

Occupant Responses in Child Restraint Systems Subjected to Full-Car Side Impact Tests

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ABSTRACT

Accident data show that the injury risks to children seated in child restraint systems (CRSs) are higher in side collisions than any other type of collision. To investigate child injury in the CRS in a side impact, it is necessary to understand the occupant responses in car-to-car crash tests. In this research, a series of full car side impact tests based on the ECE R95 test procedure was conducted. In the vehicle's struck-side rear seat location, a Q3s three-year-old child dummy was seated in a forward facing (FF) CRS, and a CRABI six-month-old (6MO) infant dummy was seated in a rear facing (RF) CRS and also was placed in car-bed restraint. In the non-struck side rear seat location, the RF CRSs also were installed. In addition to testing the CRSs installed by a seatbelt, an ISOFIX FF CRS and an ISOFIX RF CRS were tested. For the evaluations, occupant kinematic behavior and injury measures were compared.

In all tests, the dummy heads were contained within the CRS shell during the entire impact event. In both the struck side FF CRS and RF CRS; the HICs were small, even though the dummy heads made indirect contact with the door beltline through the CRS side wing in these struck side CRSs. The dummy chest was loaded by an intruding door and the resulting chest deflection of the Q3s child dummy in the FF CRS was comparable with the injury assessment reference value. In the non-struck side, the loading of the CRABI 6MO seated in the CRS was substantially small. In the FF and RF ISOFIX CRS with a top tether, the acceleration of some body regions of the dummy could be high because the ISOFIX

CRS moved from the initial phase of the impact and contacted the dummy at a high velocity. However, the CRS and the dummy displacement were small, which is an advantage of the ISOFIX CRS because occupant excursion could be a major source of injuries in the real-world accidents.

INTRODUCTION

This study was undertaken to understand better the injury mechanisms of children seated in a CRS and involved in a side impact as well as to validate a side impact test procedure. The accident analyses indicate that the number of children involved in side collisions is from 50% to 65% times compared to that in frontal collisions [1,2], but the risk for severe-to-fatal injuries to children seated in a CRS is higher in side collisions than in that in any other type of collision [1,3]. From German in-depth data, the fatality risk of children involved in side impacts was twice as high as that of children involved in frontal impacts [1]. Features of injuries for children seated in CRSs and involved in side collisions have been investigated using global and in-depth accident data. In side collisions, the injury severity of a child depends on seating position because the injury risks depend on the vehicle intrusion as well as the car acceleration. The injury risk of children seated in CRSs located on the struck side is higher than that for children seated in CRSs located on the non-struck side [3,4]. It is also shown by the accident data that the injury risks of children seated in RF CRS are lower than that for children seated in FF CRS. This was found to be true for frontal crashes as well as for side collisions [5,6]. In side crashes, the frequently injured body regions of children

seated on the struck side were the head, face, neck, chest and lower extremities [3,4,7,8]. It is pointed out that the head, chest, and neck are inclined to sustain serious injuries; and reducing injuries to these body regions requires improvement in CRS design [3,7,9]. According to an analysis using in-depth accident data by Langwieder et al. [3], the sources of AIS 5-6 head injuries for children on the vehicle struck side were the door, an intruding object, the A/B pillar, and the front seat; and for AIS 1-3 head injuries were the side window glass frame and plastic trim. From the NASS-CDS and CIREN database, McCray et al. [2] indicated that the upper door in the window sill area was often the injury source of the head.

The anatomical structure of children is different from that of adults, and can lead to an entirely different set of injuries to children [10]. For example, the pediatric bone is elastic and the rib cage is so flexible that rib fractures are rare among children. The child pelvis is continuing to develop; and the ilium, pubis, and ischium are connected by Y-cartilage. Although adults often sustain pelvic fractures in side collision accidents, these are rare for children under 7 or 8 years old [11]. From finite element analyses using a 3-year-old child model, Mizuno et al. [12] showed that the stress within the pelvis is substantially smaller if the aforementioned cartilage within the pelvic region is included in the model. In addition to the pelvis anatomy, the loading on the pelvis of the child seated in the CRS during side impact can affect the low injury risk to the pelvis.

A sled test procedure to evaluate CRS performance in side impact was proposed in the ISO/TC22/SC12 WG1 [3,9]. Since the injury risk to occupants in side collision could be affected by the vehicle acceleration and door intrusion, these factors were reflected in the ISO sled test procedure. In the ISO proposed sled test, a hinged-door panel rotates and impacts the CRS on the accelerated sled. Based on full-car side impact tests, a corridor of the sled delta-V and the door angular velocity has been prescribed [9]. On the other hand, Takata Corporation has proposed a sled test where the door impacts the CRS at a constant velocity [13]. This latter test method is simple, and the loading on the chest of the dummy as observed in full car side impact tests was reproduced.

In order to understand the injury mechanisms of children seated in a CRS and involved in a side impact as well as to validate the side impact test procedure, an evaluation of occupant responses in full car side impact tests is needed. There has been only minimal research that investigates occupant responses of child dummies seated in various CRS types based on full car side impact tests. Moreover, in Japan, the car-bed restraints are widely used. Weber [14] pointed out that the car-bed restraint may have some disadvantages if there is a direct head loading by the vehicle intrusion, though this has not been confirmed in full car side impact tests. The National Traffic Safety Laboratory and Environment

Laboratory (NTSEL) has a research project of side impact occupant protection for a future side impact test procedure [15]. In this research project, full car side impact tests were conducted for various conditions using the ES-2 and the SID IIs dummy. In some of the tests, the child dummy was seated in the CRS on the rear seat of the car. Some of these results were already published in the literature for the FF and RF CRSs, and the car-bed restraint [16]. In this research project, the FF ISOFIX CRS installed on the struck side and the RF ISOFIX CRS installed on the non-struck side ISOFIX CRS were newly tested. In this paper, the kinematic behavior and injury measures were compared for the child occupants seated in an FF vs. RF CRS, an ISOFIX vs. seatbelt installed CRS, and a struck side vs. non-struck side CRSs. These full vehicle crash test results provide additional validation data for the ISO sled test procedure.

METHOD

Five full car side impact tests were carried out according to the test procedures of ECE R95. A child dummy was seated in the rear seat on either the vehicle struck or non-struck side in these tests (Fig. 1). Table 1 shows the test matrix. In all tests except Test 04, a moving deformable barrier (MDB) impacted the target car. The MDB was the ECE R95 barrier (which has a weight of 950 kg). The target cars were small sedans. The ECE R95 test procedure specifies that the centerline of the MDB impacts the front seat reference point of the target car. In the vehicle's front seat, an adult dummy was seated. In Test 04, a multi-purpose vehicle (MPV) which has a stiff frame impacted the target car. The striking vehicle (MDB or MPV) impacted the stationary target car at 50 km/h. The driver side (right side) was impacted in Tests 01 to 04, and the passenger side was impacted in Test 05.

In order to compare the child dummy responses for CRSs in various seating locations in a side impact, an FF and RF CRS and a car-bed restraint were used. Figure 2 presents the CRS setup for the tests. The similar model of a convertible CRS with a 5-point harness (made by Takata Corp.) was used in Tests 01 to 04, and was used either as a FF CRS or a RF CRS in each test. In these CRS models, the same shell was used and the depth of the side wing was 150 mm. A Q3s dummy was seated in the FF CRS. The Q3s is a dummy that represents a 3-year-old (3YO) child, and can be used under side impact loadings [17,18,19]. Since there are no commercial based infant dummies that are designed to be used for side impact testing, a CRABI 6-month-old (6MO) infant dummy was seated in the RF CRS. In Test 01, the Q3s dummy in the FF CRS was seated using a three-point seatbelt on the struck side. In Test 02, the FF CRS was installed with an ISOFIX and top tether on the struck side (Test 02a) and an RF CRS was installed on the non-struck side with an ISOFIX and a top tether (Test 02b). In Test 03, the CRABI 6MO was seated in the RF CRS on the struck side. In Test 04, the MPV impacted the car, the CRABI 6MO was seated in the RF CRS

on the non-struck side, and a SID IIs dummy was seated on the struck side. In Test 05, the CRABI 6MO infant dummy was laid on a car-bed restraint. This CRS used in Test 05 is also a convertible five-point harness type (made by Aprica) which can be changed to a FF CRS, RF CRS, or a car-bed restraint. This CRS type is intended for use as the car-bed restraint for infants weighing 2.5 to 8 kg. According to the specifications provided for this CRS, the CRABI 6MO infant dummy was laid such that the head of the dummy was directed in-board.

A uni-axial accelerometer (semiconductor strain gage type: Kyowa ASM-200BA) was attached to the side sill at the rear of the B-pillar bottom on the non-impact side to measure the car floor acceleration. Three uni-axial accelerometers were attached at the front, middle, and rear locations of the rear door inner panel behind the armrest (see [Fig. 3\(a\)\(b\)](#)). In considering the contact location of the armrest with the CRS, the data measured from the armrest rear location accelerometer were used for the FF CRS, and the data measured from the armrest middle location were used for both the RF CRS and the car-bed restraint. The uni-axial accelerometers also were attached to the CRS with rivets (see [Fig. 3\(c\)](#)). Velocity-time histories of the car (floor), rear door, CRS, and dummies were plotted to examine the relative motion among them. The absolute velocity was calculated from the integral of the car lateral acceleration.

The injury measures of the Q3s child and the CRABI 6MO infant dummies were compared to the injury assessment reference values (IARVs) of three-year-old children and 6-month infants as proposed by Mertz et al. [20]. The IARVs proposed by Mertz were for the Hybrid III and CRABI dummy. Though the European Enhanced Vehicle-safety Committee (EEVC) proposed the IARVs of a Q3 for frontal impact [21], the IARVs for side impact have not been proposed yet. In this study, the IARVs by Mertz were used since they include IARVs of children for side impact.

<[figure 1](#) here>

<[table 1](#) here>

<[figure 2](#) here>

<[figure 3](#) here>

RESULTS

CAR RESIDUAL DEFORMATION

The static or residual deformation of the car outer panel and interior at the AM50 thorax height level is presented in [Fig. 4](#). The deformation of the interior was measured in Test 03 and 05. In Tests 01, 02, 03, 04 and 05, the exterior deformations at the rear door center were 151 mm, 144 mm,

166 mm, 250 mm and 205 mm, respectively. The intrusion of the rear door interior was small due to its location being closer to the C-pillar.

<[figure 4](#) here>

FORWARD FACING CRS IN STRUCK SIDE

In Tests 01 and 02a, the Q3s dummy was seated in a FF CRS that was installed on the struck side rear seat of the vehicle. The CRS was installed with a conventional seat belt in Test 01, and the CRS was installed by an ISOFIX and a top tether in the Test 02a. [Figures 5](#) and [6](#) present the dummy kinetic behavior in Tests 01 and 02a at 20 ms intervals. The door armrest contacted the CRS shell area that is lower than the pelvic region, and the door beltline contacted the CRS side wing around the shoulder, thereby making a bridge between the door and the CRS (see [Fig. 7](#)). The CRS side structure near the dummy pelvis was compressed by the door armrest, and the CRS made contact with the right arm of the Q3s dummy. Forces were transferred to the chest through the right arm. In Test 01, the head rotated toward the impacted door, made contact with the CRS side wing at 60 ms, and then made indirect contact with the rear location of the rear door beltline through the CRS side wing. Judging from the positional relation between the gravity center of the dummy head and the CRS side wing outline, the head was contained in the CRS shell during the entire crash sequence during the test. In Test 02a, a curtain side airbag was deployed and inflated between the Q3s head and the CRS side wing at 25 ms. Lateral force was applied from the airbag at the upper part of the head, and the neck bent laterally and twisted. The dummy torso behavior during door impact was comparable to that in Test 01 before the curtain side airbag affected the dummy kinematic behavior. In the rebound phase (140 ms), the CRS and dummy lateral displacement in Test 02a were smaller than that observed in Test 01.

<[figure 5](#) here>

<[figure 6](#) here>

[Figure 8](#) shows the acceleration time histories at the CRS base and the CRS seat back. There are two phases in the CRS acceleration. First phase occurred around 30 ms and was due to the contact from door armrest, and second phase occurred around 60 ms and was due to the contact from the door beltline. For the CRS installed with a conventional seatbelt (Test 01), the acceleration at the CRS base in the first phase was high, and was followed by a high acceleration at the CRS shell in the second phase. For the CRS installed with an ISOFIX and top tether (Test 02), the acceleration of the CRS base and seat back was high in the first phase, and the CRS seat back acceleration in the second phase was low. In the first phase, the CRS was impacted by the door armrest (at 29

ms), and the CRS was accelerated also by the ISOFIX attachment and top tether (at 37 ms).

The acceleration time histories of the head, chest, and pelvis, and the chest deflection in Tests 01 and 02a are shown in [Fig. 9](#). In Test 1, the pelvis and the chest resultant acceleration attained their peaks of 600 m/s^2 (at 46.3 ms) and 520 m/s^2 (at 56 ms). The head resultant acceleration had a peak of 478.2 m/s^2 (at 69.7 ms) by impact from the CRS side wing through door beltline. In Test 2a, the pelvis resultant acceleration had a peak of 759 m/s^2 (at 45.7 ms). The chest acceleration has two peaks that were 472 m/s^2 (at 50.8 ms) and 482 m/s^2 (at 58.2 ms). During the time between the two peaks, the head moved laterally with the deploying airbag and applied force to the chest, which could result in second peak of the chest acceleration. In Test 2a, the head acceleration was small in general though it rebounded by the deploying curtain side airbag. At the first peak of the head acceleration (at 25 ms), the airbag deployed and interacted with the head, and at the second peak (at 60 ms) the inflated airbag made contact to the head. The maximum chest deflection was 20.5 mm (at 58.4 ms) in Test 01, and 16.5 mm (at 60.6 ms) in Test 02a. In Test 02a, the chest deflection may have been reduced by the head motion due to the airbag deployment. The upper neck force and moment of the dummy in Test 02a are shown in [Fig. 10](#). The airbag deployment caused the neck compression force (F_z) and lateral moment (M_x).

The velocity time histories of the car center of gravity, door, CRS, and Q3s in Tests 01 and 02 are shown in [Figs. 11](#) and [12](#), respectively. During impact, the car velocity increased whereas the MDB velocity was decreased. In Test 01, when the CRS base started to contact the door at 28 ms, the door velocity at the armrest rearward location was about 8.9 m/s and the velocity of car gravity center was 2.7 m/s. In Test 02, these velocities were 9 m/s and 2.8 m/s at 29 ms, respectively. Then, the CRS velocity began to approach the magnitude of the door velocity. Because the CRS was installed by an ISOFIX and a top tether in Test 02a and connected tightly with the car, the CRS velocity was higher for Test 02a than for Test 01 when the Q3s made contact with the CRS. Accordingly, the slope of the dummy's pelvis velocity in Test 02b was greater. In Test 01, the head velocity started to increase at 50 ms, and in Test 02b the head velocity increased gradually since the head was accelerated by the airbag interaction starting at 25 ms.

The injury measures of the Q3s child dummy are shown in [Table 2](#). All measures were less than their corresponding IARVs. The chest deflection as measured in the Q3s in Test 1 was 20.5 mm, which is slightly less than the IARV (23 mm). Irrespective of the head's indirect contact with the door beltline through the CRS side wing (Test 01), the HIC was only 182, i.e., far less than the IARV (568). In Test 02a,

though the head rebounded by the airbag deployment, the HIC and neck forces and moments were less than the IARVs.

<[figure 7](#) here>

<[figure 8](#) here>

<[figure 9](#) here>

<[figure 10](#) here>

<[figure 11](#) here>

<[figure 12](#) here>

<[table 2](#) here>

REAR FACING CRS INSTALLED ON THE STRUCK SIDE

In Test 03, the CRABI 6MO infant dummy was seated in the RF CRS that was installed on the struck side rear seat with a conventional seat belt. [Figure 13](#) presents the dummy kinematics during the crash sequence at 20 ms intervals. At 40 ms, the pelvis and chest started to contact the CRS side structure. Then, the head contacted the CRS side wing, and also indirectly contacted the door beltline through the CRS side wing. The head was contained in the CRS shell during the entire crash event. [Figure 14](#) shows the contact locations between the CRS and the door. The door armrest impacted the CRS base and lower location of the CRS shell.

[Figure 15](#) shows the acceleration time histories of the head, chest and pelvis, and the neck force time histories. Each body region was accelerated in a lateral direction. The peak resultant accelerations of the pelvis, chest, and head were 1035.2 m/s^2 (at 53.3 ms), 768.5 m/s^2 (at 50.9 ms), and 442 m/s^2 (at 54.9 ms), respectively. Since the CRABI 6MO does not have a rib cage, the chest acceleration is very high. The neck lateral shear force and tensile force are high due to the head impact. The velocity of the car, door, and dummy body regions in the impact direction was calculated. The velocity time histories are plotted in [Fig. 16](#). The velocity of the door and car gravity center, at the time when the door made contact with the CRS seat back (at 34 ms), was 9.0 m/s and 4.1 m/s, respectively. As the RF CRS was located near the B-pillar, the CRS seat back was accelerated at a high velocity of 7.8 m/s (at 49 ms). When the CRS velocity was close to its peak value, the pelvis, the chest, and head started to be accelerated together. However, the head was accelerated more gradually due to its lateral rotation.

The injury measures of the CRABI 6MO are presented in [Table 3](#). All injury measures are less than the IARVs. Although the head made contact with door beltline through

the CRS side wing, the HIC was small (117). However, the chest acceleration was relatively high (694 m/s^2) compared to the IARV of the chest (863 m/s^2). Moreover, the neck tension and shear force were high due to the head impact.

<figure 13 here>

<figure 14 here>

<figure 15 here>

<figure 16 here>

<table 3 here>

REAR FACING CRS INSTALLED ON NON-STRUCK SIDE

In general, a CRS installed on the non-struck side is not impacted by the intruding door. The CRS is accelerated by a seatbelt tension and car seat contact force. [Figure 17](#) shows the CRABI 6MO kinematic behavior in a RF CRS installed by conventional seatbelt on the non-struck side in Test 04 at 20 ms intervals. Since the seatbelt was connected only to the CRS base, the CRS rotated toward the impact side, and finally at 120 ms it made contact with the femur of SID II dummy seated on the struck side. The child dummy moved together with the CRS. The child dummy head did not make contact with the CRS side wing until the CRS completed its rotation. [Figure 18](#) shows the dummy kinematic behavior in Test 02b at 20 ms intervals where the CRS was installed with an ISOFIX and a top tether. Because of the ISOFIX attachment, the lateral displacement of the CRS base was small. The rotation of the ISOFIX CRS with top tether was stopped by the contact with the seatback of the front driver seat (90 ms) since the front driver seat was located in the rearmost position in Test 02. However, judging from the high speed video, the angular velocity of the CRS was smaller for the ISOFIX CRS with top tether than that for the CRS installed by the seatbelt. The head started to make contact with CRS side wing at 70 ms. The CRABI 6MO started to rebound at 90 ms toward the non-struck side.

[Figure 19](#) shows the acceleration time histories of the CRS and the car center of gravity. The peak of the CRS acceleration is higher than that of car acceleration. There is one large peak in the acceleration pulse at 68 ms for the test with the CRS installed on the car by a conventional seatbelt (Test 04). In the CRS installed with an ISOFIX and a top tether (Test 02b), the acceleration increased earlier because of this attachment. The acceleration phase of the CRS seatback was delayed about 10 ms compared to the CRS base. There are two peaks occurring at 30 ms and 70 ms in the acceleration pulse of CRS base. Between the two peaks of the

acceleration pulse, the CRABI 6MO made contact with the CRS, and the CRS acceleration decreased.

<figure 17 here>

<figure 18 here>

<figure 19 here>

The acceleration time histories of the CRABI 6MO are shown in [Fig. 20](#). The acceleration of the CRABI 6MO dummy seated in the ISOFIX installed CRS increased earlier and its level was high compared to the CRABI 6MO dummy seated in the CRS installed by a seatbelt. The neck force was also large for the CRABI 6MO in the ISOFIX CRS. However, the peak of CRABI 6MO accelerations in the RF CRS installed on the non-struck side were substantially lower compared to the acceleration of the CRABI 6MO seated on the struck side (see [Fig. 15](#)). In Test 04, the CRS made contact with the femur of the SID II at 120 ms. Since the accelerations of the CRABI 6MO dummy had peaks before this contact, the influence of this contact on the dummy accelerations may be small.

<figure 20 here>

[Table 4](#) presents the injury measures of the CRABI 6MO dummy seated in a RF CRS installed on the non-struck side. The HIC and chest accelerations were small and less than those of the CRABI 6MO seated on the struck side (see [Table 3](#)). The chest acceleration (3 ms) was 228.1 m/s^2 in Test 04 (conventional seatbelt) and 311.8 m/s^2 in Test 02 (ISOFIX and top tether). The neck axial force and shear force were also smaller than those in the struck side. However, due to the swinging motion of the head, the neck twist moment (M_z) exceeded the IARV (13 Nm).

<table 4 here>

CAR BED RESTRAINT

In Test 05, the CRABI 6MO infant dummy was laid in the car-bed restraint which was installed on the struck side of the rear seat (as previously mentioned). [Figure 21](#) presents the dummy kinematic behavior during the crash sequence at 20 ms intervals. At 20 ms, the rear door intruded and impacted the foot soles (i.e., the bottom of the feet). The front-end of the CRS seat pan was impacted by the door armrest, and the CRS was accelerated toward the car's in-board direction. Then, through the loading imparted by the crotch harness of the CRS, the dummy torso was accelerated laterally across the car or toward the dummy's cranial direction. After 60 ms, although the CRS head protection pad had rotated, it did not interrupt the dummy's cranial movement. The whole body of the CRABI 6MO infant dummy was contained in the CRS during the entire crash event during this test.

Figure 22 shows the acceleration time histories of the dummy head, chest, and pelvis. The accelerations are high in the dummy's inferior-superior or cranial direction. The peak resultant accelerations of the pelvis, chest, and head were 510 m/s² (at 44.6 ms), 445 m/s² (at 45.1 ms) and 322 m/s² (at 45.7 ms), respectively. The head and chest accelerations had a second peak at 60 ms because, at this time, the chin made contact with the chest. Figure 23 shows the time histories of the velocities in the vehicle's lateral direction. The gap between the CRS seat pan front-end and the armrest was so small that the rear door made contact with the CRS at the initial phase of impact (12 ms). At this time, the door was in an accelerating phase and the door velocity was still relatively low (2.6 m/s). Both of the dummy's feet were impacted by the door at a velocity of 7.3 m/s at 25 ms. Since the CRS's crotch harness applied a force to the pelvis in the cranial direction, the CRS and dummy were accelerated together. The dummy's head was accelerated with a gradual onset rate due to the neck flexion.

In this CRS, the crotch harness is likely to be the major load path when the dummy was accelerated in the car's lateral direction. This is because the shoulder and lap harnesses cannot support the dummy in this direction. Assuming that the dummy torso is accelerated only by the crotch harness and the shoulder joint force can be omitted, the force applied from the crotch harness to the dummy pelvis in the dummy cranial direction can be estimated by the masses and accelerations of its head, chest, and pelvis as follows:

$$F_{\text{crotch}} = -m_{\text{chest}} a_{\text{chest}} - m_{\text{pelvis}} a_{\text{pelvis}} - F_{\text{neck, axial}}$$

where F_{crotch} is the crotch force, m_{chest} , a_{chest} , m_{pelvis} , a_{pelvis} are the masses and the z-accelerations of the chest and pelvis, and $F_{\text{neck, axial}}$ is the neck axial force. The maximum force is 1827 N at 44.7 ms. Around this time, the head, chest, and pelvis accelerations also reach their peak.

Table 5 shows the injury measures of the CRABI 6MO infant dummy. All of the injury measures were less than their corresponding IARVs. As the dummy was accelerated laterally across the car, the neck compression force was relatively high at 541.3 N, but still less than the neck compression IARV of 890 N.

<figure 21 here>

<figure 22 here>

<figure 23 here>

<table 5 here>

DISCUSSION

During the review and evaluation of the testing results, a number of observations were made that were determined to have an influence on the test measures. In the tests of the FF and RF CRSs installed on the struck side, the door armrest contacted the CRS area that is lower than the pelvic region, and the door beltline contacted the CRS side wing around the shoulder. These two contacts made a bridge, and the CRS side structure between them did not make contact with the door (see Fig. 24). Then, the pelvis and the chest impact forces could be mitigated more readily than the contact forces imparted by a flat rigid structure. The head was indirectly impacted by the door beltline through the CRS side wing though the dummy head was contained within CRS shell. The arm position of the dummies in these tests was important since the chest was compressed indirectly by the CRS through the upper arm. In the tests with the CRSs installed on the struck side, all of the dummy injury measures were less than their corresponding IARVs. However, the chest deflection of the Q3s dummy in the FF CRS (Test 01) was 20.5 mm, and the chest acceleration of CRABI 6MO in the RF CRS (Test 03) was 694.3 m/s², which are close to the 3YO IARV (23 mm) and 6MO IARV (863 m/s²).

In the FF CRS, it was difficult to directly examine the influence of an ISOFIX with a top tether on the kinematic behavior and injury measures of the Q3s from the results of Test 01 and Test 02a. This is because the curtain side airbag deployed between the CRS side wing and the dummy head in Test 02a, and it affected the dummy kinematic behavior. From the velocity-time history, the ISOFIX CRS with a top tether moved earlier than the CRS installed by a seat belt. Then, the velocity of the ISOFIX CRS with a top tether was high when it made contact with Q3s torso. This high velocity could lead to higher accelerations of the Q3s pelvis. Since the dummy head moved by the force exerted by the curtain side airbag in Test 02a, the head could accelerate the dummy torso through its neck. Then, the chest acceleration had a second peak as shown in Fig. 9(b). Since there was not a large difference in the peak levels of the chest accelerations in both installation types of FF CRSs, it is probable that the dummy chest acceleration was comparable in the ISOFIX CRS with a top tether to that in the CRS installed by seatbelt. The chest deflection could be affected by the head behavior with the airbag interaction in Test 02a. Thus, from Test 01 and Test 02a, the effect of the ISOFIX and a top tether on the chest deflection could not be identified. The CRS and child dummy displacement in the ISOFIX CRS with top tether was substantially small, especially for the rebound phase. This small displacement of the dummy could have an advantage for the child occupant protection in a side impact in the real world where a child moving out of the CRS shell could be a major cause of injuries, particularly for preventing head injuries.

<figure 24 here>

In Test 02a, the curtain side airbag deployed between the child dummy head and the CRS side wing. From the high speed video, the head upper part was loaded by the airbag. As a result, the neck compression force, the flexion moment, and lateral bending moment were large. The torso behavior and acceleration were also affected by lateral head displacement. However, the neck injury measures were less than IARVs. Although further research will be needed, it is probable that the injury risk to a child's neck by the curtain side airbag is not so high.

The chest and pelvis accelerations of the dummy were higher for the CRABI 6MO infant dummy in the RF CRS as compared to those for the Q3s child dummy in the FF CRS. One possible reason for this difference is that small mass of the CRABI 6MO dummy makes it easier to be accelerated. Another reason is that the design of the CRABI 6MO infant dummy has no energy-absorbing chest structure for the lateral direction. Its stiff lumbar spine can also transfer pelvis accelerations directly to the chest. In the ECE R95 test, the MDB centerline impacts the front seat reference point. Accordingly, the rear door intrusion velocity is relatively higher for the location closer to the B-pillar, which also can be another reason for the high dummy chest and pelvis accelerations in the RF CRS. The high accelerations of the CRABI 6MO infant dummy may be contrary to the accident analysis that the injury risk to children is the lowest in the RF CRS [5,6]. Further research is needed for the infant injury risk in RF CRS, the infant IARV, and the CRABI 6MO infant dummy body structures used in side impact testing.

For the RF CRS installed on the non-struck side, the loadings on the CRABI 6MO (Tests 02b and 04) were substantially smaller compared to that for the RF CRS installed on the struck side (Test 03). However, due to dummy head motion, the neck extension and twist moment were large. It is difficult to compare the effect of the CRS installation configuration in the non-struck side (Tests 02b and 04) since the ISOFIX CRS made contact with the front seat in Test 02b. This contact would not have a large influence on the dummy measures as the dummy accelerations had its peak before the contact with the front seat. Because the ISOFIX CRS moved beginning with the initial phase of the impact, the acceleration of the CRABI 6MO dummy seated in the ISOFIX CRS was higher than that of the dummy seated in the CRS installed by a seatbelt.

In the car-bed restraint, the dummy torso was not impacted by the CRS shell, but the pelvis was accelerated by the crotch harness laterally across the car or toward the dummy's cranial direction. In the car-bed restraint, the injury measures were small and less than their corresponding IARVs. However, from the dummy injury measures, it is rather difficult to discuss the injury risk to child in the car-bed restraint because

the large force (1827 N) was applied from the crotch harness to the pelvis in the infant dummy's cranial direction. This situation is different from the 5-point harness FF CRS where the role of the crotch harness is not to apply force but is designed to hold the lap harness on the pelvis [14]. Moreover, in the car-bed restraint, the feet bottom were impacted directly by the door structure at a velocity of 7.3 m/s. Biomechanical data are needed to discuss the injury risks to infant pelvis and feet under this loading.

In the FF and RF CRS installed on the struck side, with the dummy chest being loaded, the chest acceleration and deflection were relatively large. Therefore, the ECE R95 test is useful to evaluate the chest injury risk to children seated in a CRS, a situation which occurs frequently in real world side impact collisions. The head accelerations were relatively small even though the head made indirect contact with the door beltline through the CRS side wing. From the accident analysis by McCray, the CRS was identified as one of the frequent sources of the child head injury in FF CRS [2]: The number of AIS 1, 2 and 3 head injuries due to CRS was 8, 1, and 1 among the 40 head injuries. Accordingly, when the child head is contained within the CRS shell, the injury risk can be small. Note that the head injury risk depends on the energy absorption and the shape of the CRS side wing. It is likely that the ECE R95 base side impact test will be useful to evaluate these factors of the CRS side wing.

However, Arbogast et al. [4], in examining in-depth accident data of side collisions, indicated that a vehicle's forward velocity component in real world crashes can make the child head have contact with the car interior. In some of these accidents, the child head may be ejected out of the CRS shell, and make contact with the car interior. In the ECE R95 test, the MDB impacts a stationary target car with 90 degrees, and there is no forward velocity component to the target car structure and occupants. NHTSA conducted FMVSS214 full car side impact tests (MDB impact angle was 27 degree) with Q3s dummy in the rear seat [22]. In one of the tests, part of the Q3s head moved outside of the CRS side wing area and made contact with the door; however, the HIC was only 200. Bilston et al. [23] conducted a series of side impact sled tests using a Hybrid III 3YO and simulated rear door structure. In the sled tests with oblique angled acceleration (45 degrees), though the head moved outside of the CRS shell area, the head did not make contact with the door structure. From accident analysis, Arbogast et al. [4] pointed out that CRS misuse can be one of factors that lead to head contact with the vehicle interior. Yamaguchi et al. [24] carried out a car-to-car side collision analysis using a child FE model, and showed that the harness slack of the CRS could lead to the head impact on the door at high velocity. In order to reproduce head injury risks of child occupants in side collision accidents, it is necessary to examine the influences of CRS side wing shape, its energy absorption, oblique impact angles,

CRS installation system and CRS misuse on the dummy's head movement and injury measures.

CONCLUSIONS

An FF and RF CRS, and a car-bed restraint were tested with a Q3s child dummy or a CRABI 6MO infant dummy seated on the target vehicle's struck or non-struck side rear seat using a ECE R95 based side impact test. The results are summarized as follows:

1. The FF and RF CRSs installed on the struck side of the rear seat were impacted by the rear door at a velocity of about 9 m/s at the armrest location. At this time, the velocity of car's center of gravity was 2.7 and 2.8 m/s (FF CRS), and 4.1 m/s (RF CRS). The CRS made contact with the door armrest and the door beltline; then the pelvis, chest, and head were accelerated after contacting the CRS side structure.
2. In the FF and RF CRS installed on the struck side, the chest injury measures were relatively large, and the chest deflection of the Q3s in the FF CRS was comparable with the corresponding IARV, though other injury measures were less than their corresponding IARVs. The head made indirect contact with the door beltline through the side wing of CRS. The head was contained in the CRS shell during the crash event and the resulting HIC was small.
3. The loading on the CRABI 6MO dummy seated on the non-struck side was substantially small compared to that for the dummy seated on the struck side. For the CRS installed by a seatbelt, the CRS and the dummy rotated toward the impact side. Due to the large head displacement, the neck bending and twist moment was large.
4. For the child dummies seated in CRSs installed on the struck side, the pelvis acceleration of the Q3s seated in the ISOFIX FF CRS was higher than that of the Q3s seated in the FF CRS installed by a seatbelt, whereas the chest accelerations were comparable. For the child dummies seated in CRSs installed on the non-struck side, the head, chest and pelvis accelerations of the CRABI 6MO seated in the ISOFIX CRS were higher than those for the CRABI 6MO seated in a CRS installed by the seatbelt. This may be because the ISOFIX CRS with top tether moved from the initial phase of the impact and the CRS made contact with the dummy torso at a high velocity. However, the ISOFIX and top tether could prevent rotation and displacement of the CRS.
5. In the car-bed restraint test, the whole body of the infant dummy was contained in the CRS during the entire crash event; and all of the injury measures were less than the corresponding IARVs. However, the calculated force of the crotch harness was large and the bottom of the feet was directly impacted by the door, both of which might induce injuries to children.
6. By using the full car side impact test procedure based on ECE R95, the dummy's chest was substantially loaded in the

FF and RF CRSs installed on the struck side. The shape and energy absorbing characteristic of CRS side wing also can be an important factor for the head protection in the ECE R95 lateral impact test.

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