Mountain Bike Frame Analysis

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Contents

1 Introduction

In this report, the dynamic analysis of a mountain bike frame is presented. The intended use of a full suspension mountain bicycle is to transport users across many different types of terrain. A common feature of most mountain bikes is a suspension system. This report shows how a mountain bike can be modeled with a full suspension system and how that model reacts to given displacements and forces. Both maximum force and displacement of the bike frame are analyzed, and a topology analysis of the model is also presented. This report also aims to find high stress areas of a bike frame that need to be potentially fortified.

2 Geometry

The geometry of this model represents the frame of a mountain bike only. None of the gearing, wheels, seat or anything other than the frame is represented. Although there are no pedals or a seat, there are still loads applied where those components would exist. The bike frame was designed to be a large size bike frame, which should fit comfortably for people that are approximately 5'11" - 6'2" tall with an inseam of 31" - 33" [1]. After determining the size of the frame, loads were applied to the frame based on the maximum weight that would be common for the frame size.

2.1 Model Simplifications and Assumptions

The model has several key simplifications that must be addressed. The first, and most important, assumption is a constant cross section over the entire geometry. This is not the case in a standard bike. However, this assumption is good to make for an initial frame design as it shows what regions of the bike frame need to be reinforced. The constant cross section assumption also allows for a 2-D planar model which allows for much much faster analysis time. Assuming a 2-D planar model means that there are no out-of-plane loads on the bike frame, which when riding straight and perpendicular to the road, is true. Another assumption made in the model is a linear suspension. True bike suspensions do not perfectly follow Hooke's law or viscous damping, but the assumption of a linear suspension is close enough to a true suspension that this assumption is a valid one. Lastly, we assumed how the loads are distributed along the bike frame. We assumed a worst case scenario of a 130 kilogram rider siting on the bike.

2.2 2-D Geometry

The geometry of the bike frame used in this analysis was extrapolated from a bike frame created by Haibike [2]. This real frame was used as a reference model that was loosely followed. This frame was chosen as it had a vertical rear spring suspension and a front fluid spring suspension. The nodal points of each connection point are given below in Table B1 in the appendix with a label for each nodal point. The geometry was originally created in Solidworks to gather the x and y coordinates that were later translated into ABAQUS. Figure 1 shows a visualization of the nodal points in Table B1.

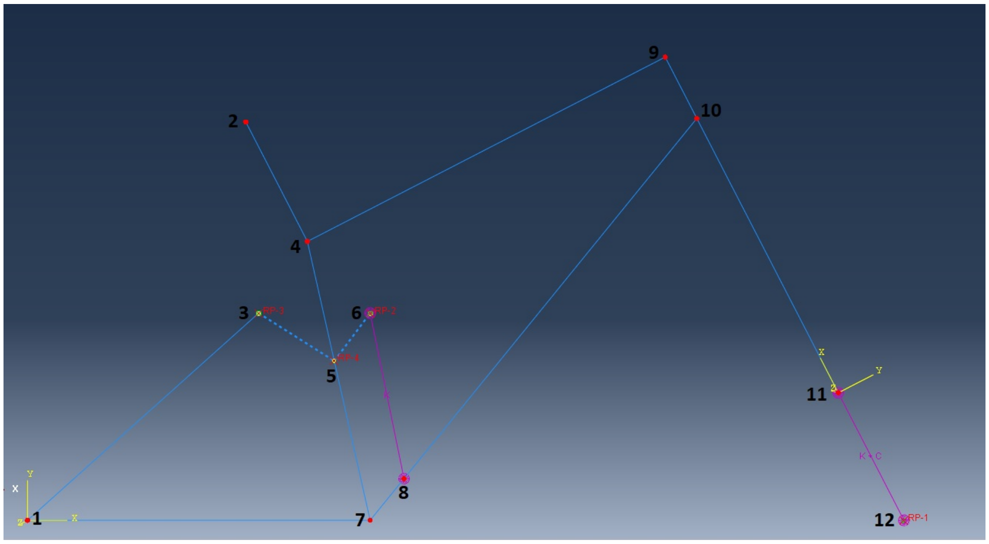

Figure 1: Visualization of the nodal points presented in Table B1.

The cross section of the bike frame is represented with a constant cross section throughout. The dimensions of the cross section are given by a hollow tube cross section with the $OD =$ 25mm and the $ID =$ 10mm.

3 Material Model

The material model can be split up into two separate parts: the frame material and the suspension material.

3.1 Frame Material

The frame material model represents all of the model, except for the suspension. The material model used was a linear-elastic isotropic material model because if the material were to reach its yield stress, it was assumed to have failed. The frame was defined to be Aluminum 7050, an aerospace aluminum alloy that Kona (a large bicycle company) uses in some of their bicycles [1]. Table 1 below shows the frame material parameters used for elastic and density properties. The uncertainty of these properties is listed in the appendix in Table B2.

Material	Property	Property Value	Citation
Aluminum 7050	ν	0.33	[3, 4]
	E [GPa]	71.7	[3]
	ρ [g/cm^3]	2.82	[3, 5]

Table 1: Isotropic material constants for Aluminum 7050.

3.2 Suspension

The suspension model is a little bit more complex. The spring part of the suspension is a simple linear spring that follows Hooke's law ($F = kx$), but the damper requires more complex calculation. Many modern mountain bikes use suspension fluid to provide damping in the suspension [6]. Equation 1 below relates the dimensions of the damper and the fluid viscosity to calculate the damping constant assuming laminar flow through the damper, where η is the dynamic viscosity, L_{head} is the piston head thickness, ID is the cross-section inner diameter, and d_{cav} is the diameter of the internal fluid passage [7].

$$128\pi\eta L_{head}\left(\frac{ID}{2d_{cav}}\right)^4 \tag{1}$$

Figure 2 gives a pictorial representation of the terms used in Equation 1.

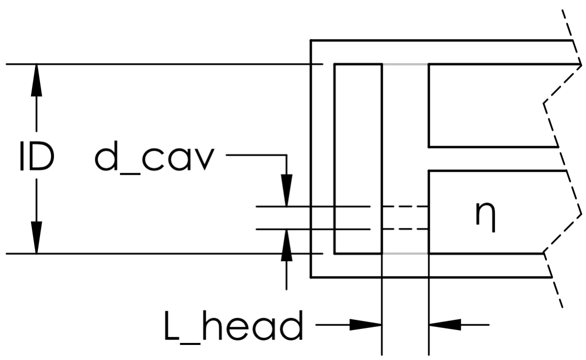

Figure 2: Diagram of the internal parameters inside the hydraulic suspension needed to define the damping constant. Damping is caused by the viscosity of the fluid flowing through an internal cavity in the piston represented by d_{cav}.

The suspension parameters required for calculating the damping constant are given in Table 2. Using the suspension parameters and the cross section geometry given in Section 2.2, the damping constant is calculated with Equation 1 and also appears in Table 2. The uncertainty of these properties is listed in the appendix in Table B2.

Material	Property		Property Value	Citation
Internal Suspension Parameters	η	[Pa· s]	15.0	[6]
	d_{cav}	[cm]	0.4	†
	L_{head}	[cm]	0.005	†
Suspension	c	[N· s/m]	1318	[7]

Table 2: Suspension parameters for the front and rear suspension. Note that the rear suspension does not have a damper. † Picked based on bike cross section.

4 Boundary Conditions

There are both displacement and force boundary conditions imposed on the model. Additionally, there are two connectors within the ABAQUS model that further define the motion of the mountain bike.

4.1 Displacements

The displacement boundary conditions on the mountain bike are both fixed and variable. There are several different boundary conditions that define different states of the bike frame. In any case, there is a general rule to the varying displacement boundary conditions. There are three displacement types imposed on this model: fixed, bump, and sinusoidal displacements. The fixed boundary condition is used on a local coordinate axis along the front fork to maintain collinearity between the front suspension and fork, which must be true on a standard mountain bike. The bump and sinusoidal displacements are used on either the rear or front wheels to define displacements similar to riding along a trail. In all cases, each wheel node has one of these displacement boundary conditions imposed on it. Figure 3 below shows the two displacement functions used.

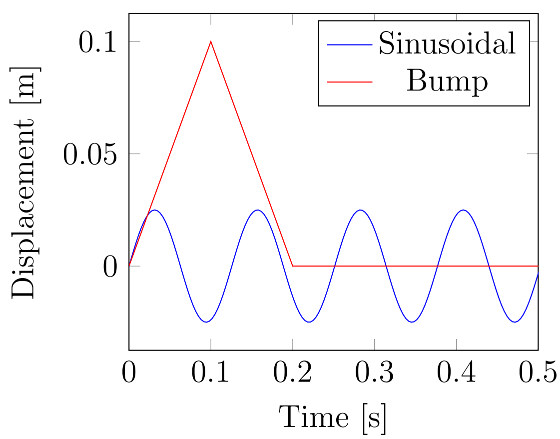

Figure 3: Equations for amplitude defined displacements for front and rear wheels.

Additionally, ABAQUS applies smoothing to these curves so there is a slight variation between the defined inputs and the actual inputs the dyanamic analysis receives.

4.2 Loads

The loading conditions are much more straight forward. In all analyses, there is a downward force imposed on the seat tube (900N), handle bars (100N), and pedals (300N). These loads represent the gravitational forces distributed on the bike by a 130kg rider.

4.3 Connectors

Connectors are used within the ABAQUS model to more accurately represent the bike frame. There is a stop linear connector along the front suspension that limits the maximum and minimum displacement of the front suspension to 0.1 and 1.9 times time the original length. This is required because real suspensions can bottom out and top out (due to minimum and maximum piston extension) which need to be imposed on the model. There is also a stop linear connector along the rear suspension that stops the rear suspension from compressing to smaller than 5 cm. Finally, a rigid body constraint was applied to nodes 3, 5, and 6 (see Figure 1) that define a rotating T-joint that compresses the rear suspension. This constraint enforces that the local nodal distances between these nodes remains constant in order for the rear suspension to activate.

5 Mesh and Setup

As previously stated, a 2-D planar model was used with beam elements. The idealizations and assumptions made with this model have also been previously stated but can be summed up to a constant cross section and in plane loading.

5.1 Mesh Convergence

The meshing of the bike frame was very straight forward. Because of the simple 2-D geometry, partitioning was not required. The edges were seeded with varying distances between nodes and a convergence study on the mesh was completed. The maximum Von Mises stress and vertical displacement of the handle bars versus the number of elements is plotted in Figure 4 below. In all cases, the .1m (.875m after smoothing) spike input was used on the front suspension while the rear suspension remained fixed. Figure 4 values are the maximum values during the entire dynamic simulation and were calculated using the script provided in Appendix C.

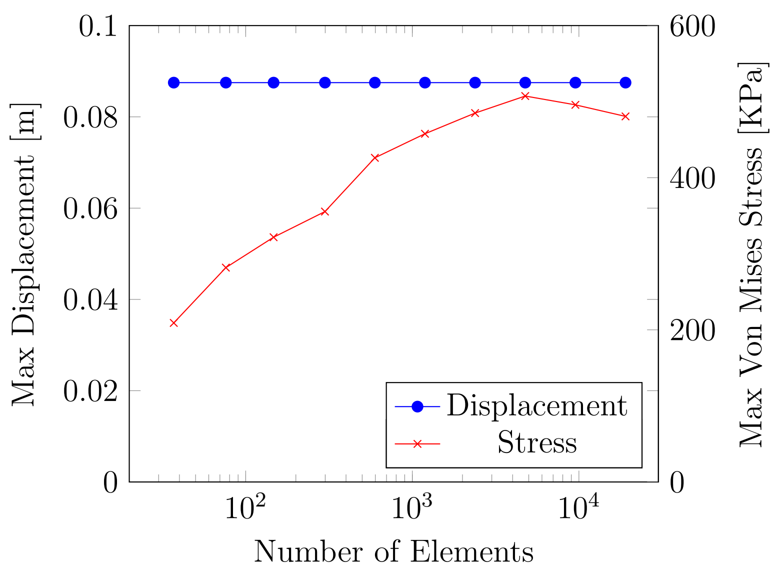

Figure 4: Convergence plot of maximum Von Mises stress and handle bar displacement versus number of elements during ABAQUS Implicit dynamic analysis.

As seen in the plot, there is a peak in the maximum stress at about 5000 elements. There is not an asymptotic convergence because there are also dynamic variables at play, so there is bound to be some noise as the number of elements increases. This maximum was calculated using a slightly smaller cross section that was retroactively increased. Note that the maximum displacement is constant at 0.0875 meters. This is due to the spike input being the maximum displacement that occurs in the model. This is not necessarily always true, such as in a resonance scenario with a sinusoidal input displacement boundary condition.

5.2 Analysis Type

The type of ABAQUS analysis used was ABAQUS Implicit. This type of dynamic analysis has no minimum time increment and is completely stable. It is also the only kind of dynamic analysis ABAQUS can run on 2-D models as ABAQUS Explicit is not currently supported for 2-D planar analysis.

5.3 Runtime Conditions

Within the ABAQUS Implicit analysis, there were a couple of different time parameters that were changed. Table 3 below shows all of the parameters input. Note that automatic time incrementation was used. All other inputs remained their defaults.

[seconds]	t_{total}	$\Delta t_{initial}$	$\Delta t_{minimum}$	Maximum Increments
ABAQUS Implicit	0.5	1E-4	5E-10	1000

Table 3: ABAQUS Implicit time step parameters.

5.4 Topology Optimization Mesh

There was also another model created specifically for topology optimization of the bike frame. Using Gmsh, a bounding box was created around specific parts of the bike frame so that a seat tube and handle bar mount were including in the resulting topology. Figure 5 below shows the initial bounding box created by Gmsh and visualized in Paraview. The volume was then seeded with a nodal distance of 10 mm and subsequently meshed. The front and rear wheels have fixed boundary conditions and there are traction forces at the seat, handle bars, and pedals. This volume represents the volume bounded by the outer elements of the bike frame used in this analysis.

Figure 5: Initial bounding box created for topology optimization.

6 Results

There were two main results that were extracted from ABAQUS. The first result was the maximum Von Mises stress. If the maximum stress was higher than the yield stress, the bike was considered to fail. The other result of interest was the maximum displacement of any node during the analysis. A smaller maximum displacement indicates a better shock absorbing suspension and thus smaller displacements were desired.

6.1 Changing Boundary Conditions

Different loading conditions were prescribed on the bike frame. Only one displacement function was applied to either the front or rear of the bike in each scenario. Table 4 shows the maximum Von Mises stress and displacement in each loading scenario. The values were calculated using the same script in Appendix C (with different input odb files), and are the maximum values of displacement and stress that occur during the entire simulation.

Loading Scenario	Maximum Stress [MPa]	Maximum Displacement [m]
Front Sinusoidal Displacement	190.2	.029
Front Spike Displacement	499.4	.0875
Rear Sinusoidal Displacement	403.6	.025
Rear Spike Displacement	1394.5	.0875

Table 4: Maximum stress and displacement under different loading conditions.

See Figure A2 for an example of the overall Von Mises stress under the same displacement conditions. For more figures for each displacement scenario, see Appendix A.

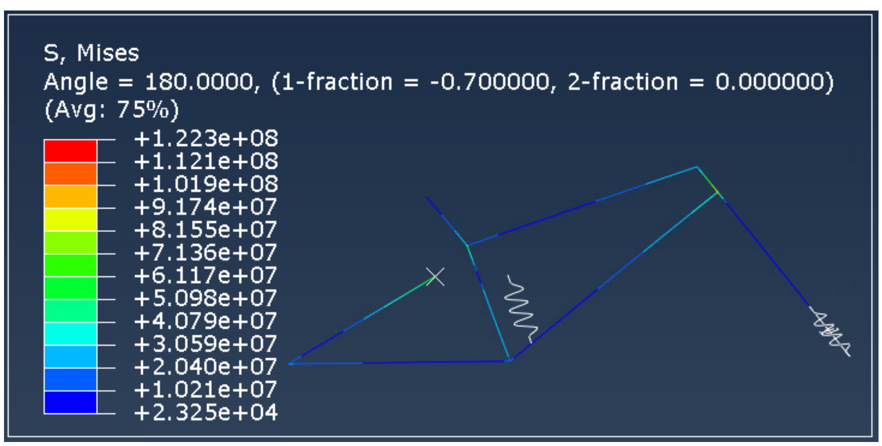

Figure 6: Plot of Von Mises stress during the front suspension sinusoidal displacement scenario at peak front displacement.

6.2 Topology Optimization

Using proprietary research topology optimization code provided by Dr. Aguilo from Sandia National Laboratory, the initial bounding box was applied with the previously mentioned boundary conditions. Figure 7 below shows the optimized topology with the prescribed boundary conditions.

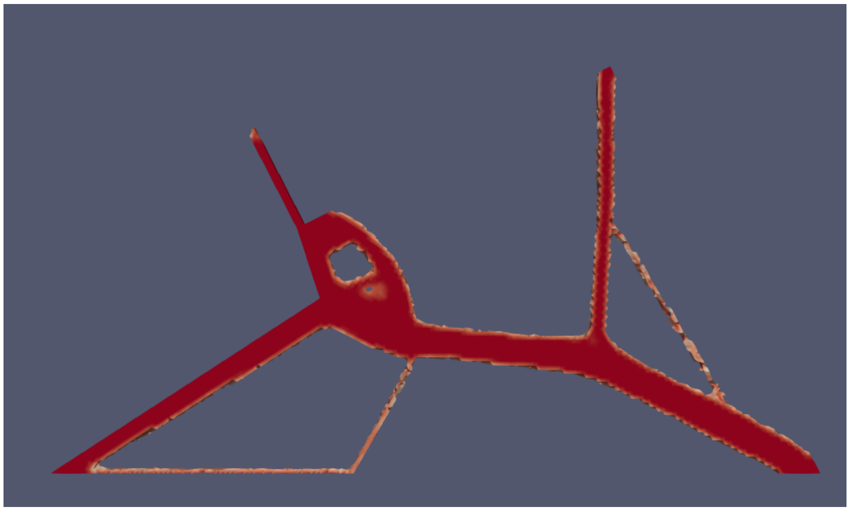

Figure 7: Initial bounding box created for topology optimization.

This topology is interesting because it features a main support beam downward and through the center of the bike rather two smaller ascending beams.

7 Verification and Validation

Verification and validation are critical to making sure the FEA result is accurate. Although there was no way to test a physical model under the exact same boundary conditions, there are a couple of ways the model could be verified and validated.

7.1 Verification

Verification is defined by comparing the FEA result to a known analytical result. Unfortunately, because of the complexities of a bike frame under dynamic analysis, verification of the entire bike frame is not possible. However, there was a simple test that could be done to see if the dynamic analysis was reaching equilibrium conditions. The forces on the frame were set to the same values as previously stated, and both the front and rear wheels were fixed. A dynamic analysis was run, and a field output was generated at the final time-step after the bike frame had settled. The reaction forces on the frame were then summed together in Excel. However, the front suspension wheel node is an assembly reference node, and does not appear in the reaction force field output. So, in order to calculate the reaction force at that node, the displacements at the upper node were multiplied by the spring constant to get the reaction force at the front wheel assembly node. Table 5 below shows the summed reaction forces.

Contribution	X Reaction Force [N]	Y Reaction Force [N]
Standard Nodes	226.0106	861.5578
Front Assembly Node	-225.9682	438.4317
Net Reaction Force	0.0424	1299.9895

Table 5: Reaction forces in the bike frame after settling from applied forces.

This shows that there is negligible net reaction forces in the x-direction, which should be the case are there were no loads applied in the x-direction. This also shows that the total net reaction force in the y-direction is very close to 1300 N, which is equal and opposite to the 1300 N of force applied downward on the bike frame. This shows that the dynamic analysis is reaching an equilibrium solution and not diverging. Although this does not guarantee the model accurately represents a real bike frame, it shows that the model is converging to an equilibrium solution.

7.2 Validation

Validation is defined by comparing the FEA result to a physical test result. Given more time, a validation study on the suspension could be completed. It would not be difficult to impose the same boundary conditions on a real bike frame. The same displacement functions could also be imposed on the wheels and strain gauges could be placed on the bike frame to see how closely the model matches reality. A full validation study would, however, require a full bike frame to be built. A simpler validation study could involve applying different forces to a bike suspension to see how it reacts. This would test the assumption of pure linear elasticity and viscosity.

8 Discussion and Conclusions

In the case of the rear .1m spike, the maximum stress tripled the yield stress and would have failed. When the rear wheel experiences large displacements, the rear suspension attempts to resists those displacements. The rear suspension spring constant is thus too high as it is bending the rear wheel upper connector under large displacements. This is why the rear suspension has much higher stresses overall. In terms of high stress areas in the bike, from Figures A2, A3, A4, and A5 it is clear that there are three main areas where the bike could be fortified. The support underneath the front handle bars has a generally higher overall stress than the model, and could possibly be fortified. In all displacement conditions, the middle support has a high stress due to it supporting most of the weight of the rider. This support could be fortified with little addition weight to bike as it is a relatively short section. The final section with high stress is the rear wheel upper connector. This section has high stress due to the high spring constant, so it is potentially not an area of concern, but should still be considered for fortification.

In terms of the topology analysis, there are a couple of issues that should be noted with the optimized topology. The main issue with this topology is there would need to be an adjustment of the front beam to maintain the suspension at a steep angle. Another solution to this could be an entirely new front suspension design altogether. This topology analysis also does not consider horizontal forces on the bike frame, such as a rider pushing on the front handle bars with a horizontal force component. Given more time, several boundary conditions could be imposed on the topology optimization mesh instead of this one scenario. Still, Figure 7 shows a very nonstandard bike frame and it could be a very interesting bike design to create.

A potential improvement to the FEA model is a more accurate spring and damper system. There was not a lot of information found online that gave us an exact answer for any type of front fork suspension system. Given exact manufacturer information on spring and damper stiffness, there would be a smaller margin of error between the model and its real world counterpart. Also, if there were more time for this project, a 3-D representation would have been a more realistic approach. The 3-D model would allow more complex cross sectional shapes, welded joints, and an overall more realistic model of the bike under the same loading conditions. This would also take much longer to run a dynamic analysis on, and would only occur once the frame topology was more refined. With how many different loading scenarios and design choices, it is clear how much design work goes into such simple machines.

References

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Appendix

A Extra Figures

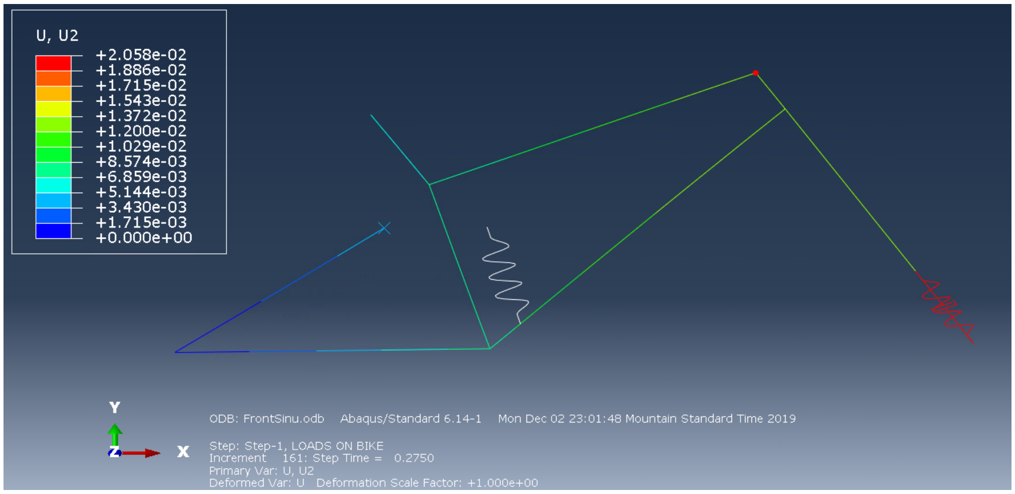

Figure A1: Plot of the maximum displacement frame of the front suspension sinusoidal displacement scenario.

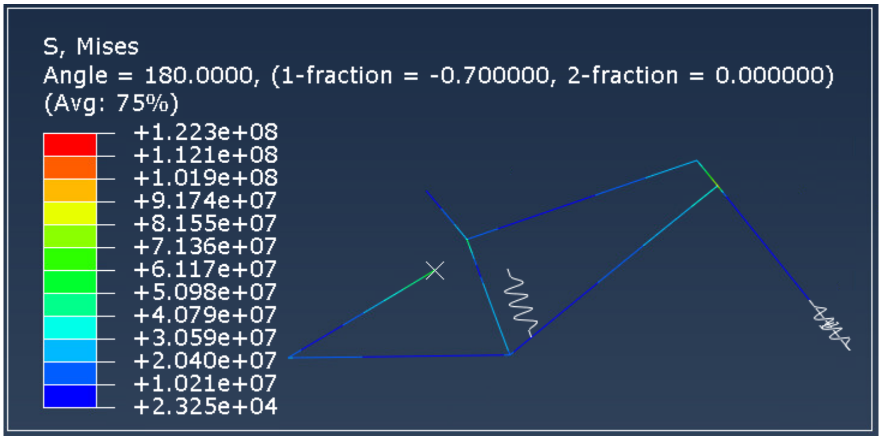

Figure A2: Plot of the maximum Von Mises stress frame of the front suspension sinusoidal displacement scenario.

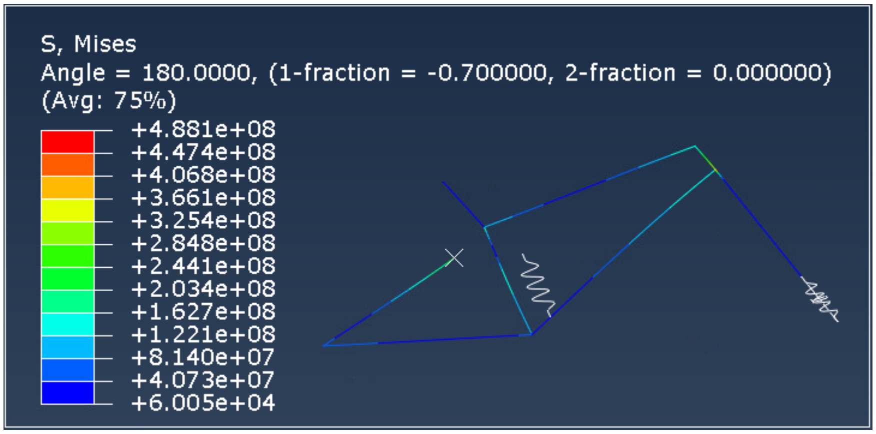

Figure A3: Plot of the maximum Von Mises stress frame of the front suspension spike displacement scenario.

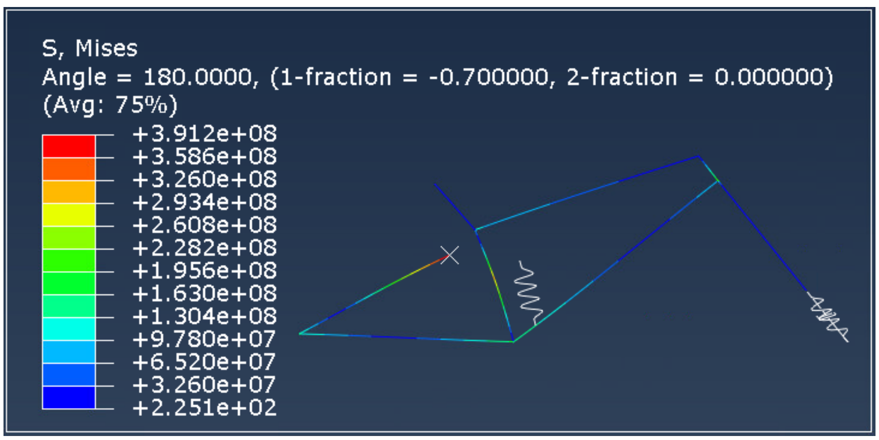

Figure A4: Plot of the maximum Von Mises stress frame of the rear suspension sinusoidal displacement scenario.

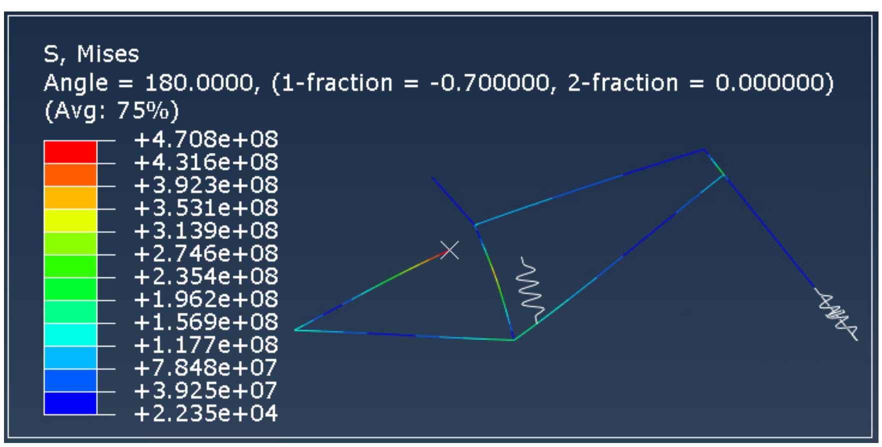

Figure A5: Plot of the maximum Von Mises stress frame of the rear suspension spike displacement scenario.

B Extra Tables

Node	Name	X (mm)	Y (mm)
1	Rear Wheel	0	0
2	Seat	273.94	500
3	Rear Connector Left	290	260
4	Seat Connector	351.25	350
5	Rear Pivot	385	200
6	Rear Connector Right	430	260
7	Pedals	430	0
8	Rear Suspension Bottom	472.50	52.29
9	Handle Bars	800.33	581.45
10	Fork Connector	840	504.47
11	Front Suspension Top	1017.54	160
12	Front Wheel	1100	0

Table B1: Nodal connection points of the bike frame. A Haibike mountain bike frame was used as a reference and resized to a 1.1 meter wheelbase [2].

Material	Property		Property Value	Error	Range	Citation
Tube Cross Section	OD	[cm]	2.5	±0.02	T	[8]
	ID	[cm]	1.0	±0.02	T	[8]
Frame Lengths	L	[cm]	N/A	±2.0%	E	
Aluminum 7050	ν		0.33	±0.08	M	[3, 4]
	E	[GPa]	71.7	±2%	M	[3]
	ρ	[g/cm^3]	2.82	±0.11	M	[3, 5]
Internal Suspension Parameters	η	[Pa$\cdot$ s]	15.0	±6.0	M	[6]
	d_{cav}	[cm]	0.4	±0.01	E	†
	L_{head}	[cm]	0.005	±0.025	E	†
Suspension	k	[N/m]	79580	±2680	M	[9, 10]
	c	[N$\cdot$ s/m]	1318	±756	M	[7]

Table B2: Uncertainty of different materials in bike frame. A "T" label in the Range column indicates a manufacturer tolerance, an "M" label error based on multiple manufacturers, and an "E" label indicates uncertainty based on engineering design intuition. Note that ID, η, L_{head} and d_{cav} define the damping constant (c) and its uncertainty. † Picked based on bike cross section.

C Python Code

```python
# Created by Carter Cocke
# u0541485
# University of Utah

from odbAccess import *
import numpy as np

def MaxStress(odbName):
    # Open odb file
    odb = openOdb(odbName)

    # Initialize Max Stress
    maxMises = -0.1
    maxDisp = -0.1

    for step in odb.steps.values():
        for frame in step.frames:
            # Get all field ouputs for current frame
            allFields = frame.fieldOutputs

            # Get max stress
            if allFields.has_key('S'):
                allStress = allFields['S']
                for stress in allStress.values:
                    if stress.mises > maxMises:
                        maxMises = stress.mises

            # Get max displacement
            if allFields.has_key('U'):
                allDisp = allFields['U']
                for disp in allDisp.values:
                    if disp.magnitude > maxDisp:
                        maxDisp = disp.magnitude

    # Get DOF
    nodes = len(allStress.values) // 2 - 1

    # Close odb file
    odb.close()

    # Return params
    return maxMises, maxDisp, nodes
```

```
if __name__ == '__main__':
    odb_files = ['08dist.odb', '04dist.odb', '02dist.odb', '01dist.odb',
    '005dist.odb', '0025dist.odb', '00125dist.odb', '000625dist.odb',
    '0003125dist.odb', '00015625dist.odb']
    max_stress = np.zeros(len(odb_files))
    max_disp = np.zeros(len(odb_files))
    nodes = np.zeros(len(odb_files))
    index = 0
    for odb in odb_files:
        max_stress[index], max_disp[index], nodes[index] = MaxStress(odb)
        print('For %s with %i nodes the maximum stress is %f MPa and maximum
        displacement is %f' %(odb, nodes[index], max_stress[index]/1000000,
        max_disp[index]))
        index += 1
```