Tandem Bicycle Design and FE Analysis

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Introduction

This report details the process of designing and analysing a tandem bicycle frame. This is achieved by using iterative design and finite element analysis to improve the performance and safety of the tandem bicycle. The requirement of the design are as follows:

- The frame must support 2 adults of average weight, with both pedalling.
- The frame must be as lightweight as possible to increase performance and decrease material use.
- The natural frequency of the frame must be above 30Hz, ideally as high as possible.
- The frame must be able to withstand at least 1,000,000 loading cycles (equivalent to approximately 10 years of regular use) without fatigue failure.

Stage 1 : *initial design geometry (material : Aluminium Alloy)*

1. Mesh creation and refinement
2. Fatigue analysis study and results
3. Vibration analysis study and results

Stage 2 : *altering geometry for better performance (material : Aluminium Alloy)*

1. Repeat the meshing & studies
2. Discuss the differences between stages 1 and 2

Stage 3 : *changing the material to Titanium Alloy*

1. Repeat the studies
2. Discuss the differences between stages 2 and 3

Stage 4 : *Discussion of validity of results & conclusion*

Some background research was done on bike manufacturing and tandem bike design in order to understand the brief better. *Figure 1* show the tandem bike that the initial design will be based upon, whilst *figure 2* shows a tubing diagram that will be helpful when referencing different parts of the design,

Figure 1: Raven Twin Tandem Bike [2]

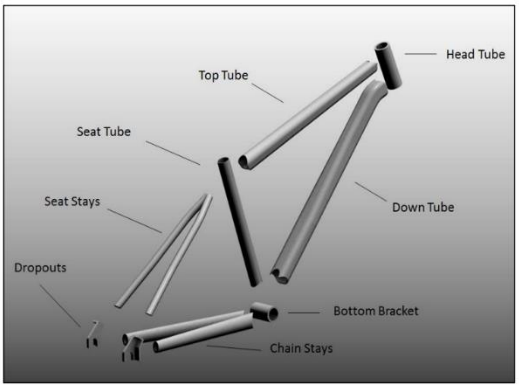


Figure 2: Tubing diagram of bicycle frame [1]

Methods

There will be 2 different study types used to analyse the performance of the bike frame: frequency analysis and fatigue analysis. They will be repeated at each stage of the design process to quantify the effectiveness of the improvements made. All the studies will both involve using the same boundary conditions and loads, which are detailed in the tables below. The failure criterion used in all studies will be Von Mises as the materials being analysed are both relatively ductile.

Table 1: Fixtures used in studies

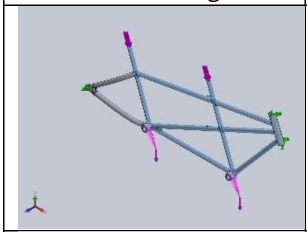
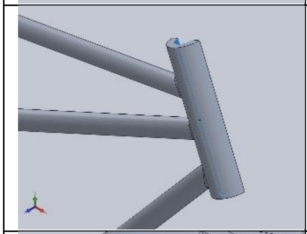
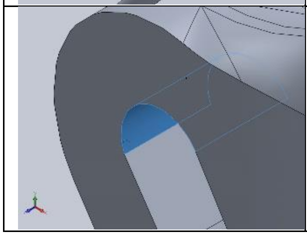
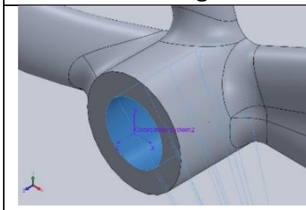
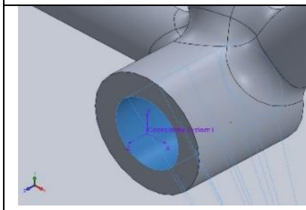
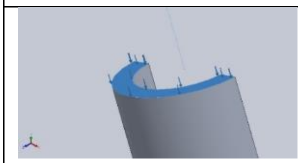
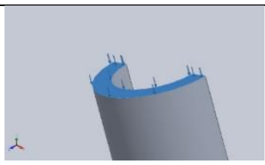
Fixture Image	Fixture Details
	Entities: 1 face Type: Symmetry
	Entities: 1 face Type: Fixed geometry (no translation or rotation)
	Entities: 1 face Type: Fixed Hinge

Table 2: Loads used in studies

Load Image	Load Details
	Entities: 1 face Type: Remote Load (Direct transfer) Coordinate System: Coordinate System2 Force Values: ---, -,700, --- N Moment Values: ---, ---, --- N.m Reference coordinates: 200 0 100 mm Components transferred: Force
	Entities: 1 face Type: Remote Load (Direct transfer) Coordinate System: Coordinate System1 Force Values: ---, -,700, --- N Moment Values: ---, ---, --- N.m Reference coordinates: 200 0 100 mm Components transferred: Force
	Entities: 1 face Type: Apply normal force Value: 1,380.7 N (cyclist 1)
	Entities: 1 face(s) Type: Apply normal force Value: 1,380.7 N (cyclist 2)

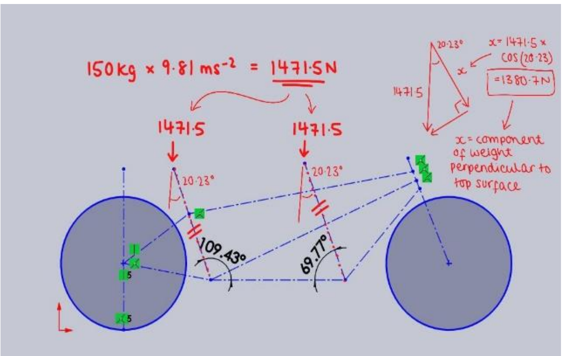


Figure 3: calculating the force on the top of the head tubes

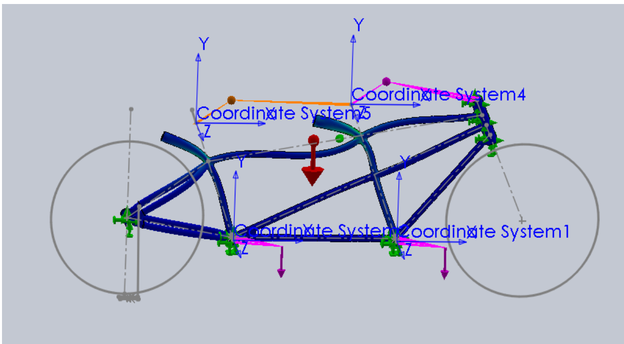


Figure 4: adding remote loads for cyclists' masses

The symmetry fixture accounts for the fact the model was cut in half to mesh more easily. The dropouts at the back of bike are hinged to the wheels and the inside of the head tube is kept as a fixed geometry as it doesn't move in relation to the rest of the bike. The loads on the bike are modelled as remote loads at the pedals to represent the pedalling force. Normal forces at the top of the seat tubes are used to model the mass of the cyclists (the process behind calculating the force value can be seen in figure 3). Figure 4 shows what one of the static studies produces if the cyclists' masses are modelled as remote loads. This is not an appropriate way of establishing loading conditions as it is difficult to precisely find the location of the cyclist's centre of mass.

Fatigue Study Method

The weight of the cyclists is a dead load, which don't oscillate, unlike the forces on pedals. Therefore, 2 static studies are needed which will be combined using the 'find peaks loading type. Gerber adjustment will be used as the materials being analysed are relatively ductile

2 static studies needed:

1. Force on seats = 3000N, load at pedals = 700N downwards
2. Force on seats = 3000N, load at pedals = 0

Vibration Study Method

All loads in table ? will be applied, and a direct sparse solver will be used to calculate the first 5 mode shapes / harmonic frequencies of the frame. These mode shapes can be compared and used for sanity checks.

Stage 1 : Initial Design

Geometry requirements:

- The length of the frame must be 1.5–2.0 m
- The seats should be 800 mm from ground level
- The frame must accommodate wheels with a 28-inch (660.4 mm) diameter
- The frame is made of hollow tubes with a circular cross section
- The tubes can have a variety of diameters (20mm internal diameter, with 4mm thickness was chosen)
- The tubes will be welded together, which can be modelled using 5-10 mm filets
- The frame must include 2 crank shells and a head tube of specific dimensions

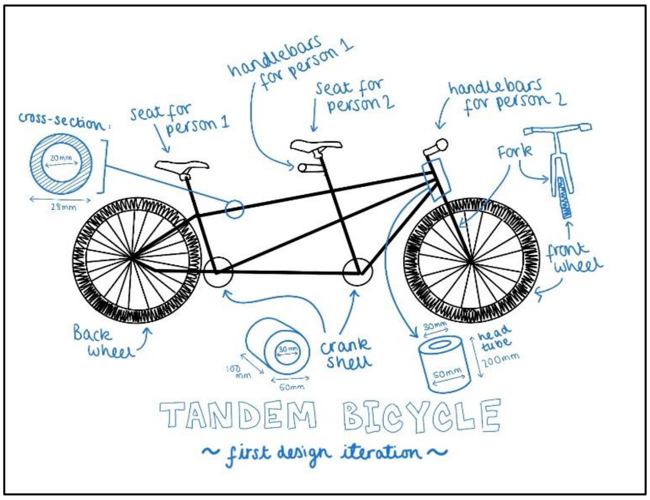


Figure 5: digital sketch of first design

CAD Model: made using Solidworks 2022

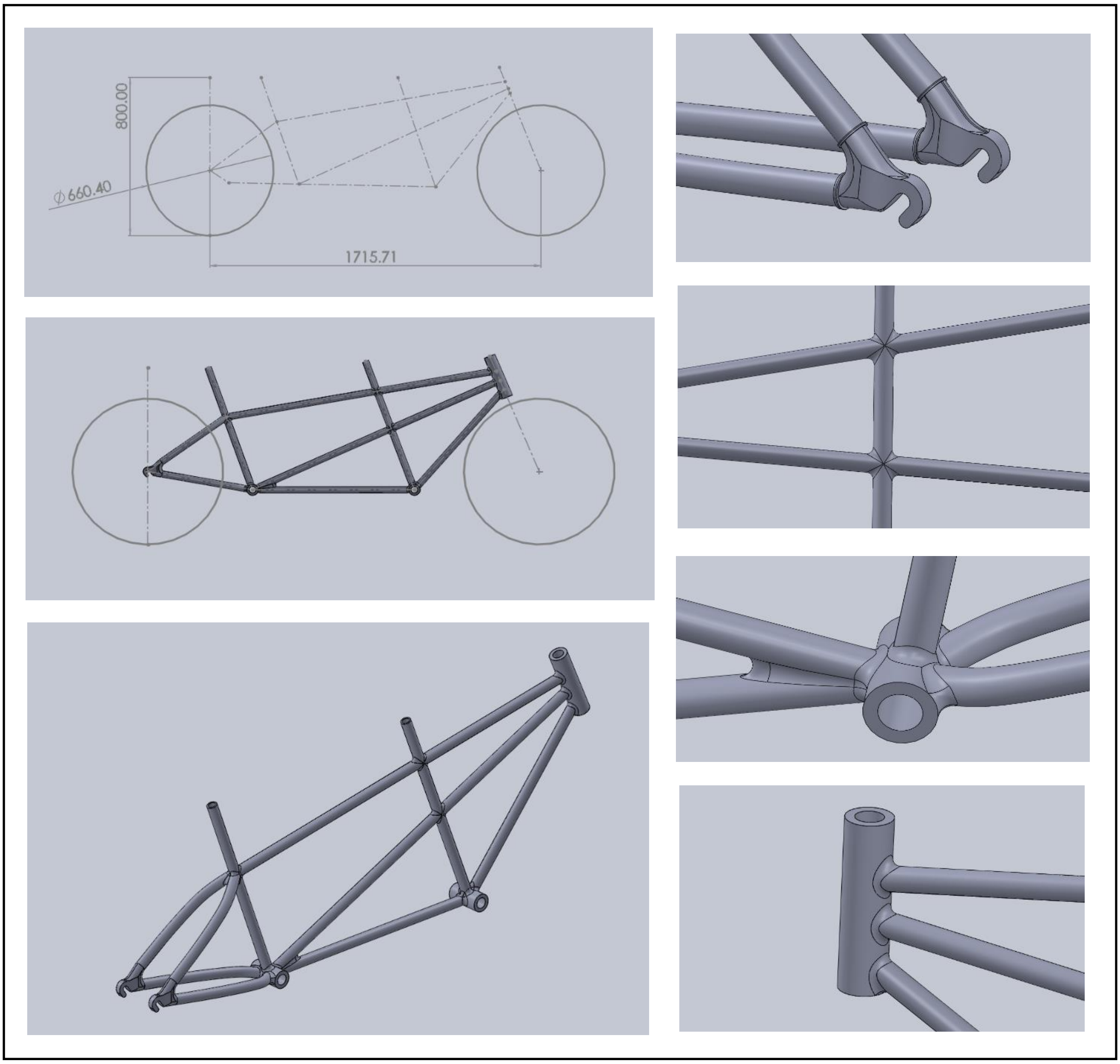


Figure 6: CAD model of initial tandem bike design (various views)

Initial design: Mesh Creation

A mesh refinement study was done to pick the most suitable mesh parameters. Computing time, number of nodes and aspect ratio were considered. The aspect ratio of most elements is ideally as close to 1 as possible. As the proportion deviates from 1, the integral approximation becomes less accurate, making the results of the studies less reliable.

Table 3: mesh refinement study data

Mesh No.	Mesh Settings		Time	No. of nodes	% of elements with aspect ratio > 10	% of elements with aspect ratio < 3	Max aspect ratio
	Largest Element Size	Smallest element size					
1	20.4 mm	4.1 mm	17 s	102,684	0.0791	79.1	42.6
2 (½ mesh)	20.4 mm	4.1 mm	10 s	56,623	0.113	78.8	42.3
3 (refined ½ mesh)	10.0mm	3.0 mm	11 s	75,917	0.0582	88.2	19.5

Initially, the whole model was used to create a mesh, which could cause issues when carrying out the studies dure to the large number of nodes. As the model is symmetrical, only half of the geometry need to be meshed, reducing the number of nodes, as seen in table 3. With less geometry to mesh, a higher quality of mesh can be used which significantly decreases the maximum aspect ratio. The chosen mesh size is mesh no. 3 (shown in figure 7), as it is the mesh with the most consistent quality. A curvature-based mesh was picked because it is more likely to run successfully. Additionally, the geometry of the entire bike frame involves circular profiles, so all the surfaces are significantly curved. The more complex features (such as the fillets) have a larger aspect ratio, but this will be improved by using mesh controls to refine the mesh in those areas.

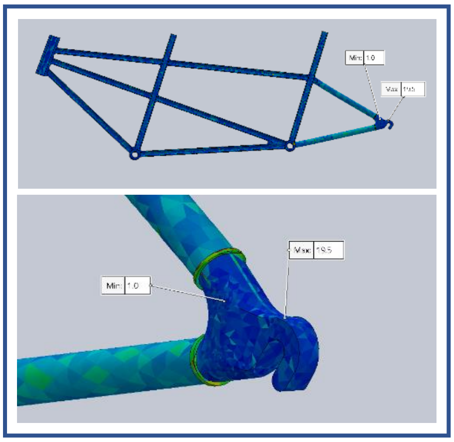
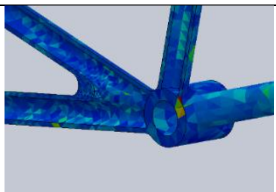
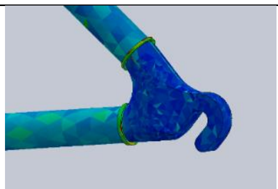
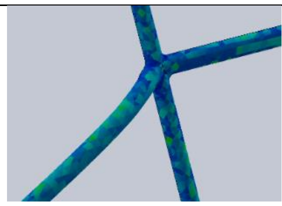
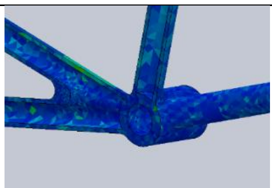
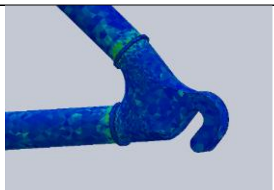
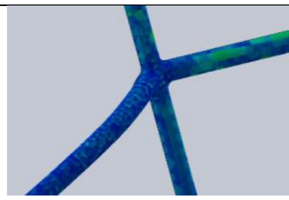


Figure 7: views of mesh no. 3

Applying Mesh Controls

A mesh control of 5mm was applied to the fillets, crank shells, head tube and the tubes attached to the rear wheel. An additional 1mm mesh control was added to the smaller geometry on dropouts. This made a significant improvement, as seen in table 4.

Table 4: before and after mesh control

Before applying mesh controls			
After applying mesh controls			

Initial design : Fatigue Study

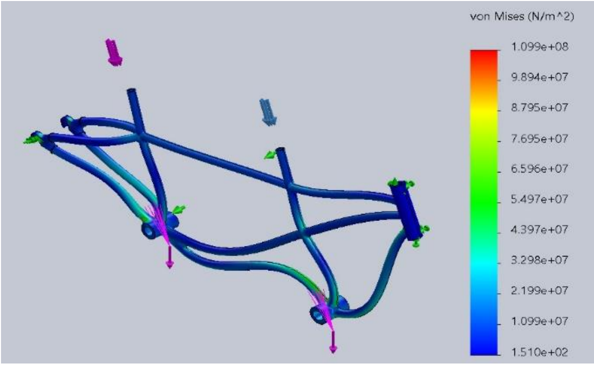


Figure 8: Stress plot from static study 1

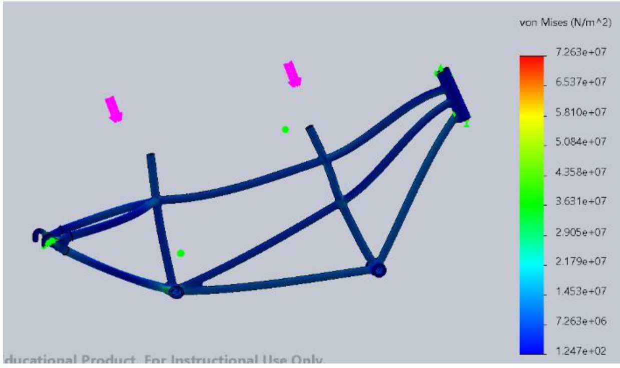


Figure 9: stress plot from static study 2

Fatigue Results

Minimum damage: 0 % Maximum damage : 1415.57 % (70,640 cycles)

The area with the largest damage is where the front crank shell connects to the front seat tube. This is a believable result as there will be more force directed to the front of the bike than the back. Additionally, the fatigue is most likely to occur at joints.

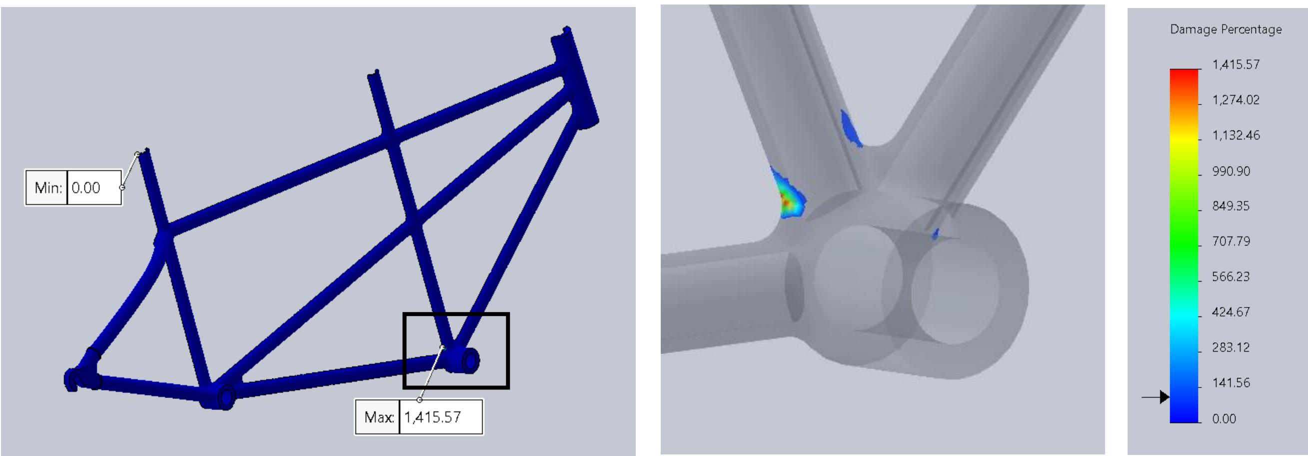


Figure 10: Iso clipping of damage plot – the remaining areas have a damage percentage above 100%

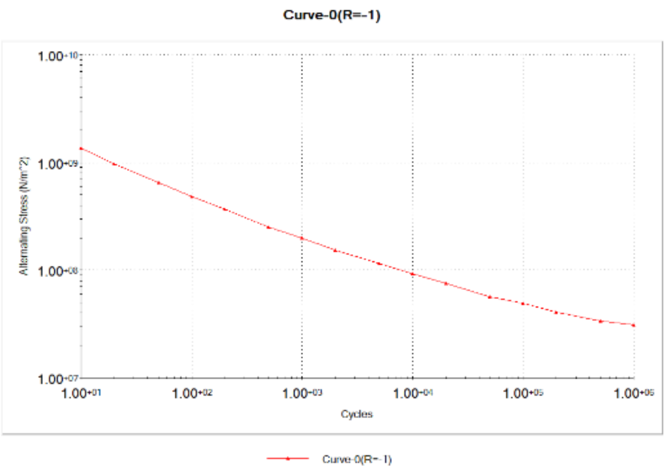


Figure 11: SN curve for Aluminium 7075-T6 (derived from elastic modulus based on ASME Carbon Steel curves)

Table 5 : material properties of Aluminium

Material Name:	**Aluminium 7075-T6**
Yield strength:	**5.05e+08 N/m^2**
Tensile strength:	**5.7e+08 N/m^2**
Mass density:	**2,810 kg/m^3**
Elastic modulus:	**7.2e+10 N/m^2**
Poisson's ratio:	**0.33**
Thermal expansion coefficient:	**2.36e-05 /Kelvin**

Initial design : Frequency Study

Natural frequency: 244.15 Hz

Resultant Amplitude Plot (mode shape 1)
Min: 0.00
Max: 1.667

Table 6: Resultant amplitude Plot for mode shape 1

Mode shape	Frequency (Hz)
1	244.15
2	271.28
3	317.29
4	344.3
5	401.96

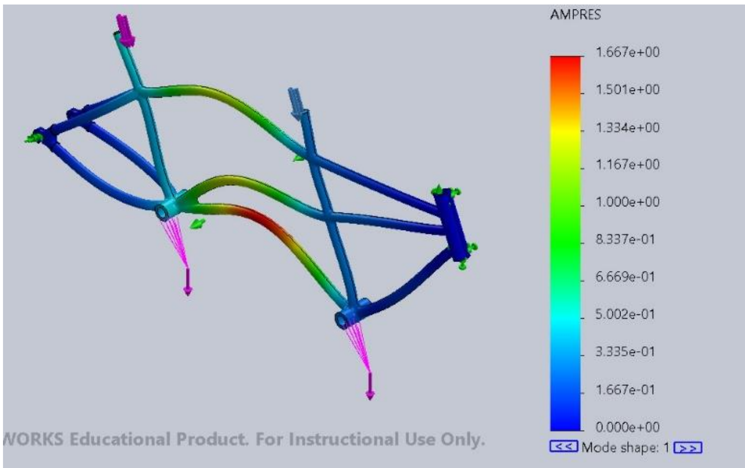


Figure 12: Resultant amplitude Plot for mode shape 1

If the bike is to resonate, it will most likely be at the natural frequency, although other mode shapes / harmonics are also possible (as seen in table 6). The natural frequency of the initial design is 244.15Hz. This is much higher than the minimum requirement, so the bike is not likely to every resonate under the stresses applied. Therefore, the bike is much more prone to breaking due to fatigue failure. This makes sense as <60% of material failure is caused by fatigue.

Stage 2 : Altering the frame geometry

The goal of this stage is to redesign the frame so as to make it perform better in the FEM studies. This means changing the size and shape of the tubing in order to get it pass the fatigue test and have a higher natural frequency.

Adding additional support structures

This will make the structure stiffer without adding too much mass. Ideally this ratio will result in a higher fundamental frequency whilst also increasing fatigue life.

Changing tube thickness

This should increase the natural frequency due to a different length to thickness ratio. This will also make the bike lighter and less expensive as less material is being used. The theory to back this up is derived from the fundamental frequency of a cantilever beam as the bike is essentially made from multiple cantilever beams.

$$fundemental\ frequency\ of\ a\ cantilever\ beam = \omega_0 = 1.875^2\sqrt{\frac{\mathrm{EI}}{\rho \mathrm{L}^4 \mathrm{A}}}$$

$$\frac{\mathrm{I}}{\mathrm{A}} = \frac{1}{4}({\mathrm{R_o}}^2 + {\mathrm{R_i}}^2)$$

$$therefore, the\ tubes\ should\ be\ made\ thinner\ with\ an\ increased\ external$$

$$diameter\ to\ increase\ the\ natural\ frequency$$

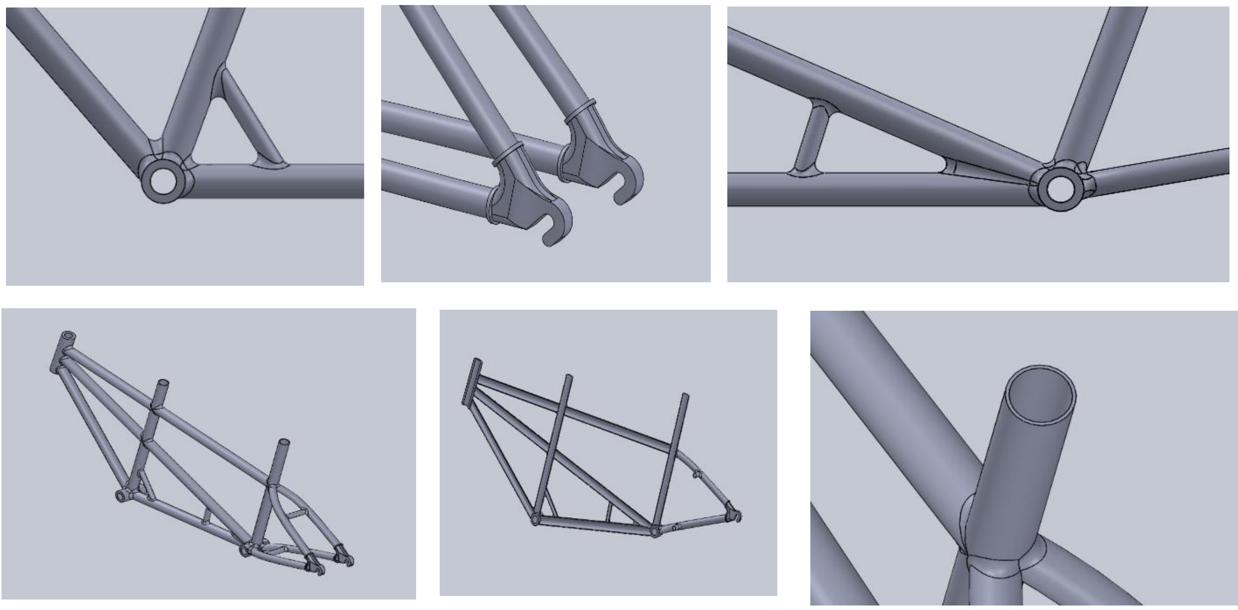


Figure 13 : CAD model of second design

New tube thickness: 2 mm

New external diameter: 38 mm

Second Design : Fatigue Study

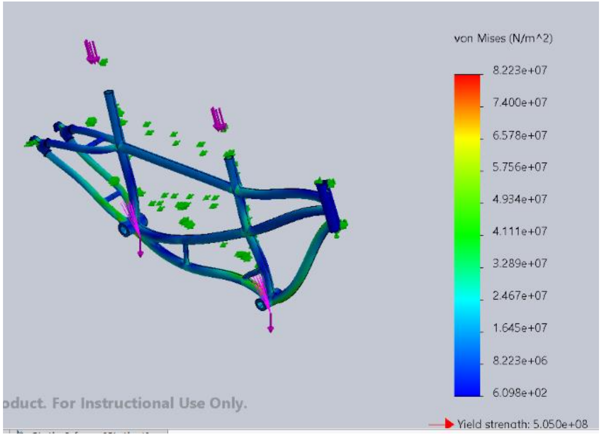


Figure 14: stress plot for static study 1

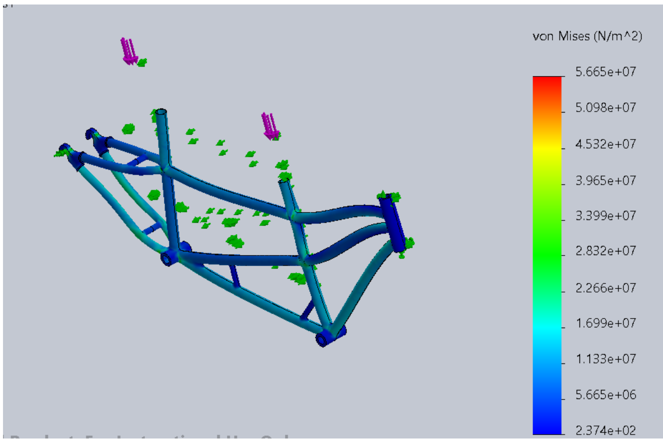


Figure 15: stress plot for static study 2

Fatigue results

Minimum damage: 0 % Maximum damage : 201.95 % (495,200 cycles)
The fatigue failure still occurs in the same place; however, the damage is greatly reduced, both in magnitude and area of damage. This is due to the addition of the support tubes near the joints to distribute stress more evenly.

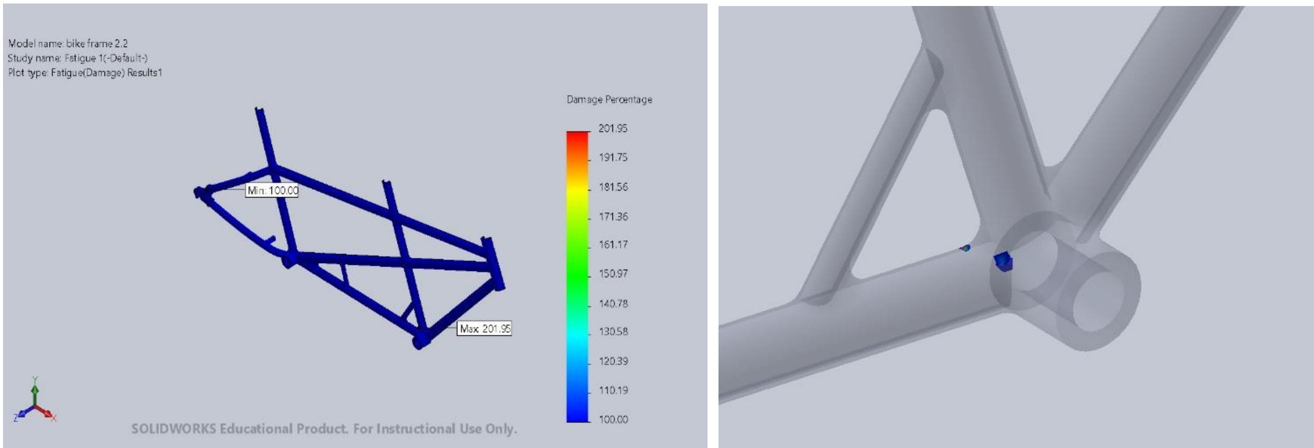


Figure 16 : second design damage plot and Iso clipping of damage plot – the remaining areas have a damage percentage above 100%

Second design : Vibration Study

Natural frequency : 280 Hz

The natural frequency is larger than the initial design due to the thinner tubes

Frequency Number	Hertz
1	**280.61**
2	**337.76**
3	**362.39**
4	**446.67**
5	**520.92**

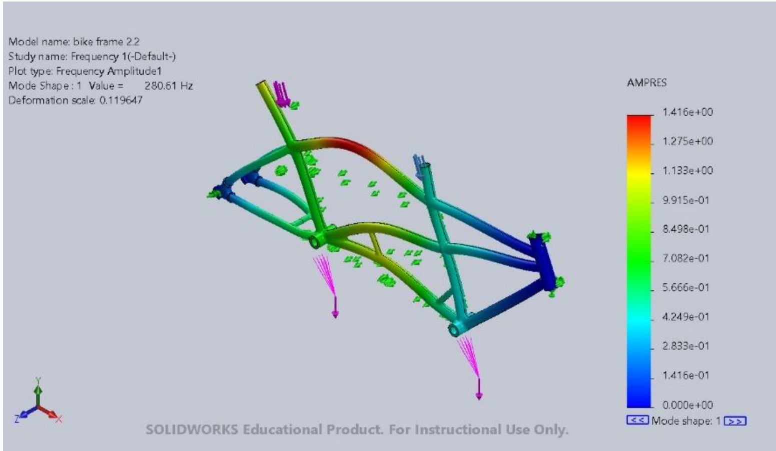


Figure 17 : AMPRES for mode shape 1

STAGE 3 : Material Change

Vibration Study (Titanium bike frame)

Natural frequency : 269.6Hz

Frequency Number	Hertz
1	**269.6**
2	**324.71**
3	**348.77**
4	**428.81**
5	**501.65**

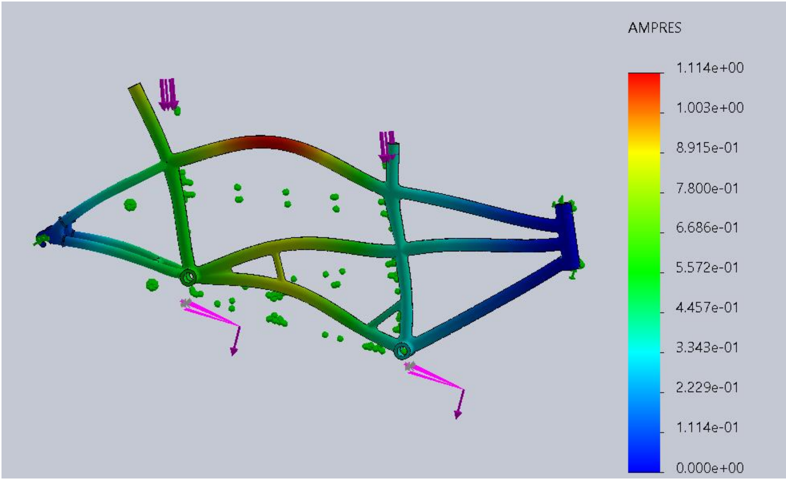


Figure 18: AMPRES for mode shape 1

	Titanium Alloy	Aluminium Alloy 7075-T6
Density, ρ [kg/m^3]	4,428.78 kg/m^3	**2,810 kg/m^3**
Elastic Modulus, E [GPa]	1.048e+2 N/m^2	**7.2e+1N/m^2**
E / ρ	0.0237	0.0256

E/p is larger for the Aluminium Alloy, resulting in a higher fundamental frequency

Fatigue Study (Titanium bike frame)

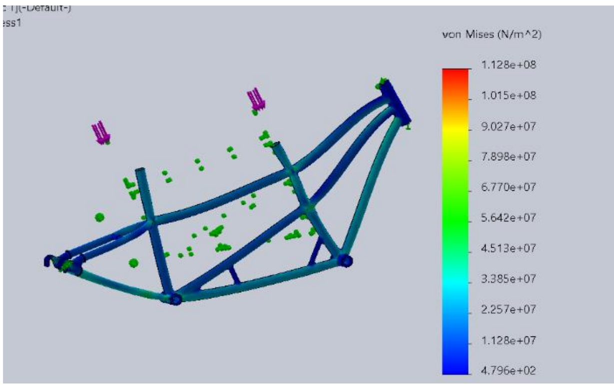


Figure 19: stress plot for static 1

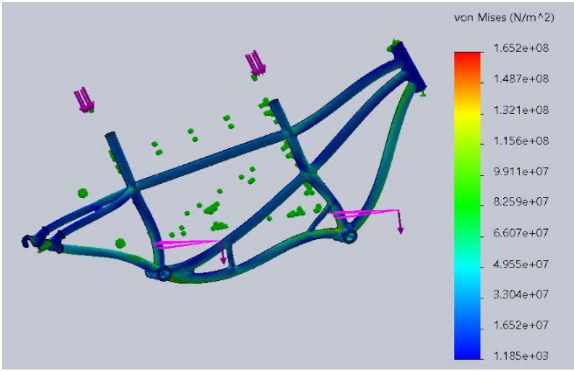


Figure 20: stress plot for static 2

Fatigue Results: the solver was not able to calculate any damage within the structure. This may be because the structure has reached its fatigue limit so will not experience any damage due to the alternating stress. As seen in figure 21 the fatigue limit of the Titanium alloy is at around 500 MPa, which is larger than the maximum stress calculated in both static studies.

Table 9: material properties for Titanium Alloy

Material Name:	Ti-6Al-4V Solution treated and aged
Yield strength:	8.27371e+08 N/m^2
Tensile strength:	1.05e+09 N/m^2
Mass density:	4,428.78 kg/m^3
Elastic modulus:	1.048e+11 N/m^2
Poisson's ratio:	0.31

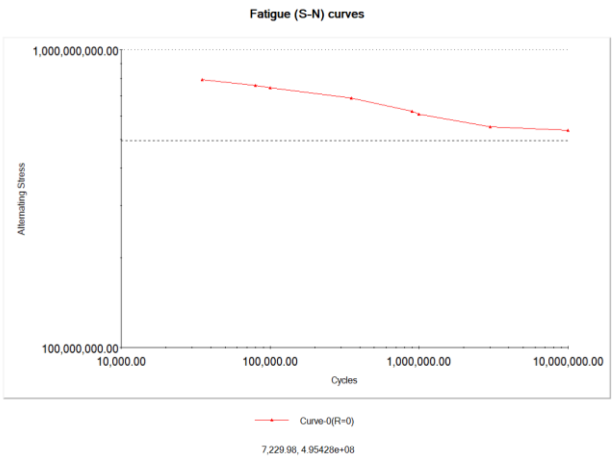


Figure 21: SN curve for Titanium Alloy

Stage 4 : Discussion

Sources of error:

- Numerical Error – this is inevitable when computing results but should not reduce to accuracy of results that much
- Discretisation Error – this is likely to be small as the mesh quality for all studies was relatively high
- Modelling Error - this will be highest source of error as the model is very simple and doesn't consider many variables (detailed below)

1. Real life inconsistences like stress concentrators and discrepancies in manufacturing.
2. Simulating the forces is not true to life. The weight distribution isn't the same (maybe people are lighter/heavier/carrying bags, leaning to one side). The weight given is very large.
3. It could be useful to simulate the whole bike (including wheels, suspension) to see how forces like uneven roads or breaking sharply with change the stress distribution. This would be much more complex though so would need a better processor.
4. Road conditions (rocky, smooth)
5. Dampers in the bike
6. Temperature and weather conditions can change the material properties