

Friction in LS-DYNA[®]: Experimental Characterization and Modeling Application

Sheng Dong

The Ohio State University

Allen Sheldon

Honda R&D Americas, Inc.

Kishore Pydimarry

Honda R&D Americas, Inc.

Marcelo Dapino

The Ohio State University

Abstract

Friction is a widely observed phenomenon in all engineering systems. The importance of friction in computer-aided engineering has long been overlooked and modeling of friction phenomenon has been oversimplified. This paper reports experimental work conducted on a pin-on-disc tribometer to characterize the coefficients of friction between various material combinations, and modeling work of using such measured coefficients in different CAE models. Tested material combinations include coated steel on coated steel and rubber on coated steel. The coefficients were measured under different normal stresses and linear velocities, and employed to a three-point bending model and a pedestrian collision model in CAE tools such as LS-DYNA. It was found that friction plays an important role in deciding the magnitudes and timing of the acceleration or force when initial collision takes place. Higher friction results in higher magnitude of acceleration and force, but shorter sliding distance after the initial collision. Parametric study adopts different values for the coefficient of friction, and the results show that there exist boundaries, within which the role of friction is more evident. Below the lower boundary value, the effect of friction was dwarfed by other factors. Above the upper boundary value, the effect of friction saturates. This methodology of measuring and applying friction coefficients can be applied to various CAE models beyond pedestrian-vehicle collision to assist finding better correlation between simulations and testing data.

Introduction

Friction is the resistance to the motion between two contacting surfaces when they slide or roll relative to each other [1]. The modeling of friction in computer-aided engineering (CAE) can greatly influence the accuracy and quality of the entire model. However, friction simulation has not received sufficient attention. Often in CAE models, friction is represented by a single value of coefficient of friction (CoF) for all contacts, despite the material and geometry difference between different parts. This paper reports experimental work for determining the correct friction coefficients under different normal stresses and linear velocities for the materials combinations used in three-point bend model and pedestrian collision model. The former is a benchmark model in CAE for correlating testing and simulation. The latter is part of the crashworthiness simulations requested by Federal Motor Vehicle Safety Standards and Regulations [2]. The

methods of defining friction in LS-DYNA are investigated. The effect of friction in model simulation is then analyzed.

Friction

Friction exists in many engineering systems; it is a complex surface system phenomenon. Despite the effort in studies, the findings are mostly based on empirical laws [1, 3-4]. Firstly, the magnitude of the friction force is proportional to the normal load, and the direction is opposite to the relative motion. This law can be expressed by a classic model proposed by Coulomb [3], which is formulated as

$$f = -N\mu\text{sgn}(v_{rel}) \quad (1)$$

where f is the friction force, N is the normal force, μ is the coefficient of friction, v_{rel} is the relative velocity between the two contacting surface, as shown in Fig. 1. The coefficient of friction is therefore the ratio of friction force and normal force, which has been widely used as an indicator of friction magnitudes between different materials.

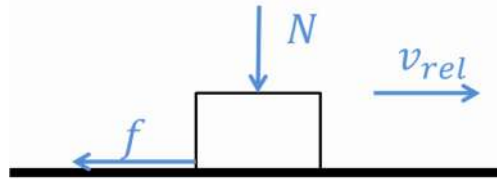


Figure 1 Schematics of the classic Coulomb model of friction

The relationship between friction and velocity has also been studied. However, there has not been a universal law that can be utilized to describe this relationship for all materials. It is generally accepted that friction is independent of the sliding velocity within a wide range once the sliding initiates, although at high speeds in orders of tens of meters per second, the coefficient of friction decreases as the velocity increases [4].

Another common observation is that the static friction is usually greater than dynamic friction. This often leads to a stick-slip phenomenon in engineering systems, which is a discontinuous sliding motion between two contacting surface caused by the variation of friction forces. Both the friction force and the stick-slip can be reduced by way of lubrication. Traditional lubrication can be employed by applying liquid or solid lubricants on to the surfaces. In addition, ultrasonic vibrations can also be used to reduce friction, wear, and stick-slip at interface [5-6].

Methods of defining friction in LS-DYNA

Most commonly-used definitions of friction in LS-DYNA are made via the *CONTACT card [7]. Friction can be defined for all the parts/part sets that use this *CONTACT. The relationship between coefficient of friction and relative sliding velocity is

$$\mu = F_D + (F_S - F_D)e^{-DC|v_{rel}|} \quad (2)$$

where F_D , F_S , DC , are mathematical parameters that modulate the coefficients of friction. The relationship between μ and v_{re} at different contact pressure with positive and negative DC

values are shown in Fig. 2. Parameter VC can be used to define the upper limit for the friction coefficient.

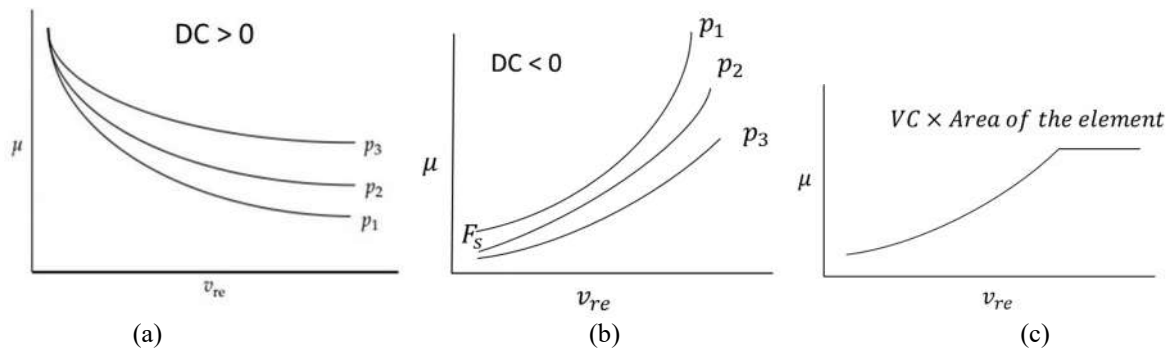


Figure 2 Curve of friction coefficient and relative velocity defined in LS-DYNA [7].

When F_S is set to -2 in *CONTACT card, another card *DEFINE_FRICTION is activated. By using *DEFINE_FRICTION, separately-defined friction curves can be assigned to desired parts or part sets without creating another *CONTACT. For the *RIGIDWALL elements, the friction coefficient is defined separately. Instead of defining a curve, this element only allows to define a constant value for friction coefficient.

Experimental measurement of friction

A tribometer is a device that is employed to measure friction and wear [1]. The experimental set-up in this study, shown in Fig. 3, adopts a pin-on-disc type tribometer, which is to measure friction between a stationary pin and a rotating plate. The plate for testing is clamped on a platform, which is held by a lathe chuck. The chuck is then driven by a motor underneath it with controllable speeds. The pin is held by an arm of a gymbal assembly. A load cell is installed onto the gymbal assembly, which measures the tangential force generated at the contact, i.e. friction force. The normal force at the contact can be applied on the interface by adding different weights to the hook that connects to the gymbal arm through two pulleys. The pin and the plate are made of different materials for different tests. For the tests between powder coated steel, the pin consists of a thread with an acorn nut connected to its end (Fig. 3). A rubber tip is used for rubber on steel tests, shown in Fig. 9.



Figure 3 Experimental set-up for friction measurements.

Table 1. Parameters used in friction measurements

Parameter	Value
Linear Speed (mm/s)	0 - 210
Normal load (N)	2, 5, 10
Nominal contact area (mm ²)	0.25
Nominal stress (MPa)	8, 20, 40
Nominal diameter of rotation (mm)	130
Sampling frequency (Hz)	400
Materials	Coated steel (class A and class C), rubber

All friction tests follow the procedures as below:

1. Place the pin on the disc surface, put on the weight for the normal loading and load cell balancing.
2. Start data acquisition.
3. Turn the control knob of the motor slowly until there is slip motion between the pin and disc.
4. Continue increasing the speed of the motor until it reaches the limit.
5. Turn off the motor and the data acquisition.

Application I: three-point bending model

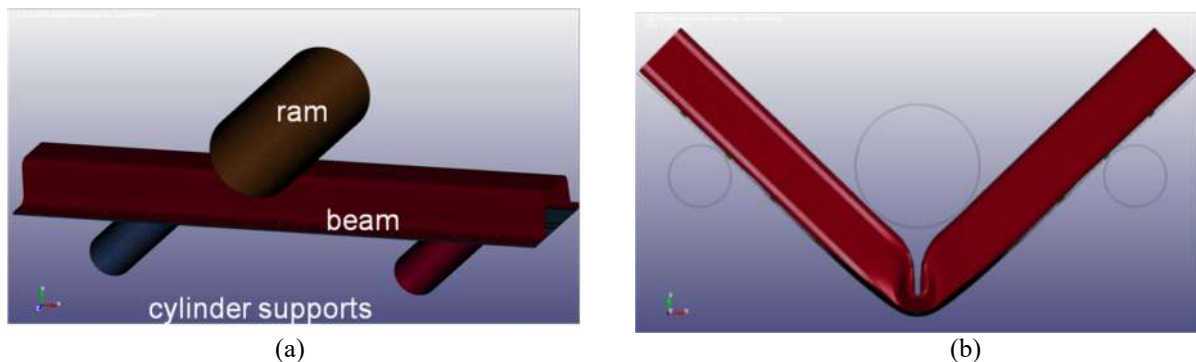


Figure 4 Illustration of the three-point bending model: (a) before collision; (b) during collision.

A three-point bend model was employed to investigate the influence of using different friction coefficients. As shown in Fig. 4, the ram is prescribed with a velocity of 2 m/s, crushing down onto a beam, which is supported by two fixed cylinders. The beam deforms into a “v” shape under the ram force, slides between the two cylindrical supports, and finally departs the cylinders.

Both the ram and the cylinders are made of powder coated steel (class C). There are two contacts need to be defined in this model. In prior efforts, the contact between the ram and the beam is defined as `*CONTACT_SINGLE_SURFACE` with the coefficient of friction equal to 0.15, and the supporting cylinders have been modeled as `*RIGIDWALL` with the coefficient of friction equal to 0.1.

Friction measured between coated steel and coated steel (class C)

Three groups of tests are conducted with normal forces being 2 N, 5 N, and 10 N. During each test, linear velocity increases from 0 to approximately 200 mm/s. The measurements are shown

in Fig. 5. Friction coefficient slightly increases at low velocities, but remains virtually constant as the velocity increases to a higher level. Average normalized friction coefficient is around 0.533.

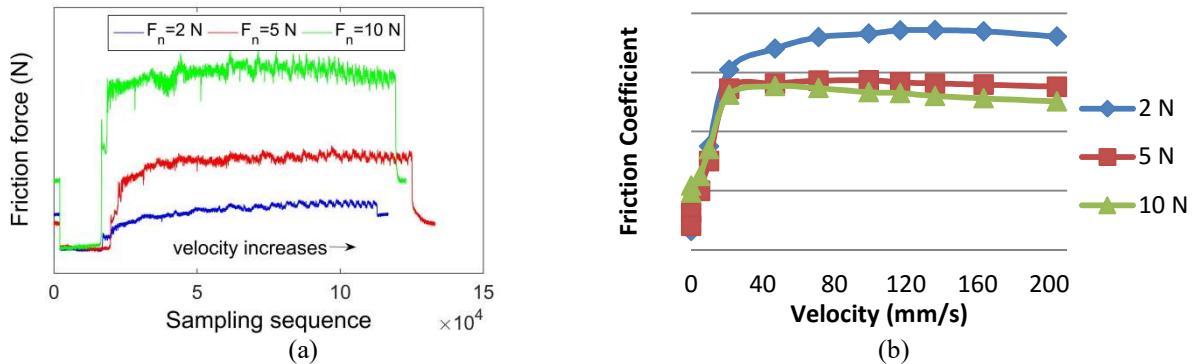


Figure 5 Measurements between coated steel and coated steel: (a) friction; (b) friction coefficients vs. velocity.

Simulations with different normalized coefficients of friction

Three simulations are conducted. In model 3, the normalized coefficients in prior simulations are repeated for comparison. In model 2, the normalized coefficient for both contact surfaces is changed to 0.667. In model 1, the normalized friction coefficients are 0.533, which is the measured value. Time-dependent forces at the ram are plotted in Fig. 6 for comparison.

Table 2. Friction definition in three-point bending models

Model	Normalized friction coefficient at contacts	Normalized friction coefficient at cylinder supports
1	0.533	Rigid body with COF=0.533
2	1	Rigid body with COF=1
3	1	Rigid wall with COF=0.667

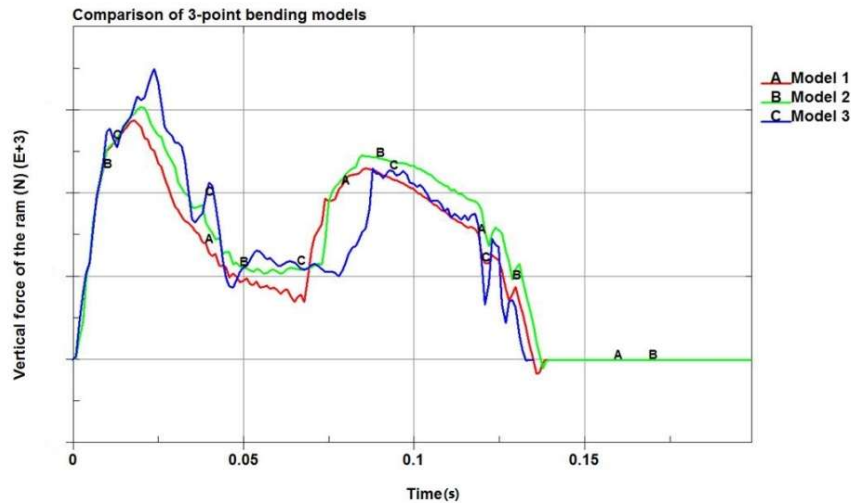


Figure 6 Comparison of the vertical forces at the ram between different models.

All three curves have similar shapes. The force generated by the ram increases rapidly to the first peak as the ram hits the beam and deforms the top of the beam. After that, the force decreases as

the beam starts to bend around the ram, therefore the ram force drops. As the bending continues, the ram pushes the deformed beam sliding down between the two supports (Fig. 5 (b)). The force increases again to overcome the friction generated between the beam bottom and the cylinder, in addition to the force needed to further bend the beam.

With smaller coefficients of friction, the first peak has smaller values. There exists a threshold for friction, below which the vertical force does not decrease when coefficient of friction decreases. The reason is that when friction is low enough, its influence on the vertical force is dwarfed by the deformation of the beam.

At the second peak, the beam finished deforming, and was dragged through the two supports. The friction between the beam and the supports becomes the major influence on the vertical force. Higher coefficient of friction results in higher vertical force.

Application II: pedestrian crash model

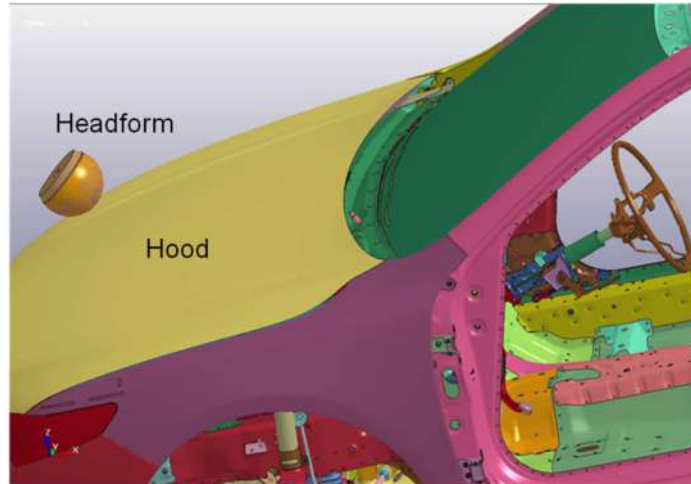


Figure 7 Illustration of pedestrian crash model.

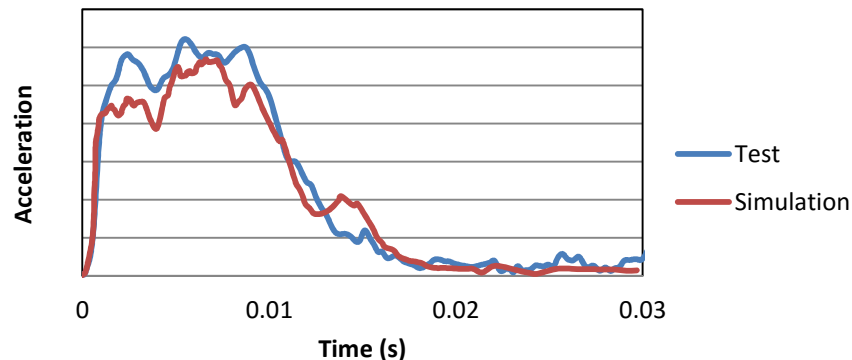


Figure 8 Comparison of acceleration and HIC values of the head piece.

Head injury criteria (*HIC*) is defined as

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \right\}_{max}$$

where t_1 and t_2 are the initial and final times of the interval during which *HIC* attains a maximum value, and a is the acceleration. The maximum time duration of *HIC*, $t_2 - t_1$, is limited to a specific value between 3 and 36 ms, in this case, 15 ms [2].

In pedestrian crash tests, a hollowed rubber sphere is often used for mimicking the head of the pedestrian. Figure 7 shows the CAE model for simulating the collision between the pedestrian headform and the vehicle hood. Measured acceleration of the head piece is shown as the blue curve in Fig. 8. The acceleration of the head piece increases rapidly as the collision takes place. The head piece slide along the length of the hood after the collision, as well as fluctuate vertically as the hood vibrating after the collision. The acceleration decreases to virtually zero rapidly as the sliding continues. The distance, velocity, and acceleration of the sliding between the head piece and hood are, to a large extent, depending on the interface friction force.

However, in simulation models, the normalized coefficient of friction between the rubber and coated steel adopted textbook values as 0.1. The simulation with 0.1 normalized friction coefficient is shown in the red curve in Fig. 8. It is evident that the curve is not able to match the peak value of the acceleration of the test data. A new, more accurate friction coefficient is required to fix this problem.

Friction measurements between rubber and coated steel (class C)



Figure 9 Experimental set-up for friction measurement between rubber and class C coated steel.

The pin-on-disc tribometer is modified to measure the actual coefficient of friction between rubber and coated steel. A round rubber piece is cut from the spherical-shaped rubber piece and placed in an aluminum piece (bottom right picture in Fig. 9). The aluminum piece is then connected to the gymbal arm so that the rubber tip is placed in contact with the steel plate installed on the platform. Different levels of normal loads are applied and the velocity is also in the range between 0 to 210 mm/s, as shown in Table 3.

Table 3. Experimental parameters

Parameter	Value
Material	Rubber, Class C coated steel
Linear Speed (mm/s)	0-210
Normal load (N)	2.3, 4.3, 7.3, 12.3
Nominal diameter of rotation (mm)	130
Sampling frequency (Hz)	400

Experimental data is shown in Fig. 10. Plot (a) shows the time-dependent friction records with four different levels of normal loads, while plot (b) shows the normalized coefficients of friction. The normalized coefficients remain virtually constant as the relative velocity increases, approximately 0.2, for all four normal loads.

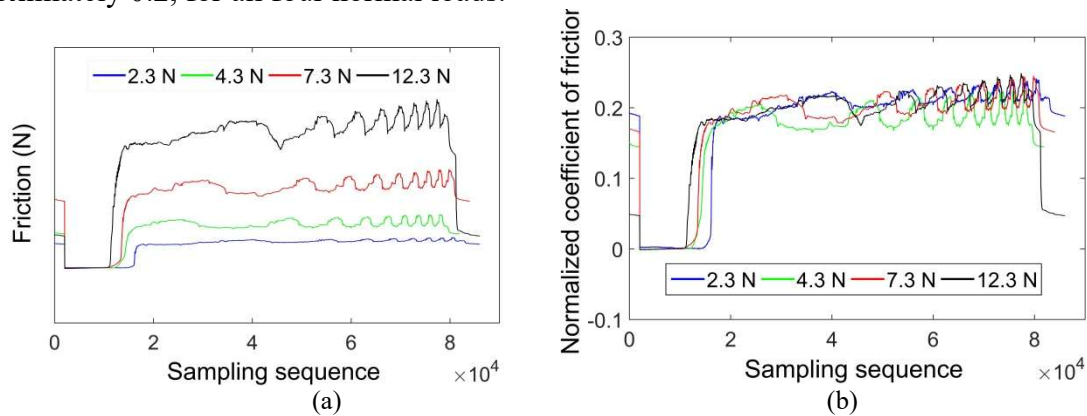


Figure 10 Measurements between rubber and class C coated steel: (a) friction; (b) normalized friction coefficient.

Friction measurements between rubber and coated steel (class A)

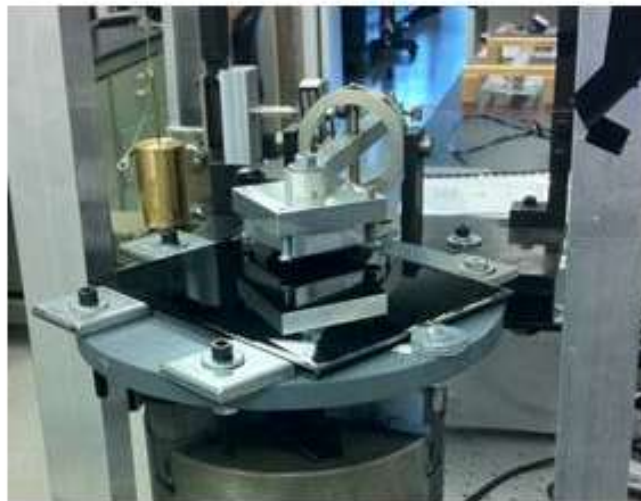


Figure 11 Experimental set-up for friction measurement between rubber and class A coated steel.

In vehicles, steel parts are usually treated with clear coating on top of the paint for corrosion protection and aesthetic purposes. This is often referred to as class A coating. Friction characteristics are therefore altered again due to the introduction of the new coating. Friction measurements were conducted between class A coated plate and rubber, as shown in Fig. 11. The set-up remains the same as in previous tests between rubber and class C steel plates (Fig. 9), except for the plates used. Class A coating provides the plate with an apparently reflective appearance. It is the clear coating that creates strong sticking force between the rubber piece and the steel plates, which results in much larger friction forces under the same normal loads.

Figure 12 shows the measurements of friction forces and the normalized friction coefficients. Normalized friction coefficient is approximately 0.8. It remains virtually constant as the linear velocity increases.

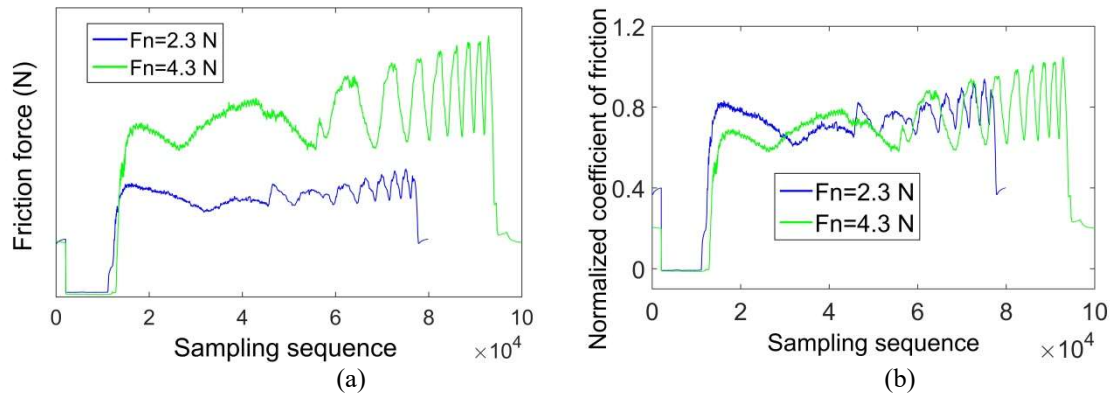


Figure 12 Measurements between rubber and class A coated steel: (a) friction; (b) normalized friction coefficient.

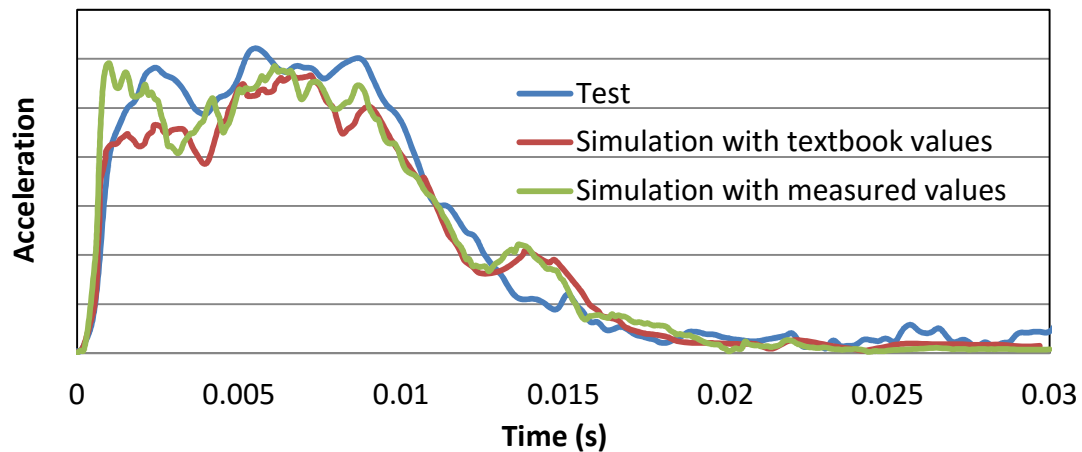


Figure 13 Comparison of acceleration and HIC values of the head piece.

A new simulation with the measured friction coefficient is conducted and compared with the test data and simulation with textbook friction coefficients, shown in Fig. 13. Simulation with measured friction coefficient is able to match the magnitude of the acceleration peak, and improve the HIC value.

Parametric study of friction coefficient in pedestrian crash model

A parametric study is conducted to demonstrate the effect of different friction coefficients. The normalized coefficient of friction was chosen to be 0, 0.02, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1, 2, respectively for each case. The curves of the vertical acceleration over time are derived from the simulations, and plotted in Fig. 14. The plot shows that the change of friction has significant influence in the first peak value of the acceleration curve, which takes place within 0.002 s in the process. It is evident that the peak values starts low when friction coefficient is 0, increases gradually when coefficient increases, and finally jump to a higher level and reach steady state as the friction coefficient continues to increase. Two distinct groups can be observed in Fig. 14.

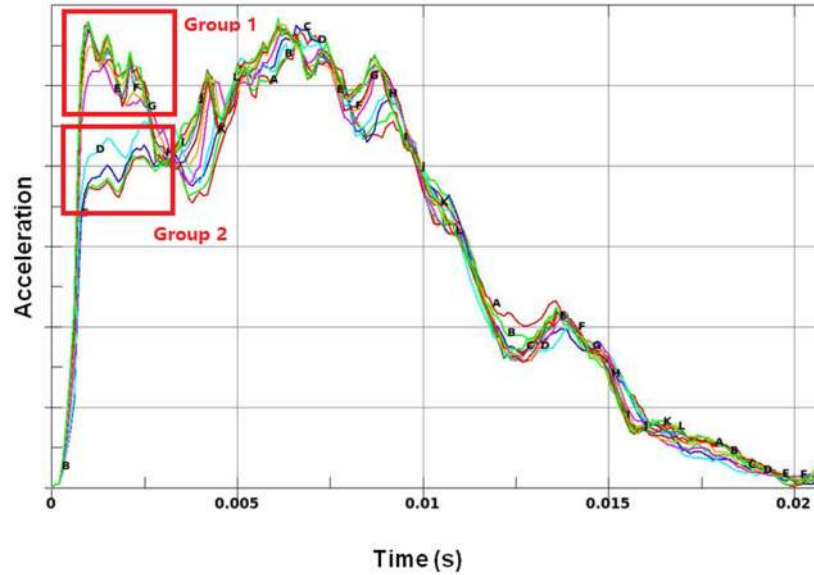


Figure 14 Time-dependent acceleration curves of the headform with different coefficients of friction.

Two indices are employed to evaluate the influence of the coefficient of friction on crash model accuracy: the peak value of the acceleration and the HIC value. The relationship between the peak value of acceleration and coefficient of friction is plotted in Fig. 15 (a). The peak value reaches its steady state when normalized coefficient of friction is higher than 0.4.

The relationship between HIC value and normalized coefficient of friction is shown in Fig. 14 (b). The value increases when friction coefficient increases. However, the values reach steady-states when the normalized coefficient is higher than 0.4. Although the HIC value has been improved by using the correct coefficient of friction, there still exists discrepancy between the simulation and test data. This discrepancy requires modification of the model beyond the scope of friction coefficient.

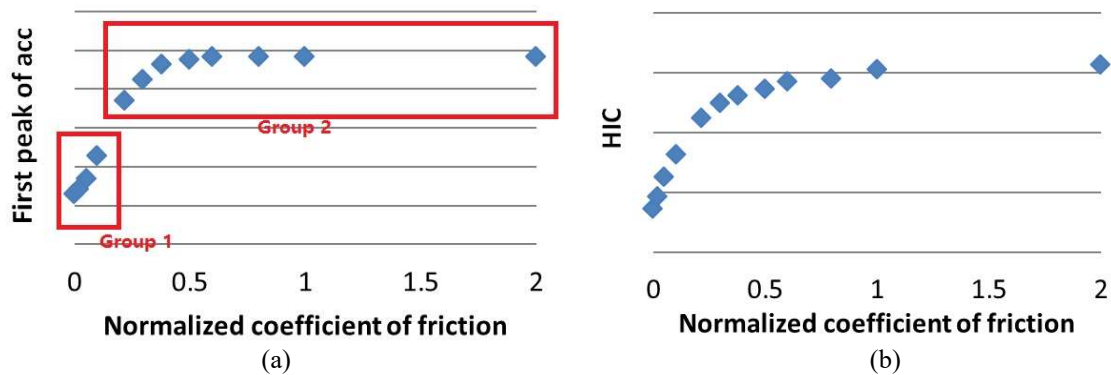


Figure 15 Relationship between normalized coefficient of friction and (a) peak value; (b) HIC value.

In addition to the sliding motion between the head form and the hood, there also exists significant rotation to the head form as it slides along the hood. This is also caused by the friction force between the bottom of the head form and the hood, as shown in Fig. 16. Friction force plays an important role in deciding the magnitudes of the rotation and sliding. Therefore, the

rotational acceleration of the head form and the distance that the head form slides are plotted against the normalized coefficient of friction in Fig. 17.

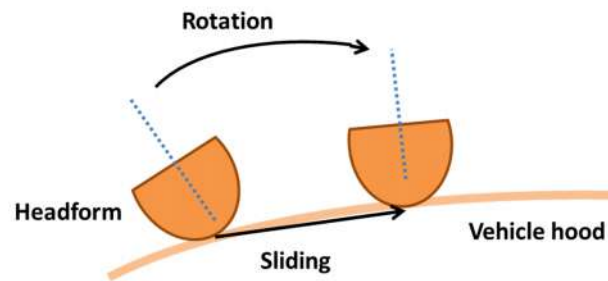


Figure 16 Schematics of the collision interaction between the head form and hood.

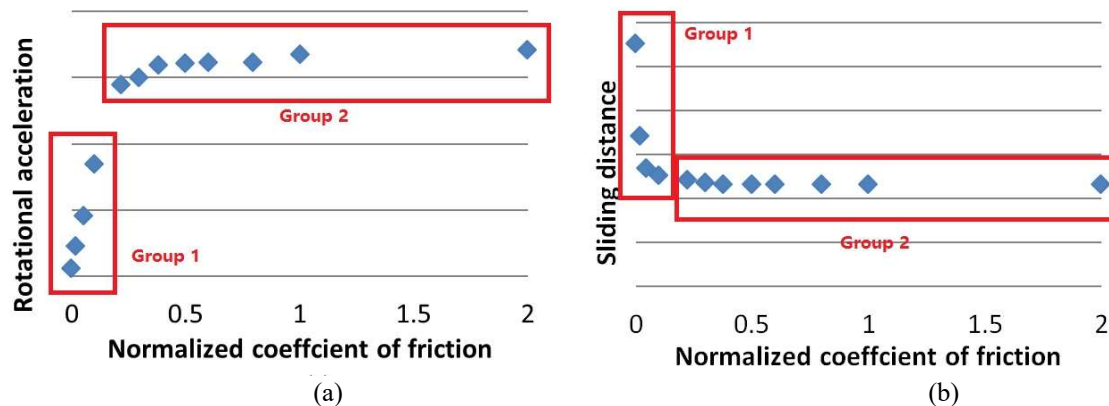


Figure 17 Relationship between normalized friction coefficient and (a) peak of rotational acceleration; (b) sliding distance of the head form.

Conclusions

A pin-on-disc tribometer is employed to measure friction between materials that are used in the three-point bend model and pedestrian collision model, which are adopted to investigate the influence of friction on simulation accuracy. Material combinations include powder-coated steel on powder-coated steel, rubber on class-C coated steel, and rubber on class-A coated steel. Measurements show friction coefficients different from textbook values, which has been widely used in simulations in industry. In pedestrian collision model, the measured friction coefficient is ten times greater than the textbook values. Coefficient of friction remains virtually constant in the range of velocities tested. The simulation results vary when measured friction coefficients are adopted, in pedestrian collision model, the match between test and simulation has been significantly improved by using the measured friction coefficients.

References

1. Bhushan, B., "Introduction to tribology," John Wiley & Sons, New York, 2002.
2. Guidelines for Rating Injury Measures, 2009, IIHS.
3. Rabinowicz, E., "Friction and wear of materials," John Wiley & Sons, New York, 1965.
4. Hutchings, I., "Tribology: friction and wear of engineering materials,"
5. Dong, S. and Dapino, M.J., "Elastic-plastic cube model for ultrasonic friction reduction via Poisson effect," *Ultrasonics*, 54, 343-350, 2014.
6. Dong, S. and Dapino, M.J., "Wear reduction through piezoelectrically-assisted ultrasonic lubrication," *Smart Materials and Structures*, 23, 104005, 2014.
7. LS-DYNA Keyword User's Manual: Volume I, 2015.