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Evaluating Stress Concentration and Displacement in Mountain Bike Rear Triangle Frames: A Finite Element Approach

Jing-Wei Zheng* and Cai-Wan Chang-Jian**

Keywords：Finite Element Analysis, Mountain Bike Rear Triangle, Fatigue.

ABSTRACT

The evolution of bicycle design has been driven by various user needs, influencing key aspects such as wheel size, handlebar length, and seat shape, all aimed at enhancing the rider's experience (Tomaszewski, 2021). Among these, the frame shape plays a crucial role in determining overall performance and comfort (Hsiao, 2015). Today, two predominant types of frames are in use: one-piece frames, commonly found in city bikes, racing bikes, and U-bikes, are designed for flat terrain or gentle slopes (Adsule, 2024). These frames are less effective at absorbing shocks and are unsuitable for handling rough impacts. In contrast, mountain bike frames, designed for steep mountain roads or rugged trails, feature a more complex structure divided into front and rear triangles. The front triangle connects the handlebars to the front wheel, while the rear triangle houses the braking system. This split-frame design improves impact absorption but introduces structural challenges, particularly in the rear triangle, which tends to be weaker due to its pivot system and disc brake integration. This study provides an in-depth analysis of the rear triangle's structural performance through three key tests: disc brake fatigue analysis, rear triangle fatigue analysis, and drop impact testing. Fatigue and impact simulations focus on identifying stress concentration points and displacement patterns to assess the frame's weaknesses. The results are compared with actual experimental conditions, with particular attention given to displacement and stress concentration, as they serve as indicators of potential frame vulnerabilities. Due to the significant external forces acting on it, the rear triangle is especially prone to noticeable force changes, making it an ideal focus for detailed analysis.

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INTRODUCTION

Mountain climbing is a popular recreational activity that offers numerous physical and mental health benefits. It enhances physical strength, endurance, and cardiovascular health, while also promoting overall well-being by allowing individuals to connect with nature, alleviate stress, and boost mental resilience. One enjoyable way to experience mountain climbing is by riding mountain bikes on rugged mountain trails (Munanura, 2024). In such extreme environments, the design of the mountain bike frame becomes critically important. Whether navigating steep uphill paths, challenging downhill slopes, muddy terrains, or fast-moving streams, the structural integrity and design of the frame must account for these diverse and demanding conditions (Abbasi and Ko, 2024). In the context of mountain bike frame research, particular attention is given to the rear triangle structure. The geometry of the rear triangle, especially the length of its components, influences the size of the rear wheel and directly affects riding comfort, posture, and the ease with which riders ascend and descend challenging terrains (Hagen, 2016). Moreover, the integration of shock absorbers is closely tied to the shape and design of the rear triangle, emphasizing its importance in overall frame performance. To ensure durability and optimal function, standardized frame testing methods have been established through extensive experimental analysis. The frame used in this study is specifically designed for forest trails, making it more versatile compared to frames engineered for specialized routes. Its design is intended to perform well across a variety of terrains, offering broader applicability.

Constructed from aluminum alloy 6061-T6, the frame boasts exceptional mechanical properties. Aluminum alloy is prized for its low density—approximately one-third that of steel—resulting in a lightweight frame that reduces rider fatigue while enhancing maneuverability. Additionally, aluminum alloys possess excellent plasticity, allowing manufacturers to create frames with varied shapes and structures to meet both functional and aesthetic demands. As a material for mountain bike frames, aluminum alloy strikes an optimal balance between weight, strength, durability, and cost-efficiency. This study employs Finite Element Analysis (FEA) using SolidWorks to conduct both static and nonlinear analyses, corresponding to fatigue and impact analysis, respectively. The fatigue analysis (Khutal, 2020) focuses on the force conditions experienced by the rear triangle. Specifically, the rear triangle dropouts, which link the rear wheel and accommodate critical components like the braking system, disc brake, and chain, endure the highest forces after braking. Design considerations for these dropouts must ensure they remain sufficiently robust while maintaining high toughness and avoiding excessive bulk (Sani et al. 2016). Callens and Bignonnet (2012) outline Decathlon's methodology for mastering fatigue design of welded aluminum-alloy bicycle frames, aiming to optimize the design before standard testing. The fatigue assessment uses the Dang Van multiaxial criterion with an S-N design curve independent of geometry and loading mode. Design stress is calculated via linear elastic finite element analysis with a specialized thin shell meshing technique. Cicero et al. (2011) examine cracks found in a bike frame after 35,000 km of use, located at the joint between the bottom bracket, chain stays, seat tube, and down tube. The analysis attributes the cracks to corrosion and Stress Corrosion Cracking (SCC) due to differences in solution potentials between the base material and precipitates from overageing treatment. Testing methods included chemical analysis, microstructural analysis, and SEM with EDX. Calvo et al. (2018) studied bicycle manufacturers using materials like magnesium, aluminum, titanium, and carbon fiber to improve performance, with aluminum being popular for cranks due to cost and ease of machining. Anodizing is a common surface treatment for aluminum, enhancing appearance but potentially reducing fatigue resistance. This study analyzes the optimal anodizing depth to balance aesthetic and fatigue resistance performance for bicycle cranks. Covill et al. (2016) used a finite element model to simulate stress behavior in steel bicycle frames under various load cases, including both laboratory and field measurements. It analyzes static and fatigue stresses at key areas like dropouts, bottom brackets, and handlebars, comparing results to existing literature. The study highlights the need for further research on tube profiles, frame strength, and failure modes to improve safety in bicycle design. Pazare and Khamankar (2014) conducted stress analysis of a bicycle frame using Finite Element Method (FEM) in Ansys, comparing the results with theoretical analysis, treating the frame as a truss structure. Stresses are evaluated under various conditions, including static startup, steady paddling, impacts, and rear wheel braking. The analysis shows good agreement between theoretical and FEA results, with the maximum stress found in the top tube, which is below the material's yield strength. Hirose et al. (2009) developed a new fatigue test machine with a laser extensometer for hot-cell use, aimed at testing limited material volumes in reactors. It investigates the fatigue life characteristics and fracture mechanisms of Japanese reduced activation ferritic/martensitic steel (RAFs) and its weldment using full- and mini-sized specimens. The results show no significant difference in fatigue cycles to failure between the two specimen sizes, except in very low cycle fatigue. Sonsino's (2007) study shows that fatigue strength continues to decrease in the high-cycle regime, even without corrosion or temperature effects. Fatigue design for components under loads below the knee point of the SN-curve must account for this to prevent failures. Material and manufacturing-dependent recommendations are provided for the very high-cycle region of the SN curve.

Fatigue analysis further investigates the plastic deformation of the rear triangle after repeated force applications, distinguishing between rear triangle fatigue and disc brake fatigue. Both analyses assess how the rear triangle dropouts deform under external forces. Impact analysis, on the other hand, examines the frame's response to sudden impacts, such as when the rear triangle hits the ground. This analysis aims to understand the structural behavior under impact loading, assessing how the frame absorbs shock and mitigates potential damage. The results from all three analyses—fatigue, impact, and static—are compared with real-world conditions, focusing on key parameters such as stress, strain, displacement, and stress concentration points. These analyses provide valuable insights into areas of the frame that may be prone to deformation or failure, allowing for a thorough evaluation of the design's accuracy and reliability when compared to actual performance in real-world conditions.

STRUCTURE AND DESIGN OF MOUNTAIN BIKE COMPONENTS

Mountain bikes feature intricate frame structures specifically designed to tackle the challenges posed by steep uphill and downhill terrains. These frames incorporate sophisticated geometries and advanced shock-absorbing systems, which are essential for navigating rugged trails. The structural integrity and durability of the frame directly influence the rider's experience. A frame lacking sufficient toughness can transmit vibrations and impacts directly to the rider, potentially causing discomfort or even injury during extended rides. Mountain bike frames typically consist of two main components: the front and rear triangles, which are connected via a rocker arm to enhance overall frame stiffness and toughness. These frames are subjected to frequent impacts, falls, and sustained vibrations, all of which can cause deformation in standard frame designs. To mitigate these stresses, the frame's design must effectively distribute external forces throughout its structure during impacts, ensuring both durability and performance under harsh conditions. The shock-absorbing system plays a critical role in supporting the frame, allowing it to undergo controlled deformation while maintaining its geometry. This system helps absorb shocks and minimize the transmission of vibrations to the rider, thereby enhancing both comfort and safety.

The design of the rear triangle is particularly important in determining the frame's overall performance. As shown in Figure 1, the rear triangle consists of the chainstay, seatstay, and rocker arm, which work together to provide additional stability and improve shock absorption. During descents, the rear triangle efficiently dissipates vibrations, significantly reducing the impact felt by the rider. Most modern mountain bikes are equipped with a rear disc brake system, offering superior stopping power, especially in emergency situations. On steep slopes, the disc brakes can rapidly decelerate or stop the bike, enhancing rider safety. In summary, the complex frame structure and efficient shock-absorbing system of mountain bikes greatly contribute to frame toughness, effectively distributing external forces, and significantly improving both riding comfort and safety. These design features ensure that the bike can withstand the rigors of challenging terrains while providing a smooth and secure ride.

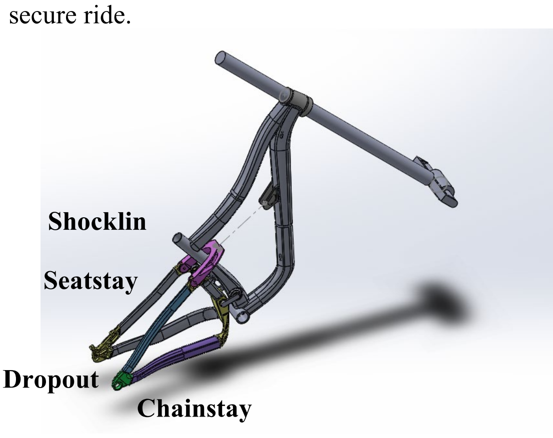


Fig. 1. Rear Triangle Structure.

THEORETICAL FRAMEWORK

Finite Element Analysis (FEA)

FEA is a powerful computational tool used to simulate real-world physical phenomena, particularly in engineering and structural analysis. It is extensively applied to analyze complex structural components and predict their behavior under various loading conditions. FEA works by discretizing a complex structure into a finite number of smaller, manageable elements. Each of these elements is individually modeled and analyzed to solve the governing mechanical equations, providing crucial information on displacement, stress, and strain within the structure. By integrating the results from all the elements and considering their boundary conditions, FEA infers the behavior of the overall structure.

The process involves integrating all the small elements and applying boundary conditions to understand the system's structural behavior. The key elements in solving the equations for each element include:

1. **Equilibrium Equations**: These ensure mechanical equilibrium within each element, balancing forces and moments.
2. **Stress-Strain Relationships**: These describe the material deformation behavior under stress, often modeled through linear elastic relationships, although more complex material models (for plasticity, viscoelasticity, etc.) can also be applied.
3. **Geometric Equations**: These equations represent the geometric properties of the elements, facilitating stress and strain calculations, particularly in regions with complex or uneven surfaces.

Boundary conditions are vital in FEA as they define how elements interact at connection or constraint points. These conditions ensure simulation accuracy by specifying interactions with external forces or other parts of the structure. FEA can effectively represent complex geometries, capture a wide array of material properties, and provide detailed insights into local phenomena, making it an ideal tool for analyzing and optimizing mountain bike frames.

Mountain bike frames, with their intricate structural requirements and the need for optimization in strength, weight, and durability, are especially suitable for FEA analysis. Using FEA, engineers can model and simulate the frame's detailed geometry, allowing for a comprehensive assessment of its performance under real-world conditions. The FEA process for mountain bike frames typically involves the following key steps:

1. **Pre-processing**: This stage includes creating a detailed geometric model of the frame, meshing the structure into finite elements, and defining material properties and boundary conditions for each element. The meshing process is critical as it determines the accuracy and level of detail in the analysis.
2. **Solving**: During this phase, the system of equations governing each finite element's behavior is solved using numerical methods. Based on the boundary conditions and material properties, the displacements, stresses, and strains of the structure are computed. This phase also involves setting degrees of freedom per ISO

standards and applying appropriate constraints or loads to simulate real-world conditions.

3. **Post-processing**: In this final phase, the simulation results are visualized in forms like stress distribution maps, displacement diagrams, and strain contours. These visualizations allow a detailed analysis of the frame's performance and help verify the accuracy of the results. Engineers can also generate comprehensive reports to

assess the overall performance of the structure and identify potential areas for improvement.

The Finite Element Analysis (FEA) method is widely used to simulate real-world physical phenomena, particularly in engineering applications that involve complex structural components. FEA works by discretizing a structure into smaller, finite elements, with each element governed by its own stiffness matrix, which defines the relationship between nodal displacements and the corresponding nodal forces. The stiffness matrix for a given element, denoted as K_e, is given by:

$$K_e = \int_V B^T D B dV \quad (1)$$

Where:

- K_e is the element stiffness matrix, an $n \times n$ matrix (with n being the number of nodes of the element), representing the relationship between nodal displacements and the corresponding nodal forces.
- B^T is the transpose of the strain-displacement matrix, which describes the internal deformation of the finite element.
- B is the strain-displacement matrix, which links the nodal displacements to strain within the element.
- D is the material elasticity matrix, capturing the material's stress-strain behavior.
- V is the volume of the finite element.

The deformation of a frame, such as a mountain bike frame, is inherently a three-dimensional problem. Thus, the deformation matrix B is a 6×3 matrix. In three-dimensional space, there are six degrees of freedom for each node: three translational (along the x, y, and z axes) and three rotational (about the x, y, and z axes).

The strain-displacement matrix B can be expressed in terms of the shape functions N_1、N_2、……N_n, which describe the nodal distribution within the finite element, and their partial derivatives with respect to the spatial coordinates x, y, and z. For each node, the strain-displacement matrix is represented as follows:

$$B = \begin{bmatrix} \frac{\partial N_1}{\partial x} & 0 & 0 \\ 0 & \frac{\partial N_1}{\partial y} & 0 \\ 0 & 0 & \frac{\partial N_1}{\partial z} \\ \frac{\partial N_1}{\partial y} & \frac{\partial N_1}{\partial x} & 0 \\ 0 & \frac{\partial N_1}{\partial z} & \frac{\partial N_1}{\partial y} \\ \frac{\partial N_1}{\partial z} & 0 & \frac{\partial N_1}{\partial x} \end{bmatrix}, \begin{bmatrix} \frac{\partial N_2}{\partial x} & 0 & 0 \\ 0 & \frac{\partial N_2}{\partial y} & 0 \\ 0 & 0 & \frac{\partial N_2}{\partial z} \\ \frac{\partial N_2}{\partial y} & \frac{\partial N_2}{\partial x} & 0 \\ 0 & \frac{\partial N_2}{\partial z} & \frac{\partial N_2}{\partial y} \\ \frac{\partial N_2}{\partial z} & 0 & \frac{\partial N_2}{\partial x} \end{bmatrix}, \begin{bmatrix} \frac{\partial N_3}{\partial x} & 0 & 0 \\ 0 & \frac{\partial N_3}{\partial y} & 0 \\ 0 & 0 & \frac{\partial N_3}{\partial z} \\ \frac{\partial N_3}{\partial y} & \frac{\partial N_3}{\partial x} & 0 \\ 0 & \frac{\partial N_3}{\partial z} & \frac{\partial N_3}{\partial y} \\ \frac{\partial N_3}{\partial z} & 0 & \frac{\partial N_3}{\partial x} \end{bmatrix} \cdots\cdots \quad (2)$$

The material elasticity matrix D defines the linear relationship between stress and strain for a material. It captures the material's elastic modulus in the principal stress directions and incorporates the effects of Poisson's ratio. The matrix is a 6×6 matrix that represents the elastic properties of an isotropic material and is defined as:

$$D = \begin{bmatrix} \frac{1-\nu}{E} & \frac{\nu}{E} & \frac{\nu}{E} & 0 & 0 & 0 \\ \frac{\nu}{E} & \frac{1-\nu}{E} & \frac{\nu}{E} & 0 & 0 & 0 \\ \frac{\nu}{E} & \frac{\nu}{E} & \frac{1-\nu}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2E} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2E} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2E} \end{bmatrix} \quad (3)$$

Where E is the elastic modulus and ν is Poisson's ratio.

To determine the overall stiffness of the entire structure, we sum the stiffness matrices of all the finite elements. The global stiffness matrix K_{ALL} is given by:

$$K_{ALL} = \sum_{e=1}^{n} K_e \quad (4)$$

Where n is the total number of elements in the model. This matrix represents the combined stiffness of all the elements and captures their interactions across the structure. The equilibrium of the entire structure is governed by the equation:

$$K_{ALL}\boldsymbol{d} = \boldsymbol{F} \quad (5)$$

Where $\boldsymbol{d}$ is the displacement vector of the entire structure and $\boldsymbol{F}$ is the vector of external forces applied to the structure.

These equations describe the behavior of each finite element based on fundamental laws of mechanics—equilibrium, material behavior, and geometry. Elements in a finite element mesh may take various forms (triangles, quadrilaterals, hexahedrons, etc.), and are interconnected via their nodes, forming a mesh. The relationship between force and displacement for each finite element under external forces is represented by:

$$K_e \boldsymbol{U_e} = \boldsymbol{F_e} \quad (6)$$

Where K_e is the element stiffness matrix. $\boldsymbol{U_e}$ is the element nodal displacement vector. $\boldsymbol{F_e}$ is the element nodal force vector.

This system of equations allows for the calculation of displacement, stress, and strain distributions throughout the entire structure by solving for all elements, providing a comprehensive understanding of the structural behavior under applied loads. With advancements in analytical methods, the analysis of mechanical motion has evolved, enabling more precise and dynamic assessments. In bicycle design, the shock-absorbing frame structure stands out due to its complex linkage system. The behavior of the frame's linkage is highly sensitive to external forces applied at various positions, leading to significant structural changes. Nonlinear analysis, which accounts for dynamic factors such as impact forces, offers valuable insights into how the frame responds to these external forces, particularly in drop tests. This approach facilitates a detailed examination of the frame's stress distribution and deformation patterns under realistic conditions, helping to identify critical areas that require design optimization. SolidWorks Simulation is an advanced optimization and design tool commonly used for structural analysis. It enables in-depth structural optimization and sensitivity analysis, helping engineers understand how different design parameters influence overall performance. By simulating real-world conditions and evaluating various design configurations, SolidWorks Simulation improves the accuracy and reliability of the design process. This ensures the final product meets both performance standards and durability requirements, ultimately enhancing the safety, reliability, and performance of the bicycle frame in real-world usage scenarios.

Stress-Life (S-N) Curve

The Stress-Life (S-N) Curve Method is a widely used technique in engineering for predicting the fatigue life of materials subjected to cyclic loading. Below is a restructured and revised explanation of the method:

(a) Overview of the S-N Curve Method (Stress-Life Method)

The S-N curve method is based on how materials behave under repeated loading. It provides a way to predict the number of load cycles a material can withstand before failure at varying stress levels. Experimental data typically generate these curves, which illustrate the relationship between stress amplitude (S) — the difference between the maximum and minimum cyclic stress — and fatigue life (N), which represents the number of cycles a material can endure without failure under a given stress amplitude. These curves generally exhibit an inverted U-shape, indicating that as the stress amplitude increases, the material's fatigue life decreases.

(b) S-N Curve Formula

Fatigue life estimation using the S-N curve method can be represented by the following formula:

$$N_f = \left(\frac{S_e}{S}\right)^b \quad (9)$$

where N_f is the fatigue life (number of cycles), S_e is the fatigue strength of the material, S is the actual stress and b is the fatigue life exponent.

(c) Fatigue Regions: Low-Cycle vs High-Cycle Fatigue

The S-N curve is typically divided into two regions based on stress levels:

- **Low-Cycle Fatigue Region**: In this zone, the material experiences higher stresses, leading to a shorter lifespan, usually in the range of a few thousand to tens of thousands of cycles.
- **High-Cycle Fatigue Region**: At lower stress levels, the material's lifespan extends significantly, often reaching hundreds of thousands of cycles or more.

(d) Steps for Fatigue Life Calculation

To determine the fatigue life using the S-N curve method:

1. **Obtain the Material's S-N Curve**: This curve is derived from experimental data and shows how the material's fatigue life relates to stress amplitude.
2. **Calculate Stress Amplitude (*S*)**: Use Finite Element Analysis (FEA) to calculate the stress amplitude under specific loading conditions.
3. **Apply the S-N Curve Formula**: Plug the material's fatigue strength (S_e), the actual stress (S), and the fatigue life exponent (b) into the formula to estimate the fatigue life.

(e) Engineering Considerations in Fatigue Life Prediction

In real-world applications, several factors must be considered when using the S-N curve method, including surface treatments, types of loading (e.g., fully reversed or tensile loading), load ratios, and structural geometry. These variables can greatly impact the predicted fatigue life of materials.

(f) Additional Consideration - Goodman's Modification

In practical scenarios, loads are often not purely cyclic but include a mean stress (either tensile or compressive). In such cases, modifications to the basic S-N curve method are applied. One such adjustment is **Goodman's Modification**, which accounts for mean stresses in fatigue life predictions. The formula is:

$$\frac{S_{max}}{S_a} + \frac{S_{min}}{S_m} \le 1 \quad (10)$$

Where S_{max} is the maximum stress, S_a is the adjusted stress amplitude, S_{min} is the minimum stress and S_m is the mean stress.

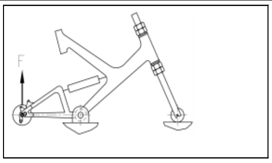
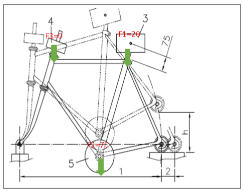
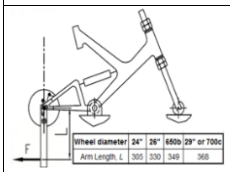
3.3 ISO 4210-6 standards for the rear triangle's structural

The ISO 4210-6 standards for the rear triangle's structural performance in disc brake fatigue analysis, rear triangle fatigue analysis, and drop impact testing are outlined in Table 1.

Structural Analysis Process of the Mountain Bike Frame

A series of detailed steps are involved in analyzing the frame's structural performance. First, the assembly must be completed, ensuring that the distances between various components are accurately adjusted, as these directly influence the forces exerted on the frame. The connection method used in this analysis is shown in Figure 3, where the frame incorporates a four-bar linkage structure. This linkage connects the upper and lower rocker arms to the down tube, with a shock absorber connector mounted on the upper rocker arm to link the shock absorber between the front triangle's down tube and the rear

Table 1 SO 4210-6 standards for the rear triangle's structural

	**Rear Triangle Fatigue Analysis** The five-link is fixed but can rotate, the front fork can only move forward and backward, and the rear triangle claw experiences an upward force. This simulates the effects on the rear triangle of the frame under load.
	**Rear Impact Shock Analysis:** The front triangle is fixed but can rotate. After raising the rear triangle claw to a certain height, it is allowed to fall freely, simulating the impact on the frame when the rear wheel makes contact with the ground first.
	**Disc Brake Fatigue:** The front triangle and bottom bracket are fixed but can rotate. A disc brake is connected at the rear triangle claw, and a pipe is connected below it, with force applied at the end of the pipe.

triangle's upper fork. These initial steps fall under the category of pre-processing. Once the assembly is complete, the boundary conditions must be defined. Each of the three analyses applied to the rear triangle uses different test fixtures, which are mounted accordingly. The degrees of freedom and geometric structure of the assembly are modified based on the specific test conditions. Table 2 provides a detailed description of the boundary conditions for each of the three test methods, illustrating how the test fixtures are mounted on the frame. These tests reveal the movement directions of the rear triangle when the frame is subjected to various forces. Since the bicycle's wheel assembly is rotatable, adjustments to the degrees of freedom in the boundary conditions are necessary. In addition to the connections in the four-bar linkage structure, which include the rocker arm and shock absorber connector, both the rear and front triangle dropouts form part of the rotatable structure.

Before analysis, the meshing process is performed to create a grid over the entire component. This mesh facilitates a more accurate interaction between external forces and the frame. The finer the mesh, the more precise the analysis results. A hybrid mesh is employed in this analysis to optimize time during the verification of mesh quality and to automatically refine the mesh in complex areas. Both fatigue and impact analyses require meshing before progressing to the next step. Rather than performing global mesh refinement, local refinement is applied in areas with intricate structures, such as connectors and impact surfaces, which experience higher external forces and contact conditions. Tetrahedral meshes offer several advantages in finite element analysis, as they are

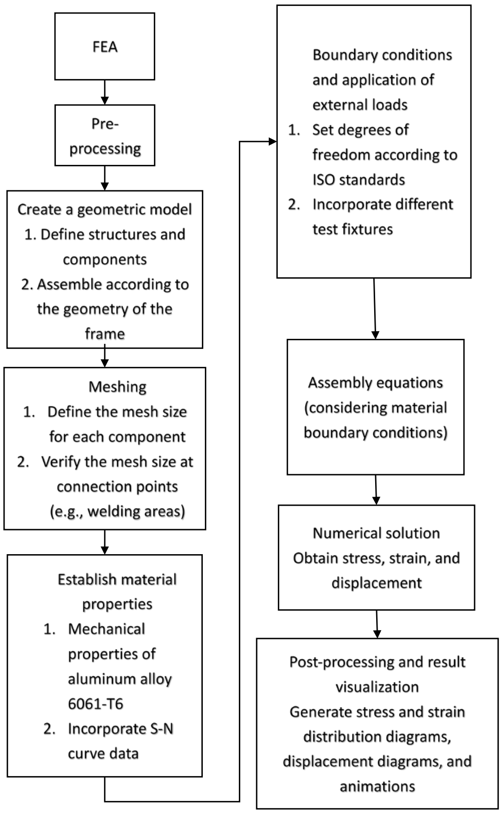


Fig 2. FEA flow chart

well-suited for complex geometries and can adapt to irregular shapes. These meshes can be easily generated automatically, making them particularly advantageous when dealing with large-scale models that require quick mesh generation. Additionally, tetrahedral meshes allow for localized mesh density refinement, enabling more accurate representation of stress concentrations and other localized phenomena. These properties make tetrahedral meshes highly effective in engineering and scientific applications, particularly in models with complex geometries. In SolidWorks, tetrahedral meshing is a standard technique for meshing three-dimensional models. The model is divided into small tetrahedral elements to create the mesh for analysis. SolidWorks automatically generates tetrahedral elements, ensuring that the nodes of each element are shared with adjacent elements, forming a continuous mesh structure. This highly automated approach enables the rapid generation of high-quality meshes, which is especially beneficial for complex models.

Once the meshing process is complete, fixtures corresponding to the boundary conditions will be applied in the three test scenarios. The rear triangle fatigue analysis and the disc brake fatigue analysis are similar in nature. These tests examine the fatigue conditions the rear triangle can withstand under the mountain bike's structural loads. In the rear triangle fatigue test, an upward force is applied to the rear triangle dropout to observe its stress behavior. Since the testing method is similar to the disc brake fatigue test, the stress concentration is connected to both the rocker arm and the rear triangle. However, the direction of the applied force and the fixtures used differ. The disc brake fatigue test takes into account the wheel diameter, whereas the force is applied directly to the rear triangle in the fatigue analysis. Figure 4 illustrates the displacement of the rear triangle during this test. During the test, the bottom bracket is locked but remains rotatable. Due to the proximity of the applied force to the frame, the displacement of the rear triangle is noticeable. Figure 5 further displays the stress-strain diagram for the rear triangle fatigue test. The rear upper fork of the rear triangle experiences significant strain when the upward force is applied to the dropout, which moves the upper rocker arm. A shock absorber is positioned in front of the rocker arm. During the analysis, the shock absorber's length is fixed, with no elasticity considered, meaning the component subjected to pressure is the rear upper fork of the rear triangle. The upward force on the rear triangle induces tensile stress on the lower rocker arm, where the stress and strain values are maximized.

The disc brake fatigue analysis simulates the effects of braking forces on the frame. Since the test is static, reaction forces cannot be used directly; instead, an opposite force is applied to simulate the braking reaction force. The analysis focuses on the impact of braking on the frame. When an external parallel force is applied below the brake fixture, the rear triangle displaces as the fixture rotates. Maximum stress occurs at the junction between the rear triangle and the upper and lower rocker arms. Figure 6 shows significant changes in the rear triangle, while Figure 7 illustrates minimal displacement in the front triangle, as the bottom bracket remains locked but rotatable. The stress distribution is concentrated near the dropout of the rear triangle's tubes. Impact tests, involving larger displacements, require distinct observation methods. Impact analysis is typically represented through a series of images compiled into an animation, allowing for the assessment of displacement changes at the moment of impact. The analysis duration is set to 2 seconds, even though impact tests usually conclude within 1 second. Extending the observation period to 2 seconds facilitates the observation of post-impact frame behavior. During the impact event, the front fork momentarily slides across the impact surface, with two images capturing this motion to compare the frame's deformation before it rebounds. The rear impact analysis focuses on the effects when the rear wheel contacts the ground first. Figure 8 illustrates the overall frame displacement when the rear triangle touches the ground. Upon ground contact, the frame remains displaced for a short period before rebounding. Similar to the front impact analysis, the results are divided into multiple steps. The test is set to 1 second, divided into 50 steps, with the moment of impact occurring between 0.48 and 0.5 seconds. This comprehensive approach allows for a precise understanding of the frame's performance under dynamic loads, contributing to design improvements aimed at enhancing strength, durability, and rider safety.

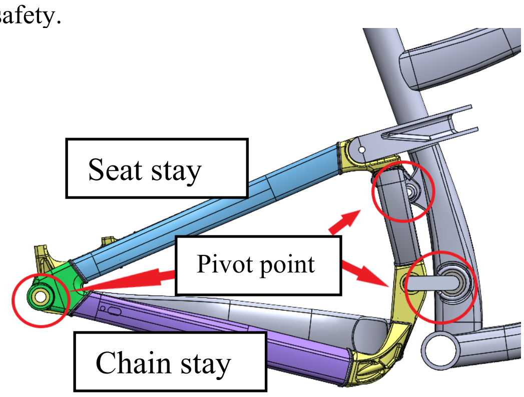


Figure 3. Geometry and Assembly of the Rear Triangle

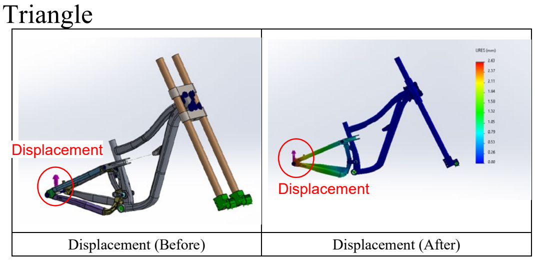


Figure 4. Displacement in Rear Triangle Fatigue Analysis

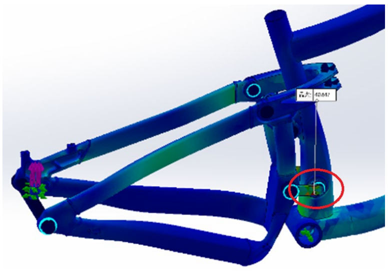


Figure 5. Stress-Strain Distribution in Rear Triangle Fatigue

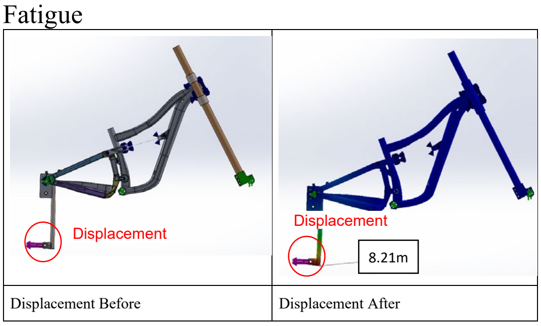
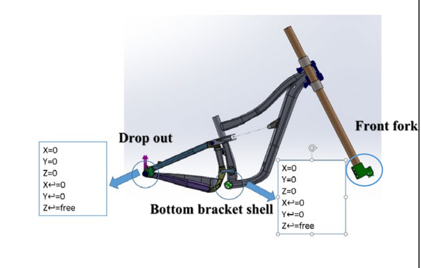
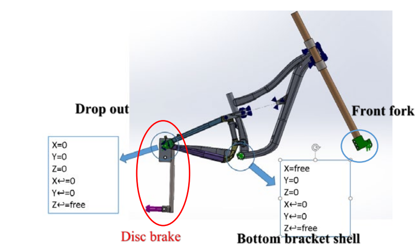
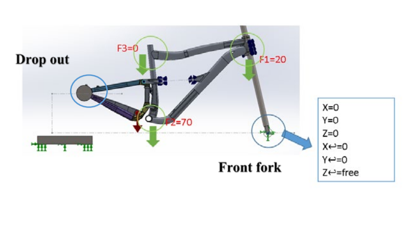


Figure 6. Displacement in Disc Brake Fatigue

Analysis

Table 2. Boundary Condition Settings for Rear Triangle Testing

	**Rear Triangle Fatigue Analysis** 1. The bottom bracket is fixed but rotatable. 2. The front fork can only move back and forth. 3. There is an upward force on the rear triangle dropout, simulating the effect of the rear triangle under load.
	**Disc Brake Fatigue** 1. The front triangle and bottom bracket are fixed but rotatable. 2. A disc is connected to the rear triangle dropout, with a tube attached at the bottom where force is applied.
	**Rear Impact Analysis** 1. The front triangle is fixed but rotatable. 2. The rear triangle dropout is raised to a certain height and then freely dropped, simulating the impact on the frame when the rear wheel lands first.

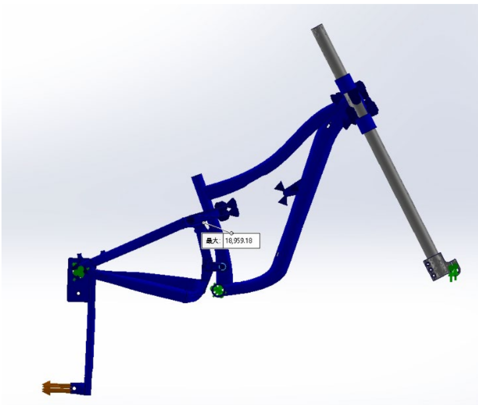
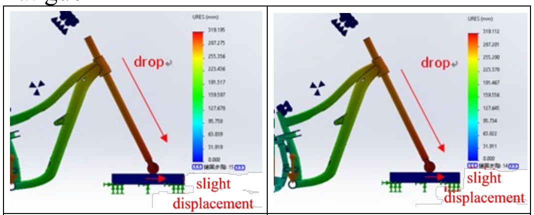


Figure 7. Stress-Strain Distribution in Disc Brake Fatigue



Impact Analysis (Instant of Impact) | Impact Analysis (Post-Rebound)

Figure 8. Rear Triangle Impact Analysis

COMPARISION OF SIMULATION AND EXPERIMENTAL RESULTS FOR MOUNTAIN BIKE FRAME ANALYSIS

The frame is made of 6061-T6 aluminum alloy, known for its excellent mechanical properties, which are outlined in Table 3. The importance of comparing simulation results with experimental data lies in the ability to accurately predict the frame's behavior under various loading and impact conditions. This comparison enables the identification of stress concentration points and potential structural weaknesses, helping refine the frame design.

Rear Triangle Fatigue Analysis:

The rear triangle fatigue analysis primarily investigates the durability of the frame under repetitive loading. The simulation results suggest that stress concentration is most significant around the welds and rocker arms, which are critical areas for potential fatigue failure. These simulation results were validated by experimental tests, revealing that the critical failure points of the rear triangle aligned closely with the predictions from the simulations. In real-world conditions, the rear triangle must endure continuous stress due to the rider's movement, especially over rough terrain. Identifying these weak points enables design improvements, enhancing the long-term reliability of the frame.

Disc Brake Fatigue Analysis:

The disc brake fatigue analysis examines the effects of repeated stress on the frame's disc brake mounting area. Both the simulation and experimental results reveal significant stress concentrations around the disc brake mount. These areas are crucial for the overall braking performance of the bike, as excessive deformation could compromise safety. Ensuring the durability of the disc brake mount and the surrounding frame sections under repeated loading enhances the bike's safety and braking efficiency, especially during prolonged use.

Drop Impact Testing:

Drop impact testing simulates real-world impacts, such as when the bike drops onto hard surfaces. Both the simulation and experimental results show substantial displacement in the rear triangle, especially near the dropout area. This behavior indicates that the frame's response to sudden impacts is crucial for maintaining structural integrity during extreme riding conditions. The observed deformation of the rear triangle during the test shows that the frame can absorb impacts to a certain extent, but additional reinforcements may be necessary to improve impact resistance.

Simulation vs. Experimental Comparison:

The simulation results align closely with the experimental data, particularly in terms of the location of potential failure points. For example, in the rear triangle fatigue analysis (Figure 9), the simulation shows a maximum displacement of 2.63 mm, while the experimental result is 2 mm (Figure 10), indicating a strong correlation between the two. Although some discrepancies are observed in the displacement magnitude in the disc brake fatigue analysis (Figures 11 and 12), the trends observed in the simulation results are well-matched with the experimental data. The differences between the simulation and experimental results can be attributed to several factors, such as variations in material properties, measurement errors, and differences in boundary conditions. Additionally, the drop impact analysis (Figures 13 and 14) also shows a good correlation between the simulation and experimental results, especially in terms of displacement changes and the frame's rebound behavior after impact.

Overall, the simulation method used in this study effectively predicts the behavior of the mountain bike frame under various extreme conditions, and the results closely align with experimental outcomes. This validation offers a reliable reference for future design optimization and structural improvements. Further studies could incorporate higher-precision material models and boundary conditions, along with enhanced measurement techniques, to reduce error margins and improve the reliability of simulation results..

Table 3. The 6061-T6 aluminum alloy material properties

Property	Value
Density	2.70 g/cm³
Tensile Strength	310 MPa (minimum)
Yield Strength	276 MPa (minimum)
Elongation	12-17%
Elastic Modulus	68.9 GPa
Shear Modulus	26.9 GPa
Hardness	95-105 (HB, Brinell Hardness)

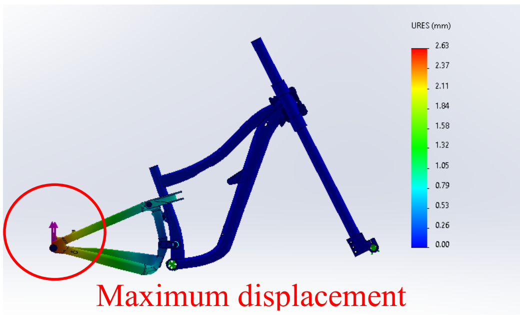


Figure 9. Rear Triangle Fatigue Displacement Analysis

Table 4. Simulation and Actual Experimental Setup

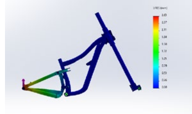
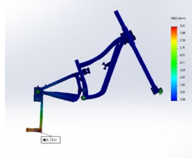
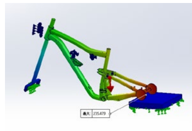
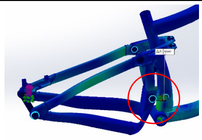
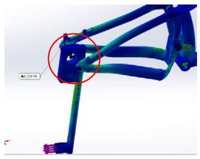
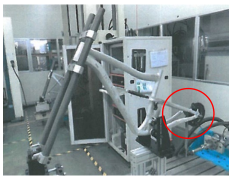
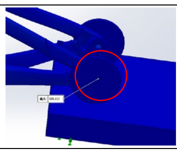
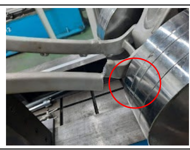
Displacement	Simulation Setup	Experimental Setup
Rear Triangle		
Disc Brake		
Rear Impact		

Table 5. Stress Concentration Points in Simulation and Actual Fracture Conditions

Fracture/ Deformation Location	Analysis Result	Experimental Result
Rear Triangle		
Disc Brake		
Rear Impact		

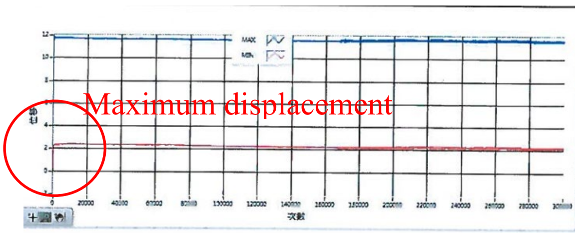


Figure 10. Rear Triangle Fatigue Test Displacement

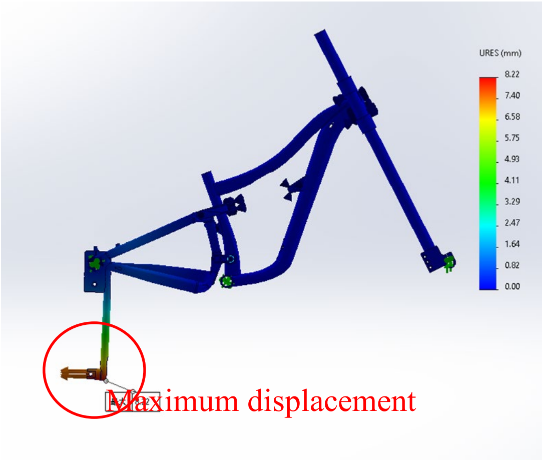


Figure 11. Disc Brake Fatigue Displacement Analysis

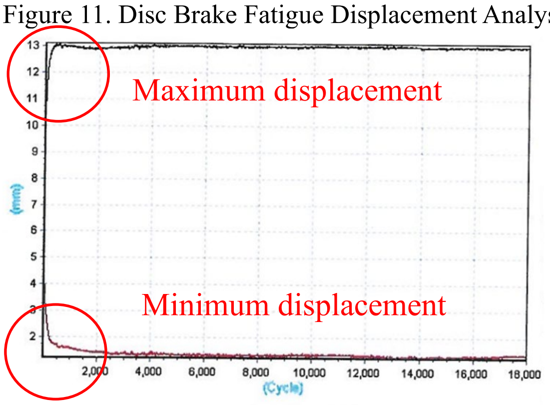


Figure 12. Disc Brake Fatigue Test Displacement

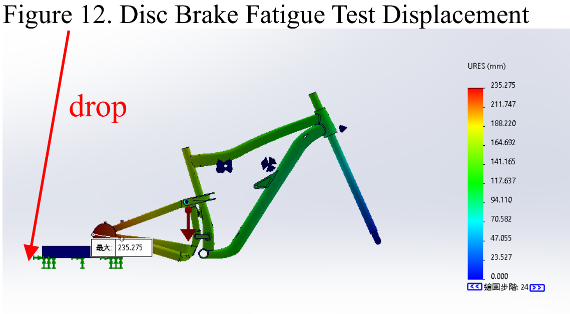


Figure 13. Rear Impact Analysis at Moment of Impact

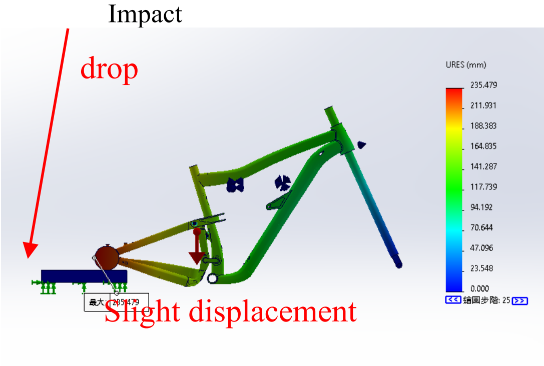


Figure 14. Rear Impact Analysis Post-Impact Without Rebound

CONCLUSIONS

The design of a mountain bike frame is critical to ensuring optimal performance and rider safety across various terrains, with particular emphasis on the rear triangle's structural integrity. As the rear triangle is subjected to significant external forces during riding, its design, material selection, and geometry directly influence the frame's overall durability, strength, and riding comfort. This study performed comprehensive fatigue and impact analyses on the rear triangle using SolidWorks' finite element analysis (FEA) capabilities. The findings highlight that the rear triangle's dropouts and disc brake system are key stress concentration areas, making them susceptible to deformation and potential damage under load. By identifying these vulnerabilities, this analysis provides valuable insights into the areas of the frame that require reinforcement. These results can inform targeted improvements in frame design, enhancing its strength, durability, and ultimately, the rider's safety and comfort across challenging riding conditions. While this study provides valuable insights, there are several areas that require further investigation. Future research can address the following aspects:

1. **Material Behavior under Extreme Conditions**: Although 6061-T6 aluminum alloy was used in this study, future work could explore the performance of other materials, such as carbon fiber or titanium, under varying loading and environmental conditions, including temperature variations and moisture exposure.

2. **Dynamic Loading Simulations**: The current study focuses primarily on static and quasi-static conditions. Future research could incorporate more complex dynamic loading conditions, including vibrations, high-impact events, and continuous stress over longer periods, to further simulate real-world riding conditions.

3. **Manufacturing Variability**: The current study assumes ideal material properties and boundary conditions. Future work could explore the effects of manufacturing variability, such as weld defects, material inconsistencies, and tolerance deviations, on the overall frame performance.

4. **Testing of Reinforcement Strategies**: Based on the identified weaknesses in the rear triangle, future research could focus on testing and validating different reinforcement methods, such as additional gusseting or the use of higher-strength materials in critical areas.

5. **Advanced Simulation Models**: The current study employed FEA using SolidWorks; however, more advanced simulation techniques, such as multi-body dynamics simulations, could be used in future studies to provide a more comprehensive analysis of the frame's performance under various riding conditions.

By addressing these areas, future research can further enhance the understanding of mountain bike frame design and contribute to the development of even more durable, lightweight, and safe frames for diverse riding conditions.

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