1 MQ1

1.1 i

The times are different for the turbines because an aero engine has a defined place to stop and, an aircraft can only carry so much fuel. An IGT will always generate power as long as it is needed, so there is no reason to stop it other than this and maintenance. An IGT can have a higher temperature, because denser materials can be used. In an aircraft, the higher weight of a more thermally resistant material has a penalty. On the ground for an IGT, this is not the case. This allows it to run higher temperatures.

1.1.1 a

The aero engine will clearly have a peak temperature of up to 1120°, and a typical cruise temperature of around 870°. Because gas turbine blades are commonly hollow with cooling ducts, the actual surface temperatures are likely lower, with the core of the blade being even cooler than the surface. This will lead to thermal gradients in the blade, likely leading to warping. There will be significant tangential loads as the blades develop significant amounts of lift to extract energy from the flow. These tangential loads will lead to a large bending moment at the root. Radial accelerations are also likely high due to the high angular velocity. Axially, force s are likely low because the blades are optimised for an ideal lift to drag ratio. These forces are likely fairly constant, as thrust demands will stay mostly constant.

1.1.2 b

For the IGT, temperatures are obviously higher for the majority of their life. They are also likely to have interior cooling. The velocities are likely similar but higher, meaning the loads will also be similar but higher. Due to erratic demand on the national grid, and the unreliability of other sources, there will likely be higher angular accelerations, and these will happen more frequently.

1.2 ii

1.2.1 a

An aero engine will likely want a high T_m. The lower the operating tempearture is relative to the melting point, the slower creep progresses. The creep will likely be in the high or low temperature creep regions due to the high stress, meaning plasticity will be dominant.

Stress relaxation isn't a factor here, as the blades lengthen stress will increase. The microstructure should be constant at high temperature. This means that ageing processes can't be used, because the high operating temperature will cause material properties to change while the blade is in operation. Any martensite or bainite would disappear as there is enough time for the material to reach equilibrium.

Grain boundaries should be avoided, these lead to higher diffusional creep, and grains can shear past eachother. If the microstructure changes, failure at brain boundaries is likely to occur.

If the engine was running at a rich condition, there would be very little free oxygen, if any. This would mean that oxidation wouldn't be an issue. This is the case for some of the operating life. Fuel economy dictates that the engine should be run lean sometimes. This means high temperature and lots of oxygen, so plenty of oxidation. For this reason, the alloy should be resistant to oxidation. Weight should also be minimised, so as not to hinder the aircraft.

Chromium could be added to create a coherent oxide layer. This will prevent further oxidation. In addition, because chromium oxide is a ceramic, this adds more protection from thermal loads. Tungsten can be added to increase the melting point and therefore reduce creep.

1.2.2 b

Lost wax processes could be used to get a cast blade with a very fine surface finish. Directional cooling should be employed, as this will allow for the final product to be made of a single crystal.

Plasma jet processes should be avoided, because the surface finish is suboptimal. This will lead to the turbine being less efficient. In addition, it can only work in line of sight. This is less of an issue if the blades and the disk are manufactured separately, but if a blisk (blade and disc in one piece) is used instead, the geometry will likely be too complex to do this effectively.

1.3 iii

The edges of the disc are most likely to experience fatigue. The root fixing has lots of small radii, leading to stress concentrations. If the disk is unbalanced, the largest forces from this will be at the edges of the blade, meaning high fluctuating stresses.

Oxidation fatigue may be a component as it is possible that hot gases could enter this region. This can initiate fatigue and increase crack rates, but only along grain boundaries. It is also frequency dependant. Advisories could be given to the engine operator to avoid running the engine at certain speeds to avoid these frequencies, and if the disk is also made of one crystal, there will be no grain boundaries meaning this is less of an issue.

Creep generally increases the rate of fatigue failure. The high temperature at the rim of the blade means that creep is probably a factor here too.

1.4 iv

Given in question: $a_i = 1.5 \times 10^{-3} m$
$\sigma_{min} = 25 \times 10^6$
$\sigma_{max} = 550 \times 10^6$
$K_{IC} = 125 \times 10^6 Pa\sqrt{m}$
$A = 7.35 \times 10^{-9}$
$m = 2.5$
$Q = 1.2$
Calculated:

$$\Delta\sigma = \sigma_{max} - \sigma_{min} = 525 \times 10^6 Pa$$

Find the critical crack length from the fracture toughness and the maximum stress. The maximum stress is used instead of the minimum or range of stresses because this is when, if ever, the material will fail.

$$a_{crit} = \frac{\left(\frac{K_{IC}}{Q\sigma_{max}}\right)}{\pi} = 0.01142m$$

This comes from integrating $\frac{da}{dN_f} = A^m$. ΔK has been expanded out.

$$N_f = \frac{\left[\frac{a^{1-\frac{m}{2}}}{1-\frac{m}{2}}\right]_{a_i}^{a_{crit}}}{A(Q\Delta\sigma\sqrt{\pi})^m} = 26.41 flights$$

Using a safety factor of 1.25, this means 21 flights are probably safe. Obviously, the fewer flights, the safer. This does lead to more costs to the airline, so they want to maximise the life that can be found from the engine.

2 MQ2

2.1 i

2.1.1 a

α is HCP β is BCC

Alloy 1 is α Alloy 2 is α Alloy 3 is $\alpha + \beta$ Alloy 4 is β

2.1.2 b

Alloy 1 has solid solution strengthening from small amounts of dissolved O. Alloy 2 also has solid solution strengthening from Al and O. Alloy 3 has laths of α in β, leading to a basketweave structure. The precipitates alone also lead to more hardening. Alloy 4 has solid solution as well as precipitate hardening.

2.1.3 c

Solid solution comes about through annealing because the high heat allows for O and other atoms to diffuse through the microstructure, leading to stresses from the different sized elements. Annealing also leads to grain boundary refinement during recrystalisation and grain growth. Precipitates are also allowed to form.

Ageing leads to even more of these mechanisms

2.1.4 d

Alloy 1 is corrosion resistant. The relatively low yield stress means that in most cases with high structural loads, other alloys are better. In addition, the density is slightly higher than others.

Alloy 2 is useful for higher temperature applications. The higher yield strength is also a benefit.

Alloy 3 has a very good strength to weight ratio, so can be used for structural elements.

Alloy 4 is good for high tensile strength structural members. It is the densest compared, so will not be used where alloy 3 could be used instead. It is also the ideal high-temperature alloy.

2.2 ii

Alloy 2 has good creep resistance, but this is not relevant as creep only starts at $0.4T_m$, or around $660°$ so is not relevant in this application. The other alloys have service temperatures below $500°$, meaning that alloy 4 is the obvious choice. In addition, it has better tensile strength.

2.3 iii

For carbon fibre, $V_m = 0.8$ gives $E_c = 1.42 \times 10^{11}$ and $S_c = 1.32 \times 10^9$, which are both within specification.

$V_f \times \rho_f = \frac{2}{5}$

For SiC, $V_m = 0.95$ gives $E_c = 1.24 \times 10^{11}$ and $S_c = 1.29 \times 10^9$, which are within specification.

$V_f \times \rho_f = \frac{3}{20}$. This means that the carbon fibre saves more weight for similar material properties, so should be used instead.

2.4 iv

The demands of a turbine mean that high strength will be needed to make the turbine spin. Also, good surface finish is ideal. Lower weight means lower loads, which is also ideal.

Martensite is extremely hard, but also brittle. Tempering it makes it less brittle and more suitable for the use case. It becomes less hard because the carbon trapped in the martensite is allowed to leave. Stainless steel is generally harder than mild steels. The higher hardness makes it more suited to the task. Through tempering, fine carbides have been formed, making the stainless steel even harder.

It also has better high-temperature strength than mild steel.

The corrosion resistance is also important, because if any steam condenses, the mild steel could begin to rust. The chromium oxide layer means that is not an issue with stainless steel.

In addition to this, stainless steel is relatively cheaper.

2.5 v

2.5.1 a

The Larsen Miller Parameter is given by $LMP = T(C + \log(t))$, where t is the time to failure. Clearly, changing T will have a non-linear effect on t.

2.5.2 b

Find C with the Larsen Miller Parameter:

$$450(C+\log(2034967)) = 700(C+\log(69558))$$

$C \approx -2.2032$ $LMP \approx 1860$

Find life used at $625°C$:

$$1860 = 625(-2.2032 + log(t))$$

$t = 151078$ $L_{625} = \frac{85000}{151078} = 0.5626$

Find how many hours at $680°C$:

$$1860 = 680(-2.2032 + \log(t))$$

$t = 86795$ $\frac{t_{680}}{86795} = 1 - 0.5626$ $t_{680} = 37964hr$

Applying a safety factor of 1.5 gives a value of 25309 hours.

3 SQ1

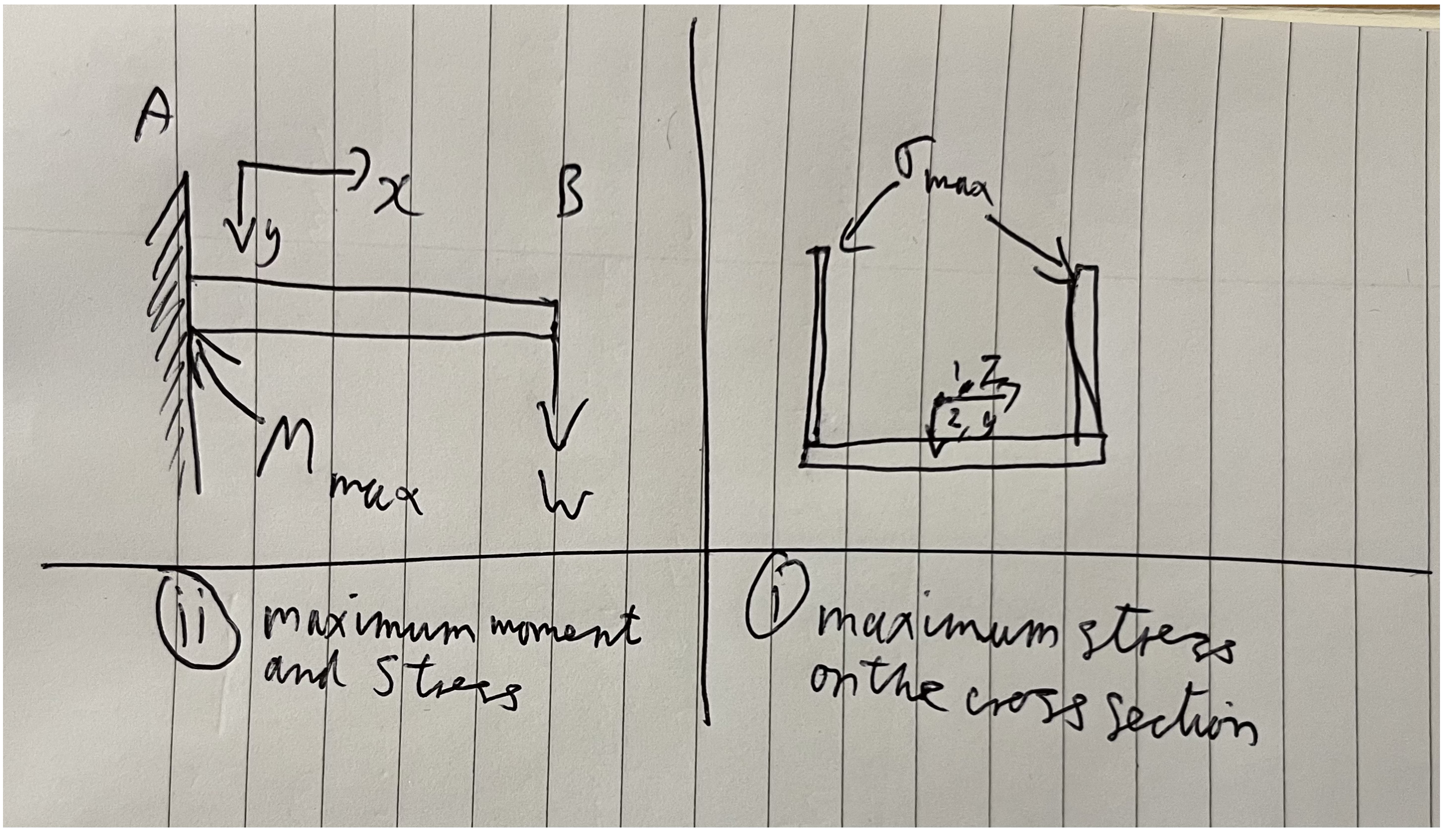
3.1 i

Chooisng option (ii) will result in less deflection in the y-direction, because $\frac{d^2v}{dx^2} = -\frac{M_2 I_1}{EI_2 I_1}$. The moment is fixed, it is the dead load of the beam and the load applied at the tip. E is a property of the material, so can't be changed. Using the larger of the second moments of area gives a smaller fraction, meaning less deflection. Intuitively, the further the material is from the bending axis, the more it resists bending, so by having a C shape rather than a U shape, the material is as far away as possible.

3.2 ii

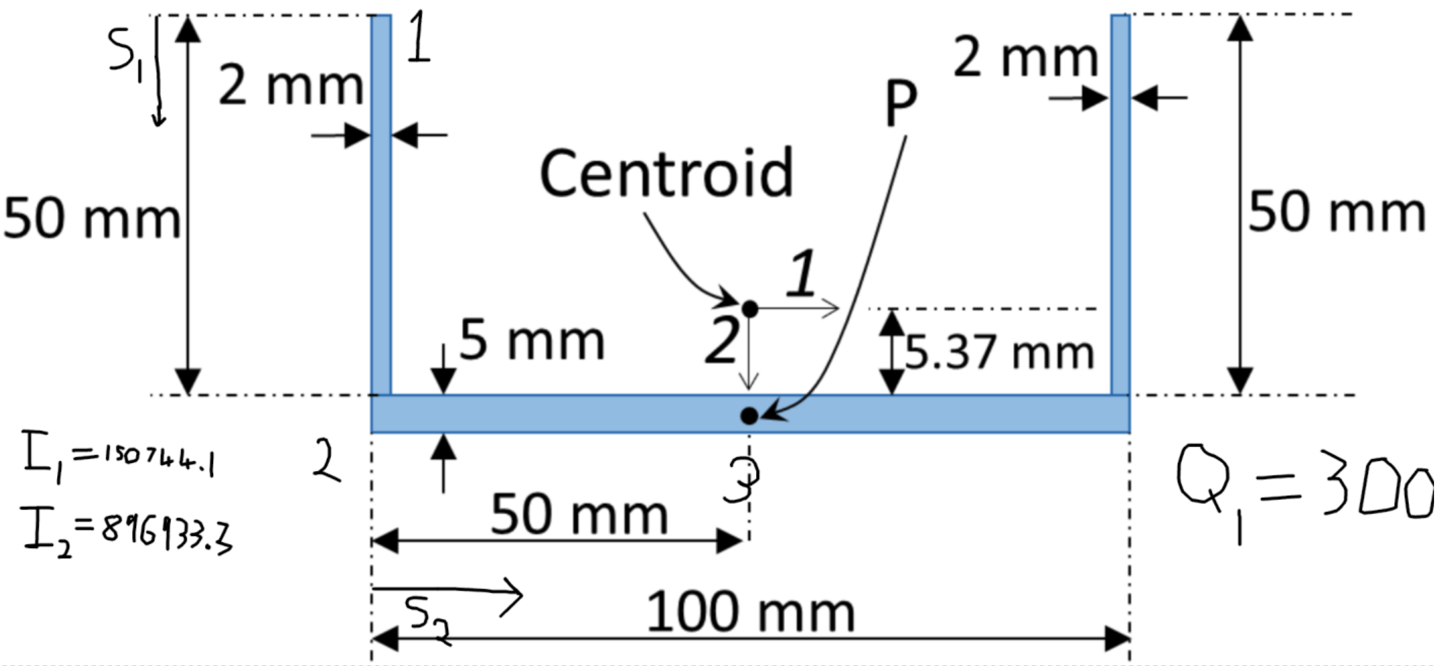
$y = 50 - 5.37 = 44.63$ $M_A = 1.5W$

Engineer's bending theory: $\sigma_x x = \frac{yM_{yz}}{I_{zz}}$ $\frac{\sigma_x x \times I_{zz}}{y} = M$ $\frac{240\times10^6\times150744.1\times10^{-12}}{44.63\times10{-}3\times1.5} = W = 540.4N$ Safety factor of 3 means $W = 180N$



3.3 iii

$I_{yz} = 0$, so $q = \frac{Q_y}{I_{zz}} \bar{y} A + q_{out}$



$$q_{12}(s_1) = \frac{Q_1}{I_2} \bar{y} A = \frac{300}{896933.3}(50-1)(2s_1) = 0.0323 s_1$$

$q_{12,max} = 1.82$

$$q_{23}(s_2) = \frac{Q_1}{I_2} \bar{y} A + q_{out} = \frac{300}{896933.3}(50 - \frac{s_2}{2})(5s_2) + 1.82 = \frac{300}{896933.3}(250s_2 - \frac{5}{2}s_2^2)$$

$q_{23,max} = \frac{300}{896933.3}\left(250 \times 50 - \frac{5}{2}50^2\right) + 1.82 = 3.910MPa$

This is point 3 on the cross section of the beam. Because there is a point load, the point on the cross section becomes a line down the beam.

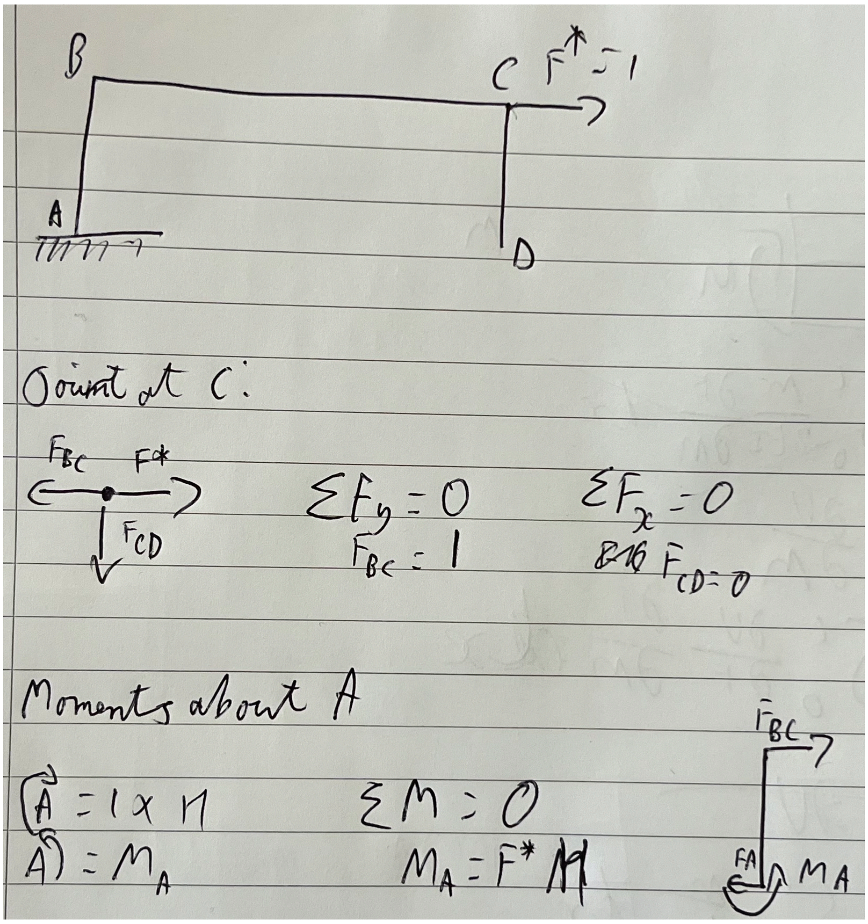
4 SQ2

4.1 i

$U = \frac{1}{2}\int_0^H \frac{M^2}{EI}dx$

$U = \left[\frac{M^2}{IE}x\right]_0^H = \frac{M^2 H}{IE}$

4.2 ii



Using method of sections and method of joins

Member	F^*_{int}
CD	0
BD	−1
AB	F^*H

$$v_D = \frac{\sigma}{E}L + \frac{F^* H I_z}{I_y I_z - I_{yz}^2}$$