied}$ is balanced by the internal moment M as a function of x so $M_{applied}(x) = -M(x)$ and $M_{applied} = F(L-x)$ so $M = -F(L-x)$ so

$$\frac{d^2w}{dx^2} = \frac{F}{E\,I}(L-x)$$

Ref: Senturia (Kluwer)
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Deflection of a Cantilever - 2

so solve $$\frac{d^2w}{dx^2} = \frac{F}{E\,I}(L - x)$$

subject to

$$w(0) = 0$$

$$\left.\frac{dw}{dx}\right|_{x=0} = 0$$ zero slope at the support

with the trial solution

$$w = A + B\,x + C\,x^2 + D\,x^3$$

we find A = B = 0 and $C = \frac{FL}{2EI}$ and $D = -\frac{F}{6EI}$ so

$$w = \frac{FL}{2EI}\,x^2\left(1 - \frac{x}{3L}\right)$$

Ref: Senturia (Kluwer)
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Deflection of a Cantilever - 3

the maximum deflection occurs at L so

$$w_{max} = \left(\frac{L^3}{3EI}\right) F$$

so the spring constant for deflection ($F = k\,\delta x$) is

$$k_{cantilever} = \frac{3EI}{L^3} \quad \text{or with} \quad I = \left(\frac{1}{12} WH^3\right)$$

W = width
H = thickness
L = length

$$k_{cantilever} = \frac{EWH^3}{4L^3}$$

Ref: Senturia (Kluwer)
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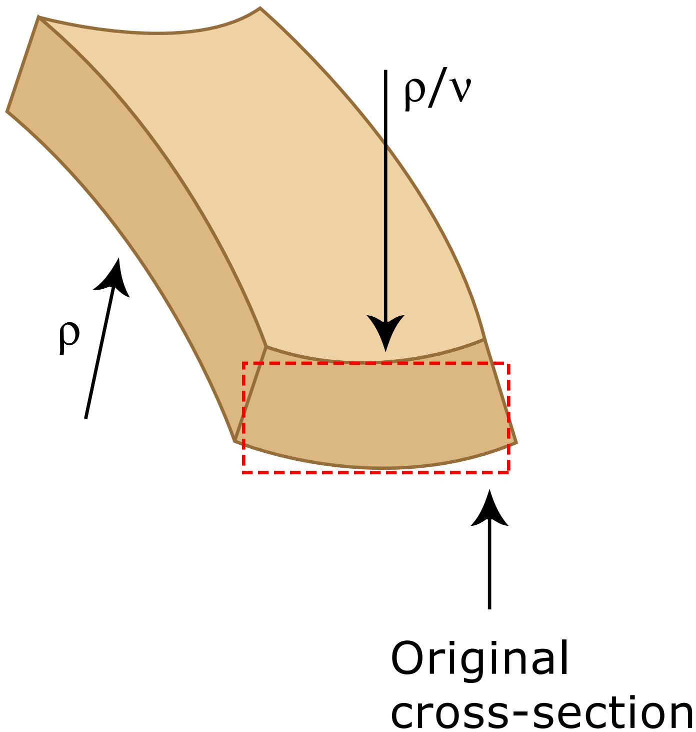
Deflection of a Plate - 1

ANTICLASTIC CURVATURE



- Given axial strain $\left(\varepsilon_x = \frac{z}{\rho}\right)$
- Poission effect leads to transverse strain ε_y given by $\varepsilon_y = -\nu\varepsilon_x$ where ν is Poisson's ratio (unitless and about 1/3 for most materials)
- So $\left(\varepsilon_y = \frac{\nu}{\rho} z\right)$
- More important as W $\longrightarrow$ L (beams approach plates)

Figure by MIT OCW.

Ref: Senturia (Kluwer)
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Deflection of a Plate - 2

$$\varepsilon_x = \frac{\sigma_x - \nu\sigma_y}{E}$$

But ε_y is constrained to be zero

$$\Rightarrow 0 = \varepsilon_y = \frac{\sigma_y - \nu\sigma_x}{E}$$

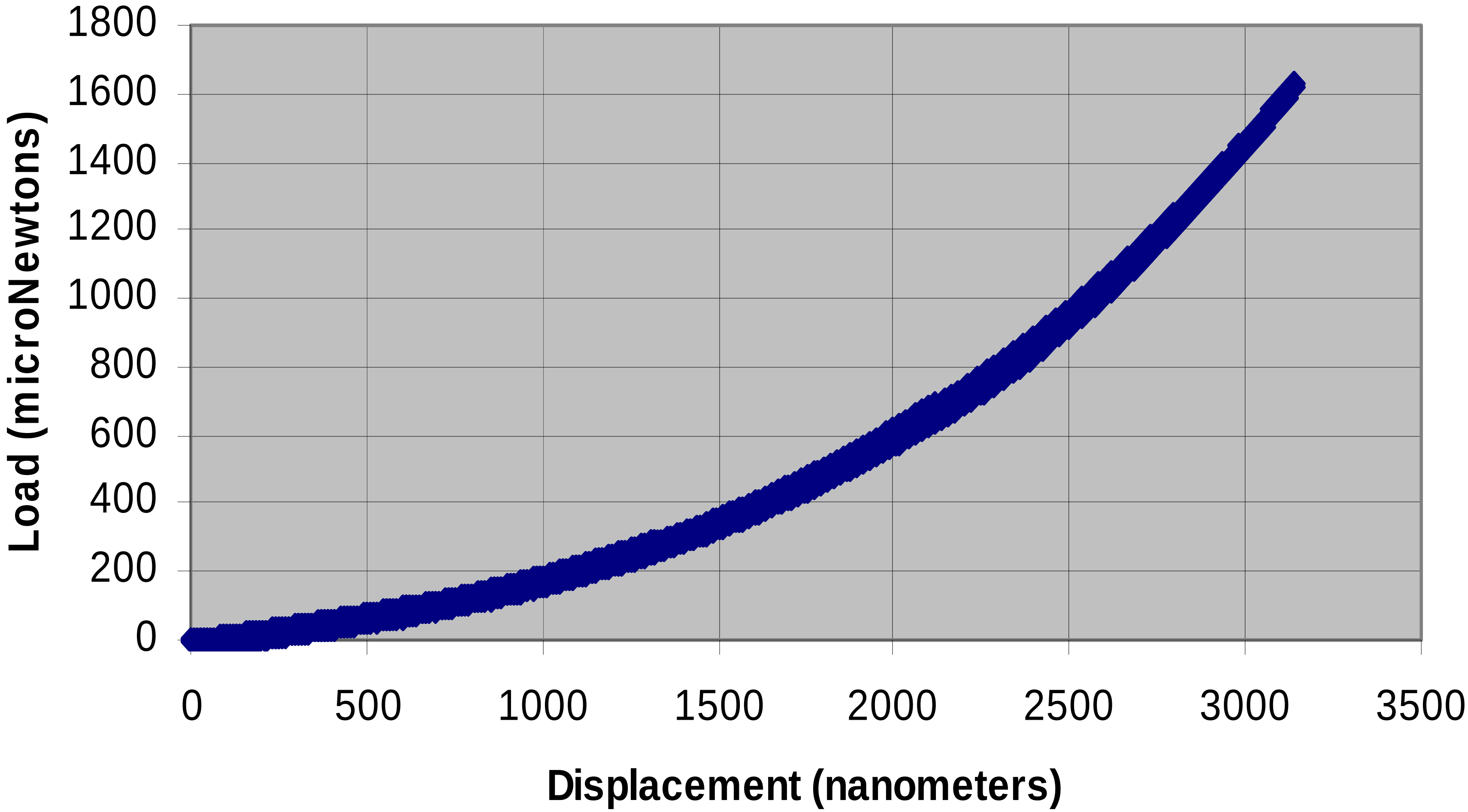
$$\Downarrow$$

$$\sigma_x = \underbrace{\left(\frac{E}{1-\nu^2}\right)}_{\text{Plate Modulus}}\varepsilon_x$$

Replace Modulus(E) with Plate Modulus

Ref: Senturia (Kluwer)

Fixed-Fixed Beam



Fixed-Fixed Beam: Large Displacement

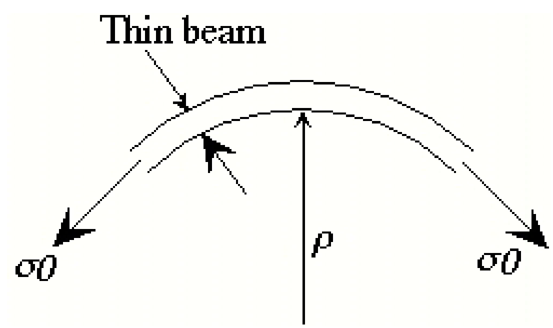
- Beam stretches under large displacement
  - Becomes ‘stiffer’
- Solved by Energy Methods
  - c = w

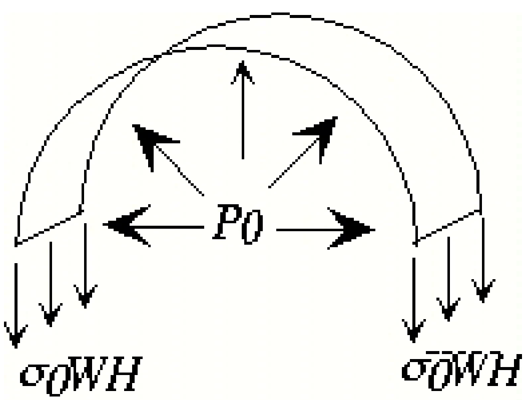
$$F = \left(\frac{\pi^4}{6}\right)\left[\frac{EWH^3}{L^3}\right]c + \left(\frac{\pi^4}{8}\right)\left[\frac{EWH}{L^3}\right]c^3$$

Ref: Senturia (Kluwer)

Residual Axial Stress in Beams

- Residual axial stress in a beam contributes to it bending stiffness
- Leads to the Euler beam equation





$$2\rho W P_0 = 2\sigma_0 W H$$

$$\Rightarrow P_0 = \frac{\sigma_0 H}{\rho}$$

which is equivalent to a distributed load

$$q_0 = P_0 W = \sigma_0 W H \frac{d^2 w}{dx^2}$$

Insert as added load into beam equation :

$$EI \frac{d^4 w}{dx^4} = q + q_0$$

$$EI \frac{d^4 w}{dx^4} - \sigma_0 W H \frac{d^2 w}{dx^2} = q$$

Ref: Senturia (6.777)

Effect of stress on stiffness

Figure removed for copyright reasons.

Graph found in Senturia, S.D. *Microsystems Design*. Norwell, MA: Kluwer Academic Publisher, 2001.

Ref: Senturia (6.777)

Effect of Residual Stress

- Not an issue in cantilevers
- For a point load, F, in the center of a bridge

$$F = \left\{ \left(\frac{\pi^2}{2}\right) \left[\frac{\sigma_0 W H}{L}\right] + \left(\frac{\pi^4}{6}\right) \left[\frac{E W H^3}{L^3}\right] \right\} c + \left(\frac{\pi^4}{8}\right) \left[\frac{E W H}{L^3}\right] c^3 \qquad (10.70)$$

- Important when

$$\sigma_0 \approx \frac{EH^2}{L^2}$$

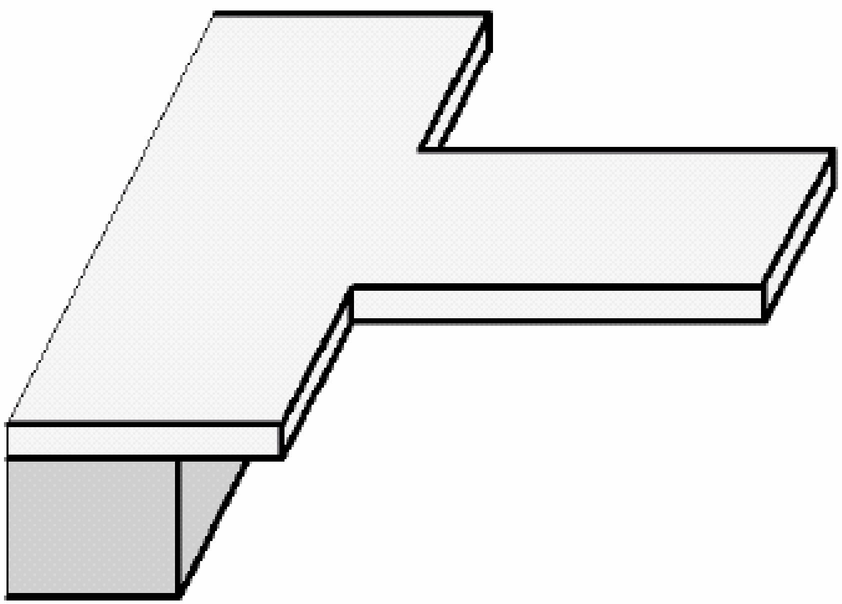
Ref: Senturia (Kluwer)

Compliant Supports

In the forgoing we have assumed that the beam support was ideal, i.e.

$$\left|\frac{dw}{dx}\right|_{x=o} = 0$$

This is often not the case. A common cause for support compliance is etch undercut. This can be rigorously dealt with mathematically, but approximate treatments are often adequate.



One approach is to introduce an effective length through a length correction, which is empirically fit to observations:

$$L = L_{measured} + L_{correction} = L_m + L_c$$

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MEMS Lab Report

- Report Young's Modulus extracted from
  - Cantilevers
  - Fixed-Fixed Beams
- Explain differences from ideal theory
- Compare to literature values for mechanical properties
- Assess the effects of:
  - Residual stress
    - Estimate from measurements
  - Experimental error
  - Compliant supports
  - Beam versus Plate
  - Others….