Evaluation of the dynamic rollover characteristics of trip-over vehicles through multi-body dynamics simulation

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ABSTRACT

Despite the high fatality rate due to rollover, this topic little features as a focus of research, when compared to studies on frontal and side collisions. As repeatability issues with the test have meant that there is not yet an established standard for dynamic rollover system that evaluates the safety of rollover of vehicles, the FMVSS 216a Static Roof Crash Resistance is currently applied.

The objective of this paper is to simulate the behavior of crash-test dummies and the deformation of a vehicle body by numerical analysis considering not only bending and torsional modulus, but also the collapse characteristics of main members.

We can find the effect of each member on the SWR of vehicle at the static test (FMVSS 216a), and the effect of SWR on the maximum acceleration value of head. The stiffness of the B-pillar is main member for increasing the SWR value as we know. Next, the A-pillar and center cross member. In terms of the maximum acceleration value of head, this value increases as the SWR of vehicle rises.

We conclude that there exists an appropriate modulus of members in order to decrease the maximum acceleration of head, and particular airbags need to sustain the pressure for about 3.5 sec in order to prevent the ejection of the crash-test dummies.

1. INTRODUCTION

Cars today are more than a means of transporting driver and passenger. They also provide an additional living space. Auto makers, therefore, are faced with a challenge to make cars that can provide not only good traveling performance, but also score well in terms of comfort, aesthetic design and safety. Of these three criteria, safety is particularly significant, as it is directly linked to the seriousness of injury that the driver might sustain in a car accident. In general, a car's safety is dependent on whether its body is designed in such a way that it can minimize the injury of the driver in the event of a frontal crash, side-impact or rear collision. Accordingly, a great deal of research has been devoted to this area, producing technologies that enable the design of highly safe bodies against those types of crashes. In contrast, rollover accidents have not been given as much attention as their proportion of total car accidents is relatively low and, as a consequence, regulations applicable to it are not stringent enough.

The number of fatalities in rollover accidents, however, has been increasing year after year, calling for greater focus. Statistics released in the U.S. show that nearly 250,000 rollover accidents occur every year nationally, claiming over 10,000 lives (35 percent). Rollover accidents in Korea, as in Europe, take up less than one percent of the total accidents, with fatalities from them accounting for around 7 percent of the total. Such a relatively low percentage can be attributed to different road structures and vehicle mix. In 2009, the Insurance Institute for Highway Safety (IIHS) added rollover test results to the criteria for the selection of the Top Safety Pick that already included frontal, side and rear impact

performance in an attempt to help reduce the facility in rollover accidents. Such a decision is significant in that it suggests the level of fatalities in rollover accidents is simply too high to ignore further.

One of the most common ways to reduce damage from car accidents is adopt active safety technologies that can prevent accidents from happening. Such advanced safety cars and intelligent cars, which have been emerging recently, are those which are equipped with such active safety technologies. Once an accident occurs, what matters is how safe the car's body is. The approach to securing safety in rollover accidents is largely centered on increasing the crush resistance of roofs, which is measured using a static, roof crush resistance test (FMVSS 216). This test, however, has come under severe scrutiny over its effectiveness in protecting occupants in actual rollover accidents. A dolly rollover test (FMVSS 208), which is a dynamic method to measure rollover safety, is often cited as an alternative, but is not widely used because of limited reproducibility.

It is widely agreed that occupant ejection and roof collapse are two major causes of passenger injury or death in rollover accidents as they actually occur on the roads. The National Highway Traffic Safety Administration (NHTSA) is striving to help reduce damage from rollover accidents by raising the minimum strength to weight ratio, which measures roof crush resistance, from 1.5 to 3.0, and requiring the adoption of electronic stability control (see FMVSS 126ESC). The installation of curtain airbags is mandated for selected models to prevent occupant ejection (see FMVSS 226 Ejection Mitigation). In addition, IIHS requires roof crush resistance of SWR=4.0 or higher. Due to this series of regulations, most vehicles launched these days meet the SWR=4.0 requirement and are equipped with various types of airbags.

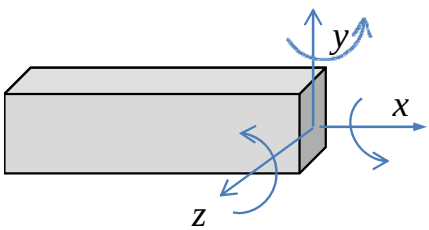
The purpose of this study is to find out whether improving roof crush resistance is the best way to protect drivers and passengers in rollover accidents. To this end, dynamic rollover simulation is carried out using multi-body dynamics. Many previous papers have examined the behavior of crash-test dummies and external forces applied to the body, but under the assumption that the body is rigid. In this study, in contrast, body modeling takes place based on the bending and torsional rigidity and the collapse properties of key body members, while the deformation of the body and the behavior of the dummy are observed in a rollover situation. The body is then subjected to a roof crush test (FMVSS 216a) to calculate its SWR. Trip-over, which is the most common type of rollover crash, is selected among others as a parameter for the controlled rollover impact system (CRIS). In order to find out whether vehicles with high SWRs also prove safe in a dynamic rollover test, the acceleration [head injury criteria (HIC) and thorax displacement of the dummy and the displacement of the A-pillar at its top are used.

2. MODELING FOR MULTI-BODY DYNAMICS SIMULATION

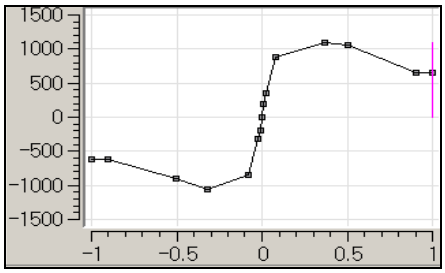
Creating a dynamic interpretation model based on the deformation of the body requires the rigidity properties of key body members to be taken into account. To this end, the bending and torsional rigidity of each pillar (A, B, C and D) and each crossbow (front, center and rear) should be calculated using the finite element method (FEM), whereby the collapse behavior of the members is taken in account.

2.1 Rigidities of member

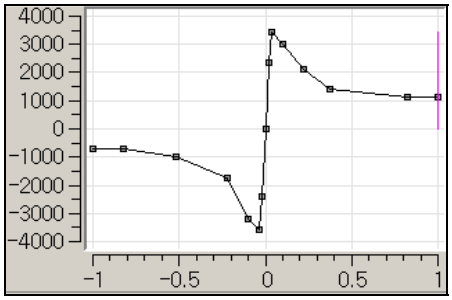
The key members of a car's body are of monocoque structure in the form of a thin tube and show a symptom of collapse beyond the level of maximum load that they can support. Figure 1 (b) through (d) shows examples of member rigidity properties obtained from FEM analysis. A load-deformation diagram is derived based on how the members collapse and applied to the simulation. Notation of axes is as shown in Figure 1 (a): x represents the longitudinal direction of the member; y the inside direction of vehicle; and z the remaining direction, the in-plane direction of vehicle surface.



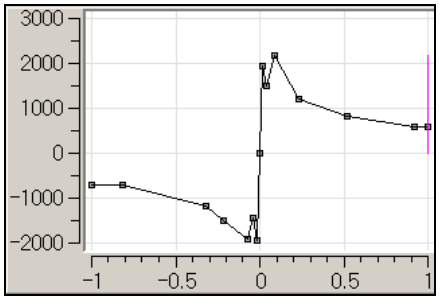
a) Notation of axes



b) Torsion about *x* axis vs. angle



c) Bending moment about *y* axis vs. angle



d) Bending moment about *z* axis vs. angle

Figure 1: Relationship between the bending/torsional moment and the deformed angle

2.2 Derivation of a characteristic curve

The following equations are used to realize the relationship between moment and angle displacement for each member obtained using the finite element method in ADAMS, a dynamic analysis program.

$$\dot{\beta} = \begin{cases} \left(1 - \left|\dfrac{k \times \beta}{T_{MAX}}\right|^{n}\right) \times \dot{\theta}, & \beta \times \dot{\theta} > 0 \\ \dot{\theta} & , \beta \times \dot{\theta} \le 0 \end{cases} \qquad (1.\ a)$$

$$T_{MAX}{}^{*} = \begin{cases} 1.0 T_{MAX}, & \beta \times \theta > 0 \\ 0.1 T_{MAX}, & \beta \times \theta \le 0 \end{cases} \qquad (1.\ b)$$

Figure 2 shows results from the modeling of A- and B- pillars' bending rigidity using the equations. It is assumed that spring-back takes place elastically during restoration until the load becomes zero and that one tenth the original load is required for restoration from bending backwards with deformation equal to zero.

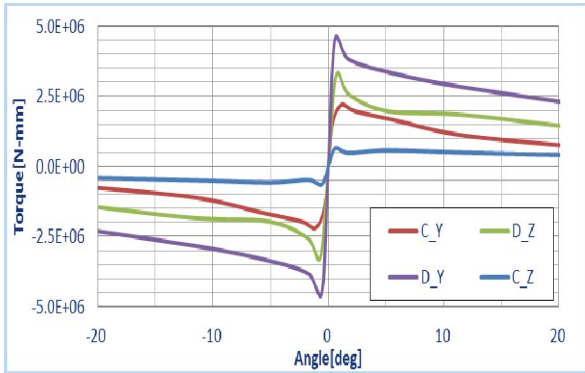


Figure 2 Bending rigidity of A- and B-pillar

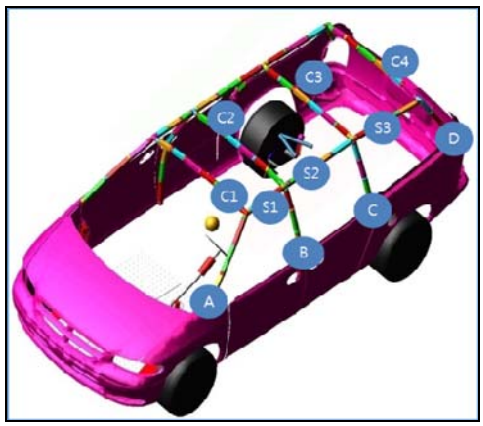


Figure 3 ADAMS Model of vehicle for simulation

The model of vehicle for simulating in ADAMS is consisted of members that consider the deformation of it. Here number of deformable members is 18 as shown in Figure 3. And the number of element of each member is chose to represent well the behavior of member.

3. SIMULATION OF ROOF CRUSH TEST (FMVSS 216)

3.1 Test protocol

Figure 4 shows how the roof crush resistance

testing (FMVSS 216) should be carried out in North America. This protocol requires that vehicles with a gross weight rating of 6000 pounds (2722kg) or less must endure load 1.5 times (SWR x 1.5) as much as their curb weight on their driver's seats and that the displacement of the roofs should be 127mm or lower.

In May 2009, NHTSA announced a tighter standard (FMVSS 216a). The requirement of new protocol (FMVSS 216a) is as follow: vehicles with a gross weight rating of 6000 pounds or less should endure a load three times (SWR x 3.0) as much as their curb weight; vehicles with a gross weight rating of 6000 to 10000 pounds (4536kg) should endure a load 1.5 times as much as their curb weight; head room maintenance is monitored through the use of a head form representing a 50th percentile male seated in the front occupant positions; and the platen force, displacement, and head form contact requirements must be met on both sides of the vehicle's roof structure. This standard must be complied with by all vehicles by 2016.

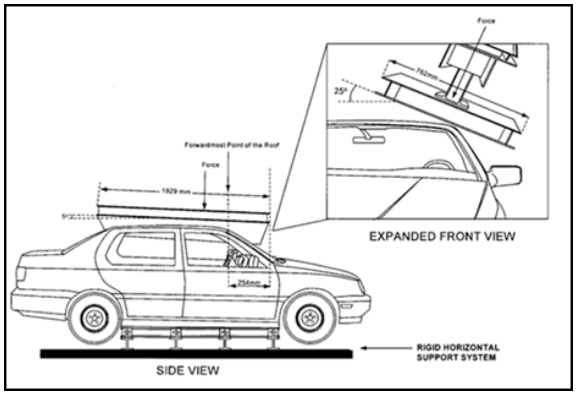


Figure 4 FMVSS 216 roof crush test protocol

Figure 5 Simulation conditions of the new roof crush test (FMVSS 216a)

Figure 5 shows how a simulation to obtain the SWR value (roof crush resistance) should be conducted using ADAMS in accordance with the new standard. The maximum displacement used in this simulation is the old threshold (127mm) for easier interpretation.

3.2 Results of simulation

Results of the simulation show that the loading curve of passenger section (right) is slightly lower than that of the driver section (left). Here the base model had original rigidities of members that were obtained from FEA. The peak load is also similar, but the location is little different. This is because the effect of geometric imperfection due to repeated load is not considered.

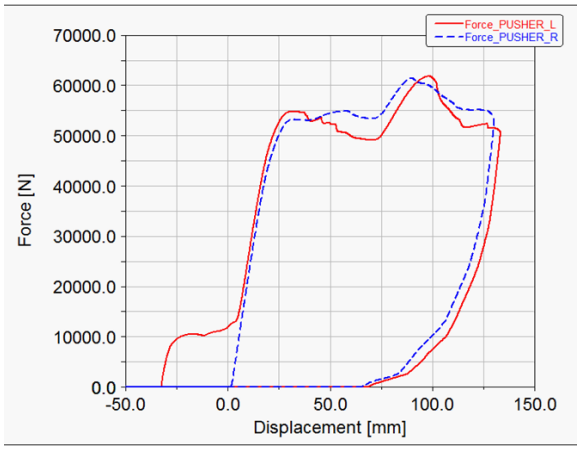
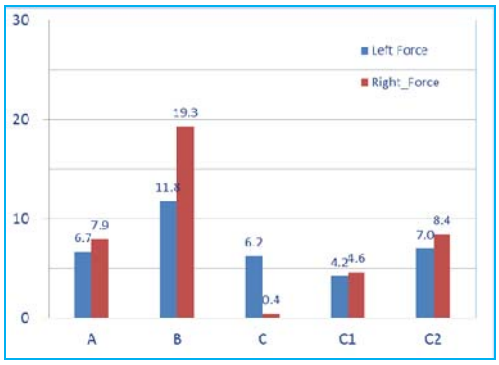
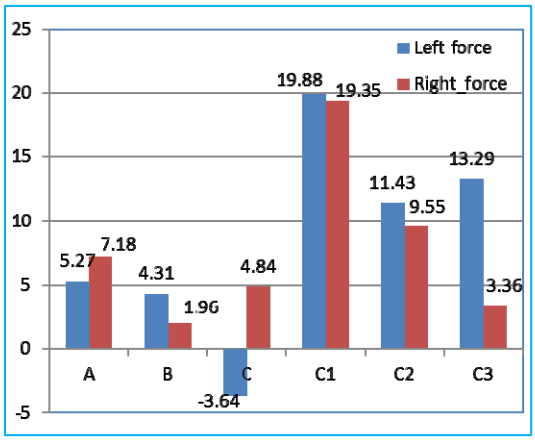


Figure 6 Simulation results of a basic model (FMVSS 216a).



a) FMVSS M216(near side; pitch 10°, yaw 25°, far side; pitch 10°, yaw 40°)



b) FMVSS M216a(both side; pitch 5°, yaw 25°)

Figure 7 Effect of design factors on peak load.

For FMVSS M216, calculation of the effect of key design elements that affect roof crush resistance, including A-, B-, and C- pillar, C1 and C2 roof bow, on peak load reveals that B-pillar has the largest impact, followed by A pillar and C2 roof bow (see Figure 7(a)). It is known that greater rigidity in the B-pillar results in an improved side-impact performance. As anticipated, greater rigidity of each member resulted in higher SWR for the roof. This suggests that SWR increases more effectively when the rigidity of A pillar, B pillar and C2 cross bow increases.

But for FMVSS 216a, quite different results are obtained. The roof bow elements affect seriously roof crush resistance.

4. SIMULATION OF CRIS (Controlled Rollover Impact System)

CRIS is one of the dynamic rollover crush resistance tests and has many benefits including multiple options available for road conditions and initial contact conditions. It however has a major shortcoming: repeatability is very low. Such a shortcoming can be overcome when simulation is used.

4.1 Simulation conditions

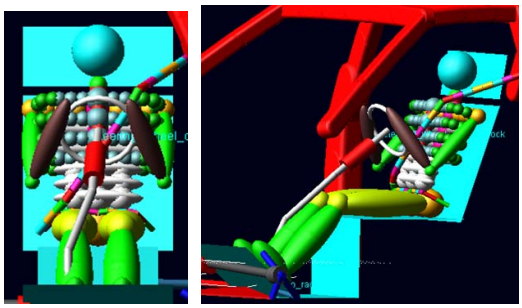
Table 1 shows the conditions under which a CRIS test is simulated in ADAMS. The initial contact with the ground is designed to take place at the edge of the near side as shown in Figure 8.

Table 1 Simulation conditions

- Angular velocity: 270deg/s
- Lateral velocity: 8000mm/s
- Weight: 2117kg
- Height of ground to COG of vehicle: 1264mm

Figure 8 Location of initial contact with the ground

A dummy used for dynamic analysis is placed on the driver's seat as shown in Figure 9 to calculate the change in head acceleration. Data used in the configuration of the dummy is from a 50 percentile hybrid, which can be used only for comparison due to its limited reliability.



a) front view b) side view

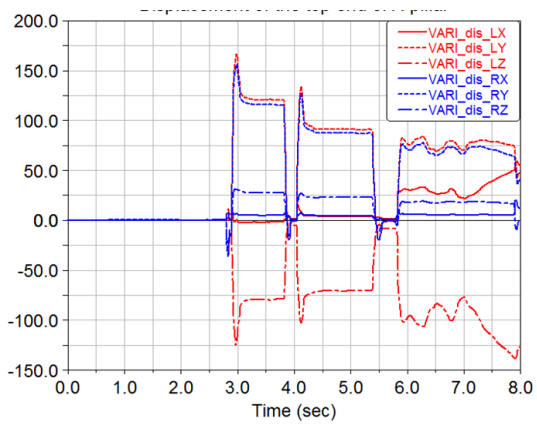
Fig. 9 View of dummy model for simulation

4.2 Simulation results

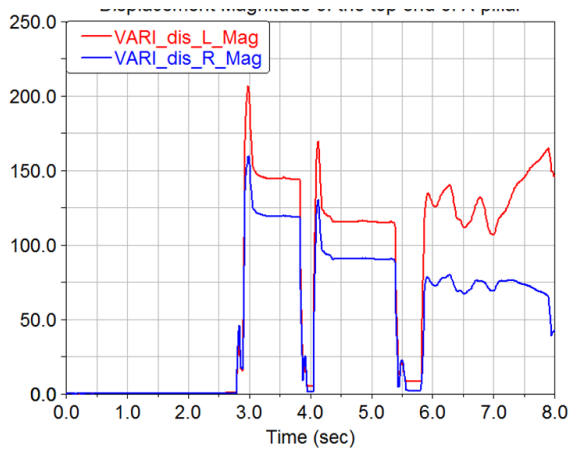
A simulation is conducted where SWR was increased to determine whether vehicles with a good roof-crush resistance prove to be safe in a dynamic rollover test. In order to determine the correlation between the results from a static roof crush resistance test and the result of a dynamic CRIS test, displacement at the point where the top end of A-pillar meets the front cross bow is calculated. Results are shown in Table2 and Figure 10. We may find that higher SWR, which translates into greater body rigidity, results in smaller displacement at the top end of A-pillar.

Table 2 Displacement of the top end of A-pillar vs. the value of SWR

Case (SWR)	Left Corner Displacement [mm]				Right Corner Displacement [mm]			
	x	y	z	Mag.	x	y	z	Mag.
1 (1.77)	11.5	227.9	-223.3	313.8	8.05	204.1	33.2	206.1
2 (2.66)	59.4	166.6	-138.7	206.7	20.4	156.5	31.1	159.5
3 (3.55)	17.9	146.3	-107.9	181.7	9.29	138.5	-40.6	141.5
4 (4.44)	18.4	134.6	-96.5	165.6	11.6	128.3	-38.3	131.1
5 (5.33)	18.6	126.9	-90.4	155.9	12.3	121.3	-25.5	124.1



a) Displacement components of the top end od A-pillar



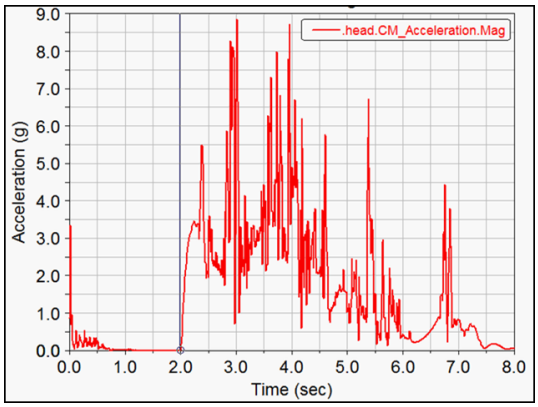
b) Magnitude of the top end od A-pillar vs. time

Figure 10 Displacement of the top end of left and right A-pillar for SWR=2.66.

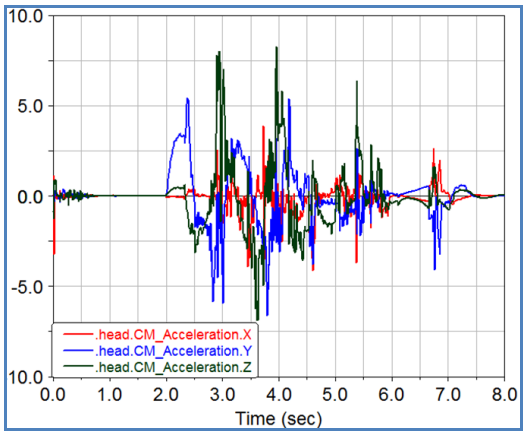
The next factor to be considered in a CRIS simulation is head acceleration. Figure 11 shows the change in head acceleration during rollover when SWR is 3.55. Table 3 shows how maximum acceleration changes for different SWRs. The CRIS simulation suggests that a car can roll over two to three turns in an actual accident and that the acceleration value of the head still retains significant influence. Figure 11.b demonstrates that the acceleration component in the y direction, which causes the dummy to be ejected from the vehicle, is significant (the rollover starts at 2 sec) within 3.5 sec. Therefore this suggests that curtain airbags should retain their pressure up to this point to fully protect the head. In addition, as shown in Table 3, excessively low SWR causes the roof to deform sufficiently to come into contact with the head, producing a greater acceleration value. Higher SWR therefore prevents contact between the roof and the head, resulting in lower acceleration. Increasing the body rigidity beyond a certain point, however, results in head acceleration increasing again, as shown in Table 3. Consequently, it can be inferred that each vehicle has its own optimal rigidity.

Table 3 Maximum value of the acceleration of head vs. the value of SWR

Case (SWR)	Acceleration of head [g]				Head contact with roof
	x	y	z	Mag.	
1(1.77)	-25.7	-47.2	70.4	80.95	contact
2(2.66)	4.58	-6.16	8.73	9.47	Not
3(3.55)	-4.11	-6.62	8.25	8.85	Not
4(4.44)	-3.97	-7.15	9.52	9.82	Not
5(5.33)	6.71	-10.1	8.87	12.67	Not



a) Magnitude of the acceleration of head



b) Components of the acceleration of head

Figure 11 Acceleration of head for SWR=3.55

4. CONCLUSION

For simulating the FMVSS 216 test, the plastic behavior of each member obtained from the FEA was considered. Additionally, the effect of each member on peak load was found. For M216 condition, the stiffness of B-pillar was found to be the most effective in increasing the SWR, while second was A-pillar and center cross member (C2). The stiffness of all members was a positive factor. For 216a condition, the stiffness of roof bow members was found to be the most effective in increasing the SWR.

A correlation was found between the SWR in FMVSS 216 simulation and the displacement of A-pillar end-point in the CRIS simulation. The displacement of A-Pillar high-end was found to decrease as the value of SWR increases. Nevertheless, the acceleration of the head does not always decrease as the SWR increases. One of the reasons for this is that the head comes into contact with the ceiling due to the large deformed frame. An additional factor is the difference in the energy absorption capacity of the vehicle in question. In other words, vehicles with a high SWR can absorb reduced impact energy compared to those with lower SWR.

Consequently, there exists an appropriate modulus of members for decreasing the maximum acceleration of head, and the pressure of a curtain airbag needs to be sustained about 3.5 sec in order to prevent the ejection of crash-test dummies.

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