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Development and Validation of a Standardized Bicycle Finite Element Model Based on ISO Standards

Lijuan He*, Bo Yang

School of Mechanical Engineering, Tianjin University of Science and Technology, Tianjin, China
**Corresponding Author*

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Abstract: Vehicle-to-bicycle impact simulation analyses require bicycle models with consistent geometric parameters, deformable structural responses, and reliable validation data. Existing studies have often adopted multi-body bicycle models or finite element models reconstructed from specific physical bicycles. These models can satisfy accident reconstruction and scenario-specific analyses, but limitations remain in the uniformity of geometric sources, model reproducibility and structural validation criteria. In this study, a standardized bicycle finite element model was developed according to the geometric requirements for bicyclist targets specified in ISO 19206-4:2020. A two-dimensional parametric wireframe sketch was first established using key reference points, including the bottom bracket center, wheel centers, frame nodes, handlebar, saddle and pedal-related locations. A three-dimensional CAD model was then constructed in SolidWorks, followed by mesh generation, material assignment and connection modeling in ANSA. The model was mainly discretized using shell elements, with a global mesh size of 8 mm and local refinement to 4 mm in key connection regions. Revolute joints and constrained nodal rigid body connections were used to represent rotational pairs and local rigid connections, respectively. The final model contained 78,249 elements. Drop-weight and free-fall impact simulations were conducted according to the frame and fork test methods specified in ISO 4210-6:2023. The maximum permanent deformation was 6.1 mm in the drop-weight test and 2.0 mm in the free-fall test, both below the corresponding standard limits. The results indicate that the developed model has a clear standardized geometric basis, reasonable connection definitions and stable component-level structural response, providing a basis for vehicle-to-bicycle impact simulations and active-safety test-scenario development.

1. Introduction

Bicycles are an important transport mode for short-distance urban travel and green mobility. With the development of shared mobility and low-carbon transport, bicycles have become increasingly involved in urban road traffic systems. In vehicle-to-bicycle collisions, a bicycle is not merely a means of motion for the cyclist, but an important contact and load-transfer medium between the vehicle front end and the rider. During the initial stage of impact, the vehicle usually contacts the front wheel, frame, fork, pedal region or areas adjacent to the lower extremity. Therefore, the geometric dimensions, structural stiffness, connection relationships and local deformation of the bicycle can directly affect the contact sequence, load-transfer path and subsequent human-bicycle-vehicle coupling boundary conditions. Establishing a bicycle model with a clear geometric source, reasonable structural response and suitability for dynamic simulation is therefore an important basis for vehicle-to-bicycle impact simulation, bicycle target development and active-safety test-scenario extension. The World Health Organization Global Status Report on Road Safety 2023 reported that road traffic deaths and injuries remain a major global public health problem, and that vulnerable road users, including pedestrians, motorcyclists and cyclists, account for a high proportion of road fatalities, with cyclists accounting for approximately 6% of global road deaths and higher proportions in some regions [1]. This further demonstrates the practical necessity of developing standardized models and simulation methods for collision scenarios involving bicycles.

A bicycle should not be regarded simply as a kinematic support [2]. Its dimensions, structural stiffness, connection relationships and local deformation can affect the vehicle contact sequence and the boundary conditions of impact simulations. Existing vehicle-to-bicycle collision studies have mainly adopted multi-body models and full bicycle finite element models [3]. Multi-body models have high computational efficiency and are suitable for accident reconstruction and large-scale parametric analyses, but their capability to describe local deformation of the frame and fork is limited [4]. Finite element bicycle models are often developed from a specific bicycle prototype, which may limit their representativeness and reusability [5]. Nakahara [6] showed that bicycle deformation and bicycle type can influence head injury values in car-to-bicycle collisions, indicating that the structural fidelity of the bicycle model has a non-negligible influence on simulation results.

Nevertheless, the sources and validation methods of bicycle models still differ among studies. Some models are reconstructed from the specific bicycle involved in an accident, some are developed from typical city bicycles, mountain bicycles or shared bicycles [7], and others are rigidized or locally simplified to improve computational efficiency. These models can meet the requirements of specific accident reconstructions or specific scenarios, but limitations remain in standardized scenario construction, model reuse and comparison of results across studies. For active safety testing, bicyclist target development and standardized vehicle-to-bicycle impact simulation, the bicycle model should have a clear standardized geometric source, a reproducible modeling process and validated structural response.

ISO 19206-4:2020 specifies the requirements for bicyclist targets used in the assessment of active safety systems, including geometric dimensions, posture and target response characteristics, thereby providing a basis for standardized bicycle and bicyclist target modeling [8]. ISO 4210-6:2023 specifies the test methods for bicycle frames and forks and can be used to evaluate the deformation response of key load-bearing bicycle structures under impact loading [9]. Based on these standards, this paper proposes an ISO-based development and validation workflow for a bicycle finite element model. Rather than being constructed from a single physical bicycle or empirical dimensions, the model is based on the key geometric parameters and reference posture defined in ISO 19206-4 and is validated through frame and fork tests specified in ISO 4210-6. The developed model is intended to provide a standardized basis for subsequent vehicle-to-cyclist impact simulations.

2. Standardized Geometric Definition Based on ISO 19206-4

2.1. Reference Coordinate System and Key Control Points

The reliability of a bicycle finite element model first depends on whether its geometric definition is clear, unified and reproducible. In this study, the model was established according to the geometric requirements for the standard adult commuter bicycle and bicyclist target specified in ISO 19206-4:2020. The standard defines the bicycle dimensions, key reference points and riding posture for a bicyclist target, and therefore provides a unified geometric basis for standardized bicycle finite element modeling.

The bottom bracket center was used as the primary coordinate reference point for the geometric definition of the bicycle model. The front and rear wheel centers, front and rear upper frame tube nodes, handlebar position, saddle position, bilateral foot-edge pedaling points and knee joint centers were used as key control points. These reference points define the spatial constraints of the bicycle geometry. Specifically, the bottom bracket center determines the arrangement of the crank and pedals, the wheel centers determine wheel placement and wheelbase, the frame nodes define the main load-bearing path of the double-triangle frame, and the handlebar and saddle positions determine the initial support boundaries for the subsequent cyclist model.

Unlike a model constructed by measuring a single physical bicycle, a geometric definition based on standard reference points can reduce inconsistency caused by differences among sample bicycles. For subsequent vehicle-to-cyclist impact simulations, the handlebar, saddle and pedal positions not only determine the bicycle geometry itself, but also define the registration relationship between the cyclist model and the bicycle. Significant deviations in these positions would directly affect the initial human posture, center-of-gravity location and vehicle contact boundary conditions. Therefore, the reference points specified in ISO 19206-4 were used as the geometric constraints for model development. As shown in Figure 1, the ISO reference points include the following: 0 denotes the bottom bracket center; 1 and 2 denote the front and rear wheel center axes, respectively; 3 and 4 denote the front and rear upper frame tube nodes; 5 and 6 denote the handlebar and saddle positions; 7 and 8 denote the left and right foot-edge points; 9 and 10 denote the left and right knee joint centers; and A denotes the trunk angle relative to the horizontal plane. The ground line was used as the reference for wheel-ground contact and vertical positioning, providing a common basis for bicycle modeling, bicyclist model development and human-bicycle registration.

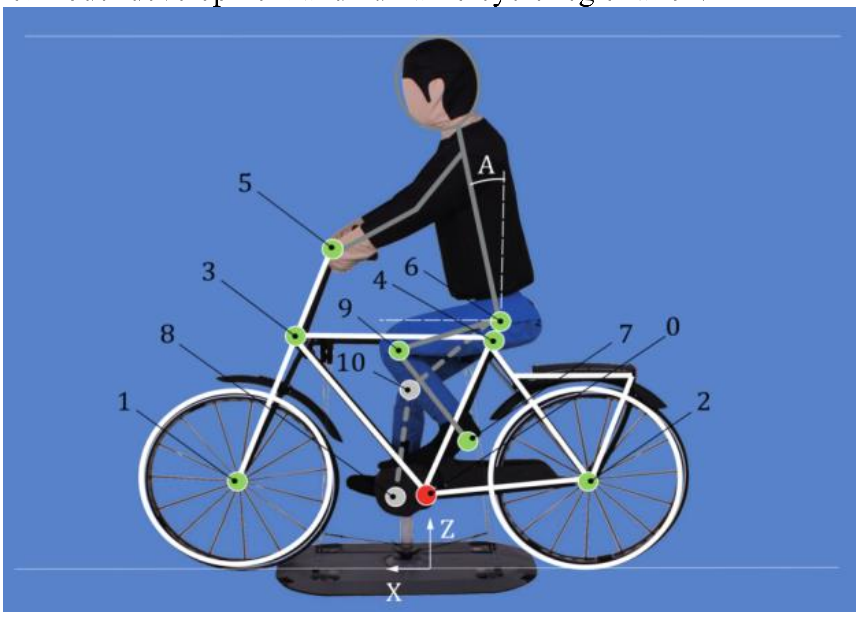


Figure 1: Reference points and standard riding posture of the bicyclist target specified in ISO 19206-4.

2.2. Two-Dimensional Parametric Wireframe Sketch

Before three-dimensional solid modeling, a two-dimensional parametric wireframe sketch was first constructed. This step was not intended to simply draw the external bicycle profile, but to convert the standard reference points, main dimensions and relative positions of components into a constrained and verifiable geometric skeleton. According to the typical geometric parameters specified in the standard, key dimensions such as a wheel diameter of 340 mm, a wheelbase of 1210 mm and a handlebar height of 900 mm were selected to determine the positions of the wheel centers, bottom bracket center, handlebar, saddle and pedals. The ground line was used as the reference for vertical positioning.

During sketch construction, the front and rear wheel centers were first determined from the wheel diameter and wheelbase, and the relative relationship between the wheel outer contours and the ground line was checked. The centerlines of the main frame tubes, including the top tube, down tube, seat tube, head tube, seat stays and chain stays, were then determined according to the typical double-triangle bicycle frame structure. Since a bicycle frame is not a regular rectangular structure and contains apparent angular and intersection relationships among tubes, the frame nodes, tube lengths and main tube angles were parametrically controlled at the wireframe stage. This ensured that the subsequent three-dimensional solid model retained both standard dimensions and reasonable structural characteristics.

The wireframe model was also used for dimensional verification during subsequent CAD modeling and finite element preprocessing. By placing the control lines of the wheel set, frame, handlebar, saddle and pedals within the same parametric framework, assembly deviations and dimensional drift during later modeling could be reduced. After the sketch was completed, the wheel diameter, wheelbase, handlebar height and relative positions of key reference points were checked one by one to ensure that the overall model geometry satisfied the standard requirements.

3. Three-Dimensional CAD Model Construction

Based on the two-dimensional parametric wireframe sketch, a three-dimensional CAD model was constructed in SolidWorks. The purpose of three-dimensional modeling was to transform the standardized geometric skeleton into a bicycle model with realistic structural features, providing the geometric basis for subsequent mesh generation, connection definition and dynamic simulation. Two requirements were emphasized during modeling: first, the overall dimensions and key reference point locations had to remain consistent with the standard sketch; second, the main components, including the frame, fork, wheel assemblies, handlebar, saddle and pedals, had to satisfy the requirements of finite element discretization and impact simulation.

The frame was constructed according to the double-triangle load-bearing structure of a typical urban commuter bicycle, including the top tube, down tube, seat tube, head tube, seat stays, chain stays and front fork. The centerlines of the tubes were determined from the two-dimensional sketch, and tube sections were assigned according to common thin-walled tubular bicycle structures. For long tubular structures, a section-and-path modeling strategy was adopted, and tubular solids were generated by extrusion, sweep or revolution features. For multi-tube intersection regions such as the head tube, bottom bracket, frame joints and fork root, appropriate chamfering and transitional treatment were applied while preserving structural function. This reduced sharp boundaries and discontinuous surfaces and provided more stable geometric conditions for subsequent meshing.

The wheel assembly mainly comprised tires, hubs and spokes. Since the tires and hubs exhibit axisymmetric characteristics, they were generated using revolution modeling. The spokes were first modeled as a single spoke and then replicated by circular patterning to form a complete spoke system, ensuring consistency in spoke number, angular distribution and hub connection positions. Auxiliary components such as the handlebar, saddle, crank and pedals were arranged according to the standard reference points and cyclist contact locations, thereby supporting subsequent registration of the cyclist model and definition of human-bicycle coupling relationships.

After the three-dimensional CAD model was completed, the wheel center distance, handlebar height, saddle position, bottom bracket location and pedal reference points were rechecked. The verification results showed that the solid modeling process did not cause obvious deviations in key dimensions. The CAD model preserved the geometric characteristics of a standard adult commuter bicycle and provided sufficient geometric continuity and engineering operability for finite element preprocessing. The overall development workflow from the two-dimensional parametric sketch to the three-dimensional CAD model and the final finite element model is shown in Figure 2.

(a) (b) (c)

Figure 2: Development workflow of the bicycle finite element model based on standardized geometry: (a) two-dimensional parametric geometric sketch; (b) three-dimensional CAD model; (c) bicycle finite element model.

4. Development of a Bicycle Finite Element Model

4.1. Mesh Generation and Quality Control

After CAD modeling, the geometric model was imported into ANSA for finite element model development. Because the bicycle frame, fork and rims are mainly thin-walled tubular structures, and their thickness dimensions are much smaller than their lengths and cross-sectional dimensions, shell elements were primarily used for discretization. Compared with solid elements, shell elements can describe bending, torsion and local deformation of thin-walled structures at a lower computational cost, making them suitable for subsequent explicit dynamic impact simulation.

Before meshing, the CAD model was cleaned geometrically by repairing free edges, merging duplicate surfaces, deleting minor features with limited influence on impact response and removing local interferences. A global mesh size of 8 mm was then specified, and quadrilateral elements were used as the main element type. In key load-transfer regions, such as the head tube, bottom bracket area, fork root, wheel-axle connection area and frame-tube intersections, the local mesh size was further refined to 4 mm to improve local deformation accuracy and contact stability. A small number of triangular elements were retained in regions with complex surfaces or geometric transitions to accommodate complex boundaries.

To ensure explicit dynamic calculation stability, strict mesh-quality criteria were adopted. The Jacobian value was required to be greater than 0.5, the warpage angle was required to be less than 50 degrees, and the aspect ratio was required to be no greater than 5. Regions that failed to meet these requirements were corrected by local remeshing, node smoothing and geometric simplification. After quality control, the overall mesh satisfied the requirements for time-step stability, contact stability and local deformation calculation in subsequent impact simulations.

4.2. Connection Relationship and Kinematic Pair Definition

The connection definitions of the bicycle finite element model directly affect the load-transfer path and global kinematic response during impact. According to the actual kinematic relationships among bicycle components, two main types of connections were used. For parts with relative rotational motion, including the front wheel and fork, the rear wheel and frame, and the crank-pedal assembly and bottom bracket, revolute joint elements were adopted to simulate rotational pairs. These connections allowed the wheels and crank to rotate around prescribed axes, thereby preserving the key rotational degrees of freedom of the bicycle during impact.

For the frame tubes, fork connection regions and other components that are mainly connected by welding or rigid connections in an actual bicycle, the constrained nodal rigid body (CNRB) method in LS-DYNA was adopted. This method couples multiple nodes into a local rigid region, facilitating load transfer between adjacent tubes and avoiding nonphysical failure caused by nodal discontinuity. After the connection relationships were defined, the directions of the rotational axes, the frame-tube connection regions and the ranges of local rigid regions were checked to ensure consistency between the connection definitions and the real structural characteristics of the bicycle. The overall bicycle finite element model and representative joint definitions are illustrated in Figure 3.

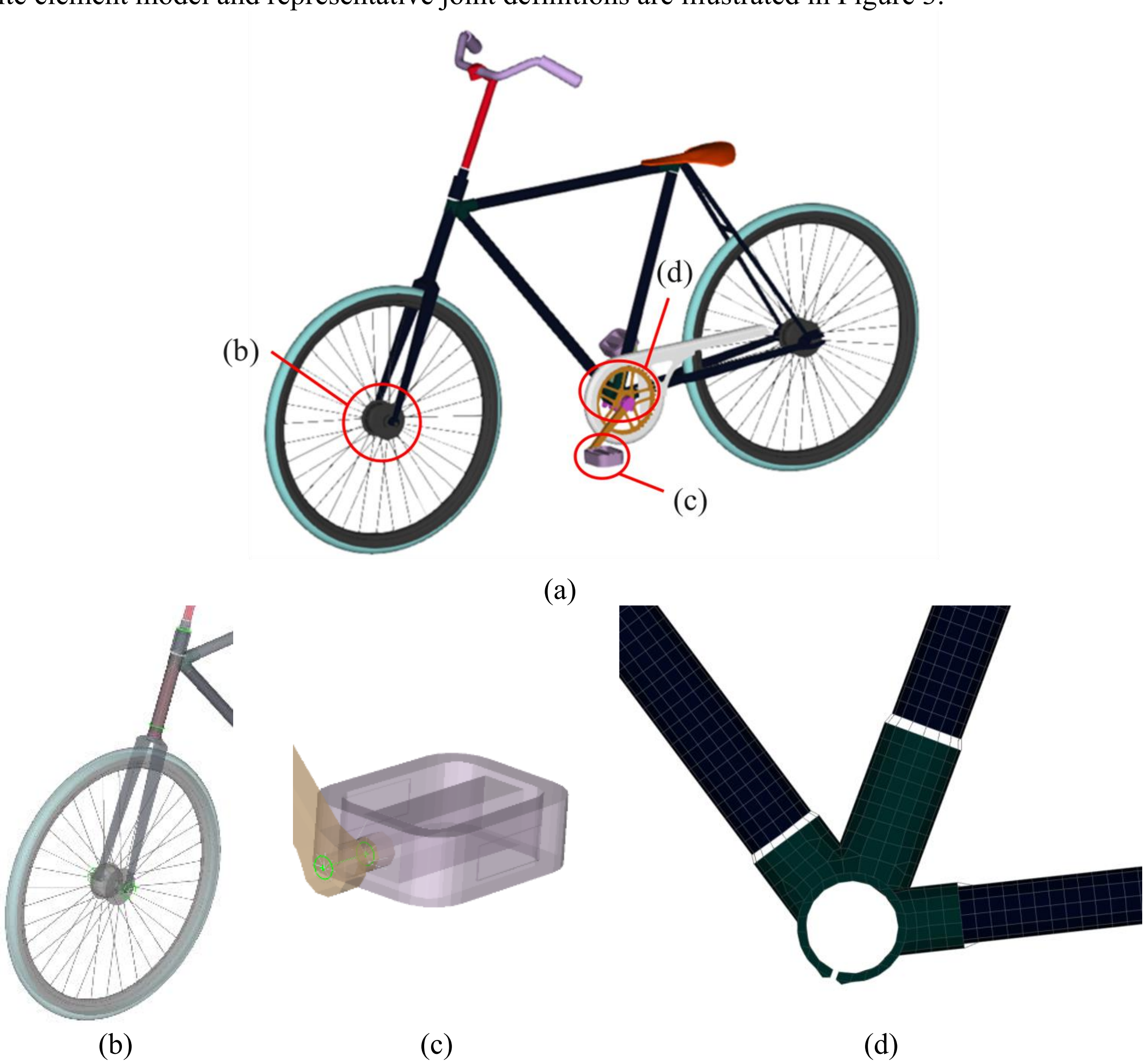


Figure 3: Typical connection definitions in the bicycle finite element model: (a) overall bicycle finite element model; (b) wheel–fork revolute joint; (c) local rigid connection definition; (d) frame-tube local rigid connection.

4.3. Material Properties and Final Model

Material properties were assigned according to the structural functions of the bicycle components and the adopted LS-DYNA unit system. An elastoplastic material model was used for the frame and fork to describe residual deformation under the standard impact loads, while appropriate material definitions were assigned to the hubs and tires according to their structural functions. The main frame was modeled using aluminum alloy to represent its structural support and impact-load-transfer functions. The hubs were modeled using steel to reflect their relatively high stiffness and strength, and the tires were modeled using rubber to describe their flexibility and cushioning behavior during contact.

The material parameters used in finite element calculations must be consistent with the adopted unit system. In this study, the material parameters in the model were converted and checked according to the LS-DYNA unit system. Through mesh generation, material assignment and connection definition, the final bicycle finite element model contained 78,249 elements, preserving the main structural features and key kinematic degrees of freedom while maintaining computational efficiency. The main material parameters adopted in the bicycle finite element model are summarized in Table 1.

Table 1: Main material parameters of the bicycle finite element model.

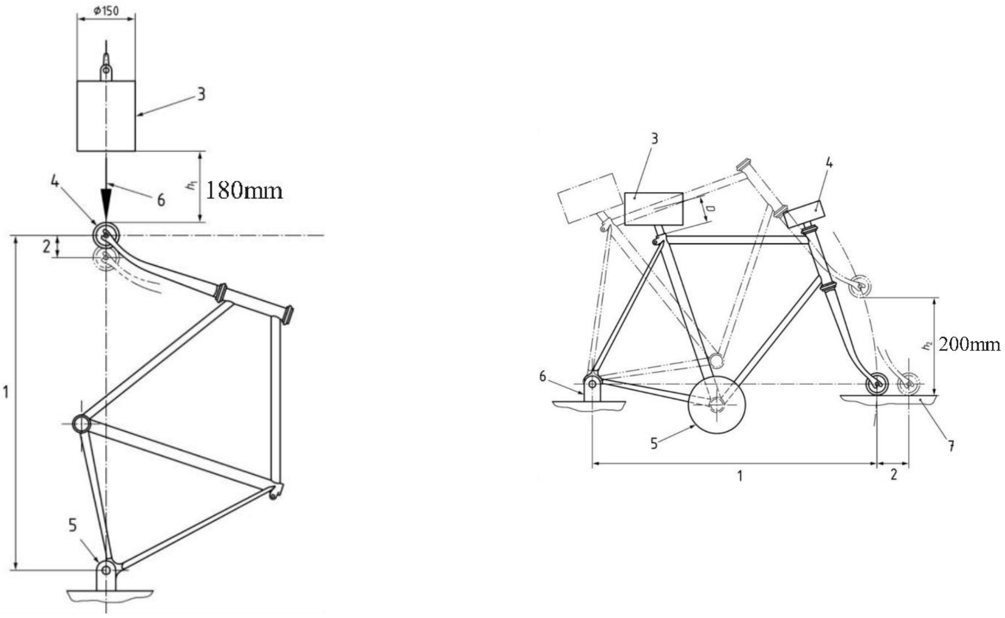
Material Type	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio	Yield Stress (MPa)
Aluminum alloy	2700	70000	0.33	280
Steel	7806	206000	0.30	540
Tire rubber	2950	1000	0.30	20

5. Model Validation Based on ISO 4210-6

5.1. Validation Method

The frame and fork assembly is the primary load-bearing structure of a bicycle. In vehicle-to-bicycle collisions, it participates in impact-load transfer and energy absorption, and its structural response affects the overall bicycle deformation mode and the subsequent kinematic response of the cyclist. Therefore, the frame and fork assembly was selected as the priority validation object to evaluate the rationality of the finite element model at the key load-bearing component level. The validation method was established according to the frame and fork test methods specified in ISO 4210-6:2023, including a drop-weight impact simulation and a free-fall impact simulation of the frame/fork assembly.

In the drop-weight impact simulation, fixed constraints were applied to the rear axle of the frame. A lightweight roller with a mass of 1 kg was placed at the top of the fork to reduce frictional effects and represent the contact state of the steering system. The impact load was simulated by a standard drop weight with a mass of 22.5 kg, which was released from a height of 180 mm and impacted the fork region. In the free-fall impact simulation of the frame/fork assembly, mass points of 50 kg, 10 kg and 30 kg were added at the positions specified by the standard. A rotational connection was defined between the rear axle and the support, the initial drop height was set to 200 mm, and a gravity field was applied so that the frame could freely fall and impact the support. The corresponding validation boundary conditions for the drop-weight and free-fall impact tests are schematically shown in Figure 4.

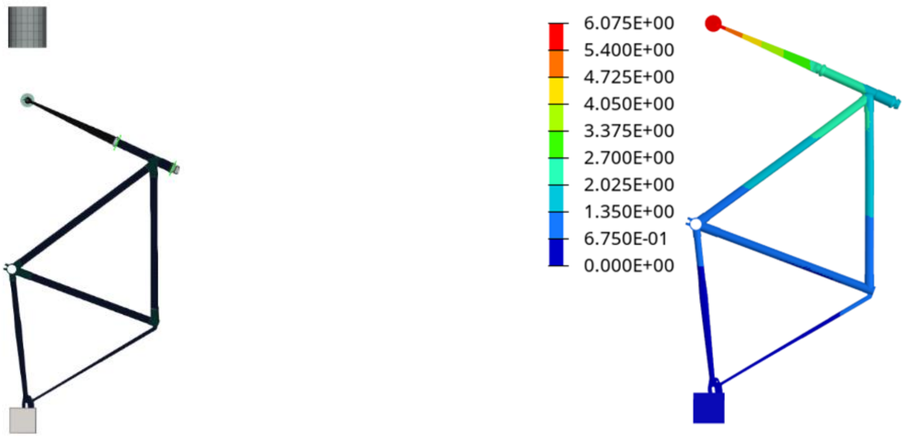


(a) (b)

Figure 4: Schematic validation conditions for the frame and fork impact tests according to ISO 4210-6: (a) drop-weight impact test; (b) free-fall impact test.

5.2. Validation Results

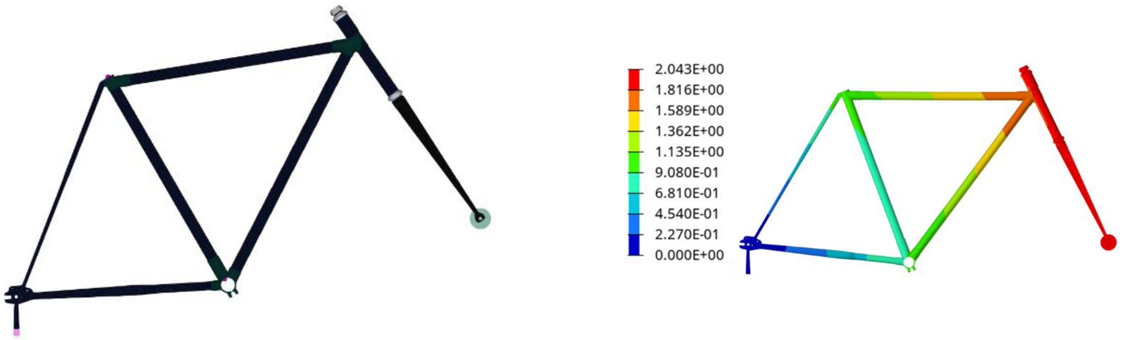
The drop-weight impact simulation showed that the fork and its adjacent connection regions underwent local deformation under the standard drop-weight impact load, while the main frame structure remained intact. No element deletion, fracture or obvious nonphysical failure occurred. The deformation region was mainly concentrated near the load-input path, which is consistent with the mechanical characteristics of load transfer from the fork to the frame. This result indicates that the mesh quality, material definition and connection relationships in the fork and frame connection regions can support standard impact-load transfer. The simulation setup and deformation response in the drop-weight impact test are shown in Figure 5.



(a) (b)

Figure 5: Simulation setup and deformation response of the bicycle frame in the drop-weight impact test: (a) simulation setup; (b) deformation response.

The free-fall impact simulation showed that the frame and fork assembly also maintained good structural integrity during the overall falling impact process. Because this test included additional masses, gravity and rotational support conditions, it provided a supplementary evaluation of the model from the perspective of the overall structural response. No abnormal buckling, connection failure or numerical instability was observed during the simulation, indicating that the model had satisfactory stability in terms of structural connections, contact definitions and mesh quality. The simulation setup and deformation response in the free-fall impact test are shown in Figure 6.



(a) (b)

Figure 6: Simulation setup and deformation response of the bicycle frame/fork assembly in the free-fall impact test: (a) simulation setup; (b) deformation response.

5.3. Comparison with Standard Limits

According to the simulation results, the maximum permanent deformation at the monitoring point in the drop-weight impact test was 6.1 mm. According to the relevant assessment requirements in ISO 4210-6:2023, the model satisfies the requirement for the real fork condition when the permanent deformation does not exceed 30 mm. The simulation result obtained in this study was far below the standard limit, indicating that the model had reasonable structural stiffness and deformation response under local impact loading.

In the free-fall impact test of the frame/fork assembly, the maximum permanent deformation at the monitoring point was 2.0 mm, while the standard limit was 60 mm. This result was also significantly below the standard limit. Together, the two validation results indicate that the established bicycle finite element model satisfies the standard test requirements at the level of key load-bearing structures and can be used for more complex full-vehicle impact simulation analyses. The quantitative comparison between the simulated permanent deformation and the ISO 4210-6 limits is summarized in Table 2.

Table 2: Comparison between simulated permanent deformation and ISO 4210-6 limits.

Validation Test	Simulated Permanent Deformation(mm)	Standard Limit (mm)	Assessment
Drop-weight impact test	6.1	30	Passed
Free-fall impact test	2.0	60	Passed

6. Discussion

The primary feature of the present model is the standardization of both its geometric source and its validation path. Compared with bicycle models reconstructed from specific commercial bicycles, shared bicycles or accident samples, the key geometric parameters of the present model were derived from ISO 19206-4:2020. Parameters such as wheel diameter, wheelbase, handlebar height, saddle position and pedal reference points therefore have explicit standard sources. This modeling strategy can improve reproducibility in standardized vehicle-to-bicycle collision scenarios and facilitate unified registration with cyclist finite element models, active-safety targets and vehicle front-end simulation environments.

From the perspective of structural response, the present model uses a deformable finite element method to describe the main structural components, including the frame, fork and wheel assemblies. Compared with fully rigid or multi-body bicycle models, this approach can more reasonably represent bicycle structural deformation and load transfer during the early stage of impact. The revolute joint elements preserve the key rotational degrees of freedom of the wheels and crank, whereas the CNRB connections represent the integral load-bearing characteristics of welded frame regions. Thus, a balance was achieved between computational efficiency and the description of structural response.

However, several limitations remain. First, the validation was mainly focused on the frame and fork assembly, and independent mechanical tests were not conducted for local components such as the tires, spokes, handlebar, saddle and pedals. Second, the material parameters were assigned according to common bicycle structural materials, and further calibration using material tensile tests, component tests or physical impact tests would improve model accuracy. Third, the validation performed in this study was a component-level standard validation, and the full bicycle response has not yet been validated through a complete vehicle-to-bicycle impact test or real-world accident reconstruction. Therefore, future studies should further couple the bicycle model with cyclist injury bionic models, vehicle finite element models and real-world accident boundary conditions to supplement the evaluation of its applicability at the level of full-impact kinematics and injury prediction.

7. Conclusions

(1) A standardized two-dimensional parametric wireframe model of a bicycle was established according to the geometric and posture requirements for bicyclist targets specified in ISO 19206-4:2020. The bottom bracket center, wheel centers, frame nodes, handlebar, saddle and foot-edge pedaling points were used as key control points, ensuring that the bicycle geometric definition had an explicit standard source.

(2) Based on the two-dimensional parametric sketch, a three-dimensional CAD model was constructed in SolidWorks and a bicycle finite element model was developed in ANSA. The model was mainly discretized using shell elements, with a global mesh size of 8 mm and local refinement to 4 mm in key connection regions. Revolute joints and CNRB connections were used to represent rotational pairs and welded connections, respectively. The final model contained 78,249 elements.

(3) Drop-weight and free-fall impact simulations of the frame and fork assembly were conducted according to ISO 4210-6:2023. The maximum permanent deformation in the drop-weight impact test was 6.1 mm, which was below the standard limit of 30 mm. The maximum permanent deformation in the free-fall impact test was 2.0 mm, which was below the standard limit of 60 mm. Both validation results satisfied the standard requirements.

(4) The developed model has a standardized geometric source, reasonable connection definitions and satisfactory structural response. It can serve as a basic model for subsequent vehicle-to-bicycle impact simulation, cyclist injury analysis and active-safety test-scenario extension.

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