INTEGRATING SUSTAINABILITY ANALYSIS WITH DESIGN: CASE STUDY OF BICYCLE FRAME

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Abstract
Designing a product to meet specific needs is the routine role of an engineer. The impact of a design to the environment is often times either minimized or ignored during the design process. The environment has some capacity to cope with impact from all human activities so that a certain level of impact can be absorbed without lasting damage. However, studies show that current human activities exceed this threshold with increasing frequency, diminishing the quality of the world in which we now live and threatening the well-being of future generations. Part of this impact derives from the manufacture, use, and disposal of products which are made from materials.

In this paper, integration of computer engineering analysis and sustainability analysis are used to evaluate three alternative materials for bicycle frame as follows; bamboo, aluminum, and carbon fiber epoxy. The assumptions used in the analyses were 250 lb (114 Kg) load on the seat tube while fixing the head tube, chain stays, and seat stays. This resulted in all of the materials to be well below the yield strength being under 3 MN/m^2 for each alternative design. The bamboo frame experienced the most displacement of 0.06 mm, followed by aluminum with 0.016 mm, and lastly carbon fiber reinforced epoxy with 0.01 mm. All of the deformations are significantly small compared to the diameter of tubing used so no fracturing will occur during use. The eco-audit tool is used to evaluate environmental impact of the alternative product designs using simplified Life Cycle Assessment (LCA) approach. The tool identifies different phases of the product life: material, manufacturing, transportation, and disposal by analyzing the specified material that carries the highest process energy, disposal energy, and which creates the greatest burden of CO_2. The eco-audit tool resulted in bamboo using the least amount of embodied energy and CO_2 compared to aluminum and carbon fiber. The material stage and manufacturing stage made up a significant portion of the total amount of embodied energy and CO_2 for all material choices.

This approach of evaluating the sustainability of alternative designs can be integrated with traditional design process taught in mechanical engineering programs. It will facilitate design of products that have minimal environmental impact and minimum embodied energy requirement.

Keywords: Sustainability, Embodied Energy, Eco-audit, and Environmental Impact

I. Introduction

The development of sophisticated products and global technological advancements coupled with the ever increasing use of non-renewable resources have led to the need to consider sustainability as an integral part of present and future developments. Also, it is important that the excessive dependence on depleting non-renewable resources be reduced drastically. This can be achieved with sustainability in mind during product development. Sustainability refers to the development of products that meet the present needs without compromising the ability of future generations to meet their needs. It considers the environmental impact, economic viability of products, and the social responsibility (people) of the product.

Bicycles are widely used in almost every part of the world and therefore it is prudent that the environmental impact of this product be considered as one of the design criteria. Bicycle frames are commonly made from materials such as aluminum, carbon fiber, and steel. The recent development of the bamboo bicycle frame, which came second in the world bicycle race has opened up opportunities to address questions such as: what material and manufacturing processes used in the production of the bicycle frame produces a more eco-friendly product and at the same time meets the stress criteria; which product is more sustainable?; is it the Bamboo frame, Carbon Fiber frame, or the Aluminum (metal) frame? A bicycle frame is the main component of a bicycle, on to which wheels and other components are fitted. The modern and most common frame design for an upright bicycle is a diamond frame and consists of two triangles: a main triangle and a paired rear triangle.

This paper presents the use of both sustainability analysis and computer engineering analysis to compare three alternative materials and manufacturing processes for making bicycle frames (diamond frame). Eco audit will be conducted on the three alternative bicycle frames. The eco data will include embodied energy usage, CO_2 emission, and water usage for each alternative frame. Then, finite element analysis of the frames will be conducted using SolidWorks software to determine the stress and deformation conditions of the frames during service.

II. Background

To evaluate the sustainability of a bicycle frame, a simplified life cycle assessment (LCA) is conducted. LCA traces the progression of a products life from raw materials to manufacture, usage, and disposal; documenting all resources consumed and emissions released at each stage of the life cycle. The results of the LCA will help both the manufacturer and the consumer to determine sustainability of a product. This will be facilitated with an eco-audit toolbox[2]. Eco-Audit will identify the phase of the product's life that carries the highest demand for energy, and which phase generates the largest CO_2 output. Figure 1, modified from Ashby[1] shows a rough diagram of the Eco-audit method. After the user inputs several variables into the program, the eco-audit tool draws various data from its databases of embodied energy of materials, processing energies, transportation type, and energy conversion efficiencies, to generate the energy breakdown and CO_2 footprint.

There are several eco-properties that the software uses to evaluate sustainability: the embodied energy, the CO_2 footprint, and the water usage. The embodied energy (H_m) is defined as the energy that must be committed to create 1 kg of usable material[1]. H_m is measured in the units of MJ/kg. To determine the embodied energy, the sum of the energies entering the plant in an hour is divided by the mass of the material being produced in an hour.

$$H_m = \frac{\sum \text{Energies entering plant per hour}}{\text{Mass of material produced per hour}} \quad \frac{MJ}{Kg} \tag{1}$$

The CO_2 footprint of a material is also determined in a similar manner, however the carbon emissions that are released upon creation of the material also include those created during transport, the feed-stocks and hydrocarbon fuels, and the electric power used by the plant. Therefore the final equation for calculating the CO_2 foot print is:

$$CO_2 = \frac{\sum \text{All contributions of } CO_2 \text{ production}}{\text{Mass of usable material exiting the plant}} \quad \frac{(CO_2)}{Kg} \tag{2}$$

The water usage is very straight forward. It is simply the amount of water that is used in the production of the product in question.

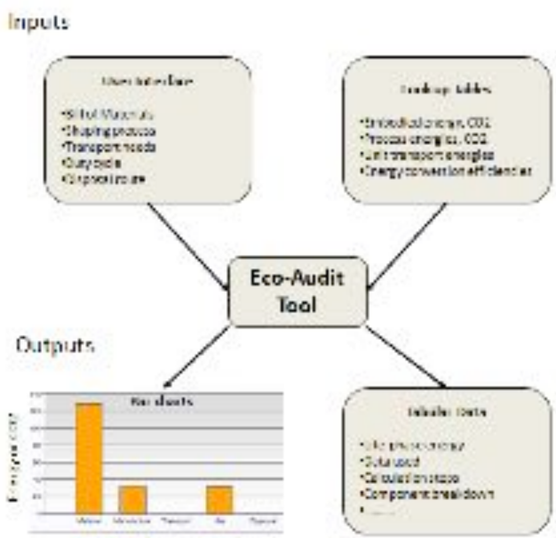

Figure 1: The Energy Audit Method

III. Procedure and Analysis

Bamboo Bicycle Frame. This frame is made from bamboo with the specifications in Table 1. The joints of the frame are formed by wrapping the joints with polytetrafluoroethylene (Teflon). Bamboo frames are made from that which has been smoked and heat treated to prevent splitting. For this product design, a propane torch is used for approximately 10 minutes to heat-treat the bamboo in order to seal the nodes and prepare it for baking. Baking is done at a temperature of about 350˚F for 1 or 2 hours. Figure 2 is an illustration of a bamboo bicycle frame.

Table 1. Bamboo bike frame specifications per component

Part	Outer Diameter (in.)	Inner Diameter (in.)
Head Tube	1.25	0.75
Down Tube	1.875	1.675
Top Tube	1.375	1.125
Seat Tube	1.375	1.00
Chain Stays	1.063	0.938
Seat Stays	1.00	.875
Pedal Tube	1.375	1.00

The bamboo bicycle frame consists of different size bamboo tubing and polytetrafluoroethylene (PTFE) is used to attach all the joints together. The bamboo is readily available in Ghana, Africa, hence does not require major transportation needs from overseas. The bamboo frame is shaped into the designed components with basic manufacturing tools: saw, drill, descent knife, rotary tool, and sandpaper. The PTFE that is used for the joints is formed through polymer molding. This does not require major transportation because a manufacturing plant can be found in Accra, Ghana. The bamboo bicycle frame is disposed by combustion at the end of its life, about 10 years expected duty cycle. The PTFE used to make the joints can be recycled.

Figure 2. A bamboo bicycle frame

Aluminum Bicycle Frame. The inside diameter of the aluminum bicycle frame is a little different from the bamboo frame with specifications illustrated in Table 2. Aluminum frames are generally recognized as having a lower weight than steel, although this is not always the case. The type of construction used for the aluminum alloy frame is tubes that are connected together by Tungsten Inert Gas (TIG) welding. They possess lower density and lower strength compared with steel alloys, however, possess a better strength-to-weight ratio, giving them notable weight advantages over steel.

Table 2: Aluminum bike frame specifications per component

Part	Outer Diameter (in.)	Inner Diameter (in.)
Head Tube	1.25	1.217
Down Tube	1.875	1.842
Top Tube	1.375	1.342
Seat Tube	1.375	1.342
Chain Stays	1.063	1.030
Seat Stays	1.00	.967
Pedal tube	1.375	1.342

Commonly made from 6061 Aluminum alloy tubing and aluminum filler rod, they are formed through the process of extrusion. Figure 3 is an illustration of aluminum bicycle frame. Hot liquid metal is poured into a die where it is then quenched to produce the desired hollow tubing dimensions. The tubes are joined together by TIG welding the same material aluminum, but in filler rod form, around the two faces to be held in place. The aluminum filler rod is made by pulling wire through a single drawing die. Transportation demands will be higher than bamboo, since they are either imported or transported from Accra, Ghana. At the end of the predicted 10 year life cycle, each component may be recycled.

Figure 3: An aluminum bicycle frame

Carbon Fiber Reinforced Epoxy (CFRE) Bicycle Frame. CFRE is among the latest materials commonly used for bicycle frames. Unlike bamboo and aluminum, CFRE is a composite consisting of carbon strands pressed together in layers within an epoxy. It can be shaped into interesting and aerodynamic forms; therefore, it is common to see carbon bike frames composed of teardrop, flat or wing shaped tubes rather than the perfect cylinders used in steel bike frames. CFRE bike frames are sometimes built as a single solid piece and they are sometimes built from individual tubes joined together with lugs much like a steel or aluminum frame. CFRE is very lightweight and can be made very stiff. Due to the alignment of the individual fibers, CFRE frames have a more distinctive grain structure. This allows it to have different amounts of stiffness in different directions and will stiffen non-linearly. Although CFRE is strong and stiff, a deep scratch or hard bump can compromise the structural integrity of its frame, making it prone to catastrophic failure.

CFRE Fiber bike frames needs a Polystyrene frame core for the carbon fiber to be wrapped. Along with the frame core and carbon fibers, an epoxy must be laminated in between the two components and around the joints to give the closely packed fibers the strength and rigidity it needs. Transportation needs for CFRE bicycle frames will be very high since the material is not readily available in the Ghana region; it must be air freighted from overseas. The product has a life span of 10 years where at the end of its life cycle the carbon fiber components will end up in a landfill and the polystyrene core will be recycled.

IV. Results and Discussion

Sustainability Results of the Three Alternative Designs. Analysis with eco-audit software shows that aluminum bicycle frame has highest embodied energy of 54000 kcal compared to CFRE bicycle frame with 44000 kcal. The bamboo bicycle frame has the lowest embodied energy of 34000 kcal as illustrated in Figure 4. The energy consumption at the material life stage of the three materials dominated the percentage of total energy consumption; about 86% and the other three life stages consumed only 14% of the total embodied energy. This information has a vital implication that a designer can focus on optimizing the material selection in order to design a sustainable product, since the other life cycle stages will contribute small percentage of energy consumed.

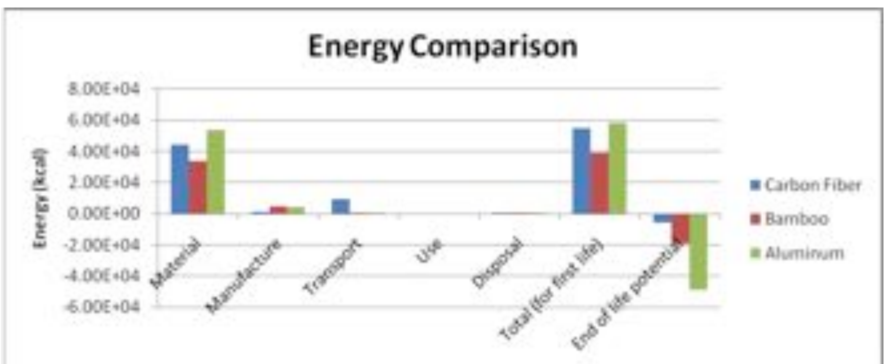

Figure 4: Embodied energy comparison of the three alternative designs

Similarly, the CO_2 emissions at the material processing life stage dominated the three materials' life cycle emission, comprising about 82% of the total estimated emissions. The processing of bamboo frame has the least CO_2 footprint of 16 lb, followed by CFRE with 23 lb CO_2. Aluminum bicycle frame has the highest amount of CO_2 emission of 28 lb (12.7 Kg) CO_2 as illustrated in Figure 5. Processing of the bamboo joints with Teflon tapes actually contributed 15 lb (6.8 Kg) out of the 16 lbs (7.3 Kg) CO_2 emission by bamboo bicycle frame. Bamboo has the least CO_2 footprint compared to the two other alternative designs because the Teflon emits 15 of the 16 total lbs of the CO_2 compared to the carbon fiber frame that lets off 20 (9 Kg) of the 23 (10.5 Kg) lbs and the aluminum frame releases 22 of the 28 lbs.

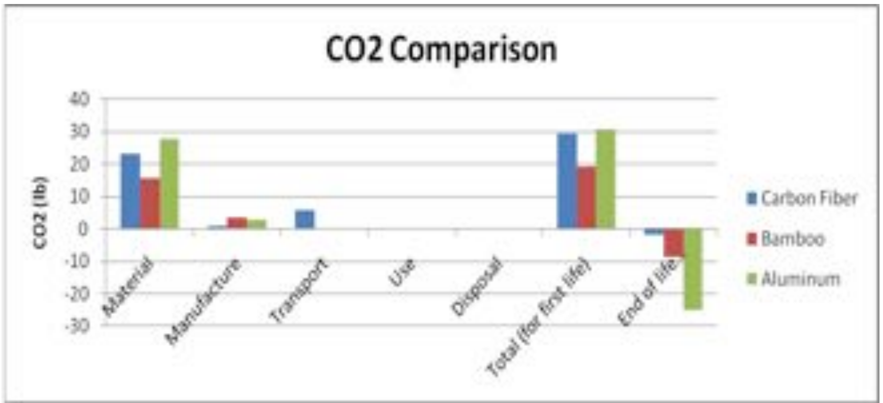

Figure 5: CO_2 comparison of the three alternative designs

The bamboo and the aluminum frame have a higher embodied energy for the manufacturing stage because of the energy used to make the joints (wrapping, extrusion and welding). Details of data from analysis of the three materials are shown in Tables 3, 4, and 5.

Table 3: Carbon fiber eco-audit results

Phase	Energy (kcal)	Energy (%)	CO_2 (lb)	CO_2 (%)
Material	4.45E+04	81.3	23	78.2
Manufacture	1.00E+03	1.8	0.71	2.4
Transport	9.15E+03	16.7	5.66	19.2
Use	0	0	0	0
Disposal	101	0.2	0.0654	0.2
Total (for first life)	5.47E+04	100	29.5	100
End of life potential	-5.80E+03		-1.65	

Table 5: Aluminum eco-audit results

Phase	Energy (kcal)	Energy (%)	CO_2 (lb)	CO_2 (%)
Material	5.39E+04	92.4	27.6	90
Manufacture	4.20E+03	7.2	2.91	9.5
Transport	54.1	0.1	0.0354	0.1
Use	0	0	0	0
Disposal	173	0.3	0.112	0.4
Total (for first life)	5.83E+04	100	30.7	100
End of life potential	-4.90E+04		-25.1	

Results of the Finite Element Analysis of the Frames.

The bamboo bike frame stress analysis shows a maximum stress of 2.8 MN/m^2, which is well below the yield strength of 39.6 MN/m^2 as shown in Figure 10. The maximum displacement of 0.06579 mm occurred at the seat stay and seat tube joints but is not a value that will result in fracturing of any of the tube or joints as shown in see Figure 11. The factor of safety for the bamboo bicycle is 14.3, which means that the frame can undergo 14.3 times the 250 lb (114 Kg) load set on the seat tube.

Figure 9: Bamboo design frame

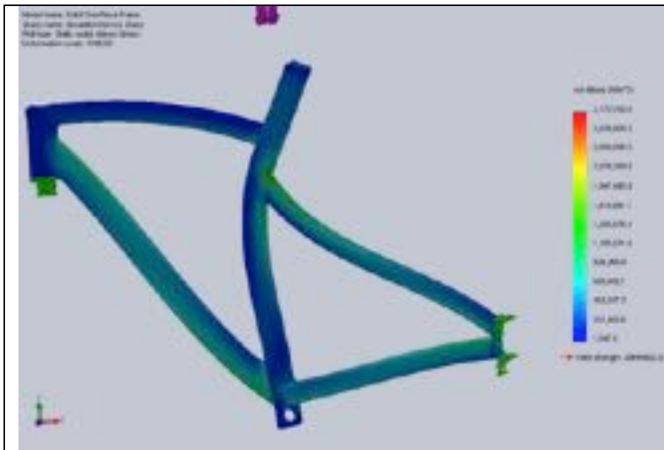

Figure 6.1 Bamboo maximum deformation

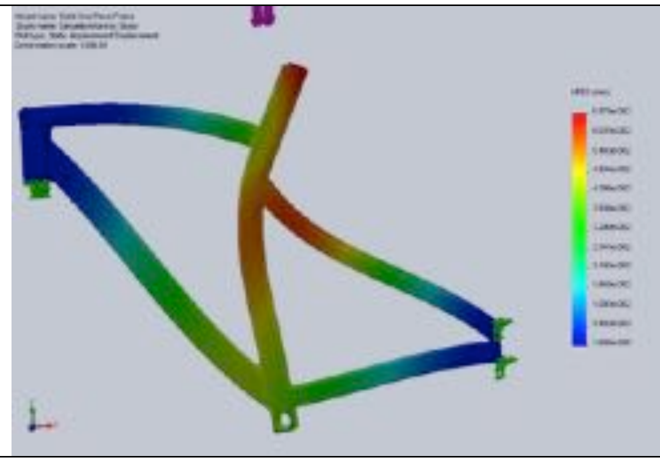

Figure 6.2 Bamboo maximum stress deformation

4.2.2 Aluminum Simulation Results with 250 lb (114 Kg) Load

The aluminum frames constructed out of 6061 aluminum alloy has a yield strength of 55.1 MN/m^2 and through the simulation express wizard on Solid Works produced a max stress at the same locations of the bamboo frame of 2.8 M N/m^2 as illustrated in Figure 13, and a max displacement of 0.016456 mm, which still is not a deformation that will cause any failure as shown in Figure 14. The factor of safety for the aluminum bicycle is 19.9 so the frame can withstand 19.9 times the 250 lb (114 Kg) load initially tested on the frame. The factor of safety is higher than that of bamboo frame.

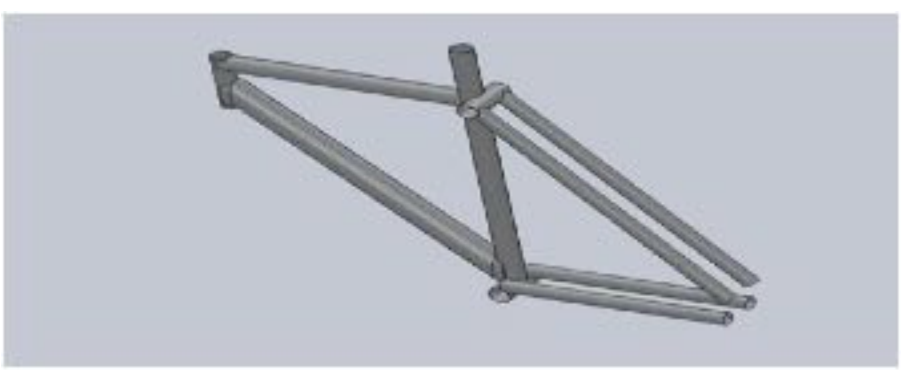

Figure 12: Aluminum frame design

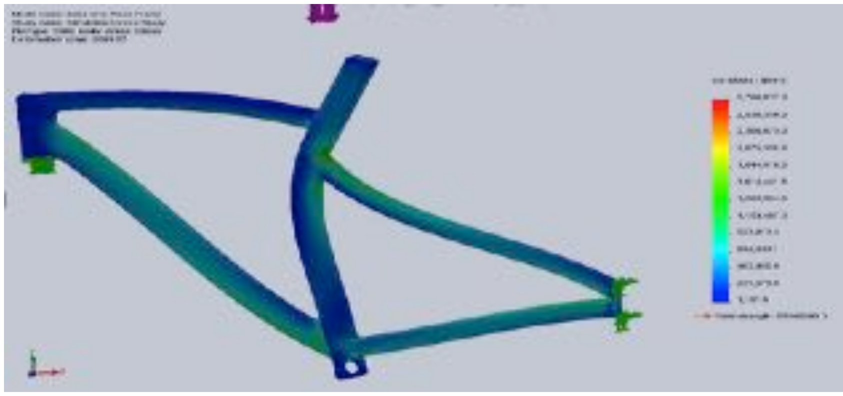

Figure 13: Aluminum maximum stress deformation

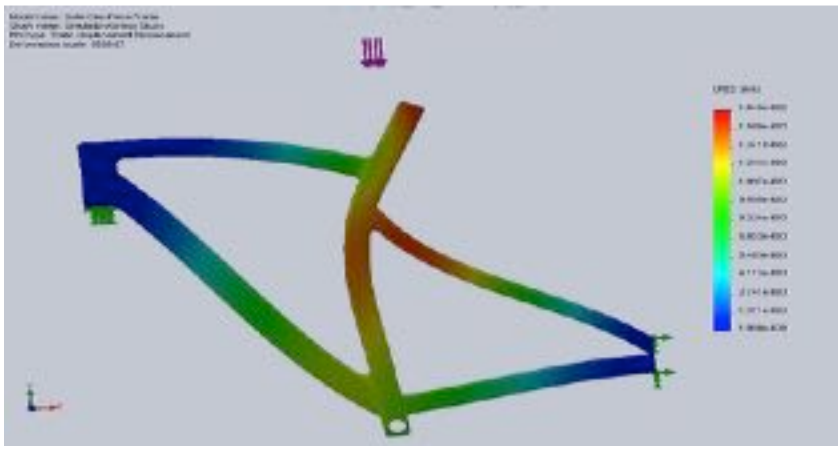

Figure 14: Aluminum maximum displacement

4.2.3 Carbon fiber Simulation Results with 250 lb (114 Kg)Load

The carbon fiber frame is similar to the bike frame constructed from aluminum alloy in that the max stress of 2.77 MN/m^2 is well below the yield strength of carbon fiber which is 800 MN/m^2 as shown in Figure 16. The maximum displacement is not a concern as well as it is only 0.01028 mm occurring at the same joints of the bamboo and aluminum frame, see Figure 17. The factor of safety for the carbon fiber bicycle is 248.9 so the frame can hold up 248.9 times the 250 (114 Kg) lb load placed on the seat tube.

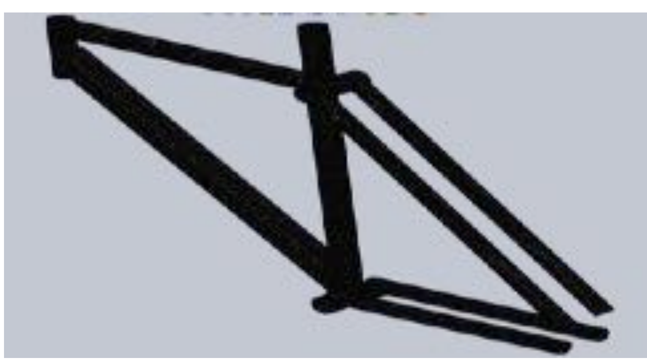

Figure 15: Carbon fiber design frame

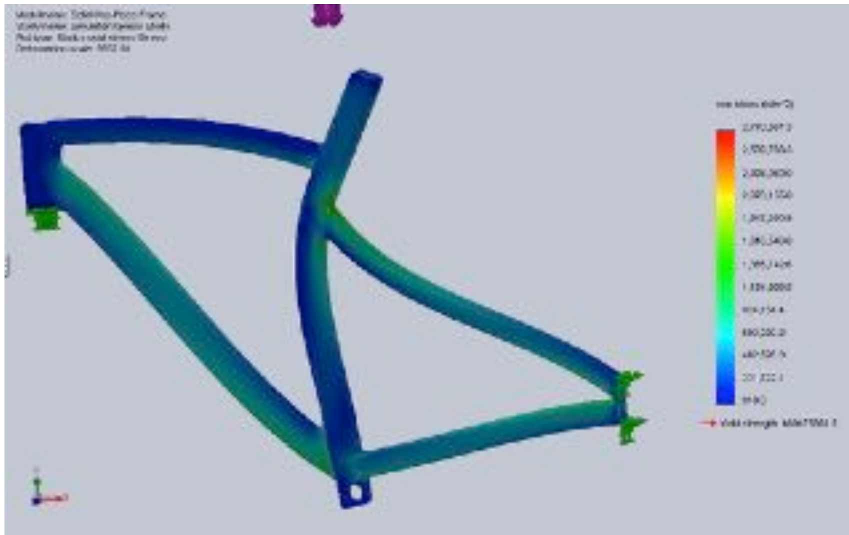

Figure 16: Carbon Fiber maximum stress deformation

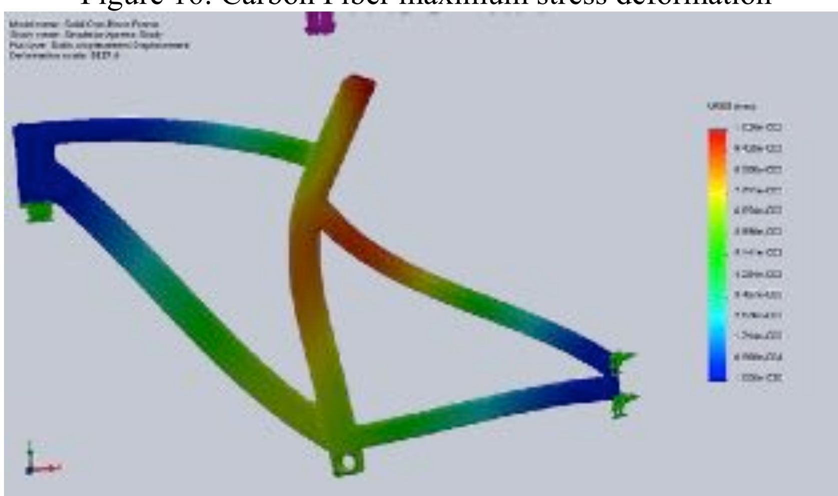

Figure 17: Carbon Fiber maximum displacement

V. RECOMMENDATION AND CONCLUSION

5.1 RECOMMENDATION

Since the assumption is that the production of the bicycle frame is in Kumasi, Ghana, the data indicates that it takes relatively lower embodied energy from cradle-to-death for the frame to be made from bamboo than aluminum and carbon fiber composite materials. The biggest portion of the embodied energy used to produce the three alternative designs is in the material phase. Aluminum requires the most amounts due to the extrusion and welding to produce the final product, followed by carbon fiber in second as it requires a lot of attention to successfully construct the frame. Bamboo material uses the least amount of energy emitted in the material phase because the adhesive is the only component affecting the final product. Also, the data indicates that the total CO_2 released into the atmosphere for the bamboo is almost half the amount compared to aluminum and carbon fiber. Therefore, the bamboo bicycle frame is the most sustainable and durable design to that of the aluminum and carbon fiber bicycle frames.

5.2 CONCLUSION

Designing and analyzing bamboo, aluminum, and carbon fiber bike frames using Solid Works and eco-audit tooling resulted in a thorough data stress analysis while also showing the carbon and energy footprint from raw materials, material production stage, product use, and disposal. Due to the difficulty of conducting engineering analysis of the different joints that the alternative bicycle frames using Solid Works, all the designs are assumed solid at the joints. Hence, the analysis is focused on materials.

It can be concluded from the FEA and Eco-Audit results and analysis that bamboo material being used as a bicycle frame will be more sustainable production than aluminum and carbon fiber composite in Kumasi, Ghana. All of the three alternative designs met the stress and displacement requirements so their sustainability comparison proves to be the next best criteria for deciding which materials and design to go with. The data presented in this document shows the facts on why bamboo is most sustainable as the total embodied energy and CO_2 emitted is significantly less than aluminum and carbon fiber bicycle frames. Combination of the CES EduPack software and the Solid Works software will be very valuable in designing both sustainable and robust engineering products. Designing and meeting the present needs to have a sustainable product while not compromising the future needs is a big issue and by considering sustainability at design stage, the planet, people, and profit can all progress to a better world.

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Biography

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