STUDY OF OPTIMAL BODY STRUCTURAL DESIGN FOR COUPE-TYPE VEHICLES IN ROLLOVER EVENTS

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ABSTRACT

Many types of car crashes can occur on the road. One of the most critical crash types that can happen in the real world is rollover. Unfortunately, analyzing the exact fundamental principle of a rollover incident is difficult and complex. Despite its rise in severity as a serious injury collision, there have been few attempts made to analyze rollover. A stronger vehicle structure corresponds to more efficient protection for the passengers. A two-door coupe or a central pillar-less body vehicle can be subject to more severe conditions in the event of a rollover. Reinforcing the side and roof structure of the body is important to secure safety. This paper presents observations from many case studies and actual tests. Central to this paper is an experimental study on the load redistribution effect. A brief overview is given on analyzing roof crush test results, and the optimal structure is investigated in greater detail.

MOTOR VEHICLE ROLLOVER COLLISION AND ROOF CRUSH TECHNOLOGIES

Rollover crashes make up a relatively small proportion of all collisions around the world, but have a disproportionate share of fatal and serious injuries occurring in rollover crashes. For example, rollovers constitute less than 4% of accidents in the USA each year but almost 36% of all fatalities. Recently, there have been many efforts to protect passengers in rollover. There are three major contributors: (1) electronic stability control (ESC) technology, (2) roof crush strength, and (3) head ejection mitigation. The National Highway Traffic Safety Administration (NHTSA) has created rules for all three elements.

(1) ESC technology: Apply the brake on each of the four wheels individually to prevent rollover.
(2) Roof crush strength: Preventing the vehicle structure from collapsing during rollover.
(3) Head ejection mitigation: Prohibiting the passenger from ejecting out of the car.

The purpose of this paper is to propose the optimal body structural design by assessing the roof crush strength. Roof crush strength will be addressed in this paper with the focus of optimal body structure design. In order to reduce the amount of rollover roof deformation, which is measured as roof deflection or residual headspace, the NHTSA instituted the Federal Motor Vehicle Safety Standard (FMVSS) 216 as a final rule in May 2009, and the Insurance Institute Highway (IIHS) has also adopted their roof crush evaluation as a requirement for the top safety pick (TSP). These two tests are not exactly same but use similar procedures to check if survival space is well enough to mitigate passenger injuries with reasonable roof strength.

ROOF CRUSH SCIENCE

Even though the static roof crush test system has been around for a long time, it is a good tool to evaluate the strength of side and roof structure from the test repeatability and experimental reliability point of view. From a holistic perspective, a brief overview of the general features of the roof crush test system is needed before analysis of the optimal vehicle structure design.

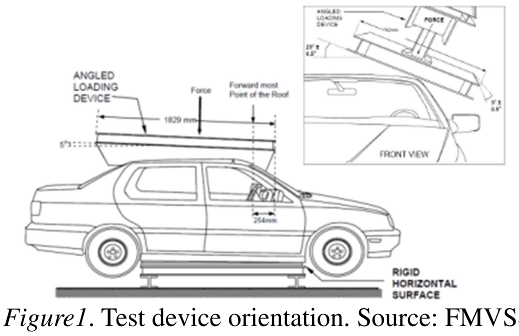


Figure1. Test device orientation. Source: FMVSS 216.

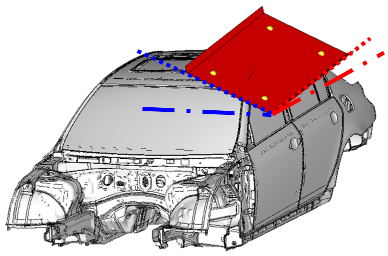


Figure2. Illustration of roof crush test.

Testing is performed with the test vehicle secured rigidly to eliminate suspension influence. The lower surface of the test platen is aligned with its forward edge 254 mm in front of the forward-most point of the roof, while its longitudinal centerline is parallel with the vehicle's longitudinal centerline and centered either with the initial roof contact point or at the center of the roof contact area. The lower surface of the test platen is oriented at a 5° pitch along its longitudinal axis and 25° roll along its traverse axis (see Figures 1 and 2). A general roof crush plot (force vs. displacement) is shown in Figure3.
Here, the general plot can be divided into 5 sections describing the behavior of the vehicle structure based on the slope of the stiffness. Each section is split by the amount of travel by the test platen. Even though the test results vary depending on the vehicle type and structure, the general characteristics of each section are as follows:

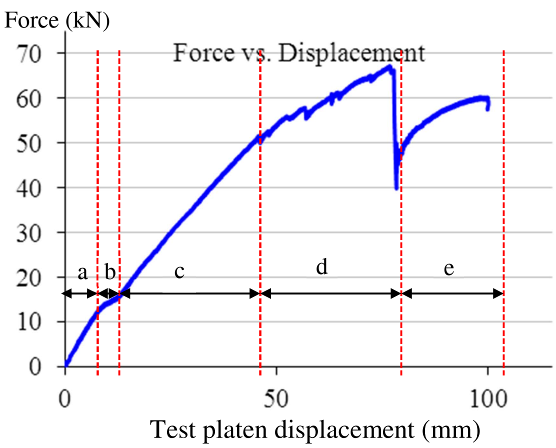


Figure3. Example of a general plot.

a. Section 0–10 mm

At the beginning of the test, the outer shell and inner reinforced panel of the vehicle are squeezed. As the outer panel is not actually a load-resisting material, the reaction force on the entire testing section is relatively small.

b. Section 10–15 mm

The reinforced panels that constitute the front pillar and upper body structure are crimped. A reaction force appears in the form of a cubic curve through the inflection point of the slope. The deformed shape is shown in Figure 4. Sometimes, this section is difficult to discern. In rare cases, some vehicles do not have this characteristic. On average, vehicles have a range of 1–2 mm. This section is important as a preliminary step for a vehicle to resist a larger reaction.

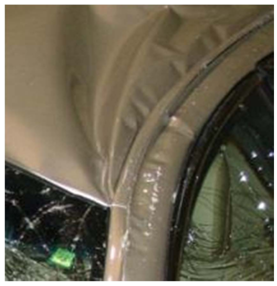


Figure4. Compressed shape of inner and outer panels.

c. Section 15–50 mm

This section should sustain a full-scale load. Each upper body member has to distribute the incoming load from the loading device efficiently. They share the task as if they are a single member of the framework. The slope is steep. The reaction force slope, which appears as almost a straight line, is very important to determining the characteristics of the vehicle. Vehicles often have their own unique slope in this section. If two vehicles have the same outward appearance, but different slope characteristics, it can be considered that they have different reinforced member designs..

d. Section 50–80 mm

Upon deflection of the vehicle structure, unlike the previous section each panel and structure behaves in different ways. Each structure is an important element to making the vehicle strong enough to withstand outside loads. The slope gradually becomes gentle.

e. Section over 80 mm

When the windshield glass cracks, many reinforcement members have collapsed. At this point, the maximum reacting load occurs. Although glass is a brittle material, it tends to bear significant loading until it breaks. Figure 5 shows the breaking point of glass.

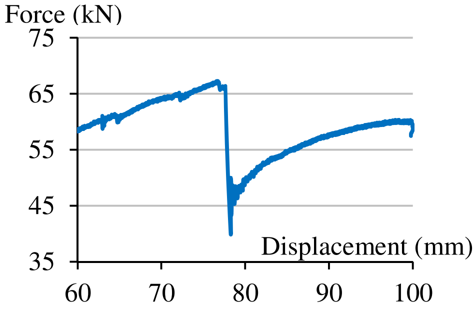


Figure5. Example of a glass breaking point.

In terms of load dispersion, the most important thing is to determine how to make every different structure component works together as a single member and react with steep slope at section c(50-80mm).

GENERAL VEHICLE STRUCTURE

A vehicle is composed of not only large structures but also many small parts. A good load path design of the vehicle is desired that can efficiently disperse an incoming force in all directions. When rollover occurs, the main elements that withstand the external force are the front roof rail, front pillar, and center pillar. A coupe-type vehicle compared with other vehicle types (sedans, SUVs), has a different design. The center pillar has been pushed reward to allow for access to the back row. The center pillar is located relatively far in the back; in some cases, there is no center pillar to support the roof. An example vehicle is shown in Figure 7.

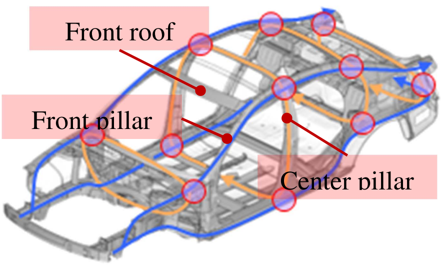


Figure6. Example of body in white (BIW)

Figure7. Example of center pillar-less design.

As these kinds of vehicles are vulnerable to outside crash forces and find it difficult to protect passengers, a good design that makes the body stronger is needed. To study the optimal body structural design for coupe-type vehicles, we considered some vehicles that showed a high strength-to-weight ratio (SWR) in roof crush tests.

STRUCTURAL CONCEPT OF COUPE-TYPE VEHICLES

The goal of this study is to make a stronger vehicle upper body by reducing the number of reinforcement parts and without increasing the overall weight. To do so, it is more important to precisely know which components affect roof crush performance critically..

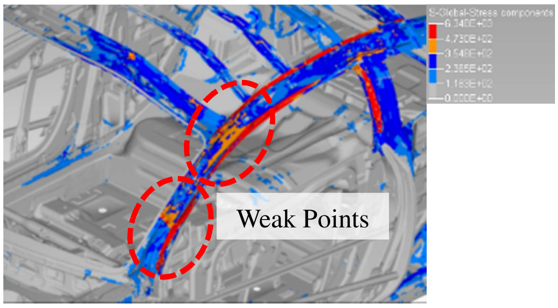


Figure8. Weak points in roof crush test.

According to CAE analysis, the main parts that take the most of the stress are at the bottom of the front pillar and the connection points of the top of the front pillar and the front roof rail. Figure 8 shows these tendencies. If these parts collapse in the beginning of the test, it is expected not to get a SWR value high enough to sustain adequate vehicle's strain energy of distortion. There have not been many coupe-type vehicles that have been evaluated for strength of their roof and side structure. Thus, a vehicle tested by IIHS for roof strength was chosen to show the difference between strong and weak structures. An example of a well performing vehicle is examined in detail as Figures 9 and 10 show the summary of its roof crush test.

Even though this vehicle does not have a center pillar connecting some side components to the roof structures, the vehicle has body stiffness with a SWR of 5.58.

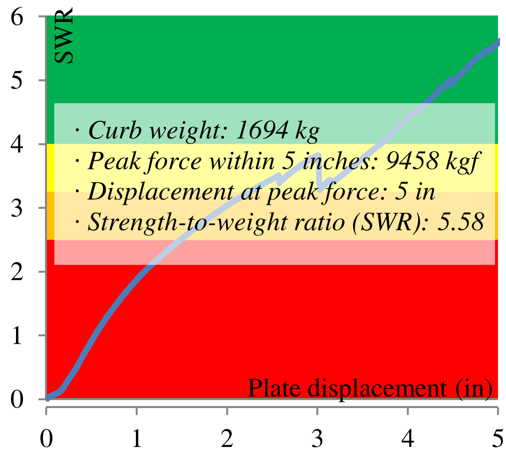


Figure9. Roof crush result. Source: IIHS, 2010.

Figure10. Post-roof crush test. Source: IIHS, 2010.

This means that the front pillar and connection between the front roof rail and upper side structure contribute more to sustain external force. It can tentatively be concluded that the connectivity between front pillar and roof side structure play an important role in determining the rigidity. Undoubtedly, a better option would be to employ the main parts as simple as possible.
It was figured out that this vehicle is composed of a few simple panels and a partially reinforced part. An example design is shown in Figure 11.

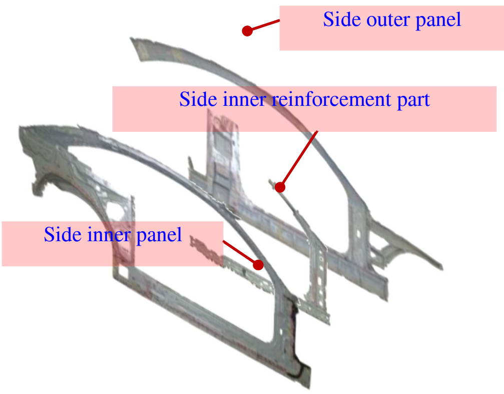


Figure11. Example vehicle with a simple structure.

As shown in Figure 11, the vehicle structure looks very simple at the surface, but the reinforced items are concentrated at load-bearing areas. In other words, the side inner reinforcement part is stronger than the others. To check the quality of the main material, tensile tests and analysis of major chemical components were conducted. The collected specimens for tensile tests of the reinforcement panel were cut into sub-sizes as specified by the American Society for Testing and Materials (ASTM). The specimen is shown in Figure 12.

Figure12. ASTM sub-size specimen.

The engineering stress of these specimens was estimated by using the stress–strain curve (S-S curve) shown in Figure 13.

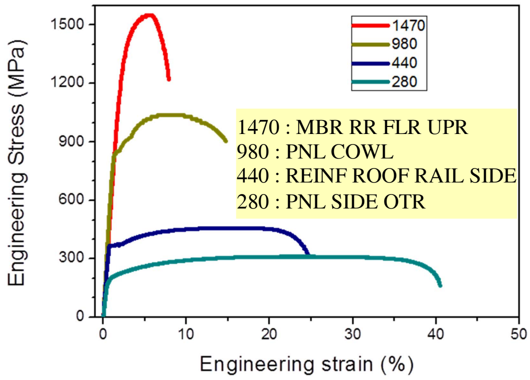


Figure13. Representative stress–strain curve (steel grade).

Also, to verify the quality of material, a chemical analysis was conducted. In addition, the major elements of carbon(C) and sulfur(S) were evaluated with extra measurement for the precision measurement. The main reinforcement is shown in Figure 14.

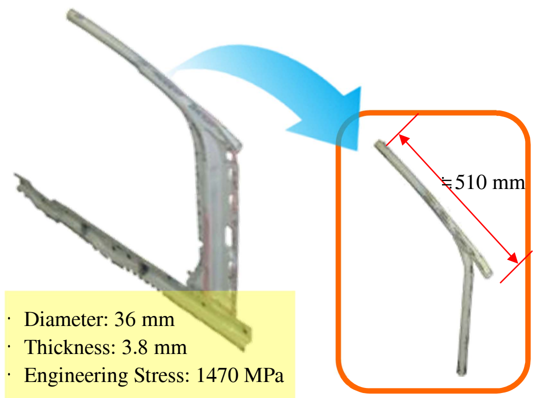
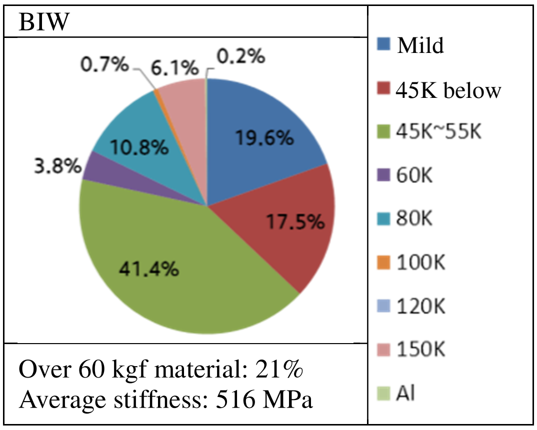


Figure14. Example of side inner main reinforcement.

For reference, Table 1 summarizes the quality of the materials in this vehicle.

Table1
Summary of material quality for vehicle



To implement this structural concept into the vehicle, a coupe-type model with a relatively weak structure in production since 2008 was chosen. This vehicle had a SWR of only 2.8. After remodeling the side structure based on the already mentioned concept, even though the number of side structure components are decreased from six to two parts. The strength of body was increased from SWR of 2.8 to an SWR of 4.2. The total weight of reinforcement was kept almost the same, about 11 kg. Figures 15 and 17 show this concept.

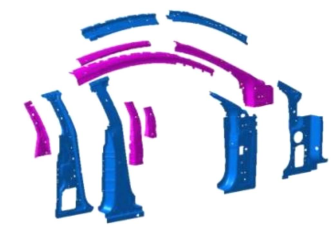
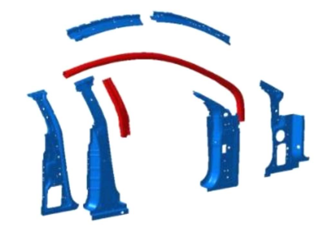
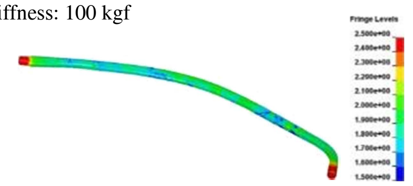
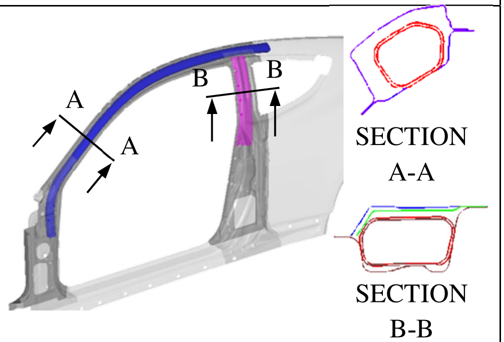
Original side structure design	
-Components: 6 -Weight: 11.7 kg	
Modified side structure design	
- Components: 2 - Weight: 11.8 kg	

Figure15. The concept of side structure.

The hydro-forming method was used to replace the many parts that made up the side structure with a simple closed pipe. Table 2 presents an illustration and specifications of this component.

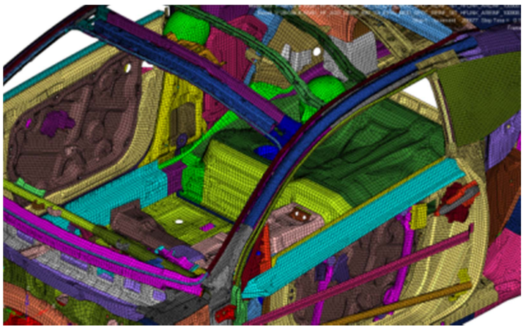
Table2
Main inner reinforcement part with using hydro-forming method

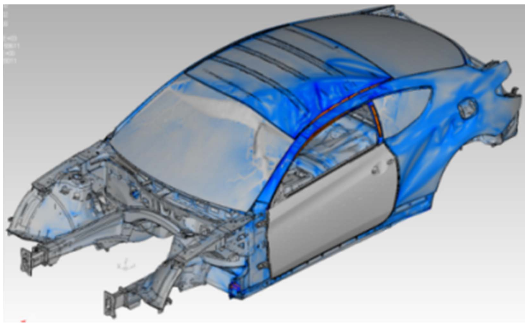
	Reinforcement in the front pillar
SPEC	Φ48.6 mm × 2.0 mm thickness × 2200 mm Stiffness: 100 kgf 
APPLICATION	

Because combining the closed pipe made by the hydro-forming method with the inner panel or other parts with the standard spot-welding method was difficult, the one-way spot-welding method should be used. This welding method is shown in Appendix A.

ANALYSIS AND FE MODEL SIMULATION

Nonlinear characteristics are largely divided into three categories: geometric nonlinear characteristics, nonlinear characteristics of materials, and nonlinear behavior due to contact. In the roof crush test, nonlinear finite element analysis was performed because all three attributes are mentioned above. The ABAQUS version 6.9EF computational model was used as the finite element analysis software for the structural response. Figure 16 illustrates the deformation between the base and improved vehicles.





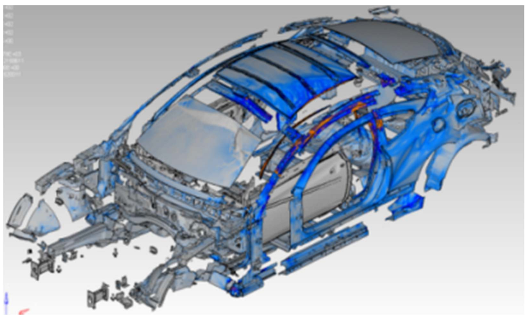


Figure16. FE model simulation: final deformation at end of test (travel range of loading device was 127 mm).

These simulations showed different structural responses by these vehicles. To compare the deformation of different the simulation results were captured by the SWR range for each vehicle and are listed in Appendix B. The travel ranges of the loading device results based on SWR are listed in Table 3 and plotted in Figure 17.

Table 3
Test platen displacement based on SWR

	Vehicle		**Remarks**
	Base vehicle	**Improved vehicle**	
SWR	**Displacement (mm)**		
0	**0**	**0**	
0.5	10	12	
1.0	23	22	
1.5	43	32	
2.0	**71**	**43**	
2.5	100	56	
2.8	**122**	**70**	**Max**
3.0	n/a	72	
3.5	n/a	87	
4.0	n/a	108	
4.2	n/a	**124**	**Max**

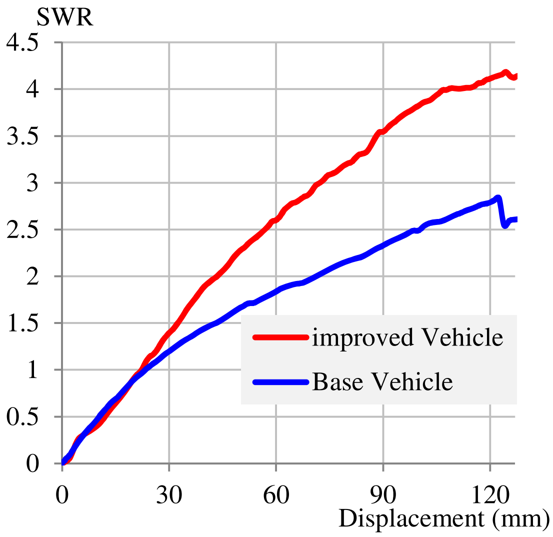


Figure17. Plot of SWR vs. displacement (displacement is travel range of loading device).

The displacement was measured by the amount of travel range of the loading device. Starting from SWR 0.0 to SWR 1.0, the structural responses of the vehicles were not so different. The amount of deformation does not seem to be a great difference either. But after SWR 1.0, the absolute amount of deformation of each vehicle increases respectively.

At the point of SWR 2.0, the base vehicle needs 127mm of loading device travel. However, the improved vehicle needs only 70mm. In the mean time, the strength of body, as have been noted above, is increased 150% during the testing from SWR 2.8 to SWR 4.2. These results show that if a vehicle has strong enough structure to resist outer load, it is easy to get a high SWR value in the beginning of roof crush. The earlier to reach the vehicle's maximum roof strength the more the vehicle can secure the occupant's safety compartment. When rollover happens, the amount of occupant's head clearance is an important element to protect occupants. In this extra space area, vehicle can use many high-tech safety gadgets, for example, rollover sensors, side airbags, or multi-link seat belts.

CONCLUSIONS

The conclusions which can be drawn from this study are these:

1) A strong A & B pillar ring is the most important component of robust roof strength.
2) Components and systems of the vehicle should be well designed to absorb or distribute the energy of roof crush in order to prevent intrusion into the occupant compartment.
3) The strength of the inner reinforcement parts in the front pillar is a core element that determines the vehicle's roof stiffness. Each part around the door openings should be well connected as a circular linked structure with the high-density spot welded joint. (Examples – front roof rail, A&B pillar, front header)
4) The balance between the front pillar and roof rail is very critical. In other words, overall roof strength will be weak, if relatively some weak points are collapsed. The balance of strength can be determined by the amount of buckling through CAE model.

All of these efforts are to protect occupants preserving space in the event of rollover. To ensure safety, adequate body stiffness is an essential condition in rollover accidents.

There have been many efforts to make new advances in rollover testing modes. The repeatability and reliability are core aspects of in-house modified tests. NHTSA, along with other organizations, makes great efforts to develop new modified rollover protocols. However, a number of problems remain to be explored because rollover accidents occur under many complex conditions, which are difficult to identify as the sole reason. Firstly, the typical main elements that cause a rollover accident should be carefully confirmed. Secondly, a reasonable and trustworthy testing facility that can represent rollover accidents should be constructed using the verified elements. Only after a vehicle's adequate stiffness is secured can other safety equipment be developed step by step. This paper lays the foundation for future work with regard to vehicle strength. Future research will involve the correlation between dynamic rollover tests and quasi-static roof crush tests in terms of stiffness. The occupant behavior in a vehicle when rollover happens will be a sequential task.

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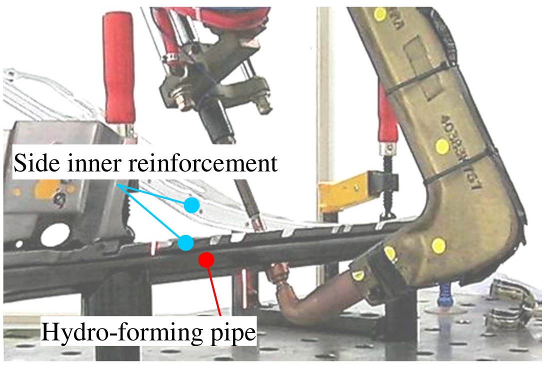
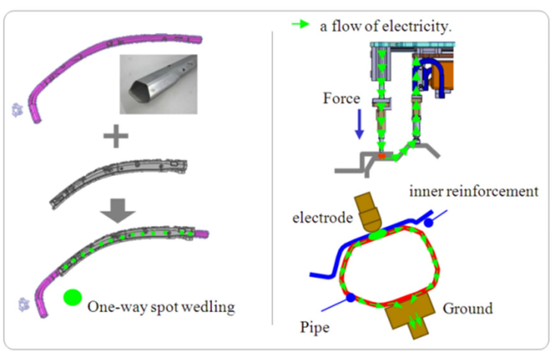
APPENDIX A

One-way spot welding method





APPENDIX B

Simulated deformation of base and improved vehicles by SWR