Universidad del País Vasco / Euskal Herriko Unibertsitatea

VITORIA-GASTEIZKO INGENIARITZA ESKOLA
ESCUELA DE INGENIERÍA DE VITORIA-GASTEIZ

DEGREE IN MECHANICAL ENGINEERING

FINAL DEGREE PROJECT

DESIGN, ANALYSIS AND COMPARISON OF DIFFERENT BICYCLE FRAME MODELS

Student: Martínez de Zuazo Martínez, Alberto

Director: García Marina, Vanessa

Year: 2021-2022

Date: 18, 07, 2022

Abstract

This project will detail the process and research work required to complete the bachelor thesis necessary to finish a mechanical engineering degree. Multiple abilities obtained during the duration of the degree have been employed and expanded on for its completion.

The project has been completed as an individual project with the assistance of a tutor from the faculty body.

It will delve on the structure of conventional bikes, the modelling of frames with the help of CAD programs and follow with the fatigue simulation of those said frames.

Its main intent is that of showcasing the practical and analytical abilities developed on the mechanical engineering degree.

Acknowledgements

This project, which culminates five years of hard work, would not have been possible without the support and patience of my family and friends. I want to thank them for helping me without condition.

I also feel obliged to thank the always involved teaching and support staff of the degree. Their attention and effort has been fundamental in developing my interest for learning. I specially want to thank and recognize my capstone project tutor, Vanessa Garcia Marina, for her constant support. She has patiently given me all the clarifications and guidance that I have required over the course of the project.

Finally, I want to show gratitude to all my classmates. Teamwork and the sharing of information has helped us all progress on the degree.

Index

ABSTRACT **2**

ACKNOWLEDGEMENTS **2**

INDEX **2**

FIGURE INDEX **4**

TABLE INDEX **6**

1. THEME SELECTION PROCESS **7**

2. SCOPE **7**

2.2. OBJECTIVES 7

2.2.1. Main objective *7*

2.2.2. Additional objectives *8*

3. PROJECT MANAGEMENT **8**

3.1. MANAGEMENT OF PREDICTED AND ENCOUNTERED PROBLEMS 8

3.2. PROJECT SCHEDULE 9

3.2.1. Gantt diagram ... 9
3.3. Material requirements ... 12
3.4. Budget estimation ... 12

4. CONTEXT ... 13

4.1. Antecedents ... 13
4.2. State of art ... 13
4.2.1. Bicycles ... 13
4.2.2. Fatigue ... 14
4.2.3. Finite element analysis ... 16

5. ANALYSIS PROCESS ... 18

5.1. Standardized bicycle measures and components ... 18
5.1.1. Fork ... 19
5.1.2. Wheels ... 19
5.1.3. Hub ... 20
5.1.4. Saddle and Shank ... 21
5.1.5. Cranks and pedals ... 21
5.2. Model design and creation ... 22
5.2.1. Base design ... 22
5.2.2. Design 1 ... 26
5.2.3. Design 2 ... 28
5.2.4. Design 3 ... 30
5.3. UNE EN-ISO 4210 ... 31
5.3.1. Fatigue test for horizontal loads ... 32
5.3.2. Fatigue test for vertical loads ... 33
5.3.3. Fatigue pedalling test ... 35
5.4. Elements used on the assemblies for each test ... 36
5.4.1. Fork ... 36
5.4.2. Rolling-pin ... 38
5.4.3. Fixed support ... 38
5.4.4. Seat and shaft ... 39
5.4.5. Pedals ... 40
5.4.6. Brace ... 41
5.4.7. Vertical and ball joints ... 41
5.4.8. Rigid assembly ... 42
5.4.9. Assembly of components ... 43
5.5. Finite element analysis program ... 44
5.5.1. Geometry ... 45
5.5.2. Material ... 45
5.5.3. Connections ... 45
5.5.4. Mesh ... 46
5.5.5. Boundary conditions ... 48
5.5.6. Fatigue and stress tools ... 49
5.5.7. Mean stress theory ... 51
5.6. Frame comparison ... 52
5.6.1. Initial comparison stage ... 53
5.6.1.1. Frame design 1 ... 53
5.6.1.2. Frame design 2 ... 56
5.6.1.3. Frame design 3 ... 57
5.6.1.4. Base frame design: ... 59
5.6.1.5. Result analysis ... 60

5.6.2. Second comparison stage 60
5.6.2.1. Closed hitches 61
5.6.2.2. Round of edges 64
5.6.2.3. Remake hitch geometry 66
5.6.2.4. Increase hitch diameter without redesigning it 67
5.6.2.5. Result analysis 68
5.6.3. Third comparison stage 68
5.6.3.1. Section change of front and central tubes 68
5.6.3.2. Section change of stay tubes 70
5.7. FINAL DESIGN 72
5.7.1 Suitability for mountain bicycles 72

6. FINAL BUDGET 75

7. CONCLUSIONS 75

8. BIBLIOGRAPHY 77

Figure index

Figure 1 Tasks of Gantt diagram – Source: Personal elaboration 10
Figure 2 Gantt diagram – Source: Personal elaboration 11
Figure 3 S-N curve diagram – Source: Callister, W. D., & Rethwisch, D. G. (2013, December 4). Maximum stress (S) versus logarithm of the number of cycles to fatigue failure (N) for seven metal alloys. Curves were generated using rotating–bending and reversed-cycle tests. [Graph]. Materials Science and Engineering: An Introduction 9th Edition. Wiley 15
Figure 4 Example of a meshed solid – Source: Personal elaboration 17
Figure 5 Common mesh element shapes – Source: SimuTech Group. (n.d.). Common Types of Mesh [Graph]. Why Is Ansys Meshing Important for Structural FEA and Fluid CFD Simulations? https://simutechgroup.com/why-is-meshing-important-for-fea-fluid-simulations/ 17
Figure 6 Unusual bicycle concepts – Source: Delcambre, J. (2015, April 8). My first job, Scott Sports [Illustration]. Scott Concept Bikes by Julien Delcambre. https://bicycledesign.net/2015/08/scott-concept-bikes-by-julien-delcambre/ 18
Figure 7 Measure nomenclature – Source: [Bicycle frame tube names]. (2013, October 4). Understanding Bicycle Frame Geometry. https://www.cyclingabout.com/understanding-bicycle-frame-geometry/ 18
Figure 8 Road bike measurement chart – Source: [Frame chart size]. (2020, November 21). ¿CÓMO ES LA GEOMETRÍA DE UNA BICICLETA? https://oxiacycles.com/geometria-de-una-bicicleta/ 19
Figure 9 Comparison of different wheel nomenclatures – Source: Moebiusuibeom-en. (2010, September 28). Bicycle Tyre Information [Illustration]. File:Tyre and Rim Technical Data 01-En.Png. https://commons.wikimedia.org/wiki/File:Tyre_and_Rim_Technical_data_01-en.png 20
Figure 10 Base design structure and tube names – Source: Personal elaboration. 23
Figure 11 Hitch profile – Source: Personal elaboration 24
Figure 12 General coordinates – Source: Personal elaboration 24
Figure 13 Base design measures – Source: Personal elaboration 25
Figure 14 Base design wheel space – Source: Personal elaboration 25
Figure 15 Design 1 structure –Source: Personal elaboration 26
Figure 16 Design 1 measures – Source: Personal elaboration 27
Figure 17 Design 1 wheel space – Source: Personal elaboration 27
Figure 18 Design 2 structure – Source: Personal elaboration 28
Figure 19 Design 2 measures – Source: Personal elaboration 29
Figure 20 Design 2 wheel space – Source: Personal elaboration 29
Figure 21 Design 3 structure – Source: Personal elaboration 30
Figure 22 Design 3 measures – Source: Personal elaboration 31

Figure 23 Design 3 wheel space – Source: Personal elaboration 31
Figure 24 Horizontal test diagram – Source: Adapted from AENOR. (2015a, January). Cuadro. Ensayo de fatiga por fuerzas horizontales [Illustration]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf....................................32
Figure 25 Vertical test diagram – Source: Adapted from AENOR. (2015a, January). Cuadro. Ensayo de fatiga con una fuerza vertical [Illustration]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf....................................34
Figure 26 Pedalling test diagram – Source: Adapted from AENOR. (2015a, January). Cuadro. Ensayo de fatiga con fuerzas de pedaleo [Illustration]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf....................................35
Figure 27 Initial hitch measures – Sources: Personal elaboration 37
Figure 28 Simplified hitch measures – Source: Personal elaboration...38
Figure 29 Rolling pin measures – Source: Personal elaboration 38
Figure 30 Fixed support measures – Source: Personal elaboration..39
Figure 31 Seat and shaft measures for design 1 – Source: Personal elaboration.................................39
Figure 32 General seat and shaft measures – Source: Personal elaboration 40
Figure 33 Pedal measures – Source: Personal elaboration 40
Figure 34 General brace measures – Source: Personal elaboration 41
Figure 35 Measures of brace for design 1 – Source: Personal elaboration..41
Figure 36 Measures of vertical and ball joints – Source: Personal elaboration....................................42
Figure 37 Rigid assembly measures – Source: Personal elaboration 42
Figure 38 Assembly of design 2 for horizontal test – Source: Personal elaboration 43
Figure 39 Assembly of design 3 for vertical test – Source: Personal elaboration.................................43
Figure 40 Assembly of design 1 for pedalling test – Source: Personal elaboration 44
Figure 41 Example of frictional contact locations – Source: Personal elaboration 46
Figure 42 Meshed assembly example – Source: Personal elaboration...47
Figure 43 Remote constraint application coordinate – Source: Personal elaboration 49
Figure 44 Fully reversed load – Source: Personal elaboration as depicted in ANSYS data 50
Figure 45 Zero-based load – Source: Personal elaboration as depicted in ANSYS data..........................50
Figure 46 Equivalent stress analysis – Source: Personal elaboration 51
Figure 47 S-N curve diagram example – Source: N. (2016, January 27). S-N curve for a brittle aluminium with a ultimate tensile strength of 320 MPa. [Diagram]. Wikipedia. https://es.m.wikipedia.org/wiki/Archivo:BrittleAluminium320MPa_S-N_Curve.svg 51
Figure 48 Fatigue limit diagram – Source: Yapparina. (2013, June 30). Fatigue limit diagram(Goodman line et al.) [Graph]. File:Fatigue Limit Diagram.Png. https://commons.wikimedia.org/wiki/File:Fatigue_limit_diagram.png...52
Figure 49 Gerber theory as depicted by ANSYS – Source: Personal elaboration from ANSYS data...........52
Figure 50 Top tube damage of design 1 – Source: Personal elaboration..54
Figure 51 Hitch damage of design 1 – Source: Personal elaboration 54
Figure 52 Seat stay tube damage of design 1 – Source: Personal elaboration......................................55
Figure 53 Reduced hitch damage on bonded tests – Source: Personal elaboration 57
Figure 54 Central tube damage on design 3 – Source: Personal elaboration 57
Figure 55 Crank and central tube damage of design 3 – Source: Personal elaboration 58
Figure 56 Closed hitch profile – Source: Personal elaboration 61
Figure 57 Asymmetric response on the hitches – Source: Personal elaboration 61
Figure 58 Head tube damage on closed hitch design – Source: Personal elaboration 63
Figure 59 Reaction of central tube of design 3 with closed hitches – Source: Personal elaboration 63
Figure 60 Closed hitch profile with rounding of edges – Source: Personal elaboration 64
Figure 61 Example of rounded tube connections – Source: Personal elaboration.................................64
Figure 62 Redesigned hitch profile and front views – Source: Personal elaboration 66
Figure 63 Redesigned hitch reaction – Source: Personal elaboration 66
Figure 64 Change in redesigned hitch reaction after size increase – Source: Personal elaboration 67

Figure 65 Measures of redesigned top tube – Source: Personal elaboration 69
Figure 66 Measures of redesigned central tube – Source: Personal elaboration....... 69
Figure 67 Measures of the redesigned stay tubes – Source: Personal elaboration....... 70
Figure 68 Crank damage on frame design with redesigned stay tubes – Source: Personal elaboration ... 71
Figure 69 Localized failling point on the central tube (seen from below) – Source: Personal elaboration 73
Figure 70 Damaged central and top tubes (seen from above) – Source: Personal elaboration....... 73
Figure 71 Affected area on the central tube (seen from below) when applying 600N – Source: Personal elaboration....... 73
Figure 72 Crank tube results when both loads act at the same time – Source: Personal elaboration 74

Table index

Table 1 List of predicted problems – Source: Personal elaboration 8
Table 2 Budget estimation – Source: Personal elaboration 12
Table 3 Base design tube size – Source: Personal elaboration....... 23
Table 4 Design 1 tube size – Source: Personal elaboration....... 26
Table 5 Design 2 tube size – Source: Personal elaboration....... 28
Table 6 Design 3 tube size – Source: Personal elaboration....... 30
Table 7 Horizontal test values – Source: Adapted from AENOR. (2015a, January). Fuerzas y ciclos en las punteras de la horquilla delantera [Table]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf....... 32
Table 8 Vertical test values – Source: Adapted from AENOR. (2015a, January). Fuerzas sobre la tija del sillín [Table]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf....... 34
Table 9 Pedalling test values – Source: Adapted from AENOR. (2015a, January). Fuerzas en el eje del pedal [Table]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf....... 35
Table 10 Material properties – Source: Personal elaboration from ANSYS material data....... 45
Table 11 Mesh size for test 1 (horizontal) – Source: Personal elaboration....... 47
Table 12 Mesh size for test 2 (vertical) – Source: Personal elaboration....... 48
Table 13 Mesh size for test 3 (pedalling) – Source: Personal elaboration 48
Table 14 Depiction of final budget – Source: Personal elaboration 75

1. Theme selection process

One of the first decisions pertaining this capstone project was that of centring it on the use of FEA (Finite Element Analysis) technology.

The bicycle frame regulation is well documented and requires new designs to pass certain fatigue tests. The requirement of using FEA to analyse fatigue was the first factor to attract attention towards this subject. The creation of the models requires the use of CAD (Computer-Aided Design), another technology worth adding to the project.

Eventually, it was selected due to the high customization options. For most market models, a very similar design is used even among different manufacturers despite the wide range of possibilities. Finding the reason for this was deemed worth researching. It was decided to place the focus on comparing the common components with others less employed, in order to find if its use is justified.

2. Scope

2.1. Introduction

The main objective of the project will be the exhaustive analysis of four bicycle frame designs. The intention is to compare the performance between the different components and geometries defined. Different shape, size and material changes will be attempted to improve the results. From all the versions examined, a final selection will be done in order to obtain the most durable and efficient model.

The initial stage will involve the creation of 3D frame models with the use of the CAD program, Siemens NX 12. A research on the market standards has been conducted in favour of maintaining coherent proportions. This will also ensure the capacity of utilizing market components and denominations.

The adequacy level will be dictated by the resistance to fatigue that each model shows. The tolerable range will be established by the UNE-EN-ISO 4210 standard for bicycle frame safety requirements. The Ansys finite element analysis tool has been used to complete the necessary calculations.

2.2. Objectives

2.2.1. Main objective

The intention of the capstone project presented here, is that of the comparison of multiple bicycle frames. Different structures will be analysed in order to note the advantages and disadvantages of each one. To perform this, fatigue tests will be made with the help of finite element analyses (FEA). The requirements for these fatigue analyses is mandated and regulated by the UNE-EN-ISO 4210 standard for bicycle safety.

2.2.2. Additional objectives

From the data obtained, an ideal frame will be selected from the ones tested by gradually incorporating the best variations. The final goal is for this frame to be capable of withstanding the minimum life cycles required by the three tests of the standard.

The correct application and expansion of skills obtained during the duration of the degree will be required. One of these abilities, will be the modelling of 3D bodies on computer-aided design programs. The interpretation of simulation results is also tested.

3. Project management

3.1. Management of predicted and encountered problems

For the duration of a project of any nature, a set of risks or setbacks are bound to happen. A previous assessment of the possible problems may help reduce their effects and possibly avoid them altogether, it may also reduce the reaction time.

-Predicted problems:

Table 1 List of predicted problems – Source: Personal elaboration

Numeration	Description of the problem	Probability of occurrence/ impact	Solution and precautions
1	Inadequacy of the FEA or CAD programs.	Medium/high	Previous research on the capacities of the program. If a setback can´t be circumvented, evaluate the option of replacing the program.
2	Lack of knowledge pertaining program usage.	High/medium	Seek assistance from customer service. If not possible, opt for unofficial sources like forums.
3	Physical discomfort or injury.	Medium/low	Keep a healthy work schedule and conditions. Maintain tidiness on the working area.
4	Loss of data.	Low/high	Create and maintain frequent security copies.
5	Lack of necessary information at different stages.	Low/medium	Initial gathering of information. If it is not possible to locate mandatory data, consider the approximation or substitution of the test.

-Encountered problems:

1) Inadequacy of the FEA or CAD programs = The program with which the project was initiated was named MSC APEX student. The latter decision of carrying out fatigue tests made its use impossible because of the fatigue module being restricted for the student version. The possibility of replacing its use for static loads with a dynamic factor was discussed but ultimately discarded. ANSYS student was acquired and used alternatively.

2) Difficulty of finding S-N information for materials = An attempt has been made to perform a comparison between different materials. For this, it is compulsory to tabulate the S-N curve data of each studied material into the material gallery of Ansys. Due to the impossibility of finding reliable curve data, the idea of comparing different materials has been discarded. All the tests have been made with the same aluminium alloy.

3) Lack of knowledge pertaining program usage = ANSYS does not provide assistance for users of the student version. The required knowledge was obtained from the official user forums.

3.2. Project schedule

The project was initiated on the 1st of February, starting with the selection of the theme. Its completion took five months, spanning from February to July and finishing on the 18th of July. With an average of 3 hours of work each day, the total number of hours until finalization amounts to 400.

Most of the bulk of the duration is dedicated to the redaction of the final document. It was initiated before finishing the simulation and analysis stage, both taking place simultaneously. The most time consuming activity was the learning of Ansys and subsequent completion of the initial simulations, being necessary to commit two months to its execution.

3.2.1. Gantt diagram

The Gantt diagram of the project is as shown on figure 1.

	Nombre de tarea	Duración	Comienzo	Fin	Predecesoras
1	**Initial stage**		**01/02/22**		
2	Theme selection	10 días	01/02/22	10/02/22	
3	Scope and objective decision	6 días	11/02/22	16/02/22	2
4	Requirement analysis	6 días	17/02/22	22/02/22	3
5	**Second stage**				
6	Initial frame concept creation	5 días	23/02/22	27/02/22	4
7	Component measure research	10 días	28/02/22	09/03/22	6
8	Creation of first 2D frame models	4 días	10/03/22	13/03/22	7
9	Creation of 3D frame models	15 días	14/03/22	28/03/22	8
10	Research on NX 12 applications	17 días	14/03/22	30/03/22	8
11	Creation of 3D support models	5 días	29/03/22	02/04/22	9
12	**Third stage**				
13	Research on fatigue tests	20 días	03/04/22	22/04/22	11
14	Research on ANSYS use	10 días	23/04/22	02/05/22	13
15	Initial fatigue tests	30 días	03/05/22	01/06/22	14
16	Additional fatigue tests	20 días	02/06/22	21/06/22	15
17	**Fourth stage**				
18	Redaction	107 días	03/04/22	18/07/22	11

Figure 1 Tasks of Gantt diagram – Source: Personal elaboration

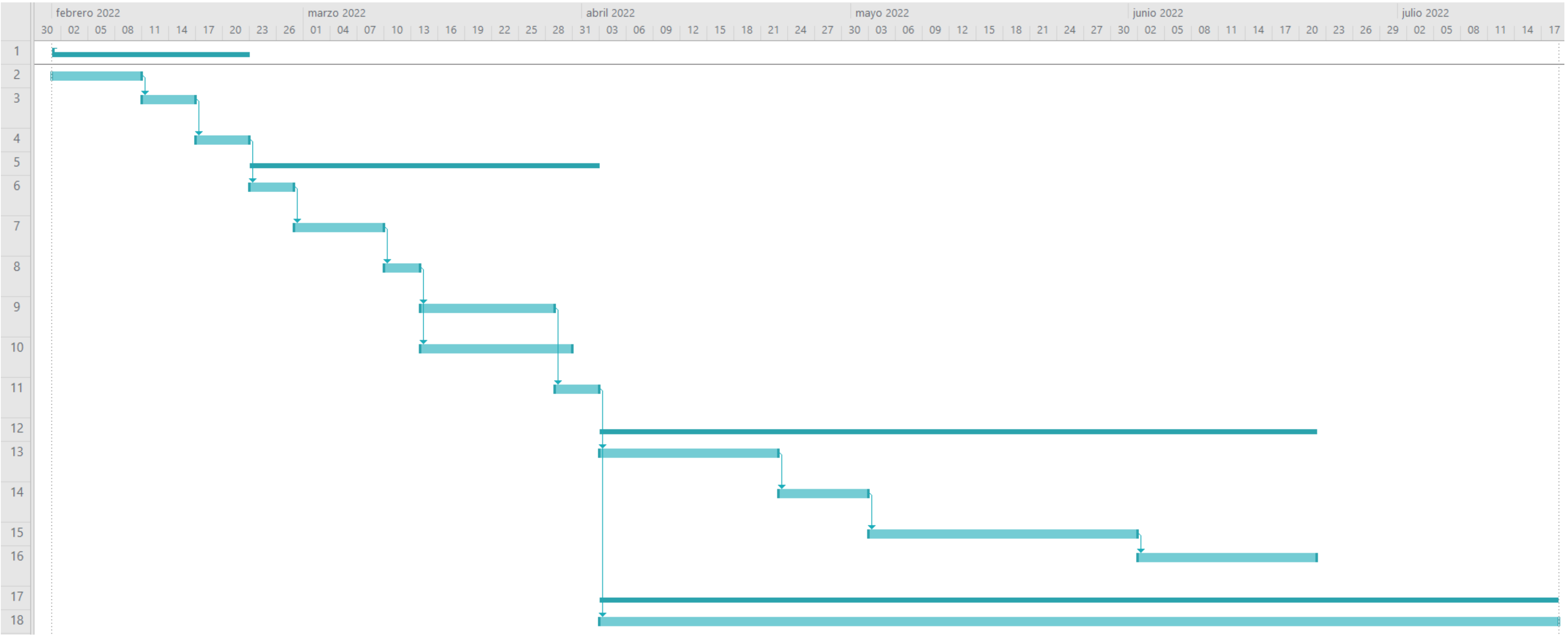


Figure 2 Gantt diagram – Source: Personal elaboration

3.3. Material requirements

Siemens NX 12

NX is the CAD program utilized for the creation and assembly of all the models.

As a tool, NX has all the capacities necessary for the development of engineering products. It can be used for design, simulation and production. It is one of the most employed programs of the industry and its popularity is rapidly increasing. [1]

Ansys student 2022 R1

Ansys provides a free version of their software for educational purposes. Among the services included, Ansys Mechanical is the one employed for this capstone project. Ansys student includes a set of products consisting of Ansys mechanical, Ansys CFD, Ansys Autodyn, Ansys SpaceClaim and Ansys DesignXplorer. Each of them is destined to a different application. As previously mentioned, Ansys mechanical is the one employed here, more specifically the “static structural" module. Static structural has the capability of performing linear and nonlinear geometric calculations. [2]

Ansys Mechanical is a well-known FEA software. It gives the possibility of performing structural, thermal and acoustic model analyses among others. [2]

3.4. Budget estimation

Table 2 Budget estimation – Source: Personal elaboration

Resources	Siemens NX 12 annual license	Ansys mechanical perpetual license	General costs (electricity, paper, etc.)	Mechanical engineer (work and training) $(21.4\ \frac{€}{hour})$	Computer	UNE standard	Total
Cost (€)	5,900	22,000	40	8,560	1,000	66	37,566

An approximation of 400 hours of work over the second semester of the 4^{th} year has been made. It amounts to a media of 3 hours per day.

The cost predictions have been obtained from online resources. [3][4][5][6][7]

4. Context

4.1. Antecedents

As stated before, the adequacy of the tests is decided by the use of the Spanish UNE-EN-ISO 4210-6 standard, which is based on the international ISO 4210-6. Due to this necessity, it can be expected that every developed model will be required to repeat the same tests performed here with the adequate alterations in hopes of it being commercialized.

Finite element technology is ingrained in the sector of bicycle confection. Not only is its use necessary to prove the quality of new components but also aids on the testing of new ideas. From this dependency its use has extended far and wide across the different manufacturers.

Its use makes it possible to find interrelations between parameters like center distance and frame rigidity, by performing subsequent analyses on a series of frames without the need of manufacturing them. The application of this method to historical frame catalogues can lead to the identification of the ideal measures of components; for example: seat height or crank length for comfort. Comparisons with optimized models can also lead to pinpoint critical deficiencies of models [8]. The improvement rate of bicycles has increased exponentially since its implementation.

FEA analyses can be as detailed as desired with the options ranging from the simplest 2D model, where each tube is a single element and nodes act as joints; to exhaustive 3D solids where the influence of all components and the rider are taken into consideration. [9]

4.2. State of art

4.2.1. Bicycles

For a long time, the search for man powered vehicles was an endeavour for many intellectuals. One of the first attempts was the so called “velocipede”. It presented a slender two wheeled vehicle balanced by the rider. The main difference being the absence of pedals, it required the user to push on the floor with their feet. Although initially gaining a semblance of interest, it soon faded into obscurity due to its flagrant inconveniences when looking at comfort. [10]

A latter attempt was made on Paris during the 1860s. While sharing a lot of common elements, it included a crank for easy pedalling. It soon gained renown and started being commercialized. For many years it remained only accessible to wealthy young men for leisure. As time progressed it opened to new markets as the prices cheapened. Later it became a popular and cheap way of transportation for workers, in addition to an entertaining way of avoiding sedentarism. It is also being advocated as a green alternative to the overused combustion cars for urban transportation. [10]

The technology has gone through plenty of alterations through the almost two centuries since its creation. The first models where made of solid iron but over the time more advanced materials have replaced it, aluminium alloys or later titanium are good examples. Carbon fibre frames are also popular despite the danger of failure due to micro stresses detaching the different layers. The emphasis is placed on lightness and endurance. [10]

Many additions have been made over the time. The original concepts didn't include brakes and instead it was necessary to pedal backwards to stop. The need to raise your legs when not pedalling was solved with the implementation of freewheels. It is also interesting how the tyre was a latter addition, the wheel being originally made of metal. [10]

Bicycles have taken on a plethora of applications, from leisure and road racing to mountain bikes. The competition between producers has led to the need of optimizing the designs. Aerodynamics are an important part, reducing the drag and contributing to a more pleasant experience. The greatest advances on this regard have been made for the racing industry. Over the time, variations like monocoque or enclosed frames where attempted, but none has been as successful as the diamond-shaped ones. The technology of improvement has also evolved from trial and error to wind tunnel tests (WT) and computational fluid dynamics (CFD). [11]

A new wave of uncommon or eye-catching designs are spreading in order to attract the attention of potential customers. Even recumbent bikes are starting to regain notoriety. The original intent of creating a man-powered vehicle is also being forgotten with the gradual inclusion of electrical bikes.

4.2.2. Fatigue

The cause of fracture or failure of structures is commonly attributed to the application of big loads that lead to instantaneous breakage. Although less conspicuous, the main reason of failure would really be the so called mechanical fatigue. Even if a load may not be enough to initially cause deformation, it may be after time progresses. Fatigue is caused by the cyclical application of a repetitive load which reduces the mechanical properties until failure ends up happening. It initiates with the formation of micro-cracks that propagate until finally reaching the fracturing stage. The ductile or brittle nature of the material has a big effect on the behaviour when facing fatigue. [12]

Every solid is susceptible to fatigue, it may be due to repetitive impacts or even to the effect of wind or the constant stepping of pedestrians. Even if no structure is immune to fatigue, some resist it better than others. Each application and release is defined as a cycle. Two different labels can be used to categorize them depending on the number of cycles withstanded. For less than 1,000 cycles ($cycles < 10^3$) it is considered *low life* and for more, *high life* ($cycles \geq 10^3$); additionally, *infinite life* ($cycles \geq 10^6$) also exists. [13]

The empirical prediction of fatigue is an expensive and time consuming task, often complemented by experience on each field of expertise. Theoretical calculations are also a possibility. The best known method is called stress-life and is based on the S-N curve of each material.

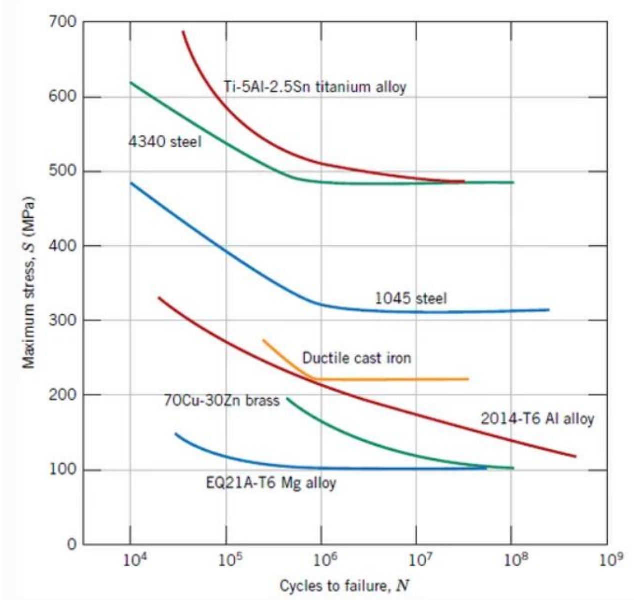


Figure 3 S-N curve diagram – Source: Callister, W. D., & Rethwisch, D. G. (2013, December 4). Maximum stress (S) versus logarithm of the number of cycles to fatigue failure (N) for seven metal alloys. Curves were generated using rotating–bending and reversed-cycle tests. [Graph]. Materials Science and Engineering: An Introduction 9th Edition. Wiley

The S-N curve values are formed from experimental data obtained from test proves. The endurance limit ($S_e^{'}$) of the rotary test bar is compared against the life cycles to which it corresponds. To approximate the values to the real behaviour (S_e) of a component, a series of factors have to be applied for each situation. Usually, most components have lower values than the test bars. [13]

$$S_e = \frac{S_e^{'} * k_a * k_b * k_c * k_d * k_e}{k_f} \quad (S_e \leq S_e^{`})$$

$$k_a = Surface\ finish\ factor$$

$$k_b = Size\ factor$$

$$k_c = Load\ type\ factor$$

$$k_d = Temperature\ factor$$

$$k_e = Reliability\ factor$$

$$k_f = non\ continuity\ factor$$

Most S-N curves are prepared for fully reversed loads where the mean stress (S_m) is equal to zero.

$$S_m = \frac{S_{max} + S_{min}}{2} = 0$$

Cases where the mean stress is not zero ($S_m \neq 0$), either because of the load not being fully reversed or due to a multidirectional application, require additional steps in order to be adapted to the S-N curves. In order to do this, an equivalent stress (S_{eq}) which fulfils the conditions has to be calculated. Multiple methods with the capability of finding this equivalent stress exist. Two of the most well-known theories are called Goodman and Soderberg, the latter being the most conservative and least lenient of the two. It is also the most convenient when analysing ductile materials, as long as it is possible to obtain the value of its yield stress. [13]

The equivalent stress can additionally be divided into the sub-types “Equivalent static” and “Equivalent alternating”. Each of them being more adequate for the procurement of different data. The latter is preferably employed when in need of obtaining the number of cycles till failure (N). The former can obtain the values of the safety coefficient or the dimensions of the studied component. [13]

-Goodman mean stress theory:

$$Equivalent\ static\ stress \rightarrow S_{eq} = \frac{S_{ult}}{SC} = S_m + \frac{S_u}{S_e} * S_a$$

$$Equivalent\ alternating\ stress \rightarrow S_{eq} = \frac{S_a * S_{ult}}{S_{ult} - S_m}$$

-Soderberg mean stress theory:

$$Equivalent\ static\ stress \rightarrow S_{eq} = \frac{S_y}{SC} = S_m + \frac{S_a}{S_e} * S_y$$

$$Equivalent\ alternating\ stress \rightarrow S_{eq} = \frac{S_a * S_y}{S_y - S_m}$$

$$S_a = Alternating\ stress$$

$$S_{ult} = Ultimate\ stress$$

$$S_y = Yield\ stress$$

$$SC = Safety\ coefficient$$

Recent advances like finite element analyses digitalize and ease this process. Static or dynamic load experiments are both possible.

4.2.3. Finite element analysis

Born from the need to reduce the cost of analyses on the aircraft industry, it has become a staple in the engineering field. It replaces the need of experimental data with computer aided approximations. Real models have an infinite amount of variables and a FEA program reduces it to a more manageable finite amount by decomposing it. [14]

This type of software, divides the geometry given into small cells or finite elements that are individually analysed. The ensemble of all the elements, gives a close simulation of the behaviour that a real model would have under the same conditions as the ones proposed for the simulation. It is worth remembering that the accuracy will depend on the conditions tabulated during the preparation step. An exhaustive interpretation is required in order to overcome these shortcomings and obtain truly trustworthy results. The previously more troublesome interpretation has been eased by the visual post-processing done by most commercial software.

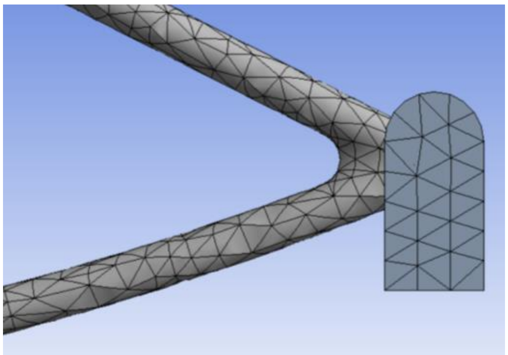


Figure 4 Example of a meshed solid – Source: Personal elaboration

Each finite element will have a so called "node" on each of its ends and possibly on the faces too depending on the order of the finite element, linear, quadratic, or less often cubic. The calculation will be done by analysing the reaction on each of those nodes. When the forces transmitted by each node match those applied to them, the model is said to converge; one of the many conditions for valid approximations.

The precision of the test will highly depend on the meshing process with which the geometry is divided into elements. Due to its importance, a wide range of options is provided to perform this task. It can, as an example, be meshed as a solid or as a surface. Different element shapes with varying node amounts are also available. Surface elements have options like triangular or quadratic surfaces while solids use tetrahedral or hexagonal. Variables like the sharpness of the angles are also fundamental for a functional mesh. [14][15]

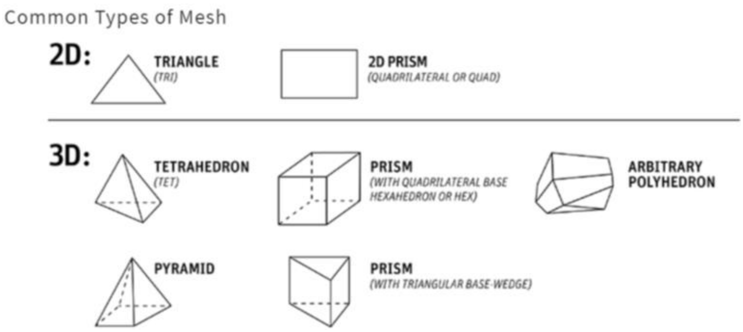


Figure 5 Common mesh element shapes – Source: SimuTech Group. (n.d.). Common Types of Mesh [Graph]. Why Is Ansys Meshing Important for Structural FEA and Fluid CFD Simulations? https://simutechgroup.com/why-is-meshing-important-for-fea-fluid-simulations/

The use of finite elements has expanded since its first implementation. Nowadays, it is not only used for mechanical analysis, but also for heat transmission, fluid simulation, noise in machinery and more.

Plenty of commercial licenses are available based on different softwares like MSC.Patran, MSC.Nastran, MSC.Apex, Ansys, Altair, or NX Siemens among others. [14]

5. Analysis process

5.1. Standardized bicycle measures and components

The design of bicycle frames offers a wide range of potential geometries. Among the possibilities, the most successful designs reach a balance between the characteristics of comfort, endurance and lightness. Both speed and safety must be ensured.

The most unconventional forms are commonly explored in custom made bicycles, where the use of high cost procedures and materials are permitted by the high-end nature of the product. The emphasis is given to shape in order to attract attention and differentiate one´s product from those of the other competitors in a lower demand market.

Figure 6 Unusual bicycle concepts – Source: Delcambre, J. (2015, April 8). My first job, Scott Sports [Illustration]. Scott Concept Bikes by Julien Delcambre. https://bicycledesign.net/2015/08/scott-concept-bikes-by-julien-delcambre/

For commercial grade designs, the emphasis is placed on standardization and mass production. While still needing to grab the attention of customers, more recognizable designs are employed in order to guarantee affordable prices and ease of selection. These frames follow a set of rules, sharing detailed measures and common components even among different brands. Thanks to this, the difficulty of finding replacements and the optimal option for each customer is greatly simplified, incentivising commerce due to its simplicity.

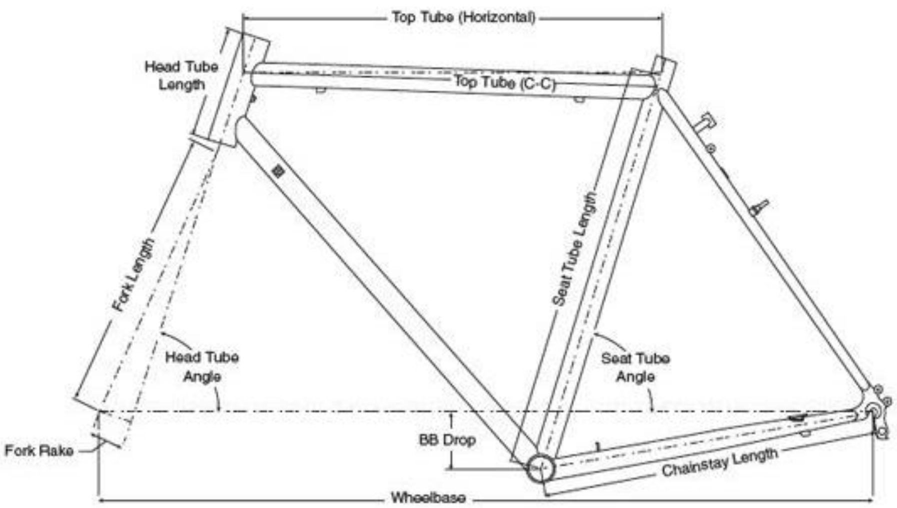
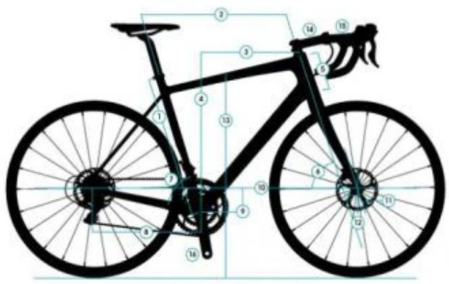


Figure 7 Measure nomenclature – Source: [Bicycle frame tube names]. (2013, October 4). Understanding Bicycle Frame Geometry. https://www.cyclingabout.com/understanding-bicycle-frame-geometry/

The value of these measures will change depending on the type of terrain or user height that they are intended to be used for.



FRAME SIZES	XS	S	M	L	XL
1. Seat Tube Length	450	480	510	530	570
2. Horizontal Toptube Length	533	547	578	604	636
3. Reach	365	375	395	415	435
4. Stack	566	580	599	618	637
5. Headtube Length	125	140	160	180	200
6. Head Angle	71°	71°	71°	71°	71°
7. Seat Angle	73.5°	73.5°	73°	73°	72.5°
8. Chanstay Length	455	455	455	455	455
9. BB Drop	75	75	75	75	75
10. Wheelbase Length	1041	1056	1083	1109	1136
11. Fork Offset	55	55	55	55	55
12. Fork Trail	61	61	61	61	61
13. Standover	758	778	799	807	843
14. Stem	100	100	100	100	100
15. Handlebar	400	420	420	440	440
16. Crankarm	165	170	175	175	175

*All length measurements are in mm

Figure 8 Road bike measurement chart – Source: [Frame chart size]. (2020, November 21). ¿CÓMO ES LA GEOMETRÍA DE UNA BICICLETA? https://oxiacycles.com/geometria-de-una-bicicleta/

The sizing of the remaining components also follow a strict guideline so as to make them compatible and exchangeable.

To create different but still comparable designs for the study, the most common component sizes have been selected and used. The following are the components that have been taken into account when defining the preliminary frame dimensions.

5.1.1. Fork

The fork fulfils the task of connecting the frame to the front wheel. The front wheel can't be connected to the frame the same way that the back one does due to it needing to be rotated in order to change directions; it also needs to be affixed to the handlebar to do this.

For this connection, the extremity of the fork has to go through the head tube of the frame. Both being cylindrical, the rotation is allowed while remaining affixed. A change in diameters or the handlebar usually prevent it from sliding out. Despite having lower requirements than other areas, a low friction contact is required to prevent them from getting stuck and reduce the effort needed to move them. A good material and surface finish help with this problem.

For the designs, a diameter of 31.6mm has been decided for both elements. This way no clearance issues will appear during the analysis. Other widely used measures include 22.2, 25.4, 26 and 31.8 mm. [16]

The length of the fork will also be limited by the wheel tyre and the hitches' shape by the wheel hub.

5.1.2. Wheels

The classification of wheels is the most cumbersome to define due to the different systems employed over time. The ISO 5775 was created to define both the size of the tyre and of the rim.

It informs about the outer diameter of the rim and the width of the tyre with which the total diameter can be obtained. [17]

The preceding systems include both the French and English classifications, both still widely used commercially. This time, the measure being referenced is the outer nominal tyre diameter. The diameter of the rim will depend on the width of the tyre while keeping constant the total diameter of the wheel. [17]

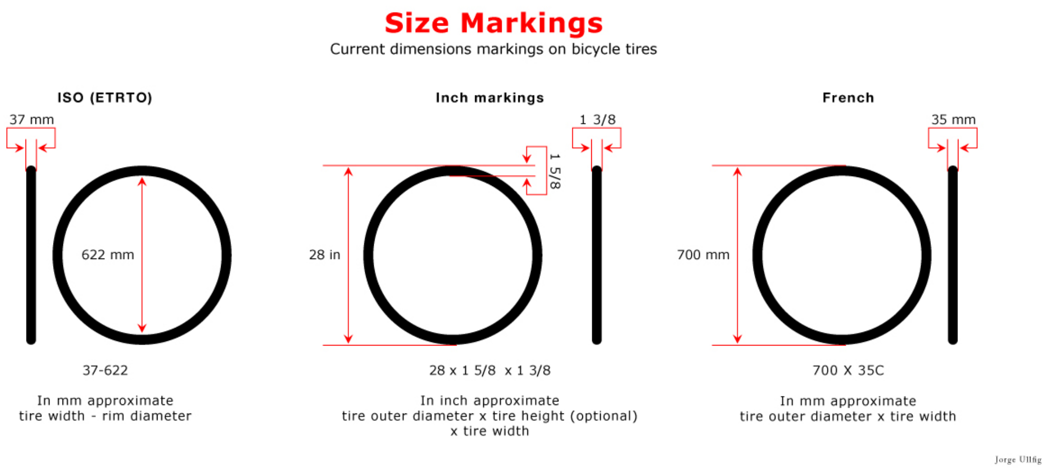


Figure 9 Comparison of different wheel nomenclatures – Source: Moebiusuibeom-en. (2010, September 28). Bicycle Tyre Information [Illustration]. File:Tyre and Rim Technical Data 01-En.Png. https://commons.wikimedia.org/wiki/File:Tyre_and_Rim_Technical_data_01-en.png

The most used rim sizes are the 700C (29" or 622mm) and 26" (559mm). The former is employed in road and hybrid bikes while the latter sees more use in mountain and comfort bikes. [16]

An older denomination is 650B (27.5" or 584mm). Normally used for younger riders, a new trend has invigorated their use as an intermediate mountain bike size. [16]

The one chosen for the following analyses is 26"; deciding to test a comfort bike. It mixes the characteristics of a MTB and touring bike, resulting in a great option for urban transport. All of the designs will have to be able to use a total wheel diameter of at least 677mm. The individual sizes of the rim and tyre won't affect the study.

5.1.3. Hub

Hubs are used for coupling the wheels to the frame and fork of the bike. These joints can´t be rigid, as it is indispensable for the wheels to rotate with a rapid angular speed. To achieve their purpose, hubs use low friction elements. They help create a transmission with low coefficients of friction (COF); the material pairing is important for this aspect. It also needs to reduce as much as possible the wear effect on both components paired by it.

Bushings can be used as hubs. While not having moving parts themselves, they allow the rotation of the wheel and transmission to the frame while reducing the wear and friction. It is recommended to regularly apply lubricants to improve the performance. A more rigid structure is looked for in more demanding uses like MTB.

Bearings are also typically installed. In this case, a pair of bearings is used, one in each side of the hub. Simple ball bearings are an economic option for casual bike usage, but more expensive types have to be used for more demanding tasks; for example cartridge bearings.

Different hub installation methods exists, with varying levels of security and ease of replacement. Some examples include: quick release, thru axle and nut types.

Length and diameter are the decisive factors when choosing the right option. These will be decided by the distance between the hitches of the frame and fork respectively. Different sizes are used for the front and back connection points.

-Front:

The options are differentiated by length and diameter. For a length of 100mm, diameters of 9 and 15 mm can be found. The diameter increases to 20mm for a longitude of 110mm. [16]

The designs have been created for a distance of 100mm and a diameter of 9mm. These will be used when deciding the front hitch dimensions.

-Back:

For the back hitches an internal diameter of 12mm has been chosen. The distance between hitches will take into consideration the potential use of a 120 mm hub. [16]

The discarded options include the 130 and 135mm lengths and a lower diameter of 10mm. [16]

5.1.4.Saddle and Shank

The type of saddle and the height that it is placed at, drastically affect the comfort of the cyclist. While being and important factor, the saddle will be highly simplified for these analysis, not to affect the performance of the frame.

On the other hand, the shank needs to be defined in order to create the frame. The range of diameters is wide and offers plenty of different options, commonly between 28 and 35 mm. The shank needs to be placed inside the frame´s seat tube and adjusted not to move. By using clamps, even if a wide clearance exists, both elements can be fixed together. To simplify the assembly, the internal diameter of the seat tube will be the same as the external of the shank. [16]

A diameter of 31.6mm has been selected, the same as in the head tube and fork.

The length of shank models is between 250 and 400mm. [16]

5.1.5. Cranks and pedals

A combination of two cranks and pedals, one of each per bike side, are an indispensable component on the propulsion of a bicycle. This mechanism converts into rotatory energy the effort of the rider, thus driving the rear wheel and pushing the bike forward.

The length and distance between cranks is also a key component when determining the user´s comfort. Both values have to be adapted to the height of the biker in order to maximize this property. [16]

The connection between both pairs is also the component in contact with the bike frame. It is fixed in place by the crank tube. The inner diameter of the tube will be 31.6 millimetres to keep a resemblance with the other tubes shaping the frame. It will also be given a length of 50 mm, enough to hold the pedal resembling support without accidentally acting as an obstacle.

In addition to the cranks and pedals, the motion transference also requires additional elements like a chainset or chain for it to be possible. This elements are not required for the simplified pedal set used on the simulations. Both pedals and cranks will be part of a single solid.

5.2. Model design and creation

All 3D solid models have been created using the CAD program NX 12. These include the frames created for the study and the support elements required for the tests.

The assembly of the components has also been performed using NX 12.

All 2D drawings of the models have been obtained on the same program.

Four initial designs have been created:

5.2.1. Base design

The designs created for this project are variations of what is commonly considered the most widely used bicycle design; the triangular frame with both seat and chain stay tubes. A model following that pattern has been created. It has been done so as to have a point of reference from where to create the next models.

During its development, the measures chosen for the non-frame components have been carried over.

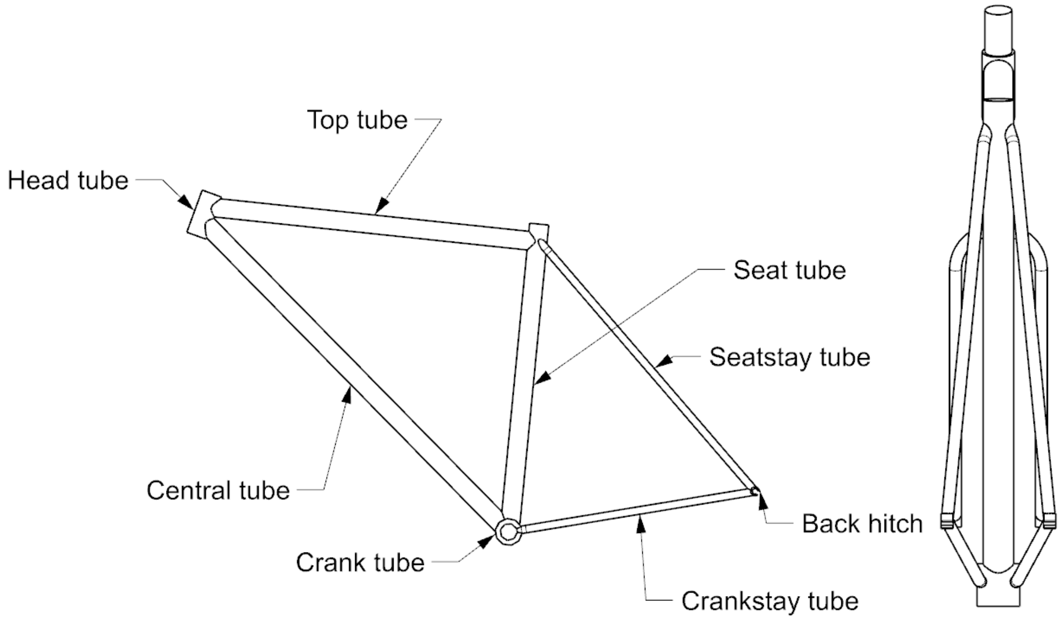


Figure 10 Base design structure and tube names – Source: Personal elaboration

Table 3 Base design tube size – Source: Personal elaboration

	Outside diameter (OD)	**Inside diameter (ID)**	**Thickness (e)**
Head tube	38 mm	31.6 mm	3.2 mm
Central tube	34.6 mm	31.6 mm	1.5 mm
Top tube	34.6 mm	31.6 mm	1.5 mm
Seat tube	35.6 mm	31.6 mm	2 mm
Seat stay tube	14 mm	11 mm	1.5 mm
Chain stay tube	14 mm	11 mm	1.5 mm
Crank tube	50 mm	31.6 mm	9.2 mm
Back hitches	18 mm	12 mm	3 mm

-Thickness:

Commercially, steel bicycle tubes have a thickness between 0.5 and 3 or 4 mm. No constant value is typically used, instead it may be changed depending on the needs of the area. In order to simplify as much as possible these first tests, constant section tubes are going to be utilized.

The thickness that has been employed as much as possible when creating the tubes is 1.5 mm. The exceptions being the crank and head tubes, which have been strengthened as a result of being connection points. The seat tube has also experimented, although smaller, an increase in thickness from the rest of structural tubes.

With the intention of placing most of the strain on the central triangle, the seat stay and crank stay tubes have been made narrower.

-Connections:

The connections between elements are considered as being welded. On the initial designs, so as to simplify them as much as possible, no rounding of edges has been done.

-Hitch:

The wheel hitches are composed of open cylinders welded to the tubes.

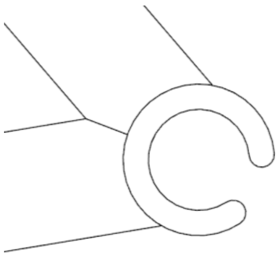


Figure 11 Hitch profile – Source: Personal elaboration

-Common coordinates and lengths:

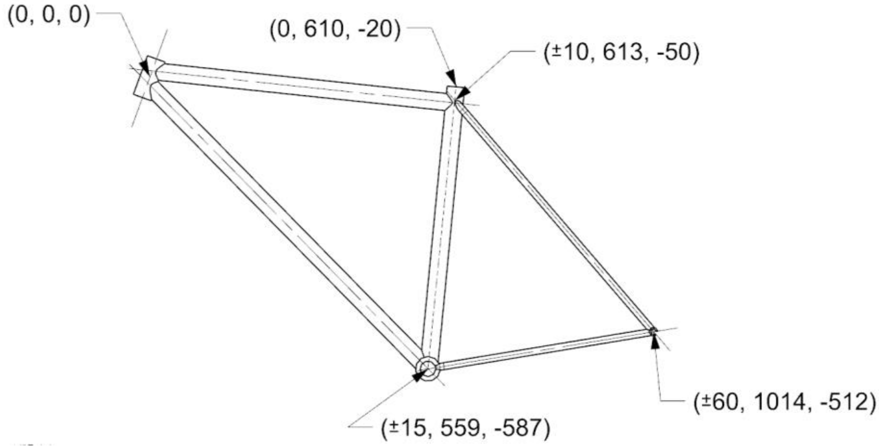


Figure 12 General coordinates – Source: Personal elaboration

During the creation of each model, these coordinates have been respected and used so as to regularize all of them. This helps add continuity to all of them and compare the results that will be obtained during the analyses.

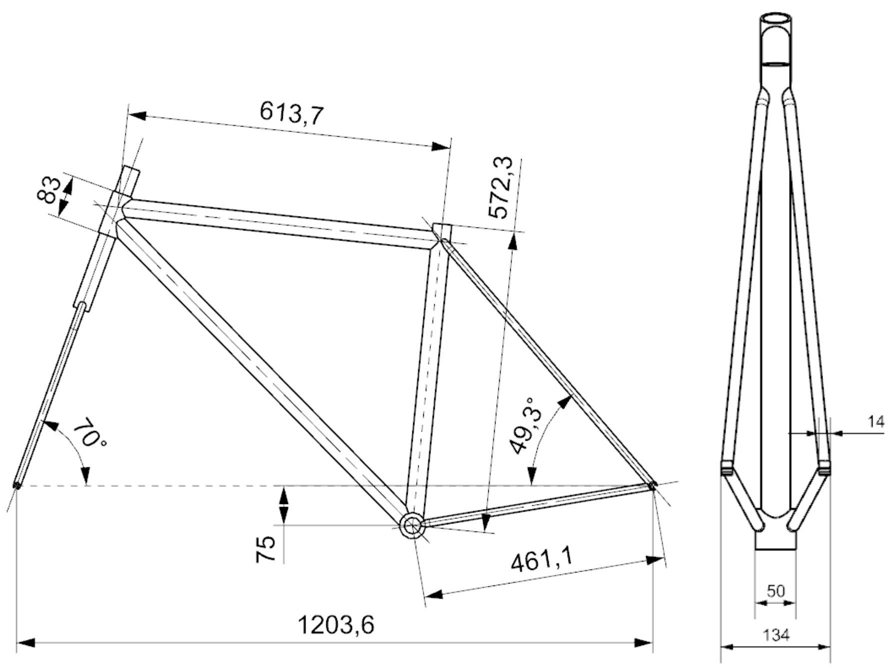


Figure 13 Base design measures – Source: Personal elaboration

The model depicted presents the main measures of what can be called a generic bicycle frame together with a fork. As it can be seen, both the front and back hub axes are aligned horizontally.

Using this model as reference and initial concept, alterations to the structure have been made in order to develop three original models. Slight diameter changes are performed to each model when seen as necessary in order to make up for the changes performed. The main coordinates are mostly the same for the three of them.

-Wheel space:

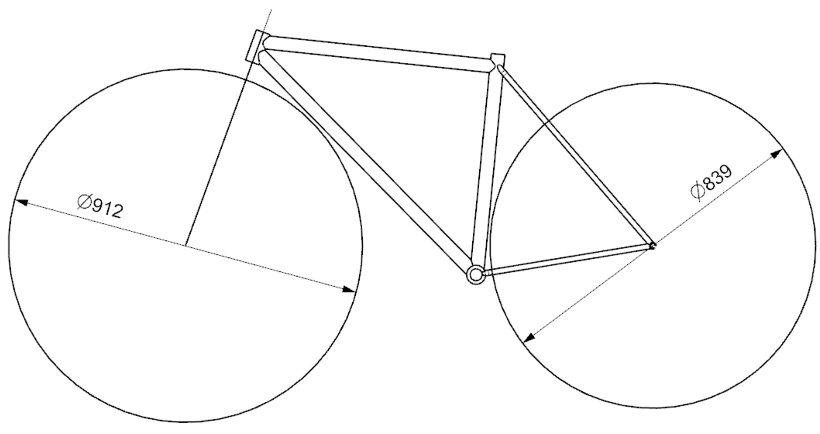


Figure 14 Base design wheel space – Source: Personal elaboration

The template based nature of the model coordinates, puts certain limitations on the wheel sizes that can be used.

As previously mentioned, all of them are designed to use 26” wheels which need a total diameter of 677mm or more. This base design fulfils that condition without problem. Due to how high the capacity is, it would also be possible to use 29” wheels; they have a 740mm outer tyre diameter.

5.2.2. Design 1

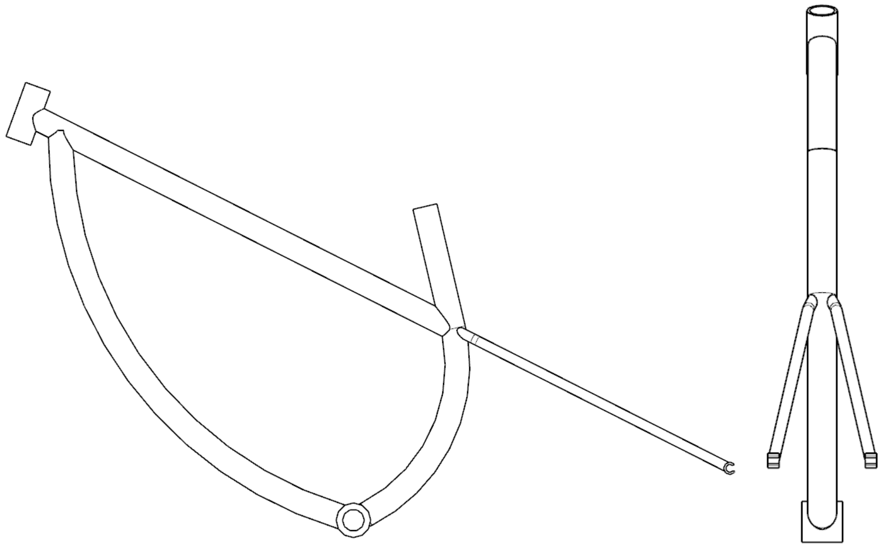


Figure 15 Design 1 structure –Source: Personal elaboration

Table 4 Design 1 tube size – Source: Personal elaboration

	Outside diameter (OD)	Inside diameter (ID)	Thickness (e)
Head tube	38 mm	31.6 mm	3.2 mm
Central tube	35.6 mm	31.6 mm	2 mm
Top tube	34.6 mm	31.6 mm	1.5 mm
Seat tube	35.6 mm	31.6 mm	2 mm
Seat stay tube	14 mm	11 mm	1.5 mm
Chain stay tube	-	-	-
Crank tube	50 mm	31.6 mm	9.2 mm
Back hitches	18 mm	12 mm	3 mm

-Changes:

One of the most obvious changes can be seen in how the central and seat tube shapes have been reshaped, giving them a more round appearance. It is especially important for the seat tube, since it deviates from the previously defined final coordinate. To make up for this, a longer seat shank will be needed.

The central tube has been changed to resemble more the seat one, slightly increasing its outer diameter. Its joining point has also been changed, instead of connecting to the head tube the connection point is done to the central tube. This last one, will have to deal with all the forces transmitted from the front wheel through the fork.

The other main change is the lack of chain stay tubes, which will increase the effort placed on the seat stay tubes. While being an aesthetic decision, it grants the opportunity to evaluate the possibility of applying this change to future iterations of the designs.

-Reason:

The criterion employed consists on the intention of evoking the idea of it only consisting of two tubes. The top and seat stay tubes are placed in the same axis, even if it divides in two; it could be seen as a single line.

Similarly, the central and seat tubes have similar curvatures in an attempt to resemble a single tube.

-Measures:

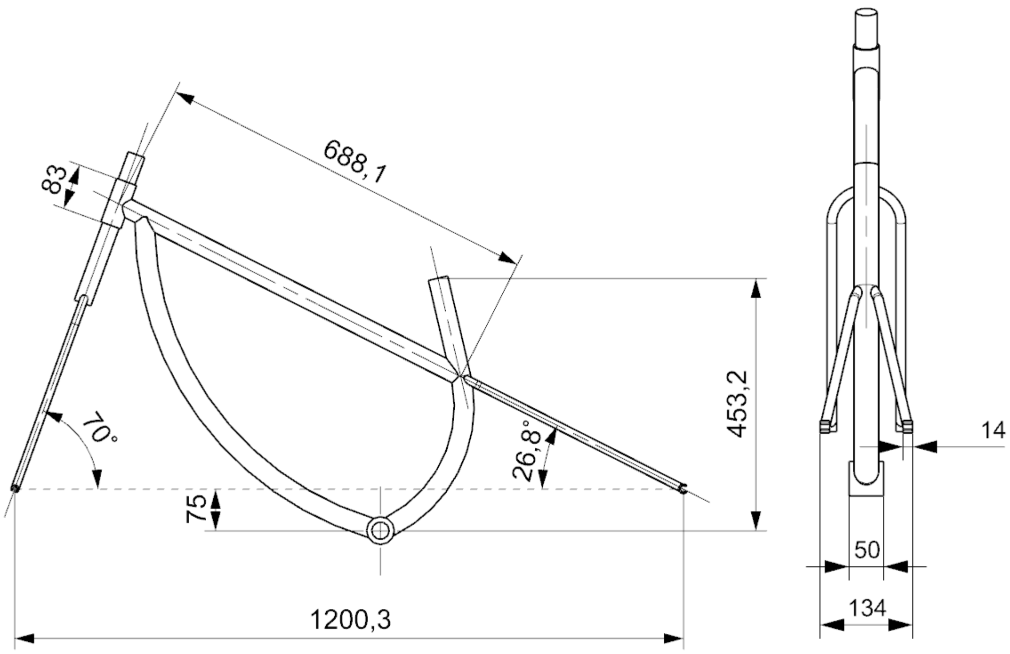


Figure 16 Design 1 measures – Source: Personal elaboration

-Wheel space:

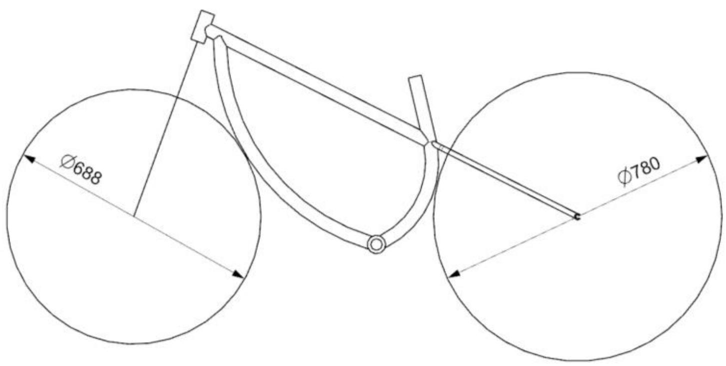


Figure 17 Design 1 wheel space – Source: Personal elaboration

This first model, fulfils the minimum size required to be able to use 26” wheels. The small remaining range makes it impossible to use 29” ones.

If it was necessary to leave more free space, by reducing the angle between the head tube and the horizontal axis it would be possible to increase the distance.

5.2.3. Design 2

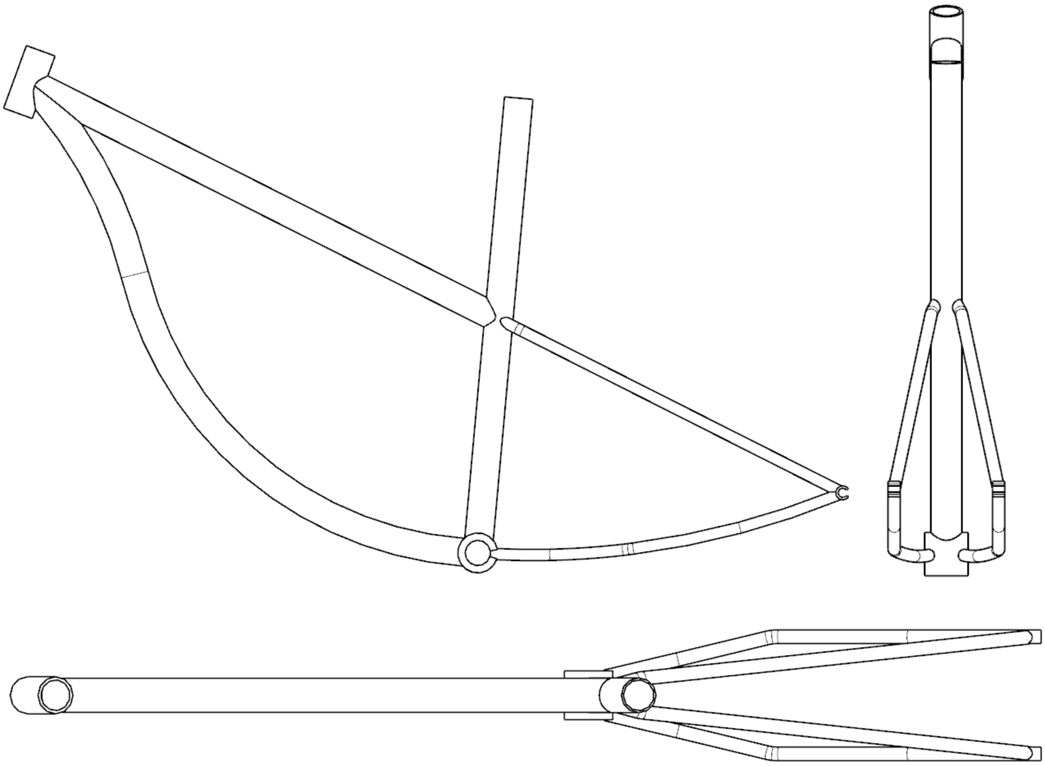


Figure 18 Design 2 structure – Source: Personal elaboration

Table 5 Design 2 tube size – Source: Personal elaboration

	Outside diameter (OD)	Inside diameter (ID)	Thickness (e)
Head tube	38 mm	31.6 mm	3.2 mm
Central tube	34.6 mm	31.6 mm	1.5 mm
Top tube	34.6 mm	31.6 mm	1.5 mm
Seat tube	35.6 mm	31.6 mm	2 mm
Seat stay tube	14 mm	11 mm	1.5 mm
Chain stay tube	14 mm	11 mm	1.5 mm
Crank tube	50 mm	31.6 mm	9.2 mm
Back hitches	18 mm	12 mm	3 mm

-Changes:

For this case, no change has been done to any of the tube types. The cross section is the same as in the base design.

A noticeable difference happens in the change that the central tube suffers, being replaced by a curved tube.

The inclination of the top tube is changed in order to, as happened in the previous design, align it with the seat stay tube.

The main difference is in the shape of the crank stay tubes that form the back wheel support. While normally being a single straight tube, it has now suffered two changes.

Firstly, to increase the gap between the supports and the wheel, instead of being a straight line it starts widening and then returns to the hitches. As a downside, it creates a corner where stress may concentrate.

Secondly, it has been given a curvature. If viewed from the side, it seems as if it is a continuation of the also curved central tube.

-Measures:

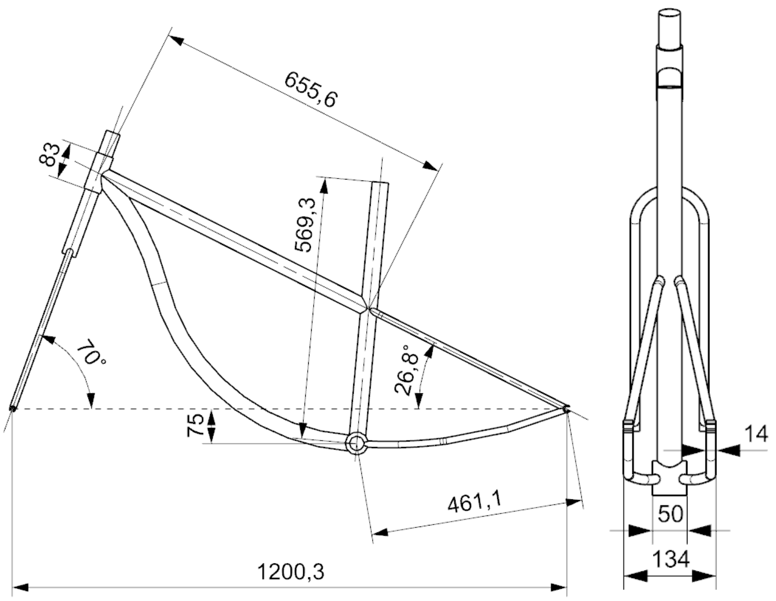


Figure 19 Design 2 measures – Source: Personal elaboration

-Wheel space:

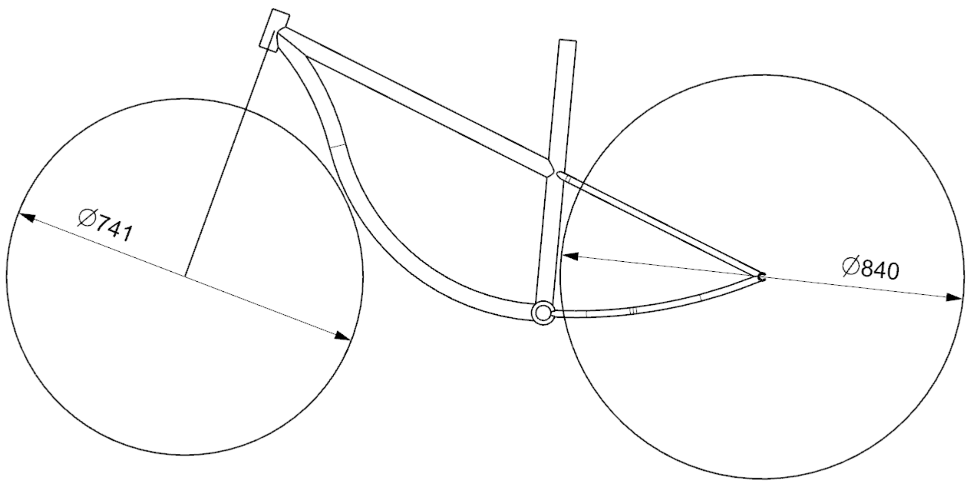


Figure 20 Design 2 wheel space – Source: Personal elaboration

The intended 26” wheels can be installed without any problem.

It is possible to install 29” tires but the remaining space is too small to do it in a safe manner. If these are required, the angle can be changed to increase the space.

5.2.4. Design 3

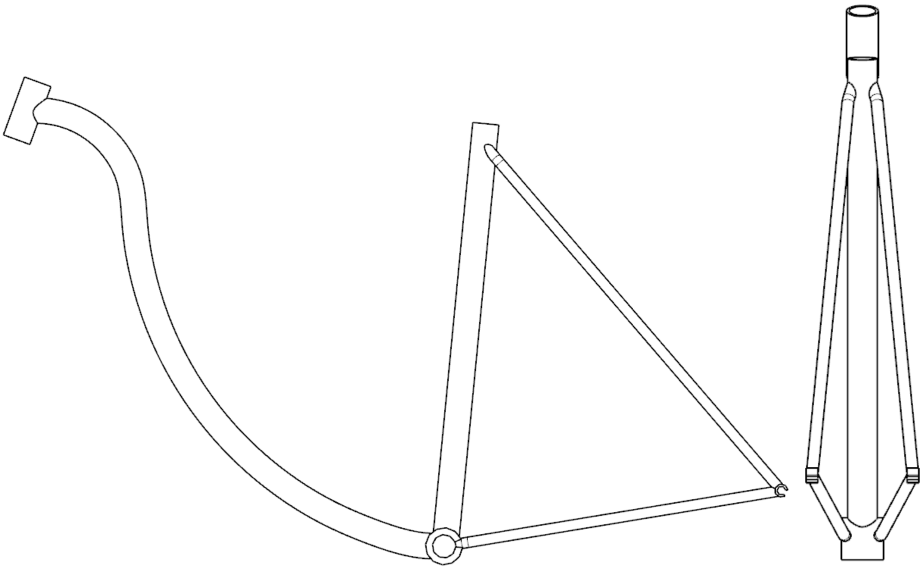


Figure 21 Design 3 structure – Source: Personal elaboration

Table 6 Design 3 tube size – Source: Personal elaboration

	Outside diameter (OD)	Inside diameter (ID)	Thickness (e)
Head tube	38 mm	31.6 mm	3.2 mm
Central tube	34.6 mm	31.6 mm	1.5 mm
Top tube	-	-	-
Seat tube	35.6 mm	31.6 mm	2 mm
Seat stay tube	14 mm	11 mm	1.5 mm
Chain stay tube	14 mm	11 mm	1.5 mm
Crank tube	50 mm	31.6 mm	9.2 mm
Back hitches	18 mm	12 mm	3 mm

-Changes:

The only variation from the base design is the lack of top tube and the redesign of the central tube. By removing the top tube all of the effort will have to be done by the central tube. This places all the strain in the connection to the crank tube.

The tube is given a curved shape for an aesthetic reason, since a straight tube would not have an attractive profile for consumers and leaves a wide unused space. By giving it a more detailed curved shape, these problems are alleviated. As a consequence, it improves the connection angle, making it closer to perpendicular than it would be otherwise.

Another point of note caused by this change, is the relocation of the center of gravity. With the structure presented, it will be located closer to the rider.

-Measures:

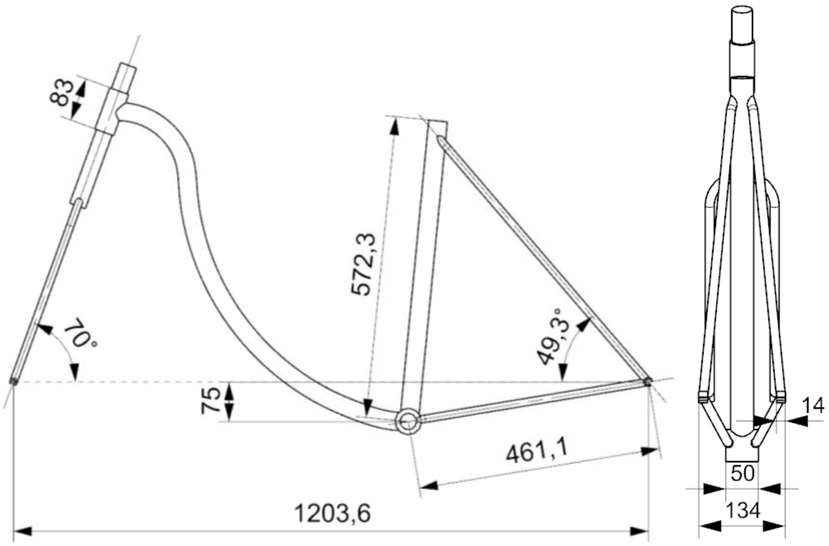


Figure 22 Design 3 measures – Source: Personal elaboration

-Wheel space:

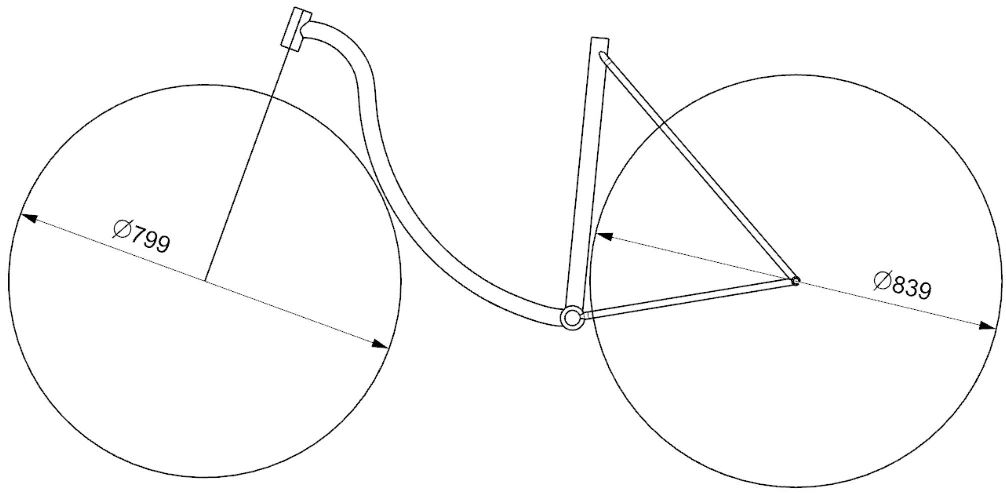


Figure 23 Design 3 wheel space – Source: Personal elaboration

Both 26” and 29” tires can be used without needing any conversion.

5.3. UNE EN-ISO 4210

To ascertain that the frame models fulfil the quality and safety requirements needed to be commercialized, they will be analysed according to the UNE EN-ISO 4210 standard. [18]

The standard deems whether a product is safe through a series of tests, assigning a life cycle threshold to each bike type. These fatigue tests expose the models to cyclic loads. If the frame lasts more cycles than the minimum required, then it is considered that it is valid. For this to happen, no fracture or visible fissure can appear during the inspection at the end of the required cycles. [18]

In addition to the analysed frame, each test requires support elements such as a fork. These elements are detailed by the standard and therefore will be designed and included when performing the experiment. [18]

As previously mentioned, different bike types exist with different requirements for each. These consist on racing, mountain, young adult and road bikes. The models are inspired in comfort bikes which could be considered as road bikes. They also take features from mountain bikes, so additional tests may be performed to confirm whether they are able to fit inside both categories. [18]

The standard details three different tests, all of them must be satisfied without exception by each model. [18]

5.3.1. Fatigue test for horizontal loads

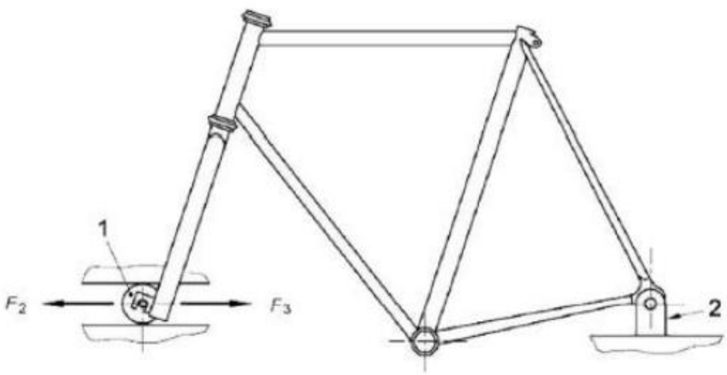


Figure 24 Horizontal test diagram – Source: Adapted from AENOR. (2015a, January). Cuadro. Ensayo de fatiga por fuerzas horizontales [Illustration]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf

Table 7 Horizontal test values – Source: Adapted from AENOR. (2015a, January). Fuerzas y ciclos en las punteras de la horquilla delantera [Table]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf

Bicycle type	Road bicycle	Bicycle for young adults	Mountain bicycle	Racing bicycle
F_2 [N]	450	450	1,200	600
F_3 [N]	450	450	600	600
C1 [cycles]	100,000	100,000	50,000	100,000

Support elements [18]:

-A fork designed to be the length necessary to align both wheels. When performing the analysis it must be made of a material more resistant than the frame or the one that would be used for a real one. Due to this, it is called a fake fork.

-The element marked as 1 is a cylinder with two smaller cylinders on its sides; these have the function of coupling it to the hitches of the fork. It can be referred to as a rolling-pin.

-The support 2, has an internal cylinder that will be inserted in the frame´s hitches.

-Both numbered geometries will be used once again in the second test.

Conditions [18]:

-Both wheel hub axes must be on the same horizontal line.

-The loads only have a horizontal component and the table marks their maximum value.

-Each single cycle will consist on a sequence with the following steps:

1- The load F2 starts at value 0.

2- It grows to its maximum value.

3- It decreases until its value reaches 0.

4- F3 starts growing from 0.

5-It reaches its maximum value.

6-It decreases to 0.

7- A new cycle begins.

-Both forces are applied on the cylinder signalled as 1.

-Element 1 can only displace and rotate on the horizontal axis as depicted, the rest of the freedom-degrees will be locked.

-Element 2 is a fixed support with no movement allowed.

5.3.2. Fatigue test for vertical loads

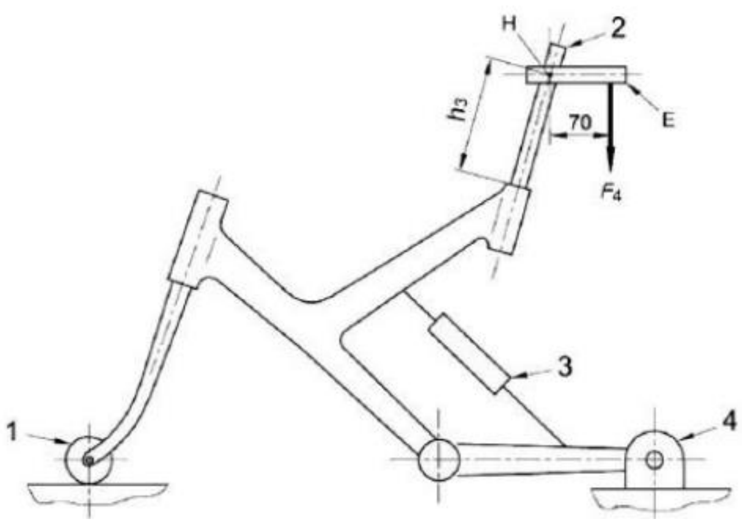


Figure 25 Vertical test diagram – Source: Adapted from AENOR. (2015a, January). Cuadro. Ensayo de fatiga con una fuerza vertical [Illustration]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf

Table 8 Vertical test values – Source: Adapted from AENOR. (2015a, January). Fuerzas sobre la tija del sillín [Table]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf

Bicycle type	Road bicycle	Bicycle for young adults	Mountain bicycle	Racing bicycle
F_4 [N]	1,000	500	1,200	1,200
C2 [cycles]	50,000	50,000	50,000	50,000

Support elements [18]:

-Both the support 1 and 4, called 1 and 2 in the first test, are reused here.

-Element 2 is composed of both the seat and the seat post. If no information is available, h_3 must equal 250mm, the maximum height allowed.

-The number 3 marks a shock absorber. It can be a rigid bar or the design intended for the frame to use. The initial models designed for these studies won´t include this element.

Conditions [18]:

-Supports 1 and 4 have the same conditions as in the previous test.

-The frame must be in its normal working position. It is not necessary for both wheel hubs to be aligned on the horizontal axis.

-The seat needs to start in a horizontal position.

-The seat post or shank needs to be introduced at least 75mm inside the frame and tightly joined.

-F4 must be applied vertically as a load perpendicular to the seat.

-Load sequence:

1-The F4 loads starts at 0 N.

2-It increases until reaching the maximum value.

3-It starts decreasing until its value reaches 0.

4-A new cycle begins.

5.3.3. Fatigue pedalling test

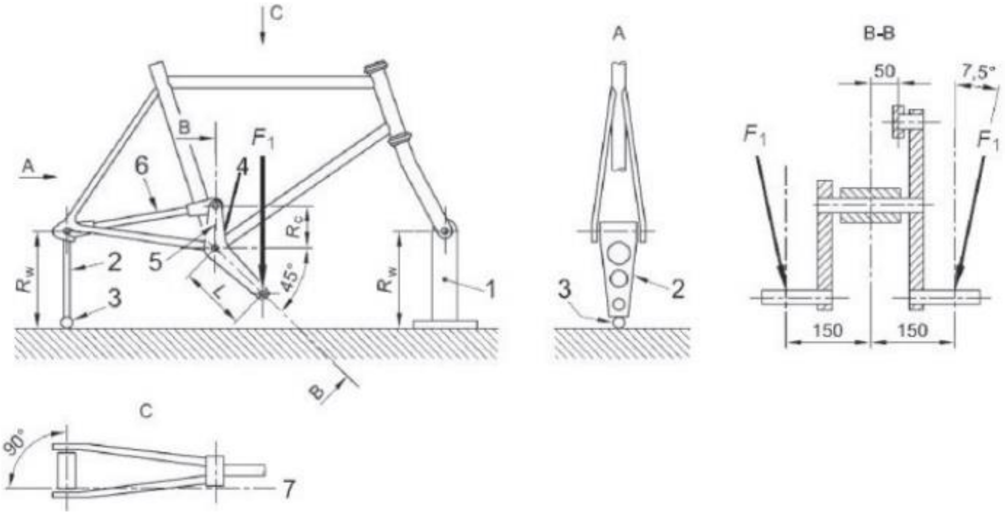


Figure 26 Pedalling test diagram – Source: Adapted from AENOR. (2015a, January). Cuadro. Ensayo de fatiga con fuerzas de pedaleo [Illustration]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf

Table 9 Pedalling test values – Source: Adapted from AENOR. (2015a, January). Fuerzas en el eje del pedal [Table]. UNE-EN ISO 4210–6. https://biblus.us.es/bibing/proyectos/abreproy/70701/fichero/ANEXO+I.pdf

Bicycle type	Road bicycle	Bicycle for young adults	Mountain bicycle	Racing bicycle
F_1 [N]	1,000	1,000	1,200	1,100
C2 [cycles]	100,000	100,000	100,000	100,000

Support elements [18]:

-1= A rigid assembly similar to the previously used fixed supports.

-2= A vertical joint. It has cylinders on its sides to act as supports to the frame hitches.

-3= A ball joint affixed to the vertical joint.

-4= Assembly adapter. It will act as rigid pedals.

-5= Vertical arm, is part of the pedal solid.

-6= Brace.

-7= Brace axis. Depicts the position in which the brace has to be installed.

Conditions [18]:

-Cycle sequence simulating a pedalling movement by alternating forces:

1-Both loads start at a value of 0.

2-One of them starts to increase until it reaches its maximum value while the other remains unchanged.

3-From the maximum value it decreases until reaching 0 Newton again.

4-When the first load reaches 0, the second starts increasing.

5-After reaching the maximum load, it starts to decrease.

6-It reaches 0.

7-A new cycle begins.

-The rigid assembly (1) is a fixed support in order to reduce the displacement suffered by the fork. The hub can rotate but not displace.

-The joints 2 and 3 allow rotation in all directions but not displacement.

-The assembly adapter (element 4) can contain a chain, both pedals and a chain-ring or be substituted by a rigid solid. To simplify the components, a rigid substitute will be used as depicted on the image.

It has to be locked in position, not allowing it to rotate, to do that the brace (6) is included. By attaching it to the vertical arm (5) and vertical joint (2), the movement is restricted.

-R_w is the vertical joint and rigid assembly height. The value given must be equal to the outer wheel diameter (tyre + rim) ±30mm.

-The vertical arm length, R_{cl}, is 75mm.

-L must be 175mm long.

5.4. Elements used on the assemblies for each test

All the components have been designed according to the indications given by the standard and the requirements of the frames. The designs have been simplified as much as possible since they are not the elements that this study seeks to analyse. By having simple designs, the analysis effort can be dedicated to the frames.

5.4.1. Fork

This is the only element that will be required for the three different fatigue tests. The prerequisites are the same for all three, so the same model will be employed.

The first condition to take care of during its development, is to make sure that it has enough space to house the intended wheel (rim and tyre).

Since a 26” wheel is being used, the wheel will have a diameter of at least 677 mm. Considering that the wheel center has to coincide with the fork hitches, at least 338.5mm of free vertical space are needed; it has been increased to at least 350mm as a security measure.

It is also important to consider the hitches that will hold the wheel hub in place. Following the data of the hub previously selected, an internal diameter of 9mm has been used for the hitches. Giving them a thickness of 3mm, an external diameter of 15mm has been obtained. Both hitches are open cylinders in a similar manner to what is used in the frames. A horizontal distance greater than the most common commercial tyre widths has been applied so it will have enough space.

For the assembly, the top of the fork needs to be long enough to be inserted in the head tube of the frame. The head tube is 83mm long; it has been decided that the fork will cross it completely and stick out 52mm so a handle could be installed. The total length has to fulfil this condition and align the hitches horizontally with those of the frame. The diameter of this prolongation is the same as the head tube´s internal.

Two designs have been made following these directions.

Initially, a model close to what a real bike could employ was created. The geometry has a detailed cross section, going from a radius of 7mm to 15.8mm.

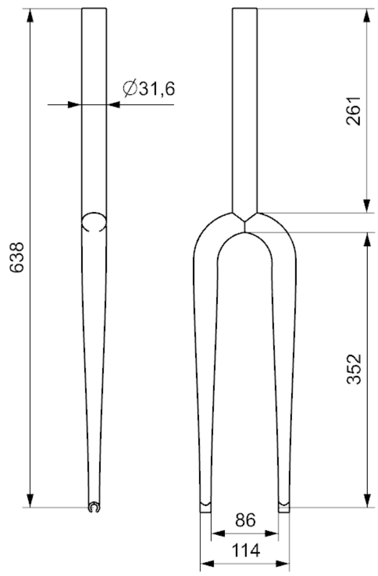


Figure 27 Initial hitch measures – Sources: Personal elaboration

Later, it was simplified while keeping the same measures. The smaller constant radius, will help with simplifying the mesh generation during the analysis, while not causing an appreciable change on the performance.

This is the one that has been employed in the majority of tests.

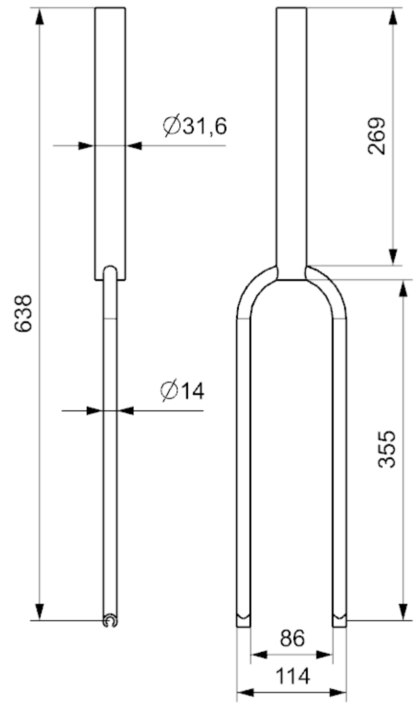


Figure 28 Simplified hitch measures – Source: Personal elaboration

5.4.2. Rolling-pin

Both test 1 and 2 require a rolling pin to be connected to the fork as a substitute of the front wheel.

The most important measure is the diameter of the lateral cylinders. They connect the pin and fork hitches, so both will have the same value.

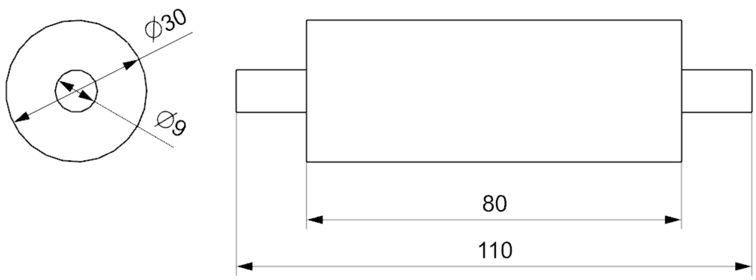


Figure 29 Rolling pin measures – Source: Personal elaboration

5.4.3. Fixed support

Used in tests 1 and 2, it consists on a cylinder that will be inserted on the frame hitches and a support structure to keep it locked in place. The diameter has to be the same as that of the hitches to ensure a good contact.

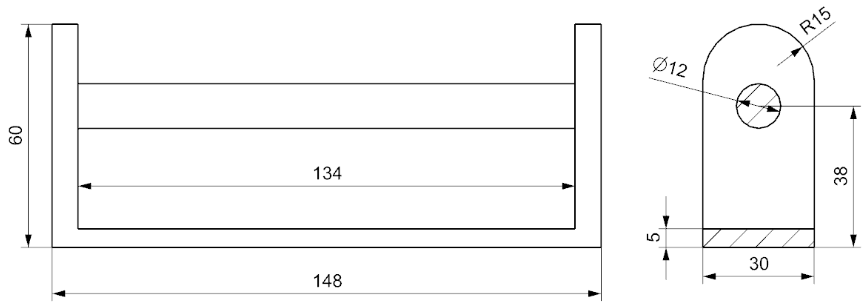


Figure 30 Fixed support measures – Source: Personal elaboration

5.4.4. Seat and shaft

The shaft shares diameter with the interior of the seat tube of the frame (31.6mm). The total length follows all the requirements established by the standard.

The seat has been simplified to a rectangle. A small indentation has been created as a visual aid to locate the load application point during the analysis. The indentation has a radius and depth of 1mm.

Two different models have been created due to the first model having a different angled seat tube. To maintain the seat horizontal in all models, the angle has to be changed.

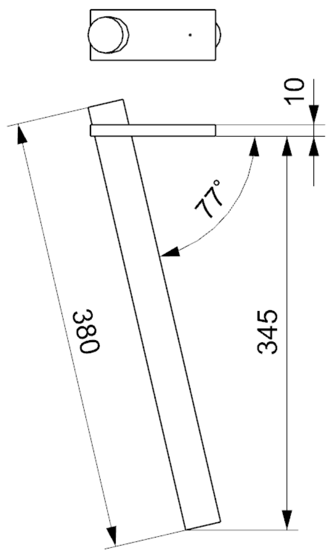


Figure 31 Seat and shaft measures for design 1 – Source: Personal elaboration

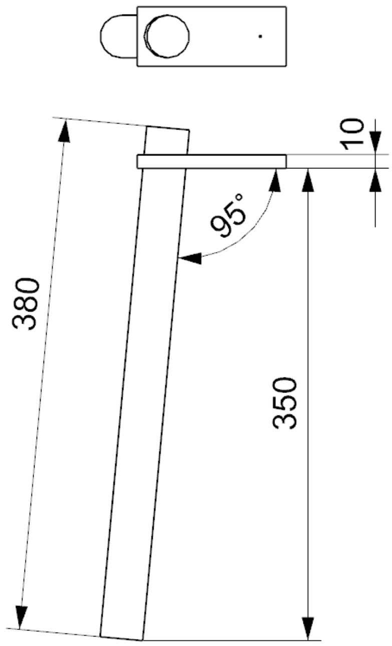


Figure 32 General seat and shaft measures – Source: Personal elaboration

5.4.5. Pedals

The support that will act as both pedals has been modelled following the instructions that the standard provides. The measures not given have been chosen to fulfil the needs of the frame models.

For a correct assembly with the frame, the cylinder in contact has been given the same diameter as that of the crank tube (31.6 mm).

In a similar manner to that of the previous case, two indentations have been made on each pedal. These are placed in the location where the load must be applied during the analysis. The indicated application angle has been used to simplify the selection process.

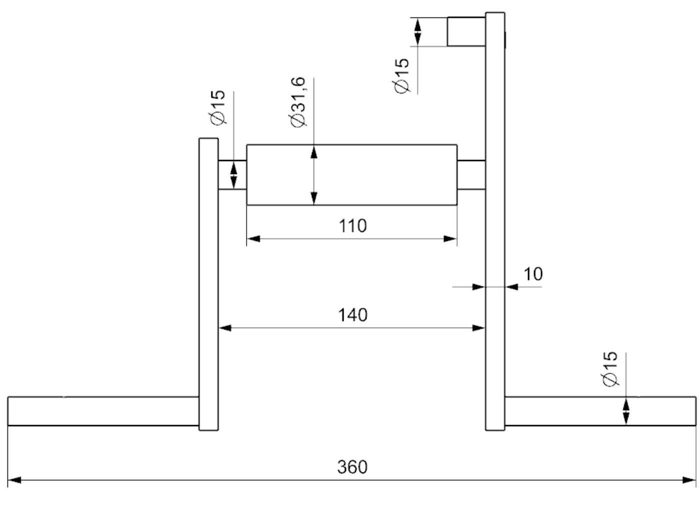


Figure 33 Pedal measures – Source: Personal elaboration

5.4.6. Brace

The brace has a simple geometry, consisting on two hitches connected by a long cylinder.

Two parameters are especially important, the length and size of the hitches. The latter will be defined by the diameter of the elements it has to grip, while the former by the distance separating them.

Two models have been created. One is tailor made for the frame design 1, since its length needs to be different from that of the rest.

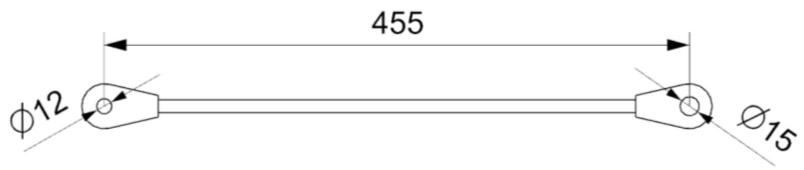


Figure 34 General brace measures – Source: Personal elaboration

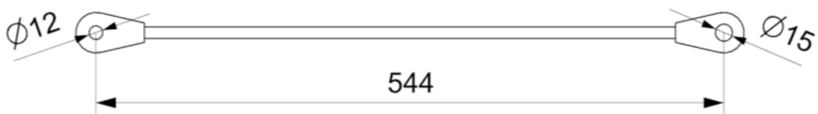


Figure 35 Measures of brace for design 1 – Source: Personal elaboration

5.4.7. Vertical and ball joints

Both elements are combined in a single solid due to them acting as one on the assembly.

Only two size indications are given by the UNE standard. Firstly, the side arms must have the adequate size to fit inside the frame hitches. Secondly, the length between the arms and the lowest part must be equal to R_w.

$$R_w = R_{wheel} \pm 30mm = \frac{677mm}{2} + 30mm = 368.5mm$$

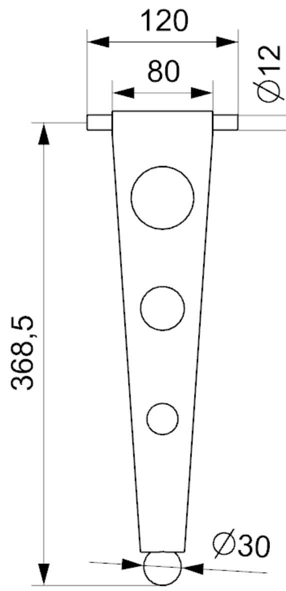


Figure 36 Measures of vertical and ball joints – Source: Personal elaboration

5.4.8. Rigid assembly

It has the same function as the fixed support of tests 1 and 2.

Similarly to the just mentioned joints, the distance between the arm´s lower face must be equal to R_w. Since both supports have the same height, the assembly hitches will be aligned horizontally.

This time, the arms will be located in the connection point with the fork, so their diameter will have to match that of the fork.

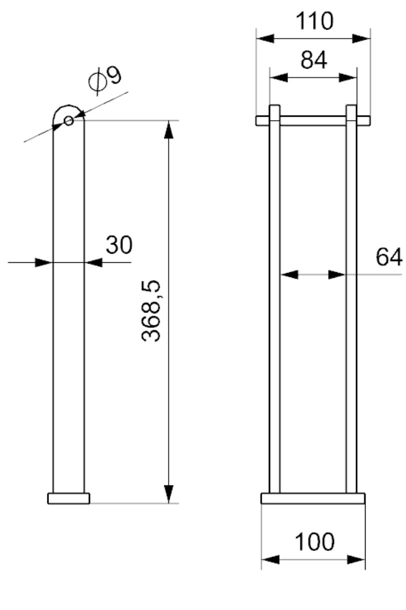


Figure 37 Rigid assembly measures – Source: Personal elaboration

5.4.9. Assembly of components

For each of the four initial frame models, an assembly has been created following the indications of each test standard. In total, 12 initial assemblies have been created for the purpose of comparing them.

Variations with small geometry changes have been generated for smaller verifications. It will be mentioned and explained if they need to be used.

They are divided in three types depending on the test that they are created for. The frame remains unchanged, but the support elements will vary between test types.

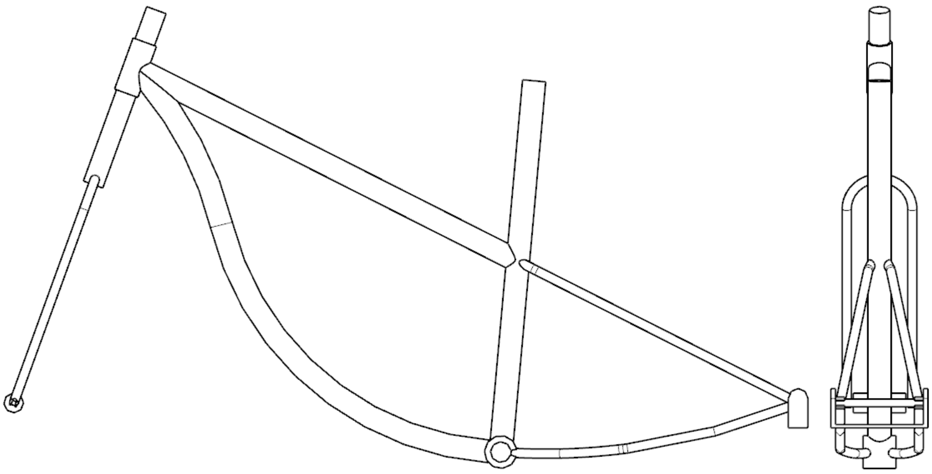


Figure 38 Assembly of design 2 for horizontal test – Source: Personal elaboration

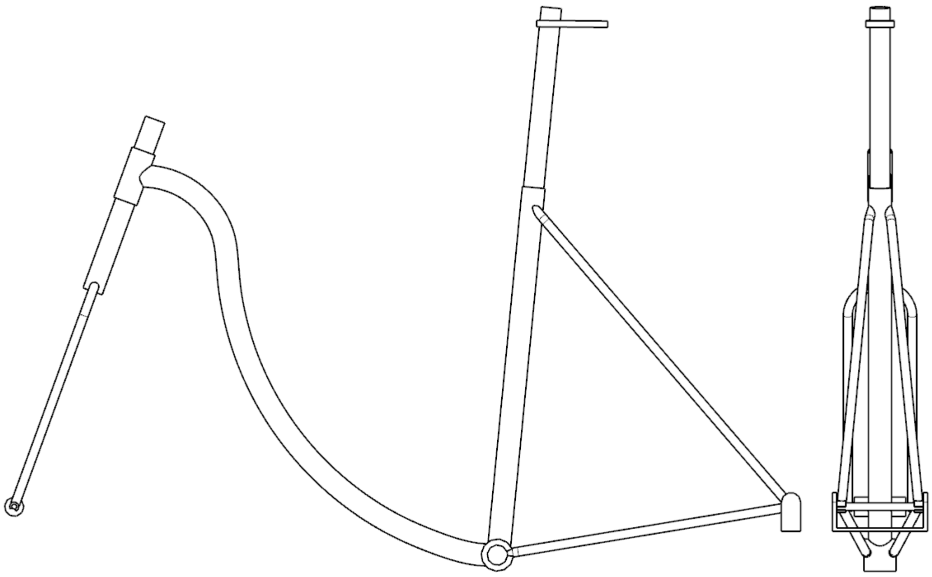


Figure 39 Assembly of design 3 for vertical test – Source: Personal elaboration

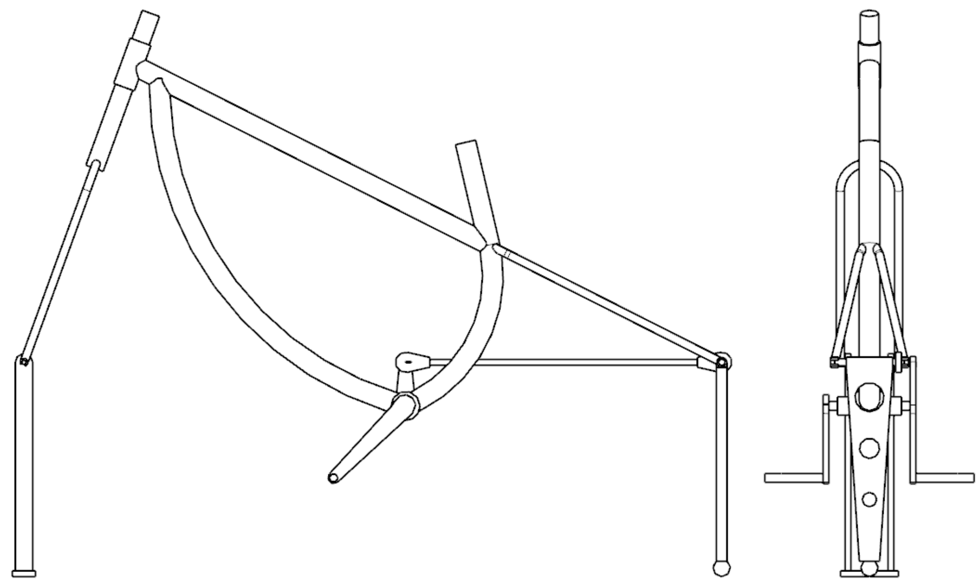


Figure 40 Assembly of design 1 for pedalling test – Source: Personal elaboration

After creating all the assemblies in NX 12, they have been exported as "*.step*" files. This is done to ease the process of importing the geometry to the program used for the analyses.

5.5. Finite element analysis program

To obtain the results required for the frame comparison, a program capable of calculating the stresses that a model will suffer in any point of its geometry is required. To perform this task, a "FEA" or "finite element analysis" program must be utilized. The application of this system reduces the cost and time that would be required to analyse a real model under the same proposed conditions.

For this project the program Ansys has been selected. The version used is "ANSYS STUDENT 2022 R1". [19]

Being a version provided for free to students it has certain limitations. It has a limit of 128K nodes and elements, enough for the models analysed on this project. [19]

Ansys was chosen due to the easy access to the program and the possibility of calculating fatigue with it.

Ansys configuration:

Among the options provided by Ansys mechanical, the module that will be used on this project is called "static structural". The steps and data required to configure it will be explored on the following segments.

5.5.1. Geometry

Ansys gives the options of creating a geometry with its own module or importing an already existing one. It has been decided to import the geometries created in NX 12. To make this possible, the assembly models have to be saved as ".step" files.

5.5.2. Material

Ansys contains a library called "Engineering data source" which contains information concerning a wide range of materials that can be applied to the previously imported solids. This includes information such as its density, elastic limit or S-N curves. The S-N curve is uncommon and only included in a small material selection.

For the initial tests, the material will be chosen from this data source. "Structural steel" is going to be used for all support elements and "Aluminium alloy" for the frames.

Table 10 Material properties – Source: Personal elaboration from ANSYS material data

	Density [Kg/m^3]	**Tensile yield strength [Pa]**	**Compressive yield strength [Pa]**	**Tensile ultimate strength [Pa]**	**Young modulus [Pa]**	**Poison´s ratio**	**Bulk modulus [Pa]**	**Shear modulus [Pa]**
Structural Steel	7,860	$2.5 * 10^8$	$2.5 * 10^8$	$4.6 * 10^8$	$2 * 10^{11}$	0.3	$1.667 * 10^{11}$	$7.692 * 10^{10}$
Aluminium Alloy	2,770	$2.8 * 10^8$	$2.8 * 10^8$	$3.1 * 10^8$	$7.1 * 10^{10}$	0.33	$6.96 * 10^{10}$	$2.669 * 10^{10}$

Ansys also allows the possibility of tabulating the data of new materials not present in the library if deemed necessary.

5.5.3. Connections

A connection is automatically created corresponding to each contact between two different solids in the imported assembly. Additional contacts can be created by selecting the faces of two solids.

During a simulation, contacts limit the movement that each component of the assembly can do. If two faces without a defined contact try to interact, they will pass through each other without resistance. A contact must be created between all foreseeable interactions of two bodies.

A contact will be created between two solids wherever the program detects a small enough distance. This can lead to contacts being created incorrectly. This error can be solved by supressing the undesired contacts or changing the selected faces of both geometries. Small changes of this nature have been performed to ensure a correct simulation.

It is possible to choose among a range of contact types when creating a connection. These include bonded, frictional and frictionless among others.

All automatic contacts are created with the “bonded” type preselected. A contact of this type causes the two solids to act as a single body. All the selected faces act as glued together and no rotation, separation or sliding can occur between them.

This is appropriate when a distance has to be kept constant or a strong coupling wants to be simulated. An example being the contact of the frame with the seat shaft. The standard defines a height that has to be maintained and it also simulates the tight grip that must happen between those two elements.

The first round of simulations has been made using this type in all contacts. While restricting the rotation, it gives valuable information on stress concentration areas of the frame. It could potentially bring to the limelight factors that would otherwise be overshadowed with a different configuration.

For the second round of analyses, the frictional and frictionless types have been considered.

The frictionless contact allows the two objects to separate tangentially and slide without resistance. It would only be applied on certain contacts that would normally slide. These include the ones affecting all hitches, simulating how wheels would need to rotate; and the brace around the vertical joint arm.

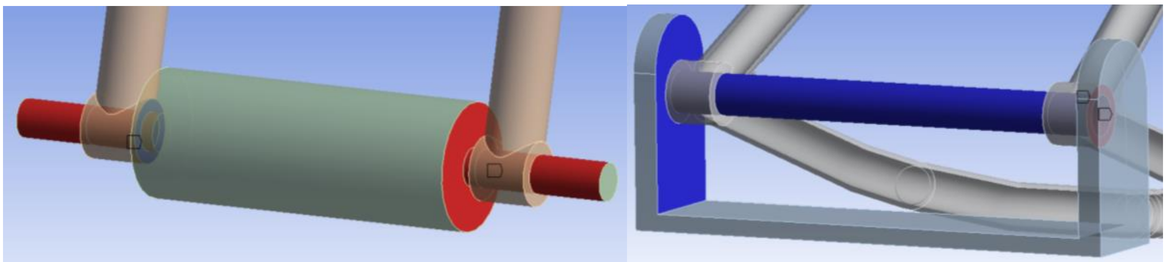


Figure 41 Example of frictional contact locations – Source: Personal elaboration

It has been decided that a frictional contact would be more appropriate. It acts similar to the frictionless variation but adding a COF or “coefficient of friction”. The addition of the coefficient will difficult the sliding movement, since in a normal wheel rotation a resistance would exist.

When tabulating the COF the two materials in contact must be taken into consideration. Between well cleaned mild steel and aluminium alloy, the value is around 0.5. To replicate the lubrication and adjustment for rotation that a hub would have, the value used has been reduced to 0.2. [20]

For a second round of simulations, the bonded contacts have been replaced by a frictional (COF=0.2) on the specified locations. The rest will remain as bonded due to it being a good approximation of the normal working condition.

The two types of simulations will be differentiated as “Frictional” and “Bonded”. No other difference exists between them apart from the ones described on this segment.

5.5.4. Mesh

To make the analysis possible, the geometry has to be divided into small elements that form a mesh. Ansys automatically meshes the whole assembly geometry with a cell size of 0.0711mm.

The mesh quality has a big effect on the simulation quality. Not being satisfied with the automatic mesh, a custom sizing has been introduced. The assembly has been divided in two, frame and supporting elements. For the frames a cell size of 0.009mm has been chosen. The supporting mesh will be of 0.02mm instead.

The whole assembly has to be simulated, but the project is only centred on the frame performance. Only the results of the frame will be compared, with the supports only having the need of providing a correct transmission of the loads. A smaller size is given to the frame to reflect this situation.

Ansys student has a limit of 128K nodes/cells and the more cells generated, the longer the calculation time [19]. For these reasons, the chosen sizes have been selected even if the size could be lowered even further. It has been considered an appropriate amount of cells for the geometry studied.

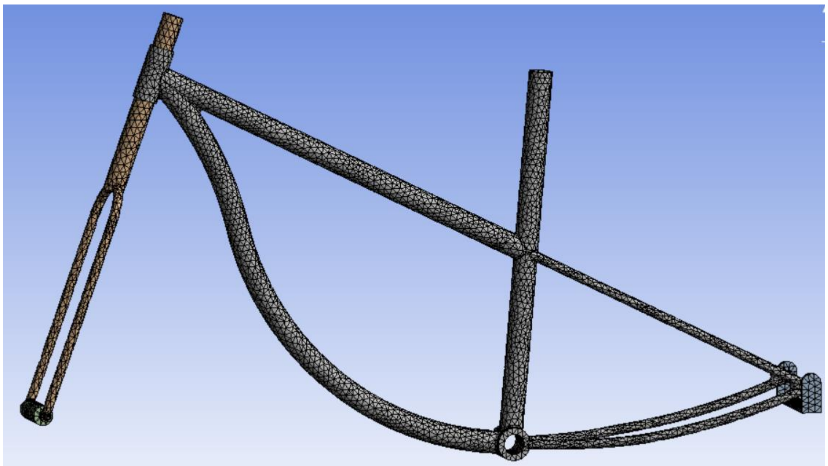


Figure 42 Meshed assembly example – Source: Personal elaboration

When creating the mesh, errors may occur. Among others problems, the Jacobian limit can be exceeded, or some cells may have angles too sharp to provide trustworthy results. As an example, the Jacobian ratio indicates the closeness of each element to its idealized shape. This resemblance is defined by a value within the range of 1 (ideal shape) and -1 (highly deformed). If the values are negative, it will result in a poor simulation unless the mesh is improved. When a complication has arisen while meshing, the sizes have been slightly altered to solve it. [21]

Final mesh values:

Table 11 Mesh size for test 1 (horizontal) – Source: Personal elaboration

Test 1	**Frame size (m)**	**Support size (m)**	**Nodes (qty)**	**Elements (qty)**
Model 1	0.009	0.02	53,880	27,081
Model 2	0.009	0.01	67,447	34,050
Model 3	0.008	0.02	62,584	31,337
Base model	0.008	0.02	72,613	36,377

Table 12 Mesh size for test 2 (vertical) – Source: Personal elaboration

Test 2	**Frame size (m)**	**Support size (m)**	**Nodes (qty)**	**Elements (qty)**
Model 1	0.007	0.02	74,665	37,284
Model 2	0.009	0.02	63,229	31,608
Model 3	0.008	0.02	63,969	32,018
Base model	0.008	0.02	73,998	37,058

Table 13 Mesh size for test 3 (pedalling) – Source: Personal elaboration

Test 3	**Frame size (m)**	**Support size (m)**	**Nodes (qty)**	**Elements (qty)**
Model 1	0.009	0.025	53,696	26,406
Model 2	0.009	0.025	67,126	33,309
Model 3	0.008	0.025	67,866	33,719
Base model	0.008	0.025	77,895	38,759

5.5.5. Boundary conditions

The loads and boundary conditions stated by the standard have to be applied to each fatigue analysis type.

-**Horizontal load (test 1):**

All degrees of freedom of the fixed support are restrained. A total constraint has been applied to the ground face.

With the displacement tool, the displacement of the rolling pin is restricted on the X and Z axis. The rotation won´t be limited, only the translation.

Finally a 450N force is applied on the Y axis to the rolling-pin main face.

-**Vertical load (test 2):**

The first two points of test 1 are repeated for this study.

The force is applied vertically (Z axis) on a downwards orientation with a value of 1,000N. The application point is located on the top face of the seat. A small indentation was created during the modelling process, it is placed on the coordinates that the standard specifies. By applying the load on the indented face, the placing process is greatly simplified.

The rest of the degrees of freedom are restrained, only allowing displacement on the Z axis.

-**Pedalling load (test 3):**

A similar complete constraint is this time placed on the ground face of the rigid assembly. This process still allows the body to deform.

A -1,000N load is placed in each pedal at an angle of 7.5º. An indentation has also been made on the required application coordinates of the pedals.

The joints need to have translation restricted to zero on all directions while allowing rotation in all three from the ball joint. A displacement constraint would not result in the desired movement, the remote displacement tool is used instead to solve the problem. It requires the coordinates of the point from which the rotation will be originated.

The four frame models share the shame coordinate origin. Since the hub placement and the joints are also equal, the same coordinates can be used.

The rotation will happen from the base of the ball joint (0, 1.014, -0.8805) m.

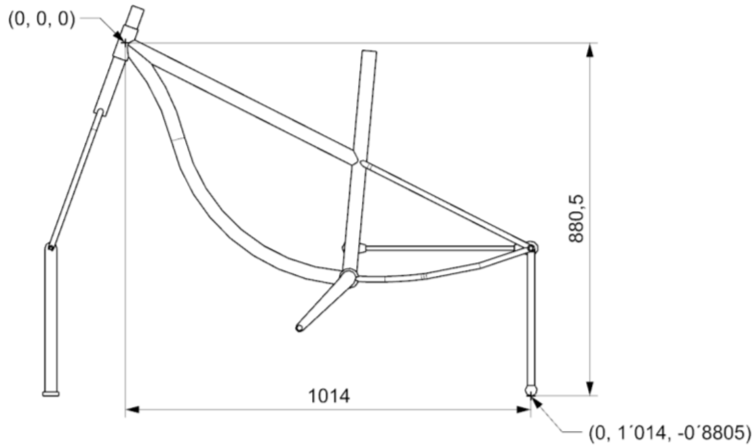


Figure 43 Remote constraint application coordinate – Source: Personal elaboration

It will then be applied to the arms of the vertical joint.

5.5.6. Fatigue and stress tools

After completing the specified steps, the data to be obtained can be specified.

The UNE standard specifies a minimum life cycle amount as the condition to ascertain the reliability of a frame. For low-life fatigue($life < 10^3 cycles$), the dynamic study could be replaced by a static load increased with a dynamic coefficient. For high-life ($life \geq 10^3\ cycles$), as is the case, the approximation would not be adequate. A dynamic fatigue study must be done. The Ansys "fatigue tool" is the one used to calculate the number of cycles that the frame can last before deteriorating. This tool is part of the "static structural" module.

Different options exist for this tool. "Life" is the most appropriate solution for the assignment, it indicates the maximum number of cycles before failure in any point of the geometry. Others include "damage", which compares the life cycles obtained with the desired limit and "safety factor" that calculates the required coefficient to apply to each area. For the last two options, a desired cycle amount must be tabulated, the obtained results are then compared side to side with that intended quantity. Safety factor displays a value between zero and fifteen, with any element with a value under zero failing the requirement. The higher the value the bigger the over-dimensioning of the structure, thus making values around two and three the most desirable.

The fatigue tool acts by turning the static load tabulated into a dynamic one. It needs to be specified the way that it has to happen. Two options have been used to analyse the assemblies, “Fully reversed” and “Zero-based”.

The first option is adequate for the horizontal test. It works by raising the load from a value of zero to its maximum (F2 = 450N) and then reversing the progression until reaching the opposite value (F3 = -450N) before returning to the starting point. This sequence fits the description of the two load sequence of test 1, where two equal but opposite loads are necessary.

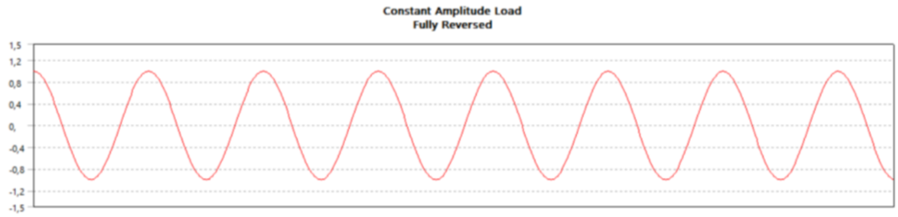


Figure 44 Fully reversed load – Source: Personal elaboration as depicted in ANSYS data

“Zero-based” has been selected for the remaining two tests. Both require the load to change from zero to its maximum value before returning to the initial state in each application. It can be summarized as applying a load before slowly removing it.

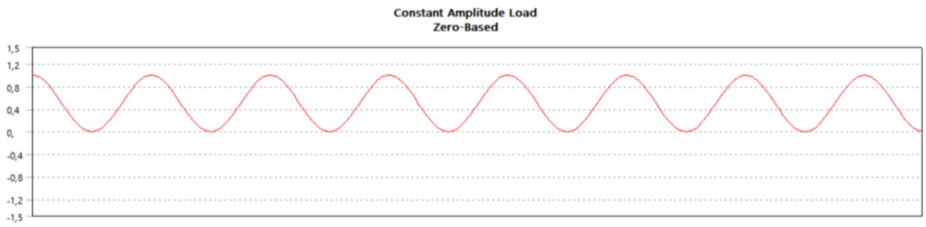


Figure 45 Zero-based load – Source: Personal elaboration as depicted in ANSYS data

It perfectly fits the needs of the vertical load test but requires further changes for the pedalling load. No fatigue tool option can create a sequence between two loads, both will act at the same time. Due to this, the simulation will be performed with only one of the two pedals being affected by a load. It will then be repeated using the other pedal. The stresses on both cases will be compared to find the highest.

To gather extra information that will help locate the failure reasons, the stress tool has also been used. The “Equivalent stress”, “Maximum shear stress” and “Maximum principal stress” options have been considered the most useful for this task. The shear and normal tools, each calculates its namesake stress type in one of three directions; they provide the most straightforward results but need effort to compare the effect that the three options will have as a whole. The equivalent stress option uses Von Mises to calculate the overall stress on each element. It eases the process of determining the total stress value but does not give information like direction or origin type. Similarly, maximum principal stress functions by figuring out the maximum stress but only in the principal direction of each element.

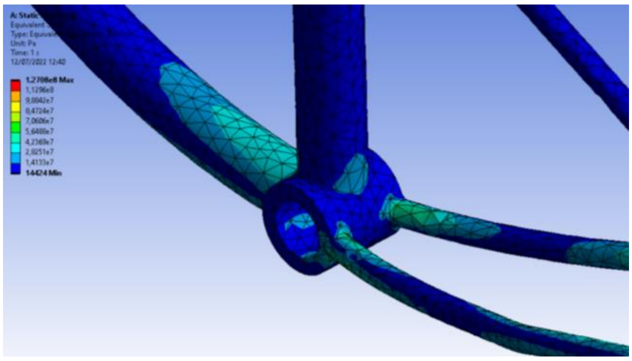


Figure 46 Equivalent stress analysis – Source: Personal elaboration

The simulation calculates the values of all the geometry bodies as a default. To improve the accuracy, the frame data can be isolated.

5.5.7. Mean stress theory

Ansys does not make a true dynamic fatigue analysis. It treats a static load as dynamic and calculates the stresses on a single cycle.

As mentioned while discussing the selection of material, Ansys has data of the S-N curve of the two materials being used. S-N curves depict the relation between the maximum stress and number of cycles before fatigue failure. Normally, materials will have an elastic limit that if exceeded will cause damage to the body. That limit can be lowered through the repetitive application of loads until even a previously harmless force can cause damage. The decline is represented on these S-N curves. [14]

Ansys compares the previously calculated set of stresses against the adequate S-N curve of the material and searches for the life cycle amount where it becomes critical. To do this, an extension is done on the diagram from the stress axis to the curve (see figure 47). Then, the obtained point is extended to the life cycle axis in order to find the number of cycles endured under that stress. That value will be given as the life of the geometry under those conditions. [22]

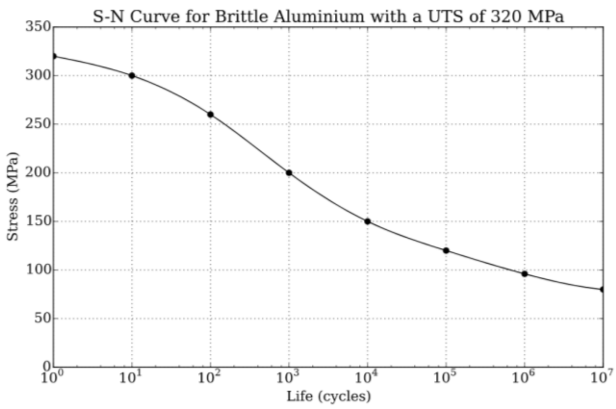


Figure 47 S-N curve diagram example – Source: N. (2016, January 27). S-N curve for a brittle aluminium with a ultimate tensile strength of 320 MPa. *[Diagram]. Wikipedia. https://es.m.wikipedia.org/wiki/Archivo:BrittleAluminium320MPa_S-N_Curve.svg*

These diagrams are usually prepared for zero-mean stress conditions ($\sigma_m = 0$) where the load is fully reversed. For cases where the mean stress is not zero, new tables or experimental data are required. When this is not possible, a mean stress theory has to be applied as previously mentioned. It converts the non-reversed values into zero-mean based. This can be done manually, but Ansys is able to automatically make the conversion and give the corrected values. For it to do this, one of the offered mean stress theories has to be selected when configuring the fatigue tool. [22]

Some of the most used options are Goodman, Soderberg and Gerber among others. Each one has advantages and disadvantages so one has to be selected depending on the necessities. Goodman is the most used but is overly conservative, the values obtained will be higher to increase safety. Soderberg is appropriate for ductile materials but is also considered too conservative. Gerber has been the chosen one due to it being the most exact and still being useful for ductile materials. [22]

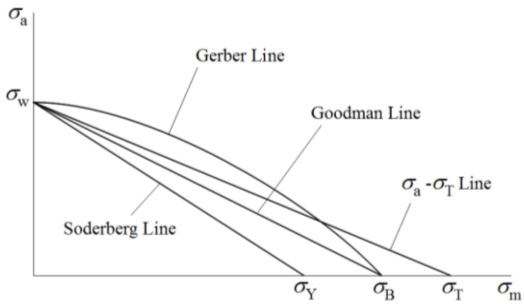


Figure 48 Fatigue limit diagram – Source: Yapparina. (2013, June 30). Fatigue limit diagram(Goodman line et al.) [Graph]. File:Fatigue Limit Diagram.Png. https://commons.wikimedia.org/wiki/File:Fatigue_limit_diagram.png

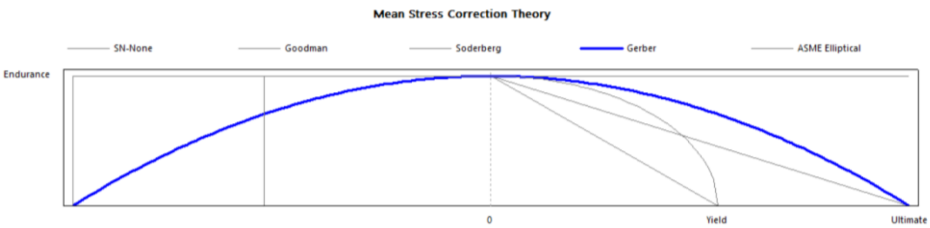


Figure 49 Gerber theory as depicted by ANSYS – Source: Personal elaboration from ANSYS data

Ansys also needs a stress-component input. It turns the simulated multiaxial FE (finite element) values into uniaxial experimental data. The one used is defined as “Equivalent (Von-Mises)” on the program. [22]

5.6. Frame comparison

Before starting the official tests a small amount of analyses have been done to ascertain that the use of a simplified fork won´t affect the veracity of the results. Two sets of tests have been done for the same design, only changing the type of fork used. Overall, the results obtained for the frame are the same in both cases. The only changes can be seen on the fork itself, the original one having a smaller area where the stress spreads and requiring a slightly longer processing time. Additionally, although rarely, the assembly with the un-simplified fork presents problems in frictional tests. In those cases, the program takes a substantially longer calculation time than the simplified option; the values obtained are still similar in both cases.

Due to these conditions, it has been decided to use the simplified fork option. It doesn´t have an appreciable effect on the results and shortens the calculation time in certain cases.

As stated on the material section, the supporting elements will be made of structural steel with a yield strength equivalent to $2.5 * 10^8\ Pa$. Alternatively, the frame is composed of aluminium alloy, having a yield strength of $2.8 * 10^8\ Pa$.

5.6.1. Initial comparison stage

As stated before, using the base design as a framework, the four frames will be compared. The comparison will be centred on the concept of fatigue presented by the UNE EN-ISO 4210 standard. Before being eligible as the best alternative, the minimum life cycles must be achieved. The first step will be dedicated to finding which meet the requirements.

For each bicycle frame three different tests will be performed: Test 1, horizontal loads; Test 2, vertical load; Test 3, pedalling loads.

Within each test, a bonded and frictional option will be studied. While frictional is the one considered as closer to reality, the bonded variation will provide additional information.

Primarily, a fatigue life tool will be used. Additionally, values like stress or safety factor will be added when deemed beneficial.

5.6.1.1. Frame design 1

-<u>Test 1</u>

Frictional:

Under these conditions, the frame fails the test. On the horizontal test, the whole frame has to present cycle values higher or equal to 10^5. At present the model does not fulfil this requirement.

Good conditions of at least 10^8 cycles are obtained for most of the geometry. The points of contention are the top and seat stay tubes. Both present lower values at around 10^5 cycles at minimum.

The displacement transmitted from the fork, causes a stress concentration on the top tube to appear, specifically on the connection with the head tube.

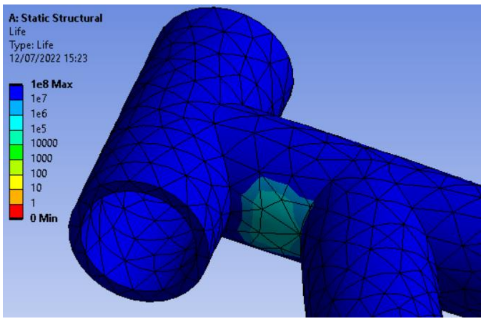


Figure 50 Top tube damage of design 1 – Source: Personal elaboration

Similarly, the seat stay tube has a tendency to bend around the contact area with the seat tube. Having only a set of stay tubes, all the tension from the back wheel concentrates here.

Although lower, both areas have values well inside the required cycle limit. The failing criteria is met on the back hubs of the frame. The stress concentration is too high to complete a single cycle without the appearance of potential damage. Both the open cylinder geometry and start of the tube, suffer more damage than the material can put up with.

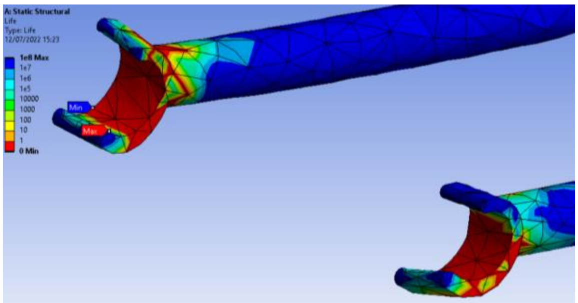


Figure 51 Hitch damage of design 1 – Source: Personal elaboration

Bonded:

The situation changes when the hitches are glued and not allowed to rotate. The two previously mentioned areas of interest have better results. The area affected is reduced and so is the damage to the life values, the minimum being at 10^6.

The hitch area suffers the greatest change. No failure or deformation happens in them. The seat stay tube bends slightly, receiving the deformation that the hitches did previously but the values are still way over the requirements.

The test can be considered as passed.

-Test 2

Frictional:

Differences with the first test can be seen at a first glance.

While the top tube is no longer affected, the seat stay tube has worse values. It reaches zero life cycles in a wide area. A single pair of tubes is not enough to resist all the tension of the back wheel.

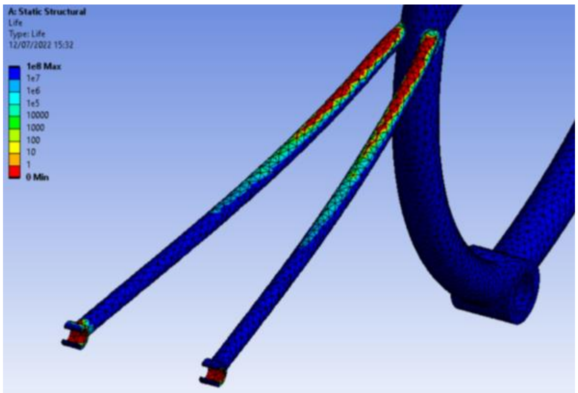


Figure 52 Seat stay tube damage of design 1 – Source: Personal elaboration

The hitches break once again on the first application, the tension being higher than their initial elastic limit.

A new affected area can be seen on the head tube. All the tension is localized in a small zone, causing it to fail. The previously mentioned $5 * 10^4$ cycle requirement of the vertical test is not fulfilled on this area.

Bonded:

The fatigue symptoms are reduced to those of the seat stay tube; this time, still obtaining good results.

As in the previous bonded tests, the hitches are not affected and instead it transfers to the stay tubes. The effect is still low (10^6 cycles) and enough to pass the test.

-<u>Test 3</u>

Frictional:

The damage is lower than in the two previous tests. The only part of the geometry with signs of damage is the hitch interior. It fails the test on that area, but it does not extend to the tubes.

This happens for both load configurations, with only a small variation on which hitch is more affected. In neither of them is achieved the goal of 10^5 cycles specified for the pedalling test.

Bonded:

Both hitches present small points of failure, but only on a single one of them with each load. Differently than on other cases, the rupture does not happen in all the interior face, only on the corner closer to the center. It is probably caused by it being compressed when the frame is pushed on that direction.

The remaining geometry is unaffected.

-<u>Summary</u>

All frictional tests fail. The bonded variations have better results due to placing less stress on the hitches, the normally most affected area. Despite this, the bonded test fails the third test.

5.6.1.2. Frame design 2

-Test 1

Frictional:

Once again, the test gives negative results although different from the previous case.

The areas with lower cycle counts on the top and seat stay tubes are almost completely missing. The overall performance in better than that of design 1.

The dual stay tubes alleviate the problems present with a single pair.

The type of connection to the head tube has to be considered as better than the previous one, the simpler connection giving better results. A slight cycle decline is still present on the underside area but has values of 10^7 cycles, greatly surpassing the 10^5 cycle limit.

The critical damage still occurs on the back hitches. It reaches zero cycles due to the great stress present. The whole hitch is affected and extends to the beginning of both stay tubes, before quickly returning to acceptable results.

Bonded:

The design is considered to have a life of 10^8 cycles in all the geometry. That is the maximum amount that Ansys calculates and can be considered as infinite life. No damaged area is detected.

-Test 2

Frictional:

The only affected parts are the hitches. While they fail the test with zero cycles, the rest of the frame is not affected by the load.

Bonded:

It does not show affected areas. It passes the test with infinite life.

-Test 3

Frictional:

The only areas affected are both hitches. Both fail on the two configurations.

Bonded:

It presents the best results for these conditions. On the same manner as the first design, fatigue happens on the corners of the hitches. This time the lowest value is 10^6. It obtains really good values in comparison with similar cases.

Even if the load is changed, it affects the same hitch. The occurrence point changes, for one the top corner is affected and for the other the lower center. It possibly depicts the compressed area during the movement. Affecting always the same hitch might lower its total life when seeing the two load configurations as a complete cycle. It will receive double the applications calculated with a single load, something not taken into account the way it is being done.

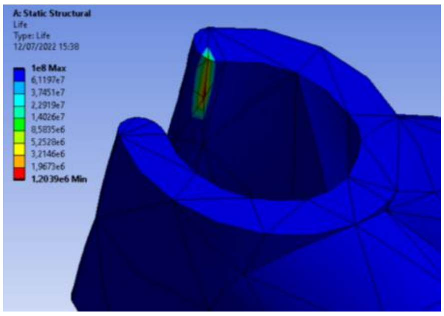


Figure 53 Reduced hitch damage on bonded tests – Source: Personal elaboration

-Summary

Contrary to all the bonded tests, which are successes, all frictional tests fail. As in the previous model, most of the problems in both variations stem from the hitches.

5.6.1.3. Frame design 3

-Test 1

Frictional:

It works in a similar manner to the previous cases. A lower but not dangerous life cycle amount of 10^5 can be seen on the beginning of the central tube, which also acts as top tube this time.

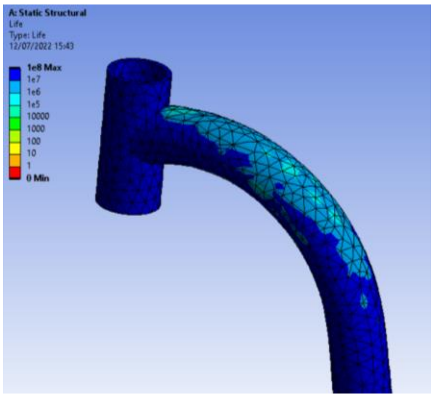


Figure 54 Central tube damage on design 3 – Source: Personal elaboration

The stay tubes have the same lifespan as the rest of the frame.

The failure cause happens on the open hitch, with a life of zero cycles. Curiously, it spreads further on the right side than on the left.

Bonded:

The only area affected by the test, is the central tube. The connection with the head tube has the lowest life of the frame, while still surpassing the required limit at more than 10^5. Not having a top tube, most of the stress is concentrated on the swan-neck lookalike tube. It is the first area of the frame to receive the load transmitted from the fork.

-Test 2

Frictional:

Only the hitches remain affected. While they fail in a similar way to the previous models, the rest of the frame has infinite life. Once again, one of the hitches is slightly more affected than the other.

Bonded:

No signs of fatigue can be seen. It passes the test.

Most of the model displays an excessive safety factor of fifteen, with some areas, especially the connections to the crank tube, being around ten. From these values it can be deducted that some structural tubes are for the most part oversized. With variable tube sections the design could be optimized, but in order to simplify the process, constant section tubes will continue to be used. Some areas on the central and crank stay tubes display safety factors closer to three. Reducing the thickness of the tubes could prove detrimental for their performance.

-Test 3

Frictional:

The failure happens as in the previous cases, in the hitch interior. This time, only one of the sides fails, while the other only has reduced life. The one affected changes with the side on which the load is applied. Due to this, both can be considered to fail, as a true complete cycle would include both loads.

The rest of the frame is almost not affected. One of the few sections with damage signs is the central tube. Instead of at the top, close to the head tube, it happens at the opposite end of the tube, next to the crank tube. At that point, the life is reduced but remains well over the requirements, reaching 10^6 cycles. A new point of critical failure is located on the crank tube as seen on figure 54. The affected area is contained to a single point. Although small, the area sustains enough damage to break before completing a single cycle.

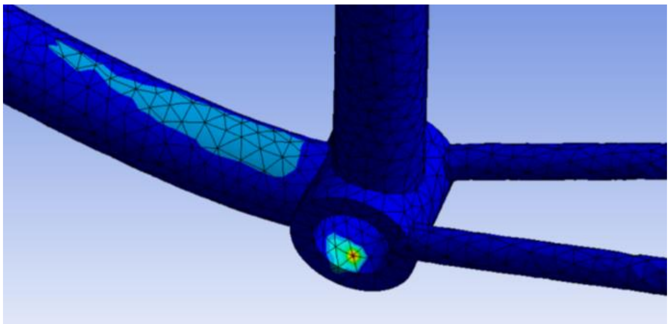


Figure 55 Crank and central tube damage of design 3 – Source: Personal elaboration

Bonded:

Small areas of both hitches are affected at the same time with values of zero complete cycles. It tends to gather at the corners but also at the center of the rounding.

-Summary

It shares its results with the first model. All frictional tests fail. The third test fails on both frictional and bonded iterations.

5.6.1.4. Base frame design:

-Test 1

Frictional:

Being the most common and refined design, it presents next to no damaged areas. The only fail zone is once again the back hitches. Both fail but the propagation is relatively low.

Bonded:

The whole frame can be considered to have infinite life. No area is specially affected.

-Test 2

Frictional:

Only the interior of the hitches is affected, failing at the first cycle. It spreads less than in the other models, an exception being the second, where the values are similar.

Bonded:

The elastic limit is never reached. It surpasses the limit of Ansys so no failure happens.

-Test 3

Frictional:

Both hitches fail on the first application with either of the two load configurations. Both cases give almost the same results.

The rest of the frame in unaffected.

Bonded:

What has been mentioned for the first and third designs can be seen here again. Failure signs can be seen on the corners and center of the hitch rounding. The improved symmetry of the affected areas is worth mentioning.

Both load configurations lead to the same results.

-Summary

As previously seen on the first and third models, all frictional tests fail in addition to the bonded variation of the third test.

5.6.1.5. Result analysis

Analysing the results obtained, it is clear that the point more prone to failure is the hitches. It suffers high values of traction and compression and due to the open geometry, it tends to deform. In addition to breaking or being damaged, it might also open and release the hub. If this happened on a real bike, it could lead to injury. From this point forward, the frame designs will receive changes to the frame hitch geometry in order to close them.

Another points of discussion include the preference towards the base design, the single stay tube pair of the first design and bonded or frictional contact.

The base frame design presents the best result among all tested. The one closer to its results is the second design, which is an evolution of it. It sharing the same general structure but being more rounded. It shows why it is so commonly utilized despite it being duller looking.

The third design doesn't lag far behind either. The lack of top tube affects the central tube, reducing its life. It still gets high values, more than enough to pass the tests and be a candidate for the final choice.

While having an interesting shape, the first design shows worse results than the other two. The single stay tube pair seems to fail in most cases while not presenting any advantage apart from weight reduction. The connection to the head tube is also different from the rest but does not provide a substantial improvement. Neither of those changes seem to be beneficial.

All of the frictional tests fail with values close to zero cycles. Although there are differences between all the models, the open hitches are repeatedly the cause of failure in this contact type. The bonded type mostly avoids this problem by not allowing the hitch to separate from the supports, subsequently not permitting it to deform. The bonded connection type was added in order to expand the information gathered, but as seen, it glosses over the behaviour of the hitches while not substantially changing the reaction of the remaining frame. Frictional connections give more restrictive values than the bonded alternative and are more faithful to reality, as they represent more closely the real interaction between the hitches and spinning wheels. Due to this, frictional will remain as the main analysis type from now on.

5.6.2. Second comparison stage

In the previous stage it was discussed and decided that the best original designs where the second and third. Therefore this stage will be performed with only these two, having eliminated the first.

This stage will be centred around the effect of changing various geometry characteristics to solve the problems present on the previous one. The initial action will involve closing the cylinders that form the back hitches. The following variations will keep that change and try to improve upon that.

Each iteration will present a new option and it won't include the previous ones. That way the impact of each one can be evaluated individually.

As mentioned before, the contact type will be reduced to frictional due to the more restrictive results and it being closer to reality. Until now all the frictional tests have failed due to the damage sustained by the hitches. By strengthening this area, it is expected to finally achieve positive results with this contact type.

5.6.2.1. Closed hitches

The only redesign performed is the closure of the opening on the back hitches. It will be treated as simply being a tube. The length and diameter measures remain intact.

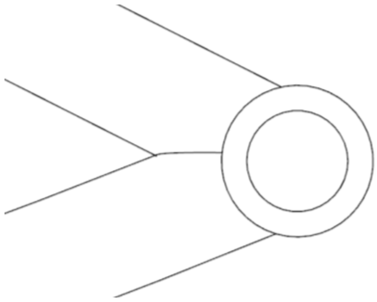


Figure 56 Closed hitch profile – Source: Personal elaboration

Design 2:

-<u>Test 1</u>

Closing the cylinder brings new problems. It causes an asymmetric response on a symmetric model. All the stress is diverted to a single hitch while the other remains unaffected. With this, only one of them fails while the other will have the maximum value together with the rest of the frame.

It is interesting that such an asymmetry would take place. No meshing or convergence problem that could justify it has been found. Until a reason is found it will be considered as the correct solution. Another course of action would be to speculate that it should be shared among the two, which would alleviate the reaction. Values of zero cycles are obtained on the affected hitch, failing the test.

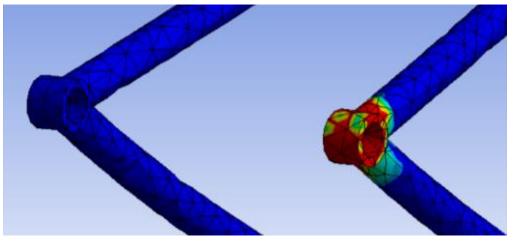


Figure 57 Asymmetric response on the hitches – Source: Personal elaboration

-<u>Test 2</u>

The result is almost identical to the previous test.

By increasing the deformation scale, it is possible to see how the stay tube on the damaged side deforms more than the other. It follows a logical behaviour in that aspect.

Although less, the other side tubes also deform, so the simulation is not affecting only half of the geometry. The load and constraint placement don´t seem to be the cause. Changing the application point does not change the result, as it is applied to the whole face.

-Test 3

It follows what has previously been seen on the two previous tests. The right side is always the one most affected, it won't change even when the load changes sides.

Likewise, the disparity is accentuated when directly analysing the stress types affecting the model. The application of a load on one of the pedals incur in some sides being more affected than others. The maximum principal stress tool shows how the central tube is undoubtedly affected by stress, although not enough to reduce the life of the model; thus not being appreciable on the fatigue test. It mainly happens on the center and connection with the crank tube. Curiously, both areas differ on the side on which the stress is present, varying with the load but always being opposite. The seat tube reacts similarly, only being affected one side, with it always coinciding with the load. The opposite happens to the top tube, the stress appears on the opposite side of the load.

Taking a look on the most noteworthy incident, the asymmetry of the hitches, it can be seen that both hitches and tubes connected to them are affected even if only one of the hitches has a reduced lifespan. While slightly redistributing the stress on the crank stay tube, alternating the loads doesn´t cause any major difference in these elements. The highest normal and shear stresses both happen on the mentioned hitch, the normal stress being the superior. They present small points where their values peak, but when looking at life, it is enough to also cause failure in the surrounding area. While still not clarifying the origin of the asymmetry, the plausible stress results make the theory of a simulation error less probable.

-Summary

The three tests fail due to the reduced life of the asymmetric hitch, which breaks on the initial cycle.

Design 3:

-Test 1

The hitch asymmetry seen in the previous design still happens here. It seems not to be an event isolated to that frame. In this case, it is located on the left side instead.

The stress on the top of the swan-neck shaped central tube is still present. The value is low ($2 * 10^5$ cycles) but won't be a determining factor on the failure of the bicycle.

-Test 2

The left hitch problem is repeated here.

As previously seen on the open-hitch test, some wear happens on the lowest zone of the central tube. The values are similar to what was seen that time (10^6), being within an acceptable range.

More curiously, a new breakage area appears on the head tube. It's a small area that can be seen from the front on the head tube. It seems to be caused by compression, the reason being the constraint placed on the front face. It can’t move on the Z axis, and it causes the fork to push on the head tube when the frame deforms. This point suffers damage since the first cycle.

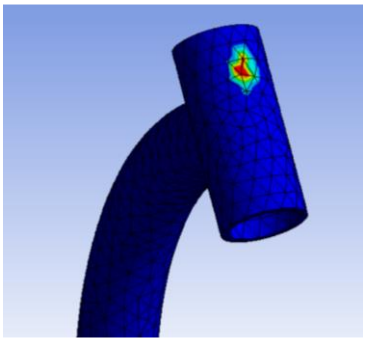


Figure 58 Head tube damage on closed hitch design – Source: Personal elaboration

-<u>Test 3</u>

The left hitch failure still happens, but this time other important changes can be observed.

Most of the central tube is affected by fatigue. The higher areas closer to the head tube have values around 10^5 cycles. The problem comes on the lower area, on the contact with the crank tube. While it does not fail on the initial cycles, it has small areas that only last between 2,000 and 10,000 cycles, not enough to pass the test.

The result on that area is worse than what was previously discerned with the open hitch. It is possible that in that case part of the stress was mitigated by the hitch opening due to deformation.

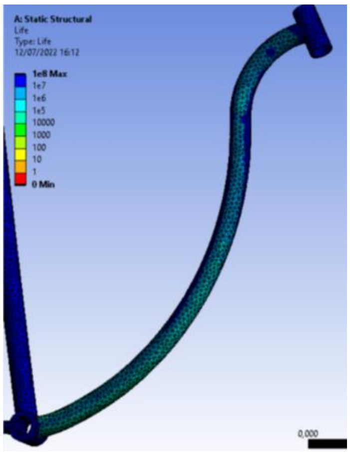


Figure 59 Reaction of central tube of design 3 with closed hitches – Source: Personal elaboration

-<u>Summary</u>

The hitch causes all tests to fail without completing a single cycle. Unlike the previous model, where the damage was solely located on the hitches, this model presents additional failure causes on the second and third tests.

5.6.2.2. Round of edges

The thought process behind this attempt is the idea of mitigating the tensional concentration on sharp edges. These usually appear on the connection between elements, so the round of edges can also be perceived as the shape that welding would leave.

A rounding of edges (Radius = 4mm) is performed on all the connections of the frame. The only exception are the hitches, which receive a different one (Radius = 8mm). This exception is done due to the importance of the hitches and how affected they are on most tests. The rounding connects both stay tubes and reinforces them.

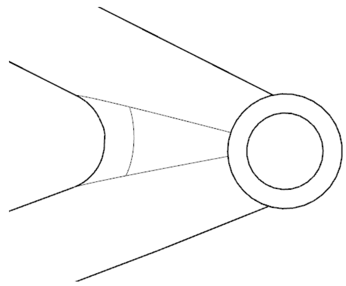


Figure 60 Closed hitch profile with rounding of edges – Source: Personal elaboration

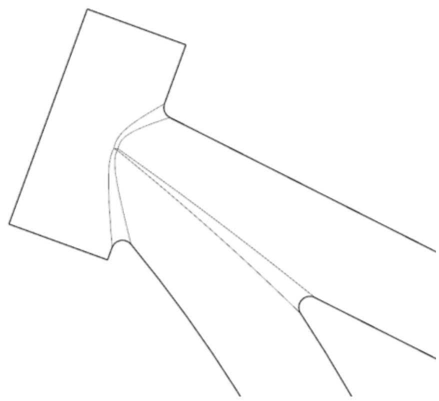


Figure 61 Example of rounded tube connections – Source: Personal elaboration

Design 2:

-<u>Test 1</u>

The results obtained from this variation are surprisingly positive. The lowest value being higher than 10^6, it would pass the test.

Not much of a variation is perceived on most areas since the previous results were already remarkably good.

The biggest change and the intended purpose of the rounding, is that the values on the hitches increase substantially. Neither of the two fail and the wear is almost reduced to nothing. Only a small area is affected on the outside of the left hitch. Curiously, the right hitch was the one affecting this model when it had sharp edges. The asymmetry is still present.

-<u>Test 2</u>

The improvement is repeated here, with the complete frame displaying infinite life.

Both shear and normal stress are present when analysing their involvement. Both happen in similar areas, the center of the tubes or especially on the rounded connections. Overall, the normal stress seems more prevalent, spreading over wider areas. Although not as strongly with the shear and normal stress tools, the maximum shear and principal stress tools mark the seat tube as the most affected, this also happens with the equivalent stress tool. While resisting and displaying exceptional results, this area is undoubtedly the most affected in the vertical test due to it being the first to receive the load from the seat.

-Test 3

The model presents infinite life for both load configurations.

-Summary

It's the first instance where all frictional tests of a model are successful.

Design 3:

-Test 1

Not much change is appreciated to be caused by the rounding of edges.

Some wear still happens on the front of the central tube but the values are not concerning and the area affected does not spread. That area, at its lowest still has values over 10^5. This is similar to the previous horizontal load tests done to this model. The stress concentrates there due to it receiving the influence of the pushed fork.

The other debilitated area remains being the left hitch, which still fails on the initial application. It still receives most of the load on an asymmetric manner. As a positive, the affected area of the hitch has been reduced, meaning that the rounding has caused an improvement.

-Test 2

Once again the only failing component is the left hitch. The effect of the strengthening on the area is once again indicated by the reduction of the area that breaks.

Another benefit of the rounding is seen on the central tube. The previously comparatively more damaged area (10^6 cycles), now shares the same 10^8 life cycles as the rest of the frame.

-Test 3

The benefits of rounded edges are reiterated.

While the left hitch sees a minor but insufficient improvement, the main consequence is spotted on the central tube. The extensive damage that it suffered on the closed hitch test has greatly been reduced. It only remains affecting the lower area close to the crank tube. Even there, the values are now within a manageable range that can pass the test as they are over 10^5 cycles.

-Summary

In spite of noticing an improvement on most of the frame, the hitch is still affected and damaged on the earliest application. All three test are affected by this phenomena.

5.6.2.3. Remake hitch geometry

For this attempt the hitch is completely reimagined, discarding the original tube. It is instead created as a solid block resembling a triangle. The edges are then rounded to give it a more streamlined appearance.

The stay tube exterior diameter has also been increased one millimetre to a total of fifteen. It has been done in hopes of reducing the bending that they suffer and improve the connection with the bulkier hitch.

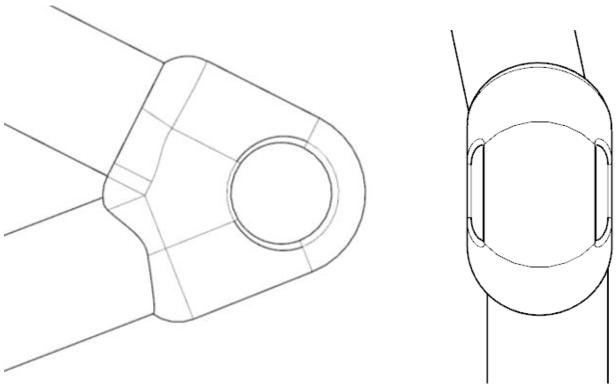


Figure 62 Redesigned hitch profile and front views – Source: Personal elaboration

Design 2:

-Test 1

The performance obtained is disappointing. Most of the frame remains in good working conditions but both hitches fail instantly. Most of the blocks forming them show signs of damage, both failing the test. A small asymmetry can be seen, the damage extending a bit more on the left one. It won't be of much importance since both are in mostly the same condition.

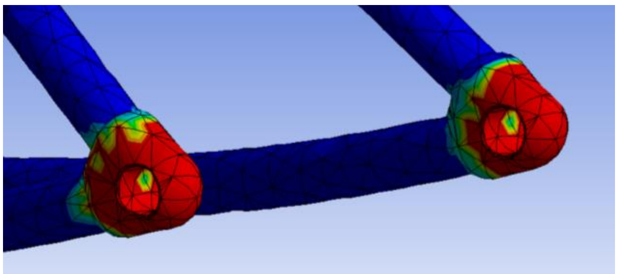


Figure 63 Redesigned hitch reaction – Source: Personal elaboration

An attempt of correcting this has been made by increasing the size of the new hitches. The original external diameter of 20 mm has been increased by 3 mm to a total of 23 mm. A small size increase results in a proportionally big reduction of damaged areas. The left hitch is completely freed of damaging tensions, reaching infinite life. The right side is also subjected to an improvement, with most of the exterior getting better results. Sadly, the interior that will be in contact with the hub is still damaged and fails the tests.

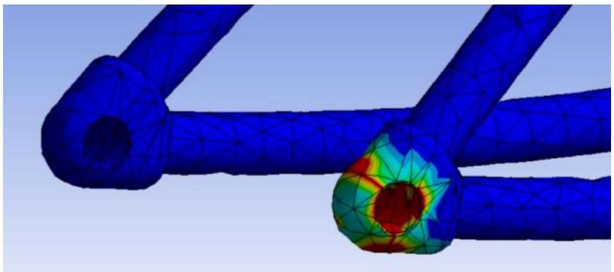


Figure 64 Change in redesigned hitch reaction after size increase – Source: Personal elaboration

An attempt could be made to keep increasing the thickness after seeing its positive influence. It has been decided not to do so due to the already present size disparities with the rest of the frame. Making it even bigger would not be an efficient option.

-Test 2

The results are similar. The right hitch fails but only on specific points. The rest of it has lowered maximum cycles but these improve with size.

In an attempt to add clarity, the stresses affecting the hitch have been analysed. The hitch is heavily affected by normal stress, while the Z axis is the most noticeable the remaining two also have a perceptible influence. The shear stress is slightly lower in either of its three components. It is similar to the behaviour presented on the original closed hitch test, but with it spreading further despite the bigger amount of material.

The remaining model does not present any noticeable difference in its stress placement compared to previous similar cases.

-Test 3

Wear affects the right hitch even with the maximum tested size. All of the interior and part of its exterior fail on the first cycle.

-Summary

The adjustment is a failure, neither of the tests or sizes being a success.

Design 3:

The third design, in overall, shows worse results than the second. Due to the change being prejudicial for the second, it has been assumed that it will also happen to the third.

It has been decided that the new design is worse than the one originally planned.

5.6.2.4. Increase hitch diameter without redesigning it

In an attempt to locate a simple solution for the persistent hitch degradation, an experiment has been done in which its thickness is increased. The only change performed is the increase of the external diameter of the two frame hitches from 18 mm to 20; increasing the thickness from three to four millimetres.

This small venture has been deemed fruitful, since the results of the six tests display an outstanding improvement. While not affecting the rest of the frame, all of them reduce to zero the damage dealt to the hitches. The desired outcome of 10^8 cycles is achieved in all the cases, also preventing the spread of damage to the stay tubes.

Despite being a small change, it has a noticeable effect on the previously harshly affected area. A bigger increase would be discouraged due to aesthetic reasons, the hitches would be disproportionately big compared with the stay tubes.

The original diameter seems to be on the brink of being not enough, varying greatly with each redesign. This property makes it a good bar for measuring the effectiveness of each change.

5.6.2.5. Result analysis

From the results, it can be deduced that the best options to keep while moving forward are the closed hitches and the rounding of edges.

The redesigned hitches will be discarded. Despite the addition of material, the results worsen from the previously seen. An emphasis was placed on the connection with the stay tubes instead of the hitch itself.

The increase of hitch thickness solves the problems of most designs. Continuing with this change would trivialize the tests done in the following stages. On account of this, despite it being the better option, the test will continue to be done with the original diameter. This way, the effect of the new variations will be made easier to quantify depending on their effect on the area most susceptible to damage, the hitches. It will be taken into consideration when deciding on the features of the final model.

Due to its higher fatigue resistance in most cases, the next attempts will be made using the second frame model. The third one that was also being studied will be eliminated for the next round of variations.

5.6.3. Third comparison stage

While on the previous stage the effort was centred on solving the shortcomings of the designs, especially the damage received on the hitches, this one will explore the effects of section and size changes. It is done in hopes of understanding the repercussions of changing the type of tubes, as a wide variety of complex sections can be found on the market.

As previously stated, this stage will be done only on the second design; the one with be best performance on the previous stages.

5.6.3.1. Section change of front and central tubes

Since the beginning, cylindrical tubes have been used for the frame, this attempt is centred on changing it to a different shape.

Due to the connection requirements, only the central and top tubes will be changed. If the seat tube was changed, it would not be possible to insert the seat shaft. The head and shaft tubes need to be cylindrical to allow the supports they hold to rotate.

If the outcome is satisfying, it might be possible to also reshape the stay tubes.

The new shape is rectangular with the shorter sides rounded.

The changes have been added to the model that had previously received a rounding of edges.

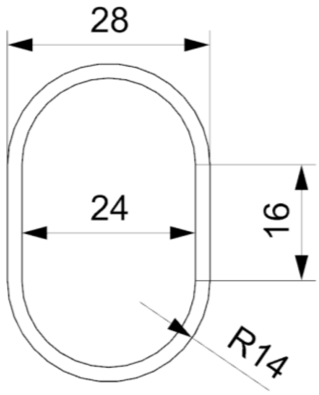


Figure 65 Measures of redesigned top tube – Source: Personal elaboration

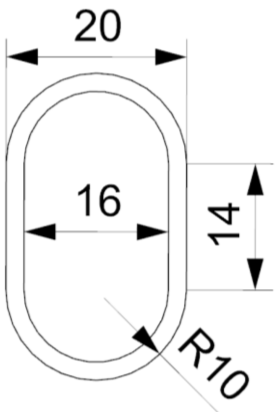


Figure 66 Measures of redesigned central tube – Source: Personal elaboration

-<u>Test 1</u>

The result on most of the frame is positive, the change is not inherently negative. It repeats a similar behaviour to what was previously seen.

The asymmetric reaction is still prevalent and intensified. It results on the right hitch being damaged since the initial cycle. It fails the test on most of the hitch surface.

It seems that the new top and central tubes transmit more load with the new shape, resulting on the hitch receiving it. The effect may vary for different application directions.

-<u>Test 2</u>

As expected, the right hitch is still the most damaged area. It behaves almost the same way as on the horizontal test.

It is worth mentioning that the top tube is almost impervious to deformation in this direction. Even at high scales the bending is almost imperceptible. The central tube bends slightly more but still gives good results.

The safety factor tool gives really high values to the new sections, almost always achieving the maximum value and close to the crank dropping to nine. Being way over the desired safety factor of three, it can be stated that these two tubes could be resized in order to obtain a better optimization.

-Test 3

The left hitch suffers damage once again, it happens with either of the two forces on the first cycle.

The central and top tubes continue to react positively in this scenario. The top tube remains almost intact, but the central tube suffers more sideways bending. It is not enough to damage it but shows how a rectangular tube has a preferred application direction. The appearance of a favoured direction is expected due to the different moments of inertia of a rectangle´s faces. The tube redesign was done in an attempt to capitalize on this characteristic, but its application has been shown not to be beneficial for this frame.

-Summary

As seen in previous variations, the hitches fail on the three tests.

5.6.3.2. Section change of stay tubes

Similarly to what was previously done to the central and top tubes, the section of the stay tubes has been tinkered with. A similar shape but with different measures has been utilized. In that case, the change reinforced the frame but placed a higher pressure on the hitches. The aim of this test, it to ascertain whether the same will happen if applied to these tubes.

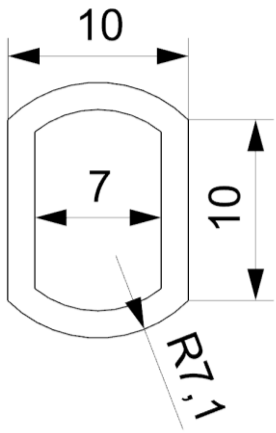


Figure 67 Measures of the redesigned stay tubes – Source: Personal elaboration

-Test 1

As expected, the section change results in the stay tubes suffering a reduced deformation from what was previously seen. Despite this positive outcome, the hitches suffer more than with the circular section. The load is transmitted to the hitches, which are not able to dissipate it without being strained over a big area.

The hitches break on zero cycles, obtaining worse results than with the un-edited rounded model.

-Test 2

The tubes show high resilience to the load and almost no deformation, but the hitches are not able to clear the test requirements. The area affected is lower than on the first test but it still breaks at certain points. A bit of asymmetry can be seen on the areas affected, with the left one suffering the most.

-Test 3

In addition to the hitches failing, a new point of interest appears on the crank tube. The lower right corner is damaged to the point of failure on the earliest cycle when applying the load of the right side pedal; this is avoided when applying it on the left one.

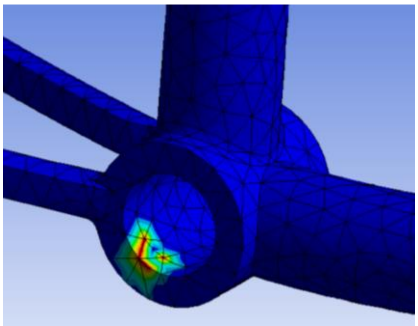


Figure 68 Crank damage on frame design with redesigned stay tubes – Source: Personal elaboration

The section change makes the stay tubes more rigid, demanding more from the crank tube in return. It can be considered an un-desired outcome.

-Summary

All three tests are unsuccessful. The failure always happens before a single cycle is completed.

5.6.3.3. Result analysis

Changing the shape of the front half of the bike gives similarly good results and makes it narrower. As a downside it absorbs less stress, causing the hitches to receive it. Some hitch improvements must be added in order to use this variation. Reducing the top tube size might help deal with this.

A similar effect is appreciated when changing the section of the stay tubes. The damage of the hitches is increased in exchange for reducing the deformation of the redesigned tubes. Additionally, it damages the crank tube when applying loads from the sides, making it even less appropriate.

Utilizing the hitch with an increased diameter could help mitigate this downside on both options. Applying the section change on all selectable tubes would result on it being too rigid.

5.7. Final design

In each comparison stage different models and upgrades have been selected or discarded depending on their performance on the fatigue tests. The best characteristics have been selected to produce the final model now presented.

Firstly, from the four models initially available, the second option has been selected. It has a close resemblance to the base design, which was only used as a placeholder for the most common design. Taking this as evidence, the test may indicate that, as expected, it is so commonly used because of it being a simple and trustworthy option. The diamond shape frame with two stay tubes is the best. The selected design, while not deviating greatly, is a twist on it, utilizing more rounded tubes and a different stay tube shape. It has the best response to the loads on the main tubes from the three options.

On the one hand, the most fragile component for all designs has been the hitches; most variations have been fashioned with it in mind. The rounding of edges has a noticeably positive repercussion on its resistance to fatigue. As a result, it has also been decided to incorporate it to the final design.

On the other hand, the hitch fragility was originally solved by the simple act of increasing its thickness. This option was not applied to the tests coming after it so as to use the hitches as a measuring tool of the upgrades´ effect. As stated when it was analysed, this change will also be added to the final frame. Without it, the model was already able of passing the requirements. This will provide a bigger error margin, making the hitches come through satisfactorily.

Being a fairly simplistic model and being made of aluminium, the weight of the model is quite low. Without any attachments it weighs 1.5 kg, a really competitive weight.

5.7.1 Suitability for mountain bicycles

During the concept creation, it was decided that the frame would be approached as a comfort bike, a mixture of mountain and urban models. Its intended use was utilized to decide that the frame would use the loads intended for road bikes, but also mentioned the idea of testing it as a mountain bike afterwards. This is what has been done to the definitive model. It can sustain the loads of road bikes, but it can be insightful to ascertain if it would be able to resist the higher loads intended for mountain bikes. The only necessary change is the increase of the loads in each ANSYS test.

-Test 1

The biggest increase from the three new tests takes place in this case. Previously, both loads had a value of 450N. Now, the F_2 load has to be changed to 1,200N and F_3 to 600N, two different values. Due to using the fully-reversed option, it is not possible to alternate between the two in each cycle. Instead, F_3 will be doubled, that way making it an opposite copy of F_2. By doing this, the requirements are increased, not invalidating the requirements established by the UNE standard. On the other side of the coin, the minimum number of cycles is reduced to 50,000, half of what was previously needed for a road bike. While the loads are more than doubled, the cycle requirement is reduced.

Analysing the frame under this new conditions shows how it won't be able to resist being utilized as a mountain bicycle. Most of it has a positive reaction but the connections with the head tube is where all the stress concentrates. It is here where the frame fails. Only a small point fails, while affected, the other damaged areas would still pass the test with 10^5 cycles.

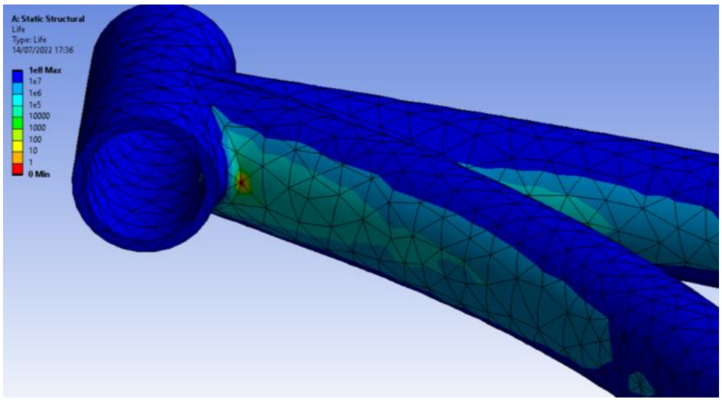


Figure 69 Localized failling point on the central tube (seen from below) – Source: Personal elaboration

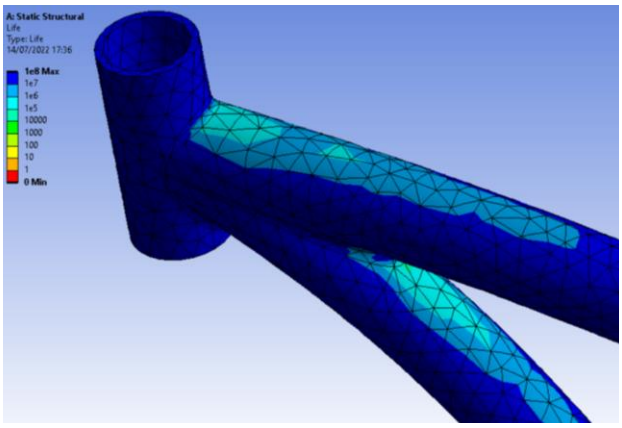


Figure 70 Damaged central and top tubes (seen from above) – Source: Personal elaboration

The failure only happens when the increased F_3 load is being applied. If all the loads are reduced to 600N, the value that it should have at that point, the results are improved. The stress still concentrates on the same point, but the consequences are trivialized. The lowest value ($8 * 10^5$ cycles) is higher than the standard condition.

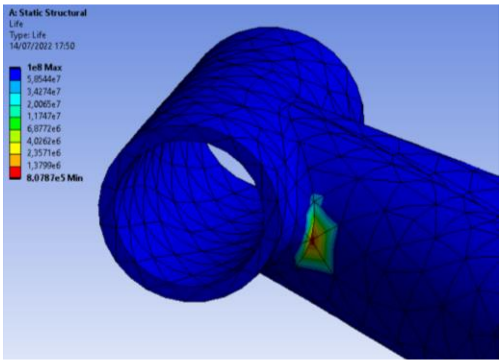


Figure 71 Affected area on the central tube (seen from below) when applying 600N – Source: Personal elaboration

-Test 2

The load has to be increased to 1,200 N, 200N more than before. The cycle requisite remains unchanged.

The frame resists the load increase without problem, no damage is detected.

Most of the structures present highly positive safety factors. The central, top and crank tubes have factors of fifteen, being over dimensioned due to them surpassing by a wide margin the intended lifespan; curiously the hitches react on the same manner. Some areas of the crank stay and seat tubes also display impressive results. These components could be reduced to optimize weight, but would possibly increase the manufacturing requirements. Outright changing the components would not be possible since part of the seat tube and connections to the crank tube have values close to two. They are within the intended range but a smaller component could not be enough.

-Test 3

Both loads have to be increased from 1,000 to 1,200N.

The frame displays perfect results with either of the two loads being supressed. Even with both loads acting simultaneously, which highly increases the stress placed over the crank tube, it is able to fulfil the cycle requirements. In this configuration the crank tube is the most damaged, but it still has results well over 10^6 cycles.

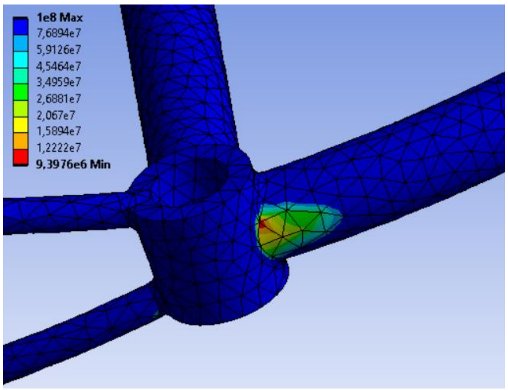


Figure 72 Crank tube results when both loads act at the same time – Source: Personal elaboration

-Summary

The second and third tests easily fulfil the conditions. The first experiment shows problems when applying a value of 1,200N to both loads. Arguably, it would be a success when using the correct load of 600N. The three of them can be considered as successful.

-Result analysis

From the data gathered, it can be induced that the final design would arguably be appropriate for the use in mountain bikes. By slightly altering the central and top tubes it could be possible to reduce the uncertainty seen on the first test, the only one that can be failed.

6. *Final budget*

The final budget takes into account the total costs derived from the material and personnel utilized after calculating the duration of the project.

Table 14 Depiction of final budget – Source: Personal elaboration

Resources	Exploitation	Cost	Total
Hardware			
Computer	Permanent	1.000,00 €	1.000,00 €
Software			
Ansys mechanical license	Permanent	22.000,00 €	22.000,00 €
Siemens NX 12 annual license	1 year	5.900,00 €	5.900,00 €
Regulations			
UNE EN-ISO 4210-6	Permanent	66,00 €	66,00 €
Energy and material resources			
Electricity consumption	400 hours	0.08 €/hour	32,00 €
Personnel			
Mechanical engineer with less than a year of experience	400 hours	21.4 €/hour	8.560,00 €
Total cost			37.558,00 €

The total cost necessary for the completion of this capstone project equals the sum of **37.558** €.

The 18th of July 2022, Vitoria-Gasteiz.

7. *Conclusions*

To conclude the capstone project, it is necessary to discuss the obtained results and conclusions.

The frame designs depicted in this text are of a conservative nature despite the alterations done to them from the base structure. The analyses show how the commonly used diamond shaped frame presents a fantastic groundwork for dependable and stylish models. The supplementary changes that each respective manufacturer could develop, reinforce certain demands and make up for the shortcomings that it may have for specific applications; like racing or MTB. Overall, most flaws can be solved with the addition of material in order to increase the thickness of the damaged area; doing it in selected points won´t affect the weight on a cumbersome manner. It is a secure design with range for further customization.

Despite discussing how appropriate the base design is, experimentation shouldn't be discarded. Some of the changes developed for this text showed reduced life cycles, but their effectiveness was lessened by the nature of the comparison, requiring to maintain similar measures and geometries. The third design already achieved acceptable results and with further tinkering it would be a formidable competitor. Even the first frame, with a single stay tube pair, could be expanded on. Strengthening the stay tubes, its main drawback, could result in a satisfying product and it would only take a diameter or material change. Many techniques that could bring an improvement are left untouched on this project; for example, the possibility of selecting different materials depending on the needs of each frame area.

The matter of bicycle designs offers a plethora of possibilities due to the simple structural requisites. This applies not only to the shape, but also to the manufacturing process. Despite its age, evolution opportunities still exist for such a simple concept.

-Experience of the student:

During the course of writing the final degree project, the student has had the opportunity to apply abilities obtained academically in a more practical setting and develop new ones.

In the case of CAD and specifically NX 12, he already had previous experience but it has served as an opportunity to expand on the foundations. As an example, it has required the investigation of ways of simplifying and optimizing the process of editing previous designs. In addition, a wide range of the options offered by the program have been tested.

The point of most interest has been the process leading to the completion of the fatigue analyses. While having a reduced experience on the field of FEA, it was mostly centred on static loads. The completion of the tests has required research on not only fatigue but also of FEA programs. The fatigue module not being accessible on the program that was originally intended to be used, has led to the necessity of learning the use of ANSYS from zero.

The project has not only served as a test of the frame design but also of the abilities of the student. It has tested the ability to adapt to frequent complications and needs of research that an engineering degree entails.

8. Bibliography

1- SIEMENS. (n.d.). *SIEMENS products*. Retrieved June 20, 2022, from https://www.plm.automation.siemens.com/global/en/products/nx/
2- ANSYS, Inc. (n.d.). *Ansys Mechanical Finite Element Analysis (FEA) Software for Structural Engineering*. ANSYS. Retrieved June 20, 2022, from https://www.ansys.com/products/structures/ansys-mechanical
3- Pow, A. (n.d.). *ANSYS COST*. ThePricer. Retrieved July 2, 2022, from https://www.thepricer.org/ansys-cost/
4- Carolo, L. (2022, February 16). *The Best CAD Software for Professionals of 2022*. All3DP. Retrieved July 2, 2022, from https://all3dp.com/1/best-cad-software/
5- *¿Qué Consumo nos Supone Utilizar el Ordenador?* (2018, November 11). GanaEnergía. Retrieved July 2, 2022, from https://ganaenergia.com/blog/que-consumo-nos-supone-utilizar-el ordenador/#:~:text=El%20consumo%20del%20ordenador%20en,mismo%20unos%20110%E2%82%AC%20anuales
6- GrupoTragsa. (2022). *TARIFAS TRAGSA 2022-Actuaciones no sujetas Tragsatec Resto-PERSONAL DE SERVICIOS, CONSULTORÍA Y ASISTENCIA TÉCNICA*. Tragsa. Retrieved July 2, 2022, from http://tarifas.tragsa.es/prestowebisapi.dll?FunctionGo&id=15489&cod=TRAGSA2022-1,0192/PS/O/O003&path=Tragsa2022W-Act-no-sujetas-Trgsatec-Resto.cfg
7- AENOR. (2015, December 15). *UNE-EN ISO 4210–6:2015 V2*. Tienda AENOR. Retrieved July 2, 2022, from https://tienda.aenor.com/norma-une-en-iso-4210-6-2015-v2-n0055959
8- Covill, D., Begg, S., Elton, E., Milne, M., Morris, R., & Katz, T. (2014). Parametric Finite Element Analysis of Bicycle Frame Geometries. Procedia Engineering, 72(The Engineering of Sport 10), 441–446. https://www.sciencedirect.com/science/article/pii/S1877705814005931#aep-article footnote-id11
9- Lin C-C, Huang S-J, Liu C-C. Structural analysis and optimization of bicycle frame designs. Advances in Mechanical Engineering. December 2017. doi:10.1177/1687814017739513
10- Herlihy, D. V. (2004). *Bicycle: The History* (1st ed.). Yale University Press.
11- Malizia, F., & Blocken, B. (2020). Bicycle aerodynamics: History, state-of-the-art and future perspectives. *Journal of Wind Engineering and Industrial Aerodynamics*, *200*(104134). https://doi.org/10.1016/j.jweia.2020.104134.
12- Lee, Y., Pan, J., Hathaway, R., & Barkey, M. (2005). *Fatigue Testing and Analysis: Theory and Practice* (Illustrated ed., Vol. 13). Butterworth-Heinemann.
13- Notes from the subject “Machine design – Topic 3: Fatigue”. Escuela de ingeniería de Vitoria-gasteiz – UPV/EHU.
14- Bhavikatti, S. S. (2005). *Finite Element Analysis* (1st ed.). New Age International.
15- Roylance, D. (2001, February). *Finite Element Analysis*. Department of Materials Science and Engineering Massachusetts Institute of Technology Cambridge, MA 02139. https://resources.saylor.org/wwwresources/archived/site/wp-content/uploads/2012/09/ME1023.2.3.pdf

16- *Medidas y estándares de la bicicleta*. (2014, February 18). NO SIN MI BICI. Retrieved February 26, 2022, from https://nosinmibici.com/2014/02/18/medidas-y-estandares-de-la-bicicleta/
17- International Organization for Standardization (2014). ISO 5775-1:2014: Bicycle tyres and rims. Part 1: Tyre designations and dimensions. ISO, August 2014.
18- Asociación Española de Normalización y Certificación. UNE-EN ISO 4210-6: Cycles. Safety requirements for bicycles. Part 6: Frame and fork test methods (ISO 4210-6:2014, Corrected version 2014-11-01). Madrid: AENOR, January 2015.
19- ANSYS, Inc. (n.d.-b). *Ansys Student - Free Software Download*. ANSYS. Retrieved March 26, 2022, from https://www.ansys.com/academic/students/ansys-student
20- *Friction Factors*. (n.d.). RoyMech. Retrieved May 25, 2022, from https://www.roymech.co.uk/Useful_Tables/Tribology/co_of_frict.htm
21- Özgün. (2022, May 31). Is Your Mesh Good Enough? MECHEAD. Retrieved July 2, 2022, from https://www.mechead.com/mesh-good-enough/#:~:text=Jacobian%20(also%20called%20Jacobian%20Ratio,represents%20a%20perfectly%20shaped%20element.&text=Skewness%20is%20the%20Angular%20Measure,Angles%20of%20Ideal%20Element%20Types.
22- Hancq, A., & Browell, R. (2006, March). *Calculating and Displaying Fatigue Results*. ANSYS, Inc. https://www.ozeninc.com/wp-content/uploads/2021/02/fatigue.pdf