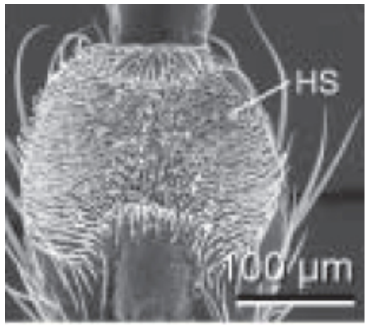
_____1. On your research trip with Professor Dudley to Panama you discover a new species of beetle that only lives upside-down stuck to the undersurface of plants and rocks. You are curious about the mechanism of attachment. You bring back several live animals. You take a picture of the foot with your electron microscope when you return.



a) The new species looks like it has Velcro-like pads with hooks. Design an experiment to test whether or not the new species adheres by interlocking. (4 points)

-Place the animal on molecularly smooth surfaces.
Or
-remove hooks and test whether then animal can still adhere to the surface

b) The whole pad looks as though it could form a tight seal with a smooth surface. Design an experiment to test whether or not the new species adheres by suction. (4 points)

-Attempt to attach foot in a vacuum.
-Break seal around outside foot (either by placing it on a rough substrate or a substrate with holes in it) and check whether the animal can still adhere.
-Measure pressure under the foot to see if it exceeds ambient pressure.

c) In the humid environment, you noticed that a fluid might be associated with the pad. You hypothesize that wet or capillary adhesion might be involved. Design experiments to test if wet or capillary adhesion is being used. State how and why the experiment will affect shear forces (parallel to the plant) and vertical (perpendicular) pull-off forces when upside-down. (4 points)

Answers worth full credit:
-Generate shear and vertical forces with a device such as a turntable.
Vary temperature. If wet adhesion is involved, then the rate of slipping in shear should increase with temperature because viscosity decreases. If wet adhesion is involved, then the forces developed perpendicular to the surface should not vary with temperature because surface tension only has weak temperature dependence.

-Vary surface properties. Compare a hydrophobic and hydrophilic surface. If wet adhesion is involved, then the pad will not stick to the hydrophobic surface.

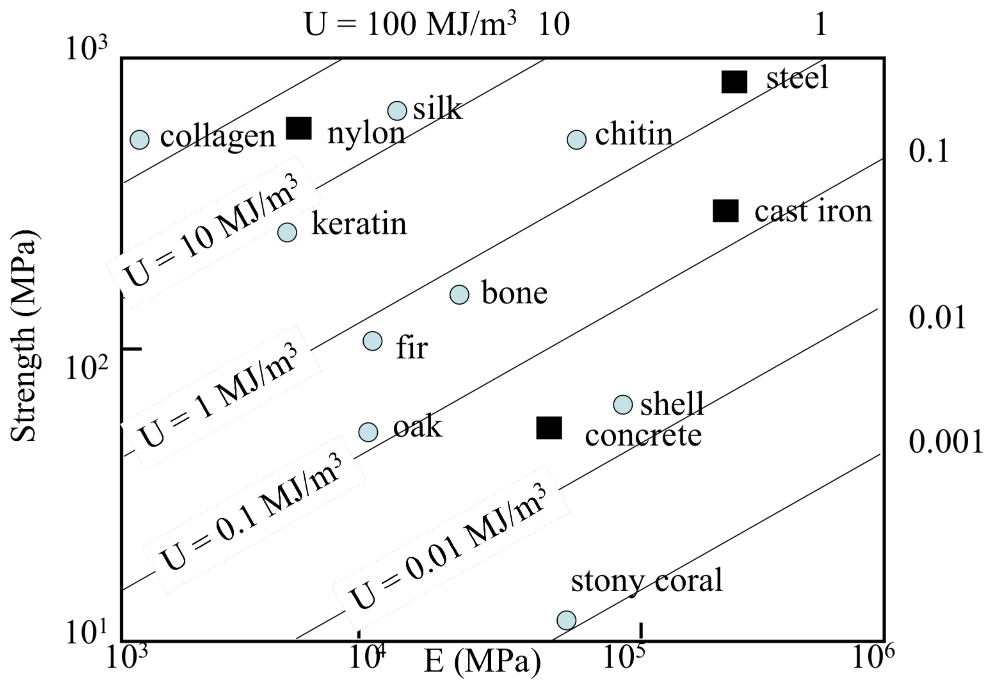
-place the organism in water and test if it can still adhere (this eliminates surface tension)

-add something to the fluid that breaks up surface tension (such as detergent).

-remove the fluid from the pad and test whether it can still adhere. (full credit).

2 points: putting the organism in a dry environment. (the organism could be excreting its own fluid)

_____2. Use the data given and the plot of breaking strength, Young's modulus (E) and toughness (U, energy per volume) in tension to compare materials and challenge the claims.



a) Oak and fir can't have the same E, because the stress measured in fir is higher when measured in tension. True or false given the following data? Fir stress = 70 MPa; strain = 0.007 ; Oak stress = 40 MPa; strain = 0.004. Assume Hookean behavior. Justify your answer by calculating E and comparing directly. (5 points)

Minus one point if units are labeled incorrectly

False (1 point)
E is the same as shown on the plot.
$E = \sigma / \varepsilon$
Fir = 70/0.007 = 10,000 MPa
Oak = 40/0.004 = 10,000 MPa
(4 points)

b) Bone and fir have the same toughness when measured in tension. True or false given the following data? Bone breaking stress = 198 MPa; E = 20,000 MPa ; Fir breaking stress = 140 MPa; E = 10,000 MPa. Justify your answer by calculating toughness for one cubic meter of material and comparing directly. (5 points)

Minus one point if units are labeled incorrectly

True (1 point)

Toughness is the same as shown on the plot.
$T = \sigma^2 / (2E)$
Bone = $(198^2)/(2*20{,}000) = 0.98$ MJ/m^3
Fir = $(140^2)/(2*10{,}000) = 0.98$ MJ/m^3
(4 points)

c) Keratin can't be 100 times tougher than cast iron because they have the same strength. True or false? Explain by comparing breaking strength, E and toughness. (6 points)

Minus one point if units are labeled incorrectly

False (1 point)

Explanation (5 points): to the extent that Keratin is 100 times tougher because it is over 10-fold more compliant (lower E). Since strength is the same, the mechanical strain energy required to break keratin is greater. This explanation could be in words or could utilize the toughness equation ($T = \sigma^2 / (2E)$).

d) Chitin from an insect's exoskeleton is over 1000 times tougher than stony coral, yet has the same normalized stiffness (Young's modulus). True or false? Explain by comparing breaking strength, E and toughness. (6 points)

True (1 point)

Explanation (5 points): Chitin is 1000 times tougher because its strength is over 100-fold greater than stony coral. Writing out the toughness equation $T = \sigma^2 / (2E)$, with no further explanation: 2 points.

Question 3 (18 points)

Part A (4 points)

(2 points): Setting up the Reynolds number equation properly:

$$\mathrm{Re} = \frac{\rho U L}{\mu}$$

(1 point): Putting in the right numbers, ie.

$$\begin{aligned} \rho &= 0.8 \times 1.205 \ \mathrm{kg\,m^{-3}} = 0.964 \ \mathrm{kg\,m^{-3}} \\ U &= 7 \ \mathrm{m\,s^{-1}} \\ L &= 0.34 \ \mathrm{m} \\ \mu &= 18.08 \times 10^{-6} \ \mathrm{Pa\,s} \end{aligned}$$

(1 point): Getting the right answer:

$$\mathrm{Re} \approx 1.3 \times 10^5$$

Part B (6 points)

(3 points): Setting up the non-dimensionalized lift equation properly, i.e.

$$L = 0.5 \rho S U^2 C_d$$

(2 points): Putting in the right numbers, ie.

$$\begin{aligned} \rho &= 0.8 \times 1.205 \ \mathrm{kg\,m^{-3}} = 0.964 \ \mathrm{kg\,m^{-3}} \\ U^2 &= 49 \ \mathrm{m^2\,s^{-2}} \\ S &= 2 \times 0.5 \ \mathrm{m^2} = 1 \ \mathrm{m^2} \quad \text{(2 wings)} \\ C_d &= 1.2 \end{aligned}$$

(1 point): Getting the right answer:

$$L \approx 28 \ N$$

Part C (8 points)

(6 points): Understanding that the glide angle θ is related to the lift to drag ratio via

$$\cot\theta = \frac{L}{D}$$

(2 points): Getting the right answer:

$$\begin{aligned} \cot\theta &= \frac{L}{D} \\ D &= L\tan\theta \\ &= 28\tan(14^\circ) \\ &\approx 7\text{N} \end{aligned}$$

Question 4 (16 points)

Part A (8 points)

(2 points): Calculating the correct wing length:

$$L = \frac{[\text{Wingspan}] - [\text{Body Width}]}{2} = \frac{1.85 - 0.342}{2} = 0.754 \text{ m}$$

(2 points): Calculating the weight supported by a single wing, assuming that each wing supports half the weight of the bird:

$$F = \frac{mg}{2} = \frac{5.8 \times 9.8}{2} \approx 28.5 \text{ N}$$

(2 points): Using the correct equation for the moment acting upon a *uniformly loaded cantilever beam*

$$M = \frac{Fx^2}{2L}$$

The maximum moment will occur when $x = L$, i.e.

$$M_{\text{max}} = \frac{FL}{2}$$

Full credit awarded for use of the point loaded cantilever beam moment equation ($M = Fx$) **if** the assumption that a uniform loading scheme could be approximated by a point load halfway out along the wing was made explicitly.

(2 points): Calculating the maximum moment correctly:

$$M = \frac{FL}{2} = \frac{28.5 \times 0.754}{2} \approx 10.8 \text{ N m}$$

Part B (8 points)

(3 points): Knowing that the stress distribution within a loaded beam is given by

$$\sigma = \frac{My}{I}$$

This equation did not appear explicitly in the appendix, and so partial credit of **2 points** was awarded for the incorrect use of the stress distribution equation for a point loaded cantilever beam:

$$\sigma = \frac{Fxy}{I}$$

(Note that the term Fx in this equation is the moment M applied by a point load at the end of a beam)

(2 points): Using the correct equation for the second moment of area, I:

$$I = \frac{\pi}{4}\left(r_{\text{outer}}^4 - r_{\text{inner}}^4\right)$$

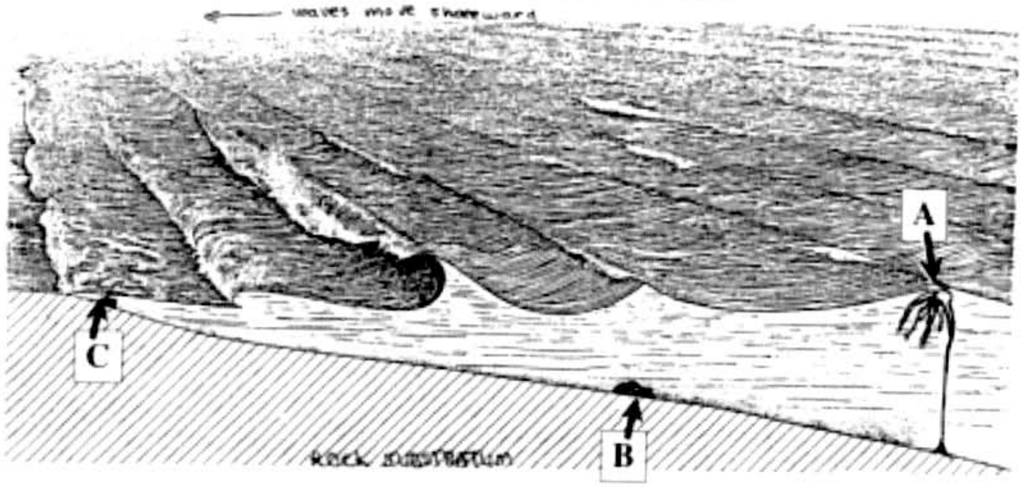
(1 point): Calculating I correctly:

$$\begin{aligned} I &= \frac{\pi}{4}\left(r_{\text{outer}}^4 - r_{\text{inner}}^4\right) \\ &= \frac{\pi}{4}\left(0.0115^4 - (0.0115 - 0.002)^4\right) \\ &\approx 7.34 \times 10^{-9} \text{ m}^4 \end{aligned}$$

(2 points): Getting the right answer:

$$\begin{aligned} \sigma &= \frac{My}{I} \\ &= \frac{10.8 \times 0.0115}{7.34 \times 10^{-9}} \\ &\approx 1.69 \times 10^{7} \text{ N m}^{-2} \end{aligned}$$

____ 6. Below is a diagram of waves moving shoreward.



a) During a full wave cycle, what direction(s) of water flow does the bulb of the kelp at position "A" (near the water surface) encounter? To answer this, start out saying what direction the water is moving at the instant shown in the diagram (the wave crest is at the kelp bulb), and then list the direction(s) the water moves as the wave shape moves shoreward, until the next wave crest arrives at the kelp bulb. (4 points)

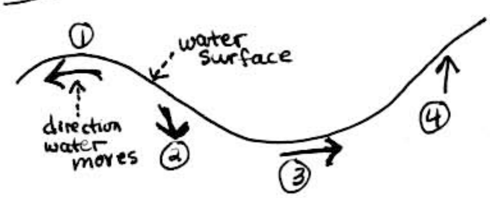
(1 pt. each)
- The water moves shoreward (at the wave crest),
- then down,
- then seaward (at the wave trough),
- and then up.

or
shoreward
down
seaward
up

or (OK for this diagram)
left
down
right
up

or a correct diagram:

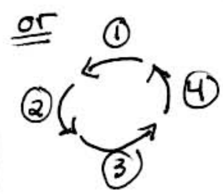
or



or
←
↓
→
↑

or ← ↓ → ↑

or



or a similar diagram that makes it clear which direction the water is moving, starting with the shoreward direction, such as this

partial credit:

(3 pts.)  a diagram or verbal description that makes it clear that the water flows in a circle or orbit, but that does not make it clear that the cycle described starts with shoreward flow

(2 pts.)  a diagram or verbal description that makes it clear that the water flows in a vertical orbit, but that has the directions backwards

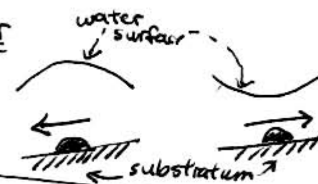
6. (continued)

b) During a full wave cycle, what direction(s) of water flow does the sponge sitting on the substratum at position B encounter? As in question "a)", start with the flow direction at the instant shown in the diagram. (4 points)

{2 pts. each} → The water flows shoreward (under the wave crest), → and then seaward (under the wave trough)

(NOTE: The point here is to recognize that the sponge is in shallow water (the depth is < ½ wavelength), and thus experiences back-and-forth flow when the wave passes overhead.)

or shoreward / seaward | or left / right | or ← → | or ① → ② ← | or

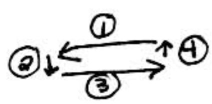


partial credit ⟷ a diagram or a verbal description that shows that the flow is back-and-forth, but that does not make it clear that the flow moves shoreward under the wave crest, or moves forward first.

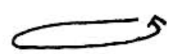
{3 pts}

{2 pts}  a diagram or verbal description that says the water is flowing in an orbital path

BUT – full credit {4 pts} if you thought that the sponge was tall enough to encounter a flattened elliptical flow pattern and you got the directions in the correct order:



or



c) Describe the water flow encountered by the barnacle at position C, shoreward of the breaking waves. It is hard to know from the diagram exactly what the wave is doing at this instant, so just state in general terms which direction(s) the water moves during one wave cycle at position C. (4 points)

{4 pts} → The water moves shoreward and seaward
or
→ back-and-forth or ⟷ etc.... (as in question "b)", except that you did not have to worry about saying shoreward first.
or left and right

partial credit: {2 pts} for giving just one direction:
{2 pts} for thinking the flow was orbital

d) If the hemispherical sponge at position B doubled its radius, what would happen to the instantaneous drag forces that it experiences? (i.e., Would they stay the same, or would they increase or decrease? If they increase or decrease, by what factor?) (5points)

Drag $\propto$ S, where S is the projected area of the sponge ⊥ to the flow
since S $\propto$ radius^2, doubling the radius would increase the drag by a factor of 4

or $D(t) = \frac{1}{2}\rho C_D U_{(t)}^2 S$ where: $D(t)$ = instantaneous drag at time t
ρ = density of water
C_D = drag coefficient
U_t = velocity at time t
S = projected area of sponge at right angles to flow
r = radius of sponge

for a hemispherical sponge, $S = \frac{1}{2}\pi r^2$

$$\left(\frac{\text{drag on large sponge}}{\text{drag on small sponge}}\right) = \frac{\frac{1}{2}\rho C_D U_t^2 \left(\frac{1}{2}\pi [2r]^2\right)}{\frac{1}{2}\rho C_D U_t^2 \left(\frac{1}{2}\pi r\right)^2} = 4$$

---

partial credit: (1 pt) for saying the drag would increase

(3 pts) for saying the drag would increase and for indicating you understood that drag depended on projected area, but getting the factor wrong

NOTE:
– drag $\propto$ projected area, not surface area

– simply writing $D \propto S$ or $D = \frac{1}{2}\rho C_D U^2 S$ without defining the symbols is not useful

normally you would have lost partial credit for these mistakes
However, since this question was near the end of an exam that appears to have been too long, we'll let these errors slip by this time without deducting any points.
BUT.... we will take points off for such mistakes on the final exam !!!

6. (continued)

e) If the sponge doubled its radius, what would happen to the instantaneous acceleration reaction forces? (i.e. Would they stay the same, or would they increase or decrease? If they increase or decrease, by what factor?) (5 points)

acceleration reaction $\propto V$, where V = volume of the sponge
since $V \propto \text{radius}^3$,
doubling radius leads to an increase in acceleration reaction by a factor of 8

---

or $A(t) = C_m V \rho \left(\frac{dU}{dt}\right)_t$

where: $A(t)$ = instantaneous acceleration reaction force at time t

V = volume of sponge

ρ = density of the water

$\left(\frac{dU}{dt}\right)_t$ = instantaneous acceleration of the water at time t

r = radius

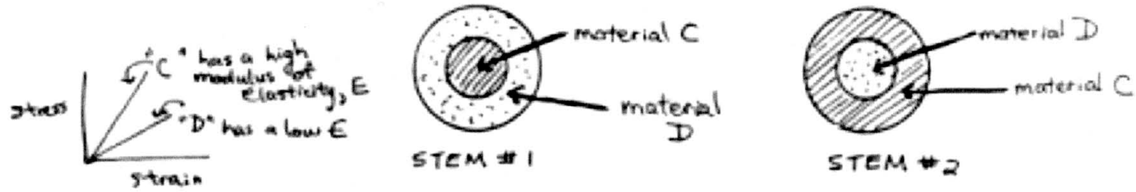
for a hemispherical sponge,
$\text{Volume} = \frac{1}{2}\left(\frac{4}{3}\pi r^3\right) = \frac{2}{3}\pi r^3$

$$\frac{A(t) \text{ on large sponge}}{A(t) \text{ on small sponge}} = \frac{C_m \rho \left(\frac{dU}{dt}\right)_t \left(\frac{2}{3}\pi [2r]^3\right)}{C_m \rho \left(\frac{dU}{dt}\right)_t \left(\frac{2}{3}\pi r^3\right)} = 8$$

---

see notes about partial credit for question 6, d)

______7. The diagrams below (drawn to the same scale) are of cross-sections of the stems of two hypothetical plants made of materials "C" and "D". The stress (s) strain (e) curves for "C" and "D" are also shown below. Assume that the entire weight on the stem is due to the crown of the plant, and that the crowns of #1 and #2 are identical in size, shape, and weight. Also assume that the stems are of uniform cross-section along their lengths.



a) Which stem can grow to a greater height before it undergoes Euler buckling. (#1 or #2)?
__#2__ (2 point)

b) Explain your answer. (8 points)

The critical load to cause Euler buckling, $F_E \propto EI$. ← (2 pts)
C is stiffer material than D (it has a higher elastic modulus, E) ← (2 pts)
In stem #2, the total EI is greater than in stem #1 because the stiffer material (C) is distributed around the periphery of the stem (far from the neutral axis) where it has a higher I, and thus contributes more to resisting the bowing of the stem. (4 pts)

(or you could write out that: total $EI = (EI)_{material\,D} + (EI)_{material\,C}$
Since the I for material C in stem #2 is greater than the I for material C in #1:
$(E_C I_C)_2 > (E_C I_C)_1$, and for material D: $(E_D I_D)_1 > (E_D I_D)_2$
$(I_C)_2 = (I_D)_1$. Since $(E_C I_C)_2 > (E_D I_D)_1$, then $(\text{total } EI_2) > (\text{total } EI_1)$.)

Note: It's actually more complex than this, so the total EI is not just this simpled sum. Nonetheless, you get full credit for reasoning through the problem this way.