Department of Mechanical Engineering

Mechanical Engineering Design

ENME 301 Assignment

Coversheet for online submission

AUTHORSHIP	
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DECLARATION (MUST BE SIGNED):	
I (we, if group work) have read and fully understood the Department's Statement Regarding Dishonest Practice (on next page) and hereby certify that this item of work submitted for assessment is entirely my/our own work.	
Signed:	Signed:
Date: 28/03/2021	Date: 28.03.21

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(in connection with work submitted for assessment)

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Assignment 2: Aluminium Structure

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ENME301
Engineering Design and Production Quality

2021

University of Canterbury

METHOD & TESTING

The ultimate tensile strength (UTS) of the material was tested using a Hounsfield tensometer, with 'dog bone' material samples compliant with ASTM E8. The design is shown below in Figure 1.

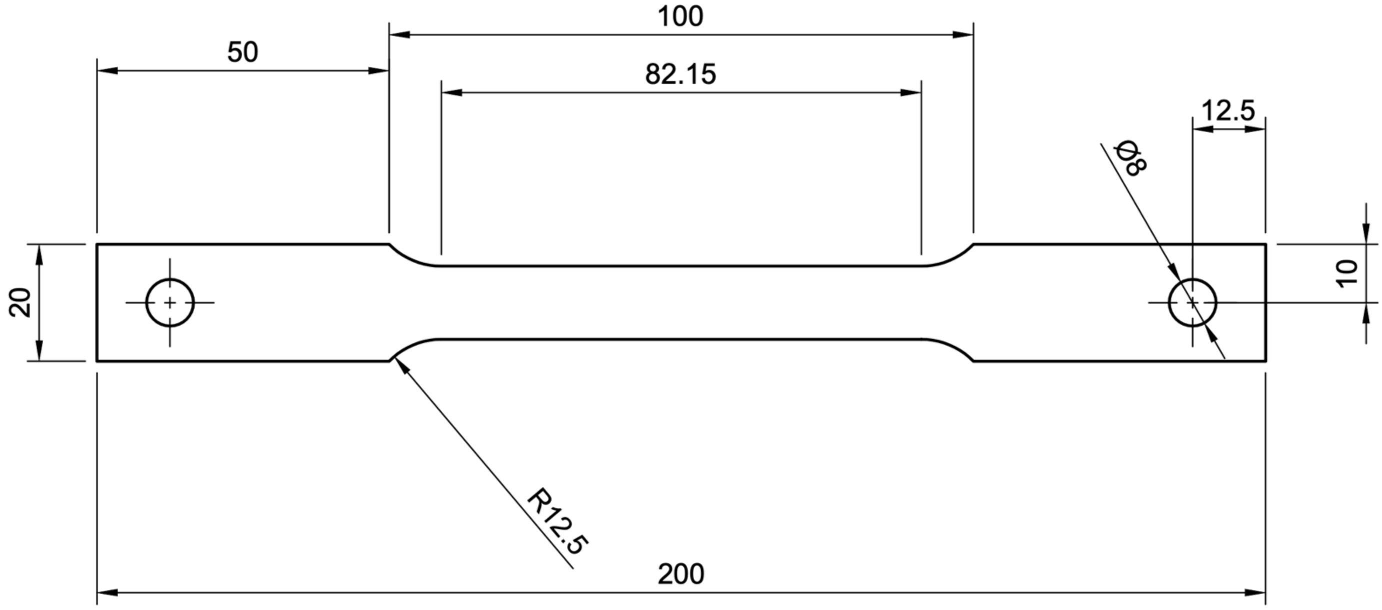


Figure 1: Geometry of the 'dog-bone' testing specimen used in the Hounsfield Tensometer.

The strips were cut to length with a press brake, then excess material was removed using tin-snips and the samples were filed to their final dimensions. Three samples were tested to get an average. Further testing was deemed unnecessary due to the similarity between tested results and the datasheet (Appendix A), and the low spread of the test results.

RESULTS

UTS test results are shown in Table 1 in Appendix B. The results obtained were averaged with the class average and the UTS value in the datasheet to give a result based on as much data as possible (Table 2, Appendix D). This result was rounded to 4 significant figures to give 140.0 MPa, and used for all following calculations.

FINAL DESIGN

DESIGN

The final design was decided to be a right-angle triangle with two compressive members and one tension member, per Figure 2.

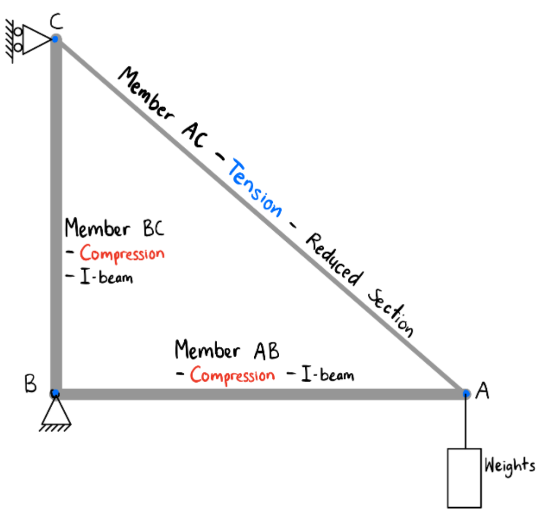


Figure 2: Sketch of the chosen structure geometry.

This geometry gives simple calculations and minimises force in compressive members while maximising force in the tension member. This reduces the load required to exceed UTS in the tensile member, helping the truss meet specifications.

This geometry also reduces the length of compressive members. I-beams use more material per unit length than the tensile member, so savings here are valuable. Minimising the force on the compressive members means weight can be saved by reducing their cross-section. A two-member design with no vertical compressive member was considered but was deemed too unreliable.

Manufacturing box beams for compressive members was considered through bending the aluminium in a press brake. Though easier to manufacture than I-beams, the unpredictable way in which the worked sections of material would deform was deemed too difficult to calculate accurately, thus I-beams were used instead.

In buckling, the I-beam can fail in one of two axes. The load at which this occurs is determined by the second moment of area about this axis. An I-beam constructed using 19 mm x 1.2 mm strips had a significantly higher critical buckling load about the x-axis than the y-axis (Figure 3).

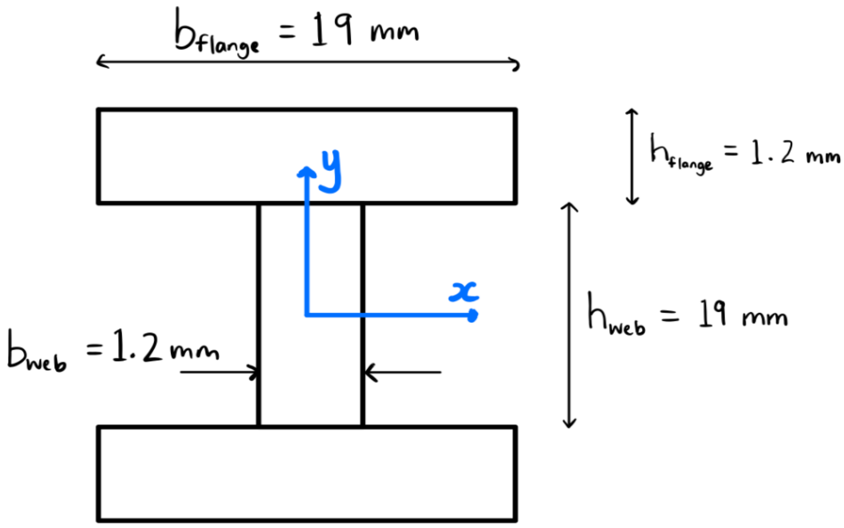


Figure 3: The cross-section geometry of the unmodified I-beams.

The member will always buckle when the force reaches the lowest critical load, and so having a second higher critical load is useless. Thus, to save weight, the web height was reduced until the buckling load was roughly equal for both axes. The I-beam web height was reduced to 10 mm. The new chosen geometry with reduced web height is shown in Figure 4.

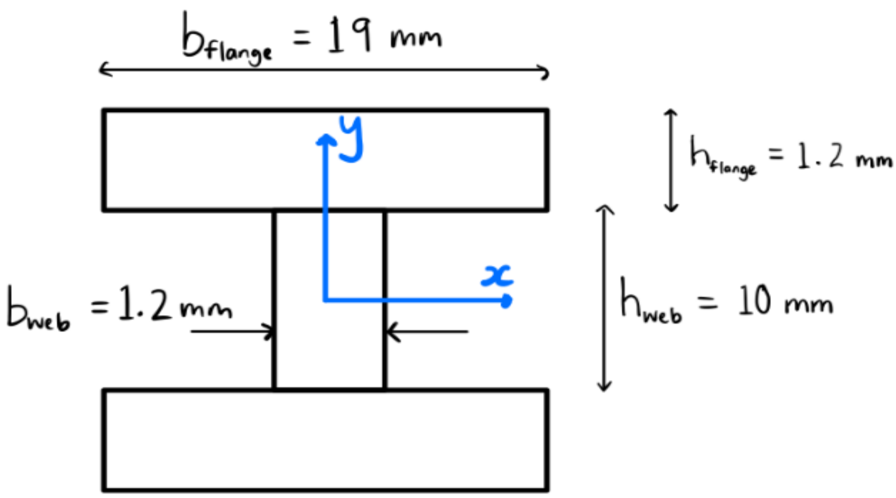


Figure 4: The cross-section geometry of the reduced I-beams

For the vertical I-beam, the web height was reduced to 7.6 mm. The horizontal I-beam will still use a web height of 10 mm, allowing the members to fit together centrally at the pin connections. This allows the members to be centred along a common axis, reducing any twisting effects.

FAILURE MODES

All calculations for failure modes can be found in Appendix E.

The first failure mode is a notch in the tension member. Failure occurs in the plastic region of stress-strain. As stress concentrations do not apply in plastic deformation, they can be ignored in this case. Thus, the goal of the notch is only to reduce the cross-section to the point where the ultimate tensile strength of the material will be exceeded. This is predicted to occur at 30.0 ± 3 kg. This range is accounting for the 5% spread in obtained results, with an added 5%[1] to account for tolerances in manufacturing the truss. This is within the ± 25% range as per specifications.

The second failure mode is a failure at the pinhole in the tensile member, predicted to occur at 36.6 ± 3.66 kg. This would occur in the reduced cross-section of the material on either side of the pin. It should also be noted that the lower bound of the second failure mode has a slight overlap with the upper bound for the first failure mode, though the chance that the second failure mode would fail first is highly unlikely.

The final failure mode is buckling of the horizontal compressive member, predicted to occur at 511 ± 128 kg. It is unlikely that this failure mode will be seen due to the high load. However, buckling calculations are also subject to a high degree of uncertainty, thus the range has been increased to the maximum within specification (25%).

[1] Most tolerances in the design are >5%, but they add up over the whole structure. This 10% range will be used for all failure modes.

APPENDICES & REFERENCES

A: Reference for the material properties of the 5005 H32 aluminium alloy used:
https://www.makeitfrom.com/material-properties/5005-H32-Aluminum#:~:text=5005%2DH32%20aluminum%20is%205005,full%2Dhard%20(H38)

Elastic Modulus of 68 GPa
UTS of 140 MPa

B: Testing results for ultimate tensile strength
Table 1: Results from Hounsfield tensometer for ultimate tensile strength of supplied aluminium

Width (mm)	Thickness (mm)	Area (m^2)	Failure Load (kN)	UTS (MPa)		Spread
12.5	1.18	0.00001475	2.698	144.503051	Min:	144.5030508
11.7	1.18	0.000013806	2.585	147.917572	Max:	147.4093105
11.05	1.18	0.000013039	2.433	147.409311	Deviation:	2.906259682
				146.609978	Spread (%) ->	1.971557748

C: Class results spreadsheet
https://ucliveac-my.sharepoint.com/:x:/g/personal/mwr59_uclive_ac_nz/EfPwPoizcitKtB30qz_gB80BLd79zaeQ9Thiz2JxS2D95Q?e=lR2csY

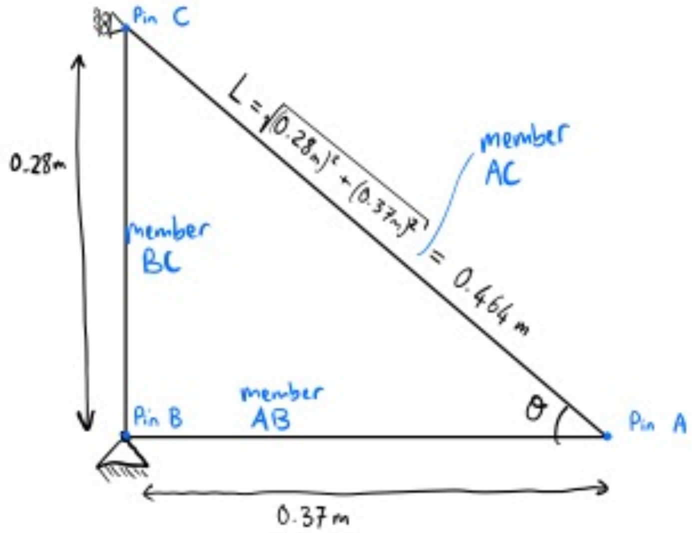
D: Calculation for overall average of ultimate tensile strength
Table 2: Calculation for overall average ultimate tensile strength

Tested Average (MPa)	Class Average (MPa)	Datasheet value (MPa)	Mean Value (MPa)
146.6	133.3	140	139.9666667

E: Hand calculations

Calculations

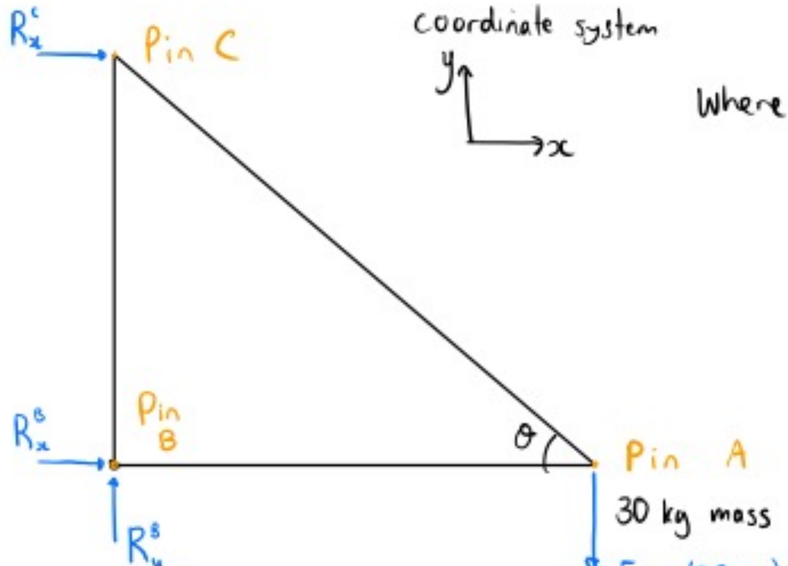
For the member geometry shown below, designing to carry a mass of 30 kg before failure.



Calculating Angle:

$$\theta = \tan^{-1}\left(\frac{0.28m}{0.37m}\right) = 37.11686^\circ$$

Which makes a FBD as shown below



$F_w = (30\text{ kg})(9.81\text{ m/s}^2) = 294.3\text{ N}$

Where:
- F_w = weight force provided by hanging 30 kg of mass at Pin A. where $F_w = mg$
- R_x^C = Reaction force in x-direction at Pin C
- R_x^B = Reaction force in x-direction at Pin B
- R_y^B = Reaction force in y-direction at Pin B

Finding Forces

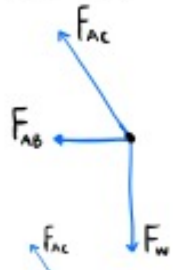
Summing forces in x and y directions, and solving for R_x^C, R_x^B, and R_y^B:

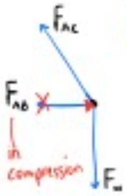
$$\Sigma F_y = 0 \Rightarrow R_y^B - F_w = 0 \quad \Rightarrow R_y^B = F_w \quad \Rightarrow R_y^B = 294.3\text{ N}$$

$$\Sigma F_x = 0 \Rightarrow R_x^B + R_x^C = 0 \quad \Rightarrow R_x^C = -R_x^B$$

Assume all forces in members are in tension (positive), so if the calculated values are negative this means the member is actually in compression.

Pin A:





Summing forces in x and y directions, and solving for F_{AB} and F_{AC}:

$$\Sigma F_y = 0 \Rightarrow F_{AC}\sin\theta - F_W = 0 \Rightarrow F_{AC} = \frac{F_W}{\sin\theta} = \frac{294.3\text{N}}{\sin(37.11686°)}$$

$$\Rightarrow \boxed{F_{AC} = 487.70168 \text{ N (Tension)}}$$

$$\Sigma F_x = 0 \Rightarrow -F_{AB} - F_{AC}\cos\theta = 0 \Rightarrow F_{AB} = -F_{AC}\cos\theta$$

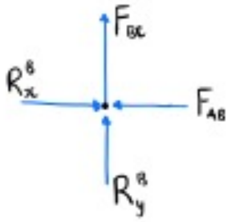
$$\Rightarrow F_{AB} = -388.89643\text{N} \quad \text{(Tension)}$$

, however the force is negative in tension so must be in compression

$$\Rightarrow \boxed{F_{AB} = 388.89643\text{N (Compression)}}$$

$\therefore$ at pin A the direction of F_{AB} is $\rightarrow$

Pin B:



Summing forces in x and y directions, and solving for F_{BC} and R_x^B:

$$\Sigma F_y = 0 \Rightarrow F_{BC} + R_y^B = 0 \Rightarrow F_{BC} = -R_y^B = -294.3\text{N} \quad \text{(Tension)}$$

$$\Rightarrow \boxed{F_{BC} = 294.3 \text{ N (Compression)}}$$

$$\Sigma F_x = 0 \Rightarrow R_x^B - F_{AB} = 0 \Rightarrow R_x^B = F_{AB}$$

$$\Rightarrow \boxed{R_x^B = 388.89643\text{N}}$$

as $R_x^C = -R_x^B \Rightarrow \boxed{R_x^C = -388.89643\text{N}}$ (in +ve x-direction $\rightarrow$)

as R_x^C is negative in the positive x-direction, then R_x^C must be in the opposite direction (in the negative x-direction $\leftarrow$)

Forces	F_{AB}	F_{AC}	F_{BC}
Values	388.9 N	487.7 N	294.3 N
Tension Or Compression	Compression	Tension	Compression

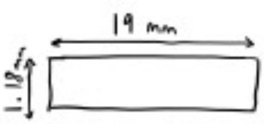
Finding Stresses

$$\sigma = \frac{F}{A}$$

Member AC

For member AC, assume initially that 19 mm × 1.2mm strips of Aluminium are used. This will allow us to find the minimum stress in member AC, allowing us to see how much we can change the cross-sectional Area of the member in order for failure to occur

Cross-Section



in reality the thickness is 1.18 mm

$$A_{AC} = (19\text{ mm})(1.18\text{ mm}) = 22.42\text{ mm}^2$$

$$\Rightarrow \sigma_{AC} = \frac{F_{AC}}{A_{AC}} = \frac{487.701681\text{ N}}{22.42\text{ mm}^2} = 21.75297\text{ MPa}$$

We are designing the member AC to fail at a stress concentration which means that the Ultimate Tensile Strength (UTS) must be met at the stress-concentration. Notches will be used to create the stress concentration.

From testing we determined the UTS = 140 MPa

Therefore in order to increase σ_{AC} to the UTS, we must reduce the cross-sectional area by a area reduction factor (ARF)

$$ARF = \frac{UTS}{\sigma_{AC}} = \frac{140 \text{ MPa}}{21.75297 \text{ MPa}} = 6.43590$$

To reduce area, the height of the strip is reduced to $h_{AC,reduced}$

$$h_{AC,reduced} = \frac{h_{AC}}{ARF} = \frac{19 \text{ mm}}{6.43590} = 2.95219 \text{ mm}$$

The height of the cross-section at the notch must be 2.95219 mm in order for the stress to reach the UTS, assuming the stress concentration factor is equal to 1.

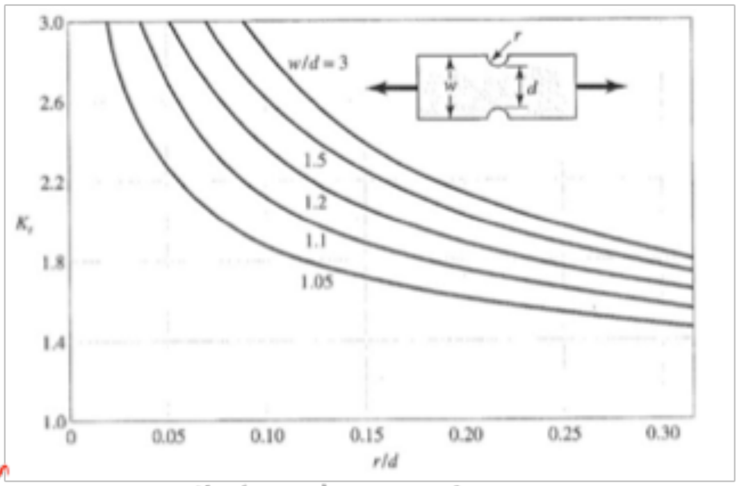
In order to reduce weight, the rest of member AC is slendered down from h = 19mm to h = 7mm, as shown in the side view below:

Stress Concentration Factor (SCF)

If $h_{AC,reduced} = 2.95219$ mm

then $r_{notch} = \frac{(7 - 2.95219) \text{mm}}{2}$

$\Rightarrow r_{notch} = 4.0478$ mm



in the diagram to the right w is used instead of h

$$\Rightarrow \frac{w}{d} = \frac{7\text{mm}}{2.95\text{mm}} = 2.3728$$

$$\Rightarrow \frac{r}{d} = \frac{4.05\text{mm}}{2.95\text{mm}} = 1.3729$$

not on graph

using the graph we can conclude that $K_t < 1.8$

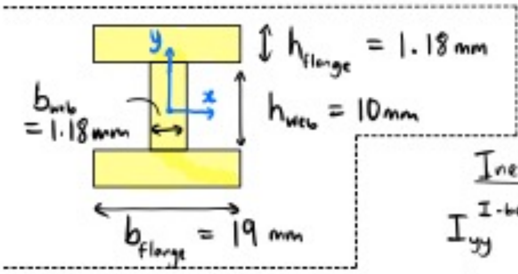
However, as the material is failing in the plastic region, the affects of stress concentrations can be ignored. This is as Aluminium is a ductile material. $\Rightarrow K_{failure} \approx 1$

$\therefore$ the stress experienced at the notch will be purely due to the reduced area.

Design of Compressive Members

Second Area Moments

We have decided to use an I-beam which is constructed of with dimensions shown below:



This I-beam will be used in members AB and BC as these are compressive members

Inertia about y-axis:

$$I_{yy}^{I\text{-beam}} = I_{yy}^{web} + 2I_{yy}^{flange}$$

where $I_{yy}^{web} = \frac{1}{12}(b_{web})^3(h_{web}) = \frac{1}{12}(0.00118\,m)^3(0.010\,m)$

$$\Rightarrow I_{yy}^{web} = 1.36919333\times10^{-12}\,m^4 = 1.3692\times10^{-12}\,m^4$$

where $I_{yy}^{flange} = \frac{1}{12}(b_{flange})^3(h_{flange}) = \frac{1}{12}(0.019\,m)^3(0.00118\,m)$

$$\Rightarrow I_{yy}^{flange} = 6.74468333\times10^{-10}\,m^4 = 6.7447\times10^{-10}\,m^4$$

$$\Rightarrow I_{yy}^{I\text{-beam}} = (1.3692\times10^{-12}\,m^4) + 2(6.7447\times10^{-10}\,m^4) = 1.35030586\times10^{-9}\,m^4$$

$$\Rightarrow I_{yy}^{I\text{-beam}} = 1.3503\times10^{-9}\,m^4$$

Inertia about x axis:

$$I_{xx}^{I\text{-beam}} = I_{xx}^{web} + 2I_{xx}^{flange}$$

where $I_{xx}^{web} = \frac{1}{12}(b_{web})(h_{web})^3 = \frac{1}{12}(0.00118\,m)(0.010\,m)^3 = 9.8333333\times10^{-11}\,m^4$

$$\Rightarrow I_{xx}^{web} = 9.8333\times10^{-11}\,m^4$$

using parallel axis thereom; $I_{xx}^{flange} = I_{xx\text{-centroid}}^{flange} + (A_{flange})(d_{x\text{-centroid}}^2)$

where: $A_{flange} = (0.019\,m)(0.00118\,m) = 2.242\times10^{-5}\,m^2$

$$d_{x\text{-centroid}} = \frac{1}{2}h_{web} + \frac{1}{2}h_{flange} = \frac{0.010\,m}{2} + \frac{0.00118\,m}{2} = 0.00559\,m$$

$$I_{xx\text{-centroid}}^{flange} = \frac{1}{12}(b_{flange})(h_{flange})^3 = \frac{1}{12}(0.019\,m)(0.00118\,m)^3 = 2.60146733\times10^{-12}\,m^4$$

$$\Rightarrow I_{xx}^{flange} = (2.60146733\times10^{-12}\,m^4) + (2.242\times10^{-5}\,m^2)(0.00559\,m)^2 = 7.03183869\times10^{-10}\,m^4$$

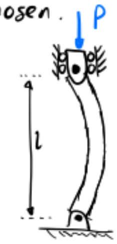
$$\Rightarrow I_{xx}^{I\text{-beam}} = (9.8333\times10^{-11}\,m^4) + 2(7.03183869\times10^{-10}\,m^4) = 1.50470107\times10^{9}\,m^4$$

$$\Rightarrow I_{xx}^{I\text{-beam}} = 1.5407\times10^{-9}\,m^4$$

Critical Buckling Loads $P_{CR} = \frac{C\pi^2 EI}{l^2}$, $E = 68$ GPa for this material

The compressive members are supported by pins at both ends, but due to friction in the pins, the pins act as a combination of Rounded-rounded and Fixed-fixed end conditions. Therefore, being conservative a value of $C = 1$ was chosen.

$$\Rightarrow P_{CR} = \frac{\pi^2 EI}{l^2}$$



Column end conditions	End-condition constant C: Theoretical value	Conservative value	Recommended value*
Fixed-free	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$
Rounded-rounded	1	1	1
Fixed-rounded	2	1	1.2
Fixed-fixed	4	1	1.2

AB Member

$l_{AB} = 0.37\,m$

Buckling about x-axis:

$$P^{AB}_{CR-x} = \frac{\pi^2 E I^{I\text{-beam}}_{xx}}{l_{AB}} = \frac{\pi^2 (68\times10^9\,Pa)(1.5407\times10^{-9}\,m^4)}{(0.37\,m)^2} = 7,377\ N$$

Buckling about y-axis:

$$P^{AB}_{CR-y} = \frac{\pi^2 E I^{I\text{-beam}}_{yy}}{l_{AB}} = \frac{\pi^2 (68\times10^9\,Pa)(1.3503\times10^{-9}\,m^4)}{(0.37\,m)^2} = 6,620\ N$$

therefore, as $P^{AB}_{CR-y} < P^{AB}_{CR-x}$ $\Rightarrow$ member AB will buckle about the y-axis before it buckles about the x-axis.
$\Rightarrow$ member AB is constrained by y-axis buckling

$$\Rightarrow P^{AB}_{CR} = 6,620\ N$$

compared with the actual force in member AB when 30kg load is applied $F_{AB} = 388.9\ N$,

$$m^{AB}_{buckling\text{-}fail} = 30\,kg\left(\frac{6,620\ N}{388.9\ N}\right) = 511\ kg$$

, $\Rightarrow$ AB will buckle with a load of 511 kg

BC Member

$l_{BC} = 0.28\,m$

Buckling about x-axis:

$$P^{BC}_{CR-x} = \frac{\pi^2 E I^{I\text{-beam}}_{xx}}{l_{BC}} = \frac{\pi^2 (68\times10^9\,Pa)(1.5407\times10^{-9}\,m^4)}{(0.28\,m)^2} = 12,881\ N$$

Buckling about y-axis:

$$P^{BC}_{CR-y} = \frac{\pi^2 E I^{I\text{-beam}}_{yy}}{l_{BC}} = \frac{\pi^2 (68\times10^9\,Pa)(1.3503\times10^{-9}\,m^4)}{(0.28\,m)^2} = 11,559\ N$$

therefore, as $P^{BC}_{CR-y} < P^{BC}_{CR-x}$

$$\Rightarrow P^{BC}_{CR} = 11,559\ N$$

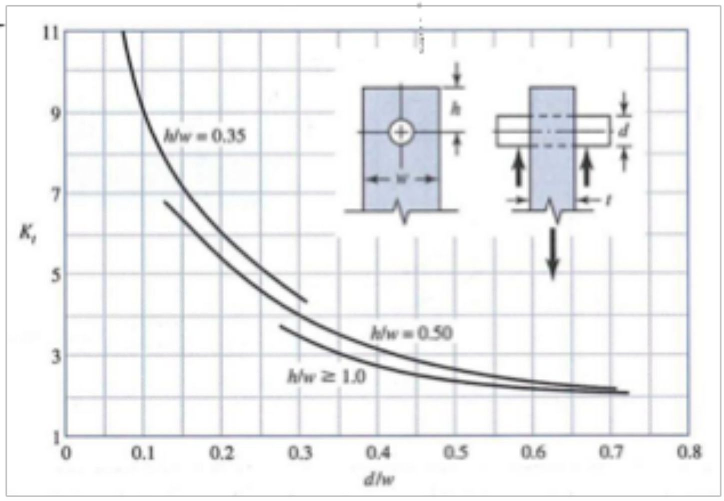
compared with the actual force in member BC when 30kg load is applied $F_{BC} = 294.3\ N$,

$$m^{BC}_{buckling\text{-}fail} = 30\,kg\left(\frac{11,559\,N}{294.3\ N}\right) = 1178\ kg$$

, $\Rightarrow$ BC will buckle with a load of 1178 kg

$\Rightarrow$ The BC member can be made weaker $\Rightarrow$ slender down the web further

Stresses at Pin Holes



$$K_t = \frac{\sigma_{max}}{\sigma_{nom}}$$

$d = 8$ mm, $w = 19$mm

$h = \frac{w}{2} = 9.5$mm , $t = 1.18$mm

$A_{without\_hole} = (w-d)t = 12.98\,mm^2$

Tensile Member AC

$$\sigma_{nom}^{AC} = \frac{F_{AC}}{A_{without\_hole}} = \frac{487.7\,N}{12.98\,mm^2}$$

$\Rightarrow \sigma_{nom}^{AC} = 37.5732$ MPa

$\frac{d}{w} = \frac{8mm}{19mm} = 0.42105$, $\frac{h}{w} = \frac{9.5mm}{19mm} = 0.5$

using the graph $\Rightarrow K_t \cong 3.1$

$\Rightarrow \sigma_{MAX}^{AC} = K_t\,\sigma_{Nom}^{AC} = 3.1\,(37.5732\text{ MPa})$

$\Rightarrow \sigma_{MAX}^{AC} = 116.5$ MPa

$\therefore \sigma_{MAX}^{AC} < UTS$

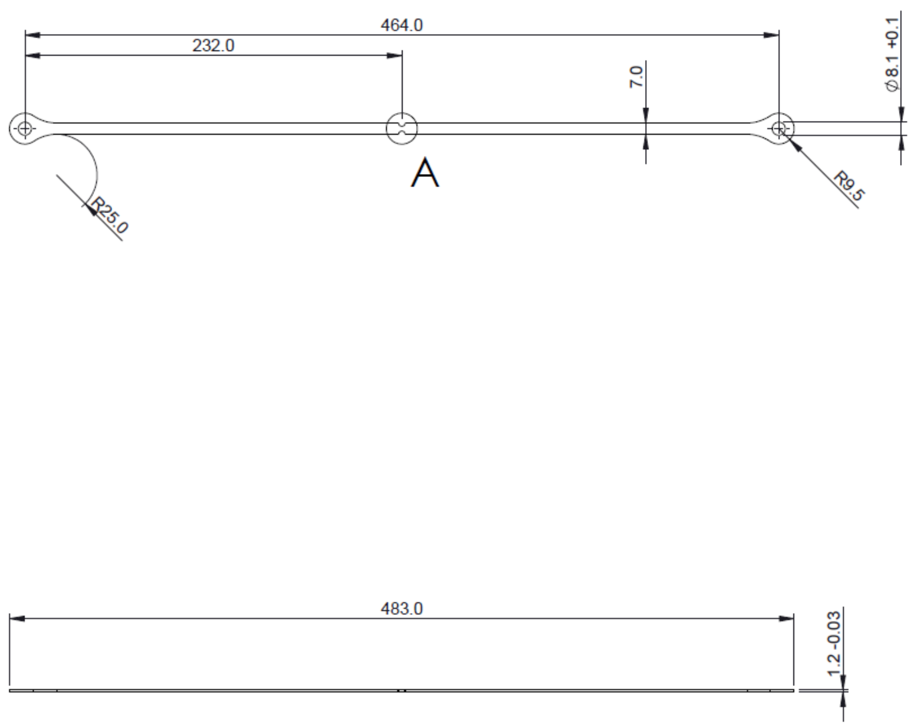
$\therefore$ Pin fails at a load of $m_{pin\text{-}fail} = 30kg\left(\frac{UTS}{\sigma_{MAX}^{AC}}\right)$

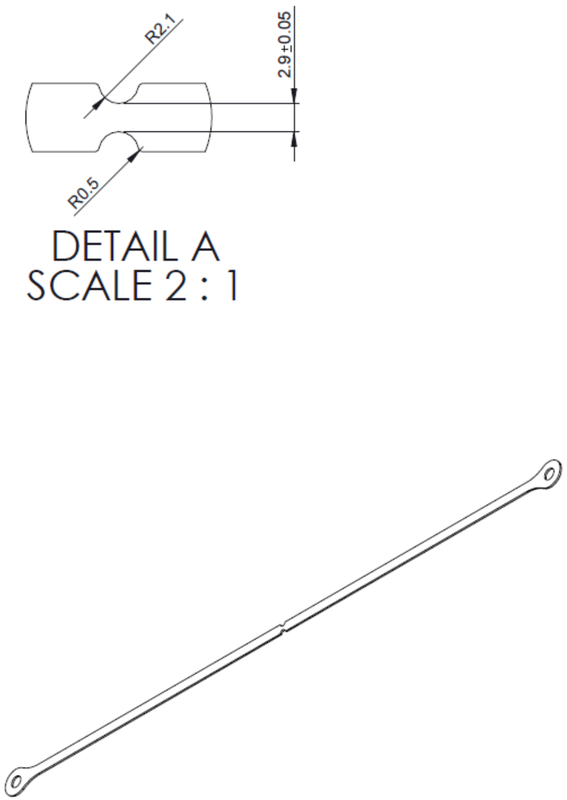
$\Rightarrow m_{pin\text{-}fail} = 30\text{ kg}\left(\frac{140\text{ MPa}}{116.5\text{ MPa}}\right) = 36.5732$ kg

$\Rightarrow m_{pin\text{-}fail} = 36.6$ kg $\Rightarrow$ pin hole will fail at a load of 36.6 kg

NOTES - (UNLESS OTHERWISE SPECIFIED)

1. ALL DIMENSIONS IN MILLIMETERS.
2. GD&T AS PER ISO1101-2004.





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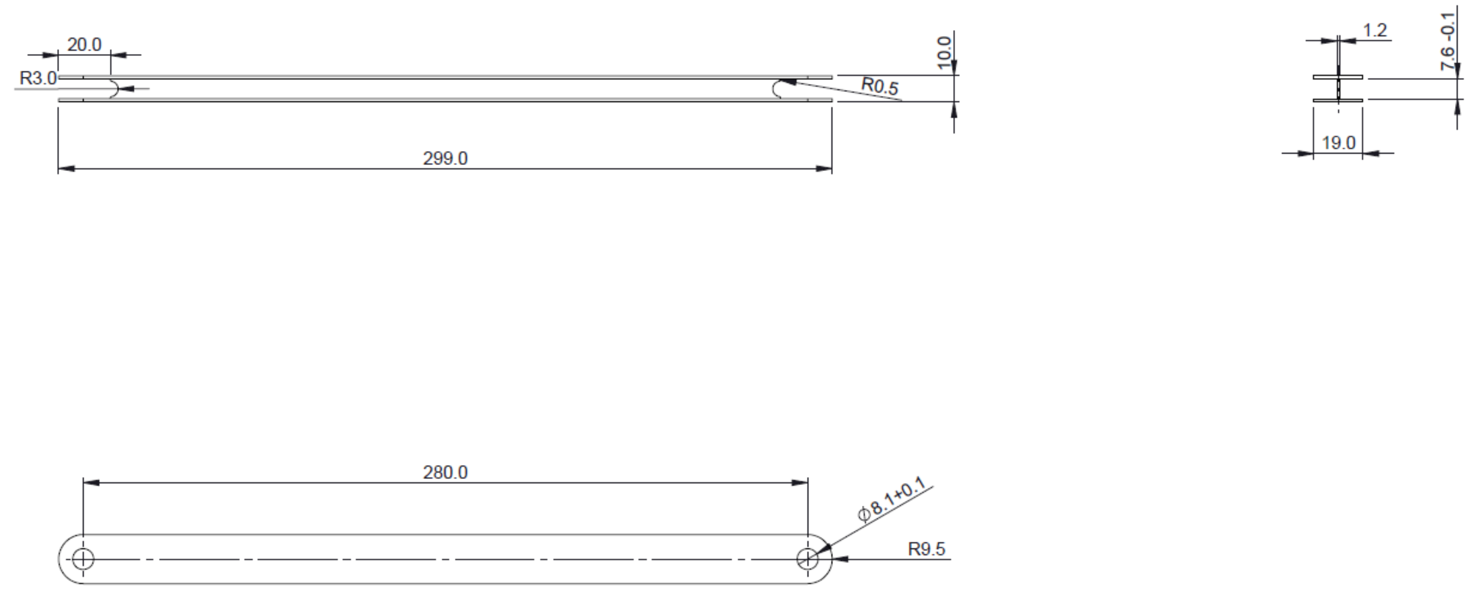
MATERIAL	AL-MG 5005 H32	TENSION MEMBER		
FINISH	NATURAL	DESIGN J CRAWFORD	DWG NO. 001	REV REV1
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN J CRAWFORD	PROJECT ENME301 ASS. 2	
.X ± .1 .XX ± .05 .XXX ± .010	ANG. ± 1°	SUPERVISOR K ALEXANDER	ISSUE DATE MAR 21	DRAWING NOT TO SCALE — SHEET 1 OF 1

NOTES - (UNLESS OTHERWISE SPECIFIED)

1. ALL DIMENSIONS IN MILLIMETERS.
2. GD&T AS PER ISO1101-2004.



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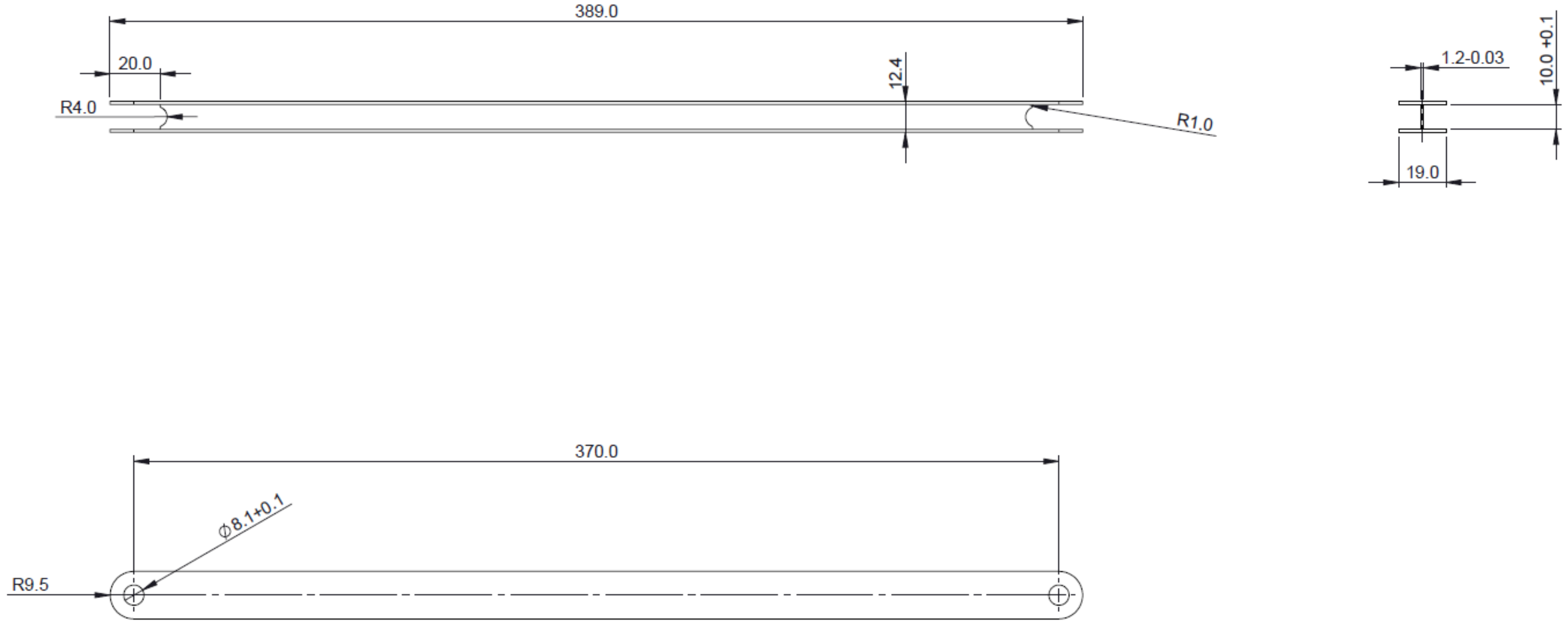
MATERIAL	AL-MG 5005 H32	I-BEAM 280	
FINISH	NATURAL	DESIGN J CRAWFORD / DWG NO. 002	REV REV1
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN J CRAWFORD / PROJECT ENME301 ASS. 2	
.X ± .1 .XX ± .05	.XXX ± .010 ANG. ± 1°	SUPERVISOR K ALEXANDER / ISSUE DATE MAR 21 / DRAWING NOT TO SCALE	SHEET 1 OF 1

NOTES - (UNLESS OTHERWISE SPECIFIED)

1. ALL DIMENSIONS IN MILLIMETERS.
2. GD&T AS PER ISO1101-2004.



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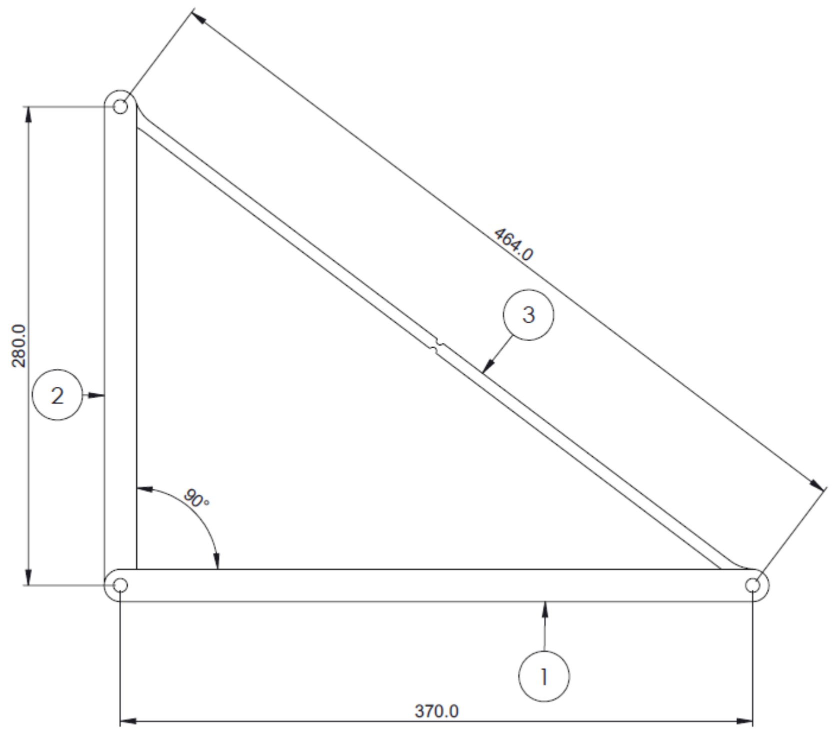
MATERIAL AL-MG 5005 H32		I-BEAM 370	
FINISH NATURAL		DESIGN J CRAWFORD / DWG NO. 002	REV REV1
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN J CRAWFORD / PROJECT ENME301 ASS. 2	
.X ± .1 .XX ± .05 .XXX ± .010 ANG. ± 1°		SUPERVISOR K ALEXANDER / ISSUE DATE MAR 21 / DRAWING NOT TO SCALE	SHEET 1 OF 1

NOTES - (UNLESS OTHERWISE SPECIFIED)

1. ALL DIMENSIONS IN MILLIMETERS.
2. GD&T AS PER ISO1101-2004.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	I_beam_370L	I-BEAM 370	1
2	I_beam_280L	I-BEAM 280	1
3	tensionbeam	TENSION MEMBER	1



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MATERIAL	SEE PART DRAWINGS	TRUSS	
FINISH	SEE PART DRAWINGS	DESIGN J CRAWFORD / DWG NO. 004	REV REV1
TOLERANCE (UNLESS OTHERWISE SPECIFIED) DECIMAL mm		DRAWN J CRAWFORD / PROJECT ENME301 ASS. 2	
.X ± 0.1 .XX ± 0.05 .XXX ± .001 ANG. ± 1°		SUPERVISOR K ALEXANDER / ISSUE DATE MAR 21 / DRAWING NOT TO SCALE	SHEET 1 OF 1

Timesheet

Task	Time Spent
Calculating loads in each member for different geometries	3 hours
Making 'dogbone' testing samples	2 hours
Testing for UTS on Hounsfield Tensometer	0.5 hours
Discussing/Choosing structure geometry	1.5 hours
Calculating stresses in each member	1 hour
Deciding on Tensile Member design	0.5 hours
Calculating second area moments and buckling loads for several compressive member designs	2.5 hours
Deciding on compressive member design	1 hour
Creating CAD design on Solidworks	2 hours
Iterating design to save weight	1.5 Hours
Iterating design on CAD	2 hours
Deciding/calculating on other failure modes	2.5 hours
Deciding Final Design	1.5 Hours
Writing Report	4.5 hours
Making CAD drawings	2 hours
Additional discussion throughout Assignment	3.5 hours
TOTAL	31.5 Hours