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# Analysis of Changes in Roof Crush Resistance of a Vehicle with the Roof and A/B-pillar Repaired after an Accident Following a Subsequent Accident

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***Abstract*—As the automobile has become a major form of everyday transportation, more and more passenger vehicles are on the road each year. Drivers are increasingly at risk of being involved in accidents, and their carelessness behind the wheel often leads to accidents. Most accidents are caused by forward, rear, or side collisions. In the case of a forward collision, the passengers can be protected with the help of the vehicle's frame and engine room to some extent. In case of a rollover accident, the overall stiffness of the vehicle's roof, doors, and pillars ensures that the roof can meet the desired strength requirement, as in a side-collision accident. Roof crush tests are performed to determine whether vehicle's safety cage is sufficiently stiff and rigid to maintain a safe space in the passenger seats in case of an accident. In case of a deformed roof, the vehicle is repaired in a repair shop. Welded joints of the roof replace it with a new one, or they may cut out and repair the damaged pillars & weld back to the roof. These operations, however, may damage the major parts of the car, thereby leading to its depreciation or raising concerns about its overall performance and safety. In this regard, in the present study, roof crush tests were simulated in the same conditions as in actual test environments. The damaged parts and their status before and after being repaired were simulated and analyzed using a commercial simulation software package.**

***Index Terms*—accident history, body damage, body repair, deformation, depreciation, roof crash resistance, welding**

## I. INTRODUCTION

As the automobile has become a major form of everyday transportation, more and more vehicles are on the road each year. Many drivers are at risk of being involved in accidents. Carelessness behind the wheel often leads to accidents in practice. In general, most accidents are caused by forward, rear, or side collisions. In the case of a forward collision, the passengers can be protected by the vehicle's frame and engine room to some extent. When a side collision occurs, the stiff doors or pillars of the vehicle may protect the passengers from external impact. In the case of a rollover accident, the overall stiffness of the vehicle's roof, doors, and pillars ensures that the roof can meet the desired strength requirement, as in a side-collision accident. Roof crush tests are performed to determine whether a vehicle's safety cage is sufficiently stiff and rigid to maintain a safe space in the passenger seats in the event of an accident. When a vehicle's roof is deformed due to an accident, the vehicle is sent to an auto repair shop for repairs. Mechanics may remove the welded joints of the roof using a drill to change it with a new one, or they may cut out and repair the damaged pillars and weld them to the roof again. These operations, however, may cause damage to the major parts of the car, thereby leading to its depreciation or raising concerns about its overall performance and safety [1]-[5]. In the present study, a semi-midsize sedan currently on the market was selected, and roof crush tests were simulated on the vehicle in the same conditions as in actual test environments using various data, including the vehicle drawings and materials specifications. The simulations were conducted in the same way as actual vehicle tests. The damaged parts of the roof and their status were examined. A finite element analysis was then performed on the parts after the repair process using LS-DYNA and Hyper Works, which are commercial software packages, and the results were further analyzed and compared.

More specifically, changes in the vehicle status resulting from the exchange of the roof and pillars were analyzed. Also, the effect of the load caused by external forces on the stiffness of the vehicle body was simulated and analyzed. Generally, the roof portion of a passenger car is reinforced by bending its steel plates or forming them into concave and convex shapes, and these structures are connected to each other through members. A monocoque body was used, to which the side panels and rear panels were welded and sealed to ensure that the required stiffness can be achieved. In automobile assembly plants, spot welding and sealing operations are conducted using various jigs to mass-produce these monocoque bodies. A vehicle's roof serves a very important role in protecting the passengers from the

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external impact exerted on the vehicle when a rollover accident occurs. Thus, it should be able to maintain its strength, especially in an emergency. When the roof and pillars, which are the main structural parts of a vehicle, are deformed, both the outer and inner panels of the vehicle are likely to be subject to deformation at the same time [4][6].

When a vehicle's roof is deformed due to an accident or the driver's carelessness, mechanics repair it by pulling or stretching the affected part using a jig to shape it into its original form, cutting out the damaged and deformed portions using a saw or cutter, and welding them, if necessary. The damaged parts are removed, and new parts are CO2-welded or spot-welded in the same places as the original locations. The welded joints are ground to ensure smooth surfaces, and the ground surfaces are filled and smoothed with putty and then painted. This is how a damaged vehicle roof is repaired [5][7].

In the present study, we focused on what would happen to a vehicle that had been repaired after a rollover accident if it was involved in another accident, especially with regard to passenger safety. We attempted to determine how the overall stiffness of the vehicle body would be affected after the second accident and compare it with its original status when the vehicle was first produced.

## II. ROOF CRUSH TESTS

Roof crush tests are performed to determine the ability of a vehicle's roof to protect the passengers from death or injury when a rollover accident occurs. More specifically, vehicle roofs are tested to determine whether they are strong enough to bear a load that is 1.5-3 times the empty Vehicle weight.

The standard static loading device is composed of a rigid, non-refracting rectangular block with dimensions of 762 mm × 1,829 mm. The device is placed on the front edge of the roof, and it must not be displaced from its proper position by 127 mm or more to ensure that the resistance load requirement can be met. The required resistance load corresponds to the unloaded vehicle weight (UVW) of the test vehicle or 17,216 Newton multiplied by 1½. The length, orientation, and major axes of the test device are configurator as follows. When viewed from the side, the bottom plane of the device should be inclined downward by 5 degrees from the horizontal surface. Also, the transverse direction of the device's bottom plane should be parallel to the vertical plane perpendicular to the longitudinal direction of the vehicle. When viewed from the front, the transverse direction of the device's bottom plane should be inclined downward by 25 degrees from the horizontal surface. The experimental setup and components are shown in Fig. 1 [8][9].

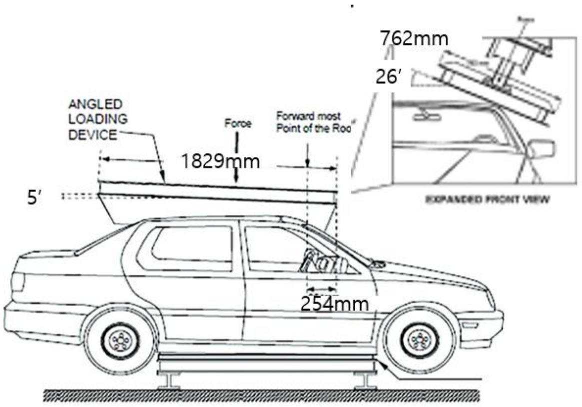

Figure 1. Test device orientation for FMVSS216.

The point or the centre line of the plane where the test device and the vehicle surface meet should be on the central longitudinal line of the device's bottom plane. Also, the distance from the very front of the device's bottom plane to the point where the bottom plane and the very front of the roof meet should be 254 mm, including the trim part that fills the gap between the body panel and the windshield end. The bottom plane of the test device is a rigid block with dimensions of 762mm × 1,829mm. Until the applied load reaches 1.5 times the vehicle weight or 1,721 kN, whichever comes first, the displacement of the roof should be kept below 127mm. The size and operating angle of the experimental setup are shown in Fig. 2.

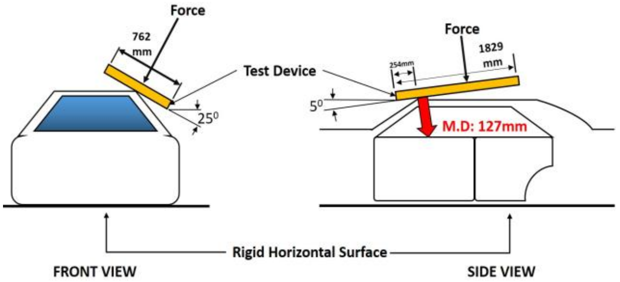

Figure 2. Test device orientation for FMVSS216.

When the applied load is 17,216N or less, instead of the 127 mm displacement threshold, the following standard applies. The load is applied while an adult male dummy is seated, and the threshold is defined as the displacement immediately before the dummy's head comes into contact with the interior roof of a vehicle. In the present study, vehicle crash tests were simulated and analysed. These tests were conducted in accordance with the test methods provided in "Roof Crush Resistance" of the Federal Motor Vehicle Safety Standard (FMVSS) 216. These tests, which generally involve the measurement of displacement, assess how much force a vehicle's roof structure can withstand, relative to the weight of the vehicle.

## III. Sructure and Repair Method of Roof and Pillar

### *A. Roof Structure*

The structure of the roof (i.e., the A,B,C Pillar & front and rear of door) is required to have sufficient rigidity to keep passengers safe in the event of a rollover accident or falling objects. It is supported by the left and right pillars and protects from external impact. Generally, the pillar part is made of high rigidity material, and three reinforcing plates are installed as separate reinforcements to maintain the strength of the ceiling in the middle of the roof. In addition, small stiffeners were attached to the front and rear parts to maintain the strength of the ceiling. In the analysis, a bracket that maintained the rigidity of the roof was set, and the spot welded part was separately marked for modeling. The modeling of roof when the structure interpretation is applied are shown in Fig. 3. Actual roof damage is shown in Figs. 4 and 5.

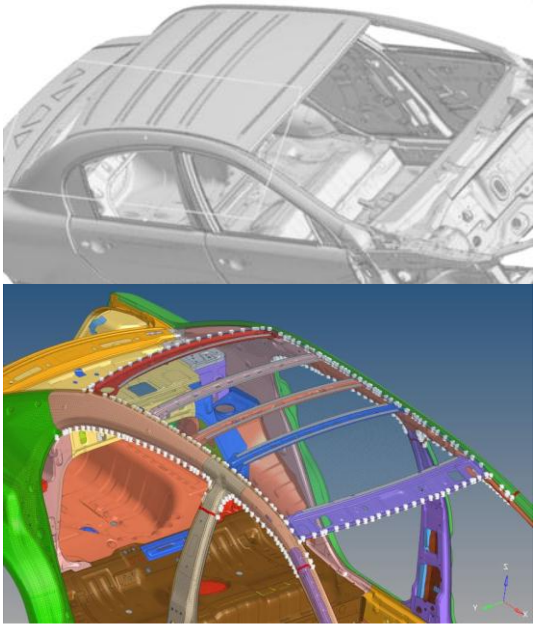

Figure 3. Shape and interpretation plots of Roof.

### *B. Roof Repair Method*

#### *1) How to repair a damaged roof*

##### *a) Sheet metal correction*

i. Check the condition of the damaged roof and panel
ii. parts with the unaided eye.
iii. If sheet metal correction is applicable, restoration of the damaged part is carried out by applying tensile force using a tool.
iv. Correct the deformed or damaged part by applying
v. heat using an oxygen welding machine or sheet
vi. metal straightening equipment.
vii. Make sure that the lengths and angels are
viii. well-matched, and the surface is even and smooth.
ix. Perform sealing and painting operations.

##### *b) How to repair damaged roof and pillars that cannot be restored*

i. Remove the welded joints of the roof using a drill or perforator.
ii. After drilling out the welded joints, remove the part.
iii. Locate the damaged portion of the pillars and correct it, if applicable.
iv. If not, cut it out and prepare a new part of the same size. Weld it in the same place.
v. Make holes in the new part using a drill. Machine the part to ensure that it can be properly placed in the same place as the original one. Assemble the part by $CO_2$ welding or spot welding shown in Fig. 6.
vi. Grind and seal the welded joints and perform painting operations shown in Fig. 7.

Figure 4. A vehicle with a damaged roof.

Figure 5. A vehicle with the damaged roof removed.

Figure 6. A vehicle with a new roof installed.

Figure 7. Painting operation following the roof repair.

## IV. TESTS

### A. *Test Vehicle Specifications*

A car currently on the road in Korea was selected as the test vehicle for the present study. Vehicle specifications are shown in Table I. The actual welding data provided by Kiswel, a manufacturer of the welding rods used in the actual welding process, was applied in our finite element analysis. The tensile strength test data were obtained from the Korea Testing Certification [10].

TABLE I. TEST VEHICLE SPECIFICATIONS

| Specification | Vehicle |
|---|---|
| Weight (kg) | 1170 |
| Engine Type | 1.8L L4 |
| Tire Size | 195/60 R15 |
| L*W*H (mm) | 4511*1745*1482 |
| Wheel Base (mm) | 2610 |
| Wheel Track (mm) Frt/Rr | 1483/1493 |
| CG Reward of Frt Wheel C/L (mm) | 1069 |

### B. *Result of Tensile Test*

In the tensile strength test, it was confirmed that the stiffness decreased after repair by $CO_2$ welding compared to spot welding at the factory. The result of tensile test is shown in Table II.

TABLE II. RESULT OF TENSILE TEST-NORMAL VEHICLE: REPAIR WELDING CO2

| Unit | Thickness | Width | Distance | Max Test Force | Max Stress | Elastic Rate |
|---|---|---|---|---|---|---|
| | mm | mm | mm | KN | $N/mm^3$ | $N/mm^2$ |
| **Spot** | 1.69 | 23.8 | 50 | 4.351 | 108.189 | 6.8 |
| **$CO_2$** | 1.99 | 25.1 | 50 | 4.69 | 93.75 | 6.8 |

### C. *Finite Element Analysis*

In the finite element analysis, modeling was performed on the CAD data. The mechanical properties of each part of the vehicle, tensile test results, and various parameters related to the test method were applied in the modeling process. Also, the collision images and actual vehicle data were compared for the verification of the modeling results.15) All data were analyzed and assessed in accordance with the designated test method. The initial parameters for the modeling procedure, such as the thickness, mass, and gross weight, were set to those of the actual vehicle. Finite element model results were analyzed according to the procedures provided in the table below. First, the *Clean up* and *Mid Surface* elements were extracted by applying the CAD data to all the parts of the vehicle body. The size and angle of the barrier were then described in the same way as the modeling and test conditions of the roof and panels, and the shell and solid elements were accordingly determined. After that, the boundary points for the materials and properties were examined, and the necessary assumptions and boundary conditions for roof crush tests were defined. Also, the welding properties were applied to ensure that the tests can be carried out in accordance with the test standards. In the finite element analysis, the analytical model used for actual roof crush tests was employed. The applied analytical model was composed of various parameters, including the Body in White (BIW), front & rear Doors, tailgate, IP structure, and windshield, and the following conditions were applied: CVW = 1170 Kg and CVW × 9.81 × 1.5 = 17.216 kN. The number of parts was 470, the number of nodes was 663,773, the number of elements was 653,171, the number of cells was 634,238, the number of solids was 1,825, and the number of 1Ds was 24,819 [14]. The test vehicle was considered to be in a normal state. Modeling methods and the data of finite element analysis is shown in Table 3. However, despite the possibility that welding operations during the repair work may cause the actual vehicle to be thermally deformed, the corresponding residual stress was not considered in the analysis because adopting this parameter may generate too many elements in the CAE configuration. The same materials as used in the actual vehicle were applied in the analysis. Also, the conditions of the normal vehicle and the repaired vehicle were compared based on their stress status and F-D curves to determine the effect of the repair work on the safety of the vehicle and its passengers.

TABLE III. FINITE ELEMENT ANALYTICAL MODELING

| Analysis Configuration Diagram | Structural Modelling | Analysis Setup | Test Setup | Result Analysis |
|---|---|---|---|---|
| **CAD** | • Monocoque Body<br>• Geometry Clean Up<br>• Mid surface<br>• Front frame | - | FMVSS216 | - |

| | | | | |
|---|---|---|---|---|
| | • Rear Trunk | | | |
| **CAE** | • Modelling<br>• Shell<br>• Solid<br>• 1D<br>• Element check | • Material property<br>• Boundary Conditions<br>• Contacts<br>• Initial Velocity<br>• Control Cards<br>• Modelling checks | FMVSS216 | • Stress<br>• Strain rate |
| **VARIABLE** | • Tensile Test<br>• Governing equation<br>• Vehicle Specification | • Weld Material to CAE<br>• Assumptions and boundary conditions<br>• Collision image | • Testing method<br>• Driving variable | • Determine the impact on passenger safety<br>• Collision stiffness evaluation by material |

## *D. Test Verification Based on Analytical Results*

It is very difficult to cause a car that was once involved in an accident and repaired at an auto repair shop to get into another accident and then examine how the roof crush resistance has been affected by the two accidents in real-life settings. To that end, a number of tests must be carried out using various types of vehicles, and the scope and method of repair work on roofs and pillars, as well as the type of vehicle and the extent of damage, must be examined and matched. In the present study, a finite element analysis was performed while applying the same test methods, as used in roof crush tests of actual vehicles, in an attempt to increase the reliability of the analysis. Figs 8 and 9 shows the roof test using the finite element model.

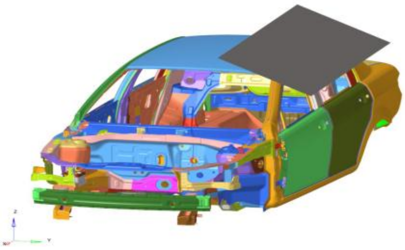

Figure 8. Illustration of a roof crush test.

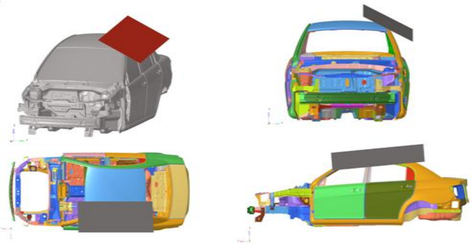

Figure 9. Illustration of a roof crush test from various angles.

Fig. 10 show the finite element modeling of normal vehicle. Fig. 11 show the vehicle of the roof replaced by $Co_2$ welding. Fig. 12 is the modeling of the A and B pillar parts deformed and welded after cutting.

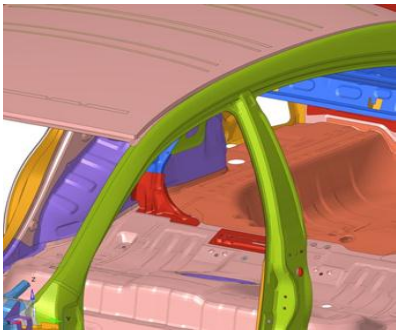

Figure10. Normal vehicle modeling

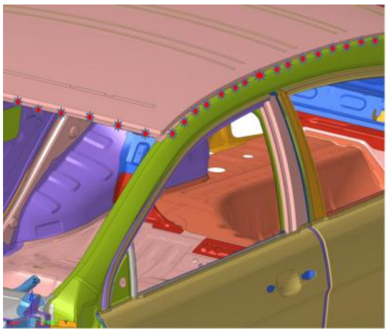

Figure 11. A vehicle with the roof replaced

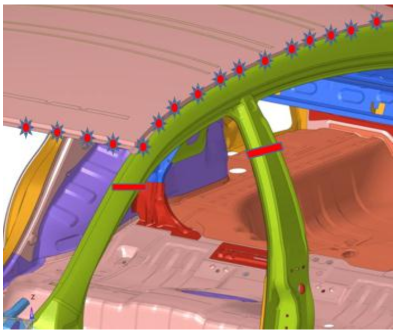

Figure 12. A vehicle with the roof and pillar replaced

Modeling and verification procedures were performed according to the test methods provided in FMVSS216, and the results were also analyzed using the same test methods to check to see if any errors occurred. It was found that most of the results were consistent. In an attempt to increase the reliability of the modeling results, the A-pillar was checked for any deformation. The part was in good condition, and there was no significant difference between the actual test results and the analysis results. Refer to Figs. 13 and 14. There were some factors that could have caused an error in the analysis; for example, the interior materials that were used in the actual vehicle were not considered in the CAE analysis. However, it was found that their effect was insignificant. A slight difference between the actual test and analysis results was attributable to the difficulty in applying the general material properties of the test vehicle to the analysis of the collision-damaged parts in the same manner [11]-[14]. The actual vehicle was tested with glasses installed, but in the analysis, a body in white (before the necessary parts have been integrated into the structure) was employed with no glasses, engine, or relevant parts installed. The behavior of the analytical model and the actual test results were compared, as shown in Fig. 8. All the parts of the normal vehicle were spot-welded. In the vehicle whose roof had been repaired, 150 points that were originally spot welded points were changed to $CO_2$-welded points. In the vehicle whose roof and pillars had been repaired, a total of 280 spot-welded points were changed to $CO_2$-welded points. $CO_2$-welded points in the pillars, in particular, were located 150mm away from the roof.

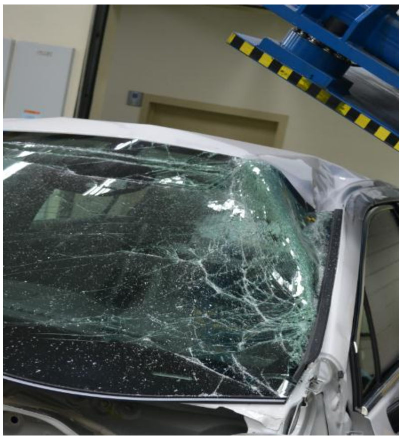

Figure 13. Actual vehicle tests

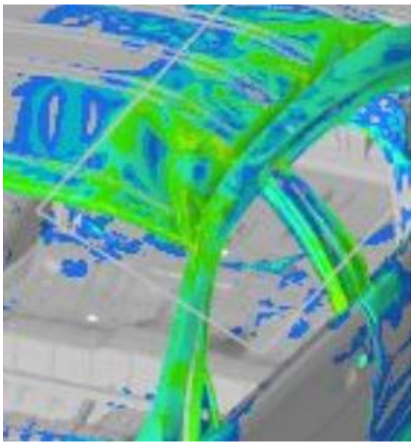

Figure 14. Analytical vehicle tests

### E. Comparison of Stress State between the Normal and Repaired Vehicles

The roof and pillars of the test vehicle that had been involved in an accident were cut out by removing the spot-welded joints during the repair operation. New parts were then $CO_2$-welded in the same places. The stress state of the normal and repaired vehicles was then measured and compared. In the case of the normal vehicle, the maximum stress was estimated to be 534.1 MPa (refer to Fig. 15). The maximum stress measured in the vehicle with the roof repaired and the vehicle with the roof and pillars repaired was 535.6 MPa (refer to Fig. 16.) and 535.4 MPa (refer to Fig. 17), respectively, which were higher than that of the normal vehicle. It was confirmed that a slight change occurred in the stress state after the repair operation.

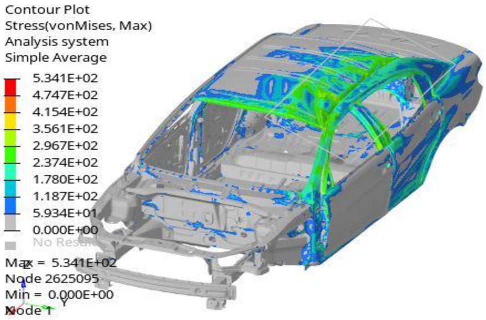

Figure 15. The stress state of the normal vehicle.

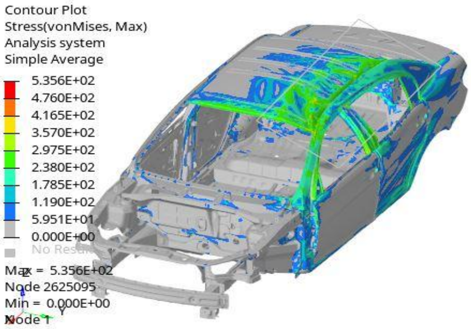

Figure 16. The stress state of the vehicle with the roof repaired.

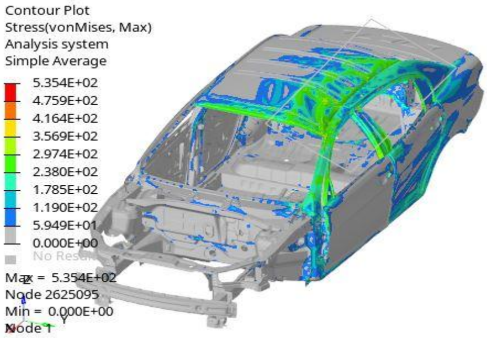

Figure 17. The stress state of the vehicle with the roof and pillars repaired.

### F. Force vs. Displacement

It is difficult to work with sheet metal or modifying the roof for a vehicle that needs repair due to damage to the roof, and it is a common work method to work by replacing the entire roof. After cutting a part and welding, the roof part is welded with $CO_2$, and then joining, seal and paint.

The force-displacement curves are presented below. In the case of the normal vehicle, the maximum load was 127.7 kN (refer to Fig. 18.) at a displacement of 119.9 mm. In the vehicle whose roof had been repaired by CO2 welding, the maximum load was 93.9 kN (refer to Fig. 19.) at a displacement of 103.1 mm. In the vehicle with the roof and pillars repaired, the maximum load was 85.4 kN at a displacement of 106.9 mm. The displacement at the maximum load was measured to be higher in the vehicle with the roof and pillars repaired than in the vehicle with the roof repaired; however, the maximum load was lower. This indicated that the vehicle with the roof and pillars repaired was in the most unfavorable state (refer to Fig. 20).

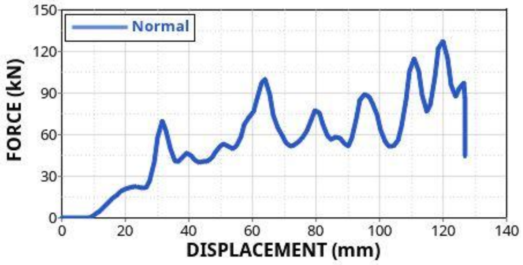

Figure 18. A force-displacement curve for the normal vehicle.

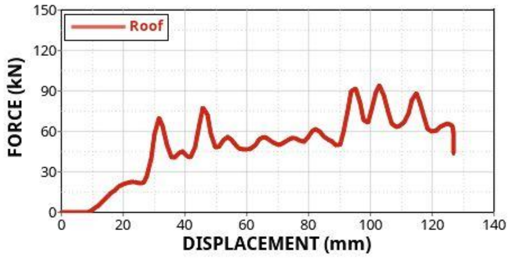

Figure 19. A force-displacement curve for the vehicle with the roof repaired.

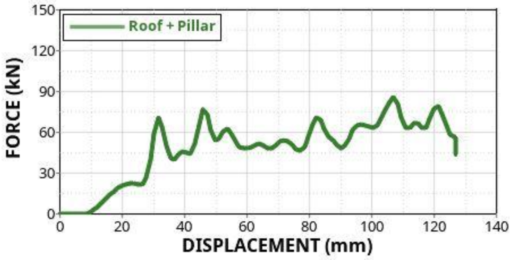

Figure 20. A force-displacement curve for the vehicle with the roof and pillars repaired.

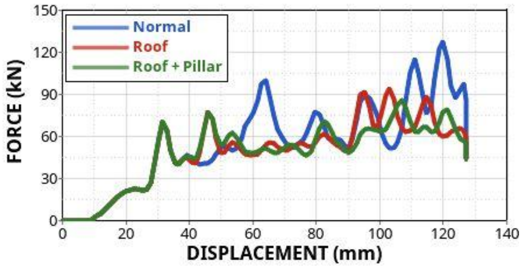

Figure 21. Force-displacement curves.

The FD curves of each vehicle were analyzed and compared as follows. In all three vehicles, the first force peak was observed at a displacement 31mm. At 45mm, another peak appeared in the two repaired vehicles. Around 60mm, the second force peak appeared in the normal vehicle; however, the load remained low in the two repaired vehicles within the same displacement range. At an early stage, it appeared that the repaired vehicles were more effective in bearing the applied load due to the $CO_2$-welded joints, but as time passed, the measured load became increasingly lower than that of the normal vehicle (refer to Fig. 21).

### *G. Force vs. Time*

The force-time curves showed that in the normal vehicle, the maximum load was 127.7 Kn (Refer to Fig. 22) at 9.2 seconds, and in the vehicle whose roof had been repaired by $CO_2$ welding, the maximum load was 93.9 kN (refer to Fig. 23) at 7.9 s. In the vehicle with the roof and pillars repaired, the maximum load was 85.4 kN (refer to Fig. 24) at 8.2 s. These results confirmed that the normal vehicle was able to bear a higher load than the repaired vehicles. The maximum load was measured to be the lowest in the vehicle with the roof and pillars repaired.

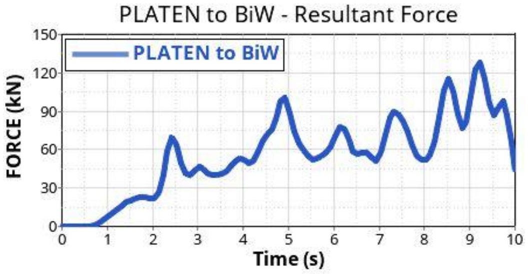

Figure 22. A force-time curve for the normal vehicle.

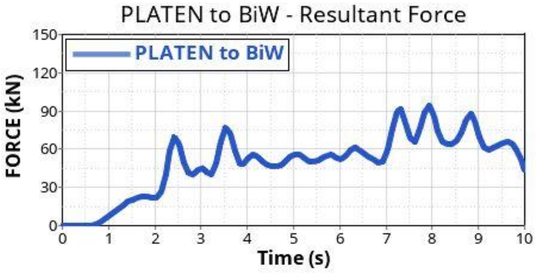

Figure 23. A force-time curve for the vehicle with the roof repaired.

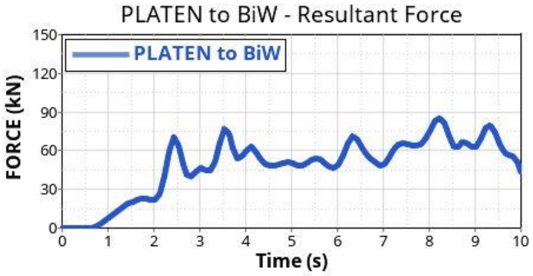

Figure 24. A force-time curve for the vehicle with the roof and pillars repaired.

## V. CONCLUSIONS

The present study examined the roof of a semi-midsize sedan that had a monocoque body, particularly with regard to how its roof was deformed and affected after the vehicle was involved in an accident. In general, the repair operation is performed as follows. The deformed roof or pillars are corrected to the possible extent, and then holes are made in the welded joints of the parts using a drill. The deformed roof is then removed, and a new roof is assembled by $CO_2$ welding, or only the deformed pillars are cut out and replaced with new ones. Following that, painting and finishing operations are conducted.

All the parts of a newly produced vehicle are spot-welded, but when a vehicle is involved in an accident and sent to an auto repair shop, all welding operations for repairs are performed using $CO_2$ welding methods. In the present study, the roof or pillars of test vehicles were removed, and new parts were welded in the same places as the original ones. Following that, the crush resistance of the normal vehicle and the repaired vehicles was analyzed and compared based on the stress state, force-displacement curves, and force-time curves obtained from each vehicle. A finite element analysis was performed to determine the effect of the repair operation on the vehicles. The obtained test and analytical results can be summarized as follows.

i. In the case of the normal vehicle, the maximum stress was 534.1 MPa. The maximum stress measured in the vehicle with the roof repaired and the vehicle with the roof and pillars repaired was 535.6 MPa and 535.4 MPa, respectively, which were higher than that of the normal vehicle.

ii. The force-displacement curves showed that in the normal vehicle, the maximum load was 127.7 kN at a displacement of 119.9 mm. In the vehicle whose roof had been repaired by $CO_2$ welding, the maximum load was 93.9kN at a displacement of 103.1 mm. In the vehicle with the roof and pillars repaired, the maximum load was 85.4 kN at a displacement of 106.9 mm.

iii. All the force-displacement curves were compared as follows. In all three vehicles, the first force peak was observed at a displacement of 31 mm. At 45 mm, another peak appeared in the two repaired vehicles. Around 60 mm, the second force peak appeared in the normal vehicle; however, the load remained low in the two repaired vehicles within the same displacement range.

iv. The force-time curves showed that in the normal vehicle, the maximum load was 127.7 kN at 9.2 s, and in the vehicle whose roof had been repaired by $CO_2$ welding, the maximum load was 93.9 kN at 7.9 s. In the vehicle with the roof and pillars repaired, the maximum load was 85.4 kN at 8.2 s. These results confirmed that the normal vehicle was able to bear a higher load than the repaired vehicles. The maximum load was measured to be the lowest in the vehicle with the roof and pillars repaired.

It was confirmed from the findings, that the rigidity of the vehicle was reduced in the condition of a repaired roof and filler after welding. It is judged that the rigidity of the vehicle after repair will be lower than that of the non-accidental vehicle, which will have a negative impact on safety in the event of a recurrence of accident.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

Sungho Kim conducted the research & wrote the paper; HaengMuk Cho analyzed the data. all authors had approved the final version.

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