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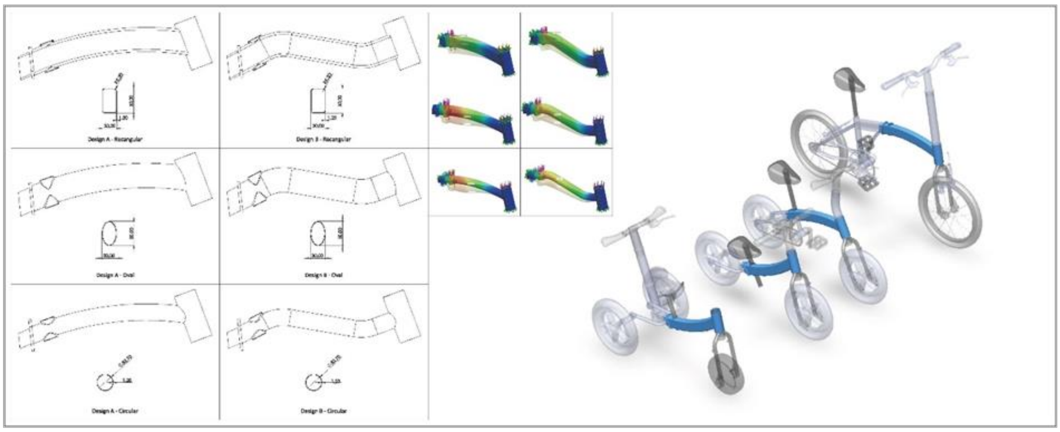
Structural strength evaluation of a modular toddler bicycle: Frame design and material considerations for children's progressive development

Katon Ageng Rezkita[1]*, Arie Kurniawan[1], Anastasia Filias Tanira[2]

[1] Department of Industrial Design, Institut Teknologi Sepuluh Nopember, 60111, **Indonesia**
[2] School of Design - School of Industrial and Information Engineering, Politecnico di Milano, 20158, **Italy**
✉ katonrezkita@its.ac.id



Highlights:

- Designed a modular toddler bicycle frame to accommodate children's growth and skill development.
- Evaluated structural strength of a modular toddler bicycle frame alternatives with different profiles designed for adaptability to children's progressive development.
- Results demonstrate design feasibility with optimal strength-to-weight ratio supporting sustainable and circular design principles.

Abstract

The toddler bicycle is essential for promoting gross motor skills in early childhood development, but its usability is often limited by fixed dimensions that do not accommodate a child's growth. This study explores the concept of modular transformability, which allows the bicycle frame to adapt to different developmental stages, enhancing functionality and supporting sustainability through reduced waste and extended usability. As children grow, their increasing weight demands a robust structural design to ensure both safety and performance. The structural strength and stability of a modular toddler bicycle frame are evaluated using numerical simulations under static loading conditions. Various frame designs and material options are analyzed for displacements and stresses, optimizing performance while maintaining safety. The findings offer insights for improving bicycle frame design and align with a circular design philosophy that prioritizes durability, adaptability, and environmental sustainability.

Keywords: Modular Toddler Bicycle; Bicycle Frame; Adaptive Design; Structural Strength; Sustainable Design

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1. Introduction

In the early stages of child development, motor skills are essential. During this time, motor behavior is built upon the development of reflexes and infant reactions, basic motor skills, and gross motor skills. These motor skills serve as the foundation for movement and include the ability to move, manipulate objects, and maintain stability. Specific gross motor skills encompass actions such as jumping, running, and kicking [1]. Children exhibit unique characteristics at each stage of development. Their growth and development vary individually, influenced by their environment. The developmental process in children is orderly, continuous, and interconnected across different stages. Early childhood is considered a critical period for every child, making careful monitoring of growth and development essential during this time [2]. However, many parents face challenges in finding products that align with their child's developmental stages. For instance, purchasing bicycles designed for specific age groups is often seen as impractical due to rapid child growth, leading to frequent replacements. This practice not only increases consumption inefficiency but also contradicts the principles of a circular economy, which emphasize modularity, upgradability, and circular business models to optimize resource utilization [3]. To address these challenges, adopting circular design principles offers a promising solution. Strategies such as remanufacturing and life cycle management can extend the usability of bicycles across multiple growth stages. By integrating these approaches, the production, use, recycling, remanufacturing, and reuse of bicycles can be optimized, reducing environmental impact while meeting developmental needs. Such solutions align with the goals of the circular economy by enhancing resource efficiency and promoting sustainability [4], [5], [6].

Zeuwts *et al.* emphasize the importance of using balance bikes for children up to 4 years old to develop perception and motor skills [7]. More recent studies recommend starting with balance bikes as early as 2.5 years old, allowing toddlers to walk or run while seated. This approach provides an intuitive and impactful way to improve balance coordination [8], [9], [10]. This approach is considered more beneficial than relying on training wheels, which prioritize pedaling skills [11]. As skills improve, children can transition to traditional bicycles in safe environments by age 4–5 and refine more complex techniques by age 8–9. These findings support the development of modular bicycles that evolve with a child's abilities. A modular design ensures the same frame can be adjusted to function as a stroller bike, tricycle, balance bike, balance bike with pedals, or standard bicycle, as shown in **Figure 1**.

This study focuses on the structural strength and stability of the modular main frame, with a particular emphasis on the 'flippable' balance bike configuration, where the frame can be reoriented vertically to support different riding modes (as shown in **Figure 1b**). This configuration is critical due to its extended usability, accommodating children from 2.5 to 9 years old. During this age range, rapid physical development and weight gain occur, necessitating a frame that is both lightweight for the youngest users' comfort and robust enough to safely support older children. Ensuring structural integrity across this developmental span aligns with the goals of usability, safety, and adaptability in the modular design. In line with these goals, the modular design supports disassembly and reuse at the component level. Parts of the product can be reused, extending its life without the need to create entirely new products [12]. This configuration introduces unique structural challenges as the "flipping" process alters load paths and stress distribution within the frame. Consequently, numerical simulations focus on evaluating the structural performance under varying external force locations and magnitudes, ensuring the frame meets safety and performance standards across all configurations.

This research uses numerical simulations to analyze displacements and stresses under static loads for various frame designs and materials [13]. In addition, it identifies critical zones, evaluates maximum stresses and deflections within permissible limits, and verifies the design's capacity to prevent fatigue failures and permanent deformations throughout its intended lifespan [14]. The results will guide design optimizations to achieve lightweight yet durable structures. Beyond supporting physical activity, the study incorporates sustainability principles by extending the lifecycle of children's bicycles. This modular approach reduces environmental impact, aligning with circular economy goals [15]. This study adopts a multidisciplinary approach, combining insights from pediatrics, biomechanics, and product design, while integrating sustainable development and circular economy principles to address design challenges and foster innovation in usability and sustainability [16].

Figure 1. The modular toddler bicycle main frame facilitates transitions between: (a) Stroller bike or tricycle for children up to 2.5 years old; (b) Balance bike (with or without pedals) for ages 2.5 to 9 years; (c) Standard children's bicycle for ages 9 and up

2. Methods

This study employed numerical simulations to preliminarily evaluate the structural strength of a modular toddler bicycle main frame, focusing on six design alternatives under static load conditions. The Finite Element Analysis (FEA) was conducted using SolidWorks 2023 SP2.1, a robust simulation tool widely used in engineering for structural analysis. The simulation process is outlined step by step in **Figure 2**.

Although physical prototype testing has not yet been conducted in this preliminary design phase, structural analysis using numerical methods is a standard practice in engineering, particularly for enhancing structural performance while minimizing material usage [17]. As discussed by Khutal *et al.* [18], although linear static FEA may underestimate stress compared to dynamic testing, it remains an effective method for preliminary structural screening and design decision-making prior to prototype validation. This approach is also reflected in studies such as Lin *et al.* [19], where structural evaluation of bicycle frames was carried out using finite element simulations under static loading conditions. The analysis focused on stress and displacement behavior for design optimization, consistent with early-stage design validation practices commonly used prior to experimental or dynamic testing. Similarly, Syehan *et al.* [20] conducted a finite element study using SolidWorks to assess the structural strength of a tilting three-wheeled electric bicycle frame under static loading conditions. Their simulation focused on evaluating material behavior and safety factors under representative loads, and concluded that dynamic and fatigue analyses should be addressed in future research phases to extend validation. FEA has become a key tool in improving bicycle frame designs through iterative testing, allowing for more efficient and precise structural development [21]. Additionally, FEA can optimize the bike frame's material selection based on mechanical properties, cost, and weight. This approach would help accelerate the product development cycle, enabling quicker iterations and more efficient manufacturing processes [22]. The finite element method combined with an optimization algorithm enables the consideration of multiple project variables, including tube geometry, material properties, and stress distribution, particularly at areas with structural constraints [23]. Although experimental data are not yet available, the FEA results in this study serve as a validated preliminary step, and physical prototype testing is planned in the next phase to corroborate these simulations.

In FEA models, especially those involving complex geometries like bicycle frames, the geometry was discretized into nodes and elements, forming a mesh for computational analysis. Each node represents a specific point in the frame where critical parameters such as stress, displacement, and strain are calculated in three directions—x, y, and z. These parameters provide insights into the mechanical behavior of the frame under load, ensuring that it meets safety and durability requirements. To validate the design, a static load test was conducted on a prototype, providing a thorough evaluation of its structural performance [24].

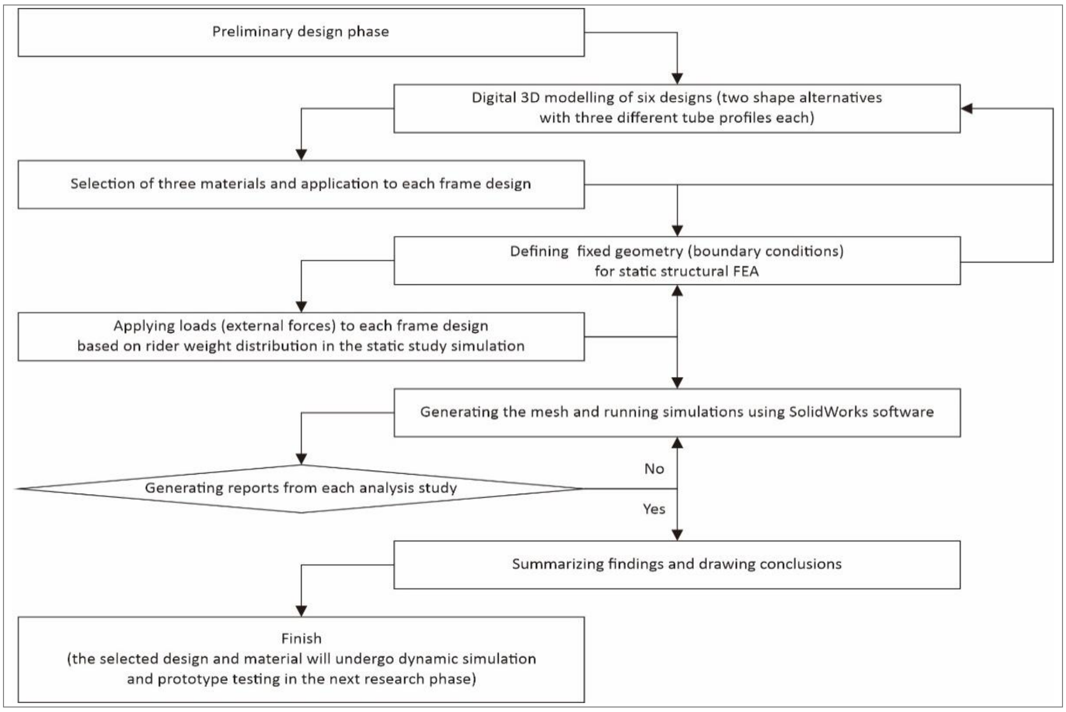

Figure 2. Workflow diagram for the Finite Element Analysis (FEA) simulation process of modular toddler bicycle frame

The stress components at each node include normal stresses (σx, σy, σz) along the x, y, and z axes and shear stresses (τxy, τxz, τyz) in their respective planes. These components are combined to compute the von Mises stress, a widely used failure criterion for ductile materials. Von Mises stress simplifies the multiaxial stress state into an equivalent uniaxial stress, making it easier to assess structural integrity. The calculation of von Mises stress is given by Eq. (1).

$$\sigma_v = \sqrt{\frac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + (\sigma_z - \sigma_x)^2 + 6\left({\tau_{xy}}^2 + {\tau_{yz}}^2 + {\tau_{zx}}^2\right)\right]} \quad (1)$$

In SolidWorks, URES refers to the resultant displacement, which is calculated for each node as the vector magnitude of displacements in the x, y, and z directions. It is an important measure of how much the frame deforms under load. The displacement vector is defined in Eq. (2).

$$u = \left[u_x, u_y, u_z\right] \quad (2)$$

The resultant displacement is given by Eq. (3).

$$URES = \sqrt{{u_x}^2 + {u_y}^2 + {u_z}^2} \quad (3)$$

The equivalent strain (ESTRN) represents the intensity of material deformation under combined loading conditions. It integrates normal and shear strain components to provide a single scalar value, summarizing the deformation state at each node. The equivalent strain is calculated using Eq. (4).

$$\epsilon_{eq} = \sqrt{\frac{2}{3}\left[\left(\epsilon_x - \epsilon_y\right)^2 + \left(\epsilon_y - \epsilon_z\right)^2 + (\epsilon_z - \epsilon_x)^2 + 6\left(\frac{{\gamma_{xy}}^2 + {\gamma_{yz}}^2 + {\gamma_{zx}}^2}{2}\right)\right]} \quad (4)$$

Where ϵ = *Normal Strain* in each direction represents the relative elongation or compression of the material in the respective axis and γ = *Shear Strain* in angular deformation due to forces applied tangentially to a surface.

3. Main Modular Frame Alternatives

In this study, six design alternatives for the modular main frame were developed, as illustrated in **Figure 3**. Curved shapes provide additional advantages beyond aesthetics, including improved structural properties and aerodynamics. Curved profiles are well-documented in lightweight design for their ability to optimize stiffness-to-weight ratios while minimizing aerodynamic resistance, as seen in high-performance industries such as aerospace and automotive manufacturing [25]. These alternatives are categorized into two main frame shapes—Design A, which features a continuous curved shape, and Design B, characterized by straighter lines. Each of these shapes is further explored with three different cross-sectional profiles: rectangular, oval, and circular.

The rectangular and oval profiles, measuring 50 mm x 30 mm with a uniform thickness of 1.2 mm, offer practical benefits for modularity due to their geometrical locking properties, which aid in secure alignment and attachment when connecting with other modules, such as the rear wheel arm. This prevents unwanted rotation and ensures better stability during use. Meanwhile, the circular profile, with a diameter of 33.7 mm and the same thickness, is advantageous for its superior symmetry, enabling even stress distribution under loading conditions.

For regions requiring additional strength, such as the head tube, seat tube (also supporting the bottom bracket), and the rear bracket interface, a thickness of 1.4 mm is utilized. This variation ensures that critical areas are robust enough to handle increased stresses during operation while maintaining an optimal balance between weight and structural performance.

4. Material Selection and Comparison

This study examines the structural performance of six modular frame design alternatives, incorporating variations in material properties for comprehensive evaluation. In SolidWorks, running a simulation study requires precise definitions of material properties tailored to the specific analysis type. These properties are set through the Material Dialog Box, with material data sourced from the Metals Handbook Desk Edition (2nd Edition) by ASM International [26].

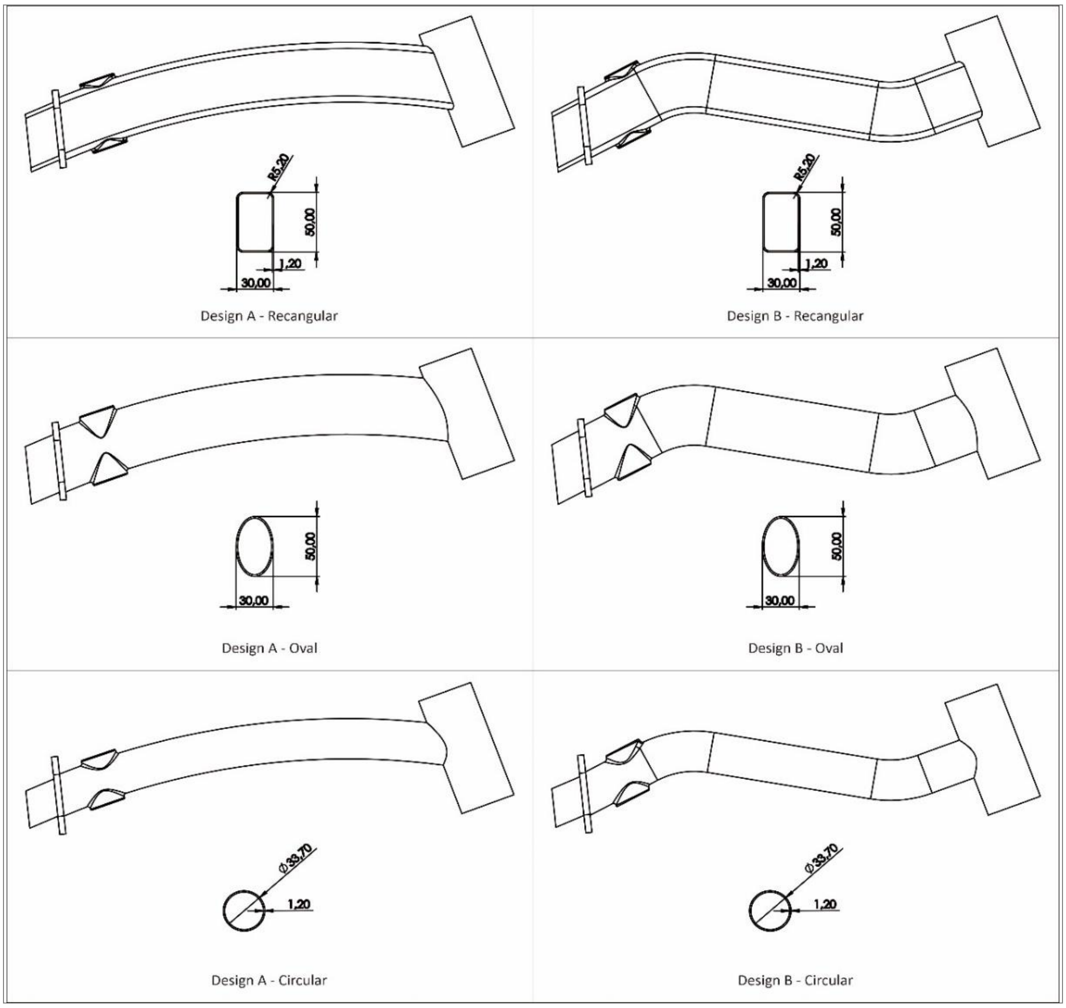

Figure 3. Design alternatives for the modular toddler bicycle main frame, showing two frame shapes (Design A: curved; Design B: straight) with three cross-sectional profiles (rectangular, oval, circular). Dimensions are provided in mm

Material selection for bicycle frames demands a balance between high strength, stiffness, and minimal weight to ensure performance, safety, and manufacturability. Sourav *et al.* employed Ashby's charts to evaluate suitable materials for bicycle frames, identifying CFRP (Carbon Fiber Reinforced Polymer), aluminum alloys, titanium alloys, and steel alloys as optimal candidates [27]. Additionally, their study highlighted AISI 1020 steel, Ti alloys, CFRP, KFRP (Kevlar Fiber Reinforced Polymer), and GFRP (Glass Fiber Reinforced Polymer) as materials commonly used for bicycle frame designs. Muhlisin & Feblidiyanti compare the strength and stability of bicycle frames made from 6061-T6 Aluminum (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) [28]. The study emphasizes that Aluminum, being lightweight—approximately one-third the weight of steel—makes it a suitable material for structural applications where static loads are a primary concern. Rontescu *et al.* explored the application of specific materials, emphasizing that series 6000 aluminum alloys, such as 6061-T6, are highly preferred for bike frames due to their excellent machinability and strength after thermal treatment [29]. Furthermore, their study noted the growing adoption of Ti6Al4V alloy (Grade 5 Titanium) in bike frames, attributed to its superior strength-to-weight ratio and corrosion resistance, which are essential for high-performance designs.

In addition to these materials, aluminum alloys stand out for their ability to reduce both vibration and overall weight, enhancing rider comfort during prolonged use. As demonstrated by Tan *et al.,* aluminum alloys effectively minimize deformation and improve vibration damping, ensuring a smoother riding experience [30]. These properties, combined with their durability and affordability, establish aluminum as a leading choice for lightweight and reliable bicycle frame designs.

Based on these evaluations and criteria, this study focuses on three materials for the modular main frame, which are AISI 1020 Steel (Hot Rolled), Aluminum 6061-T6, and Ti6Al4V (Grade 5 Titanium). By selecting these materials, the study aims to balance structural performance, manufacturability, and cost efficiency. The variations in material properties allow for comprehensive evaluation under different loading conditions, guiding the development of sustainable and durable modular frame designs.

Table 1. The chosen material properties of common bike frame materials [23], [24], [25], [26]

Material Properties	AISI 1020 Steel (Hot Rolled)	Aluminum 6061-T6	Ti6Al4V (Grade 5 Titanium)
Density (g/cm³)	7.87	2.70	4.43
Young's Modulus (GPa)	186	68.9	114
Poisson's Ratio	0.29	0.33	0.33
Ultimate Strength (MPa)	380	310	1170
Yield Strength (MPa)	205	276	1100
Shear Modulus (GPa)	72	26	44

5. Boundary Conditions and Loading

The modular main frame of the bicycle features a unique flippable concept, allowing for two vertical orientation configurations, as illustrated in **Figure 1b**. To ensure accurate simulation, the analysis focuses on the configuration subjected to the highest loads: the balance bike with pedals. This configuration represents the most critical case for structural evaluation. For the simulation, the fixed geometry is defined at two critical locations on the main frame. These include the inner surface of the head tube and its bottom section, where the front wheel's fork spacer is supported and the rear module extension, which supports the attachment of the rear triangle frames in the standard children's bicycle configuration or the rear wheel arms in this configuration. These fixed boundaries replicate the actual constraints during real-world operation as shown in **Figure 4**.

External forces are applied to specific regions of the frame to simulate the rider's weight distribution and operational load conditions (**Figure 5**). The loading values are based on the maximum weight of a 9-year-old child in Indonesia, approximately 385 N, multiplied by a safety factor of 2, resulting in a total applied load of 770 N. The rider's weight distribution is assumed to be 30% on the handlebar, 45% on the bottom bracket, and 25% on the seat post [27]. Accordingly, external forces are applied to two key locations on the frame: a force of 231 N at the head tube area to represent the load transmitted through the handlebar, and a force of 539 N at the seat post tube area (including the bottom bracket attachment) to replicate the combined load acting on this section. Stress concentration typically occurs at critical joints, such as the seat tube and upper stay junction, highlighting the need for localized reinforcement in bicycle frame design [31].

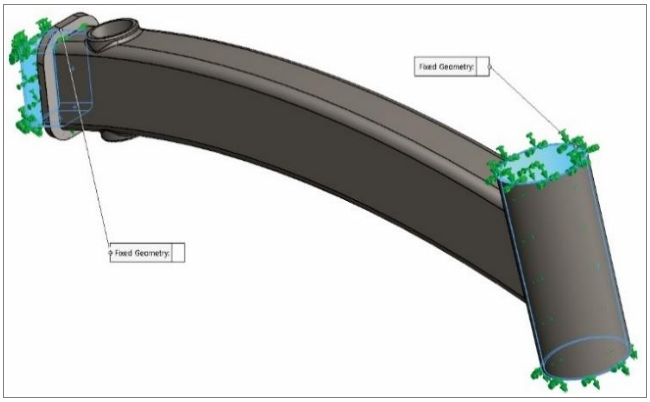

Figure 4. The locations of fixed geometry on the main bicycle frame

This study is limited to static structural analysis and does not yet incorporate dynamic loading, vibration, or material fatigue simulations. These aspects are essential for evaluating long-term durability and real-world performance but fall beyond the scope of this preliminary design phase. Future research will include dynamic simulation, fatigue analysis, and physical prototype testing to validate and expand upon the current findings.

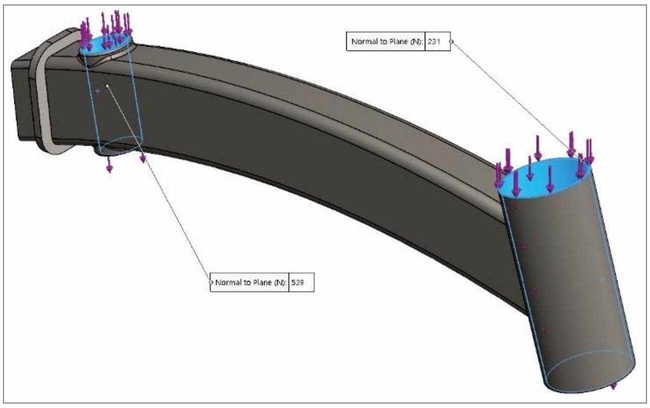

Figure 5. External force locations, magnitudes, and directions applied to the main bicycle frame for FEA simulation

6. Results and Discussion

6.1. Maximum Stress (von Mises)

The von Mises stress analysis was conducted to assess the structural performance of the six design alternatives under static loading conditions. The simulations were performed using AISI 1020 Steel (Hot Rolled) as the material. This material was chosen due to its balanced mechanical properties and cost-effectiveness, making it a suitable baseline for comparison. Table 2 presents the weight comparison of each design, all using the same material. The differences in weight highlight the influence of cross-sectional profiles on material usage efficiency. Design A with the circular profile is the lightest, weighing 0.56 kg, which is approximately 22.2% lighter than the rectangular profile. This difference underscores the significance of profile geometry in optimizing weight, particularly for modular designs where material efficiency is paramount.

Table 2. Weight comparison of each design with uniform material

Design	Profile	Weight (kg)
A	Rectangular	0.72
	Oval	0.66
	Circular	0.56
B	Rectangular	0.77
	Oval	0.67
	Circular	0.57

As shown in Figure 6, Design A with the rectangular profile exhibited the highest stress concentration compared to the oval and circular profiles. This indicates that while rectangular profiles offer modularity advantages, they may require reinforcement to handle localized stress peaks effectively. In contrast, Design B with the oval profile showed lower stress levels, indicating better stress distribution. This is attributed to the profile's curvature, which helps diffuse the applied load more effectively.

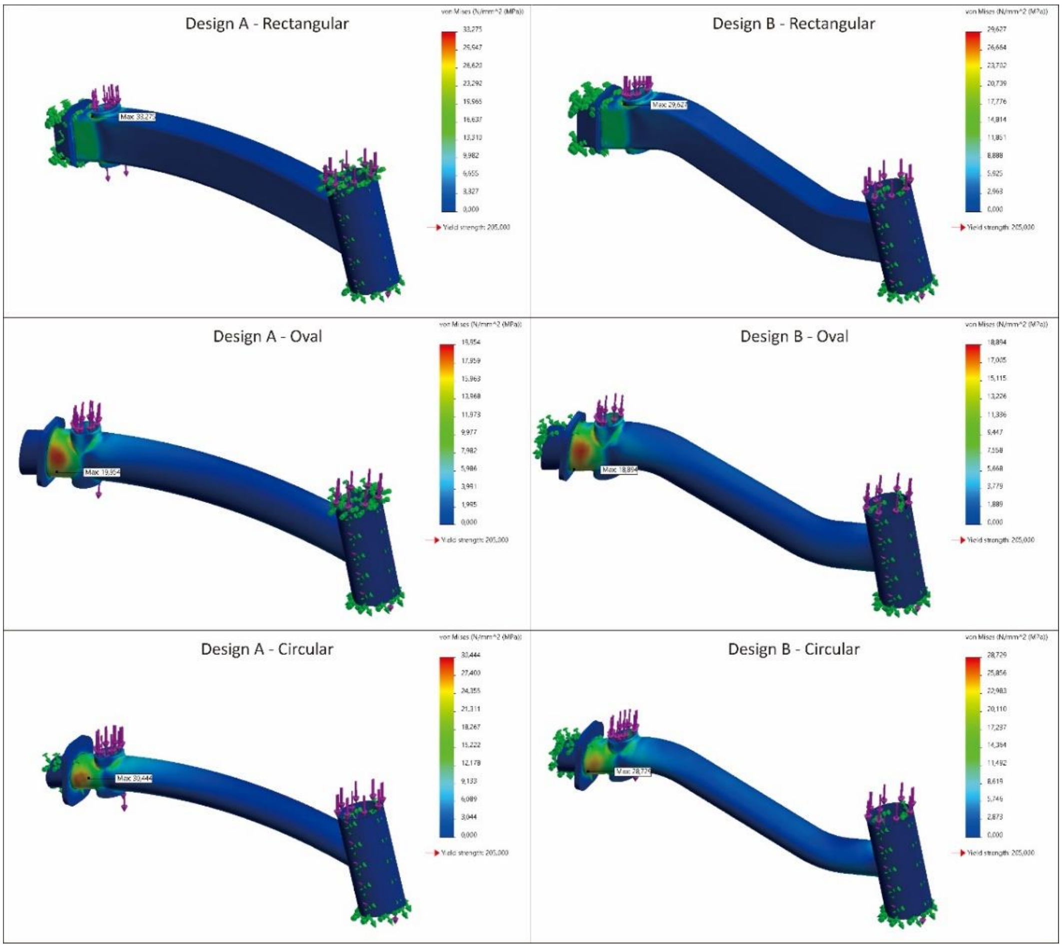

Figure 6. Maximum von Mises stress distribution for six design alternatives under static load conditions

Table 3 compares the maximum von Mises stress values for all six designs across the three cross-sectional profiles. Design A with the rectangular profile exhibited the highest stress (33.275 MPa), while the oval profile in Design B demonstrated the lowest stress value (18.894 MPa). These findings suggest that while circular profiles generally perform better under uniform loading due to their symmetry, the rectangular and oval profiles excel in specific regions due to their modular attachment advantages, such as geometrical locking for secure module connections.

Table 3. Maximum von Mises stress for six design alternatives

Design	Profile	Weight (kg)
A	Rectangular	33.275
	Oval	19.954
	Circular	30.444
B	Rectangular	29.627
	Oval	18.894
	Circular	28.729

6.2. Maximum Displacement

The displacement (URES) analysis provides insight into how each design deforms under load. High displacement can compromise frame rigidity, particularly in modular connections, affecting performance and safety. As shown in **Figure 7**, circular profiles experienced the largest displacement due to their uniform cross-section and isotropic properties. Rectangular and oval profiles, on the other hand, showed relatively lower displacement values, especially near the modular attachment points, a crucial factor for modular bicycle frames.

Table 4 summarizes the maximum displacement values. Notably, the rectangular profile in Design A exhibited the lowest displacement (0.009 mm), demonstrating its structural rigidity. Oval profiles performed similarly in Design A (0.007 mm), reinforcing their suitability for modularity-focused designs.

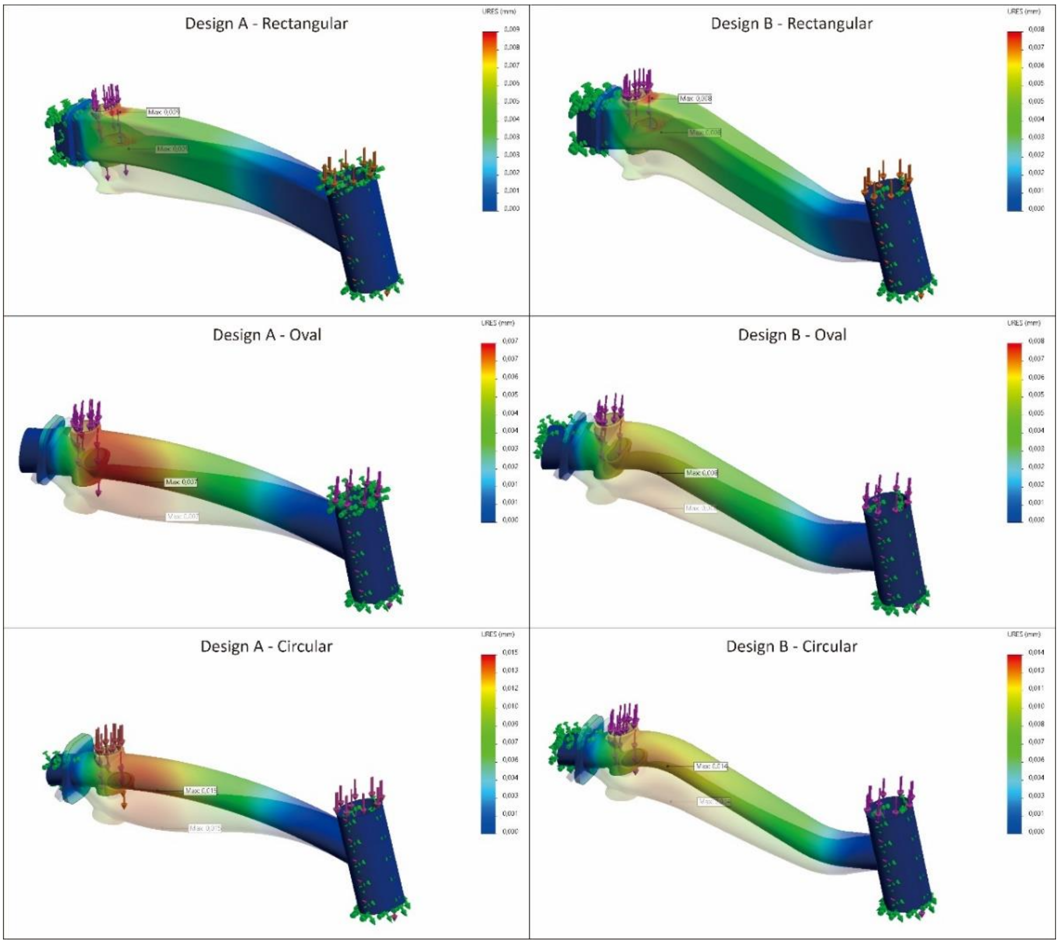

Figure 7. Maximum displacement (URES) for six design alternatives under static load conditions

Table 4. Maximum displacement (URES) for six design alternatives

Design	Profile	Weight (kg)
A	Rectangular	0.009
	Oval	0.007
	Circular	0.015
B	Rectangular	0.008
	Oval	0.008
	Circular	0.014

6.3. Material Comparison

Design A with the rectangular profile was selected as a representative model for further material analysis due to its modular attachment advantages. Three materials—AISI 1020 Steel (Hot Rolled), Aluminum 6061-T6, and Ti6Al4V (Grade 5 Titanium)—were evaluated for their impact on stress, displacement, and weight optimization as shown in **Figure 8**. This comparison highlights trade-offs between performance, weight, and cost.

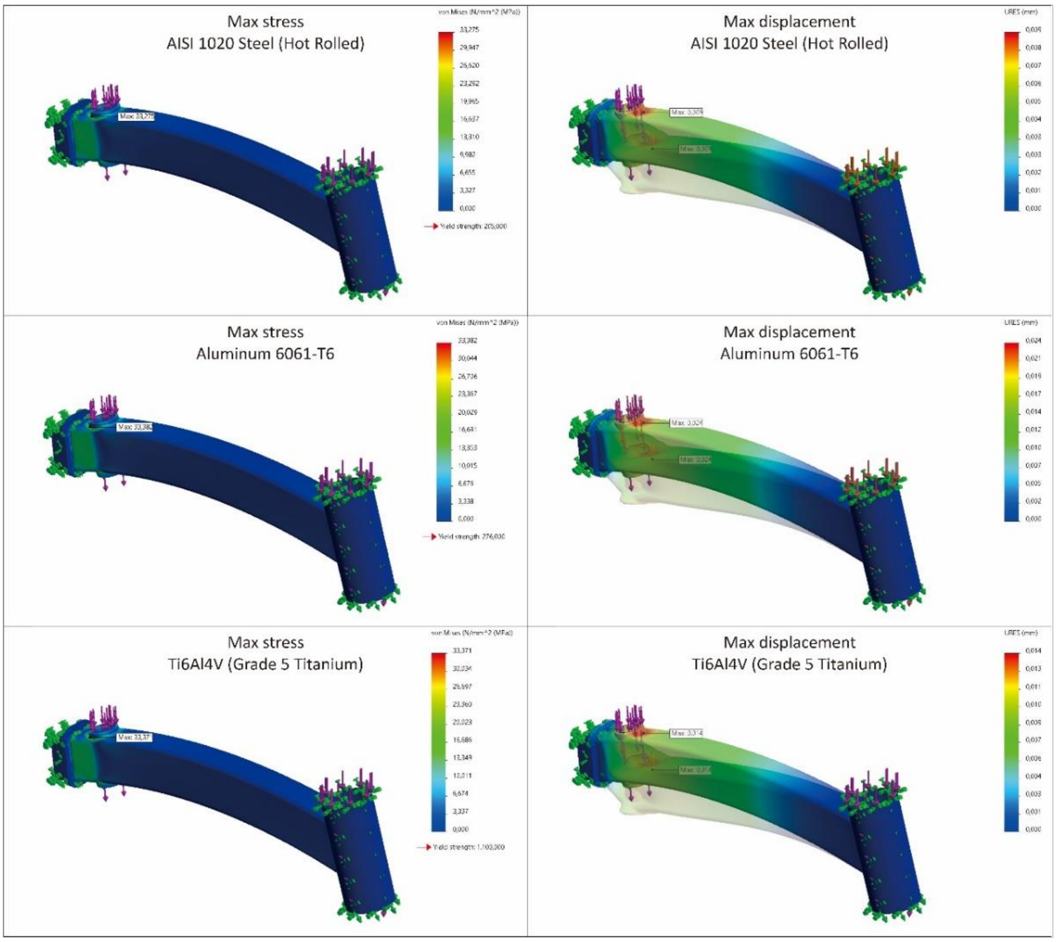

Figure 8. Stress and displacement distributions for Design A (rectangular profile) with AISI 1020 Steel, Aluminum 6061-T6, and Ti6Al4V (Grade 5 Titanium)

Table 5 provides a detailed comparison of material performance for Design A. AISI 1020 Steel exhibited moderate stress and displacement, offering a balanced solution in terms of performance and cost. Aluminum 6061-T6 demonstrated lower displacement due to its higher stiffness but significantly increased costs. Ti6Al4V provided exceptional stress and displacement performance but at a much higher material cost, limiting its feasibility for cost-sensitive modular designs.

Table 5. Material performance comparison for design A (rectangular profile tube)

Design A (rectangular profile tube)	AISI 1020 Steel (Hot Rolled)	Aluminum 6061-T6	Ti6Al4V (Grade 5 Titanium)
Stress (Mpa)	33.275	33.382	33.371
Displacement (mm)	0.009	0.024	0.014
Weight (kg)	0.72	0.25	0.41
Weldability	Excellent	Excellent	Fair
Cost type	Modest	Average	High Ends

7. Discussion

The results highlight the critical influence of cross-sectional profiles on the structural and modular performance of children's bicycle frames. Rectangular and oval profiles demonstrate advantages in modularity, providing secure geometrical locking features essential for connecting frame modules like the rear triangle. This characteristic is vital for implementing a modular design that supports growth-related adjustments and additional features. Circular profiles, although less modular, show superior performance under stress and displacement due to their symmetrical geometry, optimizing load distribution and reducing the risk of material fatigue. These findings underline the importance of balancing modularity and structural performance in profile selection.

Future research could focus on optimizing cross-sectional topologies beyond the predefined shapes examined in this study. A free-form design approach could identify geometries that maximize the strength-to-weight ratio while addressing uncertainties such as manufacturing tolerances or variable loading conditions [32]. This approach holds promise for advancing the structural and ergonomic design of modular bicycle frames.

Weight plays a crucial role in children's bike design, significantly affecting balance and usability. Guidelines recommend that a child's bike should not exceed 30% of the user's body weight, as heavier bikes can impair balance and maneuverability. This limit typically accounts for the bike's overall weight, encompassing components such as wheels, drivetrain, and handlebars, rather than just the frame. For children weighing 12–20 kg, corresponding to ages 3–5, the total bike weight should remain within 3.6–6 kg. The proposed frame designs in this study weigh less than 1 kg, ensuring ample allowance for additional components while adhering to weight recommendations. These lightweight frames align with ergonomic needs, providing children with manageable and safe biking experiences.

Material selection further impacts the balance between weight and structural performance. AISI 1020 Steel, despite its higher density, achieves moderate weight due to its high strength allowing thinner profiles. Aluminum 6061-T6, known for its lightweight properties, is well-suited for children's bikes, though cost considerations must be addressed. Ti6Al4V offers exceptional lightweight and performance qualities but at a premium price, limiting its applicability to high-end designs.

This study contributes a vital perspective to existing literature by incorporating structural strength assessments into modular bike design. Prior research has primarily focused on materials and processing technology in function combined method for children's bike [33], while others explored flippable frames for transitioning from balance bikes to pedal bikes [34]. Additionally, stress analysis and deformation considerations, as highlighted in the structural simulations of bicycle frame behavior under various load conditions [35], emphasize the significance of evaluating stress distribution and displacement under different scenarios. These analyses reveal critical stress areas such as the seat beam, chain stay-seat stay, and top beam, underscoring the need for optimization to ensure structural integrity. The findings set a foundation for future advancements in dynamic loading assessments and alternative material exploration to enhance durability and cost-effectiveness.

8. Conclusion

This study successfully addresses the research objectives of the preliminary design phase by using static simulation as a foundational step toward subsequent research involving prototype testing and dynamic simulation, while also presenting a modular toddler bicycle design that embodies sustainable innovation, user-centric ergonomics, and structural reliability. The research outcomes include a novel bicycle frame design that transforms to accommodate children's growth stages while adhering to the principles of sustainability and the circular economy. Through the integration of anthropometric analysis, design innovation, and material science, this work contributes significantly to the development of modular product models that balance functionality, durability, and ecological responsibility.

The findings introduce a significant advancement by performing comprehensive strength assessments for the bicycle frame. While previous studies that focused on frame transitions or materials and processing technology without validating structural integrity, this research highlights the critical importance of mechanical validation. Such validation ensures the bicycle can withstand increased weight and activity-related impacts, which are fundamental for user safety and product longevity. Additionally, the design optimization targeted minimal weight while maintaining stress levels below the material's yield strength, achieving a balance between rigidity and weight.

By selecting materials such as AISI 1020, Aluminum 6061, and Ti6Al4V, chosen for their strength-to-weight efficiencies and sustainability, and leveraging tools like SolidWorks for structural simulations, this research provides a robust framework for future innovation in children's bicycles. This study not only demonstrates practical advancements but also provides theoretical insights by proposing scalable methods for modular design and durability assessment that are applicable to a broad spectrum of industrial design challenges.

Ultimately, the research establishes a foundation for new theories and methodologies in sustainable product innovation. Integrating modular product design into circular economy strategies offers significant potential to reduce environmental impact. Circular principles, such as designing for upgradability can enhance the sustainability of similar product categories by ensuring adaptability to user needs while minimizing material waste. Additionally, the study aligns with Smart Circular Product Design strategies through lean eco-design, which focuses on improving product design, reducing costs and environmental impacts, and enhancing business efficiency. Future research should focus on long-term dynamic and fatigue testing of materials, along with user ergonomics assessment in real-world settings, to support comprehensive validation and performance evaluation.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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