Development and design of the rear upright for the Garuda UNY Team UG-23 car

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Article history
Submitted: 5 March 2026
Revised: 20 April 2026
Accepted: 28 April 2026
Published: 9 May 2026

Keywords
Computer aided engineering
Finite element analysis
Upright
Urban car

Abstract
The development and design of the rear upright for the Urban Car Garuda UNY UG-23 was carried out to improve the previous design that was no longer compatible due to changes in the car frame. This study aimed to find strong and lightweight materials for the rear upright, and to analyze the structure to get the best design with better performance and lower weight. The development method used an engineering approach based on Computer Aided Engineering (CAE). The design process started by using software for parametric, solid modelling, and numerical analysis with the Finite Element Analysis (FEA) method. FEA was used to measure stress, deformation, and safety factors of the rear upright. The simulation also considered different forces, such as the weight on the upright and the force from the brake caliper. The Ashby Method was used to choose materials based on their properties and the design needs. The analysis results showed that the rear upright made from 7075-T6 aluminum met the strength and efficiency requirements. The analysis showed that the factor of safety was at least 15.62 with a maximum stress of 32.34 MPa. The maximum displacement was 0.08 mm and strain were 0.0 mm. The optimization process reduced the mass from 553.64 grams to 322.73 grams. In the best condition (wheel system), the weight was reduced by 41.7% or about 231.64 grams without significantly reducing the strength.

1. Introduction

Garuda UNY Team is a division within the Technology Engineering UKM of Yogyakarta State University which was established in 2009. This team accommodates students' interests in the field of automotive technology, especially vehicle design, manufacturing, and assembly. Since its establishment, Garuda UNY Team has developed several types of competition vehicles, including Urban Concept, Prototype, and Formula Student cars. Through this activity, students not only gain practical experience in the field of vehicle engineering, but also contribute to the development of automotive technology that is more efficient and sustainable.

One of the focus of vehicle development by Garuda UNY Team is the Urban Concept category cars. Urban cars are designed with the main goal of achieving high energy efficiency, both through reducing fuel consumption and optimizing vehicle design. This concept is very important considering the increasing global energy needs and the limited fossil energy sources available. Therefore, the development of energy-efficient vehicles is one of the solutions that continues to be developed to support energy sustainability in the future [1].

In an effort to develop efficient vehicles, Garuda UNY Team routinely participates in various energy-efficient vehicle competitions, both at the national and international levels. At the national level, the team participates in the Energy Efficient Car Contest (KMHE), while at the international level participates in the Shell Eco-Marathon competition. In the competition, Garuda UNY's Urban cars compete in the Internal Combustion Engine (ICE) category, which requires vehicles to be able to travel as far as possible with minimal fuel consumption. To achieve this performance, various aspects of vehicle design must be optimized, such as vehicle weight, suspension system stability, powertrain performance, and vehicle aerodynamic design.

One of the factors that greatly affects the efficiency of the vehicle is the total weight of the vehicle. Vehicles with lighter mass require less energy to move so that it can significantly increase fuel efficiency. Research shows that reducing vehicle mass can make a major contribution to improving the energy efficiency of vehicles [2]. Therefore, the strategy of reducing the mass of vehicle components is one of the important approaches in the design process of energy-efficient vehicles [3].

However, mass reduction should not reduce the structural strength or safety of vehicle components. Thus, it is necessary to design components that are able to produce a lightweight structure but still have adequate strength and rigidity. One of the important components in the vehicle wheel system is the rear wheel upright. This component functions as a link between the suspension system, braking system, and vehicle wheels. In the Garuda UNY Urban car, there are four uprights, each of which must be able to withstand various types of loads

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that work during the vehicle's operation. These loads come from the weight of the vehicle, the force when the vehicle accelerates, the force when the vehicle turns, and the force that arises during the braking process. Especially in maximum braking conditions, the upright receives a considerable load because it is the point of installation of the brake caliper bracket.

In the development of the previous generation Garuda UNY Urban car, the upright design used was still adjusted to the old frame configuration. However, in the development of the Garuda UNY UG-23 Urban car, there were changes in the frame design, including changes in the ground clearance value and the configuration of the vehicle's legs system. This change caused the previous rear upright design to no longer be compatible with the new frame structure. Therefore, a process of development and redesign of the rear upright is needed in order to adapt to the latest frame design and still meet the needs of structural strength and weight efficiency.

In addition, in the competition for energy-efficient vehicles, there are no regulations that specifically regulate the design and dimensions of upright components. However, these components must be able to ensure the safety of the vehicle by bearing the load on the vehicle and the driver during the vehicle's operation. Therefore, the selection of materials and the design of the upright structure are very important factors. The selection of the right material is an important factor in the engineering design process because it can affect structural performance, component mass, and production costs [4], [5].

Along with the development of modern engineering technology, the process of designing vehicle components can be carried out more efficiently through the Computer Aided Engineering (CAE) approach. Through this method, component designs can be analyzed numerically using the Finite Element Analysis (FEA) method to determine the distribution of voltages, deformations, and safety factors that occur in components before they are physically produced [6]. The FEA method is widely used in the field of mechanical engineering to analyze the strength of structures and improve the reliability of mechanical component designs. Thus, the design development process can be carried out more effectively and efficiently.

Based on this description, research is needed on the development and design of rear upright on the Garuda UNY UG-23 Urban car by considering the right material selection, structural strength analysis, and component weight optimization. Through a Computer Aided Engineering-based engineering approach, it is hoped that a lighter rear upright design can be produced but still has sufficient strength and safety factors to support vehicle performance in energy-efficient vehicle competitions.

2. Method

2.1. Types of research

The upright redesign was carried out by Garuda UNY Team using the Finite Element Analysis (FEA) method, one of the Computer Aided Engineering (CAE) tools to support mechanical design efficiently. FEA allows simulation of design strength before prototyping, thus saving time and cost [7]. Through the SolidWorks 2024 Student Edition software, static loading simulations were carried out at two main points: shaft mount and bracket caliper, to determine the stress, deformation, and safety factors of the new design.

2.2. Design Design Model

This final project uses the design process model from Shigley because it applies a systematic approach to designing mechanical components and engineering systems. This approach focuses on rigorous analysis and application of the principles of engineering mechanics and materials science. Flowchart design prosess can be seen in Figure 1.

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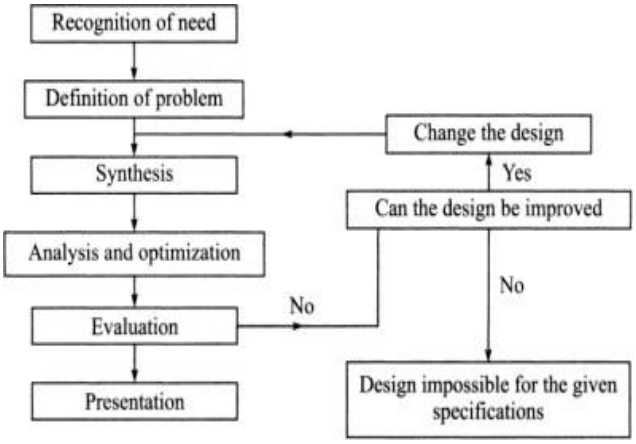

Figure 1. Flowchart Design Process

The development of the rear upright design of the Garuda UG-23 car follows the design process model of shigley "in the book Mechanical Engineering Design, Ninth Edition [8]. The following procedure in the design process:

2.2.1. Recognition of Need

The design begins by identifying the needs of the product to be designed. The design of the Garuda UG-23 Rear Upright Car is made in accordance with the need's analysis in the Shell Eco Marathon 2023 regulations [9]. The Shell Eco Marathon Urban Concept class competition has two categories, namely millage and regional championship drivers. At the time of millage, it is stated in the Shell Eco-Marathon Chapter III Regulation that the maximum speed of the vehicle is 40 KM/H. At the time of millage, the distance traveled is 12.900 M or 3 laps of the Mandalika International circuit. When taking the millage, the driver will do 2 stops and goes every lap. The stress on the rear upright is greatest when braking so that the components are really tested for strength and durability. Therefore, it is necessary to calculate the maximum braking force of the rear axle and the load received by the rear upright based on the parameters and brake specifications of the Garuda UG-23 Car. In addition to calculating the maximum load during braking that will be borne by the rear upright, it also needs to be designed according to the criteria of the rear upright specification and the specifications of related components.

a. Braking

Braking is related to Newton's second law which deals with the concepts of force, deceleration, and mass of objects. The description of the braking calculation is seen in Figure 2.

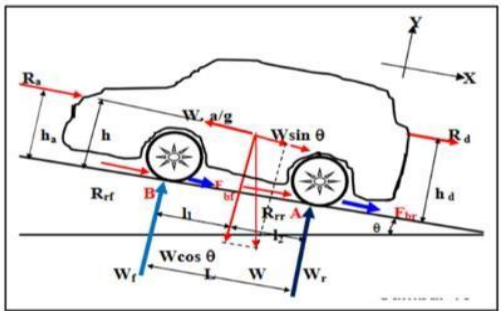

Figure 2. Braking calculation description
(Source: Mathematical Analysis of Vehicle Motion) [10]

The maximum braking force in a two-axle vehicle that can be supported by the contact of the tire with the road is determined by the normal load and the road adhesion coefficient (μ). If the maximum braking force for the rear axle is expressed Fbr then the magnitude can be calculated by the formula in Equation (1) as follows:

$$F_{br}\ max = \mu \cdot W_r \quad (1)$$

When,
$F_{br\ maks}$ = maximum braking force (N)
μ = adhesion coefficient (friction of the tire with the road)
Wr = normal force (weight the wheels receive, usually the rear wheels)
The derivative equation is written in Equation (2).

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$$W_r = \frac{F_{br\,max}}{\mu} \quad (2)$$

The relationship to dynamics (Newton's Law) is formulated in Equation (3)

$$F = m \cdot a \quad (3)$$

Description:
F = Forces at work (in vehicle) (N)
m = Forced-given mass of object (vehicle) (kg)
a = Deceleration (vehicle) of a stylized object (m/s2)

Braking is generated by the contact between the vehicle's wheels and the road surface, resulting in a normal force with an Equation (4)

$$N = W = m \cdot g \quad (4)$$

Description:
N = Normal force of the object (vehicle) (N)
W = Weight force of object (vehicle) (N)
m = Mass of objects (vehicles) (N)
g = acceleration of gravity (m/s2)

If Wr is substituted into this formula an Equation (5) is obtained.

$$F_{br}\,max = \mu . W_r \quad (5)$$

Developed into Equation (6).

$$F_{br\,max} = \mu . \frac{W.\ l_1 - h\,(F_b + F_{br} W)}{L} \quad (6)$$

Then it is simplified to Equation (7).

$$F_{br\,max} = \frac{\mu\, W\,(l_1 - h\,(\mu + f_r))}{L} \quad (7)$$

Longitudinal weight Tranfer

After knowing the maximum Brake Force on the rear wheel, the load received by the rear upright can be calculated as Equation (8) as follows:

$$\Delta W_r = \frac{h}{L} . F_{br\,max} \quad (8)$$

Rear Wheel Loads

The total load on the rear wheel when braking is shown as Equation (9).

$$WR = Wr - \Delta Wx \quad (9)$$

The load distribution on the left and right rear wheels can be determined as Equations (10) and Equation (11) as follows:

$$W_{RL} = \frac{W_R}{2} \quad (10)$$

$$W_{RR} = \frac{W_R}{2} \quad (11)$$

Vertical Load Distribution

The vertical load on each wheel can be expressed as the following Equation (12):

$$Wvert = WRR \times 1.3 \quad (12)$$

The distribution of the load between the outer and inner wheels is as Equation (15) and Equation (16):

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$$V_{Outer} = \frac{W_{vert} \cdot (l_1 + l_2)}{l_1} \quad (15)$$

$$V_{inner} = V_{outer} - W_{vert} \quad (16)$$

Longitudinal Braking Style

The longitudinal directional braking force acting on the wheel can be calculated by Equation (17):

$$W_{long} = \mu - W_{vert} \quad (17)$$

Description:

$F_{br\ maks}$ = maximum braking force (N)
W = total vehicle weight (N)
ΔW_x = longitudinal displacement (N)
W_r = normal rear wheel force (N)
W_R = rear wheel load when braking (N)
W_{RL}, W_{RR} = rear left and right wheel load (N)
W_{vert} = vertical load on wheels (N)
W_{long} = longitudinal braking force (N)
μ = coefazine Gesek Ban
f_r = Rolling Resistance Coefficient
h = height of the vehicle's center of mass (m)
L = wheelbase (m)
l_1, l_2 = vehicle load distribution distance (m)

Force Distribution in the Brake System

Assuming the wheels are locked during maximum braking, the entire braking force will be held by the brake system, especially the brake calipers. Figure 3 shown a deep upright rear load. The force acting on the brake pad can be calculated as the following Equation (18):

$$F_{brake} = \frac{W_{vert} \cdot r}{(l_3 + l_4)} \quad (18)$$

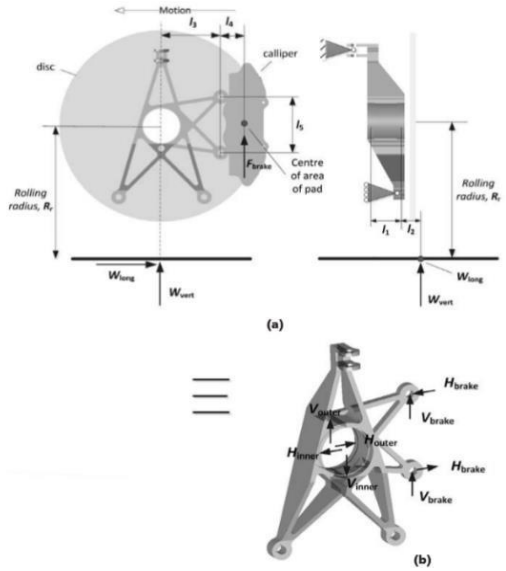

Figure 3. Deep upright rear load (Source: Race Car Book, 2014)

Vertical Load on Caliper Bracket

To find out the vertical force acting on each of the bolt holes of the caliper bracket during maximum braking, Equation (19) is used:

$$V_{brake} = \frac{W_{long}}{2} \quad (19)$$

Horizontal Forces on the Brake System

In addition to vertical force, there is also a horizontal force that works in the opposite direction due to braking. The force can be calculated as the following Equation (20):

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$$H_{brake} = \frac{F_{brake} \cdot l_4}{l_5} \quad (20)$$

From Figure 3, it can be seen the direction of the load on the rear upright when braking is maximum. Then it can be known that the load received by the housing bearing is as follows, moments against the center of the inner bearing:

b. Specific criteria for rear upright

The dimensions of the rear upright must be designed as compact as possible to get a light weight of the component so that the component will be optimized topically, there is a bearing housing that functions as a wheel shaft mount, the component uses a constituent material with a light mass, has sufficient component strength and the component will be bonded to the frame using M10 bolts.

Calipers: Calipers use Brembo-branded aftermarket components. Brembo Type P2 34 120A44110 with 34 mm diameter piston with 2 M8 size bolt locks connected to the upright. So that the rear upright component must have a structure for the installation of bolts with a diameter of 8 mm to facilitate assembly.

Rear Upright Bearings: Rear Upright bearings use SKF 6002 bearings on the rear upright components that serve as rear axle mounts. The use of bearings with type 6002 is due to high durability, easy to maintain and widely distributed in bearing stores. This component measures an outer diameter of 32 mm, an inner diameter of 15 mm, and a width of 9 mm therefore the bearing housing must be designed to have a diameter of 32 H8 and a width of at least 10 mm [12], [13].

2.2.2. Definition of problem

This stage of the activity carried out is to formulate the needs of the product to be designed so that specifications (design targets) are obtained from the designed product. The rear upright design will have the following specifications:

a. Has a light weight
b. Using Brembo P2 34 120A44110 Brembo type calipers
c. Lightweight component constituent material
d. The components will work on supporting the calipers and be able to withstand a braking force of 163.96 N.
e. Has a width of 25 mm where the components come into contact with the car frame.
f. The area attached to the upright bearing has a diameter of 32.
g. It has a 2-bolt placement place to fasten M8-sized calipers installed with a diameter distance between bolts of 83.5 mm.
h. Has a place for the placement of 2 locking bolts to an M10 sized frame mounted with a diameter of 98 mm.

2.2.3. Synthesis

Synthesis is the stage of realizing the design of the specifications described above. The design will be made with the help of computer software or commonly called Computer Aided Design (CAD). The tools used in data collection are the Acer Nitro 5 AN515-58 laptop device with Intel core i5-12500H8 specifications, Nvidia Geforce RTX 3050, 16GB Dual channel 512GB Ram, NVME M.2 SSD. Design drawing is done using SolidWork 2024 Student Edition software. The design result is in the form of component design drawings in the form of SLDPRT files.

2.2.4. Analysis

The analysis stage is carried out after the Rear Upright design drawings are successfully made. The design drawings are then analyzed for compatibility with supporting components such as calipers, bearings, bolts and so on to find out that the components can be assembled into a unit and conduct a "Finite Element Analysis" analysis with braking simulation at the maximum braking point so as to produce data in the form of Stress Von-Misses values at each stress point so that the Factor of Safety is known after being compared with the yield of the material strain The constituent is also the maximum deformation and strain of the components. The target Factor of Safety is set at least 4 for dynamic load treatment in ensuring that components remain safe in various driving conditions, if the target of the Factor of Safety component has not been achieved, then the design needs to be designed and re-analyzed.

2.3. Material selection method

In this material selection, the method used is the material selection method [11]. There are several steps in selecting materials, namely:

a. Translating design requirements (stating functions, constraints, objectives and free variables)
b. Screening using constraint constraints, (removing materials that cannot do the job)

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c. Ranking (sorting materials that can work well)
d. Search for data/documentation (search for material specifications of candidates)
e. Material selection

2.3.1. Translating Design Requirements

Table 1 showed a design requirement for rear upright. Next, Material charts Ashby can be seen in Figure 4.

Table 1. Design Requirements for Rear Upright

Function	Can accept maximum braking force Able to withstand vehicle loads
Constraints	Yield strength minimum 250 MPa. Non-flammable Material made of metal
Objective	Light material Low cost Ingredients can be found in Indonesia
Free variables	All metal materials

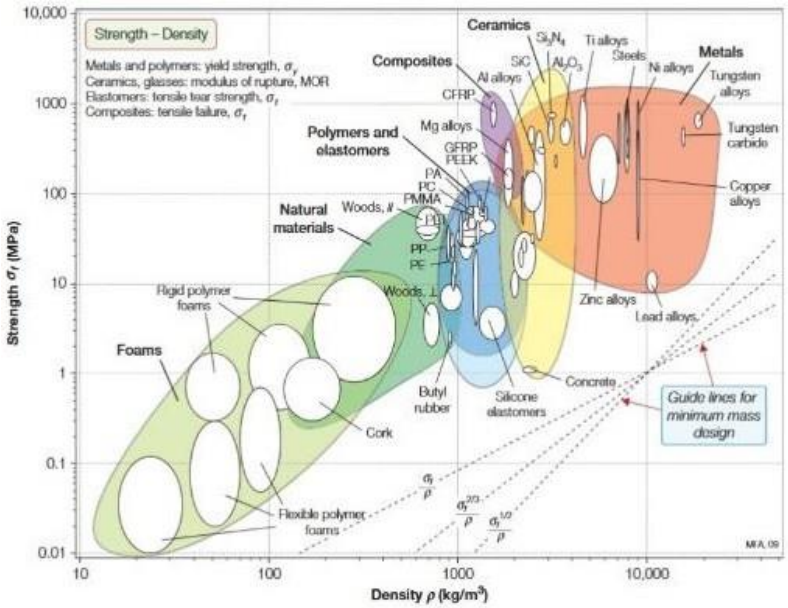

Figure 4. Material charts Ashby

2.3.2. Screening and Rating

Figure 4 is an Ashby diagram showing the relationship between the mechanical strength (σ) in MPa units to density (ρ) in kg/m^3 for various groups of engineering materials, such as metals, ceramics, composites, polymers, elastomers, natural materials, and foam. These diagrams are used to assist in the selection of materials based on strength and weight criteria, especially in designs that prioritize structural efficiency [14]. The dotted lines on the graph are guide lines for material selection based on the strength-to-density ratio (σt/ρ), which reflects the structural efficiency of lightweight components. The more it is pulled to the left, the lighter the material produced. If translated from the design requirements, the candidate material is a metal material that has a strength above 250 MPa.

2.3.3. Material Documentation Data

After the process of filtering and grading the material based on the ratio between the mechanical strength (σ) in megapascal units (MPa) to density (ρ), the next stage is to review the historical data of the selected material candidates. This assessment includes tracing the history of the use of these materials in various applications or engineering products, both in the automotive, construction, and general manufacturing industries. The purpose of this analysis is to obtain a more comprehensive picture of the reliability, performance, and suitability of materials in the context of rear upright design, so as to support more precise and efficient material selection decisions.

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3. Results and Discussion

3.1. New Design of Rear Upright and Fitting of Supporting Components

3.1.1. Rear Upright

The results of making Figure 5 Garuda UG-23 Car Rear Upright design can be seen in the image above. This component is designed with topology optimization. It has a thickness of 25 mm where the components intersect with the car frame with 2 bolt holes to be tied with a 10 mm diameter frame designed with a distance of 98 mm between holes. It has a caliper bracket with a thickness of 9 mm with 2 bolt locks measuring M8 installed with a diameter distance between bolts of 83.5 mm. This component has an area attached to the upright bearing having a diameter of 32. It has a height of 85 mm when calculated from the center of the shaft hole down to adjust the ground clearance of the vehicle.

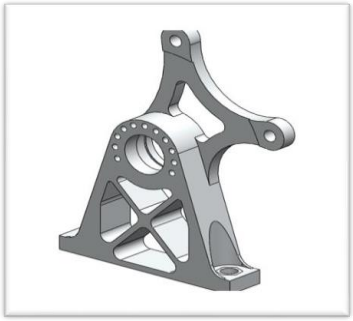

Figure 5. Rear Upright

3.1.2. Caliper

Caliper yang digunakan yaitu Brembo P2 34 120A44110 dengan spesifikasi dua piston berdiameter 34 mm, material aluminium CNC, berat 518 gr dan menggunakan minyak rem DOT 4. Pemilihan kaliper jenis ini didasari dari perhitungan piston kaliper yang ideal didapatkan hasil untuk kaliper 2 piston ukuran pistonnya berdiameter 29.6 mm. Perhitungan yang dilakukan menghasilkan gaya jepit kaliper untuk setiap roda sebesar 1236.81 N dengan tekanan fluida sebesar 1.36 Mpa. Komponen rear upright dan caliper diikat dengan 2 baut socket head tipe Hex Socket Head ISO 4762 grade 8.8 dengan spesifikasi baut M8x1.25 dan Panjang 25 mm. dengan torsi pengencangan sebesar 28.2. Figure 6 shown a caliper Brembo.



Figure 6. Caliper Brembo

3.1.3. Bearing Rear Upright

Upright bearings use bearings with type SKF 6002 in Figure 7 with an outer diameter of 32 mm, an inner diameter of 15 mm, and a width of 9 mm.

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Figure 7. Bearing 6002

On the rear upright there is one bearing located in the middle and has a bearing housing where the bearings work. The bearing will support the shaft with an outer diameter of 15 mm. The rear upright component with the upright bearing will intersect so that the conditions are suitable for the wide appropriate type and use ISO

The H7/g6 symbol with an intersecting area of 32 mm obtained a minimum congestion value of 0 and a maximum of + 0.021 mm. Meanwhile, upright bearings and wheel shafts are used in accordance conditions with the type of area and use ISO Symbol H7/g6 with an intersecting area of 15 mm to obtain a minimum congestion value of -0.011 mm and a maximum of -0.032 mm. The standard is used because the upright rear bearing is used as a shaft mounting medium and the shaft rotates only under certain conditions. The rear upright bearings are pre-installed and locked by internal circlips.

3.2. Material Selection

Material selection uses an ashby chart to filter and compare materials based on the ratio of strength to mass. With the help of guidelines that have been made as in Figure 8.

3.2.1. Material Filtration Results

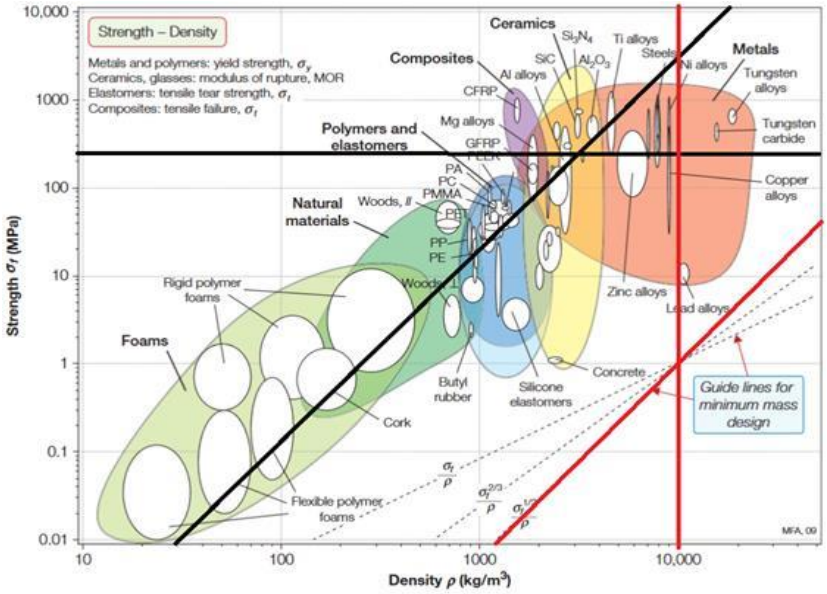

Figure 8. Selection Material charts ashby

The black lines in this image represent the minimum strength limit required or as a material feasibility limit. Horizontal lines can indicate the minimum strength limit. While the black diagonal line symbolizes a higher strength-to-density ratio (σ/ρ). Materials that are above or parallel to these lines have good structural performance for lightweight and strong designs. The red line is a guideline for minimum mass design. This line has a constant gradient to the ratio of σ/ρ, and helps determine the optimal material for structures with minimum mass. Materials that are above the red line tend to do better in applications that require high strength and low mass. Screening and rating for rear upright are presented in Table 3.

Table 2 and documentation for upright material can be seen in Table 3.

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Table 2. Screening and rating for rear upright

Screening and Rating for Rear Upright		
The search for metal materials that have a Minimum Yield Strength of 250 Mpa, and are not flammable with light weight are as follows.		
Material	Strength (MPa.)	Density (kg/m3)
Al 7075 T6	505	2700
Titanium (Ti-6Al-4V)	900-1200	4500
Low carbon steels DIN	260	7850

Table 3. Documentation for upright materials

Documentation for upright materials	
Material	History
Al 7075 T6	Motor gears, aircraft wings, automotive parts, alloy wheels
Titanium (Ti- 6Al-4V)	Production of aircraft frames, engine components, steam turbine blades, superconductors, missiles
Low carbon steels DIN	Car body, engine components, etc.

3.2.2. Candidate Material

Based on the design requirements, there are several types of materials that meet the criteria, namely Al 7075 T6, Titanium Ti-6Al-4V, and Low carbon steels. These materials have their own advantages. Therefore, it needs to be considered based on the strength index to the density of the material.

3.2.3. Material Selection Results

Based on the ashby material selection method, 3 types of superior materials were obtained for the manufacture of rear upright. The material Al 7075 is the most favored in the selection of this material because AL 7075 T6 meets the design requirements with a yield strength value of 505 MPa and a lower density than the three selected materials, which is 2700 kg/m3. Therefore, for the manufacture of rear upright cars Garuda UG-23 will use AL 7075 T6 material. On the other hand, AL 7075 T6 materials are widely found in Indonesia which makes it easier to provide or purchase materials. Furthermore, the rear upright will be simulated for strength using AL 7075 T6 material in the SolidWork software to see the toughness of the material.

3.3. Finite Element Analysis Rear Upright Mobil Garuda UG-23

Finite Element Analysis was carried out after the rear upright design for the Garuda UG-23 car was successfully designed according to the design target. There are several processes when performing Finite Element Analysis, namely:

3.3.1. Material

The material used in this study uses Aluminum 7075 T6. Shown in Figure 9 engineering data of the materials used.

Property	Value	Units
Elastic Modulus	72000	N/mm^2
Poisson's Ratio	0.33	N/A
Shear Modulus	26900	N/mm^2
Mass Density	2810	kg/m^3
Tensile Strength	570	N/mm^2
Compressive Strength		N/mm^2
Yield Strength	505	N/mm^2
Thermal Expansion Coefficient	2.36e-05	/K
Thermal Conductivity	130	W/(m·K)
Specific Heat	960	J/(kg·K)
Material Damping Ratio		N/A

Figure 9. Engineering Data Aluminium7075 T6 pada SolidWork

Figure 9 is an engineering data of Aluminum 7075 T6 in solidWork applications, with a density of 2,810 kg/m^3, modulus of elasticity of 72.000 N/mm^2, and tensile strength of 570 N/mm^2. The material also has a

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melting strength of 505 N/mm^2 and a shear modulus of 26.900 N/mm^2, making it strong and lightweight. Thermally, this material has a thermal conductivity of 130 W/(m·K) and a thermal expansion coefficient of 2.36 × 10^{-5} /K, suitable for use for vehicle components that require thermal strength and efficiency.

3.3.2. Geometry

The geometry used in this study is the result of three-dimensional (3D) modeling made using SolidWorks software. The resulting model is fully in accordance with the original design without undergoing any changes in shape or dimensions. The file format used is SLDPRT. verifying the quality of the model's geometry before entering the meshing process. The results of the inspection did not find any damage or error in the edge or face. As stated in Figure 10.

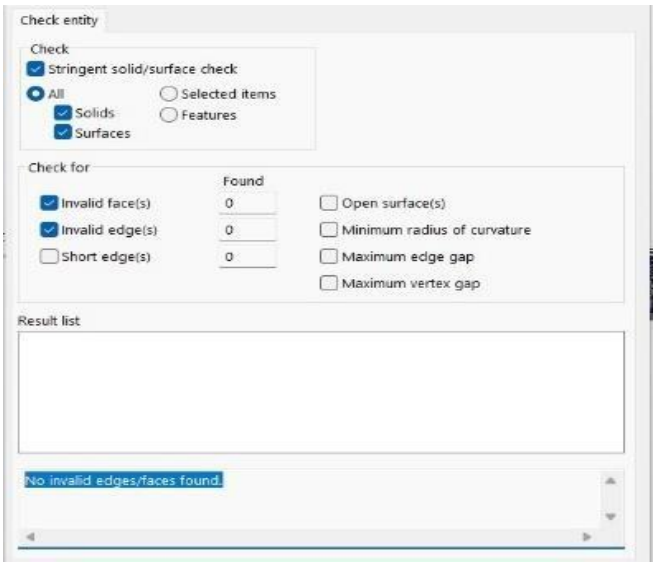

Figure 10. Check Entity Results

3.3.3. Meshing

Before entering the results of the load calculation for the analysis simulation, it is necessary to meshing. The type of meshing used is adaptive meshing. This aims to allow mesh elements to automatically adjust to the stress points and contours of the workpiece. The result of the mesh convergence reached a stable point at the maximum element size of 8.14 mm and the minimum element size of 1.3 mm which can be seen in Figure 11. The convergence graph image is shown in Figure 12 and the meshing result display on the rear upright design can be seen in Figure 13.

Mesh Details

Study name	Rear Upright Static 2 (-Default-)
DetailsMesh type	Solid Mesh
Mesher Used	Curvature-based mesh
Jacobian points for High quality mesh	16 points
Max Element Size	8,14484 mm
Min Element Size	1,3 mm
Mesh quality	High
Total nodes	1829552
Total elements	1254001
Maximum Aspect Ratio	10,624
Percentage of elements with Aspect Ratio < 3	95,7
Percentage of elements with Aspect Ratio > 10	0,0114
Percentage of distorted elements	0
Number of distorted elements	0

Figure 11. Details of the results of the Rear Upright meshing process.

The type of mesh used is Solid Mesh with the Curvature-based meshing method. The mesh parameters show that the quality of the mesh is in the category (High Quality), with a maximum element size of 8.41484 mm and a minimum size of 1.3 mm. The meshing process resulted in a total of 1.825.552 nodes and 1.254.001

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elements. The maximum aspect ratio was recorded as 10.624, but only 0.0114% of the elements had an aspect ratio above 10, indicating that most elements were in good shape. A total of 95.7 elements had an aspect ratio Figure 12, which indicates that the mesh quality is excellent for numerical simulation purposes. No distorted elements were found, so the mesh can be considered valid and suitable for further analysis of the elements, both in terms of accuracy of results and numerical stability.

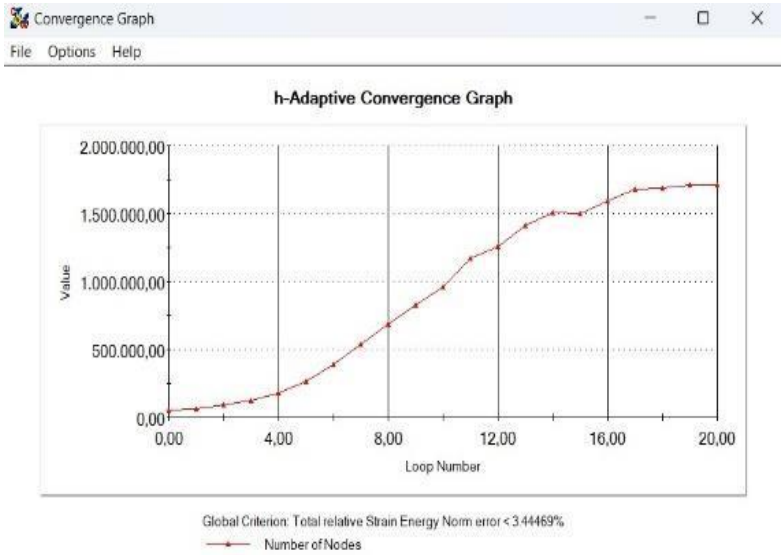

Figure 12. Graphics: h-Adaptive Convergence

Figure 12 shows an H-refinement-based adaptive convergence graph of the number of nodes in an iterative process in finite element analysis. This graph illustrates the relationship between the number of loops (Loop Number) and the number of nodes (Number of Nodes) used in the modeling. It is seen that at the beginning of the iteration (loops 0 to 8), the number of nodes increases exponentially. This improvement reflects the addition of mesh elements to improve the accuracy of the model. Entering the 12th iteration, the rate of increase in the number of nodes began to decline and tended to be close to a stable value in the range of 1.700.000 to 1.850.000 nodes. This shows that the system has achieved convergence, which is a condition in which the change in the values of the calculation results between iterations is getting smaller. Meshing results on components can be seen in Figure 13.

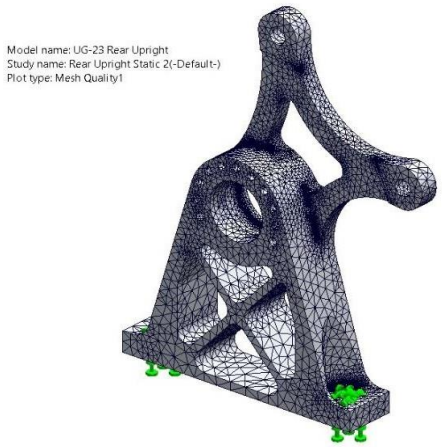

Figure 13. Meshing results on components

In Figure 13, the formed mesh indicates a tight and even distribution of elements across the entire surface of the rear upright, especially in areas with complex contours and sharp angles. This shows the effective application of curvature-based meshing to maintain numerical accuracy in areas with significant geometric changes.

3.3.4. Boundary Condition

Load

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Before entering the load value for the analysis simulation, it is first necessary to calculate the load on the rear upright. Stress analysis on the upright can be done upright, there is a brake bracket that receives the load from the total braking force and axle force at the time of braking. Based on the parameters and brake specifications of the Garuda UG-23 Car, it can be calculated as follows in Table 4.

Table 4. Brake parameters and specifications of Garuda UG-23 cars

Parameter	Simbol	Value	Units
Car mass	mc	90	Kg
Mass of drivers	md	70	Kg
Car weight + driver	W	1600	N
Panjang Wheel Base	L	1.4	m
Front Axle to CG Distance	$l1$	0.71	m
Front Axle to CG Distance	$l2$	0.68	m
High CG	H	0.42	m
Tyre adhesion coefficient with road	μ	0.75	
Friction coefficient of brake pads with disc brake	μb	0.5	
Coefasia tahanan relief	fr	0.013	
Radius roda	rr	0.2392	M
Shaft to brake pad distance	rb	0.09	m
Cross-sectional area of the master cylinder front or rear	Am	0.000198	$m2$
Cross-sectional area of piston caliper 2 piston	As	0.000907	$m2$
Pedal Racing		1.44	
Speed before braking	$V1$	13.8	m/s^2
Aerodynamic Coefficients	Cae	0.21	
Delay in brake reaction	td	0.1	s
Earth's gravity	g	9.81	m/s^2
Corner slope road Cos 11.3°		0.980	
Slope Corner of Sin Road 11.3°		0.195	

Calculation of the maximum braking force of the rear axle

The maximum braking force on the rear axle can be calculated using the braking simulation method with the Equation (22):

$$F_{br\ max} = \frac{\mu .W.(l1-h\ (\mu+fr))}{L} \quad (21)$$

$$F_{br\ max} = \frac{0.75 \times 1600\ (0.42-0.15\ (0.75+0.013))}{1.4}$$

$$F_{br\ max} = \frac{0.75 \times 1600 \times 0.39}{1.4}$$

$$F_{br\ max} = 466.50\ N$$

Outer horizontal force (Houter)

The external horizontal force can be seen in Equation (22).

$$H_{outer} = \frac{Wlong \times (l1+l2)}{l1} \quad (22)$$

$$H_{outer} = \frac{168.39 \times (9+7)}{9}$$

$$H_{outer} = 349.87\ N$$

Vertical Force Summing

The sum of vertical forces can be known through Equations (23).

$$V_{inner} = V_{outher} - W_{vert} \quad (23)$$

$$V_{inner} = 446.50 - 224.53$$

$$V_{inner} = 221.97\ N$$

Sum of Horizontal Forces

The sum of the hizontal style can be seen in the Equation (24)

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$$H_{inner} = \frac{Houter}{\mu} - Wlong \quad (24)$$

$$H_{inner} = \frac{349.87}{0.75} - 168.39$$

$$H_{inner} = 181.48 \text{ N}$$

The maximum load of the rear axle is known to be Wr = 445.71 N

Longitudinal Weight Transfer

At the time the wheel is at a locked point during braking, all torque is held by the brake calipers. The force acting on the brake pad can be calculated as Equation (25).

$$\Delta Wx = \frac{Fbrmax \,.\, h}{L} \quad (25)$$

$$\Delta Wx = \frac{168.39 \times 0.2032}{0.09463}$$

$$\Delta Wx = 361.58 \text{ N}$$

Maximum Braking Force on Calipers

EThe total maximum braking force is seen in the Equation (26)

$$F_{br\,max} = \frac{Fbr\ max \,.\, Rr}{2} \quad (26)$$

$$F_{br\,max} = \frac{168.39 \times 0.2032}{2}$$

$$F_{br\,max} = 17.215 \text{ N}$$

Rear wheel vertical load (Wvert) can be seen in Equation (27)

$$W_{vert} = W_{rr} \times 1.3 \quad (27)$$

$$W_{vert} = 172.715 \times 1.3$$

$$W_{vert} = 224.52 \text{ N}$$

The vertical force of each bracket caliper bolt bracket wedge is known through the Equation (28).

$$W_{bolt} = \frac{Wvert}{2} - \frac{Fbrake\ maks}{2} \quad (28)$$

$$W_{bolt} = \frac{224.52}{2} - \frac{361.58}{2}$$

$$W_{bolt} = 68.74 \text{ N (Each bolt hole)}$$

Longitudinal Braking Style

The longitudinal braking force can be seen in the Equation (29).

$$W_{long} = W_{vert} \times \mu \quad (29)$$

$$V_{brake} = \frac{Wlong}{2}$$

When:
W_{vert} = 224.52 N
μ = 0.75

Maka,

$$W_{long} = 224.52 \times 0.75$$

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W_{long} = 168.39 N

$V_{brake} = \frac{168.39}{2}$

V_{brake} = 84.20 N (setiap kapiler)

The moment against the center of the inner bearing is known from the Equation (30).

$$M_{brake} = H_{brake} \times l_r \quad (30)$$

Known,
H_{brake} = 0.0429 N
I_r = 83.5 mm = 0.0835 m

$M_{brake} = 0.0429 \times 0.0835$

M_{brake} = 0.00358 N.m

Resultan gaya pada bearing (outer) can be seen in Equation (31).

$$V_{outer} = \frac{Wvert \times (l1+l2)}{l1} \quad (31)$$

It is known,
W_{vert} = 224.52 N
l_1 = 9 mm = 0.009 m
l_2 = 9.7 mm = 0.0097 m

$V_{outer} = \frac{224.52 \times (0.009+0.0097)}{0.009}$

$V_{outer} = \frac{224.52 \times 0.0187}{0.009}$

V_{outer} = 466.23 N

The analysis was carried out by simulating the car performing maximum braking. The rear upright receives the load from the calculated maximum braking. When the car brakes to the maximum, the component load can be calculated and entered into the calculation of the software, namely on the bearing housing (bearing housing) and shaft, bracket caliper (mounting caliper). Meanwhile, what acts as a fixed support is the point of the bolt that ties the rear upright to the frame (cassis). Shown in Load type on rear upright

Figure 14 (A) is a point of burden that will be accepted by upright. Load type on rear upright

Figure 14 (B) shows the type of load and the direction of loading. Details of the accepted style values are shown in Table 5. . The amount of force is entered into the SolidWork software, in Figure 15 the display of the placement of the force and support on the rear upright in the SolidWork Software and load on rear upright can be seen in Figure 16.

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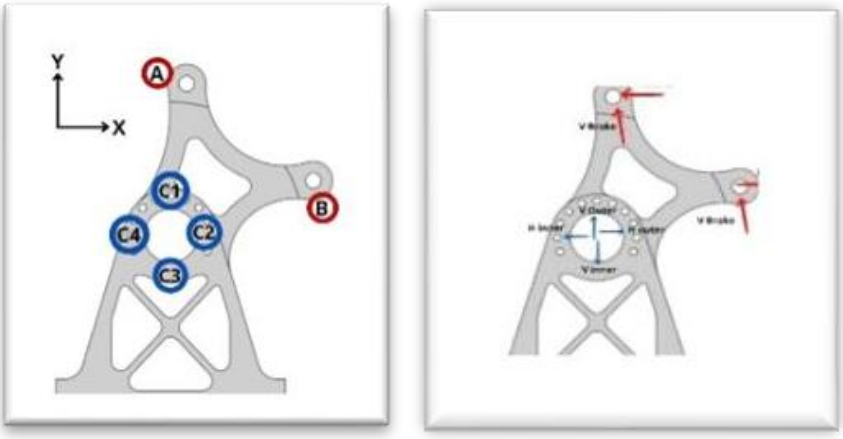

A. Loading Location **B. Load type on rear upright**

Figure 14. Load location and load type on rear upright

Table 5. Direction and magnitude of force on rear upright UG-23

Indokator	Style Direction	Magnitude of Style (N)
A	-X	86.06
	+Y	180.17
B	+X	86.06
	+Y	180.17
C1	+Y	466.50
C2	+X	349.87
C3	-Y	221.97
C4	-X	181.48

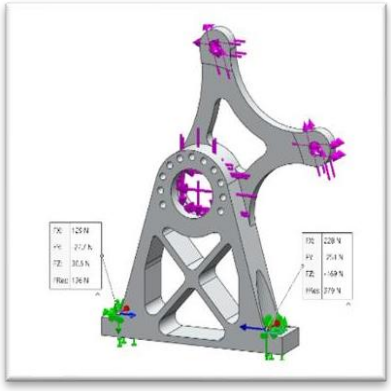

Figure 15. Style placement and rear support in SolidWork apps

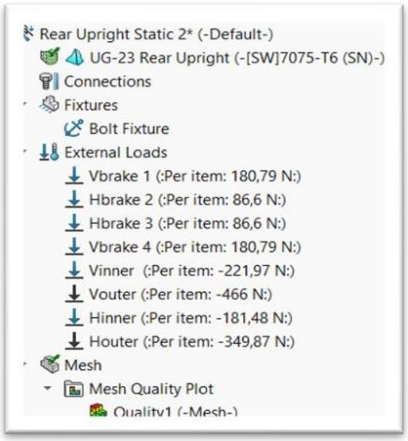

Figure 16. Load on rear upright

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Based on the results of the calculation of the maximum braking force, the loading force on each rear upright section is obtained. The results of this calculation will be included in the calculation of Finite Element Analysis as a result of the component design.

3.3.5. Support

The support is placed on the rear upright locks that are attached to the car frame. Details in Figure 17.

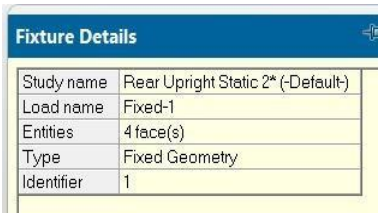

Figure 17. Detail Fixture

Figure 17 shows Fixed Geometry, which means that the assigned part does not undergo displacement or deformation during the simulation process. This arrangement aims to represent the actual conditions under which components in the area are assumed to be firmly bound or immobile, such as the condition of bolts or welds in an actual assembly [15]. Figure 18 shows the fixture on the Rear Upright component used in the static analysis simulation, indicated by a green symbol indicating that the surface is subject to Fixed Geometry conditions, meaning that it does not undergo displacement or rotation during the simulation.

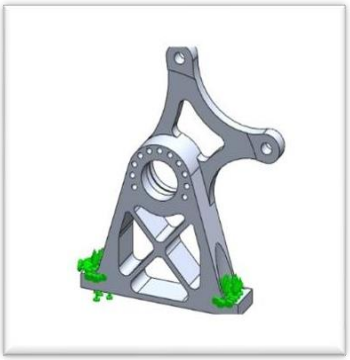

Figure 18. Fixture

3.4. Simulation run dan result

The results of this analysis will be divided into several parts to make it easier to understand the strength of the component structure in each critical part, so that the Von-misses Strees, the Factor of Safety to the constituent and the Deformation and Strain of the Rear Upright Design of the Garuda UG-23 Car will be known.

3.4.1. Stress Von-Misses

Full rear upright

Figure 19 shows the stress on the entire rear upright.

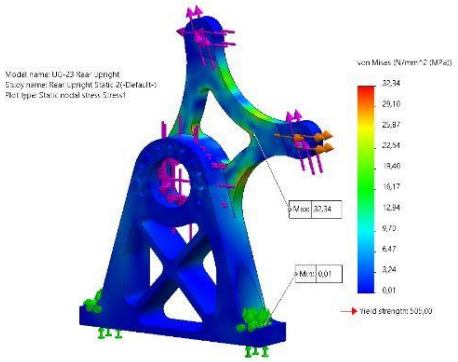

Figure 19. Stress on the entire rear upright

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Inner side rear upright and rear upright inner side

Figure 20 shows the stress on the outer side and stress on the inner side can be seen in

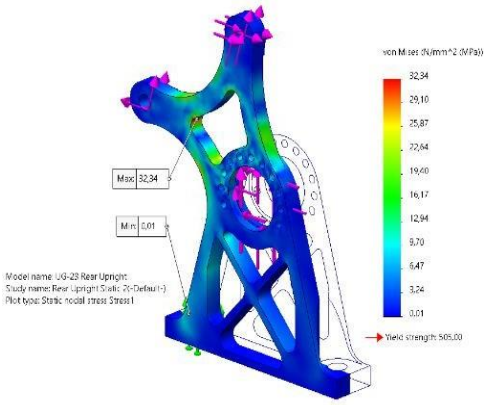

Figure 20. Stress on the outer side

Based on the image above, there are several critical stress points, namely in the caliper bracket and the right and left sides of the upright. In Figure 19, it can be seen that the lower bracket has a max stress of 32.34 MPa. Then Figure 20 on the outside of the critical point of stress is found in the caliper bracket right at the bottom radius of 32.34. In Figure 19 we can see that the outer housing bearing part is given a vertical and horizontal force under a stress of 3.24-9.70 MPa. Then Figure 21 on the inside of the rear upright critical stress point is located on the left side near the houshing bearing of 3.24-6.47 MPa. This stress is caused by shear stress because the caliper components through the caliper bolts attached to the caliper bracket hold the moment of rotation of the vehicle's wheels that are channeled to all upright parts.

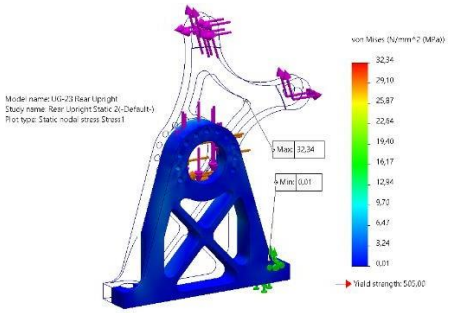

Figure 21. Stress on the inner side

3.4.2. Factor Of Safety

The factor of safety is based on the calculation of the Yield Strength of the constituent material divided by the Von-Misses Stress. The manufacture of rear upright uses the constituent material of Aluminum 7075-T6 with a yield strength of 505 MPa. Figure 22 is the result of the calculation of the Factor of Safety through software calculation resulting in a factor of safety point of at least 15.62 at the point where the caliper bracket meets the main structure upright.

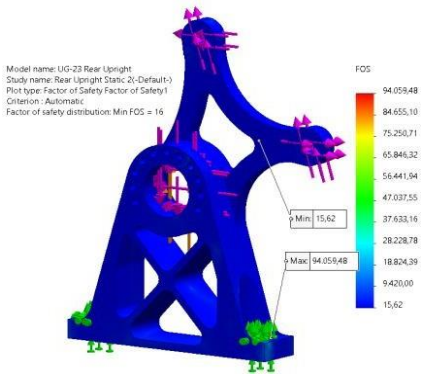

Figure 22. Factor of Safety value

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The rear upright component that has a known von-misses stress value at each stress point is then calculated the safety factor based on the yield strength of the material of the constituent components and the results are obtained as shown in Table 6 below.

Table 6. Upright Back Safety Factor Calculation Table

No	Component Stress Points	Stress Von- misse s (Mpa)	Yield Strengh t Materia l	Factor of Safety
1	Caliper bracket part	32.34	505	15.61
2	Housing Bearing part	9.70	505	52.06
3	Locking Bolt Section Upright to the Frame	3.24	505	155.86

The calculation table is used to make it easier to see the maximum stress point data in each position located in the Rear upright component.

3.4.3. Displacement

Rear Upright has the maximum potential for displacement of the outer area of the caliper bracket bolt which is the binder between the caliper and the rear upright of 0.08 mm which shows that the area has the greatest potential for deformation, this occurs due to the braking force of the car wheels when braking maximum barking. Displacement on components can be seen in Figure 23.

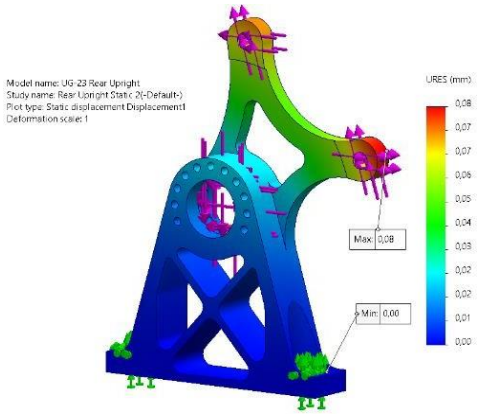

Figure 23. Displacement on Components

3.4.4. Strain

The rear upright has a maximum strain of 0, but based on the visual image, there are several critical points that have the potential to cause stress, namely in the caliper bracket area, so if the rear upright gets a higher load, stress on that area can occur. Strain on components can be seen in Figure 24.

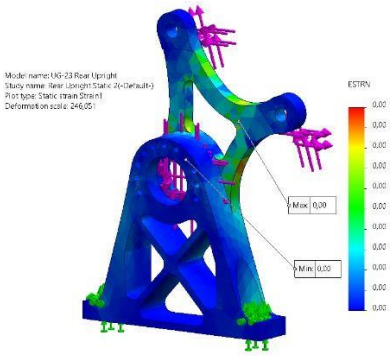

Figure 24. Strain on Components

The conclusion obtained is that the strength of the Rear Upright design is simulated when the car is braking at maximum speed, the component load can be calculated and included in the calculation that will be received by the rear upright through Finite Element Analysis producing data in the form of stress points on the rear upright so that the value of the factor of safety can be known. The maximum stress point is at the point of the caliper bracket, more precisely at the meeting between the caliper bracket and the main body of the upright with a stress value of 32.34 MPa so that it is known that the Factor of Safety is 15.62 Based on the Yield Strength

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of the material of 505 MPa which shows that the strength of the rear upright is adequate because it meets the target value of a Factor of Safety of at least 4. In addition, the components have a maximum Displacment value of 0.08 mm in the caliper bracket and a maximum strain of 0. all data shows that the rear upright is safe so that it can be used on the Garuda UG-23 car. Table 7 shown an data evaluation table result.

Table 7. Data Evaluation Table Results

No	Data	Target	Results	Conclusion
1	Desain	Rear Upright UG-23	The design was successfully created	Conform
2	Stress	< 505 MPa	32.34MPa	Fulfil
3	Factor of safety	> 4	15.62	Fulfil
4	Displacement	< 0.1 mm	0.08 mm	Fulfil

The evaluation of the problems in this final project, namely the creation of a new design of the Rear Upright for the Garuda UG-23 Car and the strength test through Finite Element Analysis has been in accordance with the target so that the next design can be manufactured and assembled components to the car must follow the instructions set by this final project such as fitting, topology manufacturing, bolt locking using torque wrenches and the process of installing supporting parts on the upright.

3.5. Topology Optimization

The weight of the vehicle has a great effect on the efficiency of the vehicle, to get a light rear upright weight, it is necessary to optimize the rear upright design. The effect of topological optimization on power is not so significant compared to the load received by the rear upright. The software calculation results in a Factor of Safety point of at least 15.62 So that the Factor of safety is still considered safe. The resulting weight comparison before topology optimization and after topology optimization can be seen in Figure 25 and Figure 26.

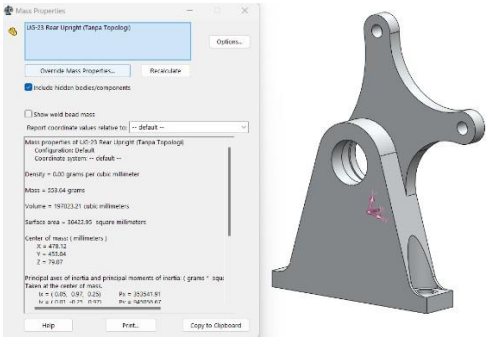

Figure 25. Weight rear upright before optimization

In Figure 25 is an upright design before optimization? The weight produced based on software calculations weighs 553.64 grams. The total volume is 197.023.21 mm^3. The component design is still solid and conventional without any significant material reduction. Weight rear upright after optimization can be seen in Figure 26.

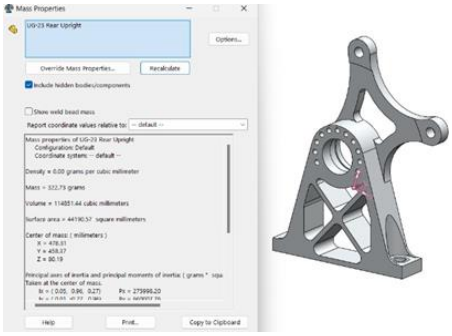

Figure 26. Weight rear upright after optimization

In Figure 26 tt is the result of topological optimization, resulting in a weight of 322.73 grams, experiencing a decrease in mass of 41.70% from the initial model. The volume also decreased to 114.851.44 mm^3. The design of components becomes more complex with the presence of cavities resulting from the optimization process, but still maintains structural strength. This shows that the topology optimization process successfully reduces the weight of the components significantly. Hasil evaluasi bisa dilihat pada Table 8.

Table 8. Evaluation results

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Kondisi	Berat (gram)	Keterangan
Sebelum Optimasi Topologi	553.64	Berat awal
Setelah Optimasi Topologi	322.73	Berat setelah optimasi
Pengurangan Berat	230.91	553.64 -322.73
Persentase Pengurangan berat	41.70%	(230.91 /553.64) ×100

Table 8 shows the results of the comparison of component weights before and after topology optimization. Based on this data, it is known that the initial weight of the component is 553.64 grams. After going through the topology optimization process, the weight of the components was reduced to 322.73 grams. Thus, there was a weight reduction of 230.91 grams. When calculated with a mathematical formula, the weight loss reached 41.70% of the initial weight. This weight reduction suggests that the topology optimization process is significantly successful in reducing the mass of the rear upright, which has the potential to improve the overall performance efficiency of the system, especially when applied to urban cars.

4. Conclusion

Based on the results of the development of the Rear upright design of the Garuda UG-23 Car with the analysis obtained and presented, it was concluded that:

a. The rear upright of the Garuda UG-23 car uses Aluminum Alloy 7075-T6 material, which was selected through the Ashby method, considering the needs of high strength and low density. Aluminum Alloy 7075-T6 has a yield strength of 505 MPa and a low density (± 2.81 g/cm^3), providing an excellent strength-to-weight ratio.

b. The design has met the target specifications, including topology optimization to lower the mass from 553.64 grams, reduced to 322.73 grams. With four rear uprights on one car, the total weight reduction reached 923.64 grams, or about 41.7% of the initial weight.

c. Analysis of the strength of the design through Finite Element Analysis (FEA) at maximum braking conditions. Shows a maximum voltage of 32.34 MPa in the caliper bracket area. A Factor of Safety (FoS) of 15.62 was obtained, far above the minimum FoS target of 4. The maximum displacement is only 0.08 mm and the maximum strain is close to zero. Based on the results of design, optimization, and testing, the new rear upright is declared safe and suitable for use on the Garuda UG-23 car.

Based on the conclusions of the results of the development of the Garuda UG-23 Rear Upright Car, it can be revealed that suggestions such as the new design of the Rear Upright are manufactured in accordance with the design of the Rear Upright to match the results of the simulation; The new design of the Rear Upright in the process of assembling components to the car must follow the instructions set out in this final project such as the granting of tolerances, adjustment and locking using torque; The new design of the rear upright was tested in the field to validate and ensure that the rear upright and installed components are safe to use in the Garuda UG-23 car.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

Funding

No funding support was received.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/ or publication of this article.

Data Availability

The datasets generated during and/ or analysed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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ISSN: 3110-1577