Reverse Engineering a Golden Cycles Vader Fixie Bicycle

Dominic Stephen

WRITER'S COMMENT: Professor Ravani expects a lot from his students. If you are fortunate enough to take his EME150A class, you will curse him for this initially, but be thankful when the hell is over. He has the rare capability of combining his real-world experience with the course material to enhance the class's understanding. For our first project, Prof. Ravani challenged us to reverse engineer a bicycle and write a paper in the style of a journal article. We were expected to analyze three loading scenarios, determine the critical component, and suggest improvements to the bike's design. I dedicated multiple weekends to measuring my bike, performing lengthy calculations, creating diagrams, and writing my findings. Prof. Ravani expects a lot from his students, and we are better engineers as a result.

INSTRUCTOR'S COMMENT: Dominic was a student in my design against mechanical failure class and did this report for his first course project involving failure analysis of the bicycle of a student's choice. His report demonstrates not only his full grasp of the subject matter of the course but also the use of a methodical approach and care in providing proper basis for all his data and assumptions. He has matched his bike's specifications to data from the relevant literature and has performed proper analysis to establish the form (material) and the function (performance) of his bike for design analysis. This methodical approach and careful evaluation show that he will be a successful engineer and a good designer.

—*Bahram Ravani, Department of Mechanical and Aerospace Engineering*

Abstract

This report intends to study the design against mechanical failure of a Golden Cycles Vader Fixie Bicycle. Three load envelopes were chosen and utilized to analyze the potential life and misuse of the bike. When considering the three scenarios, two of them resulted in a factor of safety less than one. This shows that the Vader Fixie is not engineered to withstand the stresses this report subjects it to. Possible design modifications are suggested to help improve the strength of the bike's design.

Introduction

A bicycle is no less essential to the modern college student than a cellphone, calculator, or laptop. This mode of transportation is crucial to the day-to-day life of nearly everyone around us. This paper seeks to understand the design and engineering behind a specific bike, a Golden Cycles Vader Fixie. Using the reverse engineering techniques and methods of stress analysis developed in our EME 150A class, I will analyze extreme cases of misuse on this bike to identify potential sources of failure.

After determining the critical components, this report will then make recommendations on how to improve the integrity of the Golden Cycles Vader Fixie bicycle (Figure 1).

Figure 1. Golden Cycles Vader Fixies

Bike Specifications: An important aspect of the Vader Fixie is its cheap price point. I was able to purchase mine for a little under $250, including shipping. It will be interesting to see if the low price is reflected in the build quality of the bicycle. The website that advertises this bike refers to the frame material as "High Tensile Steel Fully Tig Welded" [1]. Though this is not very descriptive, there are two likely materials "High Tensile Steel" could refer

to: AISI 1020 and AISI 4130. Both of these steels are common in bike frames and components [2,3]. However, it is unlikely to be 4130 because of the price point. Most bikes that are advertised as having 4130 bike frames are closer to $500 [4]. The Vader Fixie is most likely constructed of low carbon AISI 1020 steel. The material properties of cold rolled AISI 1020 are tabulated below:

Table 1. AISI 1020 Properties [5].

Property	Value
Hardness, Brinell	121
Ultimate Tensile Strength (S_ut)	71 ksi
Yield Tensile Strength (σ_yp)	61 ksi
Modulus of Elasticity (E)	27000 ksi
Shear Modulus	10400 ksi

It is a conservative assumption to say that the other components of the bike are also constructed of 1020 steel (besides the wheels, which are an aluminum alloy).

Bike Weight and CG: The Vader Fixie is advertised to weigh around 25 lbs [1]. To confirm this, I used a bathroom scale, which read that the bike weighs 24.3 lbs.

To find the center of gravity (CG) of the bike, the structure is split into three sub-structures: the frame, front wheel, and rear wheel. The center of gravity of each sub-structure is found and then the average is taken. AutoCAD was used to find the area and geometric center of the five sections.

First, the CG of the frame was found using the method of composite bodies. The planar density of the bike is assumed to be constant in the plane of the bike. Next, the frame is split into 5 sections (Figure 2). For clarity, the section areas, and CGs are tabulated in Table 2.
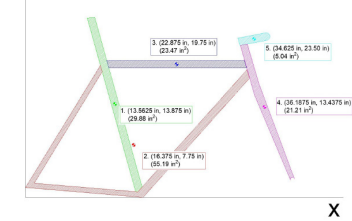
Figure 2. Frame Composite Bodies

Table 2. Frame Section CGs & Areas

Shape	Area (in²)	$\bar{X}$ (in)	$\bar{y}$ (in)
1 (Green)	29.88	13.5625	13.875
2 (Red)	55.19	16.375	7.75
3 (Blue)	23.47	22.875	19.75
4 (Purple)	21.21	36.1875	13.4375
5 (Cyan)	5.04	34.625	23.5
Total Area:	134.79		

The frame's CG was calculated using the formula below:

$$\bar{x}_{frame} = \frac{\sum Area_i \bar{x}_i}{Area_{total}}$$

$$= \frac{405.2 + 903.7 + 536.9 + 767.5 + 39.7}{134.79}$$

$$\bar{x}_{frame} = \boxed{19.68 \ in}$$

$$\bar{y}_{frame} = \frac{\sum Area_i \bar{y}_i}{Area_{total}}$$

$$= \frac{414.6 + 427.7 + 462.5 + 285 + 118.4}{134.79}$$

$$\bar{y}_{frame} = \boxed{12.68 \ in}$$

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The wheels were weighed individually and found to both be 2.6 lbs, leaving the frame to weigh 19.1 lbs. To find the CG of the bike as a whole, the method of composite bodies was utilized again. Figure 3 and Table 3 show the sections: frame, front wheel, and rear wheel.
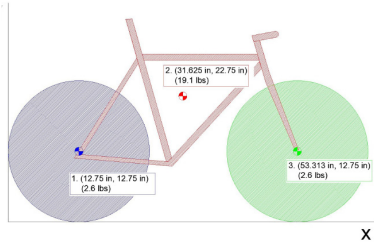
Figure 3. Bike Composite Bodies.

Table 3. Bike Composite Bodies Data

Shape	Weight (lbs)	$\bar{X}$ (in)	$\bar{y}$ (in)
1 (Rear)	2.6	12.75	12.75
2 (Frame)	19.1	31.625	22.75
3 (Front)	2.6	52.3125	12.75
Total Area:	24.3		

The frame's CG was calculated using the process below:

$$\bar{x}_{bike} = \frac{\sum Area_i \bar{x}_i}{Area_{total}}$$
$$= \frac{33.15 + 604 + 162}{24.3}$$
$$\bar{x}_{bike} = \boxed{32.89 \; in}$$

$$\bar{y}_{bike} = \frac{\sum Area_i \bar{y}_i}{Area_{total}}$$
$$= \frac{33.2 + 434.5 + 33.2}{24.3}$$
$$\bar{y}_{bike} = \boxed{20.6 \; in}$$

Approach

Now that the specifications of the Vader Fixie have been determined, the analysis can begin. This analysis will use the Methodology for Design Against Mechanical Failure discussed in lecture [6]. The steps for this process are as follows:

1. Develop realistic model of system
2. Determine load envelope during expected life
3. Identify critical components
4. Draw free body diagrams (FBD) for critical components
5. Determine critical cross section for component
6. Determine critical points on critical cross sections

Step 1, developing a realistic model, will be done in this section. The following steps (2-6) will be tackled later in this report.

For the realistic model, certain assumptions will be made to simplify the problem-solving process. For example, when the load envelopes are determined, aerodynamic and internal forces will be neglected. Also, the dynamic forces are simplified using D'Alembert's principle, transforming the problem into

a static problem [6]. To further simplify the load envelopes, the bike and biker are assumed to be one rigid body. Throughout the analysis, transverse shear is also neglected. Finally, only the forces in the plane of the bike and biker will be considered.

Further simplifications will be used specific to load envelopes and will be explained when presenting the load envelope.

System CG – Model: Before beginning the analysis, the CG for the system is required. Once again, I will utilize the method of composite bodies to determine the CG. For this, the biker is assumed to be 400 lbs. This is a conservative assumption, of course. Also, the CG for the sitting biker is determined using research conducted at the University of Michigan [7]. The x and y position of the biker's CG is +11 in and +8.9 in, respectively, from the top of the bike's seat. The method of composite bodies is as follows:
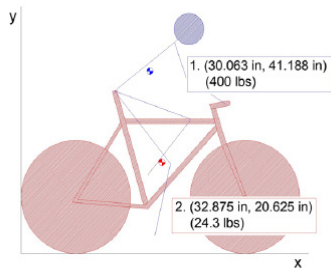
Figure 4. System Composite Bodies.

Table 4. System CG Model.

Shape	Weight (lbs)	$\bar{X}$ (in)	$\bar{y}$ (in)
Biker	400	30.063	41.188
Bike	24.3	32.875	20.625
Total Area:	424.3		

$$\bar{x}_{system} = \frac{\sum Area_i \bar{x}_i}{Area_{total}}$$

$$= \frac{12,025 + 798.9}{424.3}$$

$$\bar{x}_{system} = \boxed{30.2\ in}$$

$$\bar{y}_{system} = \frac{\sum Area_i \bar{y}_i}{Area_{total}}$$

$$= \frac{16,475 + 501.2}{424.3}$$

$$\bar{y}_{system} = \boxed{40.0\ in}$$

Load Envelopes and Analysis

For this report, three load envelopes will be considered:
1. Downhill braking to tipping point
2. Dropping off typical curb
3. Wheelie at balancing point

These load envelopes are intended to model the typical life and misuse of a bicycle, specifically a bicycle owned by a college student.

Downhill Braking to Tipping Point: The first model studied in this report replicates the situation where a biker is going downhill and braking only with the front brake. The slope of

the hill is assumed to be 10% [6]. For the worst scenario, it is assumed that the bike is on the brink of tipping; therefore, all of the weight is on the front wheel (Figure 5) for the model used for this scenario:

Figure 5. *Downhill Braking Envelope*
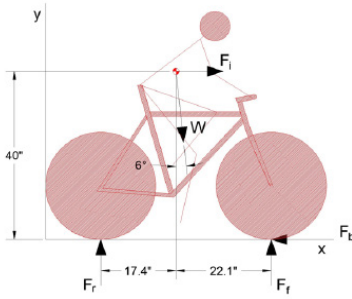
Note that for this model, the system weight is 6° from the horizontal due to the downhill slope. There are additional assumptions for this model. For one, the bike is assumed to be decelerating at 0.3g [6]. Also, F_r will equal zero because of the previously discussed tipping conditions. The inertial and reaction forces are calculated below:

$$F_i = ma = \frac{W}{g}(0.3g) = .3W = 127.3lb$$

$$\sum F_y = 0$$
$$F_f = W \cos 6° - F_r = 422lb$$

$$\sum F_x = 0$$
$$F_b = F_i + W \sin 6° = 171.7lb$$

Now that the reaction forces have been solved for, the critical component can be analyzed. For this envelope, the critical component is the front wheel hub. The wheel hub is where the spokes come together and attach to the front wheel. The x-y FBD for this component is shown in Figure 6. The analysis is simplified using the natural symmetry of the hub.

Figure 6. *X-Y Front Wheel Hub FBD.*
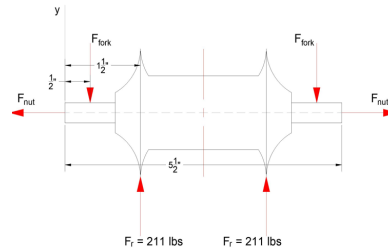
The above diagram shows the critical component under load. F_{nut} is the axial stress caused by the tighten nut on the hub. This force is calculated using the following equation [8]:
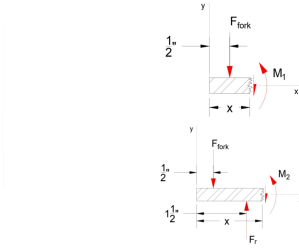
$$T_{nut} = KF_{nut}d$$
$$K = 0.3; T_{nut} = 15lb - ft; d = 3/8"$$

$$F_{nut} = \frac{15lb - ft}{(0.3)(.375)} \cdot \frac{12\ in}{1\ ft} = 1{,}600\ lb$$

Next, the part's moment diagram must be made to determine the critical cross section

and critical moment (Figure 7).

Figure 7. Front Wheel Hub Moments.

Using the information from Figure 7, the moments can be calculated. Note that the force of the fork is equal to the 211lb forces:
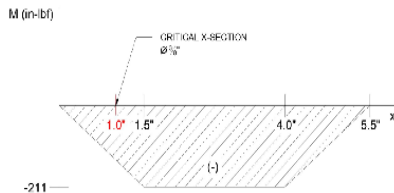
$$M_1 = -F_{fork}(.5 - x)$$
$$M_1 = 211(x - .5)$$

$$M_2 = -F_{fork}(.5 - x) + F_f(.5 - x)$$
$$M_2 = -211in - lb$$

Figure 8 illustrates the resulting moment diagram for the wheel hub. Note that the critical cross section occurs at x=1" because of the small thread diameter of 3/8". The max moment occurs at x=1.5", but the cross section is significantly larger at this point.

Figure 8. Front Wheel Hub Moment Diagram.

The moment at the critical cross section in the x-y plane is calculated:

$$M_{crit-x} = 211(.5 - 1)$$
$$M_{crit-x} = -105.5in - lb$$

The same process is done for the z-y plane where the braking force occurs. The critical moment depends on F_b instead of F_f.

$$M_{crit-z} = 85.9(.5 - 1)$$
$$M_{crit-x} = -42.9in - lb$$

The resultant moment is calculated using the magnitude equation:

$$M = \sqrt{M_{crit-x}^2 + M_{crit-z}^2}$$

$$M = \sqrt{(-105.5)^2 + (-42.9)^2}$$
$$|M| = 113.9in - lb$$

The critical cross section is a solid circle with a 3/8" diameter. Both moment of inertias and area are calculated as follows:

$$A_{bolt} = \pi \cdot \left(\frac{D}{2}\right)^2 = 110.5 \times 10^{-3}in^2$$
$$I_{bolt} = \frac{\pi}{4} \cdot \left(\frac{D}{2}\right)^4 = 970.7 \times 10^{-6}in^4$$
$$J_{bolt} = \frac{\pi}{2} \cdot \left(\frac{D}{2}\right)^4 = 1.941 \times 10^{-3}in^4$$

The moment, nut force, and nut torque are used to

find the axial and shear stresses. The axial stress is the sum of the stresses caused by the moment and force from the nut.

$$\sigma_M = \frac{M \cdot D}{2I} = \frac{(113.9in - lb)(.375in)}{2(970.7 \times 10^{-6}in^4)}$$

$$\sigma_M = 22.0ksi$$

$$\sigma_{axial} = \frac{F_{nut}}{A} = \frac{1600lb}{110.5 \times 10^{-3}in^2}$$

$$\sigma_{axial} = 14.5ksi$$

$$\sigma_x = \sigma_{axial} + \sigma_M = 36.5ksi$$

For the shear stress on the critical cross section:

$$\tau_{xy} = \frac{T_{nut} \cdot D}{2J} = \frac{(276in - lb)(.375)}{2(1.941 \times 10^{-3}in^4)}$$

$$\tau_{xy} = 26.7ksi$$

Now the principal stresses can be calculated for the final analysis (Figure 9).

Figure 9. Braking Material Section.

$$\sigma_{I,II} = \frac{\sigma_x}{2} \pm \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + \tau_{xy}^2}$$

$$\sigma_{I,II} = 18.2ksi \pm 32.3ksi$$

$$\sigma_I = 50.6ksi$$
$$\sigma_{II} = -14.1ksi$$

Because AISI 1020 is a ductile material, the octahedral stress theory is used. In two dimensions, octahedral stress theory is calculated using Von Mises's Stress:

$$(\sigma_I^2 + \sigma_{II}^2 - \sigma_I\sigma_{II})^{1/2} = \frac{\sigma_{yp}}{n}$$

$$n = \frac{\sigma_{yp}}{\sigma_{VM}} = \frac{61ksi}{58.9ksi}$$

$$n = \boxed{1.1}$$

The final result for the downhill braking load envelope shows that the factor of safety is barely above one. The engineers who designed the Vader Fixie most likely did not intend for a 400lb biker braking so suddenly on a downhill. However, further analysis using the next two load envelopes could confirm this finding.

Dropping off Typical Curb: The second load envelope studied in this report models a 400lb biker dropping off a standard 7" curb [9]. According to my dynamics

textbook, the deceleration of the bike-biker system would be roughly a quarter of a second [10] (Figure 10).

Figure 10. Curb Drop Envelope.
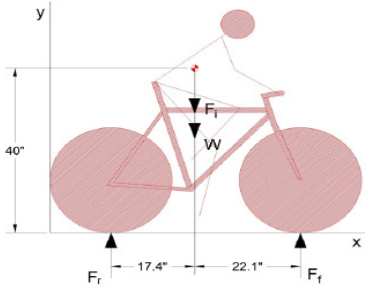
To begin this analysis, a combination of the equations of motion is required to find the inertial force. First, the velocity of the bike-biker system prior to contacting the ground needs to be calculated:

$$v_{system} = \sqrt{2g(7in)} = 73.5 \ in/s$$

Now, average acceleration during the collision is found in order to find the inertial force:

$$a = \frac{\Delta v}{\Delta t} = \frac{73.5 \ in/s}{0.25s} = 294 \ in/s^2 = 0.76g$$

$$F_i = ma = \frac{W}{g}(0.76g) = 323.2lb$$

The normal statics problem solving process is utilized at this point.

$$\sum M_{rear} = 0$$

$$F_f(39.5in) - F_i(17.4in) - W(17.4in) = 0$$
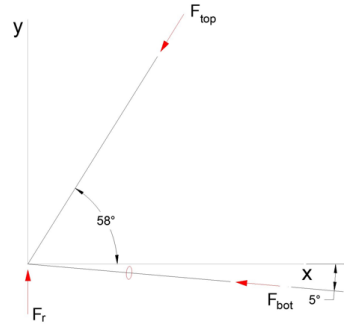
$$F_f = 329.3lb$$

$$\sum F_y = 0$$

$$F_r + F_f = F_i + W$$

$$F_r = 418.2lb$$

The load envelope has been fully solved. Next, the critical component is identified. For this model, the rear bottom strut is the critical component. Figure 11 shows the FBD for the bottom and top strut to begin analysis.

Figure 11. Rear Strut FBD.

In the above figure, the rear bottom strut is identified by a red circle. To find the forces in these strut members, typical truss analysis is performed.

$$\sum F_x = 0$$
$$F_{top} \cos 58° = F_{bot} \cos 5°$$
$$F_{bot} = 0.532 F_{top}$$

$$\sum F_y = 0$$
$$F_{top} \sin 58° + F_{bot} \sin 5° = F_r$$
$$F_{top} \sin 58° + 0.532 F_{top} \sin 5° = 418.2 lb$$
$$F_{top} = 467.6 lb$$
$$F_{bot} = 248.8 lb$$

The bottom strut can now be analyzed separately using these force values (Figure 12). It is important to note that F_w is half of F_r, because we are analyzing one of two rear bottom struts.

Figure 12. Rear Strut Analysis
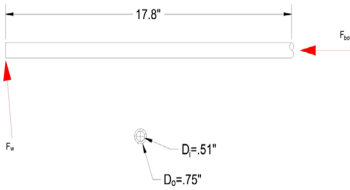
For the bottom strut analysis, the wall thickness is assumed to be 0.12" according to stock AISI 1020 tubing [11]. The hollow tubing cross sectional area and second area moment of inertia must be calculated:

$$A_{strut} = \pi \left[\left(\frac{D_o}{2} \right)^2 - \left(\frac{D_i}{2} \right)^2 \right] = 0.2375 in^2$$

$$I_{strut} = \frac{\pi}{4} \left[\left(\frac{D_o}{2} \right)^4 - \left(\frac{D_i}{2} \right)^4 \right]$$
$$= 12.21 \times 10^{-3} in^4$$

Once again, the axial and shear stresses of the critical component will need to be found

before determining the principal stresses.

$$M = \frac{1}{2} F_r \cos 5° x = 209.1x$$

$$M_{max} = 209.1 lb (17.8 in) = 3,722 in - lb$$
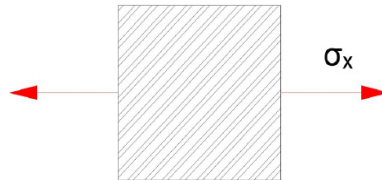
$$F_{axial} = F_{bot} + \frac{1}{2} F_r \sin 5° = 292.5 lb$$

$$\sigma_M = \frac{M_{max} \cdot D}{2 I_{strut}} = 114.3 ksi$$

$$\sigma_{axial} = \frac{F_{axial}}{A_{strut}} = 1.23 ksi$$

$$\sigma_x = \sigma_{axial} + \sigma_M = 115.5 ksi$$

Max shear stress theory will be used again for this critical component. Because this is a strut system, the member is in pure tension. Therefore:

Figure 13. Curb Drop Material Section.

$$\sigma_{VM} = \sigma_x = \frac{\sigma_{yp}}{n}$$

$$n = \frac{\sigma_{yp}}{\sigma_{VM}} = \frac{61 ksi}{115.5 ksi}$$

$$n = \boxed{0.53}$$

This load envelope results in a factor of safety well below one. The curb-drop confirms the previous hypothesis that the Golden Cycle engineers did

not design the Vader Fixie to withstand the misuse this report is testing. However, there is still one last load envelope to study.

<u>Wheelie at Balancing Point</u>: The final load envelope models a scenario that is seen often on the UC Davis campus: a biker performing a wheelie. In this model, the biker is perfectly balanced, meaning the system CG is directly above the point of contact the tire makes with the road. It is interesting that the top rear struts of the Vader Fixie align perfectly with this CG-contact-point-line (Figure 14).

*Figure 14. Balancing Point Wheelie Envelope.*
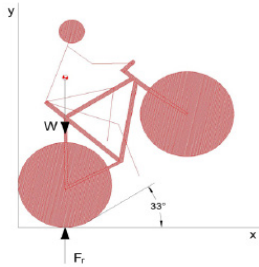
In this model there are only two forces, the system weight and the reaction force on the rear wheel. This makes for an easy calculation for the reaction force:

$$F_r = W = 424.3lb$$

Because the top rear strut aligns perfectly with the line of balance, it can be modeled as a compression member. For this reason, this strut is the critical component for this load envelope. Figure 15 demonstrates the logic behind this analysis.
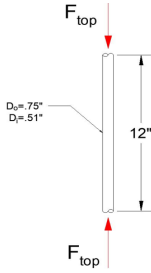
Figure 15. Top Strut Compression Member.
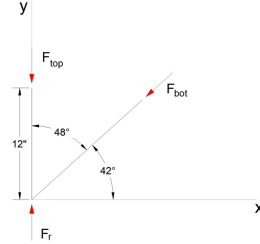
Finding the forces in the strut members is done:

$$\sum F_x = 0$$
$$F_{bot} \cos 42° = 0$$
$$F_{bot} = 0$$

$$\sum F_y = 0$$
$$F_{top} + F_{bot} \sin 42° = F_r$$
$$F_{top} = F_r = 424.3lb$$

The above figure and calculations show that the top strut is in pure compression. Figure 16 shows the critical component analysis for the struts. Note that there are two top struts, so the load is split equally between them.

Figure 16. Top Strut Compression Member

This compression member is modeled as being fixed on either side, with a maximum unsupported section of 12". The critical force to cause buckling is calculated:

$$F_{crit} = \frac{\pi^2 EI}{L_{eff}^2}$$

The second area moment for the top strut is the same as the bottom strut calculated earlier in the report. Also, since both sides are modeled as fixed L_{eff} is equal to half of the true length [6]. Using this information, the critical forces to cause buckling can be calculated.

$$F_{crit} = \frac{\pi^2 EI}{L_{eff}^2}$$

$$F_{crit} = \frac{\pi^2(27,000ksi)(12.21 \times 10^{-3}in^4)}{(6in)^2}$$

$$F_{crit} = 90.4lb$$

The factor of safety is calculated using the limit design equation:

$$n = \frac{F_{crit}}{1/2\, F_{top}} = \frac{90.4lb}{212.2lb}$$

$$n = \boxed{0.43}$$

For the final load envelope, the factor of safety is again less than one. This result further confirms that the Vader Fixie is not intended for the misuse studied in this load envelope or in this report as a whole. This bicycle would have to be modified significantly to withstand the tested scenarios.

Suggested Design Modifications

As demonstrated in the previous section, the Golden Cycles Vader Fixie is not built to a high enough quality to avoid mechanical failure from the three load envelopes. It is important to reiterate that this particular bicycle is on the lowest end of the prove spectrum for bikes. At a mere $250, this bike is intended to be a cheaper alternative to high-end expensive fixies. For this reason, it is likely not designed using the best materials nor optimal components.

The simplest suggestion to improve the performance of the

Vader Fixie is to use a steel alloy instead of 1020 low carbon steel. For example, using AISI 4130 steel could increase the strength of the bike by nearly three times. The yield strength of quenched 4130 steel is around 161ksi, which would easily handle the stresses calculated in this report [12]. Of course, by making this change one would increase the price of the bike.

A more difficult modification would be to increase the size of the rear struts. This would increase the strength of the bike but it could also affect the aesthetics and further increase the weight. By modern standards, the Vader Fixie is already a heavy bike, so adding more material would exacerbate this issue.

Really, the easiest way to prevent mechanical failure with the Vader Fixie is to implement a weight limit. There is no documentation for the bike that suggests a weight limit; but as this report shows, a 400lb rider would certainly cause yielding. To keep the bike at its low price point and current weight, one would simply advertise a 200lb weight limit for the rider. This limit would certainly help prevent failure during misuse.

Conclusion

It is incredible that you can order a bike and have it delivered to your doorstep for less than $250; it seems too good to be true. This report confirms that it may indeed be too good to be true.

Of the three load envelopes test, the factor of safety was less than one for two of them: dropping off a curb and wheelie. This confirms that the bike is not engineered to withstand the stresses calculated in this report.

There are a few proposed modifications that could help improve the Vader Fixie design. For one, utilizing stronger materials could help, such as AISI 4030. Also, increasing the size of the rear struts would improve the strength of the bike, but add weight. I think it would be best to keep the bike cheap and simply implement a weight limit. Further study could be used to suggest specific material and dimension changes.

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