Fatigue Analysis of an Aluminum Tricycle Frame

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Abstract: As a sustainable urban transport system, the tricycle can represent an adaptive mobility vehicle used to transport people and bulk load. This transport system must guarantee the security of its end users, then experimental and modeling works are very useful tools in order to evaluate the mechanical performance of its frame. In a previous work, a finite element model of a 6061-T6 aluminum tricycle frame was developed, stress and deformation distributions calculated and analyzed, showing that the long-term durability of the design was compromised. For this reason, now we apply additional fatigue simulations to the improved design of the tricycle. We use the Fatigue Module of Comsol Multiphysics® 5.2 and the S-N curves for the material, evaluating the number of cycles that the structure might stand before fatigue cracks appear or some part of the tricycle fails. The computational simulations provide useful information for improving the mechanical performance of the tricycle.

Keywords: aluminum tricycle, solid mechanics, FEM, fatigue analysis.

1. Introduction

The MUR-A tricycle was initially developed in the Design School of the Costa Rica Institute in Technology. As a sustainable urban transport system, the tricycle can represent an adaptive mobility vehicle used to transport people and bulk load. As a transport system, the tricycle must ensure the security of its end users, then experimental and modeling works are very useful tools to evaluate the mechanical performance of this kind of structures. A previous static mechanical analysis was made which showed, by comparing the stress levels with the fatigue limit of 6061-T6 aluminum, evidence that on the long term, the design could not hold up to the loads it will be subjected to. However this method was simple, did not provide information on the number of cycles the frame might tolerate before failing and did not take into account the direction of the stresses caused by loading.

Gupta and Rao (2016) carried out a comparative stress analysis for common aluminum alloys used for mountain bike frames. Dwyer et al. (2012) applied finite element analysis to predict fatigue failure locations and cycles to failure of mountain bike frames. In addition, they validated the computational results using the experimental fatigue tests obtained from the prototype frames.

The main objective of the present study is to check the long term durability of the improved design and double check potentially weak areas before working models are built and tested. The loading of the structure is obtained from bicycle design standards and some published works of literature. Two cases are used, based on ASTM F2711-08 (2012) horizontal and vertical loading durability fatigue tests. For horizontal loads, ASTM F2043-13 (2013) defines bicycle usage classes. Furthermore, ASTM F2802-09 (2015) defines that a bicycle used on paved roads and smooth surfaces is subject to a load of 600 N in tension and compression for each cycle. The load used is 980 N as in the previous study.

Stress-Life and Stress-Based models are used, since it is unclear how the load cycle will affect the stress tensor in the structure. The Stress-Bases model could be a better source of evaluation for non-proportional loads as in the case of the Vertical loads case.

MMPDS-01 (2003) gives S-N curves for the 6061 T6 aluminum alloy at different 'R' values. Data obtained from two of this curves was used for the Stress-Life model as well as to obtain the parameters for the Findley model. Yahr (no date) states a knock down factor of 2 for evaluation of welds, so a k of 0.5 will be used for the Stress-Life model since it's expected that the mayor stresses are found in weld areas of the design. From the SN curves, fatigue limit for comparison was taken as 106.5 MPa at 10^7 cycles. Fig. 1 shows an example of the S-N Curves used for the study.

In the next section, we describe the finite element model of an aluminum tricycle frame developed with Comsol Multiphysics® 5.2. The previous analysis showed that the fork needs to be completely redesigned, so in this case only the frame will be evaluated.

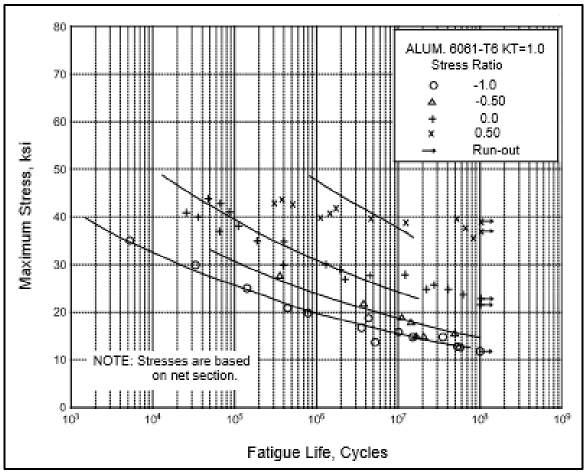

Figure 1. S-N curves for unnotched 6061-T6 aluminum alloy (MMPDS-01, 2003).

2. Model

As seen on Fig. 2, the tricycle consists of basic standard bicycle parts with a passenger/load zone on the backside. Only the frame is modeled, with the rest of the parts (seat tube, bottom bracket, fork, stem and handlebar) being used to define the loading conditions. Aluminum 6063-T6 is the material of the frame while for bottom bracket, fork and handlebars are made of 4130 steel.

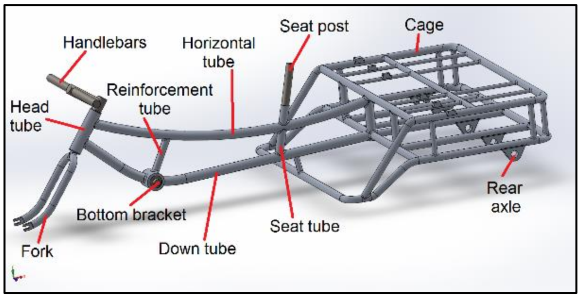

Figure 2. Components of the structure.

The Solid Structure Module is used to analyze the structure for stress distribution. Next, the Fatigue Module rests on this information to calculate the number of loading cycles before fatigue cracks might occur for each zone of the design (Stress-Life) or the fatigue usage factor (Findley Stress-Based model). The equations of the models are the following:

Solid Mechanics

The conservation equation is:

$$0 = \nabla \cdot \sigma + F_v \quad (1)$$

where σ is the stress tensor and F_v represents the volumetric forces. Then, for linear elastic materials the relationship between the stress tensor and the small strain tensor is given by:

$$\sigma = C{:}\varepsilon = C(E,V) \quad (2)$$

which corresponds to the Hooke's Law, where C is the elasticity or stiffness tensor, ε is the small strain tensor, E is Young's modulus and V is the Poisson's ratio.

Fatigue

Stress-Life models take the stress amplitude

$$\sigma_a = (\Delta\sigma/2) \quad (3)$$

and compare it to the Wohler curve to predict the number of cycles at that stress amplitude:

$$\sigma_a = k f_{SN}(N) \quad (4)$$

Here k is a modification factor to account for surface finish, size, reliability, among other conditions.

For Stress-Based models, the Findley criterion can be stated as:

$$\left(\frac{\Delta\tau}{2} + \mathrm{k}\sigma_n\right)_{max} = f \quad (5)$$

where k and f are material parameters, Δτ is the maximum shear stress range on a plane and σ_n is the largest normal stress on the same plane. The plane that maximizes the left-hand side of the equation is considered to be critical.

A fatigue usage factor, f_{us}, is calculated as the ratio between the left-hand side of the Findley criterion and the material parameter *f*. A value below 1 means that the component is loaded below the fatigue limit. For high compressive stress states, the normal stress can predict a negative f_{us}. In those cases fatigue usage factor is set to zero.

3. Methods

The geometry of the tridimensional frame is imported in Comsol Multiphysics® by means of the CAD Import Module capabilities. Then the Solid Structure Module is used with Solid Mechanics and Fatigue interfaces. Using different colors for each force, Fig. 3 shows the loads applied in the different areas of the tricycle, while Table 1 gives the combination of loads for vertical and horizontal loading cases.

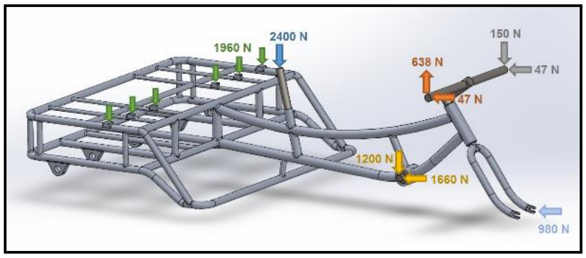

Figure 3. Loading values.

Table 1. Loading cases

Load case						
Vertical load				√	√	√
Horizontal load	√					

The vertical load case will involve pedaling forces at the bottom bracket, driver and passenger weight. Pedaling forces will remain constant during the load cycle, while driver and passenger weights will go from zero to maximum value and down to zero again. The horizontal load cycle will vary from -980N up to 980N and down again. The British Standard – Mountain-bicycles – Safety requirements and test methods (2005) describes the different tests used to examine safety of mountain bike frames. In particular, Section 4.8.2 indicates how the frame is constrained from movement during impact testing. In the computational model, the frame is constrained from movement in the rear axle, the fork is allowed to slide only along the horizontal *X* and *Y* axes and the vertical *Z* displacement is set to zero on the front axle boundaries. Spooles is used as solver for the Solid Mechanics Model. The frame consists of around $6x10^5$ tetrahedral elements (3.3x106 DOFs in the computations).

4. Computational results and discussion

The computational results show that for the vertical loading case, comparing stress to the fatigue limit of the material is somewhat more conservative than the Findley and SN Curve models predictions. Figs. 4, 5 and 6 show the differences in the headtube area just behind the fork insertion point. As can be seen, the Stress-Life model predicts more than 10^7 cycles in the headtube area, while the Findley model predicts that a small area in the weld bed is above the usage factor for the material, which could generate cracks and eventual failure.

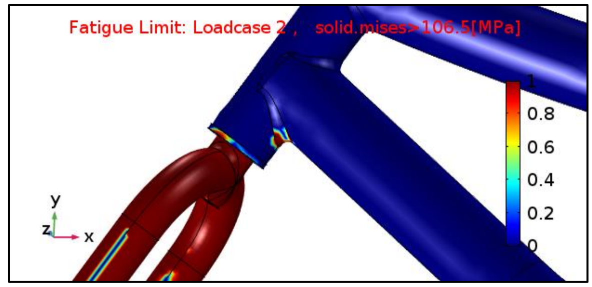

Figure 4. Lower headtube area, stress vs. fatigue limit, vertical load case.

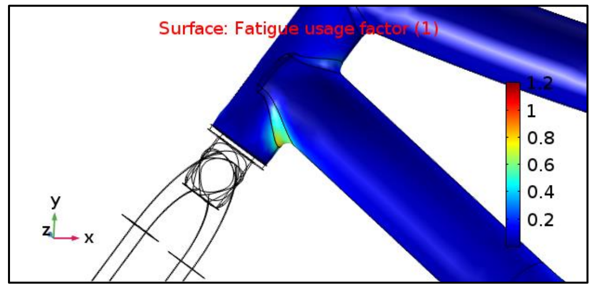

Figure 5. Lower headtube area, Stress-Based Findley model usage factor, vertical load case.

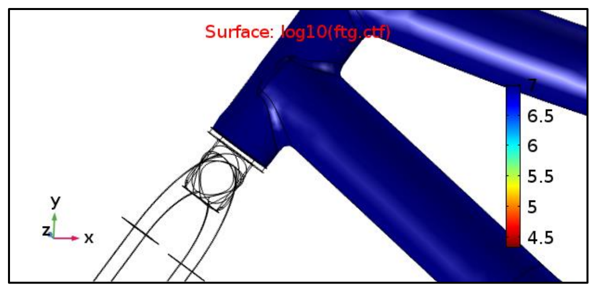

Figure 6. Lower headtube area, Stress-Life model, log10 cycles to failure, vertical load case.

For the horizontal loading case, an opposite condition occurs. The comparison to the fatigue limit does not predict any failure but the Findley method predicts a usage factor close to 1 and the Stress-Life model gives a service life of around 10^5 cycles. This could be explained since in this case the load cycle involves a load that goes from positive to negative and back, while originally, for comparison to the fatigue limit, only the stress caused by the positive force on the load cycle was considered (Fig. 7). This force generates compression on the weld bed, which is probably more rigid in compression than in tension and generates less stress than the negative portion of the cycle (Fig. 8). This is a good example of why specific fatigue models are important for structure and load analysis, since they consider the full load cycle, and of how it affects

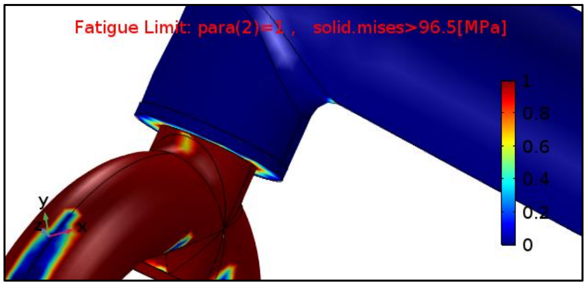

Figure 7. Lower headtube area, stress vs fatigue limit, positive load, horizontal load case.

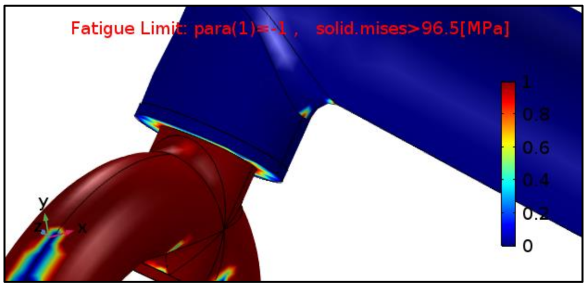

Figure 8. Lower headtube area, stress vs fatigue limit, negative load, horizontal load case.

the stresses and whether they promote crack growth or not. An area of a structure which is always in tension will tend to develop cracks faster than an area that cycles between tension and compression, since this last part of the cycle will close the crack instead of opening it.

In the vertical loads case, it is necessary to consider that the loads are applied in different points of the design and vary in different ways during the load cycle, which makes it difficult to know whether the components of the stress tensor will change out of phase or not. Even though one load remains constant and the other two loads vary in phase, the Stress-Based Findley model is recommended for cases in which loads are applied in more than one point (Comsol Multiphysics®, Fatigue Module Users Guide, 2016).

As can be seen from previous examples, the lower headtube area shows weakness in all the load cases, so it is a good idea to reinforce it with some kind of gusset as is used on several bicycle designs which had an extra piece of material welded in the area.

As for the rest of the structure, the vertical load case seems to be more critical when compared to the horizontal load case, which is understandable as it involves more and heavier loads distributed along the structure. Fig. 9 shows the results for the horizontal load case, where the maximum usage factor is 0.98 and Fig. 10 shows the vertical load case where the maximum factor is 1.21.

Figure 9. Passenger/load area, Stress-Based Findley model, horizontal load case.

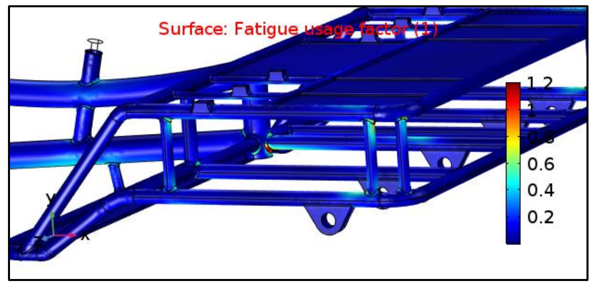

Figure 10. Passenger/load area, Stress-Based Findley model, vertical load case.

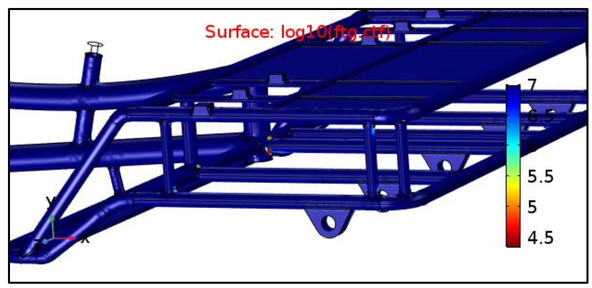

Figure 11. Passenger/load area, Stress-Life model, vertical load case.

Fig. 11 shows that for the vertical load case the predicted number of cycles is as low as $10^{4.5}$ cycles, which could be considered too low for the application. As can be seen in Fig. 12, weld beds continue to be potentially weak areas in the design. For this reason it would be good advice to modify the tube geometry at the weld, using bigger diameters or reinforcement

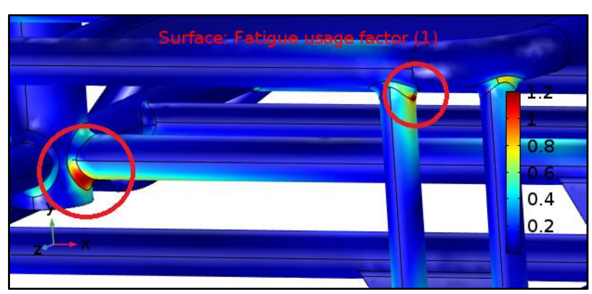

Figure 12. Passenger/load area, close up of weld beds, Stress-Based model, vertical load case.

gussets, allowing for improved weld areas as well as stiffer unions.

Overall, the Stress-Life model has two benefits. The most important is that it allows the evaluation of the number of cycles that the structure might resist. Hence, the manufacturer can decide whether or not the design meets the expectations and requirements or if it should be modified to have a longer, or in some cases shorter, life cycle. The other benefit is that it directly allows the use of correction or modification factors to include factors that the CAD or FEA models might overlook, such as surface finish, environmental factors, reliability and safety factors, among others.

Evaluating fatigue is not a simple task, the statistical nature of the data which is used demands knowledge of the specific cases under evaluation and how the stresses will affect the material, in order to select the best data available for each case. In this case, we have choosen data for an R value of -1 (fully reversing loads) for the horizontal load case and an R value of 0 (mean load above zero and minimum load of zero) for the vertical load case, to reflect as well as possible each instance. For this reason, the study provided an opportunity to gather knowledge which will be hopefully applied in future fatigue evaluation studies.

5. Conclusions

- A finite element analysis of an aluminum tricycle frame has been carried out by using Comsol Multiphysics® 5.2.
- For two different load cases, the effects of stresses on the service cycle of the design have been evaluated with the Stress-Life and Sress-Based Fatigue interfaces.
- The analysis shows that certain regions of the frame still need to be fine-tuned to withstand the loads.
- A simple fatigue analysis may not properly show the long term durability of the design. Proper fatigue simulations should be used in order to evaluate the design of the tricycle.
- The FEM simulations have provided useful insights in learning about fatigue models available to evaluate long term life of a structure, gathering knowledge for future studies.

6. References

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