Child Restraint System Modeling and the Preliminary Study on 3YO Child Occupant Injuries in Vehicle Side Impact

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Abstract: This research is aimed at the development of CRS (child restraint system) model applying the MADYMO and FE coupling method and validation the whole models by contrast to impact test. In MADYMO program it has simulated 3 YO child occupant dynamic behavior in the case of a vehicle side impact, considering door intrusion. This paper has studied the door intrusion of the different impact velocity influence against 3YO child occupants' injuries that seated in the CRS which is positioned on the outboard nearside to the impact place. In this paper, a study on the influence of the seating position on 3 YO child occupants' injury has been carried. The simulation results show that door intrusion has greatly influence on child occupants' head neck and thorax injuries. The risk of injuried is higher for the children who seated on the struck side than on the non-struck side.
Key words: 3YO child occupants, CRS, side impact, injuries, door intrusion, seating position

1. Introduction

Motor vehicle crashes continue to be a leading cause of serious injury for children over age 1 in the United States [1]. The FARS data shows that in U.S.A., 1317children between 0-12 have been killed in motor vehicle crashes in 1999 and 31.89 percent of them were involved in side impact crashes. Of these, children seated on the side nearest to the impact represent 55 percent of the fatalities(NHTSA,2002).Canadian statistics side impact accident data confirms that this is the most dangerous position in the vehicle. Moreover, the vehicle body intrusion is very important especially when the child restraint system is positioned on the outboard nearside to the impact place (Howard, Rothman, Moses Mckeag, and Pazmino-Canizares et al., 2003). About one third of the restrained child with AIS3+ injuries included in a European study were involved in side collisions [2].A Swedish study has shown that approximately 50% of the fatally injured children, up to 3 years of age, occurred in side impacts [3].In the USA, agran et al examined injury patterns in children aged 4 to 9 years who were restrained in motor vehicle crashes. Through a hospital-based monitoring system ,it was found that MAIS2+ are more frequent in near-side impact (41%) than in frontal (15%) and rear-end crashes (3%)[4].CDS data from 1993-2000 indicate that 16% of nonfatal pediatric crash injuries resulted from side impacts. Because occupants seated on the struck side of a vehicle in a side impact collision (i.e., near-side occupants) are at the highest risk of serious and fatal injuries because of direct loading by the struck door [5]. Therefore, corrcet using child restraint system was considered the most effective method for reducing child occupant trauma in traffic crashes.

2. Methods

ECE-R44 regulation stipulates 1～3 years old child should use forward facing child restraint system. This paper builds forward facing CRS model. Figure1 shows the full simulation model. The model was consisted of rear door, rear seat, seatbelts, CRS and Q3 dummy. Rear doors and the CRS were built by finite element coupling with multi-body method, to allow for a better representation of the contacts between child dummy, CRS and the structure of the vehicle and to make possible the simulation of vehicle body deformation. Because full finite element models are large in terms of CPU time consumption, the vehicle deformation was simulated using the MADYMO's prescribed structural motion feature. The CRS model is consisted of child safety seat and 5-point harness. The child restraint system is installed using the vehicle safety belts. Q3 dummy was positioned in the child restraint system by applying 5-point harness. The rear seat was based on a multi-body method.

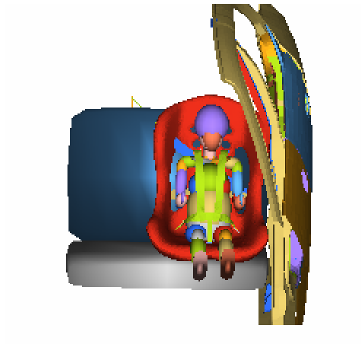

Figure 1 Simulation model

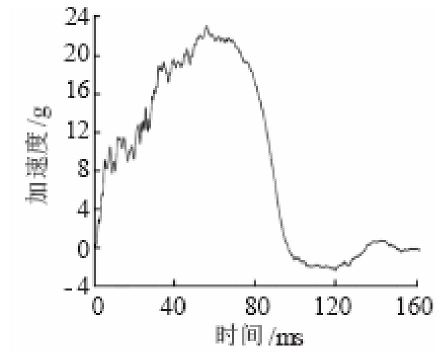

Figure 2 ECER44 crash pulse curve

2.1 CRS model

The CRS model includes child safety seat and 5-point harness. The prototype child safety seat is produced in china which has passed ECE-R44 regulation. The child safety seat is a convertible seat which can be installed in forward or rearward. The body of seat can slide along the arc tramroad on the seat base in order to adjust seat angle. The convertible seat accommodates children from birth to 4 years. The geometry of child safety seat was created based on reverse engineering methodology. The reverse engineering includes the following processes: First of all, apply three coordinate laser scanner scans the seat and obtaining the point clouds data. Second, transform the point clouds into polygon, establish NURBS faces and export iges file using geomagic studio software. Finally, import iges file into hypermesh, plot grid and create FE model.

The FE model includes 10378 nodes, 11175 quadrangle shell element. In order to simulate in madymo software, the nodes and elements information were imported into madymo software. The seat model of this paper only includes body of seat in order to reduce computational time. The 5-point harness was composed of FE belt segments and multi-body belt segments.

2.2 Q-series dummies model

In order to improve the child safety in European, a new dummy development program called Q-series dummies was launched a few years ago. To date, there are two main kinds of European Child dummies, P-dummies and Q-dummies.P-dummies were the first European child dummies and they became official in 1981. In 1993, the international Child Dummy Working Group (CDWG) was formed with the mission to develop the Q-series of child dummies as successor to the P-series. The new Q-dummies are supposed to have better biofidelity, durability and repeatability than the P-series. During the latter years, a series of Q-dummies were built, including the new-born (Q0), the 12 months (Q1), and the18months (Q1.5), three-year old (Q3) and six-year old (Q6). The 3-year-old version, Q3, has been developed as the first dummy of the Q-series. The new Q-series of child dummies is designed to be used in both front and side impact and is developed on the basis of a comprehensive set of biomechanical data [6].The 3-years old child dummy numerical model is available in MADYMO Data Base and has been validated by TNO for side impact. The model consists of 40 ellipsoid and 32 bodies. The inertia of each ellipsoid is obtained by measure corresponding physical dummy. Every ellipsoid is connected by kinematics joint.

2.2 PSM substructure model-door structural assembly model

As a result of full vehicle analysis complexity and lower efficient, moreover PSM (Prescribed Structure Motion) method modeling quickly, reducing CPU time consumption and computation result precise so this method applies broadly in vehicle side impact safety design assessment and optimization[7]. MADYMO PSM substructure method can use different model and modeling method according to different design stage. This paper mainly wants to obtains child dummy's injury in side impact by applying this method not for vehicle body parts optimization.Therefore, according to the aim of this paper research, Large Region sub-structure was chosen for it's higher computation efficiency and precise . The parts of outer vehicle were defined as initial boundaries. As initial border condition substructure model displacement-time history data was derived from LS-Dyna result. So the deformation mode and velocity of each node of sub-structure were consistent with FVA (full vehicle analysis) model. It more actually reflects the dummy's injury as result of door intrusion .PSM sub-structure model was exported from original full vehicle baseline model. All parts, element properties and material models were derived from the FVA model. Door structural assembly include the inner and outer door panel, the crash beam with front and rear crash beam brackets,hinge,latch, window frame, waistline reinforcements , B-pillar inner panel and middle reinforcement panel, the reinforcement parts below A-pillar et 19 parts. The validity of the PSM sub-structure had been validated in the literature [8].

3. Validation of CRS model

Validation is somehow still a vague concept since it depends of the final purpose of the model. Once the purpose of the simulation model is defined, the validation goals can be stated and the model results can then be assessed by comparison with those targets. In many cases, simulation tends to focus less on the performance of an individual vehicle or safety system and more on the characteristic of a vehicle class or type of restraint On the other hand, a ten percent variability in real-life test is also common and consequently admitted when comparing test and simulation results. For the purpose of this research, validation status will be defined as "the ability to replicate the general behavior of a child safety seat" [9]. In this research, validation of the complete CRS+bench+dummy multi-body model was conducted by assessing both the realistic behavior of components during the simulation (child safety seat, CRS harness, bench cushion, seatbelt, and dummy) and the relevant injury criteria measurements during a frontal simulation. In order to validate the CRS model validity, the sled test was performed according to ECER44 regulation requirement in Tsinghua University. The crash pulse curve is described in Figure 2. The parameters used for head and thorax injury risk of Q3 dummy sled tests are resultant head acceleration and chest acceleration. Figure 3 illustrates a good correlation of resultant head acceleration for simulation and sled test results. Morever, the simulation peak is near sled test peak. Figure 4 shows that correlation between the resultant chest acceleration for simulation and sled tests is good.

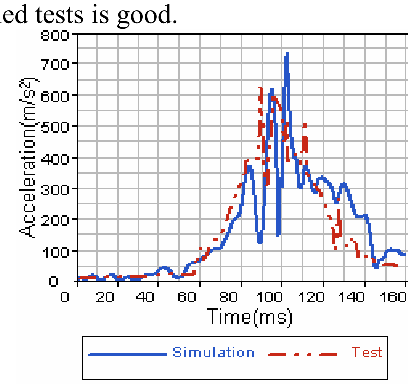

Figure 3 Head resultant acceleration

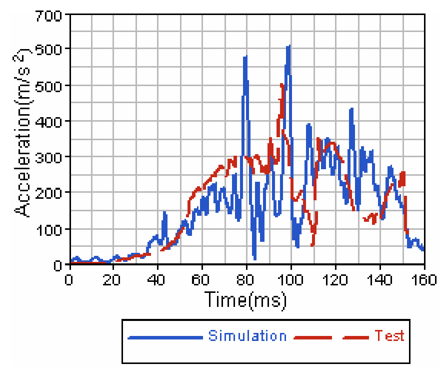

Figure 4 Chest resultant acceleration

4. Simulations

4.1 Child injury Criteria

（1）Head injury criteria

Although great progress achieved in Crash Safety, there is still argument about how to measure head injury. The most widely used one is Head Injury Criteria (HIC), proposed by Versace (1971) and was adopted thirty years ago calculating the injury by measuring the head acceleration (Eppinger et al, 1999).HIC is computed using the following equation:

$$HIC_{t2-t1} = \max\left[\frac{1}{t_1 - t_2}\int_{t1}^{t2} a(t)dt\right]^{2.5}(t_1 - t_2) \qquad (1)$$

Where， t1 and t2 are two arbitrary times during the acceleration pulse, a(t) is the centre accelerof gravity resultant acceleration.

In the beginning, NHTSA proposed the time interval limit to be 36 milliseconds and the maximum HIC36value for adult is 1000 and for 3YO child to be 700.NCAP and FMVSS 208 found out by using the 15 milliseconds time interval, the failure rate can reduce from 46% to 35%.For 50th percentile male, the threshold value of HIC15 is 700 and 570 for 3YO child. (Kleinberger et al., 1998).

(2)Injury criteria for neck

A common used neck injury criterion is Nij, proposed by the NHTSA (Klinch et al., 1996, Kleinberger et al., 1998).The criterion combines the axial force and the flexion/extension moment.

$$Nij = (\frac{Fz}{Fzc}) + (\frac{My}{Myc})$$

Nij represents a combination of the force in the z direction and flexion /extension moment while the measure point is at occipital condyles.For different age of child; different Nij intercept values are used.

The following Table1 gives the critical values for calculation Nij as included in FMVSS208 for 3YO child（Eppinger et al.,1999）.

Table1 Intercept values for calculation Nij

M_y(flexion)	M_y(extension)	F_z(compression/tension)
68 Nm	27 Nm	2120 N

（3）Chest injury criteria

Chest injury risk is evaluated on the basis of sternum defection, sternum deflection rates, viscous criterion and thoracic spine acceleration .A sternum deflection of 60mm represents either a 45% or 70% risk of an AIS3+chest injury depending on whether the airbag or seatbelt causes the chest deformation. A safety need for adopting the proposal has not been established by NHTSA [10].

In side impact, head、neck、chest、abdomen、pelvis and lower limbs are vulnerable[11].Therefore, it is necessary to study the injury of the body region in order to provide further protection for occupants. This paper chooses head resultant acceleration (aH)、 chest resultant acceleration (aT)、neck axial force in the z direction (Fz) and flexion and extension moments about the occipital condyles (My) as study injury parameters.

4.2 Injury parameters analysis

4.2.1 The influence of impact velocity against child occupants' injury

The most important injury inducing mechanism in side impact is the intrusion of the side structure. The intrusion can be described by velocity and depth. Especially the intrusion velocity is the injury inducing factor. There is a definite proportion relation in the door intrusion and the impact velocity. So that, this paper considers two impact situation: (1)90o side impact, at 33.8km/h with the intrusion; (2) 90o side impact, at 50km/h with the intrusion.

Traffic accident statistical data indicates that whether in frontal impact or in side impact the occupant's severe injury rate will greatly increase with the door intrusion increasing. The relation of door intrusion and injury rate is shown in figure 6 [12].

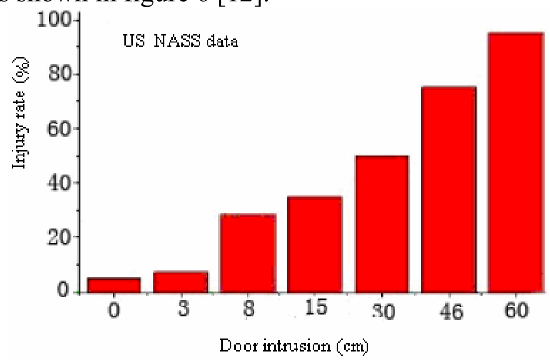

Figure 6 Door intrusion and injury rate

In table 2 and figures 7 to 10 illustrate the comparative simulation results of the head resultant acceleration（aH）、chest acceleration（aT ）、axis force in the z direction（Fz）and Y axis moment (My) at 50km/h and 33.8km/h side impact speed.

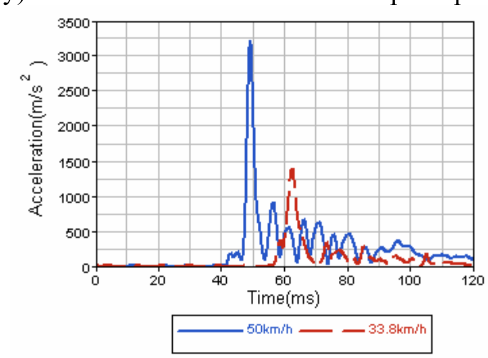

Figure 7 Head resultant acceleration

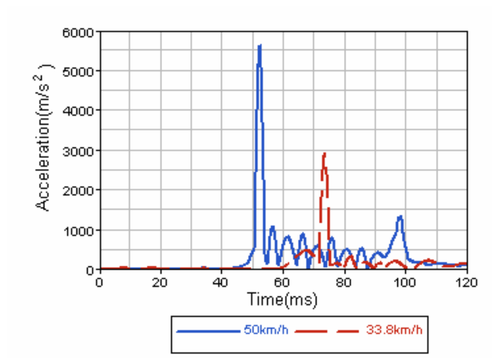

Figure 8 Chest resultant acceleration

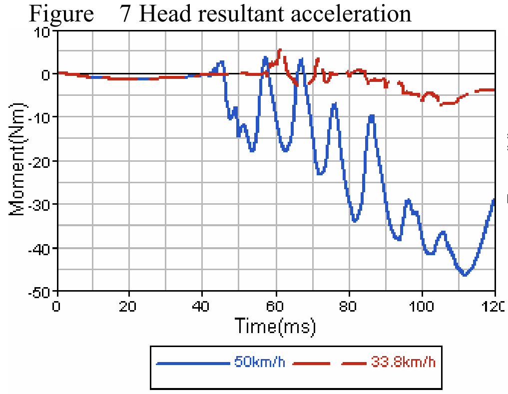

Figure 9 Neck Z-direction force

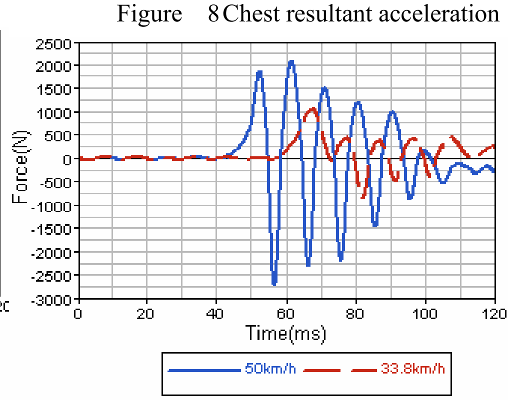

Figure 10 Neck Y-direction moment

From figures 7 to 10, the comparison of the head acceleration、 thorax acceleration、 neck axis force in the z direction and neck axis moment about the occipital condyles curves shows a lag between the two peaks at 33.8km/h and 50km/h. In figure 7, at the time of 52.4ms, because of the dummy's head hits the intruding door, the head acceleration reaches to the peak value 5613.2m/s2.While at the time of 98.4ms, as result of the dummy's head impacts to the child safety seat, the head acceleration again reaches to the peak value 1328.99m/s2.

Table2 Injury parameters comparison at 33.8km/h and 50 km/h

Injury parameters \ Impact velocity	V=33.8km/h	V=50km/h
aH (m/s2)	2908.8	5613.2
aT (m/s2)	1402.8	3211.6
Fz(N)	1050.4	2070.8
-Fz(N)	859.08	2718.1
My(N • m)	5.7354	3.5125
-My(N • m)	8.3507	46.47

From Table 2, it can be concluded that the head acceleration（aH） peak value at 50km/h is 1.9 times comparison with it at 33.8km/h,the thorax acceleration （aT ）peak value in the velocity (V=50km/h) is 2.3 times than that in the velocity (V=33.8km/h),the neck axis force（Fz）peak value in the velocity (V=50km/h) is 1.97 and 3.16 times than that in the velocity (V=33.8km/h), the neck axis moment(My) peak value is 0.61 and 5.56 times than that in the velocity (V=33.8km/h). In conclusion, with the impact speed increasing, the door intrusion increasing and the risk of child occupant injured remarkably higher

4.2.2 The influence of seating position on child occupant's injury

Several studies have characterized the benefit of rear seating on injury outcome in children. Risk of injury was lower to children seated on the non-struck-side (1.4%) as compared to those on the struck-side (2.6%). Through analysis of the Fatality Analysis Reporting System (FARS), Howard found that for restrained children, the children seated on the near side were 2.5 times as likely to receive fatal injury than children seated in the centre, and also found through analysis of NASS that among children known to be restrained, severe injury was much more common for those seated in the near side seat than for those in the center [13]. In order to study the influence of seating position against child occupants' injuries, this paper separately creates the models on the struck side and non-struck side at impact speed 50km/h.The two models have the same parameters except the different seating position, figures 11 to 14 show the head resultant acceleration （aH）、chest acceleration （aT ）、neck axis force（Fz）and neck axis moment about the occipital condyles (My) curves of Q3 child occupant in two different seating position. The injury parameters peak value is showed in table 3.

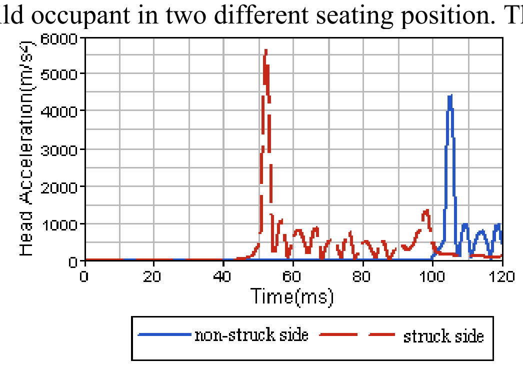

Figure 11 Head resultant acceleration

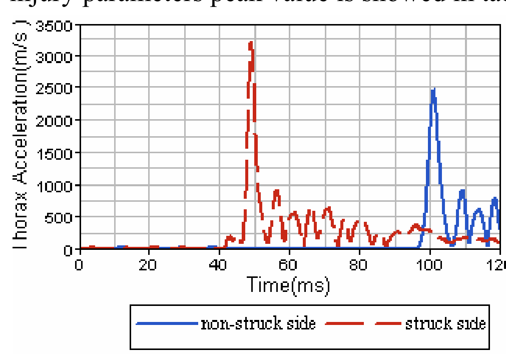

Figure 12 Chest resultant acceleration

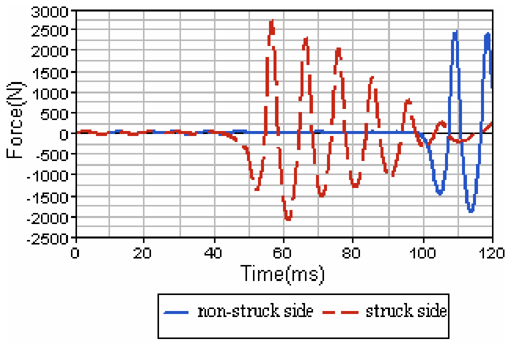

Figure 13 Neck axis force (Fz)

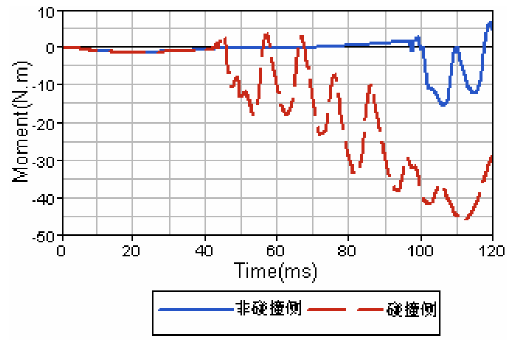

Figure 14 Neck axis moment (My)

Table 3 Injury parameters comparison in struck side and non-struck side

Seating position / Injury parameters	Non-struck side	Struck side
aH (m/s2)	4384.4	5613.2
aT (m/s2)	2453	3211.6
Fz(N)	2437.5	2718.1
-Fz(N)	1905.8	2070.8
My(N • m)	6.4059	3.5125
-My(N • m)	15.596	46.47

From Figures 11 to 14 and table 3, the curves and tables of results clearly show that injury parameters peak values on the struck of the crash are considerably higher than those on the non-struck side.

5. Discussion and Conclusions

This research was aimed at the development of a numerical method to evaluate the intrusion influence on a child occupant restrained in the CRS in the case of a vehicle side impact, considering vehicle body deformation. The CRS and vehicle body model have been built using multi-body technique combined with the finite element method, to allow for a better representation of the contacts between the child dummy, the CRS and the structure of the vehicle. The simulation results show that the intrusion influence is very important for the child occupants' injury. Based on the conclusion, In order to reduce the injury induced by the side structure of the vehicle intrusion, through enhancing the stiffness of the side wall will disperse the impact force and transmit it to beam 、floor 、roof and other body parts. Thus, the impact force will be absorbed dispersedly and the injury inducing by impact will be maximally decreased. Thereby the vehicle crashworthiness in side impact will be improved.

This paper also studies the influence of seating position on the risk of injury to children in side impact. The results of simulation indicate that the injury risk for children on the struck of the crash is considerably higher than those seating on the non-struck side, and suggest that the injury mitigation approach in the non-struck side is unique to that of the other rear seating positions.

The CRS is installed using the vehicle safety belts in this study, further research is needed to study the intrusion influence when the CRS is installed using the various installation configurations (ISOFIX system、lower anchorages belt system) .

Although the results of the project successfully responded to the initial objectives, the model is offering a lot of possibilities of improvement, development and exploitation and other developments aim to evaluate different child dummies responses in the case of various side impact and frontal collision configuration.

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