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NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 1 EXAMINATION 2020-2021

CV1011 – MECHANICS OF MATERIALS

November / December 2020 **Time Allowed: 2 hours**

INSTRUCTIONS

1. This paper contains **FOUR (4)** questions and comprises **SIX (6)** pages.
2. Answer **ALL FOUR (4)** questions.
3. All questions carry equal marks.
4. An Appendix of **TWO (2)** pages is attached together with this paper.
5. This is a Closed-Book Examination.
6. All answers must be written in the answer book provided. Answer each question beginning on the **FRESH** page of the answer book.

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1. Two tractors pull on the tree with the forces shown in **Figure Q1**. Take note that point A and point C on the two tractors are 3 m and 1 m above ground, respectively. The Cartesian coordinates of point A, point B, and point C are (1, -2, 3), (0, 0, 5), and (2, 4, 1), respectively. Note: The drawing is not to scale.

(a) Given the magnitude of $\mathbf{F_{BA}}$ = 600 N and $\mathbf{F_{BC}}$ = 300 N, express the two force vectors $\mathbf{F_{BA}}$ and $\mathbf{F_{BC}}$ in Cartesian vector form.

(6 Marks)

(b) Determine the angle θ between the two forces and the magnitude of projection of the force $\mathbf{F_{BA}}$ along the rope BC, i.e., $F_{BA/BC}$.

(8 Marks)

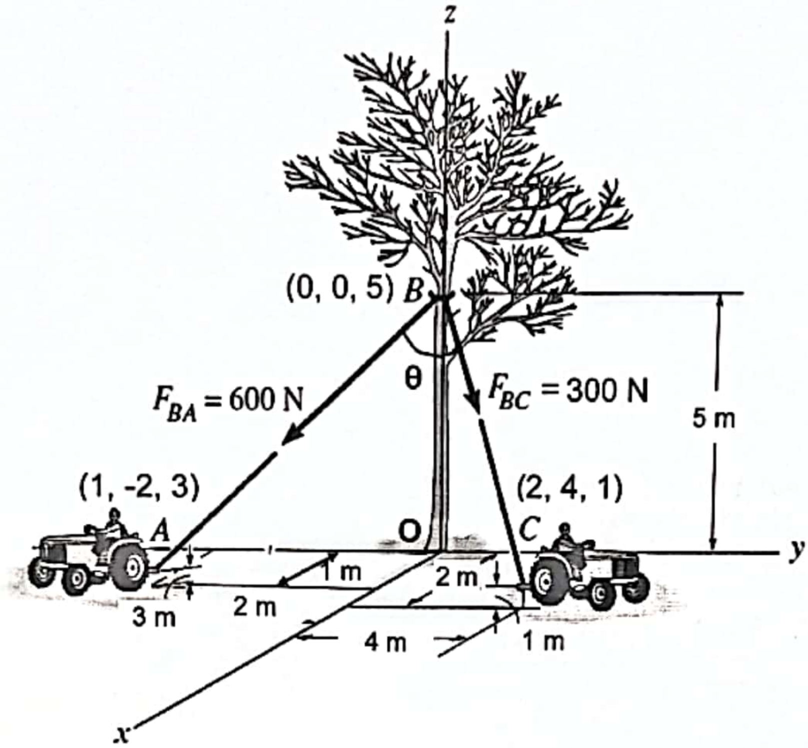
(c) Determine the moment of force $\mathbf{F_{BC}}$ about the y axis.

(4 Marks)

(d) Replace the two forces by a resultant force $\mathbf{F_R}$ and couple moment at point O, $(\mathbf{M_R})_O$. Express the results in Cartesian vector form.

(7 Marks)

Note: Question No. 1 continues on page 2.



[The drawing is not to scale]

Figure Q1

2. A frame is used to support a uniformly distributed load as shown in **Figure Q2**.

(a) Determine the support reactions at A and C.

(8 Marks)

(b) Draw the shear force and bending moment diagrams of member AD.

(8 Marks)

(c) Determine the required cross-sectional area of member BC if the allowable stress for member BC is σ_{allow} = 200 MPa.

(2 Marks)

(d) Determine the decrease in length of member BC. Given E_{BC} = 50 GPa.

(2 Marks)

Note: Question No. 2 continues on page 3.

(e) Determine the required diameter to the nearest 1 mm of the pins A and B if the allowable shear stress for the pins is τ_{allow} = 100 MPa.

(5 Marks)

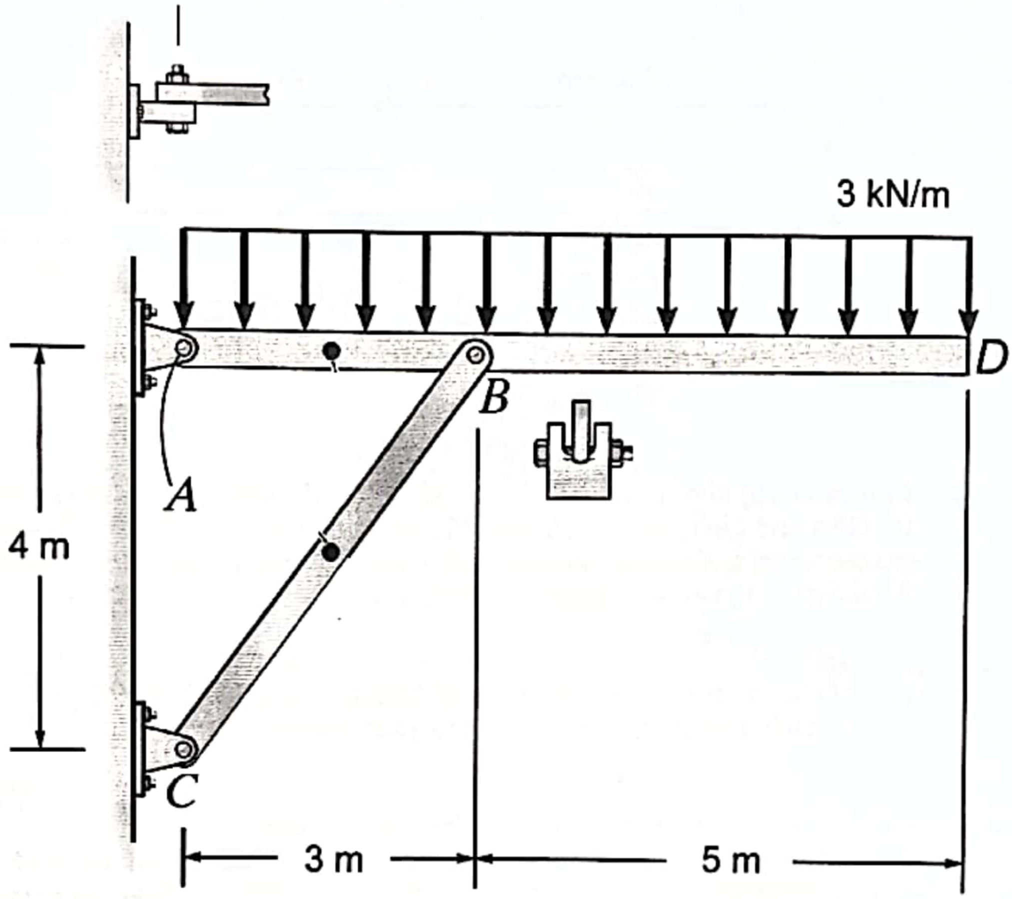


Figure Q2

3. (a) **Figure Q3(a)** shows a 1 m long bar with uniform cross sectional area 2500 mm^2 and Young's modulus 200 GPa. It is fixed at the left end and free at the right end. The bar comprises two segments, A and B, whose coefficients of thermal expansion are $2 \times 10^{-5}/^{\circ}C$ and $4 \times 10^{-5}/^{\circ}C$, respectively. There is a 1 mm gap between the right end of the bar and another rigid wall. The bar is now heated up uniformly by $50^{\circ}C$. Determine the axial force (if any) induced in the bar and state whether it is tensile or compressive. Ignore the possibility of buckling (if any).

(8 Marks)

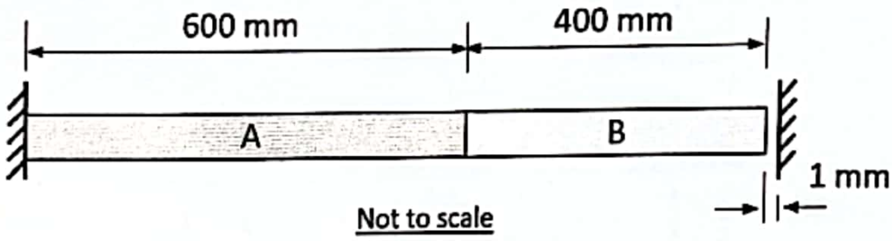


Figure Q3(a)

(b) **Figure Q3(b)** shows a solid circular shaft ABCD with uniform shear modulus of 80 GPa and diameter of 100 mm. Fix-supported at A and free at D, the shaft is subjected to a clockwise couple of 3 kNm at B and an anti-clockwise couple of 2 kNm at C. Ignore self-weight of the shaft.

(i) Determine the maximum shear stress in the shaft ABCD and the likely location where it occurs. Express your answer in MPa.

(12 Marks)

(ii) Over time the shaft ABCD corrodes, resulting in a reduction of torsional resistance. Based on the idea that under constant torque the angle of twist of a shaft will increase if torsional resistance decreases, a device is installed to measure and monitor the angle of twist at D. The manufacturer of the device claims that the deterioration at any section of the shaft from A to D can be detected. A graduate engineer has doubt on this claim, i.e., whether there may be some section between A to D whose deterioration cannot be detected by the device. Comment on whether the claim of the manufacturer is valid with regard to the doubt of the graduate engineer. Explain your answer briefly.

(5 Marks)

Note: Question No. 3 continues on page 5.

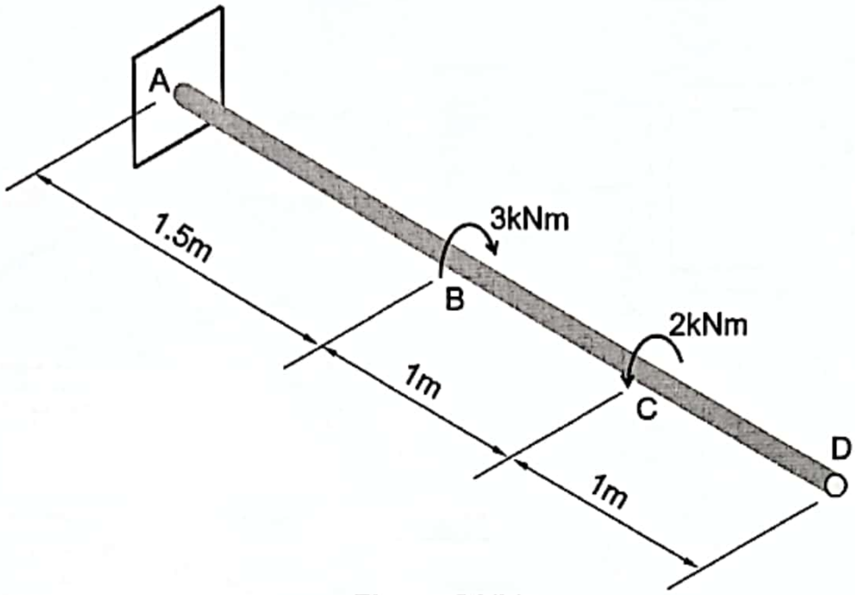


Figure Q3(b)

4. (a) **Figure Q4(a)(i)** shows the in-plane stress state of a point on the free surface of a concrete member when subjected to applied loads.

(i) Draw the Mohr circle for the stress element. Indicate the points that correspond to the right face and the top face.

(6 Marks)

(ii) It is known that the concrete will crack if the tensile stress reaches a threshold value σ_c. The stress state in **Figure Q4(a)(i)** in fact corresponds to the location where a crack has just formed when loading increases. The neighborhood of the crack is shown schematically in **Figure Q4(a)(ii)**. Using the result in **Q4(a)(i)**, or otherwise, estimate the threshold σ_c and the angle α (in degrees) of the crack.

(6 Marks)

Note: Question No. 4 continues on page 6.

(i) Stress state

(ii) Region near crack
(do not measure α from the figure)

Figure Q4(a)

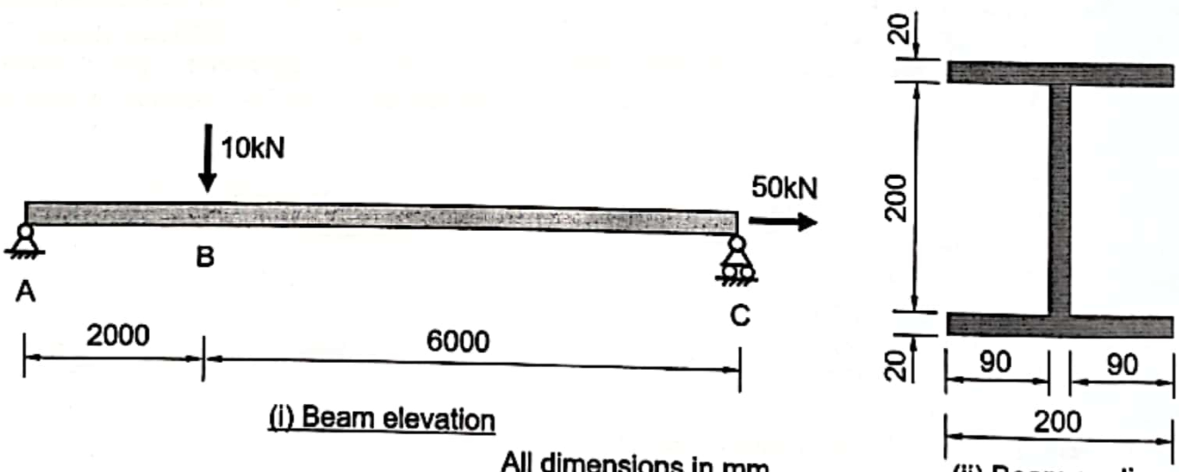
(b) **Figure Q4(b)(i)** shows a steel beam pin-supported at A and roller-supported at C. It is subjected to a point load of 10 kN at B and a horizontal load of 50 kN at C. The beam has a uniform cross section as shown in **Figure Q4(b)(ii)**. Ignore self-weight of the beam. Ignore stress concentration effects.

(i) Determine the maximum normal stress (i.e., perpendicular to section) in the beam and the likely location where it occurs. Express the stress value in MPa.

(10 Marks)

(ii) For situation in **Figure Q4(b)**, an engineer commented that the beam may buckle along the longitudinal direction (i.e., AC) if the 50kN load is further increased to beyond some threshold value. Comment on the validity of this statement. Explain your answer briefly.

(3 Marks)



(i) Beam elevation

All dimensions in mm

(ii) Beam section

Figure Q4(b)

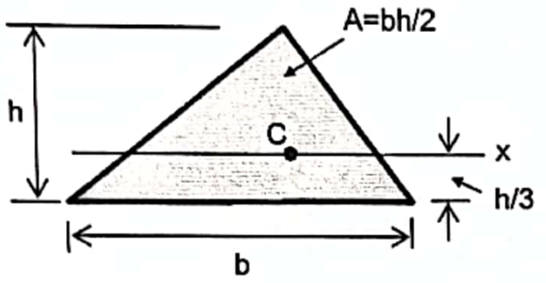
END OF PAPER

1. Equilibrium

Particle $\sum F_x = 0$, $\sum F_y = 0$, $\sum F_z = 0$

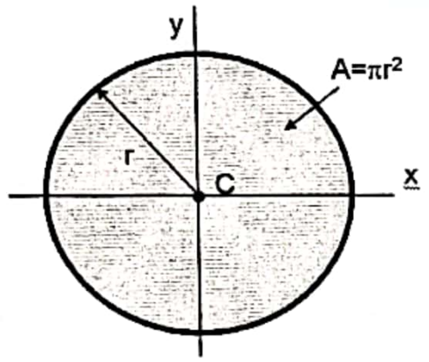
Rigid Body – Two dimensions $\sum F_x = 0$, $\sum F_y = 0$, $\sum M_o = 0$

2. Geometric properties of area elements



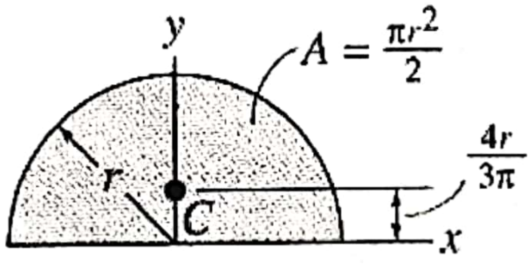
$$I_x = \frac{1}{36} bh^3$$

Triangular



$$I_x = \frac{1}{4} \pi r^4$$
$$I_y = \frac{1}{4} \pi r^4$$

Circular area



$$I_x = \frac{1}{8} \pi r^4$$
$$I_y = \frac{1}{8} \pi r^4$$

Semicircular area

Parallel-Axis Theorem $I = \bar{I} + Ad^2$

3. Axial load

Normal Stress $\sigma = \frac{P}{A}$

Displacement $\delta = \int_0^L \frac{P dx}{EA}$, $\delta = \sum \frac{PL}{EA}$, $\delta_T = \alpha \Delta T L$

4. Torsion

Shear Stress in Circular Shaft $\tau = \dfrac{T\rho}{J}$

where $J = \dfrac{\pi}{2}c^4$ solid cross section; $J = \dfrac{\pi}{2}(c_o^4 - c_i^4)$ tubular cross section

Angle of Twist $\phi = \sum \dfrac{TL}{GJ}$

5. Bending

Normal Stress $\sigma = \dfrac{My}{I}$

Unsymmetric Bending $\sigma = -\dfrac{M_z y}{I_z} + \dfrac{M_y z}{I_y}$, $\tan\alpha = \dfrac{I_z}{I_y}\tan\theta$

6. Shear

Average Direct Shear Stress $\tau_{ave} = \dfrac{V}{A}$

Transverse Shear Stress $\tau = \dfrac{VQ}{It}$

Shear Flow $q = \tau \cdot t = \dfrac{VQ}{I}$

7. Stress Transformation Equations

$$\sigma_{x'} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$

$$\tau_{x'y'} = -\frac{\sigma_x - \sigma_y}{2}\sin 2\theta + \tau_{xy}\cos 2\theta$$

Principal Stress,

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

$$\tan 2\theta_p = \frac{2\tau_{xy}}{\sigma_x - \sigma_y}$$

Maximum In-Plane Shear Stress,

$$\tau_{\max} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}, \quad \sigma_{ave} = \frac{\sigma_x + \sigma_y}{2}$$

$$\tan 2\theta_s = -\frac{\sigma_x - \sigma_y}{2\tau_{xy}}$$

8. Buckling

Critical Axial Load, $P_{cr} = \dfrac{\pi^2 EI}{(KL)^2}$

CV1011 MECHANICS OF MATERIALS

Please read the following instructions carefully:

1. **Please do not turn over the question paper until you are told to do so. Disciplinary action may be taken against you if you do so.**

2. You are not allowed to leave the examination hall unless accompanied by an invigilator. You may raise your hand if you need to communicate with the invigilator.

3. Please write your Matriculation Number on the front of the answer book.

4. Please indicate clearly in the answer book (at the appropriate place) if you are continuing the answer to a question elsewhere in the book.

PYP Solution by Renardi

1. (a) $\vec{r}_{BA} = \begin{pmatrix} 1-0 \\ -2-0 \\ 3-5 \end{pmatrix} = \begin{pmatrix} 1 \\ -2 \\ -2 \end{pmatrix}$ $\quad |\vec{r}_{BA}| = \sqrt{1^2 + 2^2 + 2^2} = 3$

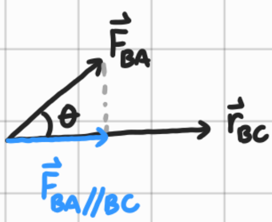
$\vec{r}_{BC} = \begin{pmatrix} 2-0 \\ 4-0 \\ 1-5 \end{pmatrix} = \begin{pmatrix} 2 \\ 4 \\ -4 \end{pmatrix}$ $\quad |\vec{r}_{BC}| = \sqrt{2^2 + 4^2 + 4^2} = 6$

$$\vec{F}_{BA} = |\vec{F}_{BA}|\,\hat{r}_{BA} = (600\text{ N})\left[\frac{1}{3}(i - 2j - 2k)\right] = \boxed{(200i - 400j - 400k)\text{ N}}$$

$$\vec{F}_{BC} = \underbrace{|\vec{F}_{BC}|}_{\text{gives magnitude of force}}\,\underbrace{\hat{r}_{BC}}_{\text{gives direction of force}} = (300\text{ N})\left[\frac{1}{6}(2i + 4j - 4k)\right] = \boxed{(100i + 200j - 200k)\text{ N}}$$

(b) $\vec{F}_{BA} \cdot \vec{F}_{BC} = |\vec{F}_{BA}|\,|\vec{F}_{BC}| \cos\theta$

$$\theta = \cos^{-1}\left(\frac{\vec{F}_{BA} \cdot \vec{F}_{BC}}{|\vec{F}_{BA}|\,|\vec{F}_{BC}|}\right) = \cos^{-1}\left(\frac{(200)(100) + (-400)(200) + (-400)(-200)}{(600)(300)}\right) = \boxed{83.6^\circ}$$



$$|\vec{F}_{BA//BC}| = |\vec{F}_{BA}| \cos\theta = 600 \cos(83.6^\circ) = \boxed{88.9\text{ N}}$$

(c) $$\vec{M}_o = \vec{r}_{OB} \times \vec{F}_{BC} = \begin{pmatrix} 0 \\ 0 \\ 5 \end{pmatrix} \times \begin{pmatrix} 100 \\ 200 \\ -200 \end{pmatrix} = \begin{vmatrix} i & j & k \\ 0 & 0 & 5 \\ 100 & 200 & -200 \end{vmatrix} = (-1000i + 500j)\text{ N}\cdot\text{m}$$

$$|\vec{M}_y| = \vec{M}_o \cdot \hat{y} = \begin{pmatrix} -1000 \\ 500 \\ 0 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} = \boxed{500\text{ N}\cdot\text{m}}$$

(d) $\vec{F}_R = \vec{F}_{BA} + \vec{F}_{BC}$

$= (200i - 400j - 400k) + (100i + 200j - 200k)$

$= \boxed{(300i - 200j - 600k)\ N}$

$(\vec{M}_R)_O = (\vec{M}_{BC})_O + (\vec{M}_{BA})_O$ → $(\vec{M}_{BC})_O$ gotten from 1(c)'s working.

$= (-1000i + 500j) + (\vec{r}_{OB} \times \vec{F}_{BA})$

$= (-1000i + 500j) + \left[\begin{pmatrix} 0 \\ 0 \\ 5 \end{pmatrix} \times \begin{pmatrix} 200 \\ -400 \\ -400 \end{pmatrix} \right]$

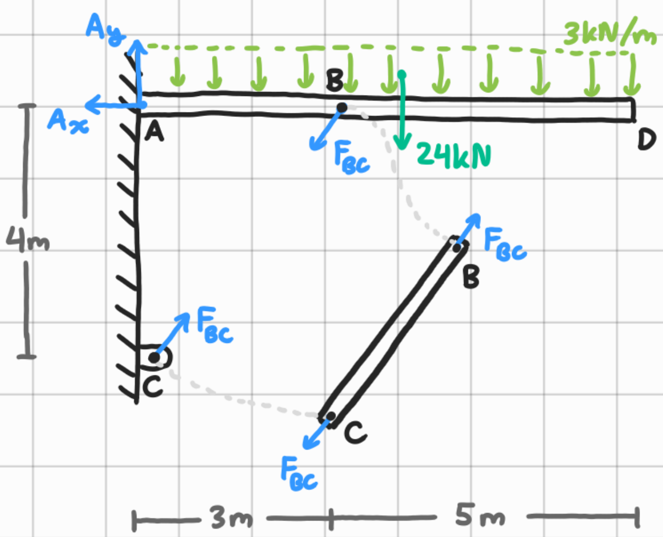
$= (-1000i + 500j) + \begin{vmatrix} i & j & k \\ 0 & 0 & 5 \\ 200 & -400 & -400 \end{vmatrix}$

$= (-1000i + 500j) + (2000i + 1000j)$

$= \boxed{(1000i + 1500j)\ N \cdot m}$

(2.) (a) Notice that member BC is a two-force member as it only has forces applied at only two points of the member. This implies that the reaction force at joint B has the same magnitude but opposite direction with the reaction force at joint C (F_{BC}).

⚠ If member BC is not a two-force member, you CANNOT use F_{BC} directly. You must assign B_x and B_y at joint B & C_x and C_y at joint C instead.



Tip: For frames, separate each member & draw action-reaction pairs.

Beam AD

$$\circlearrowleft + \Sigma M_B = -A_y(3) - 24(1) = 0$$

$$\Rightarrow A_y = -8\,kN$$

$$+\uparrow \Sigma F_y = A_y - 24 - F_{BC}\left(\tfrac{4}{5}\right) = 0$$

$$-8 - 24 - \tfrac{4}{5}F_{BC} = 0$$

$$\Rightarrow F_{BC} = -40\,kN$$

$$\overset{+}{\rightarrow} \Sigma F_x = -A_x - F_{BC}\left(\tfrac{3}{5}\right) = 0$$

$$-A_x - (-40)\left(\tfrac{3}{5}\right) = 0$$

$$\Rightarrow A_x = 24\,kN$$

$$\boxed{\begin{aligned} \therefore\ A_x &= 24\,kN\ (\leftarrow) \\ A_y &= 8\,kN\ (\downarrow) \\ F_{BC} &= 40\,kN\ (\swarrow) \end{aligned}}$$

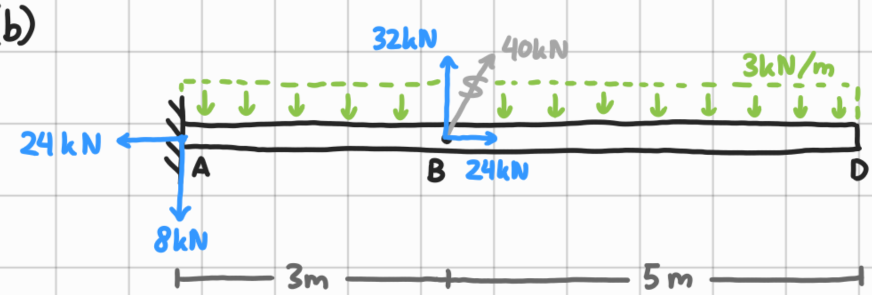
$\}$ at A

→ at C

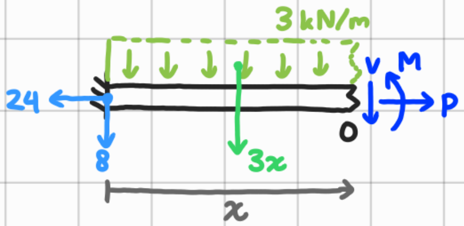
* It's okay to have negative numbers in working; it means the force is in opposite direction to your FBD.

NO NEED to REDRAW. Just remember to state the direction of your force in your final answer.

(b)



Section AB:



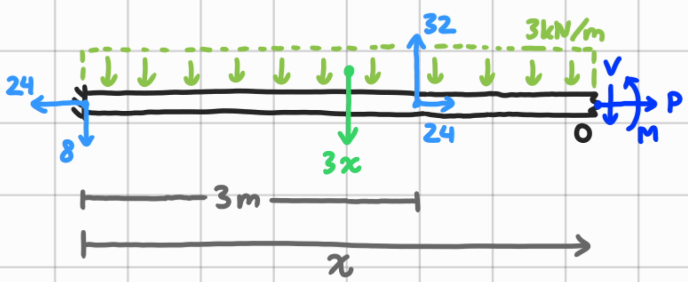
$$+\uparrow \Sigma F_y = -V - 3x - 8 = 0$$

$$V = -3x - 8$$

$$\circlearrowleft + \Sigma M_o = M + 3x\left(\frac{x}{2}\right) + 8(x) = 0$$

$$M = -\frac{3}{2}x^2 - 8x$$ (You should get $V = \frac{dM}{dx}$)

Section BD:

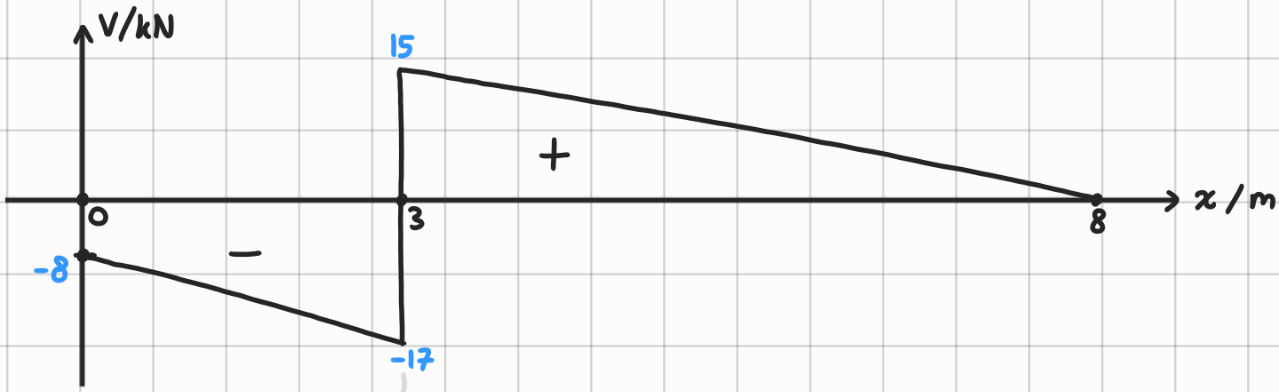


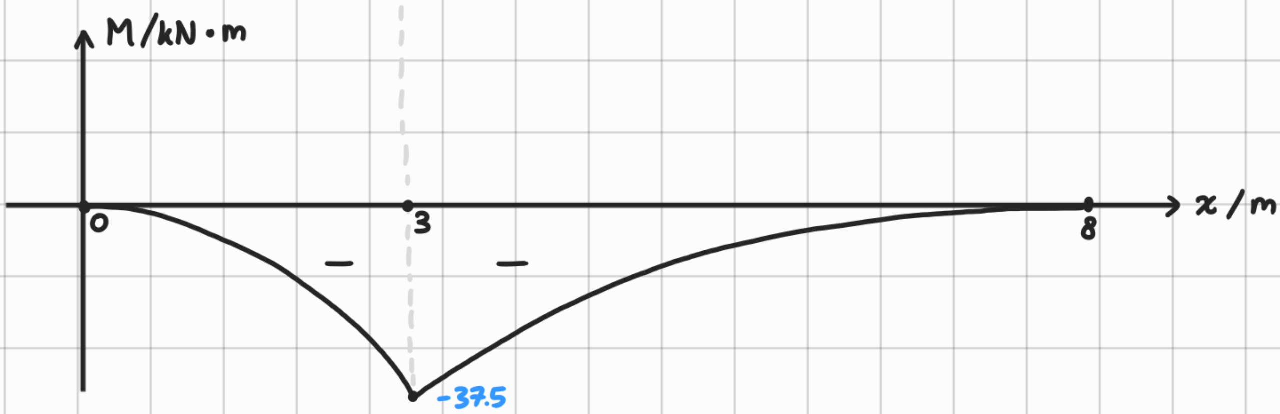
$$+\uparrow \Sigma F_y = -V + 32 - 3x - 8 = 0$$

$$V = -3x + 24$$

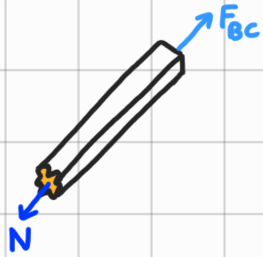
$$\circlearrowleft + \Sigma M_o = M - 32(x-3) + 3x\left(\frac{x}{2}\right) + 8(x) = 0$$

$$M = -\frac{3}{2}x^2 + 24x - 96$$





(c)



$$\sigma_{allow} = \frac{N}{A}$$

$$A = \frac{N}{\sigma} = \frac{F_{BC}}{\sigma} = \frac{40 \times 10^3 \text{ N}}{200 \times 10^6 \text{ Pa}} = 2 \times 10^{-4} \text{ m}^2 = \boxed{2 \text{ mm}^2}$$

(d) As member BC has a constant cross-section area & material,

$$\delta = \frac{NL}{AE} = \frac{(40 \times 10^3)(5)}{(2 \times 10^{-4})(50 \times 10^9)} = 0.02 \text{ m} = \boxed{20 \text{ mm}}$$

(e) Pin A:

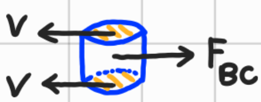
$$F_A = \sqrt{A_x^2 + A_y^2} = \sqrt{24^2 + 8^2} = 25.30 \text{ kN}$$

$$\tau = \frac{V}{A}$$

$$\tau = \frac{F_A}{\frac{\pi}{4} d^2}$$

$$d = \sqrt{\frac{4F_A}{\pi \tau}} = \sqrt{\frac{4(25.30 \times 10^3)}{\pi (100 \times 10^6)}} = 0.01795 \text{ m} = \boxed{18 \text{ mm}}$$

Pin B:

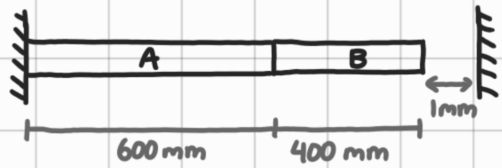


$V = \frac{1}{2} F_{BC}$!

$$\tau = \frac{V}{A} = \frac{\frac{1}{2} F_{BC}}{\frac{\pi}{4} d^2}$$

$$d = \sqrt{\frac{2F_{BC}}{\pi \tau}} = \sqrt{\frac{2(40 \times 10^3)}{\pi (100 \times 10^6)}} = 0.01596 \text{ m} = \boxed{16 \text{ mm}}$$

3. (a)



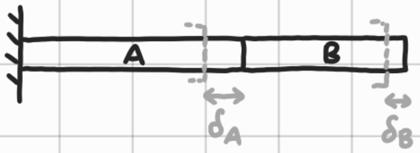
$A = 2500 \text{ mm}^2$ $\quad \alpha_A = 2 \times 10^{-5} /°C$

$E = 200 \text{ GPa}$ $\quad \alpha_B = 4 \times 10^{-5} /°C$

$\Delta T = 50°C$

Using the flexibility / force method ...

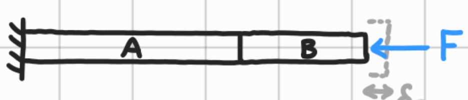
Stage 1 : Expansion



$$\delta_H = \delta_A + \delta_B = (L_A \cdot \alpha_A \cdot \Delta T) + (L_B \cdot \alpha_B \cdot \Delta T)$$
$$= (600 \cdot 2 \times 10^{-5} \cdot 50) + (400 \cdot 4 \times 10^{-5} \cdot 50)$$
$$= 1.4 \text{ mm}$$

As the expansion by heat, δ_H, is greater than the gap, 1mm, there is an axial force as the rod reaches the right wall.

Stage 2 : Axial force



Internal axial force, N, is = F throughout.

$$\delta_F = \delta_{N_A} + \delta_{N_B}$$
$$= \frac{F \cdot L_A}{A \cdot E} + \frac{F \cdot L_B}{A \cdot E}$$

Section A & B has the same area & Young's modulus & axial force.

$$= \frac{F}{A \cdot E}(L_A + L_B)$$

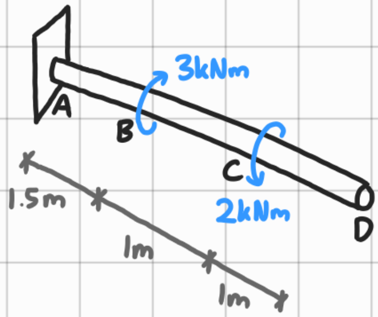
By compatibility, $\delta_H - \delta_F = 1 \text{mm}$

$$1.4 - \delta_F = 1$$
$$\delta_F = 0.4 \text{ mm}$$
$$\frac{F}{A \cdot E}(L_A + L_B) = 0.4 \times 10^{-3} \text{ m}$$

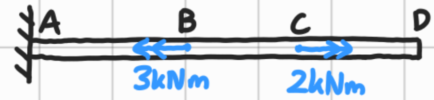
$$F = \frac{(0.4 \times 10^{-3})AE}{(L_A + L_B)} = \frac{(0.4 \times 10^{-3})(2500 \times 10^{-6})(200 \times 10^9)}{(1)} = 200\,000 \text{ N}$$

$$= \boxed{200 \text{ kN, compressive.}}$$

(b) (i)



$\Rightarrow$



$G = 80$ GPa $\quad \varnothing$ 100 mm

$$J = \frac{\pi}{2}c^4 = \frac{\pi}{2}\left(\frac{100}{2}\times 10^{-3}\right)^4 = 9.817\times 10^{-6}\ m^4$$

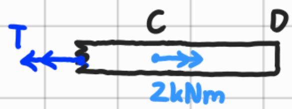
<u>Finding internal torques:</u>

Note:
Internal torque is assigned positive if directed away from the shaft.

Section CD:

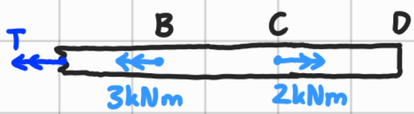
$T = 0$

Section BC:



$\overset{+}{\twoheadrightarrow} \Sigma M = 2 - T = 0 \Rightarrow T = +2$ kNm

Section AB:



$\overset{+}{\twoheadrightarrow} \Sigma M = 2 - 3 - T = 0 \Rightarrow T = -1$ kNm

Max. torque at section BC, so max. shear stress happens at the outer-most surface of section BC.

$$\tau = \frac{Tc}{J} = \frac{(2\times 10^3)\left(\frac{100}{2}\times 10^{-3}\right)}{(9.817\times 10^{-6})} = 10\,180\,000 \text{ Pa} = 10.2 \text{ MPa}$$

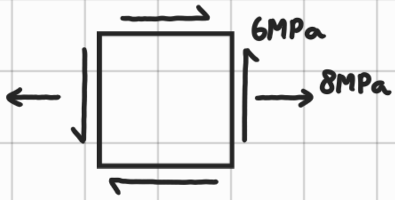
$$\boxed{\therefore\ \tau_{max} = 10.2 \text{ MPa, outer-most surface of section BC.}}$$ //

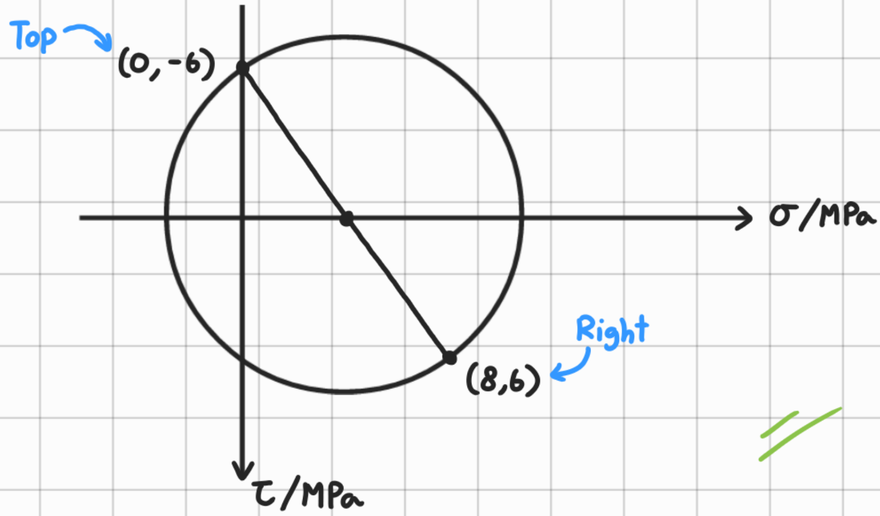
(ii) The graduate engineer is right.

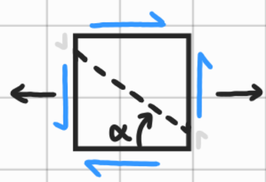
Let's say the angle of twist of section BC ($\phi_{C/B}$) changes by +1, while the angle of twist of section AB ($\phi_{B/A}$) changes by −1. The net change of the angle ($\phi_{D/A}$) at D would be zero.

As the device only measure the angle of twist at D, the corrosion would be undetected.

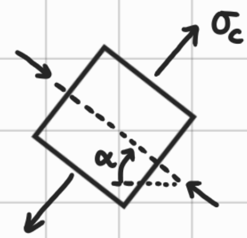
4. (a) (i)

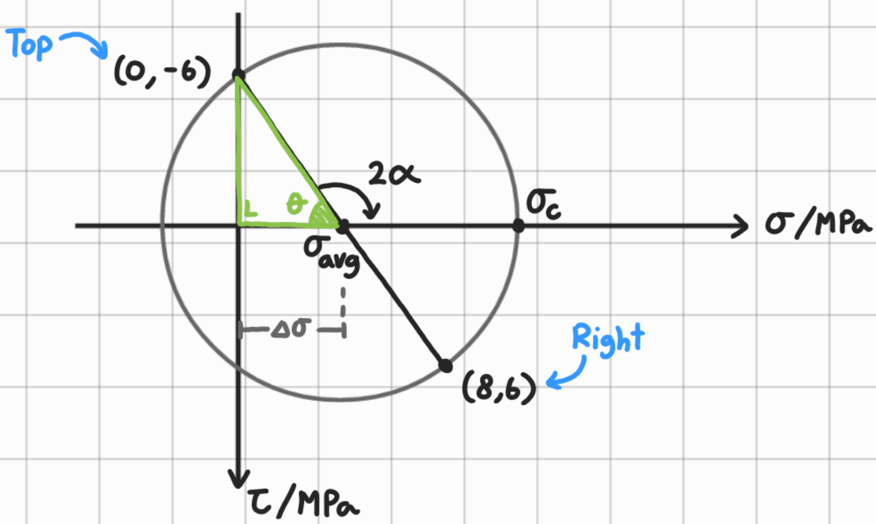




(ii) 

can be transformed to





$\sigma_c = \sigma_{avg} + R$ → R is the radius of the circle.

$$= \sigma_{avg} + \sqrt{\Delta\sigma^2 + \tau_{xy}^2} = \left(\frac{0+8}{2}\right) + \sqrt{\left(\frac{0-8}{2}\right)^2 + (6)^2} = \boxed{11.2 \text{ MPa}}$$

$\triangle$: $\tan\theta = \dfrac{\tau_{xy}}{\Delta\sigma}$

$$\theta = \tan^{-1}\left(\frac{\tau_{xy}}{\Delta\sigma}\right) = \tan^{-1}\left(\frac{6}{\frac{8-0}{2}}\right)$$

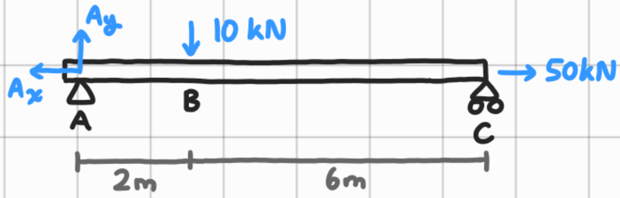
$$= 56.3^\circ$$

$2\alpha + \theta = 180^\circ$

$$\alpha = \frac{180^\circ - \theta}{2} = \frac{180^\circ - 56.3^\circ}{2}$$

$$\boxed{\therefore \alpha = 61.6^\circ}$$

(b) (i)



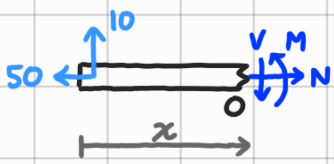
$\overset{+}{\rightarrow}\sum F_x = 50 - A_x = 0$

$\Rightarrow A_x = 50 \text{ kN}$

$+\uparrow \sum F_y = A_y - 10 = 0$

$\Rightarrow A_y = 10 \text{ kN}$

Section AB:

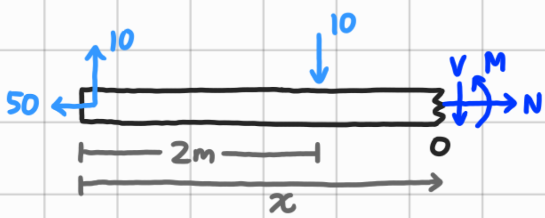


$\overset{+}{\rightarrow}\sum F_x = N - 50 = 0 \Rightarrow N = 50$

$+\uparrow \sum F_y = -V + 10 = 0 \Rightarrow V = 10$

$\circlearrowleft + \sum M_o = M - 10x = 0 \Rightarrow M = 10x$

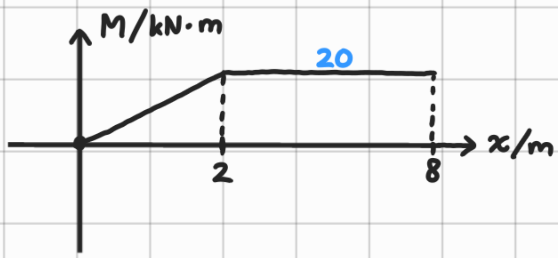
Section BC:



$\overset{+}{\rightarrow}\sum F_x = N - 50 = 0 \Rightarrow N = 50$

$+\uparrow \sum F_y = -V - 10 + 10 = 0 \Rightarrow V = 0$

$\circlearrowleft + \sum M_o = M + 10(x-2) - 10x = 0 \Rightarrow M = 20$

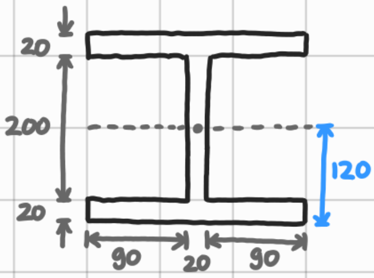


* No need shear as it does not affect normal stress.

- Max. bending moment is at section BC, which is + 20 kN·m (hogging).

- Axial force is constantly + 50 kN (tensile).

- To get max. normal stress, we want the normal stress from the hogging moment to add up with the one from the tensile force. This happens at the bottom of the beam. ()



$$A = 3(20 \times 200) = 12000 \text{ mm}^2 = 0.012 \text{ m}^2$$

$$I = I_{big} - 2I_{small}$$

$$= \frac{1}{12}(200)(240)^3 - 2\left[\frac{1}{12}(90)(200)^3\right]$$

$$= 110400000 \text{ mm}^4 = 1.104 \times 10^{-4} \text{ m}^4$$

*May also use $(I_{top} + I_{web} + I_{bottom})$ instead, just a bit longer as must use parallel axis theorem on I_{top} & I_{bottom}.

$$\sigma_{max} = \frac{My}{I} + \frac{N}{A} = \left[\frac{(20 \times 10^3)(120 \times 10^{-3})}{(1.104 \times 10^{-4})} + \frac{(50 \times 10^3)}{0.012}\right] \times 10^{-6} \text{ MPa}$$

$$= 21.7 \text{ MPa} + 4.16 \text{ MPa}$$

$$= 25.9 \text{ MPa}$$

$$\boxed{\therefore \sigma_{max} = 25.9 \text{ MPa, at the bottom of section BC.}}$$ //

(ii) Statement invalid. Buckling can only happen when the beam is in axial compression. //