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Task 1. Fracture mechanics (10 points, Lecture 5)

1.1 The fracture strength of glass may be increased by etching away a thin surface layer. It is believed that the etching may alter the surface crack geometry (i.e. reduce the crack length and increase tip radius). Calculate the ratio of the etched and original crack tip radii if the fracture strength is increased by a factor of 7.6 when 37% of the crack length is removed. (Please give the detailed calculation process)

Task 1.1

Let subscript -o denotes properties of the original glass and -e denotes the etched glass.

Fracture strength is increased by a factor of 7.6 $\Rightarrow \sigma_{0e} = 7.6\,\sigma_{0o}$

37% of the crack length is remove $\Rightarrow a_e = a_o - 0.37a_o \Rightarrow a_e = 0.63\,a_o$

Stress at crack tip / theoretical fracture strength of the glass stays the same $\Rightarrow \sigma_{m_e} = \sigma_{m_o}$

Fracture mechanics formula: $\sigma_m = 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{\frac{1}{2}}$

Since $\sigma_{m_e} = \sigma_{m_o}$

$$\Rightarrow 2\sigma_{0e}\left(\frac{a_e}{\rho_{te}}\right)^{\frac{1}{2}} = 2\sigma_{0o}\left(\frac{a_o}{\rho_{to}}\right)^{\frac{1}{2}} \Rightarrow \sigma_{0e}^2\frac{a_e}{\rho_{te}} = \sigma_{0o}^2\frac{a_o}{\rho_{to}}$$

Ratio of etched and original crack tip radii is given by

$$\frac{\rho_{te}}{\rho_{to}} = \frac{\sigma_{0e}^2}{\sigma_{0o}^2}\cdot\frac{a_e}{a_o} = \left(\frac{(7.6\,\sigma_{0o})^2}{\sigma_{0o}^2}\right)\left(\frac{0.63a_o}{a_o}\right) \approx 36.38 \text{ (answer)}$$

1.2 A structural component in the shape of a flat plate 17 mm thick is to be fabricated from a metal alloy for which the yield strength and plane strain fracture toughness values are 536 MPa and 25.0 MPa√m, respectively. For this particular geometry, the value of Y is 1.3. Assuming a design stress of 0.4 times the yield strength, calculate the critical length of a surface flaw. (Please give the detailed calculation process)

Task 1.2

The values are: $s = 17\,mm$, $K_{Ic} = 25\,MPa\sqrt{m}$, $\sigma_y = 536\,MPa$, $\sigma_c = 0.4\,\sigma_y$

$Y = 1.3$ $\Rightarrow \sigma_c = 0.4 \times 536MPa = 214.4\,MPa$

Critical length of the surface flaw is given by the formula

$$a_c = \frac{1}{\pi}\left(\frac{K_{Ic}}{Y\sigma_c}\right)^2 = \frac{1}{\pi}\left(\frac{(25\cdot 10^6)}{1.3\times 214.4\cdot 10^6}\right)^2 = 2.56\times 10^{-3}\,m$$

$$= 2.56\,mm \text{ (answer)}$$

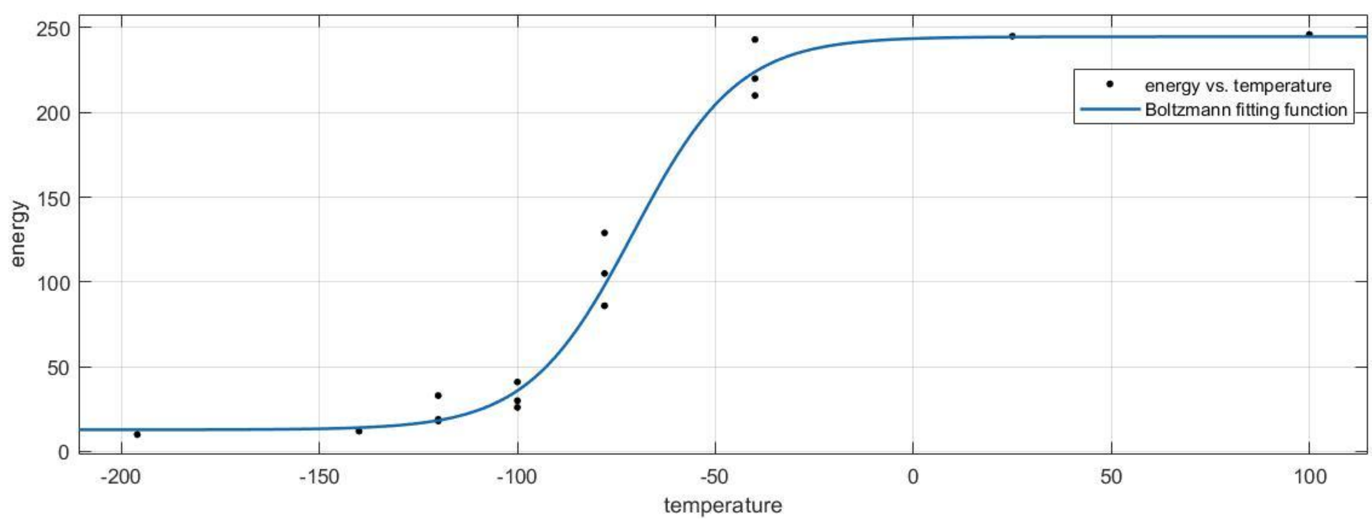
Task 2. Charpy test (20 points, Lecture 5 & 6)

2.1 Please use the test results given in Table 1 to fit the transition curves for steel A. Give your fitting function and fitted parameters, show the fitting figure. (Hint: Use a proper equation e.g. the Boltzmann function to fit the data.)

Table 1 Charpy test results of steel A.

T, °C	-196	-140	-120	-120	-120	-100	-100	-100	-78	-78	-78	-40	-40	-40	25	100
A_V, J	10	12	33	19	18	26	41	30	86	105	129	210	243	220	245	246

Boltzmann fitting curve of the Charpy test results



Where the Boltzmann function is of the form:

$$y = f(x) = \mathrm{a} + \frac{b-a}{1+e^{\left(\frac{c-x}{d}\right)}}$$

The fitted parameters are:

General model:
f(x) = a+(b-a)./(1 + exp((c-x)./d))
Coefficients (with 95% confidence bounds):
a = 12.85 (-2.049, 27.74)
b = 244.7 (225.4, 264)
c = -70.79 (-76.37, -65.21)
d = 13.26 (8.259, 18.26)

Goodness of fit:
SSE: 2085
R-square: 0.9848
Adjusted R-square: 0.981
RMSE: 13.18

2.2 Based on your curve fitting in Task 2.1, give the following characteristic values of a Charpy test:

(a) What is the temperature (in °C) with an impact energy of 27 J?

```
temperature = [-196 -140 -120 -120 -120 -100 -100 -100 -78 -78 -78 -40 -40 -40 25 100];
energy = [10 12 33 19 18 26 41 30 86 105 129 210 243 220 245 246];
plot(temperature, energy, '*b')
a = 12.85;
b = 244.7;
c = -70.79;
d = 13.26;
syms x
equation = a+(b-a)./(1 + exp((c-x)./d)) == 27;
root=solve(equation, x, 'Real', true);
double(root)
disp(root)
```

The temperature (in °C) with an impact energy of 27 J is -107.0349°C (answer)

```
ans =

  -107.0349
```

(b) What is the upper shelf toughness A_{Vmax} (in J)?

According to my fitting curve, 244.696 (rounded 244.7) J is the upper shelf toughness, which is the b parameter found in (a)

(c) What is the transition temperature $T_{AVmax/2}$ (in °C)?

Transition temperature is found by the temperature where the energy occurs as the average of lower and upper shelf toughness, which is given by the formula

$A_{Vmax/2} = (a+b)/2 = 128.775$ J

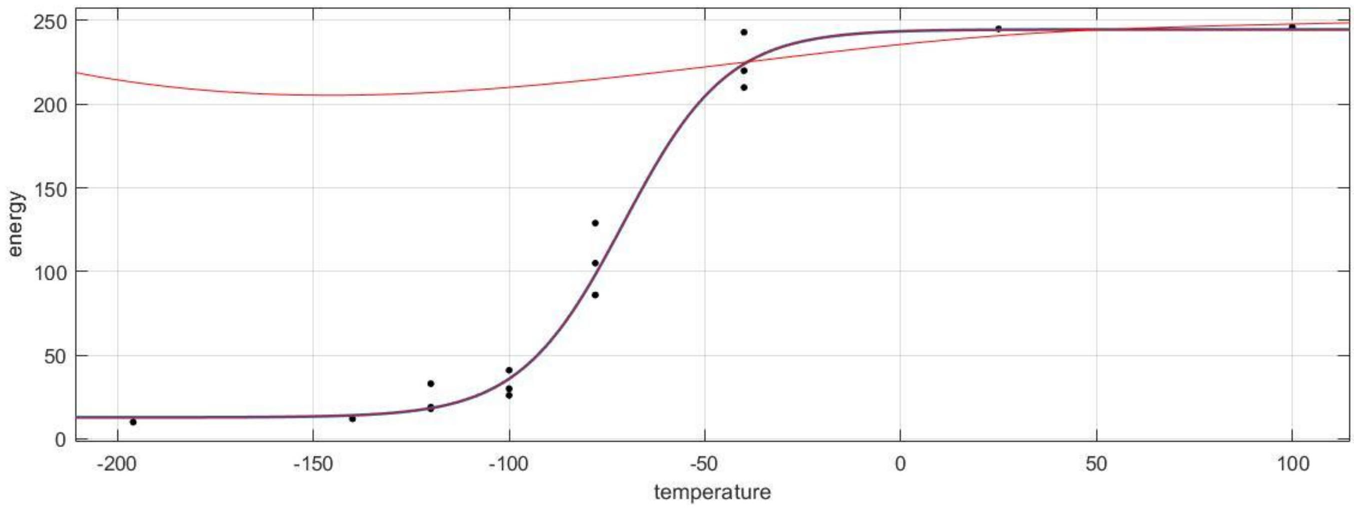
The transition temperature at this energy level given by the fitting curve is

$T_{AVmax/2} = -70.79$ °C (answer)

```
ans =

   -70.7900
```

2.3 Please add the schematic transition curve of an FCC material on the fitted curve in Task 2.1, and explain the failure mechanisms of BCC and FCC materials in Charpy tests at different temperatures.



(I cannot seem to plot the FCC curve correctly, this is my best try)

The red curve is FCC material and the purple curve is BCC material.
+ For BCC structure, at very low temperature, it fails after only absorbing little energy from forces created in the Charpy test. However, BCC material has ductile to brittle transition (DBTT) from higher to lower temperature => BCC structure is more ductile at normal and high temperature. It absorbs more energy from forces in the Charpy tests at higher temperature before failure . Noticeably, BCC material has a transitioning temperature ranging from -100°C to -30°C where its energy absorption from Charpy tests increases linearly with temperature
+ For FCC structure, its energy absorption is always high at any temperature => FCC energy absorption does not seem to depend on temperature and thus, FCC does not have DBTT like BCC material. In the graph above, we can see that FCC material fails at a consistently high energy absorption from the Charpy test.
=> BCC metals exhibiting DBTT should only be used at temperatures where they are ductile

2.4 The force–deflection curves of two Charpy impact tests are shown in Figure 1. Both of the tests were performed at 30°C. The areas under these two curves are the same, i.e. I=II. Which steel shall have a lower transition temperature? Please explain the reason.

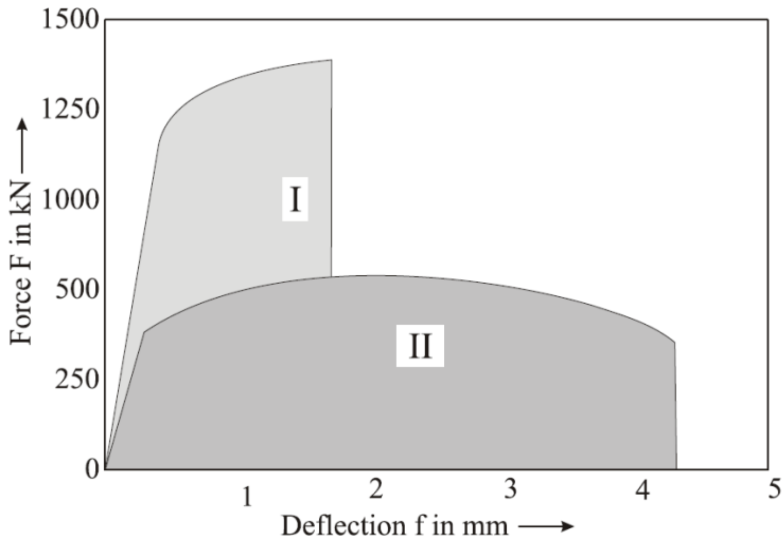


Figure 1 Force–deflection curves for the Charpy test

The area under the Force-Deflection curve represents the work done by the Charpy test, where work is the energy transferred from Charpy mechanics via the application of force along the deflection. Since areas under the two curves are equal (I = II) => Both steels absorb the same amount of energy. Now what matters is only the force-deflection curves of these two steels.

+ For the first steel, it absorbs the force in large amount while deflecting very little and at its yield strength, its deflection accelerates and fails.
+ For the second steel, we notice that the force is distributed at a much lower level as the metal displacements grow over a long range before failure.

Based on this observation, we conclude that the first steel is very brittle (high yield strength) and the second steel is ductile (low yield strength)

- As we know, as temperature rises, metals may exhibit brittle to ductile transition property, where metals become more ductile with higher temperature. Assuming that both steels have this property, since the second steel is already ductile at room temperature 30°C, this 30°C has already passed the second steel's transition temperature . On the other hand, the first steel is still brittle, which means its transition temperature will be higher than 30°C

=> Combined with this logic, we can assume that the transition temperature of the first steel is higher than that of the second steel ($T_{trans1}>T_{trans2}$). In order words, the second steel has lower transition temperature (answer)

Task 3. Failure behavior (30 points, Lecture 5 & 6)

Choose three of the failure types of metals from the list, and give a description of each:

- Creep,
- Fatigue,
- Corrosion,
- Cleavage fracture,
- Ductile fracture,
- Abrasion.

The description shall include the following aspects:

(1) a brief definition of this term,
(2) an example,
(3) the conditions/situation this failure might happen,
(4) affecting factors,
(5) how to improve the resistance to this kind of failure.

I choose creep, fatigue and corrosion failures

- Creep

(1) Definition: Creep is a phenomenon when the material is subject to a permanent stress (normally at high temperature) lower than its yield stress for a long period of time. As such, the material will deform at a slow rate but irreversible => Creep is is a time dependent deformation
(2) Example: High energy components are subject to creep, such as nuclear power reactors, pipe flows and jet engines
(3) Conditions/situation creep might happen:
+ Any situations where the materials are subject to permanent stress, even if the stress do not have immediate visible effect
+ At critical temperature: creep deformation will take place when a material is stressed at a temperature near its melting point, accelerating the rate of deformation
+ Grain boundary area: the more grain boundary area, the more likely creep deformation will become => resulting in intergranular fracture
(4) Affecting factors: material's crystal structure, melting point, grain size, chemical valence and modulus of elasticity. For example, low elasticity modulus will make the materials subjected to higher strain in permanent loading
(5) How to improve resistance to creep:
+ Use materials with high melting point: this will make the materials last longer in high temperature environment and it also helps decrease the diffusivity or creep rate of the material
+ Limiting dislocation motion: use materials whose crystal structure are less subject to dislocations, such as order hardening of materials in fcc structure
+ Solid solution strengthening limits possible dislocations across lattice directions

- Fatigue

(1) Definition: Fatigue on a material happens when the material is subject to a non-permanent but cyclic stress, leading to crack initiation and propagation. When the crack accumulates, the material will result in failure at some time.
(2) Example: Turbine blades revolving in the water when the ship runs or airplane wings flying against the fluid flows are subject to fatigue
(3) Conditions/situation fatigue might happen:
+ Fatigue is usually initiated at stress concentrators or structural discontinuities.
+ Fatigue can also be propagated from existing cracks that originate from production flaws or from cracks formed by corrosion.
(4) Affecting factors: Most common parameters related to fatigue are surface finish, material composition, purity, residual stress and the microstructure. For example, if the surface is easily corroded, fatigue can propagate at a faster rate within the material than a surface finish that is anti corrosion
Cycling frequency also matters significantly, such as hinges that will result in faster fracture if the structure (doors, phones) is closed and open frequently.
(5) How to improve resistance to fatigue:
+ Reducing magnitude of mean stress: because materials are subject to cyclic stress, they will last longer if the stresses are more distributed, reducing the mean stress. Lower mean stress increases fatigue life
+ Surface treatments: shot peening and carburizing techniques bolster surface hardness to prevent crackings
+ Design changes, such as rounding sharp corners to reduce stress concentration

- Corrosion

(1) Definition: Corrosion is a gradual change of the original material into another material when it is in contact with the surrounding environment due to chemical reactions. This chemical change will result in failure or destruction of the original material
(2) Example: bridge stands submerged in the water for a long time will be gradually oxidized, or gears/chains will erode as they are constantly exposed to moisture and steam.
(3) Conditions/situation corrosion might happen: corrosion will always occur if there is an electrolyte, an exposed metal surface, and an electron acceptor in the surrounding environment. Especially, metals are highly corroded if exposed to corrosive gases such as chlorine and hydrogen oxides.
(4) Affecting factors:
+ Internal factors: diffusion, temperature, conductivity, type of ions, pH value and electrolytes potential. For example, the presence of high ratios of reductant metals on the material surface in contact with oxidants in the environment will accelerate corrosion rate
+ External factors: the environment/materials in contact with the materials in question, such as moisture, water, oil, etc

(5) How to improve resistance to corrosion:
+ Materials Selection: use unreactive metals such as copper, lead and nickel
+ Lower temperature: low temperature will decrease rates of electron exchanges between reductants and oxidants
+ Apply physical barriers: films and coatings in stabilized oxidized form will help prevent corrosion of the inner metals inside the barriers
+ Corrosion inhibitors: chemicals that is applied to the metals to reduce their the corrosion rate
+ Cathodic protection: connects the base metal at risk to a sacrificial metal that corrodes in place of the base metal

Task 4. Simulation (25 points, Exercise 3)

Build up the 2D CAE model according to the specimen geometry drawing in Figure 2. Run a plastic deformation simulation until 10% global engineering strain using the flow curve given in A3T4data.txt. Define the boundary conditions. Give the resulting von Mises stress and strain distribution patterns for the whole sample, including the legends. Extract and plot the reflection force–displacement curve.
(Hints: Use the ¼ symmetry model. Use a mesh size as finer as possible with total nodes less than 1000. Show your definition of loading condition for the requested global engineering strain. Except for the final result patterns, you are welcome to give any necessary figures to show your simulation process.)

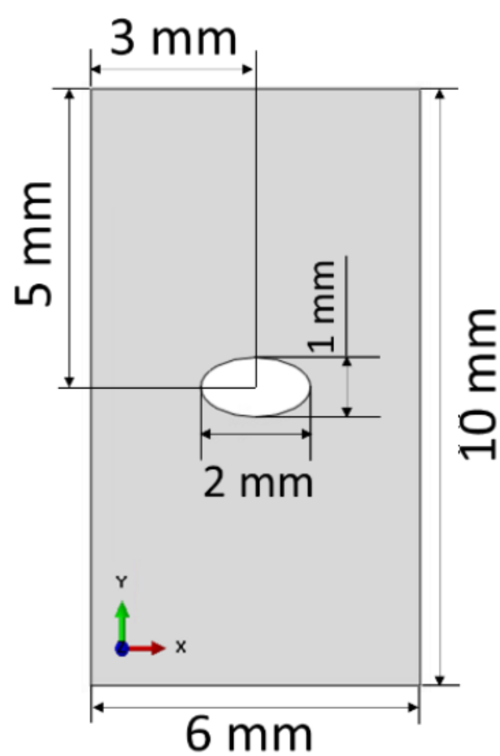
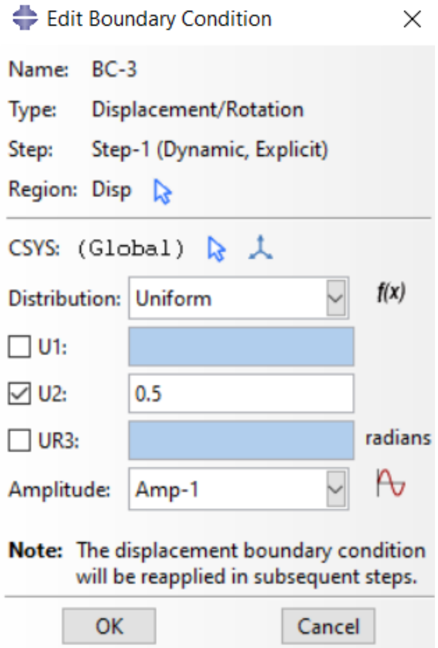
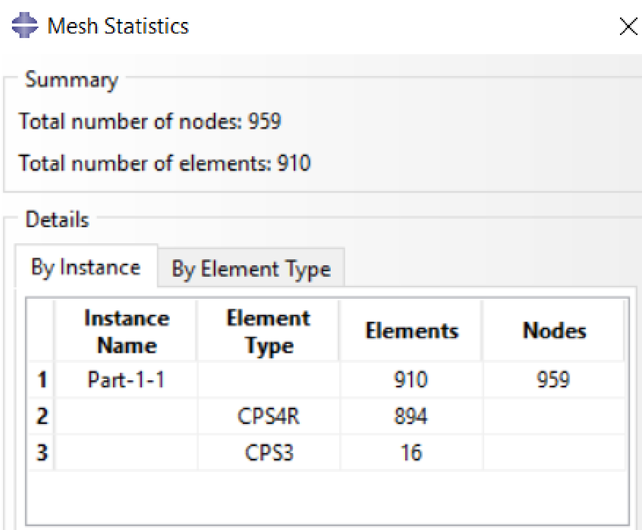


Figure 2 Specimen geometry drawing for Task 4.

Global strain is 10% along the y direction. Since the length of the specimen quadrant is 5mm, 10% of it will be 0.5mm, as given in the loading condition above

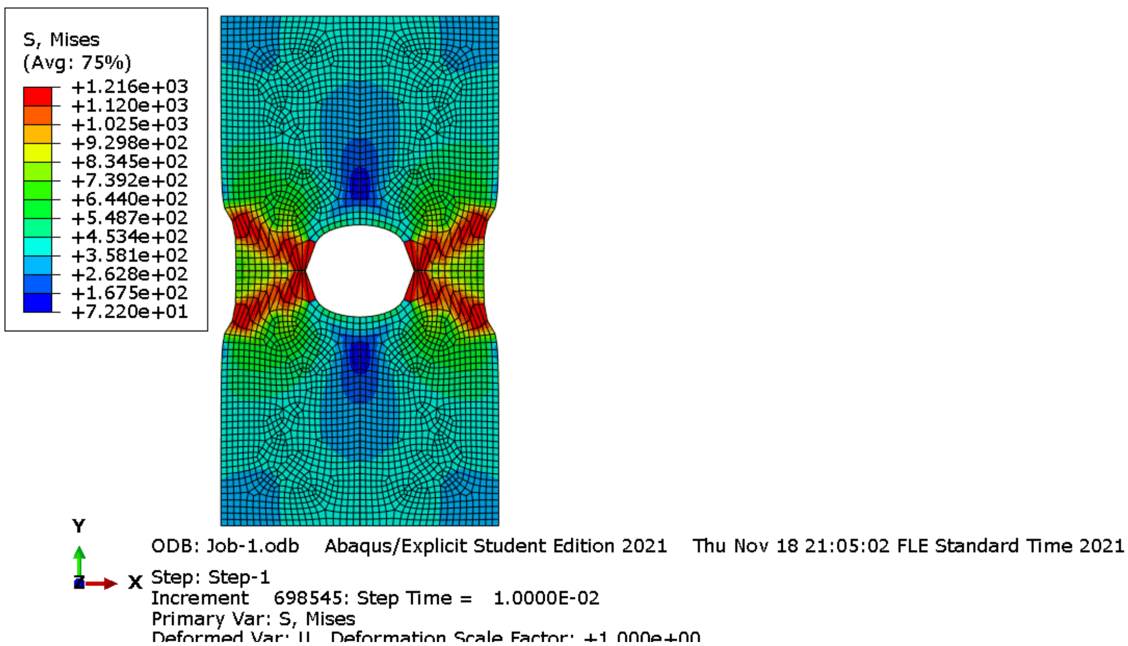


The mesh statistics: as required, my total number of nodes are smaller than 1000

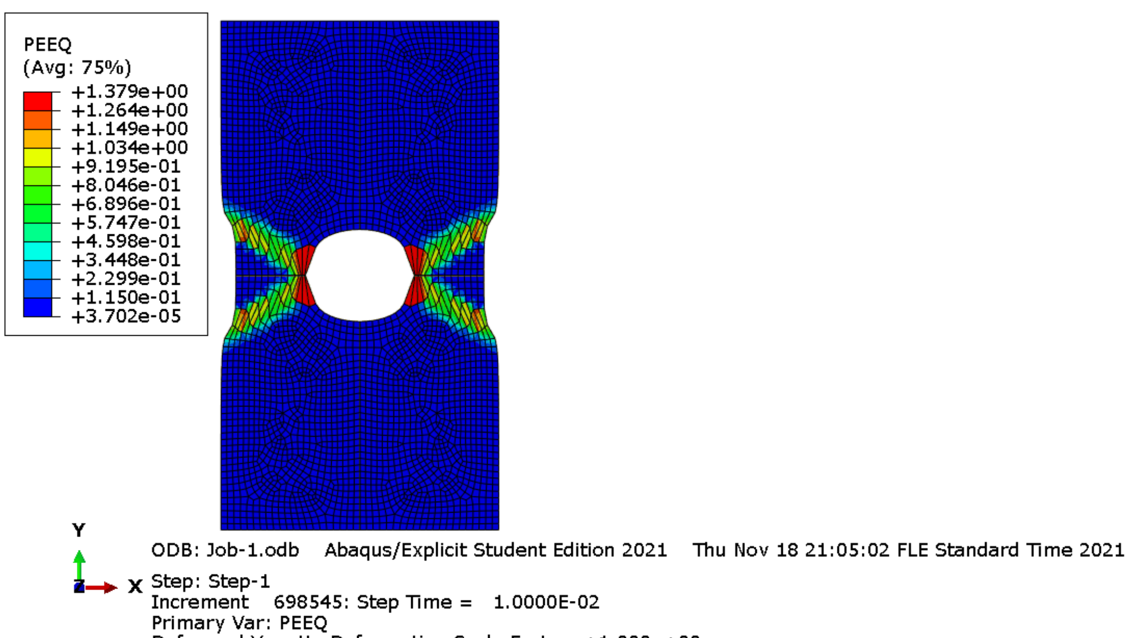


	Instance Name	Element Type	Elements	Nodes
1	Part-1-1		910	959
2		CPS4R	894	
3		CPS3	16	

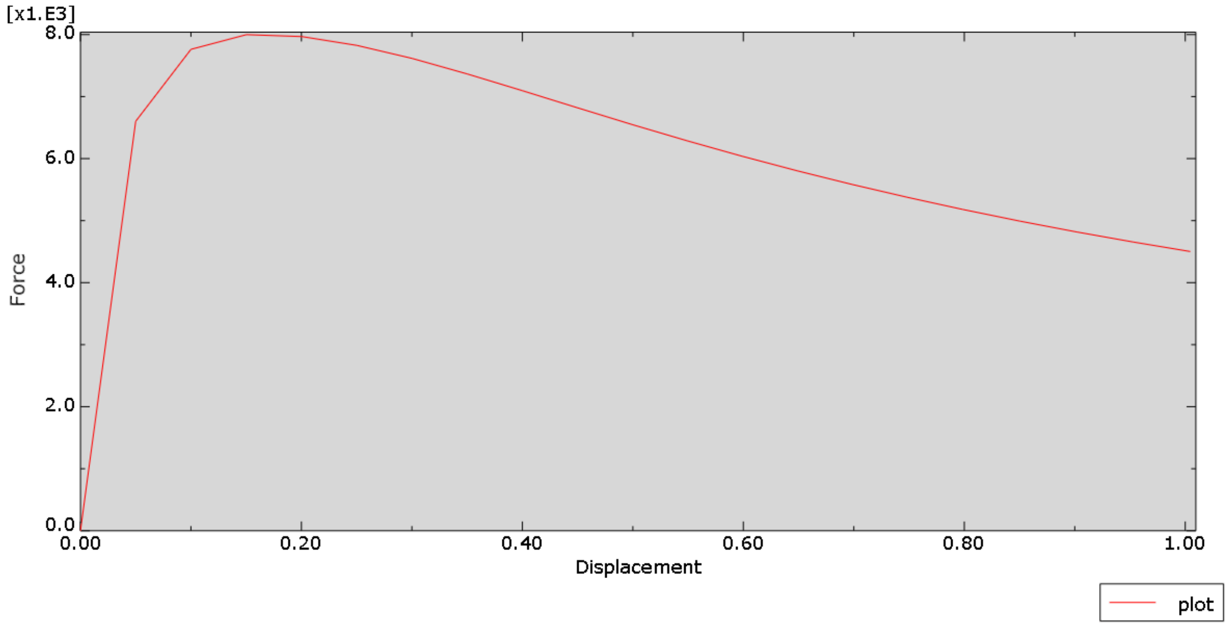
The Mises stress distribution patterns



The Mises strain distribution patterns



Force-Displacement Curve



Force-displacement data report

X	Displacement	Force
0.	0.	1.31025
500.005E-06	49.9906E-03	6.60116E+03
1.00001E-03	100.022E-03	7.76187E+03
1.5E-03	150.226E-03	7.99849E+03
2.E-03	200.4E-03	7.96732E+03
2.50001E-03	250.206E-03	7.8253E+03
3.00001E-03	300.013E-03	7.61619E+03
3.50001E-03	349.82E-03	7.36648E+03
4.00001E-03	399.626E-03	7.09733E+03
4.5E-03	449.432E-03	6.82174E+03
5.E-03	499.238E-03	6.54952E+03
5.50001E-03	549.045E-03	6.28762E+03
6.00001E-03	598.852E-03	6.03843E+03
6.50001E-03	648.658E-03	5.80384E+03
7.00001E-03	698.465E-03	5.58327E+03
7.5E-03	748.27E-03	5.37703E+03
8.E-03	798.7E-03	5.17993E+03
8.50001E-03	850.167E-03	4.99246E+03
9.00001E-03	901.634E-03	4.81776E+03
9.5E-03	953.1E-03	4.65435E+03
10.E-03	1.00457	4.50202E+03

Task 5. Self-assessment (15 points)

It is right in the middle of the course. We only have a half to finish the course in about 3 weeks. Please take a moment to reflect on what you have learned during the first half of the course and assess your learning experience. The writing format is flexible and you write it in a way like your learning diary.

This material science course has taught me quite some new knowledge that I have not seen nor thought of before. To be honest, this is the most realistic engineering course I have taken, because I can visualize the physical and chemical behaviors of the materials when they are studied at microscopic level.

- For the first week, my rusty knowledge of highschool chemistry is being reviewed. Because materials properties are stemming from atomic interactions, studying the microscopic atomic structures is extremely helpful. Since orders are more easier to analyze than chaos, it is best to start with crystalline structures. I am quite fascinated with the unit cells SC, BCC, FCC and HCP, as they are aligned in a way that can be carefully analyzed, such as finding the lattices, atomic packing factor, etc. As it turns out, these microscopic structures will be important to understand crystalline materials properly. I rate myself as barely knowing anything at this point

- For the second week, knowledge of macroscopic physics is studied, such as compressive, tensile stress, strain, shear stress, modulus of elasticity and shear, etc. At first I found the stress-strain curve quite illogical, as there is a portion where reduced stress causes more strain. Later, I discovered that the reason is this part occurs in the necking process of the materials, where it has surpassed the ultimate tensile strength. I also started to notice the occurrences of linear and plastic deformations in real life, such as a toy spring I played as a kid: when I stretched it a short distance, it would revert back to normal state when released. But when I stretched it too much, the spring would be loose forever and it did not return to its original state.

The slip system is what connects the first and second week knowledge together, where I can study the microscopic behavior of the unit cell when macroscopic shear stresses are applied, that is, slide direction and plane with biggest Schmid factor will resolve the most shear stress

- For the third week, crackings, fractures and failures are the focus theme. There are many different reasons for material failures such as creep, fatigue, corrosion and abrasion. I think that knowing the reasons for failures and how to prevent them is very useful knowledge in real life applications, especially if the structure is important or cannot be allowed to fail, such as bridges, houses and ships. The video provided demonstrating the Charpy test is also interesting, as it demonstrates that ductile materials can absorb more energy than brittle materials, which accounts for the reason why ductile materials are generally favored in materials selection

By the third week, I think I have a general sense of what material science really is - It is the science that emphasizes material properties. Unlike fluids, solid or continuum mechanics where all materials are regarded as one entity that behaves in the same way, in this course, I can now visualize how different materials behave and what their properties are.