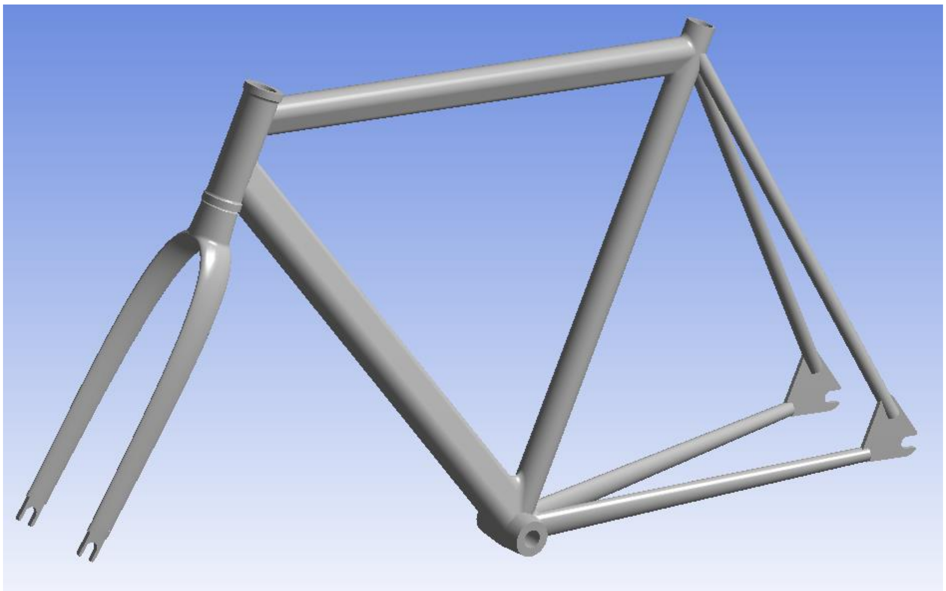
Finite Element Analysis of an Aluminium Bike Frame



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1. Introduction

Each new bike model must pass a series of structural tests before being released for public retail. The purpose of this is to ensure that the bike is safe to ride and offers protection for the rider in the event of a collision.

A company designed a new road bike and wished to perform an impact strength test on the bicycle frame, as outlined in the ASTM F2711-08 (2012) standard. For a bike to pass this test the frame may deform by up to 40mm following an impact with a known mass. This is an expensive process for the manufacturer. A single bike can be tested only once, and failed tests necessitate alterations to the bike geometry, which in turn creates material wastage as multiple bikes are produced. Finite Element Analysis (FEA) offers an alternative approach to performing the impact test by simulating the event. A 3-dimensional Computer-Aided Design (CAD) model is constructed via a computer package and an impact force applied. FE analyses offer a revealing insight into how the model will perform under a particular set of conditions, and enable the user to quickly make alterations to the material or geometry without financial expense (Lessard et al. 1995).

2. Methods

2.1 Bicycle Properties

The manufacturer supplied a partially comprehensive set of engineering drawings. This allowed scope for alteration in response to the structural analysis. The 3-dimensional CAD model of the frame and fork was created using SOLIDWORKS (Figure 1). All features of the frame and fork were made hollow, save the front and rear dropouts (Table 1). The total mass was 3.21kg.

Table 1. Thickness settings of the component parts

Feature	Minimum Thickness (mm)	Maximum Thickness (mm)
Head Tube	6	6
Top Tube	3	3
Down Tube	3	3
Seat Tube	3	3
Bottom Bracket	10	10
Seat Stays	3	3
Chain Stays	2	3
Crown	3	3
Blades	2	3
Steering Tube	3	3

Aluminium alloy was selected for the frame and fork. This is a popular material in the bike industry as it is lightweight and relatively inexpensive at $0.95/kg. On the contrary, aluminium alloy has a relatively low density and yield stress compared to titanium, which costs $57.40/kg (Dwyer et al. 2012).

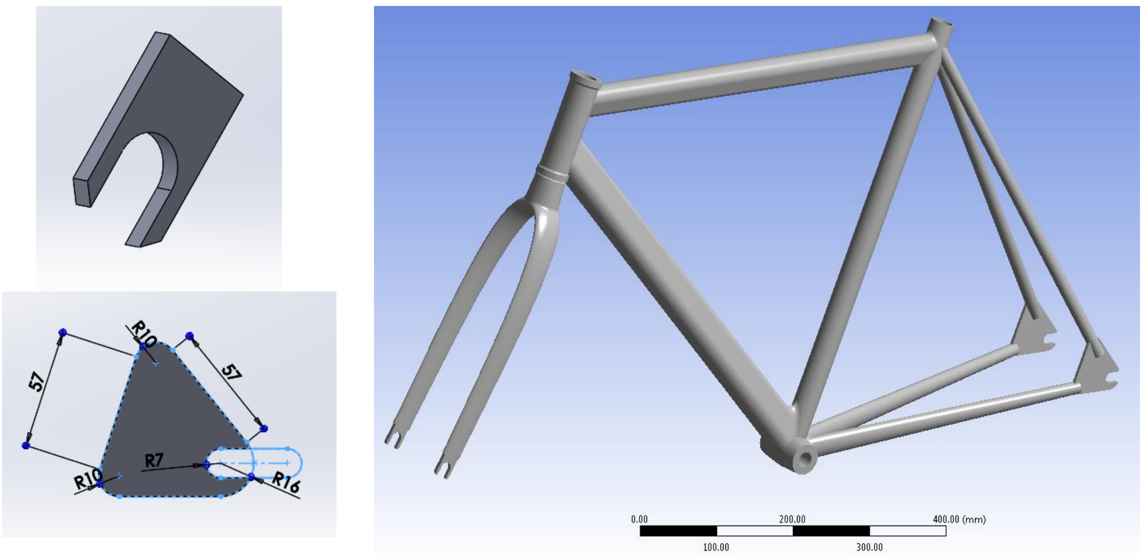

Figure 1. CAD model of bike frame and fork.

2.2 Computational Mesh

A mechanical mesh was applied and refined in response to the results of quasi-static simulations of deformation and stress. The same force was applied for each stage of mesh refinement. For the first run of the simulation, a coarse mesh with a minimum element size of 2mm was globally applied. A medium global mesh was applied with minimum element size of 0.5mm for subsequent simulations. A fine discretization was applied to areas exhibiting a high gradient of deformation or stress (Miller et al. 1997). Conversely, areas that exhibited a shallow gradient of stress or deformation, and were coarsened so as to reduce the processing time. The mesh was gradually refined until the change in maximum deformation and stress values were negligible such that simulation results were not mesh-dependent (Figure 2).

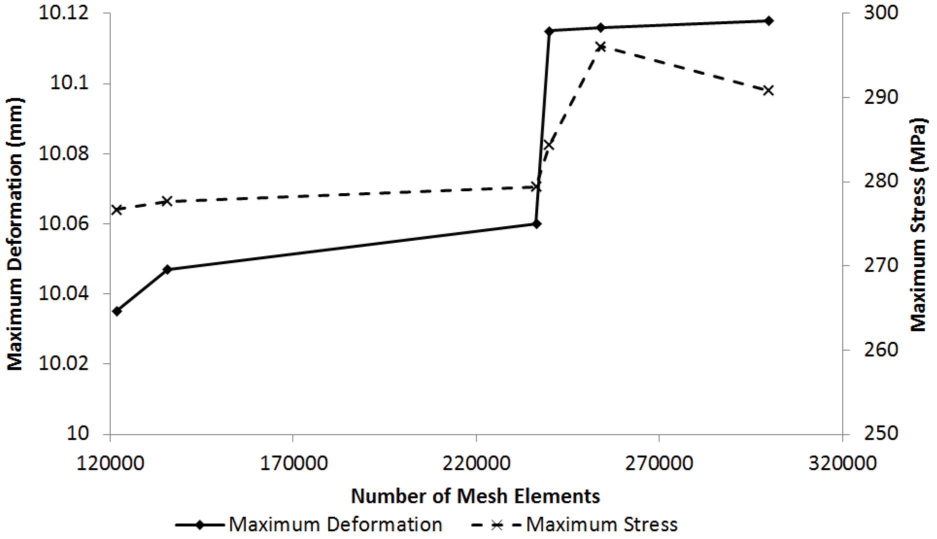

Figure 2. Convergence curve for mesh refinement.

All levels of discretization had a growth rate of 1.2 and the mean aspect ratio was 2.0. Some nodes had a very high aspect ratio. These nodes were considered non-problematic as they were not located in areas of a high deformation or stress gradient. The final element quality was 0.797 (0.12).

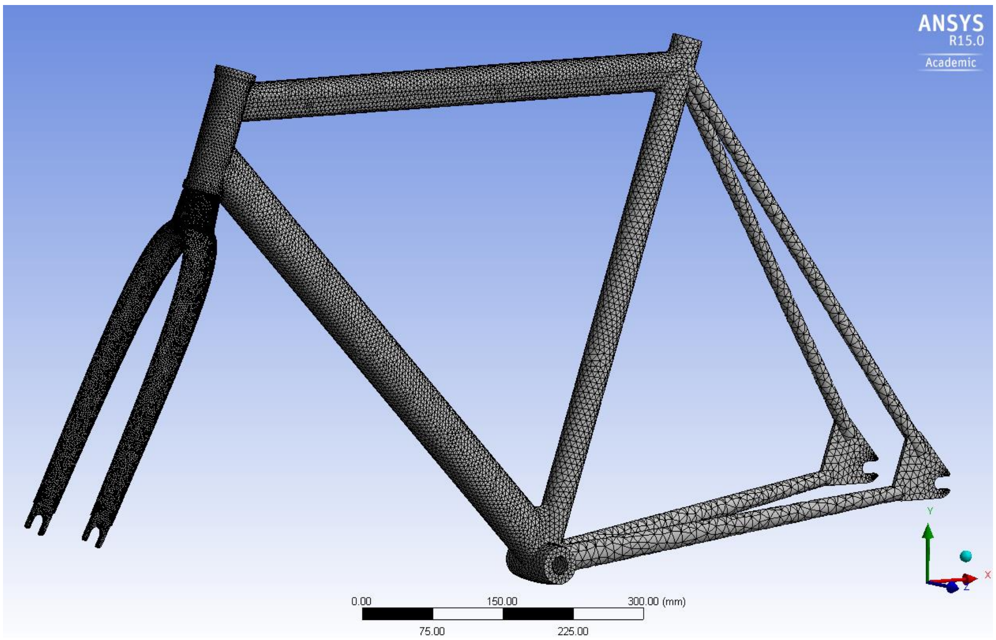

Figure 3. Bike mesh with local refinements

2.3 Test Protocol

An impact test was simulated in ANSYS Mechanical as described in the ASTM (F2711-08) standard (Figure 3). The analysis was simplified to a quasi-static analysis. Whilst this was not a true representation of the real-world dynamic impact, it was regarded a more appropriate test as it was less computationally intensive. The front and rear dropouts were aligned vertically with the rear dropouts constrained at the bottom. A force acting along the vertical axis was applied to the inner faces of the front dropouts. It was assumed that all force was equally dissipated from the dropped mass via the roller to the front dropouts. Realistically energy is lost from the system via sound and heat; however estimation of the viscoelastic properties of this collision would likely introduce further errors. Furthermore, as this was a test regarding human safety, it was deemed more important to err on the side of caution and for a bike to pass the test standard on exposure to a greater force. The impact force was derived iteratively; the details of which will be discussed in section 2.4. The total deformation and von-Mises stress were calculated at each node on the bike using ANSYS Mechanical and values were mapped illustratively. A safety factor of 2.5 was set.

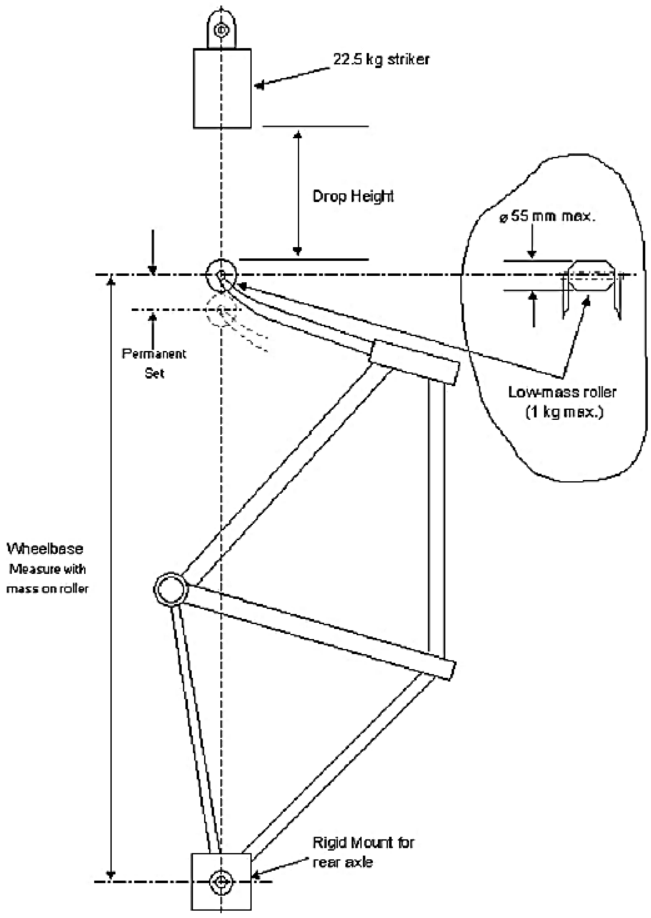

FIG. 3 Frame Impact Test

Figure 4. Setup for the impact strength test outlined in ASTM (F2711-08)

2.4 Determining the Impact Force

The impact force was approximated using the conservation of momentum law and the work-energy principle, where *d* is the maximum permanent set permitted by the test standard.

$$KE = \frac{1}{2}.m.{v_f}^2$$

$$F = \frac{KE}{d}$$

It was estimated that an impact force of 993.27N would result in a maximum deformation of 0.04m.

The FE analysis revealed a permanent set of 10.117mm. An iterative process was employed to determine the maximum impact force of the 22.5kg mass dropped 0.18m, such that the predicted deformation was equivalent to the maximum deformation calculated by the simulation (Table 2).

Table 2. Iterative derivation of maximum impact force for collision of a 22.5kg mass dropped 180mm onto an aluminium bike frame

Simulation	Predicted Deformation (mm)	Force applied (N)	Actual Deformation (mm)
1	40	993.26	10.12
2	25	1589.22	16.19
3	20	1986.53	20.23
4	20.1	1976.64	20.13

3. Results

FE analysis revealed a maximum deformation of 20.1mm at the front dropouts and was regarded as the permanent set. Under these test conditions the modelled bike passed the impact strength test. Deformation decreased with distance away from the front drop outs, with negligible deformation at the seat stays, chain stays and rear dropouts (Figure 4).

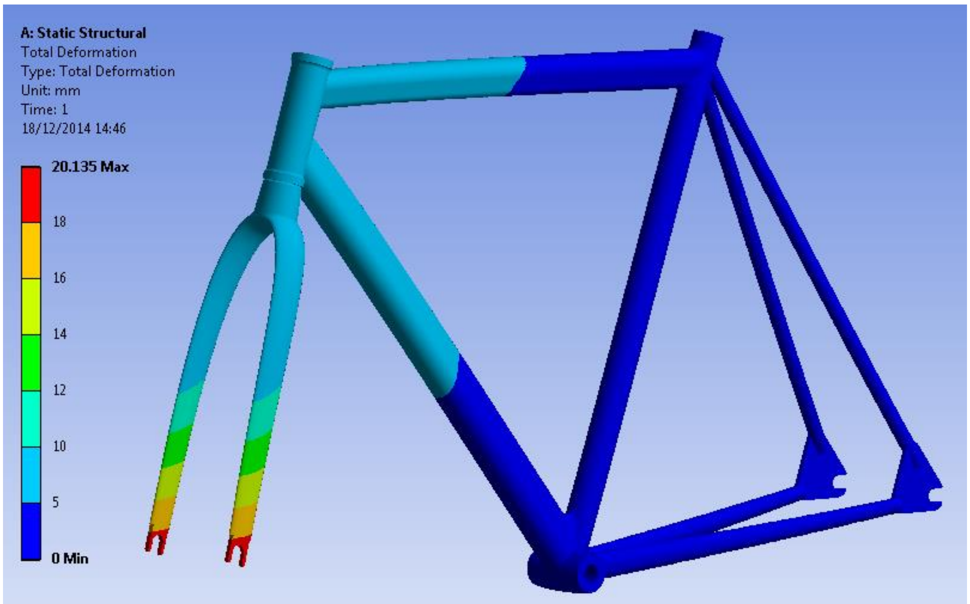

Figure 5. Finite element analysis of total deformation of aluminium bike frame

The equivalent (von-Mises) stress was determined at each node. The maximum stress was 282.25MPa and located inside the top of the crown (Figure 7). The yield stress of the aluminium alloy was 250MPa, giving a safety factor of less than 1. Areas of high stress exceeding 100MPa were localised around the top of the fork and the crown, suggesting that these areas were subject to plastic deformation from the impact test. Consequently, with a safety factor of 2.5 in place the bike failed and would not be fit for market. The maximum stress did not exceed the ultimate tensile strength of aluminium.

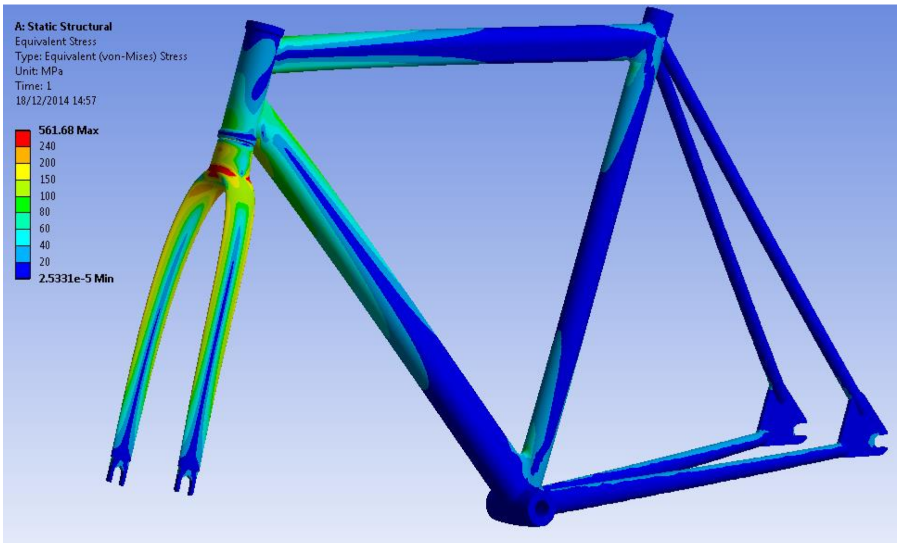

Figure 6. Stress analysis for the aluminium bike frame.

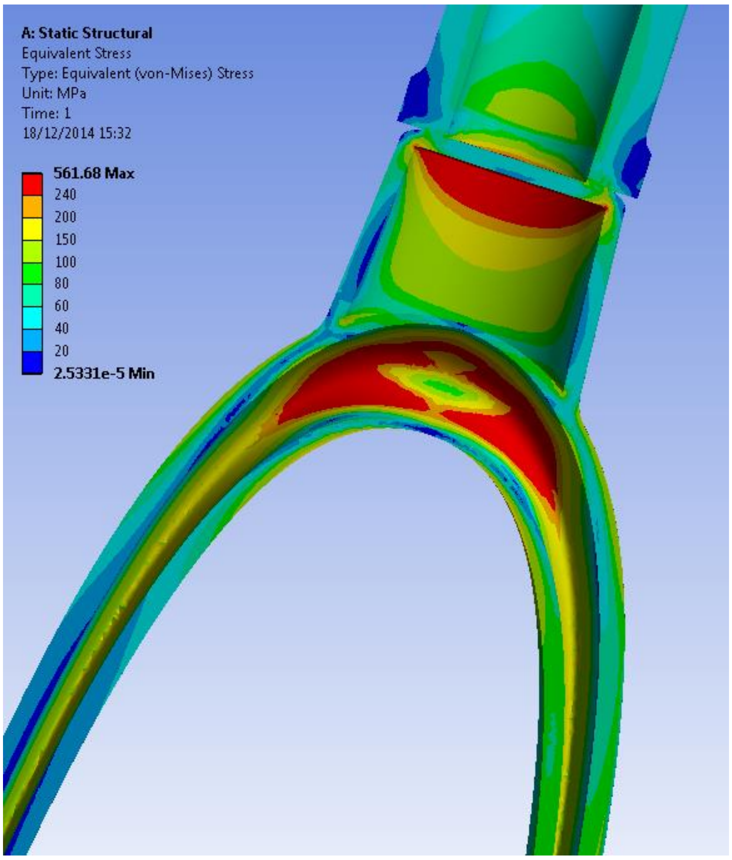

Figure 7. Cross-section of the area exhibiting high stress for an aluminium bike frame

4. Discussion

The results from the finite element model indicate that the aluminium bike frame is not safe for road use. The bike underwent plastic deformation at the top of the fork and the material was permanently weakened, however the bike did not fracture or crack. Alterations could be made in order to reduce the stresses induced, including increasing the thickness of the crown, head tube and forks, or modifying the geometry. Alternatively, a stronger material such as titanium could be used; however it is important to note the substantially increased financial expense when using titanium.

The results obtained using FEA are solely approximate and rely on a number of factors including the complexity of the model, mesh quality, understanding of the software and assumptions made in the simulation process. It is important that the analysis is interpreted with caution and is verified by comparing to the real-world test; however the use of FEA is still beneficial as fewer prototypes need to be constructed (Thornton 2010). Insufficient resources were available to perform the impact strength test on a prototype of the bike; an alternative method of verification could be approached using hand calculations of beam theory.

The impact test was modelled statically as opposed to dynamically. Whilst the drop test was a low-energy impact, the FE simulation did not account for the rate of the applied load. For a dynamic impact the maximum impact force is likely to be much higher, hence the bike would be more likely to fail the impact test.

For a real bike the component parts of the bike frame are welded together. Welding decreases the yield stress of the aluminium at the sites exposed to high temperatures (Brungraber 1973). This was not demonstrated in the FE analysis, so whether the welded areas underwent plastic deformation from the dynamic impact was unknown.

The discretised elements were tetrahedral with some of a very high aspect ratio. Tetrahedral elements are easy to fit to the contours of the geometry and are computationally inexpensive; however the use of hexahedral elements would have increased the accuracy of the results (Wang 2004).

Contrary to the limitations of FEA it is still a useful and intuitive tool for equipment engineers to highlight structural areas of concern or opportunities for enhancement.

5. Conclusion

An impact strength test of an aluminium bike frame was simulated using FEA. Results showed that the bike was unsafe for road use and indicated areas where the design could be modified to be more structurally sound. The FEA model should be verified against a real-world impact test with a prototype of the bike.

6. References

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