DESIGN OF A BICYCLE'S STRUCTURAL COMPONENTS AND A COMPARISON OF THEIR CHARACTERISTICS IN STEEL, ALUMINUM AND CARBON

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Resume

The design of a bicycle frame in Creo Parametric and the following simulation comparison of three frame materials - steel, aluminium and carbon, using the software from Marc Mentat, are the main subjects of this article. In this article, the authors explain how to model a bicycle frame in three dimensions and contrast it with frames made of the other two materials. The simulation's findings demonstrate how various elements, such as load, affect a steel, aluminium and carbon frame's behaviour in specific circumstances and under identical settings. Engineers may choose the best material and optimize the geometry and topology of the frame, based on the findings of the simulation, to get the best outcomes in terms of the stiffness requirements and rider comfort.

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1 Main objectives

The modern bike frame design is incredibly inventive and dynamic. For different types of bikes and riders, manufacturers are trying to develop the best and most efficient solutions. The design of the bicycle frame structure and the subsequent simulation to find out the best material to be used for the structure are the main topics of this study, Figure 1 [1-2].

2 Introduction

One of the most important components of a bike's design is the frame. The frame must be rigid and robust enough to support the rider's load and demands of the road while remaining light and comfortable enough to prevent riders' fatigue and enable a pleasurable ride. The frame must also be both aesthetically pleasing and ergonomic, as well [3].

A bicycle's frame is crucial to both its creation and operation. All the other components of the bike, including the forks, seat, wheels, brakes and derailleurs, are held and supported by the frame, [4].

In addition, the frame also determines the geometry and size of the bike, which affect its rideability and rider comfort. Depending on the type of a bike, different materials are used to make frames, such as steel, aluminium, carbon, titanium and more. Each material has its own properties that affect the weight, strength and price of the frames. The right frame can improve the bike's rideability and provide the rider with a comfortable ride. Therefore, it is important to consider the frame and its characteristics when choosing a bike and match it to the rider's needs and intended use, [5].

Bicycle frames can be made of different materials and in different designs, differing in the shape and geometry of the tubes and the way they are connected. The most common frame designs include:

- Classic diamond frame

The classic diamond frame is shaped like a diamond and is the most common frame construction for road, mountain and city bikes. The frame consists of an upper and lower frame beam, a centre frame and a rear frame.

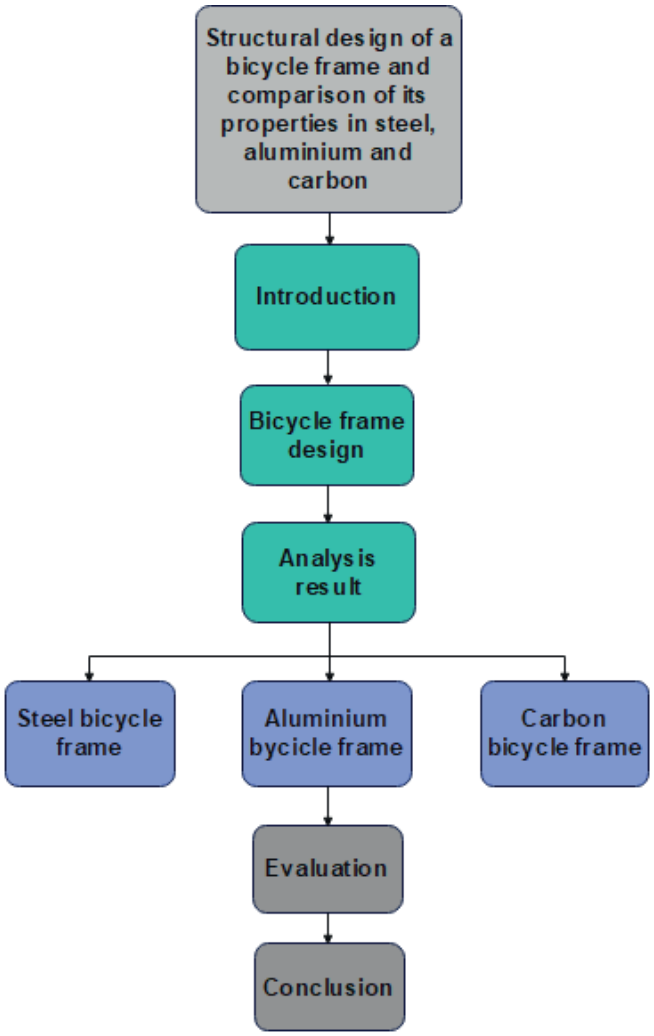

Figure 1 *Algorithm of the article*

This construction allows for an even distribution of the rider's weight and increases stability.

- Transitional frame

To make it simpler to hop on and off the bike, this sort of frame has a diamond shape with a noticeable transition at the front. These frames are frequently found on hybrid or urban bicycles.

- Frame with a sloping top

The top tube of this kind of bike frame slopes and it is rather stiff while riding. Most road bikes use it.

- Time trial period

This kind of frame features a noticeably longer top tube and a narrower angle between the frame and fork since it is intended for time-trial racing, [6-7].

There is currently a lot of focus on use of the new materials, such as super lightweight and extra strong polymers, which have the potential to improve the strength and weight of bicycle frames. In addition, frame manufacturing technology continues to improve, allowing the use of new tube forming and material joining technologies, [8].

The last but not the least, nowadays a lot of attention is also paid to sustainability and the environmental aspect of the production of bicycle frames, which strive to be made from recyclable materials and to minimize the negative impact on the environment, [9].

3 Bicycle frame design

Many conditions must be satisfied to generate a model of the bicycle frame structure. These prerequisites consist of:

1. Material knowledge - Understanding the materials that can be utilized to build a bicycle frame structure is crucial. The most widely utilized materials nowadays are carbon fibre, aluminium and steel.
2. Construction knowledge - Understanding how a bicycle frame is built is necessary when designing a frame. The head, down tube, top tube, seat tube and the rear triangle are just a few of the components that make up the frame. To create a proper model, one must be aware of the shapes and their interactions.

3. Using a CAD application - A suitable CAD program that supports the development of the 3D models is required to generate a model of the bicycle frame structure. The market is filled with CAD software, including Creo Parametric, SolidWorks, Autodesk Inventor and others.
4. Simulation - It is crucial to validate the model of the bicycle frame construction using simulation after it has been built. One can use simulation to make sure that the frame is sturdy and load-resistant enough. The design can be changed if necessary to better meet the specifications.
5. Fabrication - The frame itself needs to be constructed after the design has been confirmed and blueprints have been created. For fabrication, a variety of processes are employed, including welding, pressing and carbon fibre winding.

The successful development of a bicycle frame design model that will be suitably sturdy and load-resistant, depends on the fulfilment of these parameters, as a whole, [10-12].

For creation of the bicycle frame, there are the predetermined conditions for the shape of the individual parts of the bicycle frame:

- The head tube and the vertical tube must have a circular cross-section,
- The top tube shall have a rectangular cross-section,
- The bottom tube must have a square cross-section,
- The rear part of the frame, which consists of the two parts, must have a rectangular cross-section,
- The wall thickness of the parts in question must be 2 millimetres,

A bicycle frame is made up of several components that work together to make its overall structure (see Figure 2). The top tube (2) and bottom tube (3), which are joined on one side by a head tube (1) and on the other by a vertical tube, are the primary components of the bicycle frame (4).

The bicycle frame's primary components are the bottom tube (3) and the top tube (2). Both the upper tube and the lower tube connect the upper and lower portions of the back construction (5), respectively. The top tube often serves as the frame's foundation line and is angled slightly, which changes the geometry of the bicycle. The bottom tube is often stronger and serves as the framework for strengthening the entire frame.

To comply with the requirement that each tube has a wall thickness of 2 mm, the bottom tube of the proposed structure will be the same as the rest of the frame in our design. We next compared the similar frame design for three alternative materials. The portion of the frame that holds the back wheel in place is called the rear structure. Its primary job is to give the bicycle frame stiffness and stability. Although the rear frames are typically built of steel or aluminium, some high-performance versions may incorporate carbon rear structures. The component that joins the downtube is called the downtube. Its main function is to support the frame triangle and ensure the stability of the frame.

3.1 Steel frame

The individual parts of the bicycle steel frame are connected by welding. A welding method called TIG (Tungsten Inert Gas) welding, which is also known as GTAW (Gas Tungsten Arc Welding), is often used to weld the steel frame of a bicycle. The TIG welding is often the preferred welding method for the steel bicycle

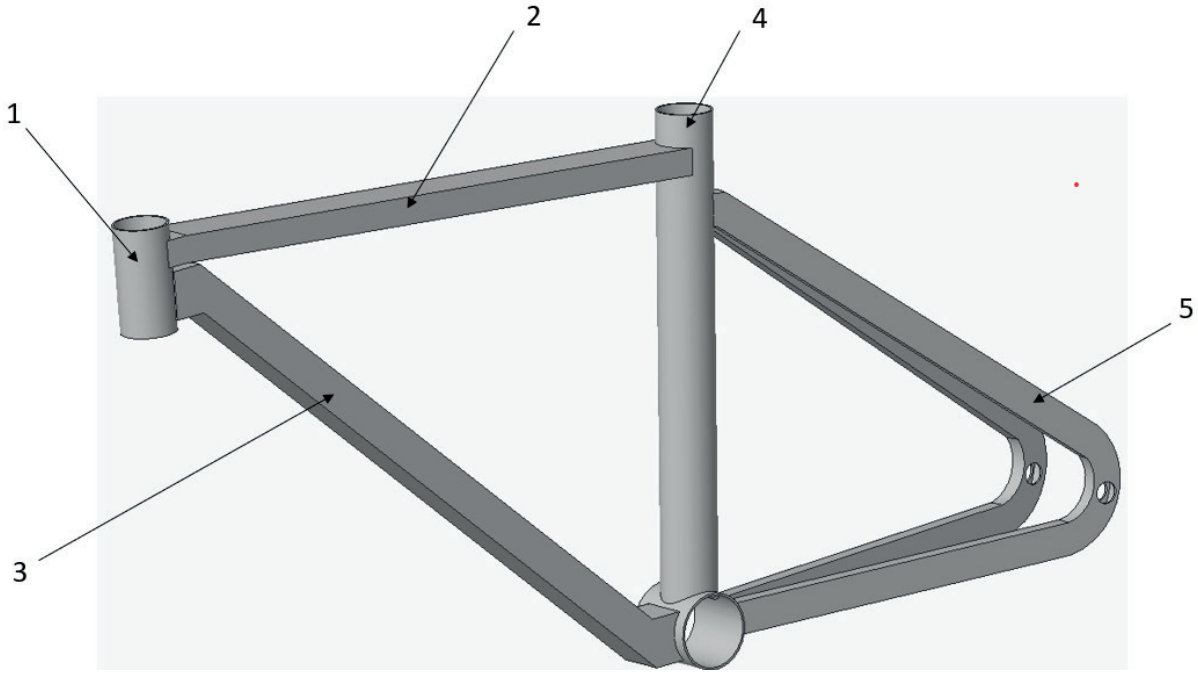

Figure 2 *Bicycle frame design in Creo parametric*

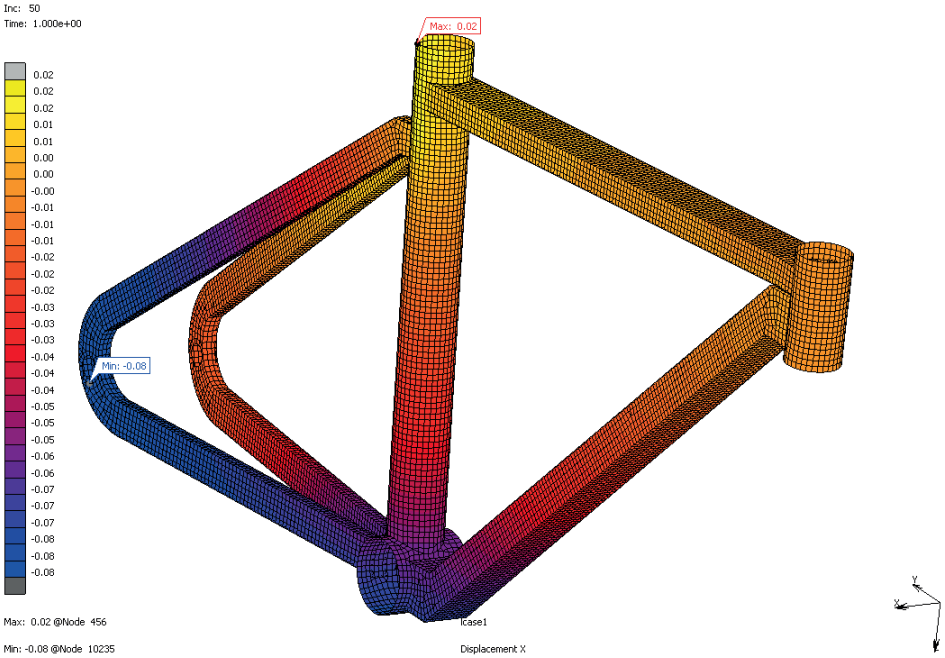

Figure 3 *Results of the displacement of the steel frame of the bicycle in the X-axis*

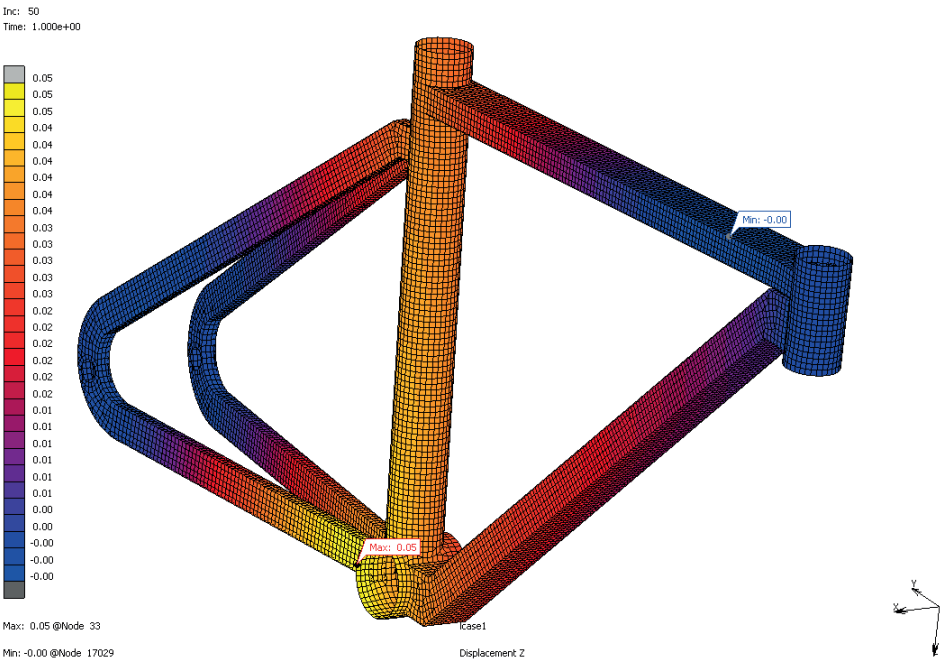

Figure 4 *Results of the displacement of the steel frame of the bicycle in the Z-axis*

frames because it provides higher welding quality and greater accuracy.

The TIG welding uses a special welding rod or wire that is made of a steel-like material. In the welding process, an electric arc heats the welding rod while a shielding gas (often argon) is used to protect the molten metal from reacting with the surrounding air.

The TIG welding allows thin and precise joints to be welded, which is ideal for steel bicycle frames. Steel is a strong and durable material and is therefore a popular material for bicycle frames, especially in the manufacture of the high-quality mountain and road bikes, [13].

3.2 Aluminium frame

Just as welding is used on a steel bicycle frame, welding is also used on an aluminium frame. A welding method called MIG (Metal Inert Gas) welding, which is also known as GMAW (Gas Metal Arc Welding), is often used to weld an aluminium bicycle frame. This welding method is widely used in the production of aluminium bicycle frames.

The MIG welding uses welding wire that contains the welding material and is inserted into the welding rods. This wire is fed with an electric arc, which melts the welding material and fuses it to the aluminium

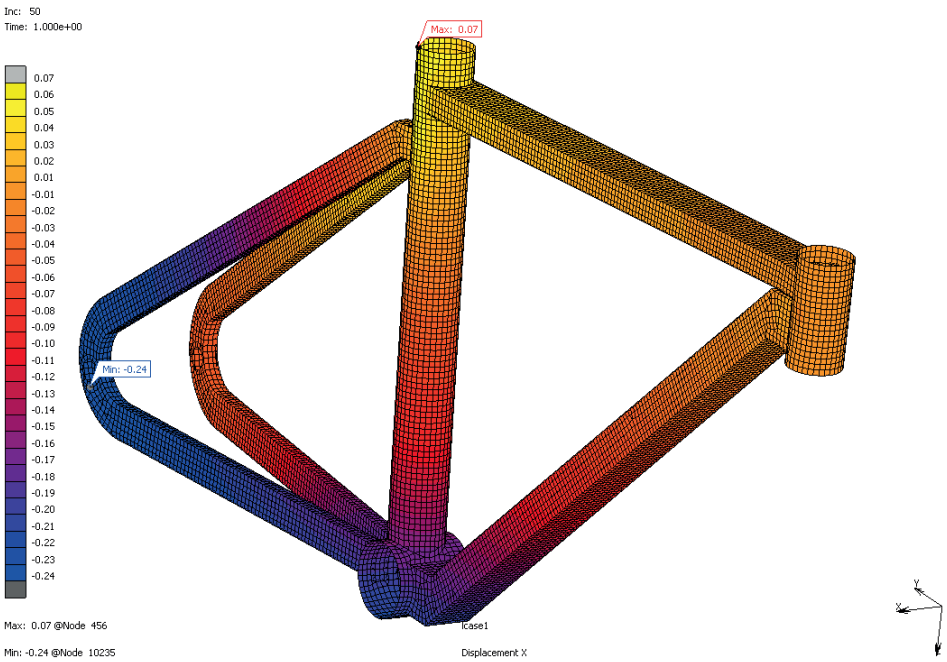

Figure 5 *Results of the displacement of the aluminium frame of the bicycle in the X-axis*

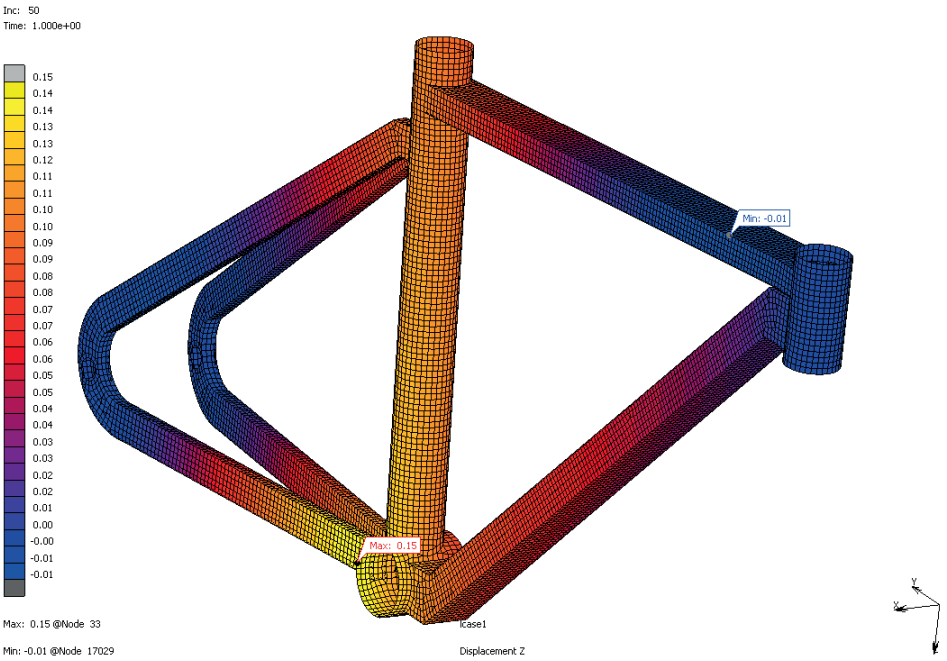

Figure 6 *Results of the displacement of the aluminium frame of the bicycle in the Z-axis*

of the frame. A shielding gas (often argon) is used to protect the molten metal.

Aluminium is a lightweight metal with high thermal conductivity and, therefore, higher currents and special techniques must be used to overcome heat dissipation when welding aluminium frames. The MIG welding is a suitable method for aluminium frames as it provides good joint strength and allows accurate welding.

In addition to the MIG welding, a welding method called TIG welding (GTAW) can also be used in production of the aluminium bicycle frames, which provides even higher welding quality and precision, [14].

3.3 Carbon frame

Manufacturing a carbon bike frame is a process that involves several steps. Here is the usual procedure for making a carbon bicycle frame:

1. Design and modelling: the manufacturing process starts with creation of a frame design in the CAD (Computer-Aided Design) software. Designers create a virtual model of the frame that includes the geometry and details of the design. (Frame design is the same as for steel and aluminium).
2. Mould making: Based on the virtual model, a mould

is created that will be used in the production of the carbon frame. This mould is often made of aluminium or other hard material and plays a key role in creating the shape of the frame.

3. Preparation of carbon plates: the layers of carbon plates are ready for insertion into the mould. These sheets are made of resin impregnated with carbon fibre. The sheets are cut and shaped to fit the mould and to maintain the required properties and lay-up.
4. Impregnation. This process can be carried out in different ways, such as manual impregnation or the use of vacuum and pressure.
5. Inserting into the mould: the impregnated carbon plates are inserted into the mould in the required layered structure. The shape and positioning of the sheets create the desired frame shapes and geometry.
6. Curing and heat treatment: The mould with the embedded carbon sheets is subjected to heat and pressure. The heat helps to cure the resin and form strong bonds between the fibres. The heat treatment can take place in special ovens or autoclaves that provide a controlled environment.
7. Demoulding and finishing: After curing, the frame is dismantled from the mould. This is followed by finishing, which includes removal of excess materials, sanding and any surface finishing, [11].

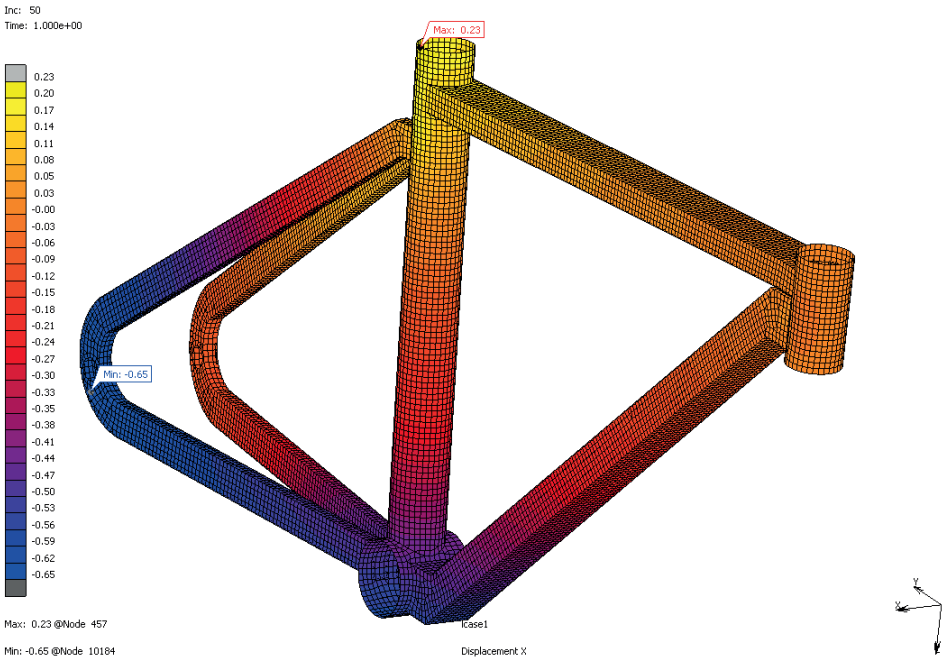

Figure 7 *Results of the displacement of the carbon frame of the bicycle in the X-axis*

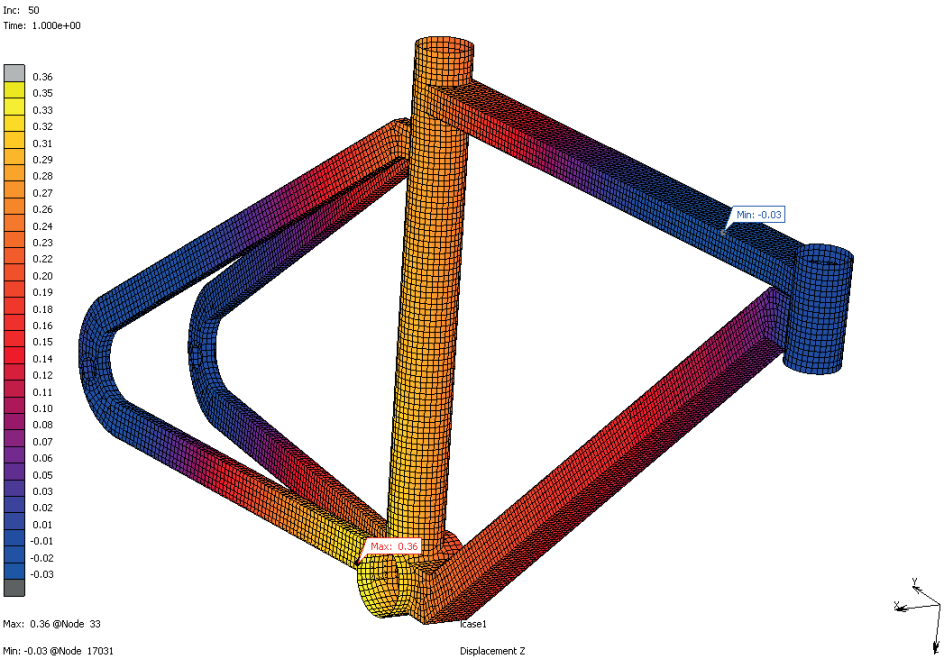

Figure 8 *Results of the displacement of the carbon frame of the bicycle in the Z-axis*

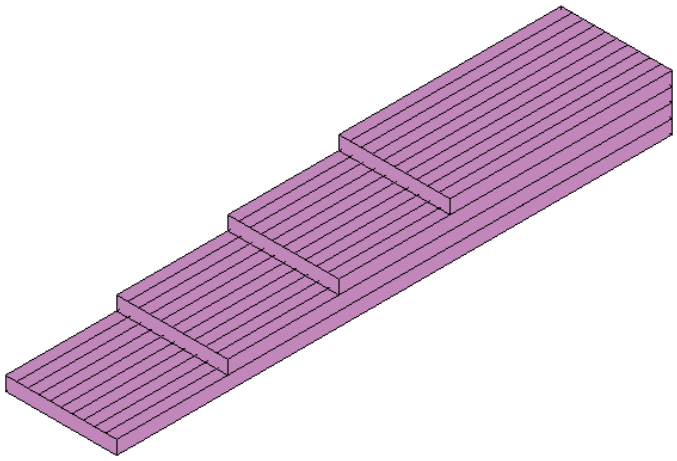

Figure 9 *Arranged layers of carbon fibre*

Table 1 *Displacement values of material frames*

	Steel frame	Aluminium frame	Carbon frame
Displacement X [mm]	0.02	0.07	0.23
Displacement Z [mm]	0.05	0.15	0.36

3.4 Fibre layers

The layers are each 0.5 mm thick. To achieve the 2-mm thickness requirement for the frame tubes, we must fasten four layers of the carbon fibre on top of one another. The illustration shows the layers to be horizontally aligned and at a 0° angle, which is known as overlap.

4 Result of analysis

In Table 1 one can see the values of the displacement results in the X and Z axis direction for each bicycle frame.

From Figures 3-9 one can see the values displacements for all the three-materials frame bicycle that are written in Table 1.

According to testing, the steel frame is more rigid than the aluminium and carbon frames. This indicates that the steel frame is flexible and has less X and Z axis movement. The bike's handling depends on X and Z axis shifts since they have an impact on the bike's stability and handling.

A carbon frame, on the other hand, is less expensive than other frames. A carbon frame will therefore have more X and Z axis shifts, which may compromise its handling and stability. A carbon frame does, however, have some benefits. Compared to a steel frame, it is significantly lighter and more corrosion resistant. This indicates that a carbon frame will last longer and be more durable. At the bottom of tube 4 in Figure 2, a force of 1.5 kN is applied and at an angle of 7° as a foot sweep on the bicycle pedal.

A steel frame bicycle is a particular kind of bicycle with a frame predominantly made of steel tubing. Steel has long been a favourite material for bicycle frames because of its strength, longevity and smooth riding.

The following are some salient features and benefits of bicycles with steel frames.

Steel is a solid material for bicycle frames because of its high strength-to-weight ratio and reputation for strength. Steel frames are appropriate for touring, commuting and off-road cycling because they can resist challenging riding conditions, high loads and challenging terrain, [15].

Undoubtedly, aluminium is the most popular material for bicycle frames. It can be found on a variety of bicycles. Not to mention that it offers a very nice weight/stiffness ratio and a fair price/performance ratio.

Currently, it is primarily utilized on less expensive bikes. Since aluminium is less rigid than steel, it requires thicker walls and greater diameter. Despite having relatively thicker tubes, aluminium frames are nonetheless lighter than the steel frames. Yet, there are disadvantages of using aluminium for bicycle frames. The material does not dampen vibrations as effectively as other materials. Aluminium can also break over time and is significantly less robust owing to material fatigue.

Do not have to worry, it takes many years and some hard driving to fatigue the material and a strong impact to break it, [15].

The majority of more expensive and professional frames are made with this material. Carbon sheets are bonded together to create carbon frames using an adhesive substance like resin. Because of this, carbon fibre frames are utilized in the most serious contests, including:

- Tour de France,
- UCI downhill world cup,
- World enduro series (EWS).

Carbon has the added benefit of making such bikes look considerably nicer. Shapes that are generally impractical with other materials can be made by designers. Because of this, designers can use their imagination to produce not unique designs but the stiffer frames, as well.

On a carbon frame, there are also no welds, leaving all the lines incredibly sleek, [15].

5 Conclusions

The structural design of the bicycle frame, by the established criteria, is developed in this paper. The shape of a bicycle frame is extremely challenging in terms of structural design, which requires attention to several details during the construction or modelling. The frame design is crucial to the rest of the bicycle manufacturing process, as it will determine how the final product will function as a whole. For the bike to be enjoyable and efficient to ride, its design and dimensions should be tailored to riders and their preferences. The last but not the least, the frame should be visually appealing and have an intriguing design to catch the rider's eye. Creo Parametric was used to develop the structure of this bicycle frame according to the best practise described in [16-18].

The design of a bicycle frame can be effectively simulated using the simulation software. A particular bicycle frame served as the basis for simulation. Comparisons were made between the outcomes of a specific construction made of three distinct materials. In more detail, it is a frame with steel, aluminium and carbon fibre reinforcements. We applied the same boundary conditions and force to the bicycle frame for each of these models according to the methods described in [19-21]. We examined these bicycle constructions using simulation software developed by Marc.

Overall, in this paper is shown that the correct choice of material, for a given design and simulation, can lead to a significant improvement in the performance of a bicycle frame and provide the rider with a more comfortable and efficient ride.

Currently, experts are trying to create a carbon frame and get to the parameters of a steel frame using the topological optimization.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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