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Investigation of motorcyclist and pillion passenger injuries using numerical simulations

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Abstract. Road traffic fatalities involving powered-two wheeler (PTW) are the highest portion in Thailand. Few studies are available concerning the head impact loading and head trauma in case of real PTW accidents. This work, therefore, aims to improve the understanding on kinematics and head trauma of PTWs rider and pillion passengers. By selecting a real-world PTW accident provided by the Central Institute of Forensics Science database, reconstruction of the accident was performed using multibody dynamics simulations. Parametric studies which focused on vehicle speed and position of rider and passenger at impact was conducted to obtain the best correlations. Then, head impact velocity, impact direction and head impact area have been extracted and implemented in the finite element head model to simulate the head trauma by impacting directly the head model on the vehicle structure. The motorcyclist's head and the pillion passenger's head impact conditions were retrieved and used as initial condition for the finite element head impact simulation. Head and brain injuries were analyzed.

1. Introduction

PTWs fatality rate in Thailand remains very high among the other type of vehicles. It has been reported that 73% of traffic deaths involved powered-two wheelers [1]. Head injury is the major cause of death [1]. The mechanisms and characteristics of injuries sustained by the PTW casualties are research interest to support improvement of countermeasures and protective system. Many studies have focused on a single rider [2] but in real accidents pillion passengers are also among the casualties. Limited studies are available concerning the head impact loading and head trauma for real PTW accidents. The objective of this study is to improve understanding of kinematics and head trauma of PTW rider and pillion passenger by using a combination of two computer simulation tools. Computer simulations of PTW-to-car collision provide an effective approach for studying injury mechanisms of motorcyclist and pillion passenger [2-4]. There are various literatures which have used multibody simulations to reconstruct the accidents [2-5] and study pedestrian kinematics [5]. Multibody dynamics simulation is not computer intensive and therefore a good tool for trend or parametric studies. However, the rigid body models cannot give details of the injuries suffered by human body. Finite element simulation can provide insight into the injuries of human body but it is time consuming. A combined approach of multibody dynamics and finite element simulations can be an effective way to study both rider and pillion kinematics as well as head injuries.

2. Methodology

Figure 1 illustrates the methodology used in this study. Combined approaches of multibody simulation and finite element simulation were employed to investigate the kinematics and head injury of both motorcyclist and pillion passenger involved in a real world PTW accident. A multi-body system generally consists of rigid and flexible bodies joined together by kinematic joints or force elements. It



is sufficiently flexible to construct a multi-body model of a human body or vehicle with various kinematic joints and discrete bodies of particular size and shape. In this study multibody simulation was used for accident reconstruction and parametric studies. Three parameters were specified including car speed, PTW speed and impact angle. With parametric studies, an optimal impact configuration for the selected PTW accident case was obtained. Head impact velocity was extracted and adopted as boundary condition for finite element human head impact simulation. The human head consist of a deformable skull and brain which can facilitate the analysis of head traumatic injury of the rider and pillion passenger.

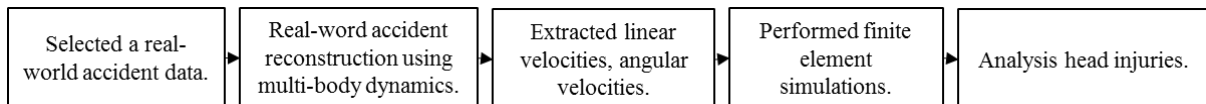


Figure 1. Research methodology diagram

3. A real-world accident reconstruction and parametric studies

3.1. *The real-world accident data*

A real-world accident data provided by the Central Institute of Forensics Science database was selected for the reconstruction. The accident involved both rider and pillion passenger. The report [6] presents evidence where a passenger car model Toyota Corolla Altis collided with a PTW (Honda series Nova 125 RS Sonic). The final resting point of the PTW and the position of the passenger car are shown on the map in figure 2. The PTW did not decelerate before collision. There were two PTW victims. The motorcyclist was 31 years old, 1.85 m tall. The medical document reported that rider was seriously injured around the face, lacerated in the region of right ear lobe, mouth, neck, right abdomen, and left hand. In addition, his femurs were broken on both sides as well as a fracture of the right wrist. He died at the scene with his body tangled with the PTW. Adult pillion passenger had serious injuries and was taken to hospital. Figure 3 shows the impact location on the car. The left door deformed due to the PTW front wheel impact as illustrated in figure 3(a). The top corner of the windshield cracked due to the head impact as shown in figure 3(b). According to figure 3 (c), the PTW front wheel deformed significantly.

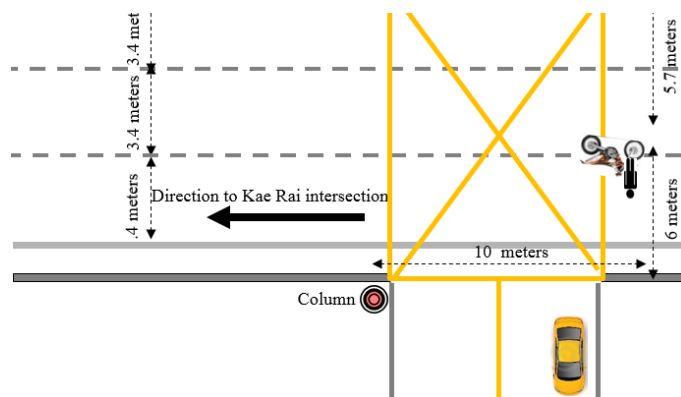


Figure 2. The map shows that the rest point of the PTW and the parking of the passenger car.



Figure 3. Illustrates (a) deformed door (b) windshield crack (c) deformed front wheel and handle bar

3.2. Multi-body model for PTW accident reconstruction

The accident scenario can be reconstructed in 3D space by establishing the model of the car, PTW and human bodies together with their movement and the load of the rider and passenger. MADYMO (mathematical dynamic model) is a multi-body dynamics software that was employed for the reconstruction. It can simulate the dynamics response and study the behaviour of interconnected rigid and flexible bodies. It is a common reconstruction tool found in literature [2-5]. The multi-body model of the car and PTW in accident cases were set up according to their real shape and mass in MADYMO. The rider and pillion passenger models were adopted from a previous investigation [4].

3.2.1. Rider and a pillion passenger multibody dynamics models

A Hybrid II 50th-percentile-male anthropomorphic test device (ATD) represented the motorcyclist consisting of 74 ellipsoids as show in figure 4. The rider was validated [4] and was modified for appropriate use in this study. The height was 1.85 m and the estimated weight was 70 kg. The adult pillion passenger was a Hybrid III 5th-percentile-female ATD that was made of 74 ellipsoids as shown in figure 4. The weight of 70 kg and height 1.76 m were estimated due to lack of information on the pillion passenger.

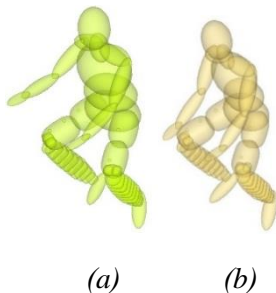


Figure 4. The multi- body system of the motorcyclist (a) and the adult pillion passenger (b).

3.2.2. Car and a PTW multibody model

The significate parameters for setting up the vehicle model are the external dimensions such as width, height, and length as shown in figure 5 and specified in table 1. A car model consisted of 39 ellipsoids. It was a simplified model of the whole car. The PTW was modified from a 1985 Kawasaki Ninja which was developed by [4]. The characteristics were obtained from literature [7]. The external appearance and specification of PTW model are shown in figure 5 and in table 1. PTW consist of 19 ellipsoids.

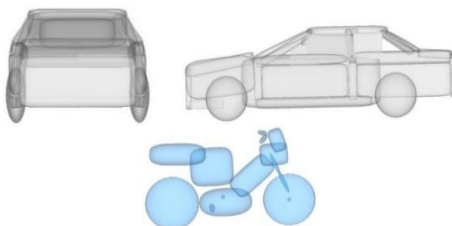


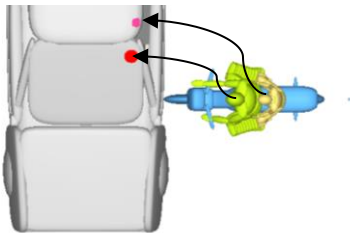
Figure 5. Multi-body dynamics of Toyota Corolla Altis (upper) and Honda Nova 125 RS Sonic (lower).

Table 1. Specifications of Toyota Corolla Altis and Honda Nova 125 RS Sonic.

| Titles | Details of Toyota Corolla Altis | Details of Honda Nova 125 RS Sonic |
|----------------|---------------------------------|------------------------------------|
| Overall length | 4,540 mm | 1,900 mm |
| Overall width | 1,760 mm | 660 mm |
| Overall height | 1,470 mm | 960 mm |
| Wheelbase | 2,600 mm | 1,250 mm |
| Weight | 1,310 kg | 100 kg |
| Front tire | 195/65R15 | 60/100-17M/C33P |
| Rear tire | 195/65R15 | 80/90-17M/C44P |

3.2.3. Impact simulation set-up

PTW model was directed towards the car model. Rider and passenger were positioned as shown in figure 6. The impact point of rider's head was at the corner of the windshield as evident from the accident scene. A red marker sensor was created at that point for head tracking. The impact point of passenger's head was at the car roof, marked with a pink sensor as in figure 6. The important parameters for simulating the accident are the speed, direction, impact area, impact angle between the passenger car and powered-two wheeler. Final position of the vehicle and the influence of deceleration of the vehicle are also considered. Based on the variation of these parameters, a number of simulations were performed to obtain the optimum configuration, which gave the best correlation with the accident scene.

**Figure 6.** PTW to car impact set up with rider and passenger on board.

3.2.4. The parametric studies

The parametric studies consisted of 1,500 different conditions. The 10 different speed of the passenger car were 3, 3.5, 4, 4.5, 5, 5.5, 5.55, 6, 6.5, and 7 m/s. PTW speed were 13, 13.5, 14, 14.5, 15, 15.2, 15.5, 16, 16.5, and 17 m/s. The 15 different impact angle between the passenger car and PTW were 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°, 100°, 110°, 120°, 130°, 140°, 150° and 160° respectively as shown in figure 7. MADYMO software version 7.5 was used.

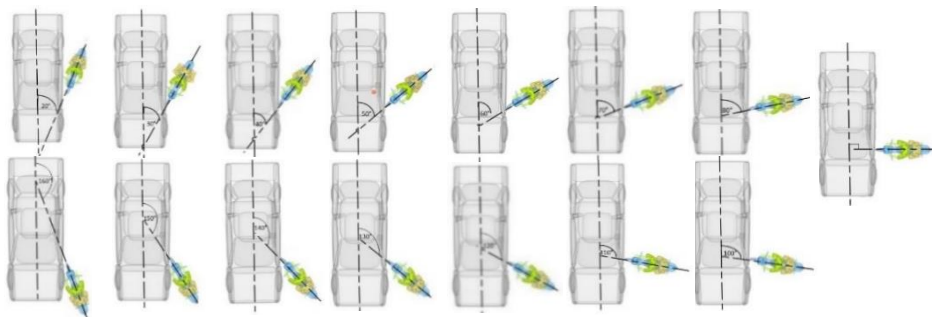
**Figure 7.** Impact angle between the passenger car and the PTW.

Table 2 illustrates example simulation results from parametric studies for car velocity of 5.5 km/h. For each simulation the head contact location of rider and passenger were identified. If both rider's and passenger's head hit the pre-defined targets i.e. marked in green in table 2, they were taken into

consideration for further kinematic comparison with the accident data. The optimum configuration was for the car speed of 5.5 m/s (20km/h), PTW speed of 15.28 m/s (55km/h) and impact angle of 90°. Figure 8 shows kinematics of rider and passenger during the impact in this optimum configuration.

Table 2. The parametric studies when the speed of the passenger car was 5.55(m/s), variety of impact angle and the speed of PTW.

| Pre-crash velocity of passenger car(m/s) | Impact angles (degree) | Pre-crash velocity of motorcycle(m/s) | | | | | | | | | | |
|--|------------------------|---------------------------------------|------|----|------|----|-------|------|----|------|----|---|
| | | 13 | 13.5 | 14 | 14.5 | 15 | 15.28 | 15.5 | 16 | 16.5 | 17 | |
| 5.55 | 20 | M | M | M | M | M | M | M | M | M | M | M |
| 5.55 | 30 | M | M | M | M | M | M | M | M | M | M | M |
| 5.55 | 40 | M | M | M | M | M | M | M | M | M | M | M |
| 5.55 | 50 | M | M | M | M | M | R | R | R | R | R | R |
| 5.55 | 60 | M | M | M | M | M | R | R | R | R | R | R |
| 5.55 | 70 | M | M | M | M | M | R | R | R | R | R | R |
| 5.55 | 80 | M | M | M | M | M | R | R | R | R | R | R |
| 5.55 | 90 | M | M | M | M | P | RP | RP | R | R | M | M |
| 5.55 | 100 | M | M | M | M | M | M | R | R | M | M | M |
| 5.55 | 110 | M | M | M | M | M | M | M | M | M | M | M |
| 5.55 | 120 | M | M | M | M | M | M | M | M | M | M | M |
| 5.55 | 130 | M | M | M | M | M | M | M | M | M | M | M |
| 5.55 | 140 | M | M | M | M | M | M | M | M | M | M | M |
| 5.55 | 150 | M | M | M | M | M | M | M | M | M | M | M |
| 5.55 | 160 | M | M | M | M | M | M | M | M | M | M | M |

- P** represents passenger's head contacts the pink mark.
R represents rider's head contacts the red mark.
RP both heads contact their sensors.
M both miss the points.

The first contact occurred at 0.03s between the front wheel of the PTW and the left front door of the passenger car. This is supported from the accident photo that shows damage to the front wheel and suspension of PTW (figure 3(c)). Also, the left door of the vehicle is damaged (as shown in figure 3 (b)). The second collision occurred at 0.05 s, with the rider's abdomen impacting against the right handle bar of the PTW. The right knee also hit the left door of the vehicle structure. The rider's chin contacted the windshield and the chest against A pillar at time 0.08 s. These matched with the crack mark on the windshield and the accident injury report. At 0.13s of simulation, the pillion passenger's head contacted the car roof structure. At 1.05s, the rider was in between the PTW and the car, which was also the final position in the picture reported from the accident scene.

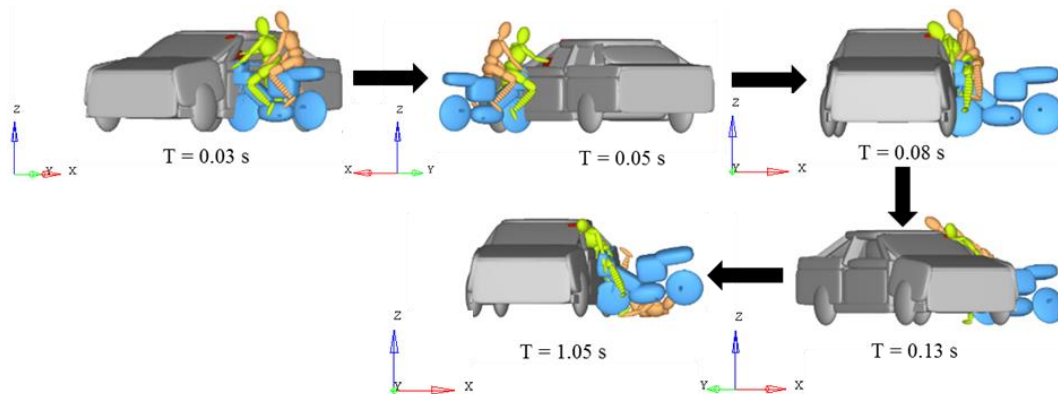


Figure 8. The diagram illustrates kinematics of the rider and the passenger during the crash.

For analysis on head injury, the linear velocities in x, y and z directions together with the angular velocities just before impact were extracted from the multibody dynamic simulation. They are summarised in table 3.

Table 3. The results of the velocity.

| | Motorcyclist | Pillion passenger |
|----------------------------|----------------|-------------------|
| Impact time | 0.071 s | 0.118 s |
| Linear velocity in x axis | -9.33288 m/s | -4.02261 m/s |
| Linear velocity in y axis | 5.52556 m/s | 5.93356 m/s |
| Linear velocity in z axis | -4.77071 m/s | -0.631232 m/s |
| Angular velocity in x axis | -13.0804 rad/s | -9.38231 rad/s |
| Angular velocity in y axis | -21.8953 rad/s | -7.74171 rad/s |
| Angular velocity in z axis | 3.81019 rad/s | 3.84717 rad/s |

4. Finite element model of human head for impact

A deformable finite element human head was taken from the Total Human Body Model for Safety developed validated by [8]. The head consists of skull and brain. The material model for skull was elastic-plastic with damage and for the brain was viscoelastic with material properties according to [9]. Each head was placed at the position just before the impact as shown in figure 9. Head velocities illustrated in table 3 was applied to both the rider and passenger head models.

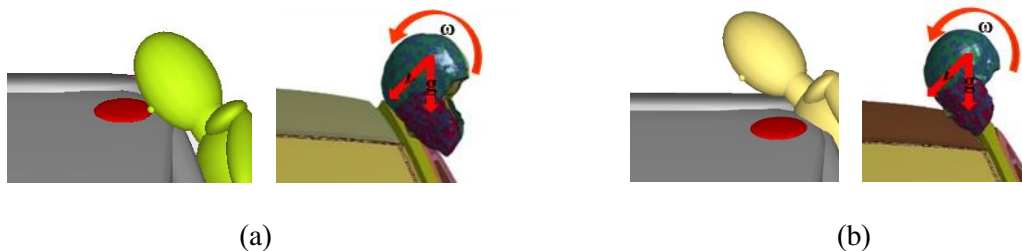


Figure 9. The illustrations of (a) set-up rider's head (b) set-up pillion passenger's head.

4.1 Head injury analysis

The Head Injury Criteria (HIC) value for the rider was 1980, higher than the acceptable threshold of 1000 for AIS 3+ injuries. This implied high risk of skull fracture. However, for the pillion passenger HIC was only 56.84, suggesting a low risk of skull fracture. Figure 10 (a, b) shows the skull stress of the rider. Maximum stress was 219 MPa at the left temporal. This is above the criteria of 80 MPa for skull fracture [5]. High stress also occurred around the chin area that matched with the injury report of the accident. Figure 10 (c) shows distribution of strain on the brain. Maximum strain of 1.09 occurred on the left white matter cerebrum. This value is much higher than the criteria of 0.2[10]. It implies contusion of the brain. Figure 11 shows the stress on the passenger's skull. The maximum stress occurred on the left mandible which did not exceed the fracture limit. The passenger was at low risk of skull fracture. The maximum brain strain was 0.3 which is just above the brain injury criteria. Moderate risk of brain injury is possible.

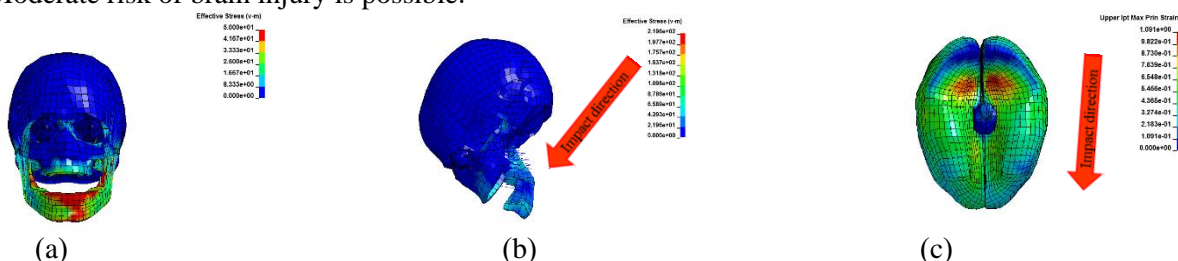


Figure 10. Distributions of (a, b) stress on skull and face (c) strain on the rider's brain.

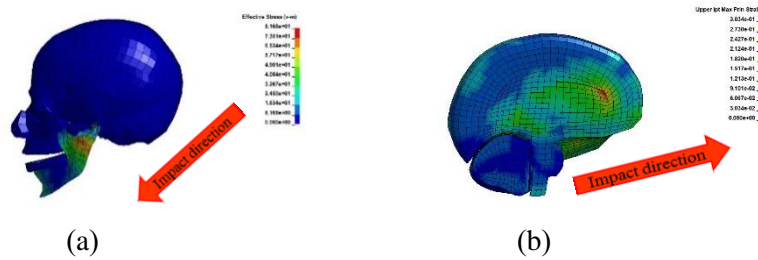


Figure 11. Distribution of (a) stress on the passenger's skull (b) strain on the passenger's brain.

5. Conclusion

A real-world road motorcycle accident was reconstructed using multibody simulation. Parametric studies were performed to obtain the impact configuration which correlated best. The optimal configuration was at the car impact speed of 5.5 m/s, PTW speed of 15.28 m/s and impact angle of 90°. The impact direction, head impact location and velocity were extracted and used as initial conditions for FE simulation. Finite element injury simulation revealed high risk of skull fracture and severe brain injury for the rider while low risk of skull fracture and moderate brain injury for the pillion passenger. The combination of multibody simulation and finite element simulation gives good understanding of kinematics and head injury experienced by the rider and pillion passenger.

Acknowledgments

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