LIGHTWEIGHT TANDEM BICYCLE FRAME

REPORT

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Contents

Introduction

The following report outlines the design of a lightweight unisex tandem bicycle with 2 seats that can accommodate adult users. The initial bike design prioritized the first two requirements (lightweight and unisex), and then the design was progressively iterated to meet the mechanical parameters.

Parameters	Requirements
Frame Length	2 < L < 2.5 m
Wheel diameter	0.66 m
Height of seats	0.8 m
Pipe Diameter	≤ 44 mm
Crank and Fork Shell Diameter	70 mm
Natural Frequencies	> 30 Hz
Effective life	≥ 1000000 loading cycles

Figure 1. Mechanical parameters outlined in brief

Finite element analysis was conducted to determine the natural frequency and fatigue life of 3 bicycle iterations. Firstly, a static simulation was created and run to determine basic comparable metrics such as von Mises stresses. A frequency simulation was run on each iteration, ensuring that the natural frequencies were above 30 Hz to avoid discomfort when riding. Fatigue simulations were then run to determine the number of life cycles the frame could withstand before failure, and iterations were made to raise this above 1000000 loading cycles, which equates to around 10 years of effective use.

All iterations were modelled using both aluminium alloy (7075 – T6) and magnesium alloy to determine the best material to use.

Method

Initially, research was done to explore the current methods of constructing a tandem bicycle, so that the initial iteration would lead to an industry standard bicycle. A frame with minimal elements and a low number of beams was constructed to be iterated and improved on.

All iterations were modelled using the following method – the same boundary conditions, parameters and loads were used so that the results gathered from the simulations were comparable and as accurate as possible.

Modelling assumptions

When modelling solid elements and running simulations, several assumptions must be made to ensure the model is valid:

- The 3 dimensions of the structure are comparable.
- The material properties are the same in any direction – the model is isotropic.
- The material properties are the same everywhere – the model is homogenous.
- Any displacements that occur are relatively small.

Boundary Conditions

The front and rear shells of the bicycle acted as fixed or hinged boundaries, to simulate the fixed reaction force created by the wheels (which were not modelled):

1. Fixed Geometry: inner surface of fork shell
2. Hinged Boundary: rear wheel bearing

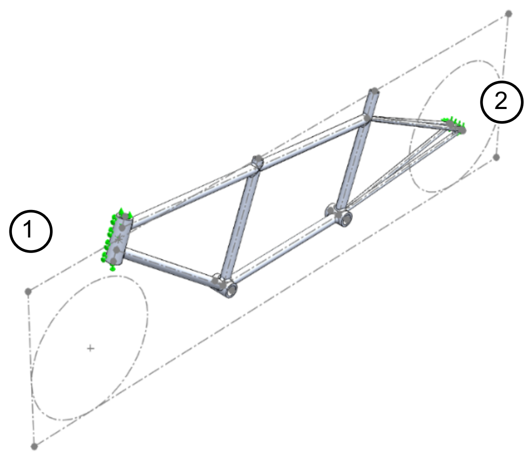


Figure 2. Frame with boundary conditions

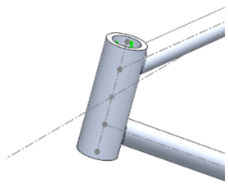


Figure 3. Fixed Geometry

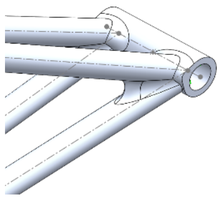


Figure 4. Hinged Boundary

Loads

Gravity - A gravitational force was set up (acting downwards) to ensure the model was as close to real life as possible.

Seating Loads - For all simulations, a force was added to each seat joint to represent an adult applying their full weight. The force added was 1471.5 N, which equates to 150 kg. The weight of the adults was exaggerated to ensure the bike can operate under the most extreme of circumstances.

Pedal Loads - In addition to the seating loads, a remote load was applied for both feet of each person; an oscillating force ranging from 0 to 1kN acting downwards. The remote load was located 200mm forward and 150 mm sideways from the crank shaft.

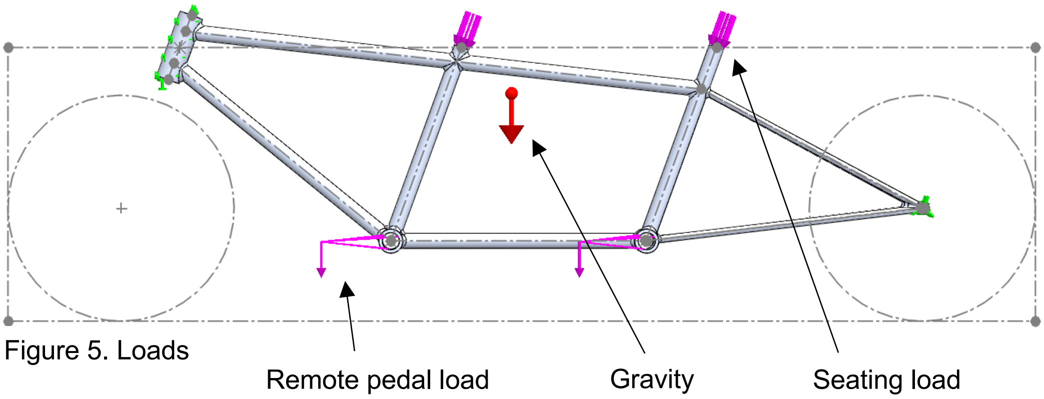


Figure 5. Loads

Load scenarios

Different load scenarios were tested in each simulation so that all possible load eventualities were covered and assessed. Each load scenario consists of a different formation of pedal load, as shown below.

Load Scenario: 1 2 3 4

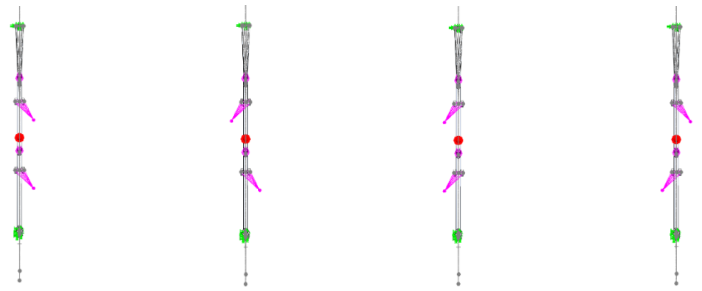


Figure 6. Load Scenarios

Initially, simulations were run on all 4 scenarios to determine where the bicycle would fail, but it was quickly confirmed that due to the symmetry of the frame, scenario 1 and 3 yielded the same results, as did 2 and 4. Subsequently the simulations were only run on 1 and 2.

Frequency and fatigue simulation parameters

Frequency simulation parameters:

During the frequency simulation, all the parameters were identical to the static simulation. The solver was changed from FFEPlus to Direct sparse solver.

Fatigue simulation parameters:

For the fatigue simulation, the focus was on the two cyclic loads of the pedals. For each pedal, alternating stresses with a stress ratio of R=0 was produced. Mean stress correction was changed to Gerber – this correction method is better for ductile materials, and both aluminium and magnesium are ductile. The correction method was implemented in order to find the right stress (with stress ratio R=0), as the loading type of the solver for the SN curve was R=-1.

SN Curves used during the fatigue analysis:

Aluminium Alloy (7075 – T6) SN Curve:

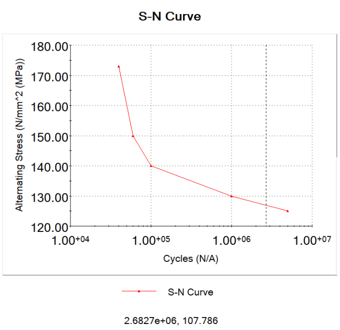


Figure 7. Aluminium SN Curve

Magnesium Alloy SN Curve:

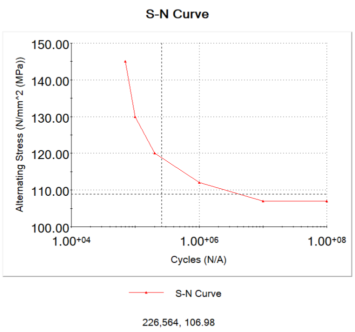


Figure 8. Magnesium SN Curve

Results

Sanity Checks

Sanity checks were conducted to investigate whether the model – and its parameters and assumptions – were logically feasible.

For each simulation result, the maximum stress and maximum displacement were analysed to see whether the results given were realistic. The deformed results were all relatively small - no more than a couple of millimetres for each iteration and were deemed to be feasible.

Resultant forces were checked to see if they corresponded to the forces being added in the simulations – the resultant forces added up to the 4 loads applied.

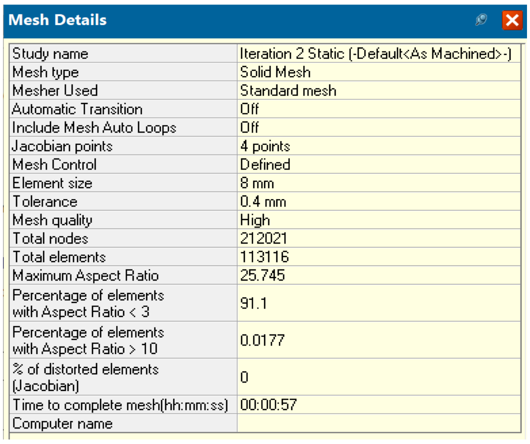
Mesh refinement

Initially, the frames were meshed with a relatively large mesh density, to get rough values for metrics such as maximum stress and displacement. Then the mesh was refined - decreasing the mesh size and eventually applying mesh control - until the last 2 values of maximum stress were within 90% of the final value. This ensures that the most accurate result (for all simulations) was obtained.

Mesh control was added at the point where the simulation showed the stress was focused – this was predominantly on the fillets near the crank shells.

Mesh quality was also verified by analyzing the mesh details: the maximum aspect ratio was 25.745, but 91.1 % of elements had an aspect ratio of less than 3, which is ideal.

I decreased global mesh size to 8 mm and no further, because decreasing it further took more than 5 minutes to mesh on my computer, so I refined the mesh in the areas of high stress further, by decreasing the size of the mesh control around the fillets.



Mesh Details

Study name	Iteration 2 Static (-Default<As Machined>-)
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Mesh Control	Defined
Element size	8 mm
Tolerance	0.4 mm
Mesh quality	High
Total nodes	212021
Total elements	113116
Maximum Aspect Ratio	25.745
Percentage of elements with Aspect Ratio < 3	91.1
Percentage of elements with Aspect Ratio > 10	0.0177
% of distorted elements (Jacobian)	0
Time to complete mesh(hh:mm:ss)	00:00:57
Computer name	

Figure 9. Mesh details

An example of how the mesh size was chosen is shown below, on the frame of iteration 2 – once a global mesh size was found to be optimum, it was applied to all iterations from then on.

Global mesh size (mm)	Mesh control size	Maximum stress (MPa)
10	N/A	7.318e+01
8	N/A	8.805e+01
8	5	9.740e+01
8	3	**1.040e+02**
8	2	**1.011e+02**

Values within 90% of final value

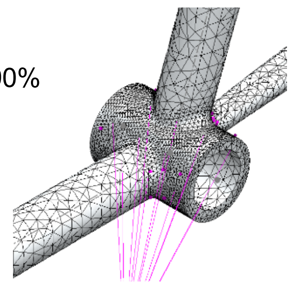
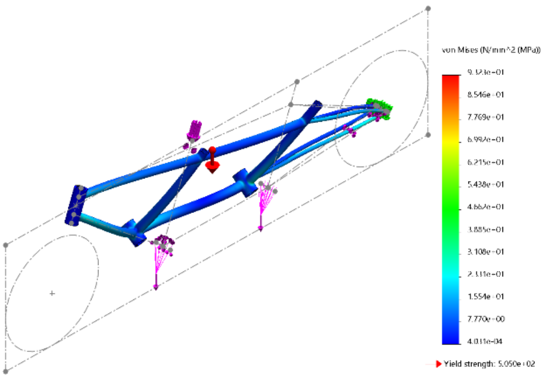


Figure 10. Refining the mesh on iteration 2

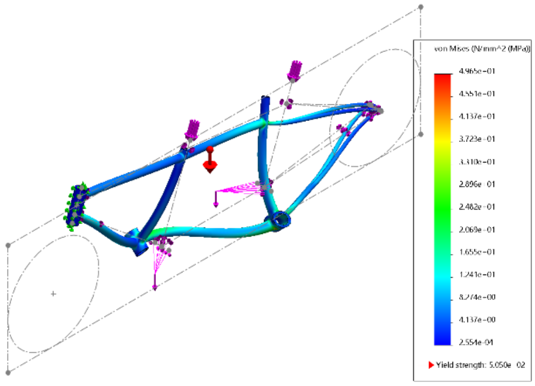
Iteration 1 – Aluminium alloy (7075-T6)

Static simulation results

Load scenario 1:



Load scenario 2:



Load scenario 1:

Maximum stress	9.890e+01 MPa
Maximum displacement	2.844e+00 mm
Minimum safety factor	5.1064

Load scenario 2:

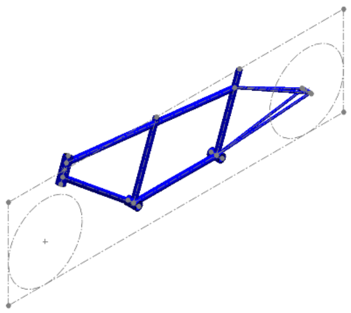
Maximum stress	5.754e+01 MPa
Maximum displacement	8.546e-01 mm
Minimum safety factor	8.7760

Frequency simulation results

Resonant frequency:

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (seconds)
1	218.63	34.796	0.028739
2	333.63	53.099	0.018833
3	504.3	80.262	0.012459
4	606.55	96.536	0.010359
5	729.38	116.08	0.0086144

Fatigue simulation results



Maximum damage percentage	5.88 %
Total life cycles before failure	1.702e+07

Survives 1000000 cycles

Iteration 1 – Magnesium alloy

(Visual images of the simulations were omitted in the magnesium alloy results as they are similar to the aluminium alloy images)

Static simulation results

Load scenario 1:

Maximum stress	9.896e+01 MPa
Maximum displacement	4.572e+00 mm

Load scenario 2:

Maximum stress	5.676e+01 MPa
Maximum displacement	1.364e+00 mm

Frequency simulation results

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (seconds)
1	224.15	35.674	0.028032
2	334.2	53.189	0.018801
3	514.87	81.944	0.012203
4	618.18	98.386	0.010164
5	735.42	117.05	0.0085437

Fatigue simulation results

Maximum damage percentage	2.503 %
Total life cycles before failure	4.004e+07

Survives 1000000 cycles

Improvements

It was determined which was the better material to use for each simulation, based on which material displayed more optimum values overall.

Better material:

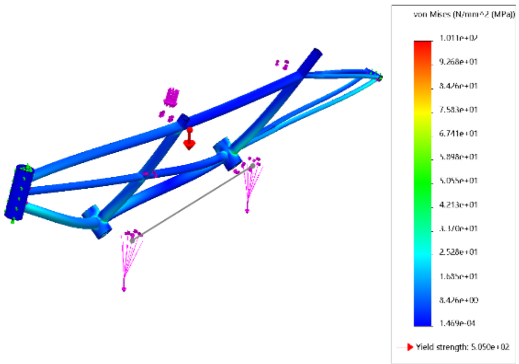
- Static simulation: magnesium alloy
- Frequency simulation: magnesium alloy
- Fatigue simulation: magnesium alloy

Analysing the deformation, it was apparent that the frame requires some increased strength and stiffness along the main frame – therefore a support bar was added to run between the front shell and the rear crank shell. The diameter of the members was also reduced from 44mm to 40mm, and the thickness remained at 12 mm.

Iteration 2 – Aluminium alloy (7075-T6)

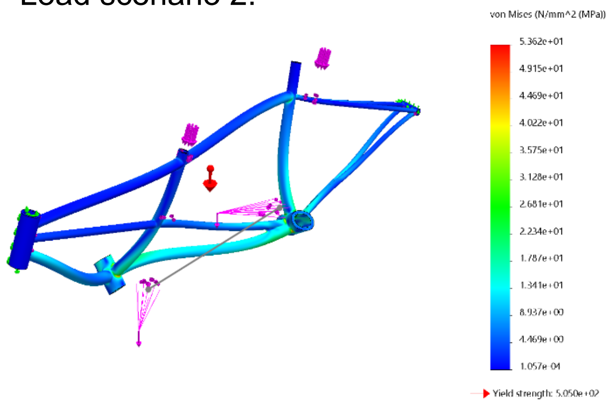
Static simulation results

Load scenario 1:



Maximum stress	1.101e+02 MPa
Maximum displacement	3.512e+00 mm
Minimum safety factor	4.995

Load scenario 2:



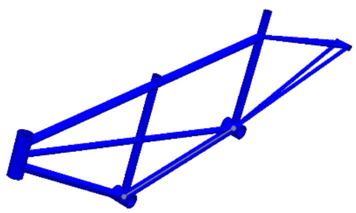
Maximum stress	5.362e+01 MPa
Maximum displacement	1.181e+00 mm
Minimum safety factor	9.417

Frequency simulation results

Resonant frequency:

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (seconds)
1	247.52	39.394	0.025384
2	344.39	54.812	0.018244
3	496.23	78.978	0.012662
4	621.58	98.928	0.0010108
5	685.21	109.05	0.0091697

Fatigue simulation results



Maximum damage percentage	5.88 %
Total life cycles before failure	1.702e+07

Survives 1000000 cycles

Iteration 2 – Magnesium alloy

Static simulation results

Load scenario 1:

Maximum stress	1.020e+02 MPa
Maximum displacement	5.719e+00 mm

Load scenario 2:

Maximum stress	7.214e+01 MPa
Maximum displacement	2.028+00 mm

Frequency simulation results

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (seconds)
1	254.66	40.531	0.024673
2	345.42	54.976	0.01819
3	509.56	81.099	0.012331
4	638.28	101.58	0.009844
5	691.71	110.09	0.0090836

Fatigue simulation results

Maximum damage percentage	2.503 %
Total life cycles before failure	4.004e+07

Survives 1000000 cycles

Improvements

Better material:

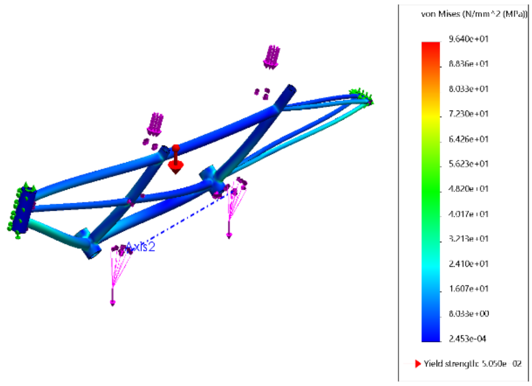
- Static simulation: aluminium alloy
- Frequency simulation: magnesium alloy
- Fatigue simulation: magnesium alloy

Adding in the central element between the front shell and the rear crank shell improved the frequency at mode number 1 by 4 Hz, keeping it above 30 Hz. To improve the natural frequency further for the next iteration, the diameter of the elements will be widened to 44 mm to increase their stiffness and the thickness of the elements will also be reduced - changing the thickness from 11 mm to 8 mm - so that weight is kept to a minimum.

Iteration 3 – Aluminium alloy (7075-T6)

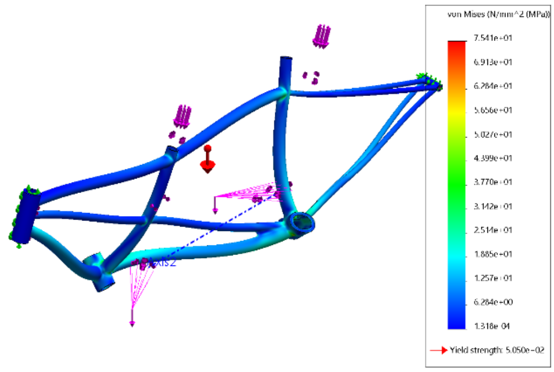
Static simulation results

Load scenario 1:



Maximum stress	9.640e+01 MPa
Maximum displacement	3.345e+00 mm
Minimum safety factor	5.23879

Load scenario 2:



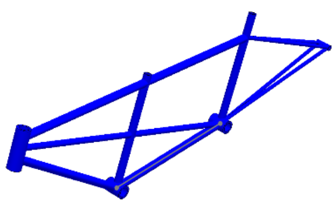
Maximum stress	7.541e+01 MPa
Maximum displacement	1.075e+00 mm
Minimum safety factor	6.69679

Frequency simulation results

Resonant frequency:

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (seconds)
1	261.78	41.664	0.024001
2	375.73	59.799	0.016723
3	526.84	83.349	0.011926
4	626.56	99.72	0.010028
5	740.29	117.82	0.0084875

Fatigue simulation results



Survives 1000000 cycles

Maximum damage percentage	5.88 %
Total life cycles before failure	1.702e+07

Iteration 3 – Magnesium alloy

Static simulation results

Load scenario 1:

Maximum stress	9.167e+01 MPa
Maximum displacement	5.337e+00 mm

Load scenario 2:

Maximum stress	7.482e+01 MPa
Maximum displacement	1.731e+00 mm

Frequency simulation results

Resonant frequency:

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (seconds)
1	269.27	42.856	0.023334
2	377.18	60.031	0.016658
3	541.32	86.154	0.011607
4	644.77	102.62	0.0097448
5	747.55	118.98	0.0084051

Fatigue simulation results

Maximum damage percentage	2.503 %
Total life cycles before failure	4.004e+07

Survives 1000000 cycles

Improvements

Better material:

- Static simulation: aluminium alloy
- Frequency simulation: magnesium alloy
- Fatigue simulation: magnesium alloy

Discussion

Static simulations

The static simulations that were run on all three iterations yielded results that proved that none would fail under basic static loading. The yield stresses for aluminium and magnesium were 5.050e+02 MPa and 3.000e+02 respectively. The maximum von Mises stress simulated on any of the iterations was 1.101e+02 MPa, and all safety factors were above 3. Due to this, and because the values used for the loads were extreme cases, it can therefore be concluded that the frames would not fail under static loads.

Frequency simulations

Frequency simulations were run with the aim of increasing the natural frequency of the frame – only the first mode was analysed, as mode 1 has the lowest frequency and would therefore affect the user most if it is below a certain level. Below is a table comparing the natural frequencies of all the iterations:

Frame iteration	Natural frequency – mode 1 (Hz)
1 – Aluminium Alloy	34.796
1 – Magnesium Alloy	35.674
2 – Aluminium Alloy	39.394
2 – Magnesium Alloy	40.531
3 – Aluminium Alloy	41.664
3 – Magnesium Alloy	42.856

Figure 11. Comparing the natural frequency of all iterations

All natural frequencies were higher than 30 Hz and therefore met the criteria. The lowest natural frequency was 34.796 Hz in the first aluminium alloy iteration, and the highest was 42.856 Hz in the third magnesium alloy iteration. The increase in natural frequency was incremental but by the sixth iteration, it had been increased by around 10 Hz. The biggest incremental increase in natural frequency was between the first and second iteration – an increase of 4.857 Hz. The central bar was added between these two iterations, and this caused the natural frequency to be raised due to added stiffness. The changes from the second to the third iteration were made based on the theory that the natural frequency is proportional to the stiffness of the frame, and inversely proportional to the mass, according to the following equation:

$$\omega_0 = \sqrt{\frac{k}{m}}$$

ω = natural frequency

k = stiffness

m = mass

Figure 12. Equation used to make iterative changes to raise natural frequency.

Therefore the diameter of the beams was increased to raise the stiffness, but the inner thickness was reduced to decrease the mass. Although this did have a positive effect on the natural frequency, the changes were too slight to lead to much increase in natural frequency as the beams of the first iteration already had a large diameter.

Fatigue Simulations

The results from the fatigue simulation suggest that the bike would be able to survive the 1,000,000 life cycles and would not fail after 10 years of use. The simulation on the aluminium alloy frames led to 5.88% damage, and the frames could withstand 17,020,000 life cycles before failure. The magnesium frames had better performance, with a damage of only 2.503%, withstanding 40,040,000 cycles before failure.

Conclusion

Considering the simulation results, it can be concluded that the third iteration frame built from magnesium alloy would be the optimal frame to use for a lightweight tandem bicycle, as it had the highest natural frequency and could withstand the largest number of life cycles before failure.

Outer diameter of beams	44mm
Inner thickness of beams	8 mm
Fillet size (weld)	10 mm
Maximum von Mises stress	9.167e+01 MPa
Maximum displacement	5.337 mm
Minimum safety factor	3.272
Natural frequency at mode 1	42.856 Hz
Maximum damage percentage	2.503%
Total life cycles before failure	4.004e+07

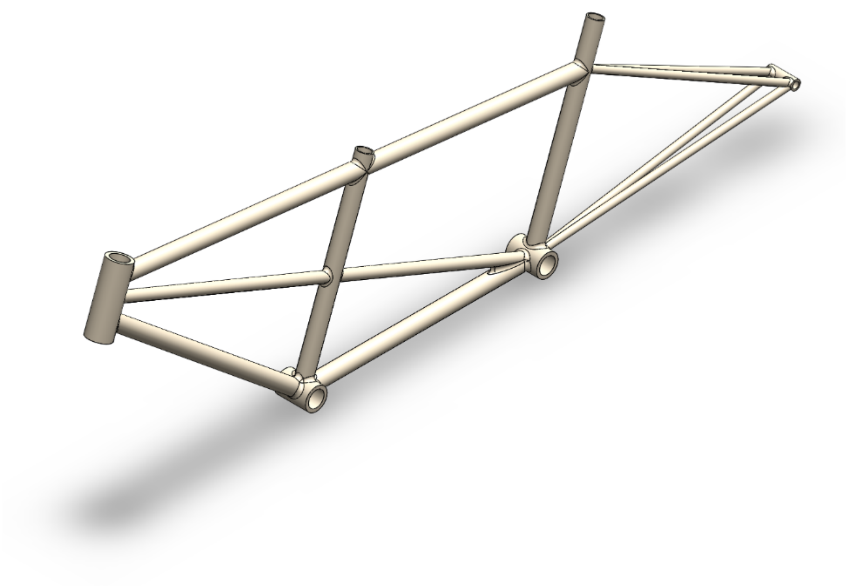


Figure 13. Iteration 3 – Magnesium alloy