3.4 Mechanics and Materials: 2-hour Pack

AQA 7408 · Calculator allowed · about 120 minutes

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 A car of mass 900 kg, travelling at 18 m/s, collides with a barrier and is brought to rest by the energy-absorbing crumple zone in the front of the car.

(a) Calculate the change in momentum of the car during the collision. **(2)**

(b) The collision brings the car to rest in 0.12 s. Given that force = change in momentum/time, calculate the average force exerted on the car during the collision. **(3)**

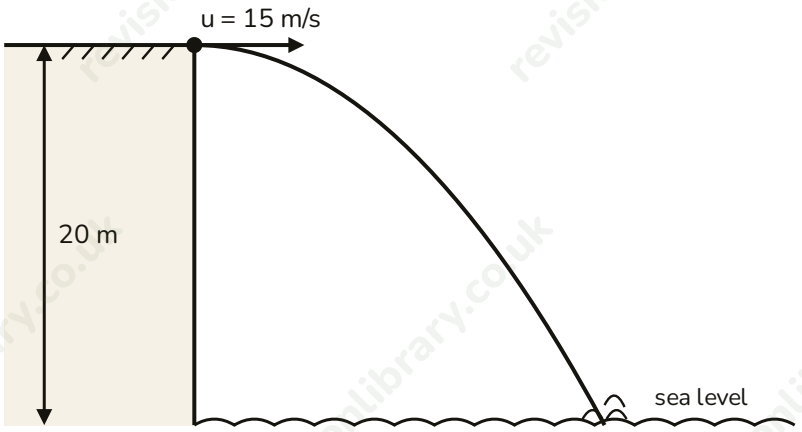
(c) The car is redesigned with a longer crumple zone, so that in an identical collision it now takes 0.20 s to come to rest. Calculate the new average force on the car. **(2)**

(d) Explain, in terms of impulse, why increasing the duration of the collision reduces the risk of injury to the occupants of the car. **(3)**

(Total for Question 1 is 10 marks)

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2 A stone is thrown horizontally with a speed of 15 m/s from the top of a cliff at Flamborough Head, 20 m above the sea. Air resistance can be ignored. Take $g = 9.81\ m/s^2$. Use the Physics Equations Sheet where needed.



(a) Show that the time taken for the stone to fall to sea level is about 2.0 s. **(2)**

(b) Calculate the horizontal distance travelled by the stone before it lands. **(2)**

(c) Calculate the vertical component of the stone's velocity as it lands. **(2)**

(d) Calculate the magnitude and direction of the stone's resultant velocity as it lands. **(4)**

(Total for Question 2 is 10 marks)

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3 Trolley A, of mass 0.80 kg, moves at 3.0 m/s and collides with stationary trolley B, of mass 1.20 kg. The trolleys stick together and move off with a common velocity.

(a) Calculate the momentum of trolley A immediately before the collision. **(2)**

(b) Use conservation of momentum to calculate the common velocity of the trolleys immediately after the collision. **(3)**

(c) Calculate the total kinetic energy before the collision, the total kinetic energy after the collision, and hence the kinetic energy lost in the collision. **(4)**

(d) State and explain what has happened to the kinetic energy lost during the collision. **(2)**

(Total for Question 3 is 11 marks)

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4 A statue made from a bronze alloy has a mass of 45 kg and a volume of 5.2×10^{-3} m^3. Density of water = 1000 kg/m^3. Take g = 9.81 m/s^2. Upthrust = density of fluid x volume displaced x g.

(a) Calculate the density of the bronze alloy. **(2)**

(b) The statue is fully submerged in a tank of water for cleaning. Calculate the upthrust acting on it. **(3)**

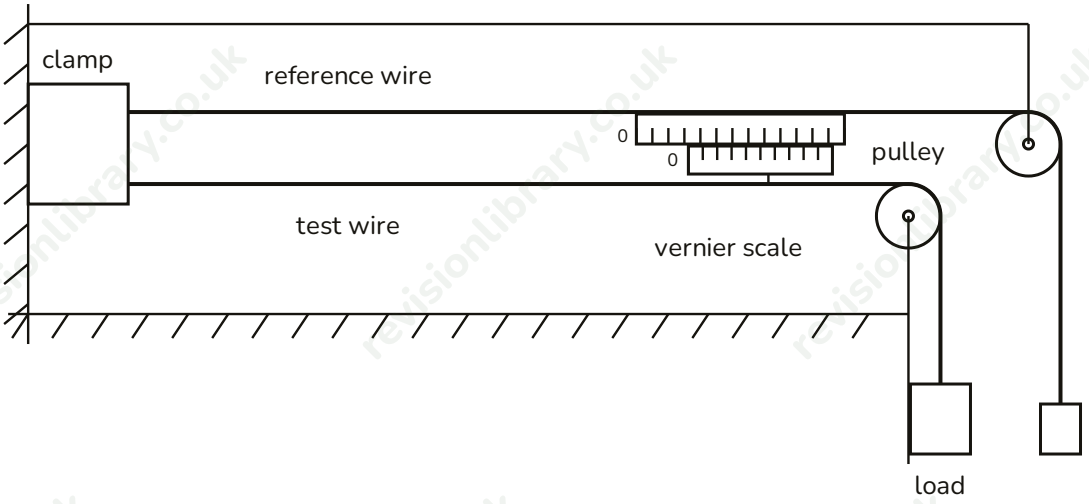
(c) Calculate the apparent weight of the statue while it is fully submerged. **(3)**

(d) Explain, using the concept of upthrust, why the reading on a support balance holding the statue decreases when it is lowered into the water. **(2)**

(Total for Question 4 is 10 marks)

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5 This question is based on the required practical: determination of the Young modulus of a metal wire. A student sets up a copper test wire of original length 2.00 m and diameter 0.28 mm, clamped horizontally and passed over a pulley with a load attached, alongside a fixed reference wire and vernier scale to measure extension. A load of 20 N produces an extension of 5.6 mm, which is within the elastic limit of the wire. Assume the wire has a uniform circular cross-section.



(a) Calculate the cross-sectional area of the wire. **(3)**

(b) Calculate the strain in the wire. **(2)**

(c) Calculate the stress in the wire when it supports the 20 N load. **(2)**

(d) Calculate the Young modulus of the copper wire from this data. **(2)**

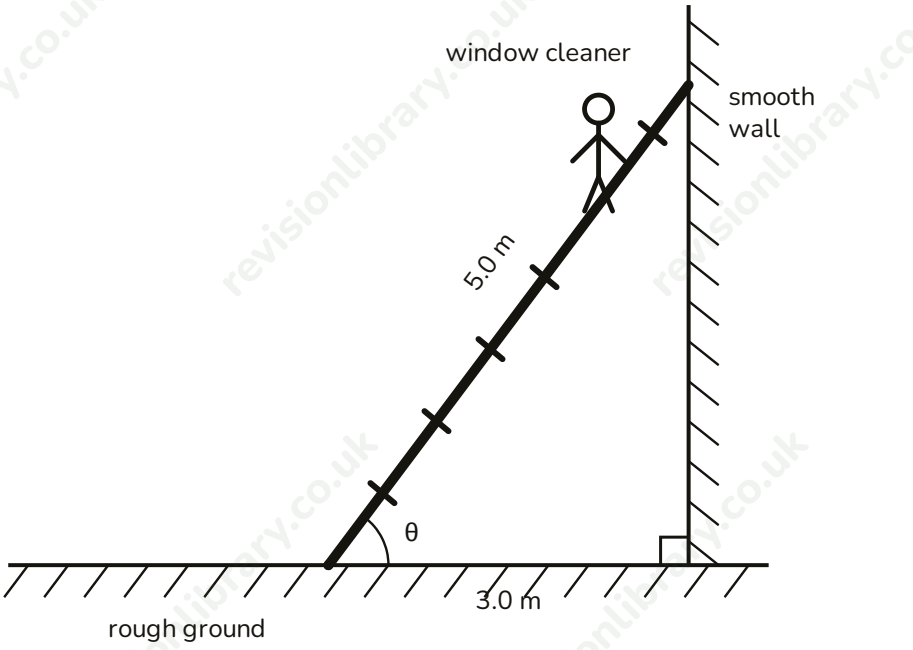
(e) State one precaution taken in this experiment that improves the reliability of the result. **(1)**

(f) Given that the elastic strain energy stored in a stretched wire is E_stored = 1/2 F x, calculate the elastic strain energy stored in the wire when the 20 N load produces the 5.6 mm extension. **(3)**

(Total for Question 5 is 13 marks)

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6 A uniform ladder of length 5.0 m and weight 120 N rests with its foot on rough ground, 3.0 m horizontally from a smooth vertical wall against which the top of the ladder leans. A window cleaner of weight 700 N stands three-quarters of the way up the ladder from the foot. Take g = 9.81 m/s^2.



(a) Calculate the angle between the ladder and the ground. **(2)**

(b) By taking moments about the foot of the ladder, calculate the normal reaction force exerted by the (smooth) wall on the ladder. **(4)**

(c) Calculate the frictional force acting at the foot of the ladder. **(2)**

(d) Calculate the normal reaction force from the ground acting on the ladder. **(2)**

(e) Calculate the minimum coefficient of friction between the ladder and the ground needed to prevent the ladder slipping. **(2)**

(Total for Question 6 is 12 marks)

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7 Car manufacturers design the front of a car to include a crumple zone: a section of the body structure that deforms plastically during a collision, absorbing energy, rather than remaining rigid. Evaluate how principles of work and energy, and the mechanical properties of the materials used, both contribute to reducing the risk of injury to occupants in a frontal collision. In your answer, refer to the work-energy relationship for bringing the car to rest, and to how the area under a force-extension (or stress-strain) graph for the crumple zone material represents energy absorbed through plastic deformation.

(Total for Question 7 is 6 marks)

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8 A conveyor belt in a warehouse carries crates of mass 40 kg up a ramp inclined at 15 degrees to the horizontal. The ramp is 6.0 m long and a constant friction force of 45 N opposes the motion of each crate. Crates are loaded onto the belt at a rate of 3 per minute and the belt moves at constant velocity. The motor driving the belt has an efficiency of 78%. Take $g = 9.81\ m/s^2$.

(a) Calculate the vertical height gained by a crate travelling the full length of the ramp. **(2)**

(b) Calculate the total work done on one crate against gravity and against friction as it travels up the full length of the ramp. **(3)**

(c) Given that crates are loaded at a rate of 3 per minute, calculate the useful mechanical power output of the belt. **(3)**

(d) Given that the motor is 78% efficient, calculate the electrical power that must be supplied to the motor. **(2)**

(Total for Question 8 is 10 marks)

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9 A block is placed on a ramp whose angle of incline can be increased. For the first surface, the block just begins to slide when the ramp angle reaches 22 degrees. A second block, on a different, rougher surface, just begins to slide at an angle of 31 degrees.

(a) By resolving the weight of the block into components parallel and perpendicular to the ramp surface, and considering the forces at the point of slipping, show that the coefficient of static friction is given by $\mu = \tan(\theta_c)$, where θ_c is the angle at which sliding just begins. **(3)**

(b) Calculate the coefficient of static friction for the first surface. **(2)**

(c) Calculate the coefficient of static friction for the second surface, and state which of the two surfaces provides more grip. **(2)**

(Total for Question 9 is 7 marks)

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Mark scheme · 3.4 Mechanics and Materials: 2-hour Pack

Question 1

(a) change in momentum = m x change in velocity, substitution **M1**

(a) 16200 kg m/s (1.62 x 10^4 kg m/s), cao **A1**

(a) Answer: 16200 kg m/s

(b) recall/apply F = change in momentum/time **M1**

(b) correct substitution using (a) and t = 0.12 s, ft **M1**

(b) 1.35 x 10^5 N, cao/ft **A1**

(b) Answer: 1.35 x 10^5 N

(c) correct substitution using (a) and new t = 0.20 s, ft **M1**

(c) 8.1 x 10^4 N, cao/ft **A1**

(c) Answer: 8.1 x 10^4 N

(d) the impulse (change in momentum) needed to stop the car is the same in both cases **B1**

(d) since force = change in momentum/time, increasing the collision time for the same change in momentum means the average force is smaller **B1**

(d) a smaller average force means a smaller deceleration of the occupants, reducing the risk of injury, oe **B1**

(d) Answer: For the same change in momentum, a longer collision time reduces the average force, and hence the deceleration and injury risk to occupants.

Question 2

(a) rearrange s = 1/2 g t^2 to make t the subject: t = $\sqrt{2s/g}$ **M1**

(a) cso: t = $\sqrt{2 \times 20/9.81}$ = 2.02 s, which is 2.0 s to 2 s.f. **A1**

(a) Answer: t = 2.0 s (2.02 s to 3 s.f.)

(b) x = v x t, using t = 2.02 s (ft from (a)) **M1**

(b) 30.3 m (accept 30-30.4 m), awrt **A1**

(b) Answer: 30.3 m

(c) v = g t, using t = 2.02 s (ft from (a)) **M1**

(c) 19.8 m/s (awrt), cao **A1**

(c) Answer: 19.8 m/s

(d) use Pythagoras: v_resultant = $\sqrt{vx^2 + vy^2}$, using values from (b)/(c), ft **M1**

(d) 24.8 m/s (accept 24.7-24.9 m/s), awrt **A1**

(d) use tan(θ) = vy/vx (or equivalent) to find the angle below the horizontal **M1**

(d) 52.9 degrees below the horizontal (accept 52-53 degrees), awrt **A1**

(d) Answer: 24.8 m/s at 52.9 degrees below the horizontal

Question 3

(a) p = m v substitution **M1**

(a) 2.4 kg m/s, cao **A1**

(a) Answer: 2.4 kg m/s

(b) apply conservation of momentum: $m_A u_A + m_B u_B = (m_A + m_B) v$ **M1**

(b) correct substitution: 0.80(3.0) + 1.20(0) = 2.00 v **M1**

(b) v = 1.2 m/s, cao **A1**

(b) Answer: 1.2 m/s

(c) KE before = 1/2 (0.80)$(3.0)^2$ = 3.6 J **M1**

(c) KE after = 1/2 (2.00)$(1.2)^2$ = 1.44 J, ft from (b) **M1**

(c) correct method: energy lost = KE before - KE after **A1**

(c) 2.16 J, cao/ft **A1**

(c) Answer: KE before = 3.6 J; KE after = 1.44 J; energy lost = 2.16 J

(d) momentum is conserved but kinetic energy is not, because the collision is inelastic **B1**

(d) the lost KE is transferred to other forms such as heat, sound and/or the permanent deformation of the trolleys, oe **B1**

(d) Answer: The collision is inelastic; kinetic energy is transferred to heat, sound and deformation of the trolleys.

Question 4

(a) density = mass/volume substitution **M1**

(a) 8650 kg/m^3 (accept 8600-8700 kg/m^3), awrt **A1**

(a) Answer: 8650 kg/m^3

(b) recall/apply upthrust = density of water x volume x g **M1**

(b) correct substitution: 1000 x 5.2x10^{-3} x 9.81 **M1**

(b) 51.0 N (accept 50.8-51.2 N), cao **A1**

(b) Answer: 51.0 N

(c) true weight = mg = 45 x 9.81 = 441 N **M1**

(c) apparent weight = true weight - upthrust, ft from (b) **M1**

(c) 390 N (accept 388-392 N, ft), cao **A1**

(c) Answer: 390 N

(d) the water exerts an upward force (upthrust) on the statue equal to the weight of water displaced **B1**

(d) this upthrust supports part of the statue's weight, so the force needed from the balance (and hence the reading) decreases, oe **B1**

(d) Answer: Upthrust from the displaced water supports part of the statue's weight, reducing the balance reading.

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Question 5

(a) radius = diameter/2 = 0.14 mm = 1.4 x 10^{-4} m **M1**

(a) correct substitution into A = πr^2 **M1**

(a) 6.16 x 10^{-8} m^2 (accept 6.1-6.2 x 10^{-8} m^2), awrt **A1**

(a) Answer: 6.16 x 10^{-8} m^2

(b) strain = extension/original length substitution **M1**

(b) 2.8 x 10^{-3}, cao **A1**

(b) Answer: 2.8 x 10^{-3}

(c) stress = force/area, using area from (a), ft **M1**

(c) 3.25 x 10^8 Pa (accept 3.2-3.3 x 10^8 Pa, ft), awrt **A1**

(c) Answer: 3.25 x 10^8 Pa

(d) Young modulus = stress/strain, using (b) and (c), ft **M1**

(d) 1.16 x 10^{11} Pa (accept 1.1-1.2 x 10^{11} Pa, ft), awrt **A1**

(d) Answer: 1.16 x 10^{11} Pa

(e) valid precaution, e.g. use of a reference wire alongside the test wire to compensate for the effects of temperature change and to support the vernier scale, or measuring the diameter at several points/orientations along the wire and using a mean value **B1**

(e) Answer: Use of a reference wire to compensate for temperature effects (or measuring the diameter at several points and averaging).

(f) recall/apply E_stored = 1/2 F x **M1**

(f) correct substitution: F = 20 N, x = 5.6 x 10^{-3} m **M1**

(f) 0.056 J (accept 0.055-0.057 J), awrt **A1**

(f) Answer: 0.056 J

Question 6

(a) use trigonometry, e.g. cos(θ) = 3.0/5.0 (or equivalent using the 3-4-5 triangle) **M1**

(a) 53.1 degrees (accept 53-53.2 degrees), awrt **A1**

(a) Answer: 53.1 degrees

(b) correct moment of the ladder's weight about the foot: 120 x 1.5 (weight x horizontal distance to centre of mass) **M1**

(b) correct moment of the person's weight about the foot: 700 x 2.25 (weight x horizontal distance to person's position) **M1**

(b) correct moments equation: R_wall x 4.0 = 120(1.5) + 700(2.25) **M1**

(b) 439 N (accept 438-440 N), awrt **A1**

(b) Answer: 439 N

(c) recognise horizontal equilibrium: since the wall is smooth, friction at the foot must equal the wall's reaction force, ft from (b) **M1**

(c) 439 N (ft), cao **A1**

(c) Answer: 439 N

(d) recognise vertical equilibrium: N = weight of ladder + weight of person **M1**

(d) 820 N, cao **A1**

(d) Answer: 820 N

(e) μ = friction force/normal reaction force, using (c) and (d), ft **M1**

(e) 0.535 (accept 0.53-0.54, ft), awrt **A1**

(e) Answer: 0.535

Question 7

Level 3 Clear, well-linked evaluation that correctly uses the work-energy relationship (work done to stop the car = initial kinetic energy = average force x stopping distance) to explain that increasing the stopping distance (via crumple zone deformation) reduces the average force and deceleration experienced by occupants, AND explains that the crumple zone material is chosen to deform plastically beyond its elastic limit, absorbing a large amount of energy (area under the force-extension/stress-strain graph, including the permanent plastic deformation region) rather than transmitting force elastically to the passenger cell. Reaches a justified conclusion connecting both mechanics (energy/force) and materials (plastic behaviour) principles. **5-6**

Level 2 Correctly explains one of the two principles (either the work-energy/stopping-distance argument, or the plastic deformation/energy-absorption argument) in reasonable detail, with only partial or underdeveloped treatment of the other. **3-4**

Level 1 Basic answer that mentions crumple zones absorb energy or reduce force, without correctly applying the work-energy relationship or explaining the role of plastic deformation in the material. **1-2**

Indicative content:

- Work-energy principle: the kinetic energy of the car must be removed by the work done by the (average) resistive force over the stopping distance, W = F x d = initial KE.
- For a fixed initial kinetic energy, increasing the stopping distance d (by allowing the front of the car to crumple over some distance) reduces the average force F needed to stop the car, and hence reduces the deceleration and force transmitted to occupants.
- A rigid (non-deforming) car structure would stop over a much shorter distance, producing a much larger average force and deceleration, increasing injury risk.
- Materials principle: the crumple zone is made from a material designed to deform plastically (beyond its elastic limit) during the collision, rather than behave purely elastically.
- The energy absorbed by the material as it deforms is represented by the area under its force-extension (or stress-strain) graph; permanent (plastic) deformation absorbs much more energy than purely elastic deformation for a given force, converting kinetic energy into other forms (heat, sound, permanent structural change) rather than elastic strain energy that could otherwise be released back into the passenger cell.
- Overall: the combination of a longer controlled stopping distance (mechanics) and a material that absorbs energy through plastic deformation (materials) both act to reduce the force and deceleration experienced by occupants, improving safety.

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Question 8

(a) h = 6.0 x sin(15) **M1**

(a) h = 1.55 m cao **A1**

(a) Answer: 1.55 m

(b) work against gravity = mgh = 40 x 9.81 x 1.55 **M1**

(b) work against friction = F x d = 45 x 6.0 = 270 J **M1**

(b) total work = 879 J (609 + 270) cao **A1**

(b) Answer: 879 J

(c) time per crate = 60/3 = 20 s **M1**

(c) power = work per crate / time per crate = 879.4 / 20 **M1**

(c) power = 44.0 W cao **A1**

(c) Answer: 44.0 W

(d) input power = output power / efficiency = 44.0 / 0.78 **M1**

(d) input power = 56.4 W cao **A1**

(d) Answer: 56.4 W

Question 9

(a) at the point of slipping, the maximum friction force equals the component of weight parallel to the ramp: F(friction, max) = mg $\sin(\theta_c)$ **M1**

(a) the normal reaction force equals the component of weight perpendicular to the ramp: N = mg $\cos(\theta_c)$ **M1**

(a) since F(friction, max) = μ N, dividing gives μ = mg $\sin(\theta_c)$ / (mg $\cos(\theta_c)$) = $\tan(\theta_c)$ **A1**

(a) Answer: μ = $\tan(\theta_c)$

(b) μ = tan(22 degrees) **M1**

(b) μ = 0.40 cao **A1**

(b) Answer: 0.40

(c) μ = tan(31 degrees) = 0.60 **M1**

(c) the second surface provides more grip, since it has the larger coefficient of friction cao **A1**

(c) Answer: μ = 0.60; the second surface provides more grip.

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