UNIVERSITY OF SOUTHAMPTON FEEG2005W1

SEMESTER 2 ASSESSMENTS 2022-23

TITLE: MATERIALS AND STRUCTURES

DURATION: 8 Hours (Online Open-Book) including up/download time

We recommend that you approach this assessment as if sitting a traditional on-campus exam. Revision and production of condensed notes/key points is an excellent way to synthesise your understanding and prepare for this assessment. This paper has been designed to take approximately 2 hours to complete in a period of focussed and sustained effort, without taking time for extensive re-reading or checking of notes.

Submissions can be handwritten or typed.

This paper contains 4 questions

Answer **ALL** questions

MQ1 and MQ2 each carry 25% of the total marks for the exam paper **SQ1** carries 30% of the total marks for the exam paper and **SQ2** carries 20% of the total marks for the exam paper, and you should therefore aim to spend about 30-40 minutes on each question.

An outline marking scheme is shown in brackets to the right of each question.

Your explanations for the Materials questions can be given in clear bullet point form or full sentences and you should use well annotated diagrams to explain any concepts you wish to discuss. You may include figures or diagrams that are digitally scanned or copied from the lecture notes without referencing. Do not however directly paste text from the lecture notes into your answers. You are expected to develop your own written answers and simply copying and pasting lecture slide content will be marked down. No external references should be used, this paper should be answered from information available on the FEEG2005 Blackboard course, i.e. from the lecture notes/tutorial discussions/lab classes, no referencing of the course content in FEEG2005 is required in your answers. You are reminded of the University's policies on academic integrity.

Materials Section

MQ1

In Figure MQ1.1 below, a typical duty cycle for temperature variation (y-axis) against time (x-axis) can be seen for the gas flow through the turbine of an aeroengine (labelled "Aero") and is compared to that for an industrial gas turbine (labelled "IGT"). A schematic diagram showing the turbine's location in the aeroengine is also shown in Figure MQ1.2. In the aeroengine the duty cycle describes the period of take-off, flight and then landing. In the IGT, a duty cycle reflects the spin up, operation and spin down when the gas turbine system is turned on (and then off) to balance power requirements in the electricity network (this is needed as renewable supplies such as wind and solar can be quite erratic at certain times).

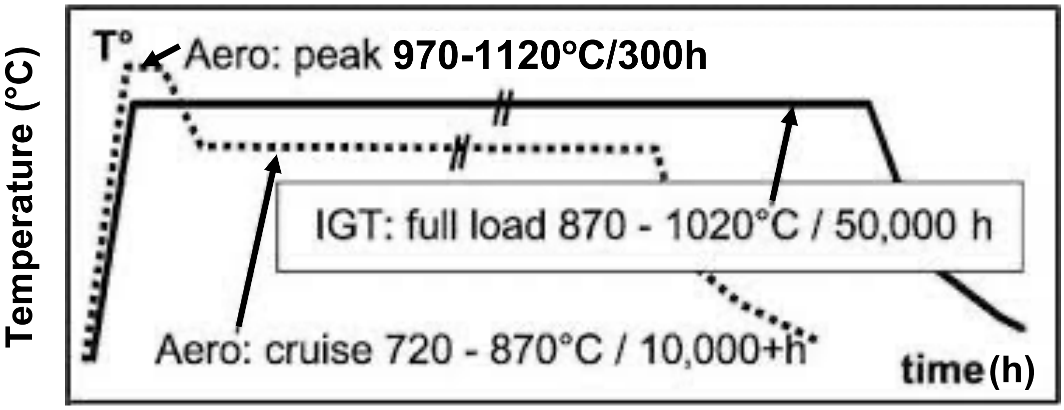


Figure MQ1.1 Temperature versus time schematic comparing aeroengine duty cycle (dotted line labelled "Aero") and industrial gas turbine duty cycle (solid line labelled "IGT"). Note total times indicate typical accumulated times over all expected cycles during lifetime of the component.

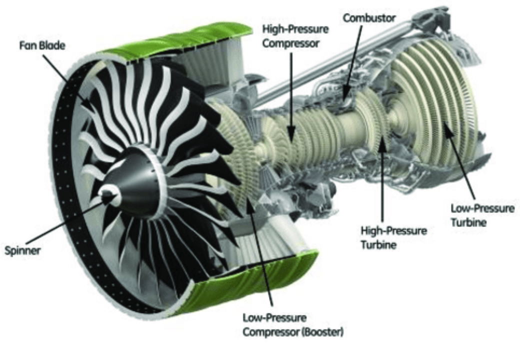


Figure MQ1.2 – Schematic diagram of an aeroengine indicating various regions: fan blades (front) compressor and turbine systems and combustor.

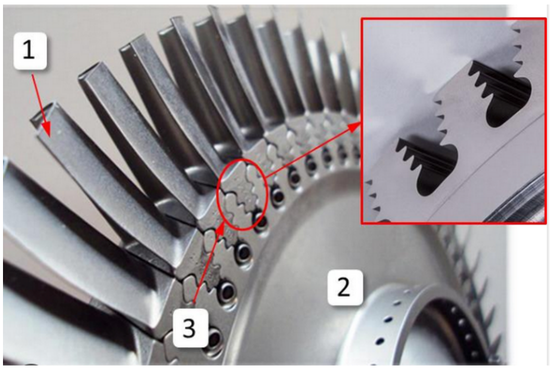


Figure MQ1.3 showing turbine blades [1] and their attachment into the turbine disc [2] via a fir-tree root fixing [3]. Inset picture shows detail of the fir-tree root fixing on the rim of the turbine disc.

(i) Considering this information and your course notes (do NOT research further information on the web, this question should be answered using your lecture notes and our tutorial discussions only) – what service (i.e. loading and temperature) conditions do you think the turbine blades will experience for (a) the aeroengine (b) the IGT? Why are the temperatures and times somewhat different for these two turbine applications?

[4 marks]

(ii) What materials properties would you therefore want in a turbine blade for an aeroengine operating at such temperatures? Based on the materials selection criteria, explain: (1) what materials choices (including alloying element choices and their role in producing a beneficial microstructure), and (2) which manufacturing routes (including protection methods) you recommend to achieve a good turbine blade performance and lifetime. A figure showing the turbine blades in more detail can be seen in Figure MQ1.3

[9 marks]

(iii) Moving on to considering the turbine **disc** in the aeroengine, this component experiences relatively lower temperatures. Specific details of the service conditions the disc experiences at different locations (i.e. the disc rim and bore) can be seen in Figure MQ1.4. Where do you think fatigue cracks are most likely to initiate in the turbine disc and why?

[2 marks]

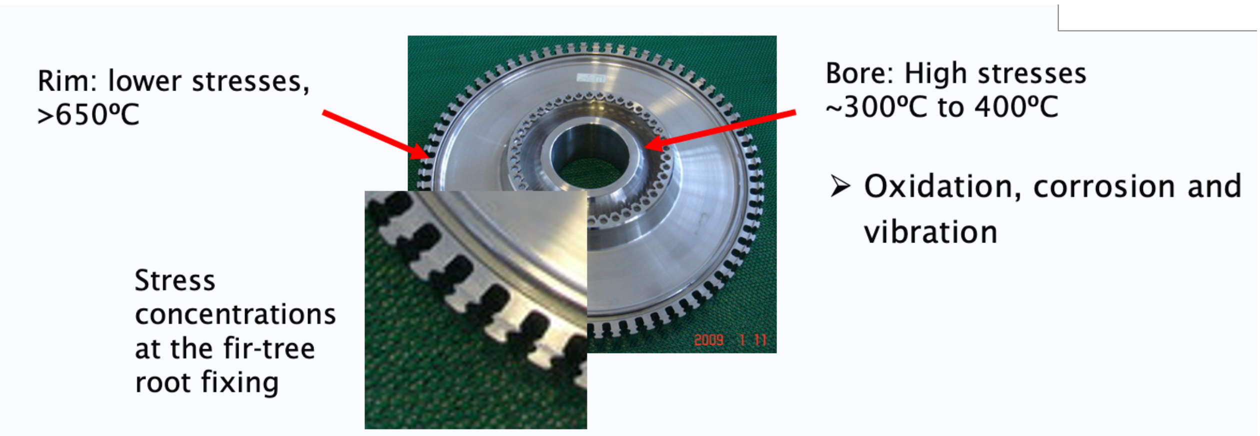


Figure MQ1.4 - Conventional turbine disc showing typical temperatures and stresses whilst in operation

(iv) A turbine disc is found to contain a surface fatigue crack of 1.5mm depth during a scheduled engine maintenance inspection. The major loading cycle experienced over each flight produces a minimum stress of 25 MPa and a maximum stress of 550 MPa at the location of the crack. At the service temperature, the turbine disc alloy has a K_{IC} of 125MPa√m. Fatigue crack growth rate data has been gathered for this alloy at the service temperature: the Paris law constant, $A = 7.35 \times 10^{-11}$ and the Paris law exponent, $m = 2.5$. How many more flights would you recommend will be safe to the airline operator? Explain your assumptions, reasoning and justify your approach. You can assume the shape factor $Q = 1.2$, K is in $MPa\sqrt{m}$ and a (crack length) is in m

[10 marks]

MQ2.

In Table MQ2.1 some compositional information on four Ti alloys and their related mechanical and physical properties can be seen:

Alloy Composition (wt %)	Heat treatment	Yield strength (MPa)	UTS (MPa)	%elongation to failure	T_m (^oC)	Density (g/cm^3)
Unalloyed Ti (commercially pure)	annealed	414	484	25	1670	4.51
5 Al, 2.5 Sn, 92.5 Ti	annealed	784	826	16	1649	4.48
6 Al, 4 V, 90 Ti	annealed	877	947	14	1649	4.43
10V, 2Fe, 3Al, 85 Ti	solution + ageing	1150	1223	10	1649	4.65

Table MQ2.1 - Four titanium alloys: listing composition, heat treatments used and various properties. Note the stiffness (Young's modulus) of Ti and its alloys can be taken to be 120 GPa.

(i) It is clear that the alloying additions have increased strength. Taking each alloy system in turn, comment on (a) the expected phases, and (b) describe the most important strengthening contribution(s) and (c) how these are linked to the heat treatment used and (d) explain why they are therefore used in one likely application for each alloy. Again, please note that you should ONLY use the course materials (lectures and tutorials) to attempt this question, everything you need to answer this is in your course notes. Google is not your friend here.

[8 marks]

(ii) For an advanced lightweight compressor blade design that will operate at 550^{o}C in a high stress environment, we are considering using a Ti metal matrix composite. Which of the above alloys would you recommend as the matrix and why? Note the compressor blade and disc geometry is very similar to the turbine blade and disc geometry shown in Figure MQ1.2 and MQ1.3 but it operates at more moderate temperatures.

[3 marks]

(iii) In Table MQ2.2 (overleaf), some properties of various potential reinforcement fibres are listed. You have established that for the new compressor blade design, the maximum loading is along the blade length (note the compressor blade and disc geometry are very similar to the turbine blade and disc geometry shown in Fig MQ1.2 and MQ1.3). The weight of the blade directly affects the efficiency of the combustor system, the blade length is fixed by aerodynamic considerations and the stiffness (Young's modulus) of the blade material must be at least 220 GPa and its yield strength needs to be at least 1250 MPa. Which reinforcement would you recommend to achieve these goals ? Explain your approach and reasoning steps used to identify the best reinforcement fibre clearly by considering each reinforcement systematically in turn.

[6 marks]

Materials Property	Materials System			
	SiC fibre	Al_2O_3 fibre	Carbon fibre	Tungsten wire
Young’s modulus (GPa)	400	379	500	407
Yield strength (MPa)	3900	1380	2000	2890
Density (g/cm^3)	3.0	3.95	2.0	19.3

Table MQ2.2 - Potential fibre/wire reinforcements and their associated properties

(iv) In a low-pressure power generation turbine blade in an IGT, we see much lower service temperatures (200-300^oC) in a steam environment, hence a tempered martensitic stainless steel is proposed. Why is this a good candidate material for this application and what beneficial properties have been developed by the alloying and heat treatment choices in this materials system?

[4 marks]

(v) The tempered martensitic stainless steel is being considered for a higher temperature service region in the piping of the power plant. It is going to see varying temperatures in this region but at a constant stress of 450 MPa. You have been supplied with some creep rupture test data over the range of temperatures of interest at 450MPa in Table MQ2.2.

Temperature (^oC)	450^oC	500^oC	550^oC	600 ^oC	650^oC	700 ^oC
$t_{rupture}$ (hrs)	2,034,967	869,849	412,268	212,843	118,044	69,558

Table MQ2.2 – creep rupture lives at a range of temperatures for martensitic stainless steel held at a stress level of 450MPa

(a) Why is the lifetime data decreasing non-linearly with increasing temperature and how can you use this data to estimate the creep rupture lifetime at the same stress level at temperatures within the specific data collected (but where the lifetimes are not directly measured)?

[1 mark]

(b) The material is to be held at 625^oC for 85,000 hours and then the temperature raised to 680^oC – how much longer will it be safe to operate at the second higher temperature? Explain your assumptions and approach clearly in making your recommendation.

[3 marks]

STRUCTURES SECTION

SQ1

We are planning to use a 1.5 m long C channel section as a cantilever beam, fixed at end A to a wall and free at the other end, B, as shown in Figure SQ1-1. The downward weight W is applied along the y-axis at the free end B at point P at the middle of the horizontal member centreline as shown in Figure SQ1-2.

Assume the global coordinate system x-y-z is fixed to the wall (not the beam) and a local coordinate system 1-2 is fixed to the beam section (not the wall). We can rotate the beam about the global x-axis before fixing it to the wall. Also, the weight W is fixed at point P and is always acting downward along the global y-axis.

The beam is made out of steel with Young's modulus E = 200 GPa, Poisson's ratio ν = 0.3 and tensile and compressive yield stress of 240 MPa. The beam cross section has three members with the dimensions shown in Figure SQ1-2. The section properties (second moment of inertia) of the beam are I_1= 150744.1 mm^4, I_2= 896933.3 mm^4 and I_{12}= 0 with respect to the local 1- and 2-axes passing through the section's centroid as shown in Figure SQ1-2.

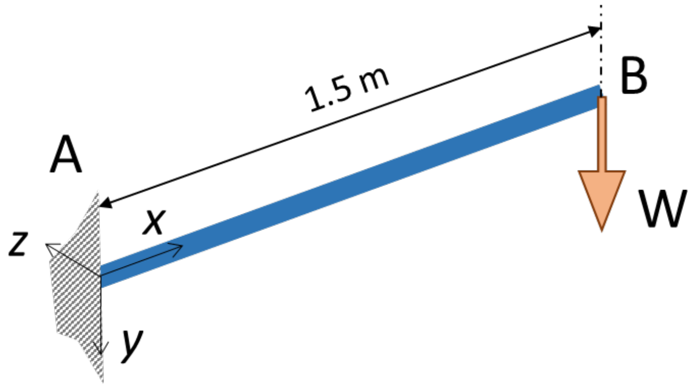


Figure SQ1-1 – A 1.5 m cantilever beam under point force

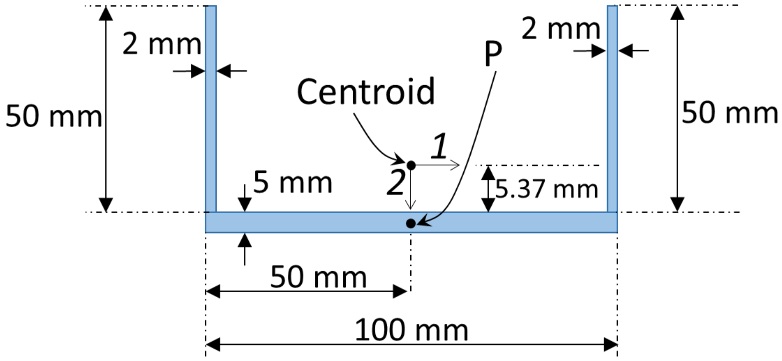


Figure SQ1-2 – Details of the beam cross section

(i) We are considering two options for fixing the beam to the wall as shown in Figure SQ1-3: (i) aligning the 1-axis with the z-axis and the 2-axis with the y-axis or (ii) aligning the 1-axis with the y-axis and the 2-axis with the opposite direction of the z-axis. Explain which option will minimise the deflection of the beam in the y direction. Justify your answer by writing down the relevant generic deflection equation(s) of beams for asymmetric sections. You don't need to calculate any quantitative value but qualitatively, you need to discuss different parameters in the equation(s) and justify your answer.

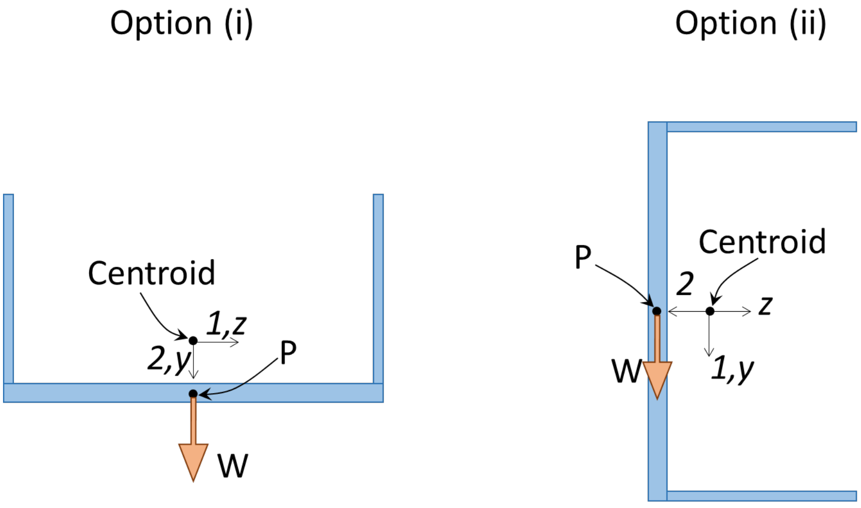
[4 marks]

(ii) Assume that Option (i) in Figure SQ1-3 is selected and the beam is fixed to the wall with the 1-axis parallel and aligned with the z-axis and the 2-axis parallel and aligned with the y-axis. Considering a safety factor of 3.0, find the maximum weight W such that the normal stresses in the beam will not cause yielding at any point. Identify the location of the most critical point(s) with the highest normal stress magnitude and indicate that/those point(s) on two separate schematics (i) on the cross section and (ii) along the beam.

[8 marks]

(iii) Assume that Option (ii) in Figure SQ1-3 is selected, the beam is fixed to the wall with the 1-axis parallel and aligned with the y-axis and the 2-axis with the opposite direction of the z-axis. The weight W=300 N is applied to point P parallel to the y-axis. Find the maximum shear stress value in the beam. Indicate that/those point(s) on a schematic of the cross section of the beam and explain where that/those point(s) are located along the x-axis.

[18 marks]


Option (i)

Option (ii)

Figure SQ1-3- Options (i) and (ii) to fix the beam to the wall

SQ2

The frame ABCD in Figure SQ2-1 is fully clamped at A. B and C are rigid joints and the lengths of the members are AB = CD = H and BC = L. The second moment of area of all members AB, BC and CD are equal to I_z and the whole frame is made out of steel with a Young's modulus of E. A bending moment M is applied at point D.

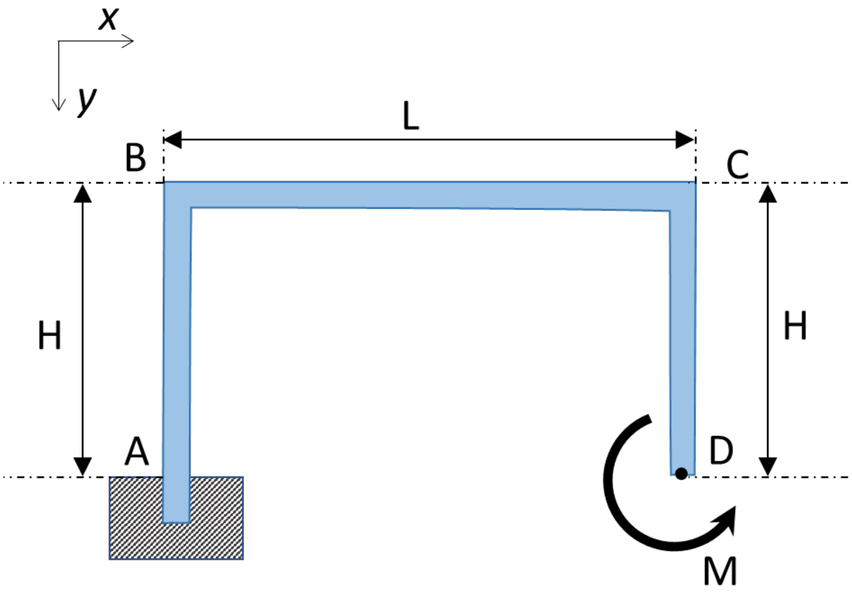


Figure SQ2-1

(i) Find the rotation of the frame at point D as a function of the geometrical and material parameters using Castigliano's theory.

[7 marks]

(ii) Find the horizontal displacement of point C along the x-axis as a function of the geometrical and material parameters using the Principle of Virtual Work.

[13 marks]

END OF PAPER