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Characterization of far-side occupant chest injuries in oblique side impact considering uncertainty

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Purpose: Oblique side impact is a common form of impact in life, and the far-side occupant's chest is highly susceptible to injury in the impact process. This study analyzed the effects of different factors on the chest response of far-side occupants in oblique side impacts. *Methods*: In this study, a simplified sled model was developed. After that, five factors, namely, impact velocity, impact angle, seat friction coefficient, seatbelt friction coefficient, and seatbelt force-limiting were considered as uncertain variables and randomly sampled. Sixteen sets of impact simulations with different parameters were performed using the sampled results to evaluate the farside occupant chest response. *Results*: Results showed that the impact velocity was positively correlated with the chest deflection and chest acceleration, with correlation coefficients 0.77 and 0.92, respectively, and the impact angle was negatively correlated with the chest deflection and chest acceleration, with correlation coefficients –0.83 and –0.54, respectively. The seatbelt friction coefficient and force limiting value were positively and negatively correlated with the occupant's chest response, respectively. *Conclusions*: The results suggested that multiple variables collectively influenced occupant injury and random combinations of different variables may play a critical role in impact outcomes. This study provides a reference for the study of occupant injury in far-side impacts.

Key words: *far-side occupant, uncertainty, correlation, chest injuries, oblique side impact*

1. Introduction

According to statistics, 1.19 million people die in road traffic accidents around the world in 2021 [29]. Among all types of traffic accidents, side impact is one of the most common types of vehicle impact on the road, and vehicle side impact accidents account for about 30% [21]. For side impacts can be categorized into two types of collisions: near-side impacts and far-side impacts. Most of the vehicle's occupant restraint systems are aimed at the near-side occupant, however, the fact is that the probability of serious injury to the far-side occupant in a side impact is as high as 35% [20]. In far-side impacts, the chest is one of the body parts most likely to be severely injured [9], [17]. The chest is compressed under the impact, and the sternum and ribs are prone to fracture, producing severe injury to internal tissues and organs [19]. Therefore, the chest injury of the far-side occupant in oblique side impacts must be studied to improve vehicle safety.

In reality, oblique side impacts are more likely to occur than pure side impacts [15]. The angle of impact is an important factor affecting far-side occupant injuries, which vary at different impact directions [3], [32]. It has been shown that far-side occupants receive greater injuries in oblique side impacts. Forman et al. [8] conducted far-side and oblique side impact sled tests using PMHSs and investigated the effects of various factors such as D-ring location, arm location, pelvic restraint, pre-tensioning, impact severity, and

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other factors on the far-side occupant. Their results showed that the far-side occupant deflection was more severe in the oblique side impact than in the side impact. In addition, the angle of impact affects the action of the restraint system. Zhou et al. [34] analyzed oblique side impacts between 10 and 50° and showed that seatbelts alter occupant kinematic changes, and the effect of seatbelt action was affected by the angle of impact. In contrast to studies of pure side impacts, there is a need to explore the effects of oblique side impacts on far-side occupant injuries.

As research continues, it is recognized that the uncertainty inherent in the model can also have a significant affect on the behavior of the system, and issues related to the quantification of uncertainty and its impact on the reliability of computational models are becoming increasingly important [26]. Virtual impact tests using finite element models are becoming increasingly important in the study of automobile safety. Stochastic simulations with finite element models can well reproduce the real stochastic response of vehicle crashes [10]. Some current studies, which use random variables for the parameters of the occupant restraint system, have investigated their effects on occupant injuries during frontal impacts [12], [14], [22]. Few studies of far-side impacts have considered uncertainty factors, and research on the use of uncertainty methods for far-side occupant chest injuries is insufficient.

This study aimed to investigate the effect of far-side occupant chest injury in oblique side impact. The THOR dummy is applied to establish a sled model. Various random combinations of working conditions were established to analyze the injury characteristics of far-side occupant chest injury under random working conditions. The factors that mainly affect the far-side occupant chest injury were also determined.

2. Materials and methods

2.1. Impact model

In this study, a model was developed, which contained three parts: the THOR 50th male dummy [23], [25], the sled, and the loading curve (Fig. 1). Sled also known as automobile impact simulator was used to simulate a real impact situation. The sled included the seat, back support, D-ring and three-point seatbelt parts, where the D-ring was a guide member for changing the direction of the seatbelt webbing. The armrest was ignored due to the existence of some models with lower armrests, which would have less impact on the occupants in a far-side oblique side impact. To simplify the calculation, the effect of the deformation of the sled on the calculation of the resulting acceleration was ignored. All the studies were calculated by LS-DYNA R11.

The loading curve used in the study was obtained from Yang's research [31]. They conducted the Advanced European Mobile Progressive Deformable Barrier (AE-MDB) side-impact test according to European New Car Assessment Programme (Euro-NCAP) and obtained the acceleration waveforms generated by this test. Other impact velocitites were obtained by scaling

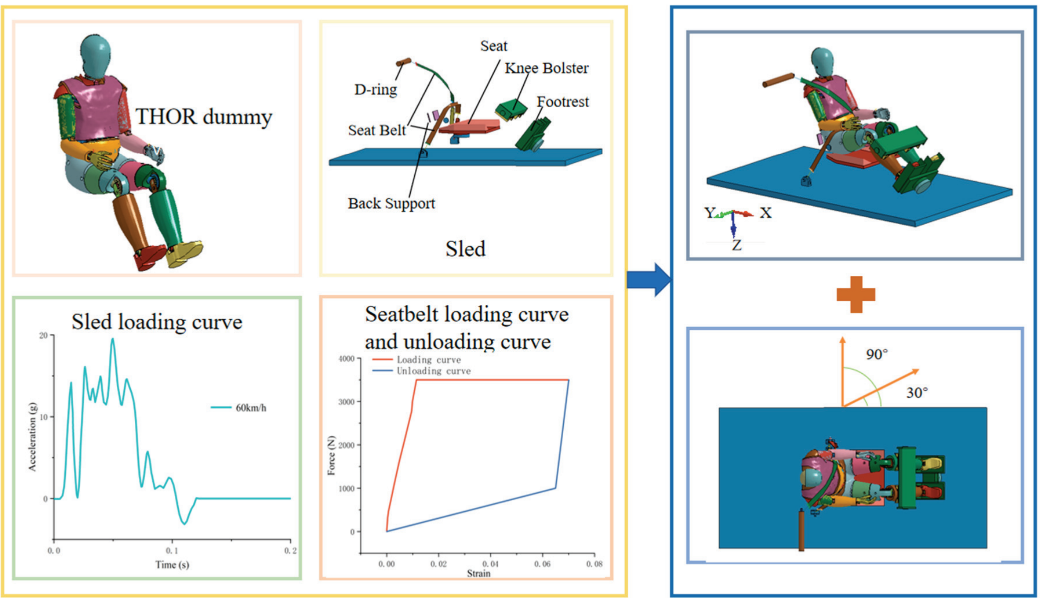

Fig. 1. Study model and simulation conditions

the loading curve. The direction of rotation of the dummy in the farside impact was labeled in Fig. 1, indicating the impact angle for the study. Its direction was opposite to the direction of the loading curve.

On the basis of the results of Acosta et al. [2], the location of the THOR dummy in the sled was determined, and it was placed on the seat by gravity. Contact between the occupant and the restraint system is also an important factor in occupant injury. Therefore, automatic surface-to-surface contact was established between the THOR dummy and the back support, knee bolster, and seat. The coefficient of friction between them was set to 0.3. The response of the THOR dummy as a far-side occupant in side and oblique side impacts has been demonstrated. Researchers compared the THOR dummy with the PMHS in side and oblique side far-side impacts, and the results showed that the THOR dummy has good kinematic response and good biofidelity in far-side impacts [18], [27], [33]. Therefore, the THOR dummy can be used for the study of far-side oblique side impacts.

Seatbelt is an important restraint system. In this study, a three-point seatbelt consisting of 1D element and 2D element was built by HyperMesh. The two ends of the seatbelt were 1D elements, and the element type was beam. The middle part of the seatbelt was 2D element, which was in contact with the dummy. The friction coefficient between the seatbelt and the dummy was set to 0.4, and the width of the belt was set to 50 mm. The seatbelt in this study had the function of force limitation, and the size of the force limitation was controlled through the setting of loading and unloading curves in the material of the seatbelt. The value of force limitation was set to 3.5 kN in this study.

2.2. Uncertainty analysis process

This study introduced a framework for assessing far-side impact occupant injuries based on uncertainty analysis to provide a realistic response to far-side impact occupant injuries (Fig. 2):

(1) the random variable to be analyzed was first identified, and the distribution of the random variable was obtained by quantifying the random influences through statistical methods;
(2) latin hypercube sampling was applied to the obtained distribution to determine independent samples of the random variables;
(3) the random variable samples obtained from each sampling were used as material boundaries and load boundaries of the far-side model, and stochastic finite element calculations were performed by repeatedly modifying the model parameters;
(4) the calculation results were extracted at the end of the calculation and analyzed accordingly;
(5) the stochastic chest injury results were obtained by statistical methods;

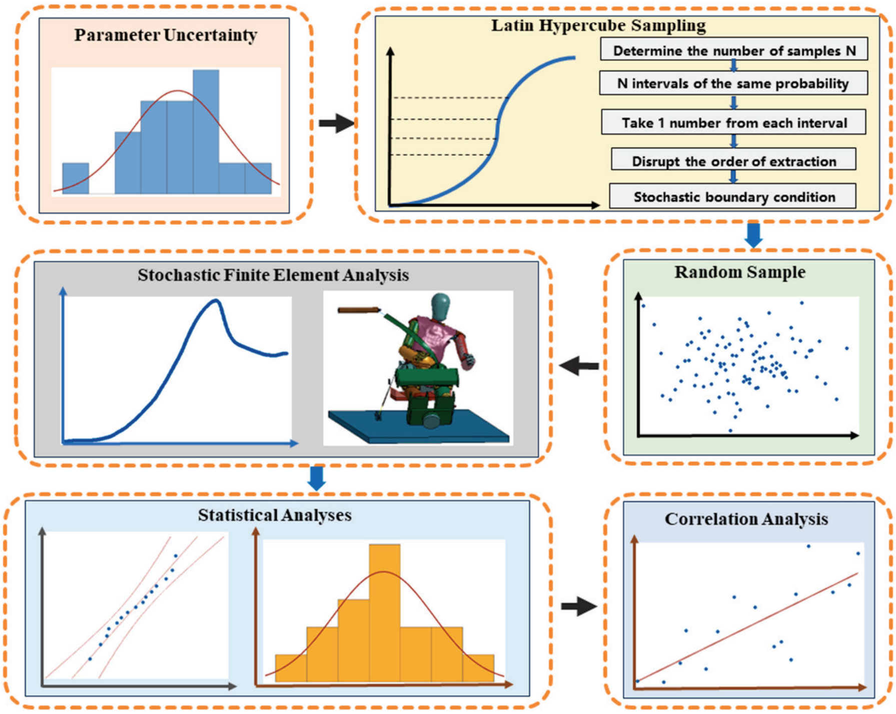

Fig. 2. Flowchart for analyzing far-side occupant injury considering uncertainty

(6) finally, correlation analysis was performed to investigate the effect of uncertainty in each input parameter on the model output.

2.3. Impact condition setting

During an impact of a vehicle, the impact load of the vehicle was uncertain. In addition, given the errors in the manufacturing process and the characteristics of the material itself, the restraint system parameters were uncertain. For the impact load and restraint system parameters, five parameters, namely, impact velocity, impact angle, seat friction coefficient, seatbelt friction coefficient and seatbelt force-limiting value, were selected as random variables in this study (Table 1).

Impact load is the main factor affecting occupant's injury. To obtain a wide range of impact load combinations, a uniform distribution was used for impact velocity and impact angle in this study. The probability of occupant with Maximum Abbreviated Injury Scale 3+ (MAIS3+) for impact velocities below 20 km/h for far-side impacts was less than 5%, and the impact velocity of far-side impacts in life hardly ever exceeds 80 km/h [6], [21]. Thus, the range of the impact velocity setting was selected as 20–80 km/h. In this study, the pure side impact was 90°. The study have shown that many of the far-side impacts occur with an impact direction of 45° [13]. Therefore, the range of impact angles was set to 30–90° in order to study more working conditions. The direction of occupant rotation for the range of impact angle settings is shown in Fig. 1. The restraint system can effectively reduce the injury caused by the occupants in an impact. Seat friction coefficients, seatbelt friction coefficients, and seatbelt limiting forces were normal distribution, with their mean values set as the initial values of the impact model, and coefficients of variation of 0.1, 0.1 and 0.05, respectively [5], [14]. A random combinations of these 5 sets of parameters were obtained by Latin hypercube sampling through the lhsdesign and lhsnorm functions in MATLAB, sampling the random variables 15 times.

Table 1. Summary of information on random parameters

Parameter	Unit	Distribution	Distribution parameters
Impact velocity	km/h	uniform	min = 20, max = 80
Impact angle	°	uniform	min = 30, max = 90
Seat coefficient of friction	–	normal	mean = 0.3, coefficient = 0.1
Seatbelt coefficient of friction	–	normal	mean = 0.4, coefficient = 0.1
Seatbelt force limit	kN	normal	mean = 3.5, coefficient = 0.05

Table 2. Random parameters obtained from sampling

Test	Impact velocity [km/h]	Impact angle [°]	Seat coefficient of friction [–]	Seatbelt coefficient of friction [–]	Seatbelt force limit [kN]
Initial value (T1)	60	90	0.300	0.400	3.50
T2	75	48	0.340	0.400	3.53
T3	51	52	0.288	0.489	3.71
T4	45	43	0.327	0.414	3.43
T5	31	71	0.311	0.365	3.36
T6	41	64	0.306	0.339	3.76
T7	56	77	0.258	0.391	3.32
T8	57	85	0.219	0.450	3.41
T9	38	88	0.301	0.418	3.58
T10	33	41	0.277	0.427	3.47
T11	77	38	0.285	0.386	3.69
T12	20	67	0.320	0.405	3.64
T13	64	33	0.294	0.342	3.49
T14	71	56	0.369	0.375	3.28
T15	61	59	0.268	0.375	3.55
T16	27	81	0.313	0.435	3.22

A total of 16 tests were conducted, with T1 being the most initial setup scenario and the rest of the scenarios being those that used random variables for testing and making the remaining scenarios T2–T16 (Table 2).

3. Results

3.1. Chest deflection

Occupant's chest injuries are often considered using chest deflection. In this study, four locations of the dummy chest were selected: Upper Left (UL), Upper Right (UR), Lower Left (LL), and Lower Right (LR) [16], [30]. The UL and UR were located on the third "rib" of the dummy, about 40 mm from the centerline of the chest. The LL and LR were located on the sixth "rib" of the dummy, about 80 mm from the centerline of the chest. The direction of chest deflection inward was positive.

Chest deflection was extracted for all four locations tested (Fig. 3). Chest deflection in the UL, UR, LL, and LR locations in the initial protocol was 7.58, 10.46, 14.14 and 12.86 mm, respectively. The dummy's chest was more compressed at this point than at the lower locations. A comparison of all test scenarios revealed that the chest deflection of the dummy at LL in T13 was the largest at 51.72 mm. In the other tests, the chest deflection of the dummy in T11 was similarly large, with a chest deflection of 49.42 mm at LL, which was only 2.30 mm less than the chest compression of the dummy at LL in T13. Although the chest deflection of the dummy in T11 was smaller than the highest value of the dummy in T13, the chest deflection of the dummy in T11 was more than 20 mm in all four locations. The chest deflection of the dummy in the UR and LR locations was more than 35 mm, which was due to the large impact velocity and small impact angle in T11, resulting in a large deflection of the dummy during the impact.

In T16, the chest deflection of the dummy was small at 1.21, 2.45, 6.88 and 1.30 mm at the UL, UR, LL and LR locations, respectively. The minimum chest deflection occurred in T12, with 1.20 mm at the LR location, and the rest of the chest deflection was less than 8 mm. In T12, the chest deflection of the dummy was also low at 11.14 mm in the LL location and less than 5 mm in the remaining three locations. The maximum chest deflection in T5 was slightly greater than that in T12, primarily due to the higher impact velocity in T5 and the lower seatbelt friction coefficients and seatbelt force limits.

A comparison of the different measurement locations revealed that the chest deflection at LL was consistently the largest, whereas the chest deflection at LR was the smallest in most of the tests, which was mainly due to the characteristics of the three-point seatbelt. Given that the chest deflection at LL was the largest, these random responses were selected for mathematical statistical analysis (Fig. 4). The results showed that the chest deflection at LL sample points fell within the 95% confidence interval and the *p*-value of the normality test was 0.52, which was greater than 0.05. This indicated that the chest deflection approximately conformed to a normal distribution with a mean value of 26.11 and a standard deviation of 14.25. These results demonstrated a similar random distribution of a far-side impact occupant's chest deflection.

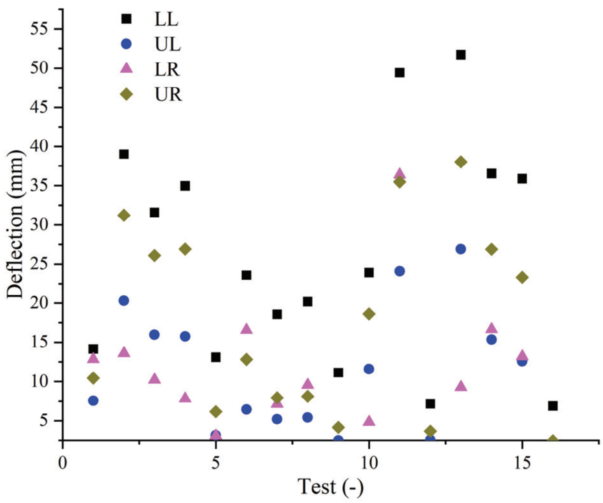

Fig. 3. Comparison of chest deflection in four locations

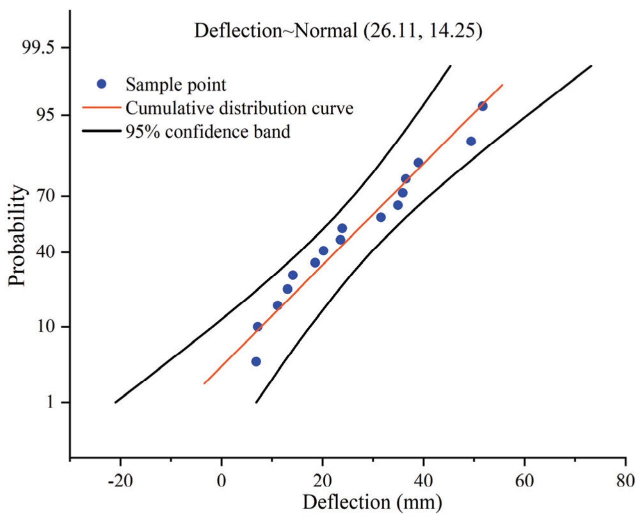

Fig. 4. Histogram of the distribution of chest deflection

3.2. Chest acceleration

Chest acceleration is an important factor in evaluating the occupant's chest response. The acceleration of the first thoracic vertebra of the dummy was extracted (Fig. 5a). Initially, given the impact angle of 90°, the dummy was gradually released from the restraint of the seatbelt after the beginning of the impact, at which time the chest acceleration gradually increased. Until 71 ms, the chest acceleration of the dummy reached the first peak at 10.73 g. The head deflection of the dummy was slower than the chest deflection, which resulted in the effect of the dummy's head on the dummy's chest deflection. As the upper limbs of the dummy continued to deflect because of inertia, the chest acceleration increased again, reaching a second peak of 12.64 g at 85 ms. Thereafter, the chest acceleration of the dummy decreased because of the restraint system. At approximately 110 ms, the arm of the dummy was subjected to the seatbelt, which caused the chest deflection velocity to increase, reaching a maximum chest acceleration of 13.33 g at 114 ms, after which, the chest acceleration of the dummy decreased with fluctuations. At about 140 ms, the lateral rotation of the dummy reached its maximum, while the dummy head was still rotating. Driven by the dummy head, the dummy chest started to rotate in the reverse direction. Thus, the chest acceleration fluctuated.

The maximum values of chest acceleration of the dummy in each test were extracted (Fig. 5b). The maximum chest acceleration occurred in T14, which was 20.59 g. However, the chest deflection at LL in this test was only 36.53 mm. The impact velocity and impact angle of this test were large, the seat friction coefficient was relatively high, and its seatbelt force limiting value was low, so the dummy had a large lateral deflection but a low forward deflection and was subjected to a small force by the seatbelt. The next result was at 20.31 g in T13. This test had an impact velocity of 64 km/h. Although the impact velocity was slightly lower than that of T14, its lower seatbelt friction coefficient resulted in similar chest accelerations for both. For T2 and T11, the chest acceleration of the dummy was also high due to the high impact velocity of these two tests, which both exceeded 70 km/h. However, given the low angle of impact and the reasonable parameters of the restraint system, the chest acceleration was not the highest in these two tests. Of all the impact tests, T16 had the lowest chest acceleration of 5.02 g, followed by T9 with a chest acceleration of 5.56 g. T9 had greater impact velocity compared to T16, but it was affected by the force-limiting effect of the seatbelt, resulting in lower chest acceleration.

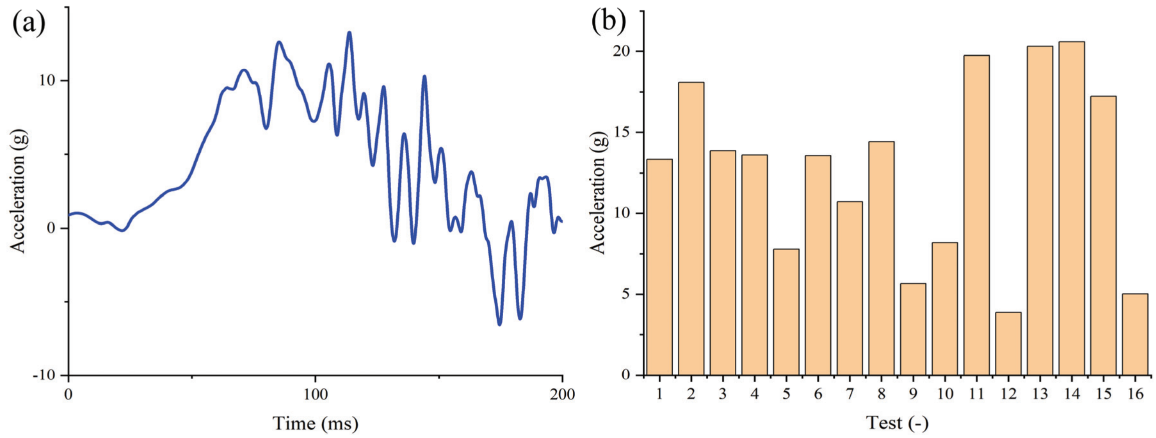

Fig. 5. Initial program chest acceleration curve (a) and maximum chest acceleration for each test (b)

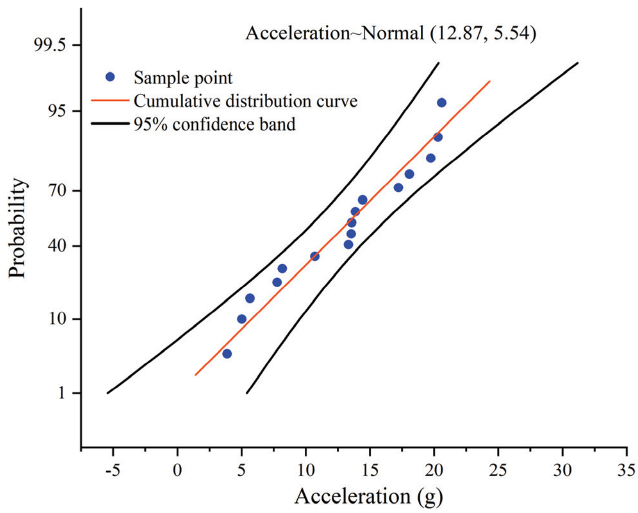

Fig. 6. Histogram of the distribution of chest acceleration

The maximum acceleration of the chest of the dummy was selected for mathematical and statistical analyses (Fig. 6). The results showed that the chest acceleration sample points fell within the 95% confidence interval and the p-value of the normality test was 0.41, which was greater than 0.05. This indicated that the chest acceleration approximately conformed to a normal distribution with a mean value of 12.87 and a standard deviation of 5.54. These results demonstrated that the far-side impact occupant's chest acceleration was randomly distributed.

3.3. Correlation analysis

To analyze the effect of each random variable on the far-side occupant's chest injury, the correlation analysis was performed. The formula for the correlation analysis was as follows:

$$r = \frac{\Sigma_{i=1}^{n}(m_i - \overline{m})(n_i - \overline{n})}{\sqrt{\Sigma_{i=1}^{n}(m_i - \overline{m})^2 \cdot \Sigma_{i=1}^{n}(n_i - \overline{n})^2}}, \qquad (1)$$

where r denotes the correlation coefficient, m denotes the independent variable, $\overline{m}$ denotes the mean value of m, and n denotes the dependent variable, $\overline{n}$ denotes the mean value of n.

The correlation coefficients r of each random variable for the far-side occupant chest deflection and chest acceleration were obtained by substituting the results of the calculations in this study into Eq. (1) (Table 3). The results showed a positive correlation between impact velocity, seat friction coefficient, and seatbelt force limitation and chest response but a negative correlation between impact angle and seatbelt friction coefficient and chest response. In the calculations, the lowest correlation was found between the seat friction coefficient and the chest response, with r of 0.08 and 0.06 with chest deflection and chest acceleration, respectively. The highest correlation was found between the impact velocity and the chest response, with r of 0.77 and 0.92 with chest deflection and chest acceleration, respectively.

4. Discussion

From the impact results, high chest acceleration was accompanied with high chest deflection in most of the tests, indicating that the random variables in this study had the same tendency to affect both chest responses. Impact velocities were greater in both the higher chest acceleration and chest deflection conditions, suggesting that impact velocity was a key factor in occupant response. However, in T13, the impact velocity was 13 km/h lower than in T11, but the impact angle was 33° and the seatbelt friction coefficient was 0.342, resulting in greater chest deflection and chest acceleration than in T11. This result demonstrated that a variety of variables collectively affect occupant injuries, and random combinations between different variables may have a large impact on impact outcomes, which was consistent with the conclusions of Seraneeprakarn et al. [24]. This suggests that the coupling effects of collision environments need to be considered during the design of the restraint system, and that different impact environments may cause the restraint system to act differently.

According to the results of the correlation coefficient calculation, the degree of correlation between the impact velocity and the far-side occupant's chest response was the strongest among these random variables and was positively correlated, indicating that the greater the impact velocity, the greater the occupant's chest response. According to the calculation results, the impact velocity was the most important factor affecting occupant injury, which was consistent with the conclusions of other study [1]. Thus, future research should consider a greater range of impact velocities, as well as determine the effect of the impact velocity and restraint system on occupant injury.

The results of the study found that with similar impact velocities, oblique side impacts may result in more severe injuries to occupants. Currently, there were many studies that illustrated this conclusion [8], [11]. Therefore, more attention needed to be paid to the effects of oblique side imapcts on occupant injuries. A comparison of all tests revealed that chest deflection at LL and UR was in most cases greater than chest deflection at

Table 3. Correlation coefficients between random variables and chest response

	Impact velocity [km/h]	Impact angle [°]	Seat coefficient of friction [–]	Seatbelt coefficient of friction [–]	Seatbelt force limit [kN]
Chest deflection	0.77	–0.83	0.08	–0.29	0.24
Chest acceleration	0.92	–0.54	0.06	–0.32	0.13

LR and UL. The reason for this was that the LL and UR positions were closer to the shoulder belt. Seatbelt restraint was also a significant contributor to chest injuries in oblique side impacts [7].

The impact angle showed a strong negative correlation with the far-side occupant's chest response. When the impact angle is small (i.e., in a side oblique impact), the occupant is restrained by the seatbelt when leaning to the side, resulting in the chest being squeezed by the seatbelt, which produces a high chest deflection. Simultaneously, when the occupant is in contact with the seatbelt, there is a sudden change in the deflection velocity of the occupant, which causes the chest acceleration to increase. When the angle of impact is large, the far-side occupant can easily break free from the restraint of the seatbelt, which makes the occupant's range of motion increase greatly. In a real impact situation, it is easy to collide with the interior or other occupants and produce a secondary impact, which was proven by the findings of other researchers [4], [31]. In addition, the above results showed that the impact angle affected the effectiveness of seatbelts, which was consistent with some research findings [34].

The correlation between the seat friction coefficient and the far-side occupant's chest response in this study was very low, which indicated that the seat friction coefficient had a small effect on the far-side occupant's chest response. Seat friction coefficient also affects occupant motion, so the study of seat friction coefficient should not be neglected.

The seatbelt friction coefficient had a weak negative correlation with the occupant's chest response, mainly because the seatbelt restrained the occupant better when the seatbelt friction coefficient was greater. The force limit value of the seatbelt had a weak positive correlation with the response of the occupant's chest, because the seatbelt and the occupant's chest were in direct contact during the far-side impact in this study, and the binding force of the seatbelt directly affected the occupant's chest, which resulted in some injury to the occupant. However, in reality, in the impact condition, when a larger seatbelt force limit value is set, the seatbelt can reduce the deflection of the occupant, which reduces the injury caused by the contact between the occupant and the rest of the vehicle. A study have also shown that larger seatbelt force limits can reduce lethal injuries [28].

5. Conclusions

In this study, the effect of uncertainty on far-side occupant chest injuries in oblique side impacts was considered, and the following conclusions were obtained from the study:

(1) results showed that the impact velocity was positively correlated with the chest deflection and chest acceleration, with correlation coefficients 0.77 and 0.92, respectively, and the impact angle was negatively correlated with the chest deflection and chest acceleration, with correlation coefficients –0.83 and –0.54, respectively;

(2) in an oblique side impact, a three-point seatbelt cannot easily limit the deflection of the far-side occupant. Meanwhile, the seatbelt friction coefficient and force limiting value are positively and negatively correlated with the occupant's chest response, respectively. Therefore, reasonable setting of the seatbelt parameters can reduce occupant injury;

(3) the stochastic finite element method can obtain a wider variety of impact conditions, which realistically simulate the actual impact situation. Multiple variables jointly affect occupant injury, and random combinations between different variables may play a key role in the impact results.

This study featured two innovations. First, the far-side occupant injury evaluation process considering uncertainty was established to make the occupant injury evaluation more accurate. In addition, the effects of impact load uncertainty and restraint system parameter uncertainty on the far-side occupant chest injury were investigated to provide a reference for the formulation of the far-side occupant protection program.

Acknowledgement

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