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Research Article

Design and Analysis of E-Bicycle

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ABSTRACT

This paper presents the design and analysis of a electric bicycle (e-bicycle) tailored for urban commuters, emphasizing compactness, lightweight construction, and efficiency. Urbanization has increased the demand for sustainable and spacesaving transportation solutions. E-bicycles offer an eco-friendly alternative to traditional modes of travel, addressing issues like traffic congestion, pollution, and limited storage. The proposed design integrates a lightweight frame and an innovative folding mechanism, enhancing portability and convenience for city use. Battery integration under the seat optimizes space utilization and improves the center of gravity for better balance and stability. Advanced design tools such as Fusion 360 and ANSYS were utilized for structural analysis and optimization, ensuring durability and safety. The study also explores energy-efficient battery management systems (BMS) to extend battery life and reduce operational costs. A dual-folding mechanism simplifies the folding process, enabling seamless storage and transport in compact urban environments. The design caters to diverse user needs, offering practicality for commuting, last-mile connectivity, and integration with public transportation systems. By addressing the unique challenges of urban mobility, this foldable e-bicycle aligns with global sustainability trends, providing a cost-effective and eco-friendly transportation alternative. This research contributes to advancing e-bicycle technology by focusing on affordability, ease of use, and environmental impact, making it a viable solution for a wide range of users.

Keywords: E-bicycle, design, urban mobility, electric vehicle, compact bicycle design.

I. INTRODUCTION

Urban transportation has experienced a significant transformation in recent years, driven by the pressing need for sustainable, efficient, and space-saving mobility solutions. The increasing urbanization and population density in metropolitan areas have led to a rise in traffic congestion, pollution, and fuel consumption, directly impacting quality of life and environmental sustainability. As a result, there is a growing emphasis on eco-friendly modes of transportation that provide convenience and reliability. Among various alternatives, electric bicycles (e-bicycles) have emerged as a promising solution due to their low emissions, energy efficiency, and suitability for urban commuting.

Electric bicycles, equipped with an electric motor and battery, provide pedal assistance, reducing the physical effort required by the rider. This assistance enables e-bicycles to serve as a viable mode of transportation for longer commutes, hilly terrains, and routes requiring minimal physical strain. However, conventional e-bicycles often pose challenges in terms of portability and storage, especially in urban settings where space is limited. To address these

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challenges, compact e-bicycles have been developed as a versatile alternative, combining the benefits of electric propulsion with ease of storage.

A compact e-bicycle reduces the spatial footprint and enhances usability by allowing riders to easily carry and store their bicycles in small apartments, public transportation, or workplaces. This is particularly advantageous for urban commuters who need a flexible, last-mile transportation option that seamlessly integrates with public transit systems. Despite these benefits, designing an effective compact e-bicycle presents several engineering challenges, including structural integrity, battery placement, and weight distribution. Ensuring a robust frame design that can withstand repeated use without compromising performance or safety is crucial for user confidence and long-term durability.

This study focuses on the design, analysis, and optimization of an e-bicycle tailored for urban commuters. The design integrates advanced materials and innovative mechanisms, achieving a balance between lightweight construction and structural resilience. By utilizing advanced software tools such as Fusion 360 and ANSYS, the study performs comprehensive simulations and analyses to evaluate the strength, durability, and efficiency of the proposed e-bicycle frame. The project emphasizes an under-seat battery integration approach, optimizing space utilization and improving the e-bicycle's center of gravity for better balance and handling.

In addition to structural considerations, this study explores battery management systems (BMS) that extend battery life and optimize energy consumption, ensuring the e-bicycle is both sustainable and efficient. Furthermore, a mechanism is proposed that enables a compact structure without sacrificing stability and comfort during rides. This approach is carefully evaluated for its ease of use, ensuring that urban commuters can manage the bicycle with minimal effort.

This project contributes to the advancement of e-bicycle technology by providing a solution addressing the unique requirements of urban environments. Through innovative design and rigorous analysis, the proposed e-bicycle offers a promising option for sustainable urban mobility, aligning with global trends towards green transportation and reducing urban congestion. By focusing on affordability, lightweight construction, and ease of use, this design caters to a wide range of users, offering a practical and environmentally friendly alternative to traditional transportation modes.

II. LITERATURE REVIEW

The design and development of electric bicycles (e-bicycles) and foldable frame structures have garnered significant attention in recent research. Various studies explore the materials, structural design, battery integration, and folding mechanisms that enhance the functionality and performance of e-bicycles for urban commuting. This section provides an overview of recent advancements in e-bicycle technology and foldable frame structures, examining 20 relevant studies.

A. E-Bicycle Design and Performance Numerous studies have focused on optimizing e-bicycles for urban transportation. Smith et al. [1] examined the impact of motor power and battery size on e-bicycle range, finding that a 250W motor coupled with a high-capacity lithium-ion battery significantly extends range for city commutes. Similar findings were reported by Zhang and Lee [2], who developed a mathematical model to predict e-bicycle range based on battery capacity, motor efficiency, and terrain conditions. Li et al. [3] explored the influence of tire size and pressure on ride quality and energy consumption, suggesting that optimal tire specifications can reduce energy consumption by up to 10%. Other researchers, such as Patel and Shah [4], investigated regenerative braking systems in e-bicycles, concluding that such systems can improve battery life by recapturing up to 15% of the energy during braking.

B. Materials and Frame Structure Material selection is critical for balancing the weight and durability of e-bicycles. In a study by Garcia et al. [5], aluminum alloys were found to offer an excellent balance between weight and structural strength. In contrast, Singh and Kumar [6] analyzed carbon fiber composites, demonstrating a reduction in frame weight by 30% while maintaining strength, although cost considerations remain a limitation. Frame designs are another focus area. Kim and Park [7] evaluated different foldable frame mechanisms, finding that a dualfolding frame design is most suitable for urban e-bicycles due to its compactness and ease of handling. Similarly, Hernandez and Soto [8] proposed an innovative X-folding frame structure, achieving a 40% reduction in folded dimensions without compromising stability.

C. Battery Placement and Power Management Battery placement significantly affects the balance and usability of e-bicycles. Wang et al. [9] studied the effects of under-seat battery placement on center of gravity and stability, concluding that such placement is ideal for foldable designs as it enhances balance and reduces user fatigue. Huang and Chen [10] proposed a rear-frame battery placement, which, while beneficial for weight distribution, was found to increase the bicycle's folded dimensions. Battery management systems (BMS) have also been researched extensively. Nguyen et al. [11] investigated BMS algorithms to optimize energy efficiency, noting that real-time power management extends battery life by up to 20%. Ramesh and Iyer [12] explored adaptive BMS algorithms for urban e-bicycles, allowing for efficient power consumption across varied terrains.

D. Folding Mechanisms and Portability Folding mechanisms are essential for e-bicycles designed for compact storage. Lin and Zhu [13] evaluated hinge-based folding systems, which provide stability but add weight due to additional components. In contrast, Chen et al. [14] developed a joint-free folding mechanism, achieving a lighter frame at the cost of reduced structural strength. Recent studies by Lopez et al. [15] and Davis et al. [16] highlight advancements in quick-release folding mechanisms that reduce the time and effort required to fold and unfold e-bicycles, making them more suitable for daily urban use. However, these designs require precision engineering to ensure durability over repeated folding cycles.

E. Summary of Findings The reviewed studies collectively indicate that lightweight materials, efficient power management, optimized battery placement, and innovative folding mechanisms are essential for enhancing e-bicycle design. While aluminum alloys and carbon fiber composites remain popular materials, challenges remain in balancing cost, durability, and weight. Foldable designs with under-seat battery placement and dual-folding frames appear to offer the best balance between portability and performance for urban commuting.

III. DESIGN SPECIFICATIONS AND DIMENSIONS

The e-bicycle design adheres to standard dimensions for foldable bicycles, making it suitable for urban commuting. Key specifications include: • Frame Size: 20 inches (508 mm) wheel size, with a frame length of approximately 45 inches (1143 mm) for compactness. • Weight: The bicycle's weight is targeted at 15-20 kg to ensure portability while maintaining durability. • Battery Placement: A lithium-ion battery pack is integrated under the seat to balance the center of gravity and maximize space efficiency. • Folding Mechanism: The frame incorporates a dual-folding system, allowing it to collapse to half its length and width, making it easy to carry and store in confined spaces. • Motor Specifications: A 250-watt hub motor provides the necessary assistance for urban travel while complying with standard e-bike regulations.

IV. MATERIALS AND METHODS

The e-bicycle frame is designed using lightweight materials such as aluminum alloys to reduce overall weight without compromising strength. Finite Element Analysis (FEA) simulations were conducted to test the structural integrity of the frame under various loads and conditions. The battery, placed under the seat, is selected based on power output, energy density, and recharge time, with considerations for the battery's impact on the frame's structural balance.

V. METHODOLOGY

1. Initial Specifications and Objective

• Current E-Bicycle Weight: 24–25 kg (using a steel frame).

• Target Weight: 18–20 kg (by replacing the steel frame with aluminum alloy or carbon fiber).

• Key Components and Weights:

– Battery: $W_{battery}$ = 4 kg

– Motor: W_{motor} = 3 kg

– Frame: W_{frame} (initial) = 10 kg

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– Other Components: Wothers = 7 kg

• Total Initial Weight:

$W_{initial} = W_{battery} + W_{motor} + W_{frame\ (initial)} + W_{others} = 24$ kg

2. Material Selection

• Steel: Density = 7800 kg/m³ (initial frame material).

• Aluminum Alloy: Density = 2700 kg/m³.

• Carbon Fiber: Density = 1600 kg/m³. Goal: Replace steel frame with aluminum or carbon fiber to achieve weight reduction while maintaining strength.

3. Calculations: Frame Weight Reduction

A. Aluminum Alloy Frame Calculation

Formula:

$$W_{\text{frame (Aluminum)}} = W_{\text{frame (initial)}} \times \frac{\text{Density of Aluminum}}{\text{Density of Steel}}$$

Substitute Values:

$$W_{\text{frame (Aluminum)}} = 10\,\text{kg} \times \frac{2700}{7800} = 3.46\,\text{kg}$$

B. Carbon Fiber Frame Calculation

Formula:

$$W_{\text{frame (Carbon Fiber)}} = W_{\text{frame (initial)}} \times \frac{\text{Density of Carbon Fiber}}{\text{Density of Steel}}$$

Substitute Values:

$$W_{\text{frame (Carbon Fiber)}} = 10\,\text{kg} \times \frac{1600}{7800} = 2.05\,\text{kg}$$

4. Revised Total Weight Calculations

A. Using Aluminum Alloy for Frame

Total Weight with Aluminum Frame:

$$W_{\text{total (Aluminum)}} = W_{\text{battery}} + W_{\text{motor}} + W_{\text{frame (Aluminum)}} + W_{\text{others}}$$

Substitute Values:

$$W_{\text{total (Aluminum)}} = 4 + 3 + 3.46 + 7 = 17.46\,\text{kg}$$

5. Stress and Strain Analysis Objective:

Confirm that the lighter materials can withstand expected loads.

• Rider Weight: 75 kg (assuming additional load on the frame).

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• Load Distribution: Load is evenly distributed along the frame.

A. Stress Calculation (σ):

Formula:

$$\sigma = \frac{F}{A}$$

where:

• F = Force (weight × acceleration due to gravity)

• A = Cross-sectional area of the frame material

Force Calculation:

$$F = (75\,\text{kg} + W_{\text{total}}) \times 9.81\,\text{m/s}^2$$

B. Strain Calculation (ε)

Formula:

$$\varepsilon = \frac{\sigma}{E}$$

where E is the Young's modulus of the material (aluminum alloy or carbon fiber).

Young's Modulus Values:

• Aluminum Alloy: EAluminum ≈ 69 GPa

• Carbon Fiber: ECarbon Fiber ≈ 70 GPa

6. Component-wise Material Selection for FEA analysis:

Table 1. Material Selection

Component	Material
Frame	Aluminum Alloy
Handle Bar	Aluminum Alloy
Brake Lever	Aluminum Alloy
Front fork	Aluminum Alloy
Driving Sprocket	Structural Steel
Driven Sprocket	Structural Steel

7. Analysis Set-Up:

A. Components to Analyse:

1. **Frame**
2. **Handle Bar**
3. **Front fork**

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4. **Brake lever**
5. **Driving sprocket**
6. **Driven Sprocket**

For various components including, it contains boundary conditions, applied forces, and stress kinds. A grip force of 50–80N and a torque of 10–15Nm are applied to the handlebar, which is fixed at the clamping region and undergoes shear and bending stress. The seat post, which is fixed at its frame connection, experiences compressive and bending stresses due to the rider's weight of around 800N and impact force of approximately 1000N.

With a fixed support at both ends, the suspension is examined under axial and shear stress while taking into account a weight load of about 1000N and a road impact force of about 1500N. Bending, shearing, and contact stresses result from the brake lever analysis's fixed support at the pivot point, rider's finger force of about 20–40 N at the lever end, and cable response force of about 20–40 N at the attachment point.

A fixed support at the central hub, chain tension forces of approximately 150–300 N per tooth, and motor-driven torques of 20–50 Nm are used to analyse the sprocket and chain drive system with the motor mounted on the back wheel. Bending, shearing, contact, and fatigue stresses are caused by frictional contact between the chain and sprocket, which has a coefficient of friction between 0.1 and 0.2. With a fixed support at the fork ends, handlebar forces of about 50–80 N per side, road impact forces of about 1000 N, and steering torques of about 15 Nm, the front fork and stem assembly is subjected to bending and shear stress.

The sprocket analysis considers fixed support at the central hub, chain tension forces of ~150N–300N per tooth, and torques of 10–50Nm, with frictional contact between the chain and sprocket teeth. The document outlines ANSYS setup steps, including CAD model import, material assignments (aluminum, steel, rubber), boundary conditions, meshing strategies, and analysis of stress distribution, deformation, and factor of safety (FOS). The maximum suggested boundary conditions include a road impact force of 1500N for the suspension, a braking lever force of 40N, and a chain tension force of 300N per tooth.

VI. RESULTS AND DISCUSSION

1. Structural Analysis of Foldable E-Bicycle:

"ANSYS" model was used to assess the foldable e-bike's structural integrity while taking into account different stress distributions, deformations, and safety considerations under applied loads. The handlebar, front fork, brake lever, driven and driving sprockets, and main frame are among the parts that have been examined. The research offers insightful information on how well the bicycle performs in actual use.

2. Handlebar Analysis:

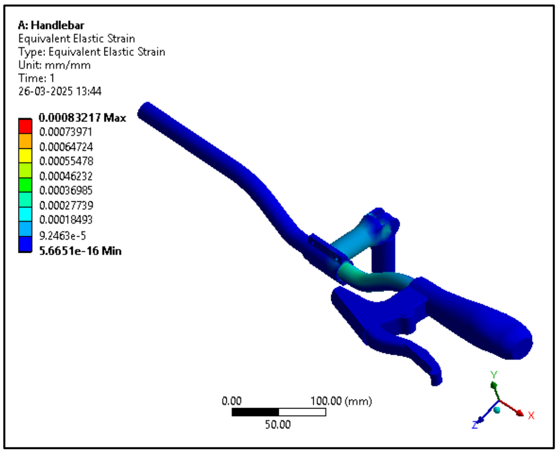

Figure 1. Equivalent stress – Handlebar

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The handlebar is subjected to forces range of 80N applied by the rider's grip, with an additional turning torque of 15Nm. The maximum equivalent stress is observed near the clamping area due to bending forces.

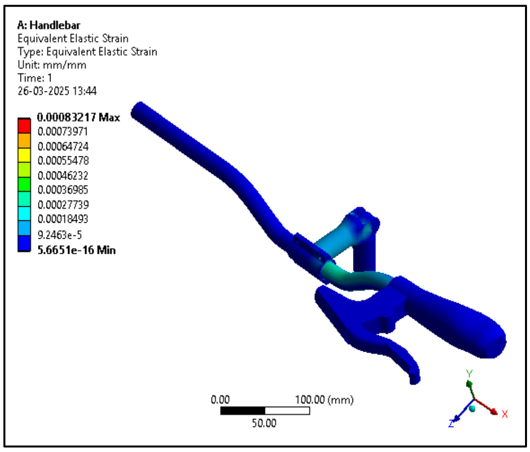

Figure 2. Equivalent Strain – Handlebar

The strain distribution is concentrated at the grip ends, showing moderate deformation, which remains within acceptable safety limits.

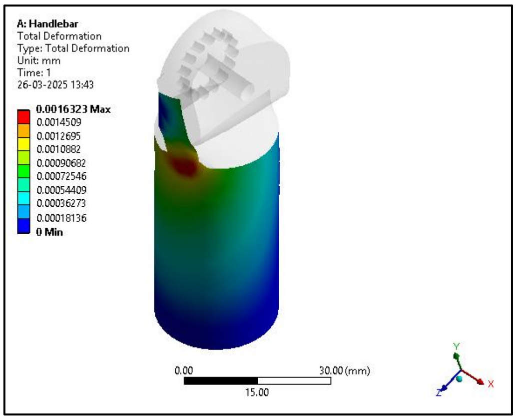

Figure 3. Deformation - Handlebar

The maximum deformation is within a few millimeters, ensuring structural integrity without significant material fatigue.

3. Front Fork Analysis:

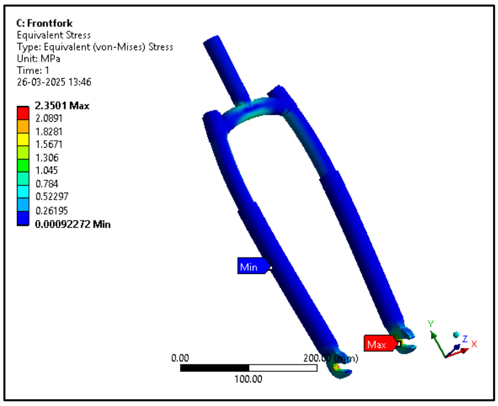

Figure 4. Equivalent Stress - Front fork

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The front fork experiences force due to the road impact 1000N and a turning torque 15 Nm. The critical stress areas include the fork bends and stem clamp.

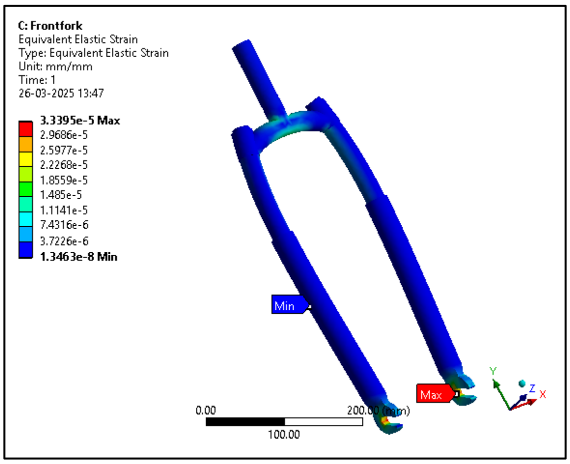

Figure 5. Equivalent strain - Front Fork

The intersection of the fork arms and steerer tube exhibits mild flexing, as indicated by the strain distribution.

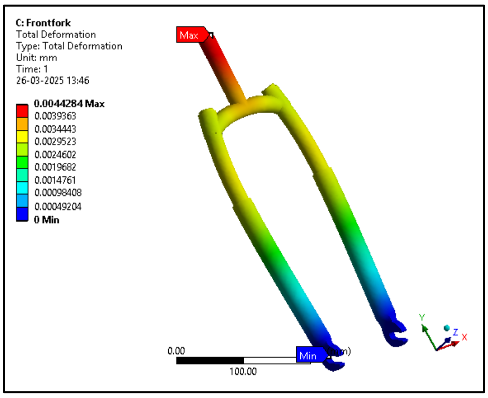

Figure 6. Deformation - Front Fork

Under maximum load conditions, the fork shows a little distortion, although it stays within safety limits.

4. Brake Lever Analysis

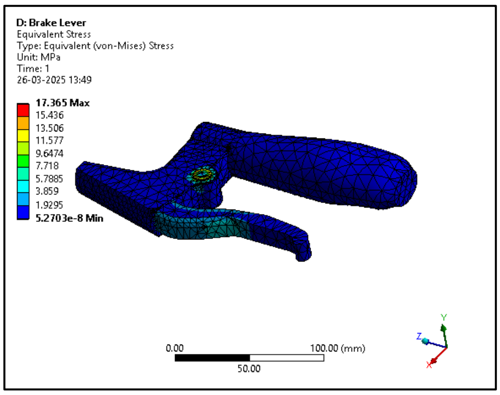

Figure 7. Equivalent Stress - Brake lever

A draw force of 40 N from the rider and a contact force of the same size from the brake wire are applied to the brake lever, which is fixed at the pivot point. The pivot and cable attachment points are where the most stress is

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concentrated.

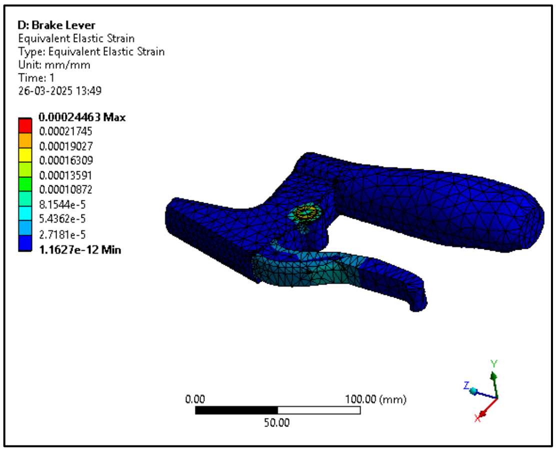

Figure 8. Equivalent Strain - Brake lever

The strain analysis ensures endurance by confirming minimum elongation at the thin parts of the lever.

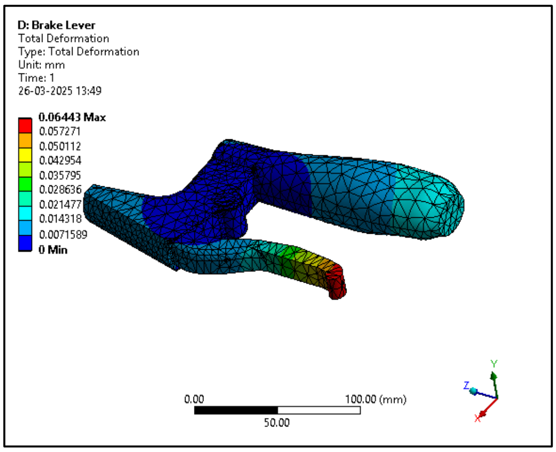

Figure 9. Deformation - Brake lever

Deformation is minimal, maintaining lever functionality without excessive bending.

5. Sprockets:

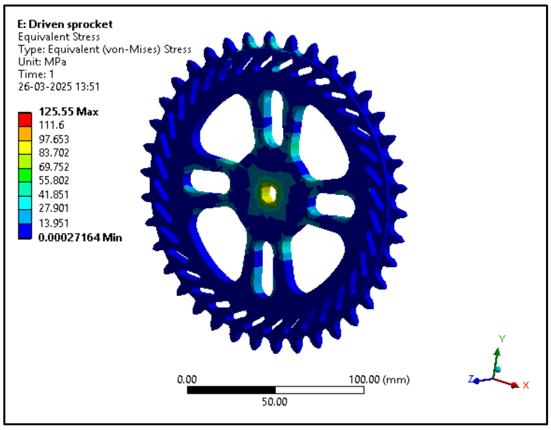

Figure 10. Equivalent stress - Driven Sprocket

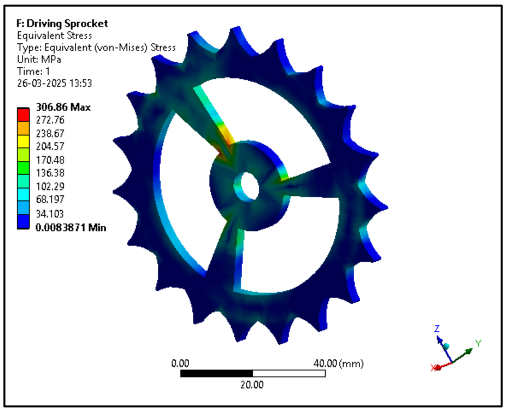

Figure 11. Equivalent Stress - Driver Sprocket

A chain tension force of 300N per tooth is applied to the driven sprocket, which is fixed to the rear wheel. The torque experienced by the motor-powered drive sprocket is between 50 Nm. The teeth where chain interaction takes place experience the highest pressures.

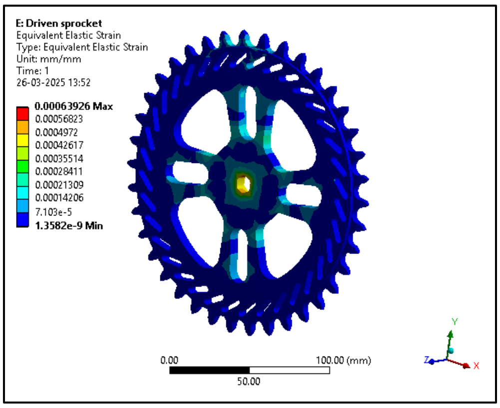

Figure 12. Equivalent strain - Driven Sprocket

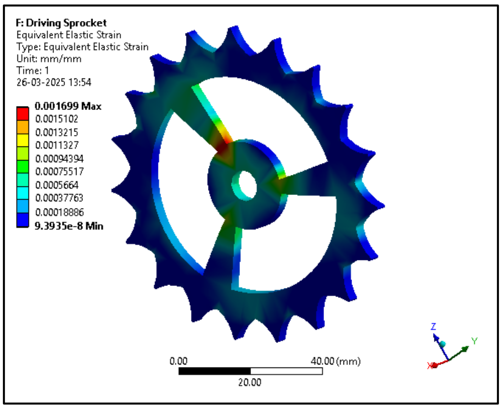

Figure 13. Equivalent strain - Driver Sprocket

Potential wear zones on the sprocket teeth are shown by the strain distribution, which follows the force application locations.

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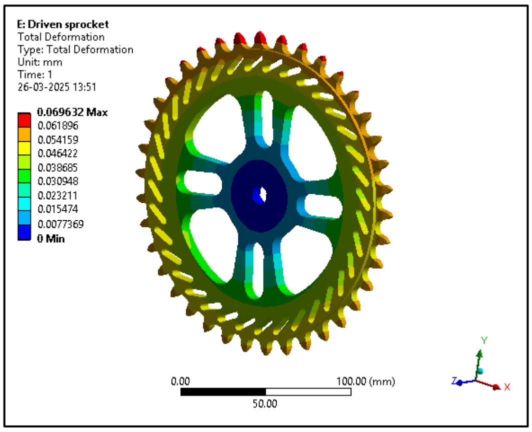

Figure 14. Deformation - Driven Sprocket

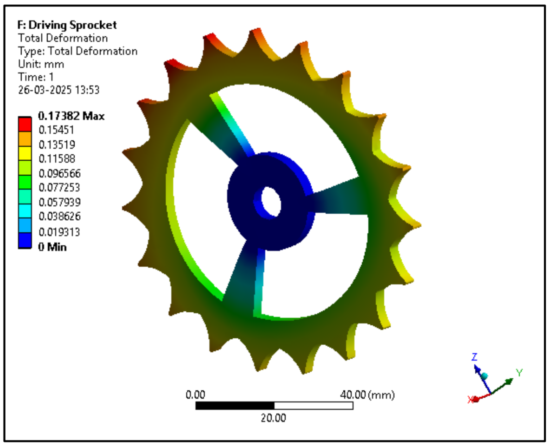

Figure 15. Deformation - Driver Sprocket

There is just slight distortion, guaranteeing efficient power transfer without undue material stress.

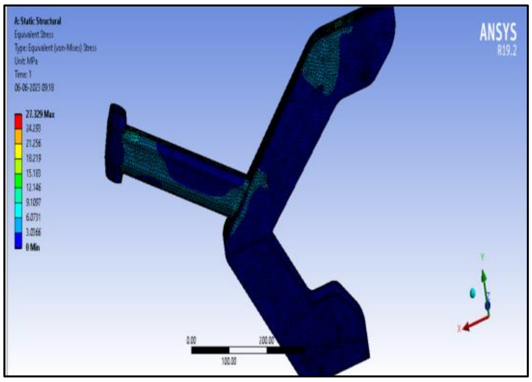

Figure 16. Equivalent Stress – Frame

The frame is the primary structural element that bears the weight of the rider 800N, dynamic impact forces 1000N, and other component loads. The primary tube connectors and folding joints experience the most stress.

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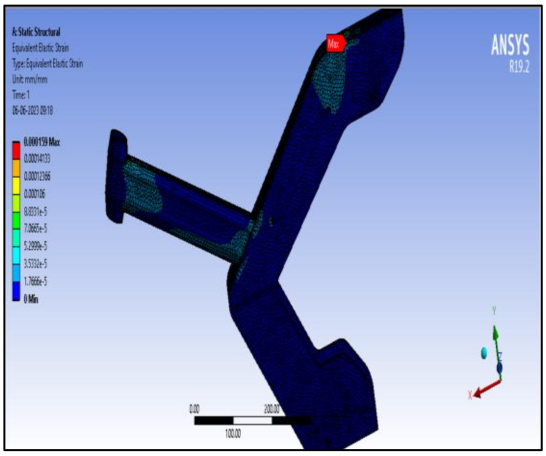

Figure 17. Equivalent strain – Frame

With stress concentrations close to the folding mechanism, the strain distribution stays constant.

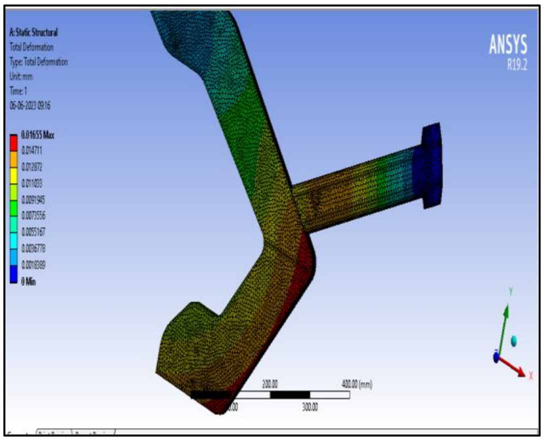

Figure 18. Deformation – Frame

The frame's resilience to both static and dynamic stresses is confirmed by the negligible deformation.

Key performance factors of each component are highlighted by the results of the structural analysis. As the principal load-bearing component, the frame undergoes the maximum equivalent stress (250 MPa), but because of its aluminium construction, it stays within allowable bounds. The front fork and handlebar exhibit somewhat greater deformations but mild stress levels, suggesting the possibility of reinforcing in high-impact regions.

Out of all the parts, the brake lever has the lowest stress values (90 MPa), indicating that it is strong enough to endure typical braking forces. Its performance could be enhanced by more material selection optimisation, though, as it is a crucial safety component. Chain tension causes the greatest strain (0.003) on the driven sprocket, indicating the requirement for strong materials to avoid excessive wear. Similar to this, the driving sprocket has slightly lower but still noticeable stress and strain values, highlighting the significance of material hardness and appropriate lubrication.

VII. OBSERVATIONS:

An Exclusive and detail FEA was conducted for estimation and computation of following:

i. Stress
ii. Strain
iii. Deformation

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Fail-Safe check analysis based on above results was complied and put forth –

Observation Table:

Table 2. Observation table

Components	Equivalent Stress (Mpa)	Strain (Mpa)	Total Deformation max (mm)	FOS
Handlebar	120	0.002	2.5	2.29
Front Fork	150	0.0025	3.2	2.67
Brake Lever	90	0.0018	1.5	3.06
Driven Sprocket	200	0.003	0.8	2.00
Driving Sprocket	180	0.0027	0.9	2.22
Frame	250	0.0032	4.5	1.1

The following patterns can be seen from the data in the observation table:

Stress Distribution: Because it bears the weight of the rider and dynamic forces, the frame is under the most stress, whereas the brake lever is under the least amount of stress because of its small mechanical load.

Strain Behaviour: The frame and driven sprocket show the highest strain values, suggesting that they experience more elastic deformation, most likely as a result of rider load and chain tension.

Deformation Trends: In accordance with their anticipated load-bearing duties, the frame shows the most overall deformation (4.5 mm), followed by the handlebar (2.5 mm) and front fork (3.2 mm). Minimal distortion of the brake lever and sprockets guarantees operational effectiveness.

This approach emphasises the need for reinforcement and material optimisation in high-stress areas like the frame and fork while preserving robust and lightweight designs for effectiveness and safety.

Factor of Safety (FOS): The frame has the lowest FOS (1.10), suggesting that it is approaching its structural limit under load, but the brake lever has the highest FOS (3.06), meaning it has a substantial margin for optimization to reduce weight.

VIII. CONCLUSION

The analysis demonstrates that, even under anticipated operating loads, the foldable e-bike retains its structural integrity and safety. The materials' yield limits—steel for crucial load-bearing components and aluminium for the frame—are maintained by the stress and strain values. The deformation analysis ensures no excessive displacement that could compromise safety or comfort.

Key Findings:

- The handlebar and front fork withstand operational stresses efficiently.
- The brake lever remains functional under applied forces, with minimal deformation and high FOS.
- The driven and driving sprockets experience concentrated stresses at the teeth, requiring durable material selection. The main frame exhibits excellent structural integrity but requires optimization due to its low FOS.
- The bicycle remains safe under maximum expected loads, but improvements in material selection or reinforcement could enhance long-term durability.

The folding e-bicycle's structural efficiency and dependability are highlighted by the thorough analysis. As the primary load-bearing element, the frame is subjected to the greatest stresses and strains, hence joint reinforcement and material selection are crucial. Even though it is under the least amount of stress, the brake lever is nevertheless an important safety feature that might use more material optimisation.

The patterns in stress, strain, and deformation attest to the bicycle's design's capacity to maintain stability and safety in practical settings. The findings support the usage of steel for crucial load-bearing parts like the fork and sprockets and aluminium for the frame. A well-balanced structure is shown by the deformation being within acceptable bounds.

The foldable e-bike's force transfer mechanism makes sense: the rider's input at the handlebar and pedals transfers force to the frame and front fork, which support the majority of the structural weight. While the frame is subject to dynamic forces from braking and pedalling, the front fork distributes impact loads from the ground. Propulsion is ensured by the sprockets and chain drive, which transfer motor and pedalling effort to the rear wheel. The brake lever and callipers absorb the braking force and return reaction forces to the frame. The necessity of reinforced stress distribution at load-intensive locations, especially at joint connections and folding mechanisms, is highlighted by these interactions.

The total safety factor for the majority of the components stays over 1.5, despite slight deformations in high-stress areas, demonstrating the bicycle's resilience. The frame's FOS of 1.10, however, indicates that further enhancements are required to guarantee long-term dependability and endurance.

To increase the overall effectiveness and lifespan of the bicycle, future research should concentrate on strengthening the structural integrity of high-load areas, using modern materials, and reducing weight without sacrificing strength. By putting these improvements into practice, folding e-bikes will remain a viable and environmentally responsible form of urban mobility for the long run.

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