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A study on the design of a child seat system with mutipoint restraints to enhance safety †

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Abstract

Currently, child seats are widely used as a child restraint system (CRS). The effects of CRS are experimentally investigated according to FMVSS213. In this paper, the dynamic simulation of a child seat is carried out using the LS-DYNA software to develop an advanced CRS. A sled test using an existing child seat is first carried out, and the computer simulations using the LS-DYNA software are compared to the sled test to validate the dummy model and computer simulation. After matching the sled test and computer simulation results of a three-point belt-type child seat, a new type of child seat is developed with the computer simulation and optimization. For weight reduction, an optimization sequence is applied to determine the thickness of each part. For the area of stress concentration, reinforced members are added. The comparison between the simulation and the sled test shows good agreement, and the simulation results are proven useful for the further development of an advanced CRS.

Keywords: Child seat; Child Restraint System (CRS); Head Injury Criterion (HIC); Chest G; Sled test; Computer simulation; FMVSS 213; ECE 44

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1. Introduction

Restraint systems have been widely developed and used to reduce injuries in car accidents. The child seat system is continuously being developed in several advanced car industries. In the US, the safety of automobile passengers has become an important social problem since the 1960s. As a result, the regulation of the child seat FMVSS213 was published in the early 1970s [1] and has since been modified and improved. The law on child seat device ECE R44 in Europe was established in the 1980s [2]. The National Highway Traffic Safety Administration (NHTSA) emphasized the importance of child seats and released the research result that putting child seats in vehicles reduced young peoples' death in traffic accidents by 71%. Without child seats, a collision below a 10 km/h speed may be fatal [3].

In Korea, the regulation of the child restraint system (CRS) was published in the early 1990s. Duty articles of safety systems for children under six years old were included in 2001 and were extended to children below 13 years old [4-7]. However, the investigation results from a research institute in Korea showed that the usage of child seats was still low. This condition mainly comes from the lack of knowledge on the importance of child seats and the oriental custom of holding babies in the arms. The importance of child seats is well recognized these days; thus, the demand for child seats rapidly increases [8-10].

The American Academy of Pediatrics (AAP) classifies child seats into three models according to the number of restraining points [11], as shown in Fig. 1. The most common model of child seats is the three-point belt type, which is shown in Fig. 1(a). Despite

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(a) 3-point belt-type (b) 5-point belt-type

(c) 6-point belt-type

Fig. 1. Various types of child seats.

its wide use, crucial damage can be caused by this system, particularly for boys. To avoid this difficulty, a more advanced child seat with a five-point CRS has been developed, which is shown in Fig. 1(b). The six-point belt-type child seat, as shown in Fig. 1(c), is the most advanced model.

In this paper, a conventional three-point belt-type child seat is first used for the sled test. Computer simulations with the LS-DYNA software are then compared with the sled test to verify the child dummy model. After matching the sled test and computer simulation, a new type of child seat is developed with the LS-DYNA simulation and optimization process. The procedure in this paper is proven applicable in developing an advanced child seat model.

2. Sled test with a commercial child seat

Sled tests were performed with a three-point belt-type CRS according to the specified regulations. Fig. 2 shows the setup for a sled test. The equipment for the crash test was designed to exert accelerations according to national standards. It was increased to a velocity of 50 km/h and was suddenly decelerated.

Accelerations of the sled should be bounded within the acceleration specified in the regulations, as shown in Fig. 3. For the child seat evaluation, a three-year-old dummy was seated to measure the accelerations at the center of the head and chest. If the acceleration were not satisfactory, the procedure would be repeated by changing the designs until the regulations were satisfied.

Fig. 2. Sled test setup for the CRS.

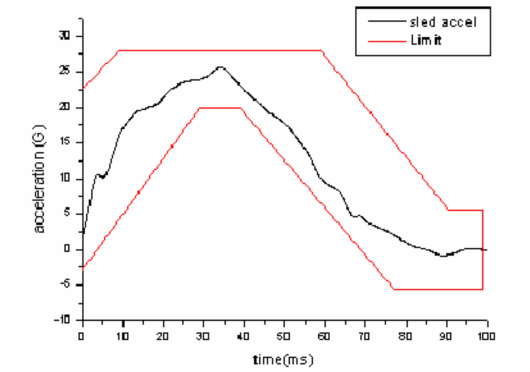


Fig. 3. Acceleration measured at the sled seat.

3. Computer simulation with ls-dyna

Computer simulation was performed with the three-point child seat that was used in the sled test. A commercial LS-DYNA program was used for contact and collision, and the computer-aided three-dimensional interactive application (CATIA) program was used for geometric modeling. The FEMB for LS-DYNA and the LS-POST were used for preprocessor and postprocessor, respectively. A surface model was also created with the CATIA program.

Fig. 4 shows the finite-element model of the three-point child seat, which is composed of shell elements under the assumption of small strain. If the number of elements was not enough, the deformation of the model may not be precise. The number of elements should then be increased to match the simulation results to the sled test.

The procedure for the LS-DYNA simulation was classified into three parts as follows.

(1) Put a child seat and a three-year-old dummy in the seat. This procedure may take a longer time for contact analysis for each nodal point.

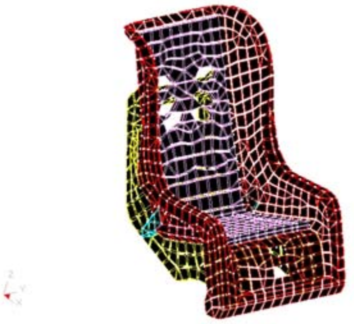


Fig. 4. Finite-element model of the three-point child seat.

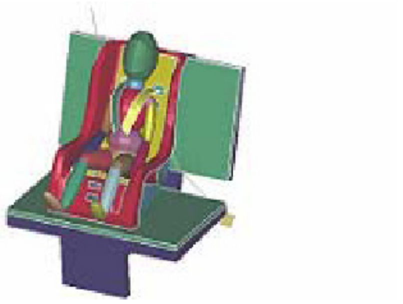


Fig. 5. Final model for the sled test simulation.

0 msec 20 msec 40 msec

60 msec 80 msec 100 msec

Fig. 6. Motions of the child and the seat obtained from LS-DYNA by applying the specified acceleration on the sled.

(2) Engage a child's seat belt depending on the restraint type.

(3) Impose the boundary conditions and start the simulation. The pre-tension of the seat belt, belt slack, and anchor points are in the category of boundary conditions. Boundary conditions should be modified and applied according to the sled test, which was repeated until the regulations were satisfied.

The sled test was executed with a velocity of 50 km/h. The test velocity curve for the analysis was transformed from the measured acceleration in the sled test.

4. Sled test versus simulation

4.1 Korean regulation

Injury criteria were measured using the accelerations of the dummy in the sled test. The resulting acceleration that was measured at the center of the mass of the head should not exceed 785 m/s^2 and that of the chest was limited to 588 m/s^2 at 0.03 s after the impact. Due to the KS R 4053 regulation, which is the Korean regulation on child seats, forward movements of the head and knee that were measured along the *z*-axis should not exceed 600 mm and 700 mm, respectively.

4.2 Computer simulation versus sled test

Crash was performed in 2.5 s in the sled test by applying acceleration on the sled, as shown in Fig. 3. One accelerometer was set at the center of the mass of the head, and another one was set at the chest. Accelerations were measured at 1 ms. Movements of the head and the chest were captured by a high-speed camera with a ±5 mm allowance in measurement error. The termination time in the simulation was set to 0.3 s to compare the crash time in the sled test.

The final model for the sled test simulation is shown in Fig. 5. The acceleration of the sled in Fig. 3 was applied for the crash simulation. Movements of the dummy from the LS-DYNA simulation are shown in Fig. 6 for several time steps. The dummy and the child seat moved together in a forward direction for 0.02 s. After 0.04 s, the dummy departed from the child seat because the dummy kept on moving forward, whereas the child seat did not because of the seatbelt. Belt slack was exerted at this moment. The maximum resulting acceleration was observed between 0.06 s and 0.08 s.

4.3 Matching of two results

Figs. 7 and 8 show the resulting accelerations of the head and the chest with a rigid body dummy model. The maximum acceleration of the head was observed at 0.06 s, while the maximum acceleration of the chest was observed at 0.03 s.

Two results of the sled test and simulation did not exactly match, but the magnitudes at the peak value and shape of the curve were in good agreement. After finding similar trends between the two results, we can

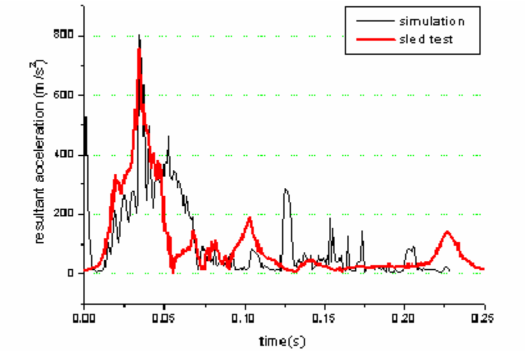


Fig. 7. Resulting acceleration of the head.

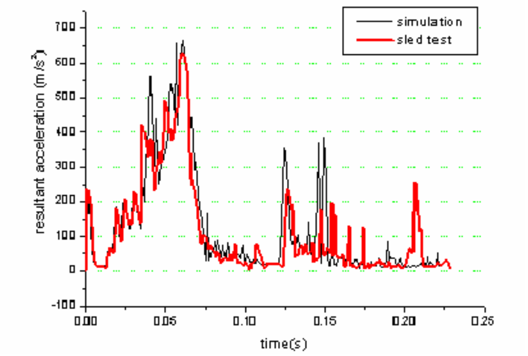


Fig. 8. Resulting acceleration of the chest.

conclude that this simulation sequence can be applied to develop a new child seat.

5. Development of an advanced child seat

5.1 Design of a new child seat

A new six-point belt-type child seat was initially designed using the CATIA program, as shown in Fig. 9. To save the materials and reduce the manufacturing cost, designing a lighter seat was recommended. However, a very lightweight design can reduce the safety level; thus, design optimization is necessary to develop a new CRS that is suitably light to protect babies [12].

Fig. 10 shows the stress distributions of a six-point child seat, with the initial design of the belt force set to 5,000 N. Using a frame that was made of a polypropylene material with a thickness of 2 mm, the resulting maximum stress had a value of 280 N/mm^2, which largely exceeds the limit of allowable stress. The maximum stress of 39 N/mm^2, which is similar to the allowable stress of this material, was computed with a 5 mm thick model. Much lower stresses were found in most parts of the seat body; thus, it was necessary to change thicknesses throughout the optimization. The total volume of this seat was selected as an objective function in the optimization process.

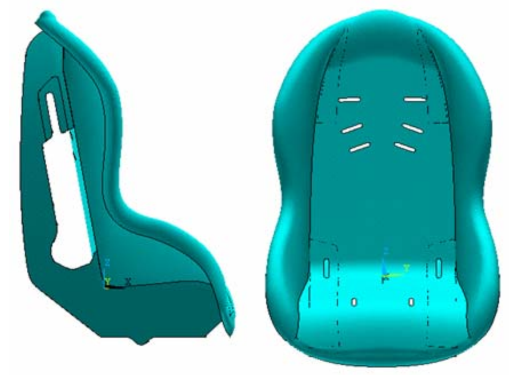


Fig. 9. Shape of the six-point child seat.

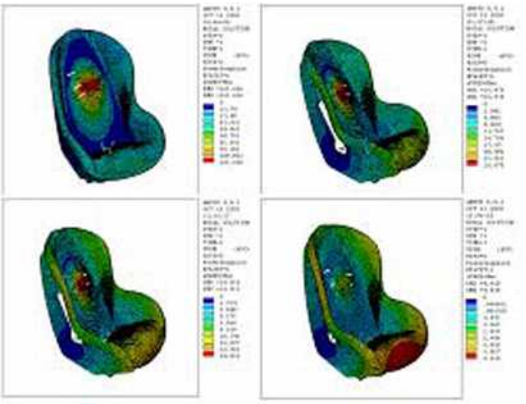


Fig. 10. Stress distribution in the six-point child seat.

5.2 Optimization of a new seat

Optimization was carried out using the ANSYS program. To reduce the total volume of the child seat, the six-point belt CRS was divided into 10 parts (i.e., seven regions in the frontal frame and three regions in the rear part), as shown in Fig. 11.

The structural and optimization analyses were repeated to increase the thickness in the weak regions and decrease the thickness in the overdesigned regions.

The optimized design variables, the 10 thicknesses, are summarized in Fig. 12, which shows how weak regions can be reinforced and materials in stiff regions can be reduced to minimize the total volume. In the optimized CRS, the total volume is reduced to

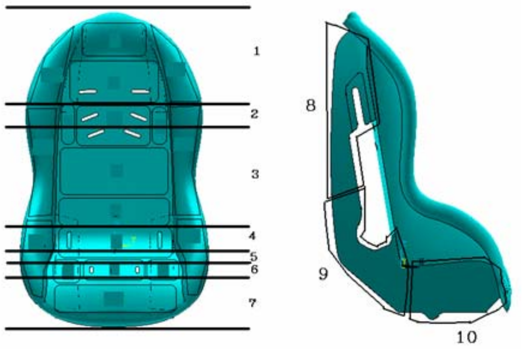
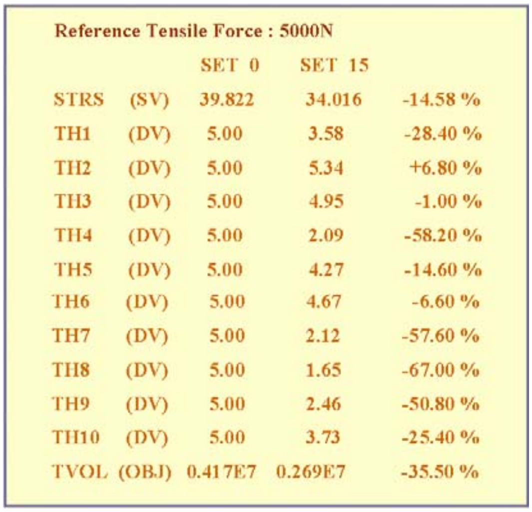


Fig. 11. Ten regions of the new six-point child seat.



Reference Tensile Force : 5000N

		SET 0	SET 15	
STRS	(SV)	39.822	34.016	-14.58 %
TH1	(DV)	5.00	3.58	-28.40 %
TH2	(DV)	5.00	5.34	+6.80 %
TH3	(DV)	5.00	4.95	-1.00 %
TH4	(DV)	5.00	2.09	-58.20 %
TH5	(DV)	5.00	4.27	-14.60 %
TH6	(DV)	5.00	4.67	-6.60 %
TH7	(DV)	5.00	2.12	-57.60 %
TH8	(DV)	5.00	1.65	-67.00 %
TH9	(DV)	5.00	2.46	-50.80 %
TH10	(DV)	5.00	3.73	-25.40 %
TVOL	(OBJ)	0.417E7	0.269E7	-35.50 %

Fig. 12. Optimization results for the 10 regions.

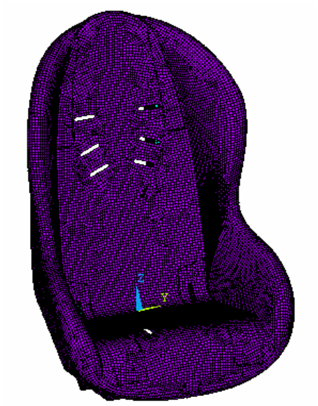


Fig. 13. Optimized shape of the new six-point seat.

Fig. 14. Optimized shape of the new six-point seat.

64.5% of its original value, and its final shape is shown in Fig. 13.

5.3 LS-DYNA Simulation

The correlation between the sled test and the computer simulations was verified with the three-point child seat model; thus, only the LS-DYNA simulations were carried out to develop a new six-point model. The acceleration data from the sled test with a three-point CRS was applied to design a six-point CRS.

Fig. 14 shows the LS-DYNA model for a six-point child seat. After the final result was obtained from the computer simulation for a six-point CRS, the sled test was carried out with the developed prototype of a six-point child seat.

5.4 Discussion of results

Figs. 15 and 16 show the resulting accelerations of the head and the chest using the finite-element dummy model, which can reduce the peak acceleration compared with a rigid-body dummy model. Thus, the peak accelerations in Figs. 15 and 16 are lower than those in Figs. 7 and 8.

The results from the six-point CRS can be compared with the three-point CRS with regard to the maximum peak values of the resulting acceleration. As shown in Figs. 15 and 16, the maximum resulting accelerations of the head and the chest are 580 m/s^2 and 341 m/s^2, respectively. This result is about 11% lower than the values of the three-point child seat. Forward movements of the head and knee were also reduced in the six-point child seat.

The analysis results indicated that a six-point CRS provides a lower impact force than a three-point belt seat because a six-point belt has the advantage in distributing force to six belt strips.

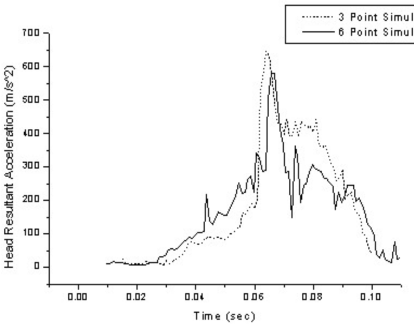


Fig. 15. Peak value of the head acceleration.

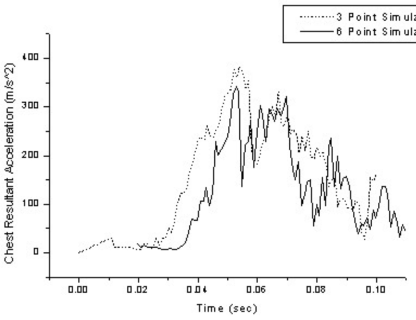


Fig. 16. Peak value of the chest acceleration.

6. Conclusion

In this paper, a dynamic simulation of a child seat has been carried out using the LS-DYNA software to develop an advanced CRS. The sled test with a three-belt child seat was first conducted, and the computer simulations with the LS-DYNA software were then compared with the sled test to validate the computer simulation. After matching the sled test and computer simulation, a new type of child seat was developed using computer simulation. For weight reduction, an optimization sequence was applied to determine the thickness of each part. For the area of stress concentration, reinforced members were added.

Based on simulation and analysis, the following conclusions are obtained:

(1) Precise material properties are important to obtain better results in the simulation.

(2) After proving the simulation results of a three-point belt-type child seat, simulations can be carried out to develop a new six-point belt-type child seat.

(3) LS-DYNA simulations can replace the sled test and reduce the cost and time for developing new products.

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