Influence of Bicycle Deformation and Type on Head Injury Values of a Cyclist in a Car-to-Bicycle Collision

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ABSTRACT: In this study, finite element models for two types of bicycles with different shapes were constructed. These deformable models were validated in quasi-static loading conditions, and were used to investigate the effect of the deformation of the bicycle body on the head injuries to its occupant. The analysis confirmed that, when deformable models are used, the kinematics of the cyclist after the contact with a vehicle changes, and the injury values are different, from those obtained by rigid models. In addition, different bicycle types produce different riding postures, which significantly change the rotational motion of the cyclist around the vertical axis, subsequently affecting head injuries.

KEY WORDS: Safety, Bicycle, Car-to-bicycle collision, Finite element method, Static load–displacement characteristics, Head injury [C1]

1. Introduction

The number of traffic accidents and casualties in Japan is decreasing every year, however, the accidents involving bicycles has constantly accounted for approximately 20% in all traffic accidents over the past 10 years (1). Over 80% of these bicycle accidents involve cars, and 43% of fatal accidents took place when the bicycle was crossing the road (2) (3). The most frequently injured body region in fatal accidents is the head, accounting for 62.7% (1). In addition, the number of bicycles in Japan has been increasing, not only for “city cycles” for daily use, but also for “X-bikes”, both in Japanese market, which have a different shape and riding posture (4). Different riding posture may influence the kinematics and injury of the bicycle occupant in impacts against cars.

Some of the previous studies (5)(6)(7)(8) have reconstructed car-to-bicycle collisions using finite element (FE) simulations. In these studies, it was found that in a car-to-bicycle collision, the kinematics and the impact angle and location against a car are different from those in a car-to-pedestrian impact, and that the kinematics and the impact location are sensitive to the front-end shape of the car. However, load-deflection characteristics of the bicycle models have not been validated and thus the influence of the bicycle deformation on cyclist kinematics and injury values has not been clarified. In addition, these studies used one single bicycle model for each, while different posture of the cyclist may influence the kinematics and injury values. Hence, this study aimed to develop FE models of two types of bicycles (city cycle and X-bike) validated in quasi-static loading conditions to clarify the influence of (1) bicycle deformation, and (2) bicycle shape and associated riding posture, on kinematics and injury values of the rider. Quasi-static loading tests were conducted on the bicycle parts that may deform in accidents to provide validation data. The tests were simulated using corresponding components of the FE bicycle models to compare load–deflection characteristics of the components. Car-to-bicycle collision simulations were performed with the validated deformable city cycle FE model and a rigid model to investigate the effect of bicycle deformation on kinematics and injury values of the cyclist. In addition, the effect of different shapes of the bicycle and riding postures on kinematics and injury values was examined using the deformable FE models of the city cycle and the X-bike.

2. Bicycle FE Models

2.1. Geometry

A review of the number of bicycles sold per year in Japan revealed that the city cycle and the sport cycle are the best and the second best seller categories. In the city cycle category, 75% were the bicycles with a double-loop type frame. In the sport cycle category, the most popular type of bicycle was a X-bike, accounting for 55%. One specific model was chosen to represent each of these two types (city cycle; Bridgestone SCRIDGE W type with 26-inch wheels, X-bike; Bridgestone CYLVA F24 with 27-inch wheels). Two bicycle FE models for these two models were developed as shown in Fig. 1 (81,139 nodes and 93,600 elements for the city cycle and 67,119 nodes and 80,633 elements for the X-bike). The dimensions and the mass of each component were measured from actual bicycles. Using a 3D scanner, the outer shape and dimensions were obtained, and each component was cut to measure the respective thickness. The shape of the components was represented only for those deemed to significantly influence car-bicycle interactions upon impact. For
example, the shape of the headlight and wires was not modeled and treated as a lumped mass in the model.

Fig. 1 Bicycle FE models

(a) City Cycle  (b) X-bike
Mass: 26 kg  Mass: 12 kg

2.2. Material property

In order to represent degrees of freedom of motion that may be used in an impact against a car, a rotational joint was set between the frame and the fork, the handlebar and the fork, front and rear ends of the frame and the hubs, the frame and the bottom bracket, the foot pedal axle and the crank, and the frame and the seat post under the saddle. Past traffic accident reports confirm that in a traffic accident, the handlebar may rotate about the fork, and the seat post may rotate about the frame; therefore, the maximum static friction moment at each of these joints when these are assembled were measured with actual bicycles and applied as a constant moment. No resistant moment was applied to other joints to simulate significantly low friction. In addition, considering the possibility of the front wheel hub of the city cycle coming out of the fork end when a downward force is applied, the maximum load when the hub comes out was measured and applied to the model. Further, the measured average tensile strength of five spokes was applied to the models, and the stiffness of the spring located inside the saddle of the city cycle was determined experimentally and applied to the model.

The material properties of the two types of bicycle models were defined by referring to the specification table of the actual models and the properties of materials commonly used in bicycles as shown in Table 1. The rubber parts of the front and rear tires were defined as an elastic material; some other components that are deemed not to deform in an impact such as the brake lever and the pedal were defined as rigid bodies. The mass density presented in Table 1 indicates representative values and were adjusted within a range of ±10% to match the measured mass of each part.

Table 1 Material Property

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass density [kg/m³]</th>
<th>Young’s modulus [GPa]</th>
<th>Poisson’s ratio</th>
<th>Yield stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloy</td>
<td>2700</td>
<td>70</td>
<td>0.33</td>
<td>280</td>
</tr>
<tr>
<td>Steel</td>
<td>7806</td>
<td>206</td>
<td>0.3</td>
<td>540</td>
</tr>
<tr>
<td>SUS</td>
<td>7806</td>
<td>206</td>
<td>0.3</td>
<td>340</td>
</tr>
</tbody>
</table>

3. FE Model Validation

3.1. Experiments

Experiments with actual bicycles of the two models were conducted to determine the quasi-static load–deflection characteristics of each of the deformable components. Based on the deformation patterns of the bicycle components obtained from traffic accident reports, loading conditions were determined for the frame, fork and wheels. In the experiment, a unidirectional load was applied at a constant speed, and the load–deflection characteristics were measured. The maximum load values were estimated from the bicycle deformation in a traffic accident. The parts with a slight deformation in traffic accidents were clamped, and two thick steel rigs were also used to prevent rotation of the part about the clamp as shown in Fig. 2. The loading speed was set to 20 mm/min.

Fig. 2 Experiment Condition for Deformation Characteristics

(a) Frame (front part)  (b) Frame (rear part)
(c) Fork  (Front unidirectional loading)  (d) Fork  (Side unidirectional loading)
(e) Wheel (vertical loading)
3.2. Validation

To validate the bicycle models, the experiments were simulated using the bicycle FE models, and the load-deflection characteristics were compared. For simplicity, only the cross-sectional shape of the indenter was modeled, and other boundary conditions were simplified. The FE solver used was LS-DYNA ver. 971 from LSTC (Livermore Software Technology Corporation), and the pre/post processing were performed with LS-Prepost 3.2 from LSTC and HyperWorks 2017 from Altair. The results of the comparison between the experimental results and the simulation results shown in Fig. 3 and Fig. 4 indicate that the component models generally well represent the load-deflection characteristics of the actual components.

4. Car-to-bicycle Collision Simulation

4.1. Simulation Condition

Car-to-bicycle impact simulations were conducted to clarify the influence of (1) bicycle deformation, and (2) bicycle shape and associated riding posture, on kinematics and injury values of the cyclist. To clarify the influence of the bicycle deformation, two FE city cycle models were used – one with deformable elements, and another with such elements switched to rigid bodies. The influence of the bicycle shape and associated riding posture was investigated by running impact simulations using the deformable city cycle and X-bike models. The bicycle models and their conditions used for the two sets of simulations are...
summarized in Table 2. For both conditions, the bicycle and the cyclist models were set in such a way that the directions of the car and bicycle travel are perpendicular to each other to simulate a side collision. The collision car was a medium-sized sedan, with the major front-end dimensions described in Table 3. The car speed was set at 40 km/h, colliding against a stationary bicycle laterally. The cyclist was represented by a pedestrian human FE model developed in a past study (9), which has been validated against human biomechanical data for the pelvic and lower limb components and whole-body kinematics. The human model was scaled to the average stature of Japanese male and female adults, riding the bicycle models. The city cycle model was positioned so that the center of gravity of the head of the cyclist was aligned to the center of the collision car. In the case of the X-bike, the center of the bottom bracket at the bottom of the frame was set at the same position as that of the city cycle, to provide a similar interaction between the car and the bicycle as shown in Fig. 5.

The FE solver used was Pam-Crash, and the pre/post processing were performed with HyperWorks.

<table>
<thead>
<tr>
<th>Table 2 Bicycle Models and Conditions Used for Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bicycle Type</td>
</tr>
<tr>
<td>Case 1</td>
</tr>
<tr>
<td>Case 2</td>
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</tbody>
</table>

4.2. Injury Metrics

In this study, focus was given to injury to the head of the cyclist, which leads to the highest fatality rate in traffic accidents. The metrics used to evaluate head injury were head injury criterion (HIC15) (10) and convolution integral of impulse response for brain injury criterion (CIBIC) (11), to monitor injury levels due to both translational and rotational accelerations imposed on the head. The respective equations are described below in Equations (1) and (2). A previous study (11) has shown that CIBIC accurately estimates the maximum principal strain of the brain.

\[
HIC = \left(\frac{t_2 - t_1}{t_2 - t_1}\right)^{2.5} \left[\int_{t_1}^{t_2} a_1 dt\right]^{2.5}_{max}\]  

\[
CIBIC = \sqrt{\sum_{t=0}^{t_{max}} \int_{t}^{t_{max}} x(t - \tau) \alpha_2(\tau) d\tau} \]  

where \( x(t) = d_1 e^{-\alpha_1 t} - d_2 e^{-\alpha_2 t} \) \( \{d_1 \cos(\beta t) + d_2 \sin(\beta t)\} \)

<table>
<thead>
<tr>
<th>Table 3 Major Front-End Dimensions in the Collision Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
</tr>
<tr>
<td>Bonnet leading edge height</td>
</tr>
<tr>
<td>Bumper lead</td>
</tr>
<tr>
<td>Upper bumper reference height</td>
</tr>
<tr>
<td>Lower bumper reference height</td>
</tr>
</tbody>
</table>

Fig. 5 Initial condition of car to cyclist collisions

Fig. 6 Collision behavior of deformable model

(a) Deformable model

(b) Rigid model

Fig. 6 Collision behavior of deformable model
5. Influence of Bicycle Deformation (Case 1)

5.1. Kinematics of bicycle and cyclist
In the analysis, the contact time between the bicycle or cyclist and the car was defined as 0 ms. For both of the deformable and rigid bicycle models, the legs of the cyclist contact the car, the cyclist starts to rotate around the anterior-posterior axis, the legs rebound from the car, the upper body starts to wrap around the car, and the elbow of the cyclist contacts the rear end of the hood at 100 ms. Subsequently to the elbow contact against the hood, the side and the back of the head contact the windshield in the deformable and rigid bicycle models, respectively, as shown in Fig. 6.

The presence and absence of the bicycle deformation resulted in the difference of the kinematics of the cyclist after being thrown up onto the hood. In the deformable model, the bicycle frame deforms along the front-end shape of the car, producing a rotation of the cyclist about its superior-inferior axis. This motion can be seen in the kinematics of the cyclist after 90 ms, where the cyclist rotates to a prone position. This makes a difference of the position of the upper body at the elbow contact, along with the aspect of the head contact location against the windshield, compared to those from the rigid bicycle model.

5.2. Head Injury Values
HIC15 and CIBIC are approximately 10% larger in the deformable model relative to the rigid model as shown in Table 4. In the deformable model, the elbow of the cyclist contacts the hood almost perpendicularly, while the angle is significantly different for the rigid model, as illustrated in Fig. 7. With this difference in the contact angle of the upper arm, the angular acceleration of the head between 90 and 120 ms and the head linear acceleration between 120 and 150 ms in the deformable model increased compared to the rigid model, affecting the injury values as shown in Figs. 8, 9 and 10.

<table>
<thead>
<tr>
<th>Table 4 Head injury values</th>
<th>Deformable Model</th>
<th>Rigid Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIC15</td>
<td>72</td>
<td>65</td>
</tr>
<tr>
<td>CIBIC</td>
<td>0.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Fig. 8 Comparison of time history of CIBIC between deformable and rigid bicycle models

Fig. 9 Comparison of head linear acceleration time history between deformable and rigid bicycle models

Fig. 10 Comparison of head angular acceleration time histories between deformable and rigid bicycle models
6. Influence of Bicycle Type (Case 2)

6.1. Kinematics of bicycle and cyclist

In the analysis, the contact time between the cyclist or bicycle and collision car was defined as 0 ms, as in the previous chapter. The kinematics of the bicycle along with the contact location and angle of the upper arm and the head of the cyclist differed between the city cycle model and the X-bike model as shown in Fig. 6 (a) and Fig. 11. As the position of the handle relative to that of the saddle is lower for the X-bike than the city cycle, the upper body of the cyclist is more inclined forward for the X-bike as shown in Fig. 12. The stiffness of the bicycle is also different between these two types. Due to these differences, the rotation of the cyclist about the anterior-posterior axis becomes smaller for the X-bike, resulting in a smaller amount of rebound of the legs. In contrast, the rotation of the upper body of the cyclist about its superior-inferior axis is larger for the X-bike, resulting in a different contact angle between the upper arm and the hood. Subsequently, the aspect of the head contacting the windshield is also different between the city cycle and the X-bike.

6.2. Head Injury Values

HIC_{15} is larger with the X-bike, whereas CIBIC is larger with the city cycle, as shown in Table 5 and Fig. 14. This difference would be primarily due to the difference in the riding posture between the two bicycle types. In the case of the X-bike, the contact angle of the upper arm becomes smaller than that of the city cycle because of the posture of the upper body inclined forward as shown in Fig. 13. For this reason, the angular acceleration of the head due to contact of the elbow against the hood is smaller for the X-bike than that for the city cycle, for which the angle of the upper arm is larger. This explains why peak CIBIC value is smaller for the X-bike compared to the city cycle (Fig. 14). In contrast, as a larger upper arm angle would apply a larger force from the hood to the upper body of the cyclist, and consequently reduce the head impact velocity upon head impact against the windshield, the peak head linear acceleration upon head impact against the windshield is smaller for the city cycle compared to the X-bike (Fig. 15). It should be noted that in addition to the difference in the posture of the cyclist, the stiffness of the bicycle is also different between the two types of bicycle used in this study. This may have some influence on the difference in the head injury values as described above.

<table>
<thead>
<tr>
<th>Table 5 Injury values</th>
<th>City cycle</th>
<th>X-bike</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIC_{15}</td>
<td>72</td>
<td>228</td>
</tr>
<tr>
<td>CIBIC</td>
<td>0.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>
7. Conclusion

In this study, two bicycle FE models representing a city cycle and an X-bike available in the Japanese market were developed and validated against quasi-static loading tests for the components potentially subjected to deformation upon impact against a car. Using these models, the influence of bicycle deformation and type on head injury metrics were examined, and the following conclusions were drawn for the specific car-to-bicycle impact conditions used in this study:

(1) Representation of bicycle deformation changed the kinematics of the cyclist and the upper arm angle upon elbow impact against the hood, resulting in significantly different head injury values and aspect of impact location on the head.

(2) The difference in the riding posture of the cyclist along with the stiffness of the bicycle due to the difference in the bicycle type affect the kinematics of the cyclist, showing the difference in the head injury values.

(3) When evaluating injuries to a cyclist, it was found to be important to use a bicycle model validated for load-deflection characteristics of the components potentially subjected to deformation in car impacts. It was also found that the type of the bicycle is one of the key factors influencing the kinematics and the injury values via the change in the riding posture and the stiffness of the bicycle.

Reference

(8) Daisuke Ito et al: Finite element analysis of kinematic behavior of cyclist and performance of cyclist helmet for...

