A Study on the Stiffness Change of a Passenger Car's Front Frame Body before and after a Collision Accident

Sungho Kim and HaengMuk Cho*
Department of Mechanical Engineering, Kongju National University, Cheonan campus, South Korea
Email: 8902ksh@daum.net, hmcho@kongju.ac.kr

***Abstract*—As cars become one of the main means of transportation, accidents have accompanied car driving. In the event of an accident, the repair is carried out at a repair shop, and in the case of damage to major parts of the car's body, the value of the car falls after the repair or concerns about its performance and safety arise, promptly causing distrust and anxiety over the repaired car. In this experiment, one high-selling passenger car is selected in the domestic market and a collision test is conducted in the same way as the actual vehicle, utilizing the drawings, materials, and relevant data of the car. The simulation identified the damaged area and condition in the same collision as in the actual crash, with the condition of the vehicle after the crash repair being interpreted and analyzed through a commercial program. The tensile strength test for the welded area confirmed that the material strength of the vehicle was reduced by 20% from the intact condition. The change in the stiffness in the vehicular body before and after the accident is compared to gather data for tensile strength, F-D diagram, and relative displacement. Judging from the stiffness and internal energy data, as well as the F-D diagram, the difference between the intact vehicle and the vehicle after the repair appeared in even a perfectly repaired car and this difference was determined to be the basis for the depreciation of value, meaning a change in the stiffness of the vehicle during restoration**

***Index Terms*—safety, HyperWorks, collision, vehicle body, tensile test, welding**

I. Introduction

As cars become one of the main means of transportation, most households buy and use cars. Usually, cars are used for work, commuting, and leisure activities. In the event of an accident, repairs are performed at a repair shop. Minor accidents involving slight body damage do not pose much difficulty in the restoration of the vehicle's original condition and performance done through simple repair and damaged parts' replacement. On the other hand, major but partial damage accidents that cause body deformations, such as on structure or frames, often lead to lawsuits for depreciation of automotive value, as well as to distrust and anxiety over repaired vehicles due to concerns over vehicular performance and safety after repairs [1][2][3].

In this experiment, one high-selling passenger car is selected in the domestic market, while a collision test is conducted in the same way as in the actual vehicle, utilizing the drawings, materials, and relevant data of the car. Through a simulation, the damaged area and the condition in the actual crash are identified, and a finite analysis is performed on the state of the car after the crash repair, using commercial programs, Hyper Works and LS-DYNA.

The changes in the condition of the vehicle following the accident are analyzed and determined by interpreting changes in body stiffness such as the F-D diagram, displacement, and strain rate factors.

Typically, the body of a passenger car is made in a monocoque type and is an integral body that is made of several sheets of steel to be welded in a bending or overlapping manner to maintain the rigidity of the vehicular body. The assembly plant uses jigs to carry out the assembly procedure step-by-step and to produce cars massively. Parts of the body that are under load or that require vibration or stiffness are added or specially strengthened with reinforcement. In the case of frames and panels, which are major structural parts, the exterior of the body, as well as the internal sheet, are deformed in the event of an accident [4][5].

When a car is repaired after an accident, the deformed part of the body is pulled with a jig to restore the basic frame, and then it unfolds the damaged parts to approximate the original shape [6]. The next step is to cut the deformed body with a saw, cutting machine, or welder, and then to perform welding. After that, the area where thermal deformation occurred due to the welding is processed with a grinder or brush to be smooth and painting follows. This is a common method of damage repair work [7][8].

Because the car's safety features and body stiffness are changed when another accident occurs after a repair, this study was conducted by comparing a brand new car with a repaired one in order to determine those two aspects.

Manuscript received October 25, 2020; revised February 4, 2021.

doi: 10.18178/ijmerr.10.5.270-275

II. Vehicle Collision Test

The methods used by the Research Council for Automobile Repairs (RCAR) are typically meant to assess damageability and repairability. RCAR assesses these factors in a brand new car via a test method that can represent the types of accidents that usually occur in the medium and low-speed sections, such as the driving patterns on city streets. In the collisions under the same conditions, depending on the type of vehicle, there are two (2) types of car in terms of damage range and damaged parts: one is the large damaged model described as having bad damageability and the other one is the small damaged model described as having good damageability [9][10].

In South Korea, there are RCAR tests conducted by the Korea Automobile Insurance Repair Research and Training Center (KART) under the Korea Insurance Development Institute to calculate auto insurance premiums before and after the launch of new cars sold in Korea, assessing and classifying damageability and repairability into grades after collision testing the front and rear portions of the vehicle at a speed of 15 km/h on a sloping wall is shown in Fig. 1. The damageability and repairability are combined in order to be used for the calculation of repair costs. They are likewise classified into Grades 1 (lowest) to 26 (highest) [11][12].

The grade of damageability and repairability assessment is divided into Grades 1 to 26 (26 grades), indicating that the higher one's grade is (close to grade 26), the better the damageability and repairability of the vehicle are in a low-speed collision. This rating is determined by means of the severity index reflecting the damageability and repairability of a vehicle (reflecting collision evaluation, parts evaluation, labor cost assessment, and painting evaluation) and the frequency index indicating the loss ratio of a vehicle [13][14][15].

The vehicle's severity index (reflecting damageability and repairability) is calculated through an evaluation of the collision characteristics, parts prices, working hours, labor cost, and painting labor cost for each model. Through the collision assessment, the properties of damageability and repairability are indexed by the front and rear collision tests on the sloping wall at the RCAR standard of 15 km/h.

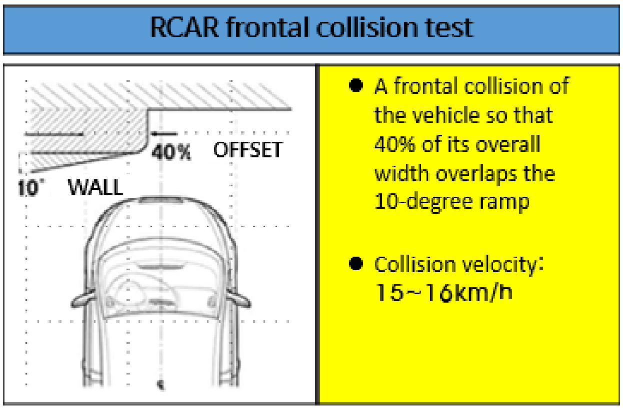

Figure 1 . RCAR collision test model

III. Body Repair Method

A. Solution for the Front Frame Deformation

1) Sheet metal working for correction

- The length of the body is measured diagonally and in a straight line to determine the correction area and degree of deformation.
- An oxygen welder is used to correct the frame by applying heat or correcting the deformation using a sheet metal device, such as a cellete.
- Both sides' lengths, angles, and heights are adjusted to match.

2) Correction after cutting

- Parts are cut into I-shape or Z-shape on welding points as designated by the manufacturer for the repair of the frame using oxygen welder, saw, and plasma cutter.
- New parts are made in the same shape as the cut parts. Such are butt-welded, then grinded and painted as shown in Fig. 2 and Fig. 3.

Figure 2 . Front frame

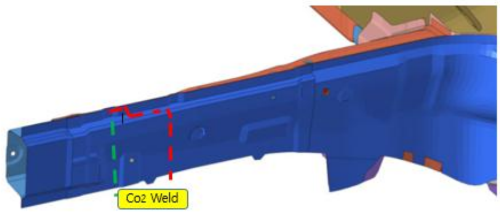

Figure 3. Front frame structure and post repair weld geometry

IV. Test

A. Test Vehicle Specification

The test vehicle is actually used in Korea and its drawings and specifications are obtained from the manufacturer's research institute through request as mentioned in Table I. The parts applied to the test are repair parts currently used and they are purchased at the aftermarket. A skilled mechanic who has worked at the test vehicle's manufacturer service center for more than 20 years is selected to perform welding. Institute through request. The parts applied to the test are repair parts currently used and they are purchased at the aftermarket. A skilled mechanic who has worked at the test vehicle's manufacturer service center for more than 20 years is selected to perform welding.

TABLE I. TEST VEHICLE SPECIFICATION

Specification	Vehicle
Weight (Kg)	1170
Engine Type	1.8L L4
Tire Size	195/60 R15
LxWxH (mm)	4511x1745x1482
Wheel Base (mm)	2610
Wheel Track (mm) Frt/Rr	1483/1493
CG Reward of Frt Wheel C/L (mm)	1069

B. Finite Element Analysis

After the CAD data analysis is modeled for the finite element analysis, the test method and property of the material, tensile test, and variables are applied, and analysis and evaluation are conducted in compliance with the test method through the process of comparing and verifying the data of the collision image and the vehicle's actual data is shown in Fig. 4.

ANALYSIS CONFIGURATION DIAGRAM	STRUCTURAL MODELING	ANALYSIS SETUP	TEST SETUP	RESULT ANALYSIS
CAD	• Monocoque Body • Geometry Clean up • Mid surface • Front Frame	-	• RCAR front retaining wall	-
CAE	• Modeling - Forward Collision - Shell , Solid, 1D • Element Check	• Material • Property Boundary Conditions • Contacts • Initial Velocity • Control Cards • Modeling Check	• RCAR Front Test 10 Degree Slope Fixed Wall 40% offset	• Normal Vehicle Collision Stiffness • Stress, strain rate, energy absorption
VARIABLE	• Specimen tensile test frame (normal, CO2) • governing equation • vehicle specifications	• Application of weld material to CAE • Assumptions and Boundary Conditions • collision image comparison	• Collision test method • Driving variable	• Determine the impact on passenger safety • Collision Stiffness Evaluation by Material

Figure 4. Finite element analysis modeling

The condition of the test vehicle is judged to be intact, and in actual accident repaired vehicles, thermal deformation occurs due to welding. However, the residual stress is ignored because such is difficult to judge among the many factors in the CAE configuration. The same material as the test vehicles is applied for the analysis of the collision stiffness, stress, strain rate, and energy absorption rate of the intact car.

C. Tensile Test

In order to identify the change in the strength of the vehicle, which incurred an accident, the material and location of the body part are confirmed, and the test area is cut under the same conditions. Further, the specimen is made, and then the tensile test was performed

First, the front frame area of the vehicle is a welded layer composed of internal sheet and external sheet, so deformation and abnormalities of the parts are checked, and the test area's external sheet and internal sheet are cut using a pneumatic saw to prevent the thermal deformation of the material during the cut. Next, a skilled mechanic conducts butt-welding with a CO2 welder, and then a tensile strength test is carried out.

The Korea Testing Certification (KTC) is commissioned to conduct the tensile test that will examine the tensile strength after welding upon application of the same parts as the front frame of the actual car. Through this process, it becomes possible to verify the properties of the material and to determine the strength of the material in case of a collision.

TABLE II. COMPARISON OF TENSILE STRENGTH BETWEEN NORMAL OR POST WELDING

Item / Test sample	Tensile strength (N/mm)	Yield strength (N/mm)	Elongation percentage (%)	Test method
Frame 1 (Intact)	605	593	4	KSB 0802 -2003
Frame 1 (CO_2)	496	453	6	
Frame 2 (Intact)	491	484	11	
Frame 2 (CO_2)	398	270	7	

First, by comparing the intact vehicle's front frame with its internal sheet and external sheet after CO_2 welding, it is confirmed that the stiffness of the frame after welding compared to the intact frame is reduced by 20%, comparison is shown in Table II.

TABLE III. COMPARISON OF SITE-SPECIFIC ERRORS OF NORMAL AND ANALYSIS VEHICLES

Categories	Before	After	Error (%)
Steering Column	2494,9	2434,6	7.9%
Steering Column (CAE)	2496,8	2241,9	
A - Pillar	2814,2	2738,3	4.3%
A – Pillar (CAE)	2946,5	2856,2	

This information can be used as indirect data to demonstrate that the stiffness of a vehicle's frame (the main part of the body) decreases further compared with its initial condition after it is repaired with welding and after being cut due to a vehicular accident. It has been confirmed that the mechanical stiffness in this case is much weaker than that of a brand new car, although some differences may occur due to the weld area, welding direction, and technician's workmanship, among others.

Because the front frame is double-bonded, the unwelded area of the inner part can make the strength weaker compared with the initial condition if the inner part is not welded with the external sheet after cutting

D. Verification of Test by Analysis

Because of the collision characteristics of a car, it is considerably difficult to use the actual driving vehicle to conduct a collision test through a re-occurrence of an accident of a repaired vehicle as show in Fig. 5.

Although many subjects and vehicles should be selected and tested in determining the scope and method of the welding repair of frames and selecting work areas in the same vehicle, the test is conducted through analysis due to too many limitations, such as the test car number, test space, test cost, repeatability, and results analysis.

Modeling and verification are carried out by means of the KNCAP test method on the actual vehicle. It is found that most of the results are produced in similar forms when the margin of error is checked after analysis with the same test method. The results of the deformation volume of the actual vehicle after the frontal impact and the results obtained from the post-modeling test of the vehicle subject to analysis are identified, as shown in the table below. An error of about 6 % occurs compared to the actual vehicle, but this is due to the difficulty in applying the same barrier material characteristics of the vehicular subject an analysis on the impact area [16][17].

The difference between the steering column section and the A-pillar in the results below is described as follows: In the case of the steering column section, the analysis is based on the condition in which the interior materials and plastic parts or rubber parts are removed, confirming that there are some differences from the A-Piller section, which is made of steel plates only. Table III shows the Comparison of site-specific errors between experimental and analytical vehicles.

In the actual vehicle, the deformation volume is measured using 3D distance measurement data, so the possibility of an error is considered to be insignificant shown in Fig. 6.

Figure 5. The actual vehicle collision test

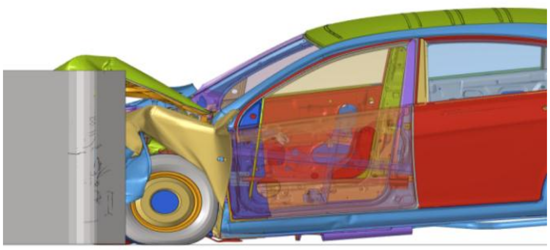

Figure 6. Collision test of the vehicle subject to analysis

E. Deformation Volume and Force Per Vehicle Speed of the Intact and Repaired Vehicles

This is the result of a comparison using a vehicle welded and repaired after an accident on the front frame, the test part, to check the deformation volume and force of the vehicle by speed depicted in Fig. 7.

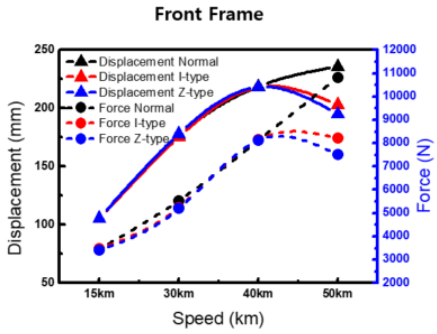

Figure 7. Speed of the front frame/deformation volume

1) Comparison: Force vs. Displacement

When the vehicle displacement and force (energy absorption capability) in the collision test are compared by speed, the front frame does not differ in force and displacement at speeds of 40 km/h and less, although there are large gaps above 40 km/h.

2) 4-5-2 Collision analysis by speed F-D Curve (front frame)

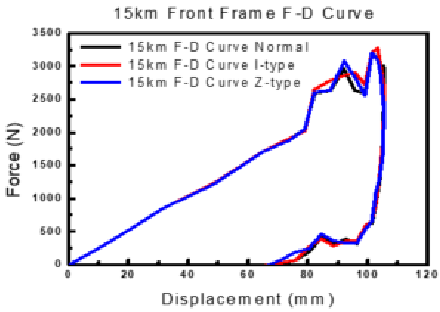

Figure 8. Front frame at 15km/h F-D Curve

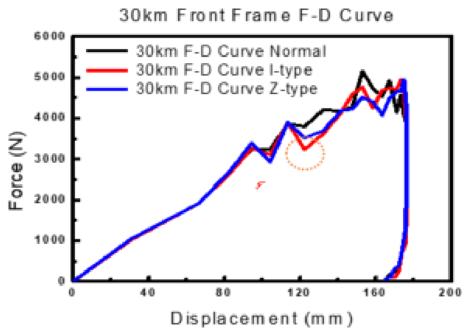

Figure 9. Front frame at 30km/h F-D Curve

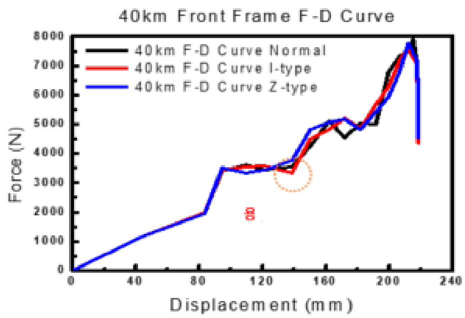

Figure 10. Front frame at 40km/h F-D Curve

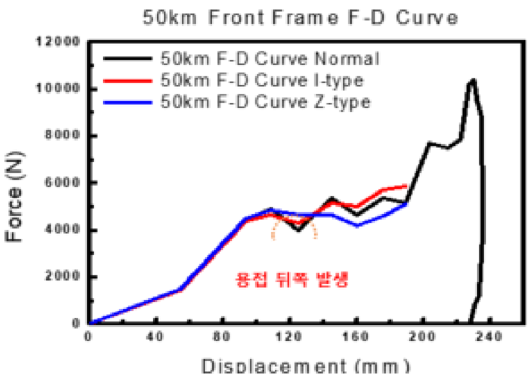

Figure 11. Front frame at 50km/h F-D Curve

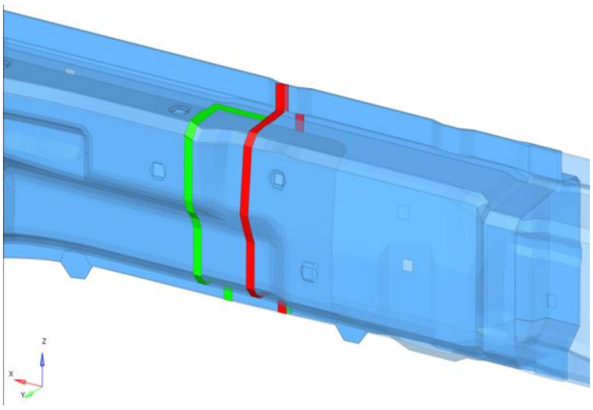

Figure 12. Type of Front Framework Weld I or Z

In the comparison experiment between the intact front frame vehicle and the welded front frame vehicle, the force (energy absorption capability) and displacement are not significantly different at speeds of 40 km/h and less, but at speeds above 40 km/h, the force is definitely reduced. In the vehicle welded after an accident, it can be inferred from the F-D diagram that there is a severe change at 30 km/h and the body collapses due to the deformation of the frame as shown in Fig. 8, Fig. 9, Fig. 10, Fig. 11 and Fig. 12. This means that the energy absorption rate in this case is lower than the intact car's, and if an accident occurs at a higher speed, it is judged to have a greater impact on the safety of passengers.

3) *Displacement*

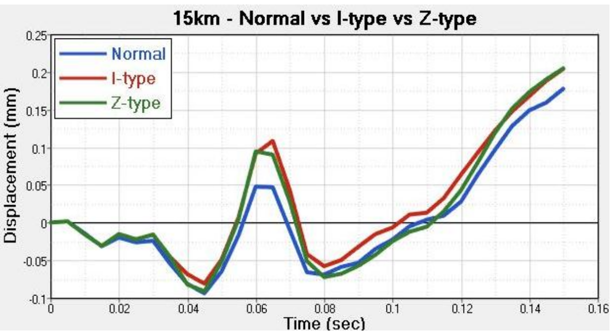

Figure 13. Front frame at 15km/h Displacement

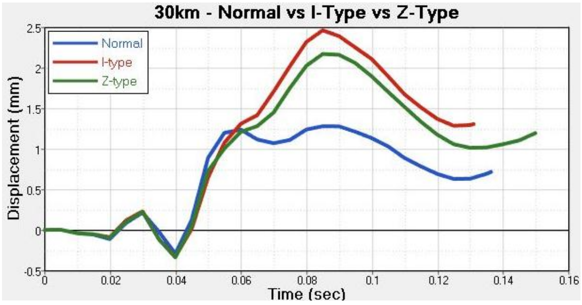

Figure 14. Front frame at 30km/h Displacement

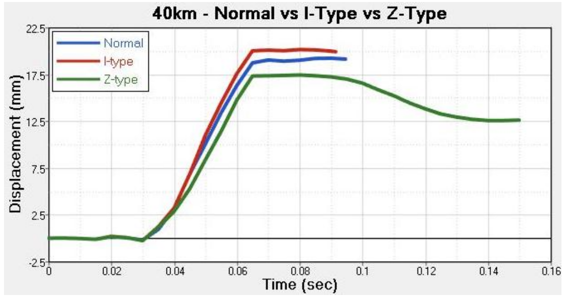

Figure 15. Front frame at 40km/h Displacement

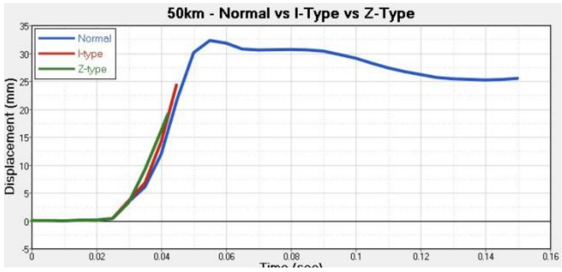

Figure 16. Front frame at 50km/h Displacement

The relative displacement between the intact car and the post-accident vehicle whose front frame is welded in I and Z-shapes after the collision test is determined by Fig. 13, Fig. 14, Fig. 15 and Fig. 16.

The determination of the relative displacement of the welded and intact vehicles in node 2714112 of the analysis shows that the displacement of the intact vehicle is greater than that of the welded one, and the comparison between I and Z-shapes confirms that the latter has an advantage in terms of relative displacement.

V. Conclusion

In this study, the front frame area of a Korean domestic compact monocoque body vehicle was repaired after an accident and, in the repair, the front frame was cut and welded in I and Z-shapes. A common maintenance technique, "Welding in I-shape and Z-shape the intermediate frame part at the crash point," was performed and the repaired car's pre-accident intact condition and post-accident repaired stiffness were compared through an F-D diagram and the displacement method.

The results of comparative testing and analysis through tensile testing and finite element analysis to determine whether or not post-accident repaired vehicles showed value depreciation and their safety was affected, which are recent issues, are summarized as follows.

- The tensile strength test for the welded area confirmed that the material strength of the vehicle was reduced by 20% from the intact condition.
- The analysis of the change in stiffness of the front frame of the post-accident car after welding confirmed that the stiffness after welding was reduced by 2 to 4% at 30 km/h and by 2% at 40 km/h. 3) In the analysis of the change in energy absorption rate after the front frame of the post-accident vehicle was welded, the change in the 15 km/h condition was insignificant, but the energy absorption rate of the welded area increased by 10 to 40% at 30 km/h, and the welded model became NG at 50 km/h.
- In the event of another collision after a repair, the vehicle was not significantly affected under the conditions of 15 to 30 km/h, but it was found that a re-occurrence of an accident at a speed exceeding 30 km/h may cause damage to passengers.
- Judging from the stiffness and internal energy data, as well as the F-D diagram, the difference between the intact vehicle and the vehicle after the repair appeared in even a perfectly repaired car and this difference was determined to be the basis for the depreciation of value, meaning a change in the stiffness of the vehicle during restoration.

Based on the result of the comparison by means of welding and testing the front frame and employing the two methods, I-shape and Z-shape, it was judged that the latter would produce a stronger frame. It is necessary to review the repair methods on the dual-layered structure of the frame and to understand the structure itself. Since body stiffness resulting from repair work may vary depending on the technician's workmanship, it was deemed that repairs in important areas would require a technician’s expertise to ensure safety.

REFERENCES

[1] S. H. Shin, “The depreciation of a partially destroyed automobile after repairs and the measurement of damages,” *Legal Practice Study*, pp. 236-266, 2004.

[2] D. K. Yun and H. T. Lee, “Study on value appraisal after the repair of cars,” *Transactions of the Korean Society of Automotive Engineers*, vol. 22, pp. 19-24, 2014.

[3] I. S. Park and S. Jin Heo, “Damageability, repairability and safety of vehicles at low speed 40% offset crash test,” *Transactions of the Korean Society of Automotive Engineers*, vol. 7, pp. 1-9, 1999.

[4] I. H. Han, "Automobile collision reconstruction using post-impact velocities and crush profile,” *Journal of Korean Society of Transportation*, vol. 18, 2000.

[5] J. M. Lim, “lumped mass-spring model construction for crash analysis using full FRONTAL impact test data,” *International Journal of Automotive Technology*, vol. 18, pp. 463-472, 2017.

[6] T. Watanabe, I. Kuroda, T. Nakajima, M. Masuda, “Relationship between frontal car-to-car test result and vehicle crash compatibility evaluation in mobile progressive deformable barrier test,” *Traffic Injury Prevention*, vol. 20, pp. 78-83, 2019.

[7] N. Asadiniaa, A. Khalkhalia, M. J. Saranjam, “Sensitivity analysis and optimization for occupant safety in automotive frontal crash test,” *Latin American Journal of Solids and Structures*, vol. 5, pp. 1-15, 2018.

[8] D. Anselm, “The passenger car body: Design, deformation characteristics, accident repair,” *Vogel*, 2000, pp. 93-96.

[9] J. H. Lim, I. S. Park, and S. J. Heo, “A study on characteristics of damageability and repairability with similar platform type at Low speed 40% offset crash test,” *Transactions of the KSAE*, vol. 13, pp. 108-113, 2005.

[10] W. Im, S. Kang, “Crash box optimal design by component analysis for RCAR test,” *Transactions of KSAE*, vol. 25, pp. 440-447, 2017.

[11] J. H. Lim, I. S. Park, and S. J. Heo, “A study on human injury characteristics and vehicle body deformation with car to car crash test for crash compatibility,” *Transactions of the KSAE*, vol. 13, pp. 135-141, 2005.

[12] J. Kyungjin, Y. Younghan, P. Jiyang, K. Dongseup, O. Myoungjin, K. Youngchan, S. Changki, S. Jaekon, L. Eundok, K. H. Boung, “Simulation analysis and comparison of new frontal impact tests,” *Journal of Auto-vehicle Safety Association*, vol. 9, pp. 20-25, 2017.

[13] V. Agaram, L. Xu, J. Wu, G. Kostyniuk, G. Nusholtz, “Comparison of frontal crashes in terms of average acceleration,” *Society of Automotive Engineers*, pp. 217-237, 2008.

[14] C. Jae-Ung, M. Byoung-Sang, “Simulation analysis on impact of automotive body,” *The Korean Society of Manufacturing Technology Engineers*, vol. 18, pp. 477-482, 2009.

[15] D. S. Dima, D. Covaciu, “Vehicles frontal impact analysis using computer simulation and crash test,” *International Journal of Automotive Technology*, vol. 20, pp. 655-661, 2019.

[16] K. Dea Up, W. Chang Gi, “Experimental study on the small overlap frontal crash test method,” *Journal of The Korean Society of Manufacturing Technology Engineers*, vol. 26, pp. 205-213, 2017.

[17] L. Xiao, L. Li, D. W. Duan, Y. B. Liu, “Modification design of a sedan based on 25% overlap frontal crash test,” *Automotive Engineering*, vol. 40, pp. 1-10, 2018.

Sung-ho kim has a master's degree from Hanyang University, Graduate School of Engineering in Korea. He has been working as an automobile engineer for 30 years at Daewoo Motors and GM Korea. He's been awarded the President's Award twice for his excellent offer. He's professional engineer and Contributions to the Development of Science and Technology in Korea. He also won the Minister's Award. He is currently pursuing his Ph.D. degree in mechanical engineering at Department of mechanical engineering, Kongju National University. His field of interest is change in rigidity and damage in a car because of crash.

HaengMuk Cho is a renowned professor in South Korea. He is working as professor at Kongju National University in South Korea. He did Post Doctorate Fellowship from Department of Automotive Engineering of Loughborough University in UK and North Texas University in USA. He earned his PhD from Hanyang University, South Korea in 1997 and completed his M.D. in Environment Engineering from Yonsei University in S Korea. He is working on national and international projects in the field of Bio-fuels for IC engines and renewable energy. Professor HaengMuk Cho is working in the field of Renewable Energy and Biofuels. He is also a member of many societies, like Korea Society of Automotive Engineers, Korean Society of Energy (Korea), Korea Society of Marine Engineering (Korea) & Korea Society of Environment Engineer (Korea). He has published many national and internal research papers. Most of his papers are indexed in Scopus and SCI.