Reverse Engineering of a Student Bicycle

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ME351: Design of Machine Elements **Semester 2024-25-II**

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Abstract

This project focuses on the reverse engineering of a student bicycle to gain a comprehensive understanding of its structural and functional aspects through systematic disassembly, measurement, computer-aided modeling, and mechanical analysis. The primary objective was to deconstruct the bicycle into its individual components, reconstruct it in a virtual environment using CAD tools for further study and evaluation and analyze their design intent.

The process began with the **complete disassembly of the bicycle**, during which each component—frame, fork, wheels, drivetrain, braking system, and accessories—was carefully documented and measured. These measurements served as the basis for **creating accurate 3D models using Autodesk AutoCAD**. The modeling stage emphasized precision and attention to detail to replicate the actual geometry and assembly of the bicycle.

Subsequently, a thorough literature review was conducted to **identify relevant loading conditions and standard assumptions under both static and dynamic scenarios**, such as rider weight, pedaling forces, and terrain-induced loads. Using this information, appropriate boundary conditions were applied to simulate real-world usage.

Stress analysis was performed to determine stress distribution across the bicycle frame and other critical components. Various loading cases were evaluated, and a Factor of Safety (FOS) was calculated for each. This analysis highlighted regions of potential failure and validated the robustness of the bicycle design.

The study provides insights into the design and engineering behind everyday mechanical systems, while also reinforcing key concepts in mechanical engineering such as load analysis, material behavior, and design optimization. The reverse engineering approach allowed for hands-on experience with both hardware and software tools, bridging the gap between theoretical knowledge and practical application.

Contents

1 Introduction

Reverse engineering is the systematic process of deconstructing a product to extract knowledge about its design intent, geometry, material selection, and functional behavior—especially in cases where original documentation such as CAD models, technical drawings, or manufacturing details are unavailable. It enables engineers and designers to work backwards from a finished product to uncover how it was built and why certain engineering decisions were made. This technique is widely employed across domains including automotive, aerospace, consumer products, and medical devices for purposes such as redesign, quality assurance, cost reduction, and legacy product documentation.

In mechanical engineering, reverse engineering typically involves disassembling a product, carefully measuring its components using precision tools, and then reconstructing it in a CAD environment for further evaluation. The reconstructed model can then be analyzed to evaluate its structural integrity under real-world loads.

Within the scope of ME351 (Design of Machine Elements), reverse engineering is not only a practical exercise but also an educational strategy. It allows students to directly apply theoretical principles—such as stress-strain behavior, fatigue analysis, and factor of safety calculations—to tangible mechanical components like shafts, gears, bearings, and fasteners. It promotes design thinking by encouraging students to ask critical questions: Why was this material chosen? How does this geometry optimize strength and weight? What failure modes does the design address? Furthermore, it integrates software proficiency with engineering intuition, strengthening the student's ability to conceptualize, analyze, and improve real-world designs.

1.1 Why Bicycle?

The bicycle serves as an ideal platform for reverse engineering due to its simplicity, accessibility, and relevance to mechanical design. Despite being one of the most energy-efficient transportation systems, the bicycle embodies nearly every foundational concept in machine design—from force transmission through chains and sprockets, to structural optimization of frames, and ergonomic considerations in component placement. Its parts—frame, crank, wheels, handlebar, and saddle—are well-suited for dimensional analysis and CAD modeling due to their moderate complexity and ease of access.

Moreover, the bicycle frame, often made from materials like steel, aluminum, or carbon fiber, offers a rich testbed for exploring static and dynamic load conditions. These conditions mimic real-world scenarios such as pedaling forces, braking loads, and terrain-induced vibrations. Studying how the bicycle responds to these loads helps students understand structural mechanics and stress distribution in real mechanical systems.

By selecting a student-grade bicycle for this project, we leverage a familiar, manageable system to explore sophisticated analysis techniques. This provides an opportunity to blend hands-on mechanical disassembly with advanced simulation and analysis, making the bicycle an exemplary tool for experiential learning in ME351.

1.2 Our Objectives

The primary aim of this project is to apply the principles of reverse engineering to a commonly used mechanical system—a student bicycle. Our specific objectives are as follows:

1. To completely disassemble the bicycle and document its individual components and subassemblies.
2. To measure key dimensions using vernier calipers, micrometers, and measuring tape, ensuring dimensional accuracy.
3. To recreate the bicycle components in a CAD environment (AutoCAD), followed by assembly modeling to visualize and simulate part interactions.
4. To conduct a literature review to determine realistic static and dynamic loading conditions, considering rider weight, pedaling force, braking loads, and terrain interaction.
5. To perform force and torque calculations, and estimate the factor of safety (FOS) under different load cases.

Through this structured and multi-disciplinary approach, the project reinforces critical aspects of mechanical engineering—load analysis, material behavior, structural design, and virtual validation—while providing hands-on exposure to industry-relevant tools and workflows.

1.3 Methodology

The methodology adopted in this project is modular and sequential, ensuring clarity, reproducibility, and accuracy. It follows a workflow widely accepted in reverse engineering literature and includes the following stages:

- **Disassembly:** The bicycle was carefully taken apart using mechanical hand tools, ensuring no damage to reusable components.
- **Measurement:** Each part was measured using calibrated tools and its features were recorded systematically for reference and modeling.
- **CAD Modeling:** Individual components were modeled in SolidWorks based on recorded dimensions. Features such as extrusions, fillets, and patterns were used to replicate real geometry.
- **Assembly:** The parts were assembled virtually to verify spatial relationships and to identify potential interferences.
- **Loading Assumptions:** Through literature review, various loading scenarios (seating pedaling, standing pedaling, uphill riding) were identified, and relevant forces were computed.
- **Evaluation:** The results were interpreted to highlight high-stress regions and suggest design improvements or material substitutions.

This structured methodology not only allowed for a comprehensive reverse engineering study but also provided a platform to apply and test theoretical concepts learned in the ME351 course.

2 Physical Disassembly & Measurements

The bicycle was taken to a workshop and systematically disassembled using standard hand tools (collet/tip wrench, open-ended wrenches, screwdrivers) to separate the frame, drivetrain, wheels, braking system, and other accessories. Each component—frame tubes, sprockets, cranks, handlebars, and wheels—was measured using vernier calipers and tape measures. Critical dimensions were recorded and tabulated for CAD modeling and verification.

2.1 Cycle Model

We chose the Hercules Brut Bicycle for our studies. As one of the most popular cycles in IITK Campus, it was readily available and easy to disassemble using conventional tools.

Figure 1: Hercules Brut Single Speed 19.5 Inch Frame 26 Inch Wheel 26T Road Cycle

Source: Hercules

Steel aisi 1020 used

Figure 2: Disassembly

Source: Project Team

2.2 Parts and Subassemblies

The following are the pictures and measurements of various components, parts, and subassemblies of the bicycle:

2.2.1 Frame

Figure 3: Frame

Source: Project Team

Insert dimensions measured here

2.2.2 Brake Assembly

Figure 4: Brakes

Source: Project Team

Pad: Length = 6cm, Breadth = 1cm

2.2.3 Chain-Sprocket

Figure 5: Chain

Source: Project Team

Figure 6: Sprocket

Source: Project Team

Chain length: 133.5cm, back sprocket diameter: 6.3cm(outer), 3.2cm(inner)

2.2.4 Steering

Figure 7: Fork

Source: Project Team

Figure 8: Handlebar

Source: Project Team

Handle length: 60cm, Grip Length: 13cm, Fork Legs: 38cm, Head: 19cm

2.2.5 Pedal Crank

Figure 9: Pedal Crank

Source: Project Team

Figure 10: Pedal Crank

Source: Project Team

paddle length: 10cm, sprocket diameter: 16.5cm, crank length: 17cm, hub diameter: 2.5cm, wheel axle length:16.3cm

2.2.6 Seating

Figure 11: Seating

Source: Project Team

Slent Length: 27cm, Base 18cm, Height 18cm

2.2.7 Miscellaneous

Figure 12: Nuts and Bolts

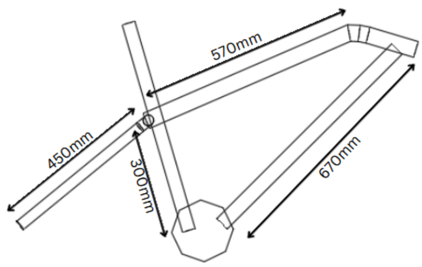
Source: Project Team

Nut & bolt: M10, M4(chain), quarter pin: M8

3 CAD Modeling

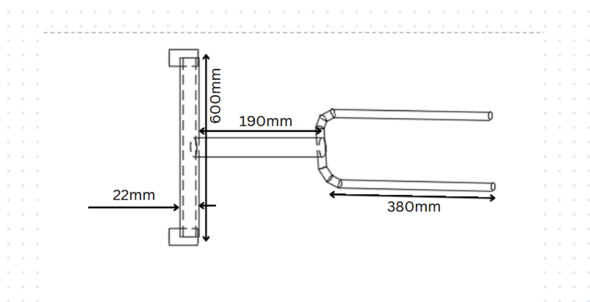
3.1 Part Drawings

Figure 13: Frame



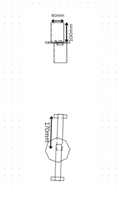
Source: Project Team

Figure 14: Steering



Source: Project Team

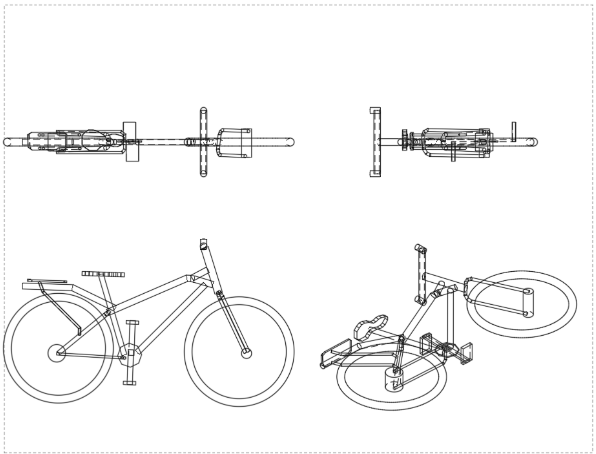
Figure 15: Crank-Pedal



Source: Project Team

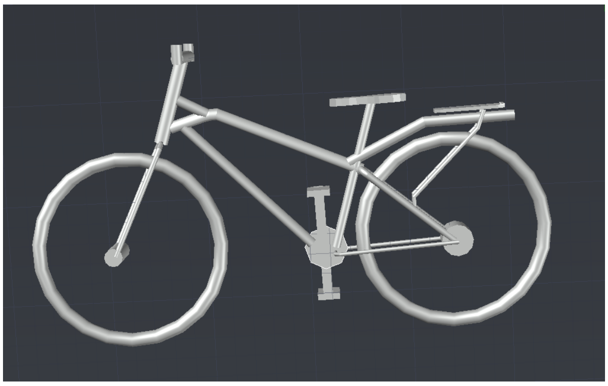
3.2 Full Assembly

Figure 16: Full Assembly Drawing



Source: Project Team

Figure 17: 3D Model

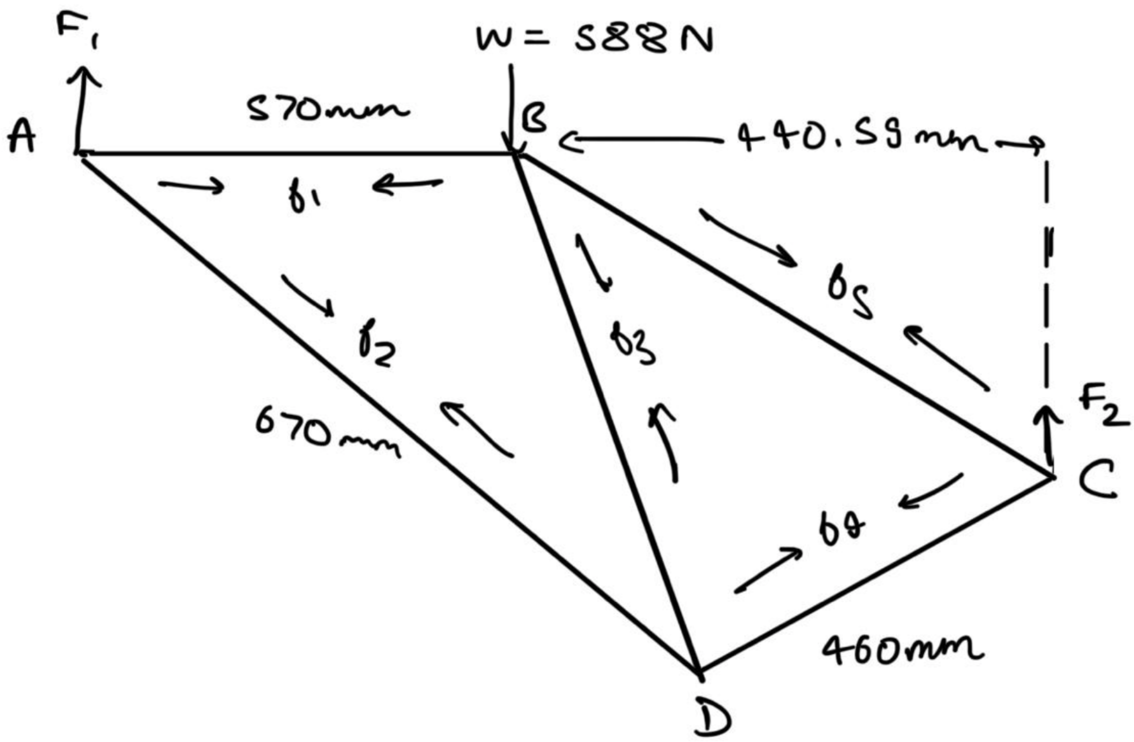


Source: Project Team

4 Analysis

4.1 Frame Geometry and Force Calculation

Figure 18: Measured frame geometry and angle definitions



The bicycle frame was disassembled, and key angular measurements were taken to understand the geometry of the truss-like structure. The values obtained are:

$$A = 26.45^\circ, \quad B_1 = 95.70^\circ, \quad B_2 = 72.56^\circ, \quad C = 38.48^\circ$$
$$D_1 = 57^\circ, \quad D_2 = 68.95^\circ$$
$$B = B_1 + B_2 = 168.26^\circ, \quad D = D_1 + D_2 = 125.95^\circ$$

Support Reactions (Neglecting Frame Mass)

Assuming the frame's mass is negligible, we computed the support reactions under a static load W using basic equilibrium:

$$F_1 + F_2 = W$$
$$W \times 570 = F_2 \times 1010.59 \Rightarrow F_2 = 331.65\,\text{N}, \quad F_1 = 238.35\,\text{N}$$

Internal Member Forces

Using trigonometric and joint equilibrium methods, internal forces were calculated:

$$f_2 = \frac{F_1}{\sin A} = 535.12\,\text{N}$$
$$f_1 = -f_2 \cos A = -479.11\,\text{N}$$
$$f_3 = 676.94\,\text{N}, \quad f_5 = -420.66\,\text{N}, \quad f_4 = 71.01\,\text{N}$$

4.2 Cross-Sectional Properties and Buckling Analysis

To evaluate the frame's structural integrity, we consider members under compression (AD, DC, BD) for buckling. We model them as hollow circular sections.

Moment of Inertia and Radius of Gyration

$$I = \frac{\pi(D^4 - d^4)}{64}, \quad D = 22\,\text{mm}, \quad d = 16\,\text{mm} = 8282.02\,\text{mm}^4$$
$$A = 179.07\,\text{mm}^2, \quad k = \sqrt{\frac{I}{A}} = 6.8\,\text{mm}$$

Johnson Buckling Criterion

The Johnson buckling limit defines the slenderness ratio threshold:

$$\left(\frac{l}{k}\right)_1 = \left(\frac{2\pi^2 CE}{\sigma_y}\right)^{1/2} = 126.72, \quad \sigma_y = 295\,\text{MPa}$$

Member 2:

$$\left(\frac{l}{k}\right)_2 = \frac{670}{6.8} = 98.53 < \left(\frac{l}{k}\right)_1$$
$$P_{cr} = 205.83 \times 179.07 = 36857.98\,\text{N}$$
$$N_d = \frac{36857.98}{f_2} = \frac{36857.98}{535.12} = \underline{68.89}$$

Member 3:

$$\left(\frac{l}{k}\right)_3 = \frac{300}{6.8} = 44.12$$
$$P_{cr} = 277.12 \times 179.07 = 49623.88\,\text{N}$$
$$N_d = \frac{49623.88}{f_3} = \frac{49623.88}{676.94} = \underline{73.31}$$

Member 4:

$$\left(\frac{l}{k}\right)_4 = \frac{460}{6.8} = 67.64$$

$$P_{cr} = 252.98 \times 179.07 = 45301.13\,\text{N}$$

$$N_d = \frac{45301.13}{f_4} = \frac{45301.13}{71.01} = \underline{637.95}$$

Conclusion

The calculated values of the factor of safety (FoS) for all critical members under compressive loads exceed industry-accepted minimum values. The minimum FoS among them is approximately 68.89 (for Member 2), which indicates substantial structural robustness. These results validate that the frame is well within safe limits for typical loading conditions, and buckling failure is highly unlikely under normal operation.

Thus, we conclude that the frame design is mechanically safe and structurally reliable.

4.3 Handlebar

To evaluate the structural response of the bicycle handlebar under dynamic loading, we consider both vertical forces due to the rider's mass and additional forces from acceleration during pedaling or maneuvering.

1. Vertical Force from Rider's Arm Input

Assuming the rider exerts a downward force at an angle of 30° from the horizontal:

$$
\begin{aligned}
\text{Vertical Force on Handlebar (VF)} &= 60 \times \sin(30^\circ) \times g \\
&= 30 \times 9.81 \\
&= 294.3\,\text{N}
\end{aligned}
$$

2. Force from Acceleration

The combined mass of the rider and bicycle is:

$M = M_{\text{Rider}} + M_{\text{Cycle}} = 60 + 12 = 72\,\text{kg}$

Assuming a final velocity of 4.167 m/s reached in 2 s:

$v = u + at \Rightarrow 4.167 = 0 + a \times 2 \Rightarrow a = 2.083\,\text{m/s}^2$

Considering the effective acceleration component along a 25° incline:

$F_B = 72 \times 2.083 \times \cos(25^\circ) = 135.93\,\text{N}$

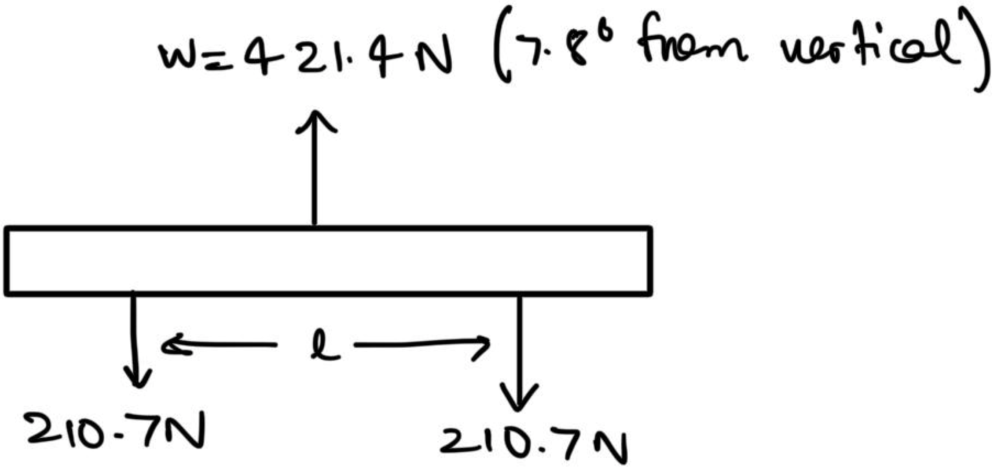
The net force acting on the handlebar, combining vertical and inclined components, is approximated as:

$F_{\text{net}} = 421.4\,\text{N}$ at 7.835° from vertical

3. Bending Stress Analysis

Handlebar dimensions and properties:

Figure 19: Handlebar loading conditions and geometry



Length $l = 47\,\text{cm} = 0.47\,\text{m}$

Outer Diameter $D = 22\,\text{mm}$, Inner Diameter $d = 16\,\text{mm}$

The maximum bending moment (assuming a point load at quarter-span of a simply supported beam):

$$M_{\max} = \frac{Wl}{4} = \frac{421.4 \times 0.47}{4} = 49.5\,\text{Nm}$$

Second moment of area for a hollow circular section:

$$I = \frac{\pi(D^4 - d^4)}{64} = \frac{\pi(0.022^4 - 0.016^4)}{64} = 8.28 \times 10^{-9}\,\text{m}^4$$

Using bending stress formula:

$$\sigma = \frac{My}{I} = \frac{49.5 \times 0.011}{8.28 \times 10^{-9}} = 65.7\,\text{MPa}$$

4. Factor of Safety (FOS)

$$\sigma_y = 295\,\text{MPa} \Rightarrow \text{FOS} = \frac{\sigma_y}{\sigma} = \frac{295}{65.7} = 4.54$$

5. Material Properties

- Yield Strength (σ_y): 295 MPa
- Ultimate Strength: 395 MPa
- Modulus of Elasticity: 200 MPa
- Hardness (Brinell): 111 MPa
- Elongation at Break: 36.5%

Conclusion: The handlebar exhibits an acceptable factor of safety under the given loading conditions, indicating that the section is structurally adequate under expected use.

4.4 Crank-pedal

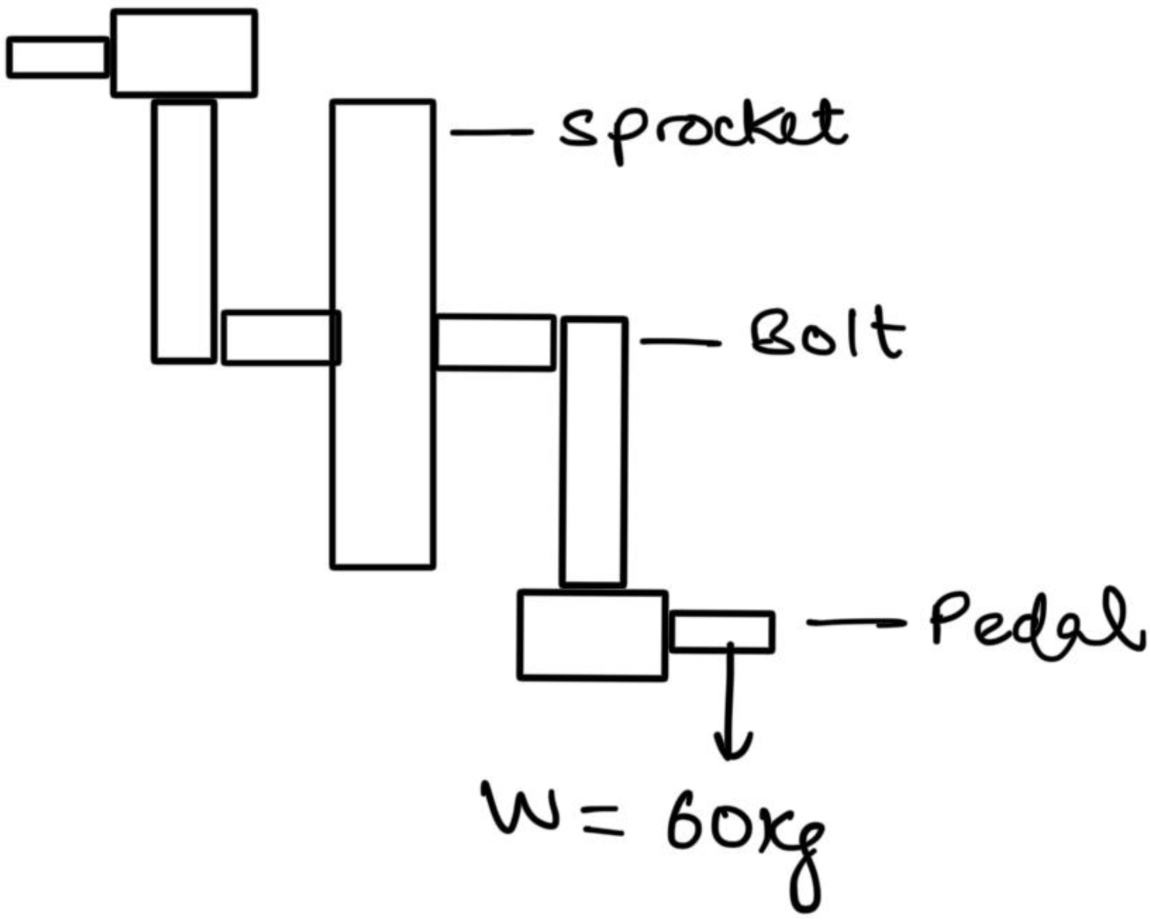
Given:

- Load applied due to rider: $F = 60 \times 9.8 = 588\,\text{N}$
- Effective tensile stress area for M8 bolt (from Design Data Book): $A_n = 32.8\,\text{mm}^2 = 32.8 \times 10^{-6}\,\text{m}^2$
- Number of bolts: $n = 1$

Tensile Stress:

$$\sigma_s = \frac{F}{nA_n} = \frac{588}{1 \times 32.8 \times 10^{-6}} = 17.9\,\text{MPa}$$

Factor of Safety (FOS):



Assuming yield strength $S_y = 240\,\text{MPa}$, using Tresca criterion:

$$\text{FOS} = \frac{0.577 \times S_y}{\sigma_s} = \frac{0.577 \times 240}{17.9} = \underline{7.74}$$

Conclusion: The bolt has a high factor of safety under the applied load, indicating safe operation within elastic limits.

5 Conclusion

The reverse engineering of a student-grade bicycle has proven to be an insightful and educational exercise that integrates the core principles of mechanical engineering with practical, hands-on learning. Through the systematic disassembly, measurement, CAD modeling, and analysis of the bicycle and its components, we were able to develop a comprehensive understanding of its design and structural performance.

The project enabled us to explore the mechanical rationale behind common design decisions—such as tube geometry, frame layout, and material selection—while reinforcing theoretical concepts like static and dynamic loading, stress distribution, and factor of safety. The use of CAD tools allowed us to create accurate digital representations of each component, which were then assembled virtually to simulate real-world conditions. Applying Analysis to this model helped us assess how the bicycle frame responds under various loading scenarios, such as seated pedaling and standing acceleration.

Furthermore, this work demonstrated the importance of considering both material properties and design geometry in ensuring structural reliability. Stress concentrations and deformation zones identified in the simulation provide valuable insights into potential failure points, offering direction for future design improvements.

From an academic perspective, this project bridged the gap between classroom learning and real-world application. It fostered a deeper appreciation for the design process, the value of reverse engineering, and the iterative nature of engineering analysis. In alignment with the learning outcomes of ME351 (Design of Machine Elements), we not only applied our theoretical knowledge but also developed critical problem-solving skills, attention to detail, and proficiency in engineering software tools.

Looking forward, this methodology can be extended to more complex systems and can serve as a foundational experience for advanced product design, optimization, and innovation in engineering practice.

Bibliography of Contributions and Declaration

Author Contributions

- **Aman Singh Gill (220120)** – Led the disassembly of the bicycle, documented the parts with photographs, and supported measurement of mechanical components.
- **Aniket Nandi (220141)** – Responsible for CAD modeling of the drivetrain and wheel assemblies; helped compile the technical drawings of individual parts.
- **Rishi Baghel (220890)** – Conducted the literature review on loading conditions and design considerations for bicycle frames under real-world scenarios.
- **Rohit Gautam (220910)** – Carried out theoretical load and torque calculations for various riding conditions such as seated and standing pedaling.
- **Sachin Kumar (220931)** – Assisted in detailed measurement of the bicycle frame and handled organization of raw data and dimension sheets.
- **Shaurya Singh (218070969)** – Wrote the methodology, introduction, and conclusion sections of the report; handled document structuring and editing in LaTeX.
- **Sharah P S (221001)** – Created labeled diagrams for the disassembled parts and assisted with CAD assembly of the full bicycle.
- **Yuval Bansal (221232)** – Played a central role in organizing the project structure and setting timelines. Assisted in CAD modeling of the frame geometry and ensured dimensional accuracy. Contributed to the background and objectives sections and provided critical feedback during report review and editing phases.

Declaration

We, the undersigned, declare that the work presented in this report titled *"Reverse Engineering of Student Bicycle"* is the result of a collaborative effort. Each team member has made a substantial and meaningful contribution toward the completion of the project. All results, observations, and interpretations are original and based solely on our own work.

Signatures: