International Journal of Crashworthiness

AN OPTIMAL DESIGN OF FRONTAL STRUCTURES TO IMPROVE SMALL-OVERLAP RATING

--Manuscript Draft--

Manuscript Number:	IJCR.987R1
Full Title:	AN OPTIMAL DESIGN OF FRONTAL STRUCTURES TO IMPROVE SMALL-OVERLAP RATING
Article Type:	Design for Transport Safety - Special Issue
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Abstract:	This paper proposes an optimal design of frontal structures to improve the small-overlap rating, based on a computer-based crash simulation model. The frontal structures such as longitudinal, A-pillar and rocker panel are analyzed to find the sensitive part in small-overlap crash test. To improve the small-overlap rating, two reinforced component models such as longitudinal reinforcement and rocker panel reinforcement are added to frontal structures then the thickness optimal design applies for the small-overlap frontal impact simulation following the real test conditions. The crash simulation results were used to evaluate the overall vehicle structure through a comparison of intrusion measurements with the rating guidelines of the Insurance Institute for Highway Safety (IIHS). The response surface method (RSM) was used to optimal frontal structures for improving the small-overlap rating of IIHS. Based on the RSM function, the optimal values of the variables were chosen as the new design. The crash analysis results showed that the serious damage to the frontal structure happened when the vehicle model run into barrier model at 25 % overlap. In this study, the overall rating of frontal structures was upgraded from "poor" to "good" in the case of Flat 150 (the Flat barrier with a 150 mm radius and 25% overlap).

Sumary of Reviewer comments and recommendations:

Comments and recommendations	What the authors did
1. In the last sentence of the first paragraph of the Introduction, an expression as "The barriers for crash tests were shown in [3]" is used. An explanation for these crash test barriers, preferably with a figure, would be beneficial for the reader. The sentence as it is does not add much to the comprehension of the concept.	The authors absolutely accept the reviewer's comments. The 2.2 Barrier model design was added to explain for the crash test barrier model. The figure 5 showed the barrier which was used in this paper.
2. In the Introduction section, the use of the word "reference" such as "reference [6] recommend…" is preferred quite a few times. The authors should consider replacing the "reference" words adequately with the names of authors such as "Sherwood et al. recommend… [6]" or with other words such as "researchers, etc.".	Thank you for your kindly comments. All "reference" words were replaced with the names of authors or used with other words such as researchers.
3. In section 2.1, more details on the FE model of the vehicle should be provided. The model is generated by some other researchers, however some fundamental specifications need to be provided so that the additions to the initial model by the authors can be better understood. One very important point is to clarify the material model and properties used as the simulation involves an impact situation resulting in transient loads. The type of analysis (dynamic transient, quasi-static, etc.) should be clarified. If dynamic transient analysis was carried out, how were the mass of the real-life vehicle in the crash test and the mass of the FE model of the vehicle matched as the model appears to have the monocoque chassis and some body parts mainly. Does it also contain the driver and/or occupants, seats, etc. that add to the mass of the vehicle? All of these should be explained in detail.	The authors definitely agree with the reviewer that the FE model of the vehicle should be provided more information about material model and properties used as the simulation involves an impact situation resulting in transient loads. The details were added in section 2.1. Description and Validation of Vehicle FE Model. The type of analysis in this paper was dynamic transient. In this study, the number of part of original model was increased because the two reinforcement models were attached to a vehicle FE model as new model which was used in this paper for crash simulations based on the IIHS small-overlap crash. The new FE model contains 521 parts and 333,455 elements without interior components or restraint systems. The FE model of the vehicle the same as reference [32] such as material model and properties. The material model and properties of reinforcements were added in section 2.3 The reinforcement model designs. The mass of the vehicle model

4. In Figure 2, there is a significant drop in the acceleration curve of the FE model at 60 ms. Were the time steps chosen appropriately in the FE model, as the graph shows a step size of 5 ms? A much smaller time step may provide better output. The authors should consider to comment on this.	Your comment is great. The time steps chosen in the FE model for ouput of acceleration curve which shows a step size of 5 ms. In this paper the step size was changed and the output as show in figure 2 [32, 36].
5. In section 2.1, the model is claimed to be validated using velocity, acceleration and energy absorption results. The figures provided only show comparisons of the responses of some of the vehicle parts such as seat cross member and a visual comparison accounting for the responses of the suspension, wheel, etc. (in Fig. 4). The authors should consider to provide more specific information on validation. If not possible, the relevant text must be rephrased just to point out the methods and results of the particular validation efforts.	The authors definitely agree with the reviewer so that this paper used 2 kind of test to validate the model such as full frontal crash test of NCAP following the reference [32] and the moderate overlap test of IIHS [38]. More specific informations on validation were added in section 2.1.
6. In paragraph 2 of section 2.1, just under Fig. 4, it is mentioned that "The shapes of the reinforcements were optimized by the analytic intrusion of full vehicle model". The authors should clarify what they mean by analytic intrusion in a sentence or two. How was the shape of the longitudinal reinforcement bracket decided?	According to the reviewer comment, more details about the shape of the longitudinal reinforcement were added into section 2.3.
7. In section 3.1, in the text, there is a jump from Figure 12 to Figure 15. Then, in the oncoming text Fig. 13 and 14 are mentioned whereas all figures are in proper order. This needs to be corrected in order of appearance in the text.	Thank you for your kindly comments. In the text all Figures were in order of apperance.
8. There are various typos and grammar errors within the text that need amendment. There are also occasional uses of unnecessary prepositions in the main text. The manuscript is recommended to be proofread thoroughly.	I apology for the poor English. The various typos and grammar errors were corrected.

All detail revisions are added directly to the document as attached

Again thank you for your comments

International Journal of Crashworthiness, 2015
Vol. ?, No. ?, pp. ?–?(year)

AN OPTIMAL DESIGN OF FRONTAL STRUCTURES TO IMPROVE SMALL-OVERLAP RATING

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ABSTRACT–This paper proposes an optimal design of frontal structures to improve the small-overlap rating, based on a computer-based crash simulation model. The frontal structures such as longitudinal, A-pillar and rocker panel are analyzed to find the sensitive part in small-overlap crash test. To improve the small-overlap rating, two reinforced component models such as longitudinal reinforcement and rocker panel reinforcement are added to frontal structures then the thickness optimal design applies for the small-overlap frontal impact simulation following the real test conditions. Based on the rating guidelines of the Insurance Institute for Highway Safety (IIHS), the crash simulation results were used to evaluate the overall vehicle structure by comparison of intrusion measurements. The response surface method (RSM) was used to optimal frontal structures for improving the small-overlap rating of IIHS. Based on the RSM function, the optimal values of the variables were chosen as the new design. The crash analysis conclusions showed that the severe damage to the frontal structure happened when the vehicle model run into barrier model at 25 % overlap. In this study, the overall rating of frontal structures was upgraded from "poor" to "good" in the case of small-overlap frontal impact with Flat 150 (the Flat barrier with a 150 mm radius and 25% overlap).

Keywords: small-overlap, crashworthiness, frontal impact, vehicle structure, crash test

1. INTRODUCTION

One of the most serious crashes, small-overlap frontal impact test was released by IIHS in 2012 to challenge auto makers for safer production as in [1]. In this test, the vehicle collided with a rigid barrier at 64 km/h at 25% overlap. This is also the same as a vehicle crashing into a pole or flat object, but only at the part of the headlight from the left side of the driver as in [2]. The barriers for crash tests were shown in section 2.2 according to [3].

Through the small-overlap frontal crash test, the crash forces are applied outboard of the vehicle's longitudinal frame rails as in [4, 5]. That reason caused occupant compartment intrusion becoming serious injuries. Sherwood et al. (2009) recommended that frontal structure designs must improve their ability to protect passengers in case small-overlap frontal crashes occur [6]. Furthermore, forces are attacked on the front suspension, at the left wheel, and at the base of the A-pillar. These zones are damaged severely because of more energy absorb in the frontal structure crashworthiness as in [7 - 9]. Due to passenger safety, researchers proposed the self-protection and partner-protection for new vehicles [10].

In recent related studies on the small-overlap crashes, the national highway traffic safety administration (NHTSA) proposes offset oblique and small overlap impact tests. The IIHS also studies on moderate and small overlap tests but in their test the overlap reduce up to 25%. Variances with regards to the consequence in vehicle deformation, vehicle kinematics, and occupant kinematics were noted between the IIHS and NHTSA test methods [11]. Hong et al. (2008) their results showed that the rails absorbed over 50% of full vehicle energy when the crash occurred in the IIHS test [12]. In 2000, Park et al. suggested that the offset-frontal crash test can be applied to enhancement the full-frontal crash test [13]. Because a part of frontal structures attack to the barrier that caused the tested vehicle moves to sideways away from the barrier. In the results of IIHS show that the accident can be critical factor for the dummy injury. Due to that problem researchers released a study of occupant protection simulation for IIHS small overlap frontal crash test to predict the dummy injury [14]. In 2014, Lee et al. researched female dummy in new car assessment program (NCAP) full frontal crash test to improve the severity of the star rating [15]. An analysis of the distinction in injury numbers of automobile frontal crash tests was proposed to enhance safety performance as in [16]. Beside the passenger vehicle the light truck also mention on improving structure as in [17] which studied on finite element based improvement of a light truck design to optimize crashworthiness by filling structural foam in the A-pillars and the side panels, adding a roof crossbeam, and reinforcing the rear wall of cab. The deceleration pulse is recommended to amend the design of an automobile for crashworthiness as in [18, 19].

Currently, there are many researchers have studied on vehicle structures to improve the IIHS rating. In 2012, Halloway et al. proposed classifiers to indicate the number of longitudinal members [20]. In 2013,

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Jakobsson et al. illustrated the significance and developments of car design for frontal crashes with partial overlap [21]. Based on the frontal offset crash protocol in IIHS test, the body structure crashworthiness simulation and development to get occupant safety in small overlap are studied by [22]. In small overlap crash test the longitudinal almost miss so that the affects of longitudinal beams deformation on vehicle crashworthiness are discussed as in [23]. They suggest the references for vehicle longitudinal beams design and improvement for the future. In 2007, Oh et al. suggested the size optimization of an engine room member for crashworthiness using response surface method [24]. The crashworthiness design using topology optimization method was shown in [25-28]. To increase safety of structure and to minimizing injury risks of flex pedestrian leg form impactor, the robust design optimization of frontal structures was proposed as in [29]. The energy absorption can be controlled for design of crashworthy based on the use of compliant mechanisms as in [30].

For the current research topic, there have been no published works so far. The thickness optimal design and reinforcement designs are applied to vehicle model, which are used in small-overlap frontal impact (SOFI) simulations, are proposed based on the IIHS small-overlap research program [31]. The aim of this study is to improve the overall ratings for frontal structure performance in the event of a SOFI based on the crash test simulations. Following the SOFI test simulation results, the sensitive components will be figured out to strengthen the vehicle structure. In this paper, the best case among of them is chosen to improve the vehicle structure in the SOFI test. The reinforcements and frontal structures are enhanced by using a thickness optimization method which is proposed to improve the structural resistance of vehicle to a SOFI and to maintain the constant mass of the vehicle model. The optimized designs with the best crashworthiness intrusion results are proposed for the comparison with the original model. In this study, a vehicle computer model [32] is applied to a real IIHS crash test condition [35] using LS-DYNA [33] software for the crash test simulations.

Following the introduction, section 2 presents the FE vehicle model and reinforcement model designs which are developed for the SOFI test simulation. Section 3 describes the model experiment to characterize the SOFI test simulation. The simulation results are applied to rate the full vehicle structure and to optimize the design of the vehicle structure. Finally, this paper concludes with a discussion of possible future extensions of this research.

2. SMALL-OVERLAP MODELING

2.1. Description and Validation of Vehicle FE Model.

This model has been developed at the FHWA/NHTSA National Crash Analysis Center of the George Washington University. In this study, the number of part of original model was increased because the two reinforcement models were attached to a vehicle FE model [32] as new model which was used in this paper for crash simulations based on the IIHS small-overlap crash test as in [34, 35, 36]. The new FE model contains 521 parts and 333,455 elements without interior components or restraint systems. The set of elements representing the vehicle was translated into an FE model, each element was defined as a shell, beam, or solid element in accordance with the requirements for using LS-DYNA software [37]. The comparison between real-life vehicle and FE vehicle model were shown in Table 1 [32, 38].

Table 1. Comparison between real-life vehicle and FE vehicle model [32, 38]

	FE Model	Test Vehicle
Weight (Kgs)	2028	2043
Engine Type	3.3L V6	3.3L V6
Tire size	P215/65 R15	P215/65 R15
Attitude (mm) **As delivered**	F - 798 R - 846	F - 769 R - 766
Wheelbase (mm)	3030	3030
CG (mm) Rearward of front wheel C/L	1320	1319

To ensue to get the accurate results as the actual vehicle, the FE model was verified and validated in several ways such as energy balance analysis, acceleration and velocity. This model was validated by comparing the test and simulation results for the velocity, acceleration and energy absorption of the vehicle according to [32] as shown in Figure 1, 2 and 3. The simulation started with an initial amount of kinetic energy, and no external work was applied. As the simulation progressed, the kinetic energy decreased, and the internal energy increased because of the impact with the wall. The total energy remained constant in the simulation since no external work was applied to the vehicle.

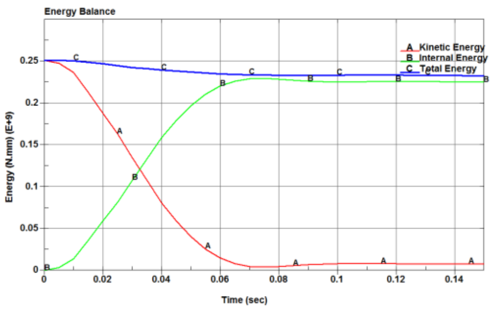


Fig. 1 Simulation energy balance analysis

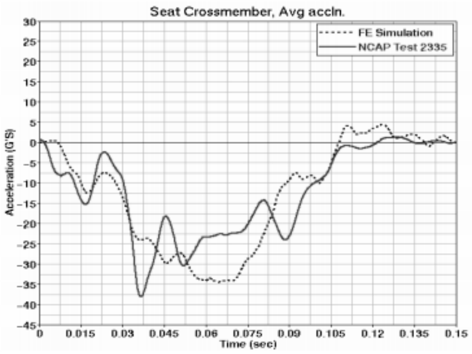


Fig. 2 Test and simulation results for seat crossmember acceleration vs. time [32, 36]

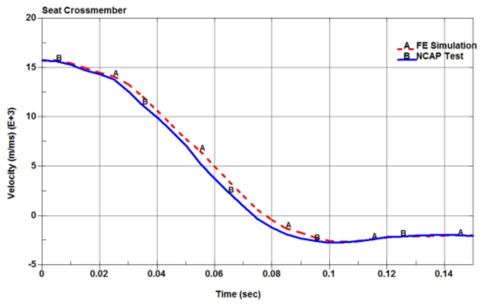


Fig. 3 Test and simulation results for seat crossmember velocity vs. time

In this paper, the frontal structures such as suspension, wheels also validated for small-overlap crash by comparing the moderate overlap test of IIHS [38] as shown in Figure 4. This model without interior components so only lower instrument panel, left footrest, seat bolts, A-pillar and B-pillar were accounted. The effective points were shown in Table 2. In this research, the vehicle model was validated for small-overlap crash by evaluating intrusion simulation results with the moderate overlap test (IIHS, 2014) as shown in [36, 37, 38]. In this case, the intrusion of seat bolts, A-pillar and B-pillar were measured and evaluated. The error between IIHS test and simulation is 6%. The parts of original model were increased because the barrier model was added. The position of barrier model was set for SOFI simulation the same as [37, 38].

Table 2. Comparison between moderate crash IIHS Test and simulation [38]

	Intrusion (cm)			
	A-pillar Rearward movement	Footrest (max)	Instrument panel rearward movement	IIHS Rating
Test	5	17	9	Marginal
Simulation	5.3	18	8	Marginal
Error	6 %	5 %	5 %	

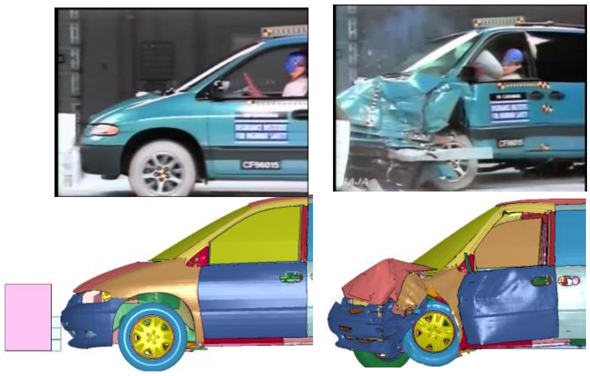
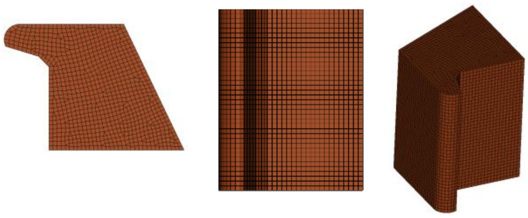


Fig. 4 IIHS Test and simulation result

2.2. Barrier Model Designs.

The IIHS investigated the possibility of adding an evaluation of crashworthiness for vehicles in these types of accidents by making small overlap crash test with Flat 150. According to the severe percentage of small overlap collisions in which passengers are seriously injured or killed. The purpose of the study was to figure out a vehicle-to-barrier simulations could apprehend the same characteristics of most actual car accidents in order to evaluate vehicle collision in small-overlap crash type (IIHS, 2012).

In this study, the barrier was designed following (Sherwood, 2012), as shown in Figure 5. The barrier had rigid, flat face with corner radii and 1533 mm high: the Flat 150 was a flat barrier with a 150 mm radius and 25% overlap. The barrier for the experiments was made using the CATIA software. Hyper Mesh was then used to derive their FE models [36].



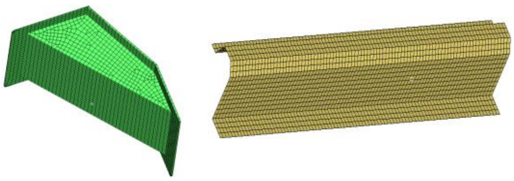
(a) Top view (b) Front view (c) Right view

Fig. 5 Different views of Flat 150 FE barrier model

2.3. The Reinforcement Model Designs. In this research, based on the sample designs [38], two reinforcements were selected for longitudinal and rocker panel as shown in Figure 6. The shapes of the reinforcements were optimized by the analytic intrusion of full vehicle model. The intrusion of occupant compartment of vehicle model was measured then comparison. The best shape which improved the vehicle structure in small-overlap was chosen from the example shapes as shown in Figure 7 and 8. Both of components for the simulations were made by using the CATIA software. Hyper Mesh was then used to derive their FE models. The material and property of reinforcements were presented in Table 3. As shown in Figure 7 and 8, the positions of two reinforcement models were in FE component of longitudinal and rocker panel models. The new vehicle model was displayed in Figure 9 which included position of longitudinal and rocker panel reinforcements in full FE vehicle model.

Table 3. The material of reinforcements

Material	Metals	Density [kg/m^3]	Modulus [G Pa]	Poisson ratio
MAT1	Carbon steel	7900	207	0.3



(a) (b)

Fig. 6 (a) Longitudinal reinforcement (b) Rocker panel reinforcement

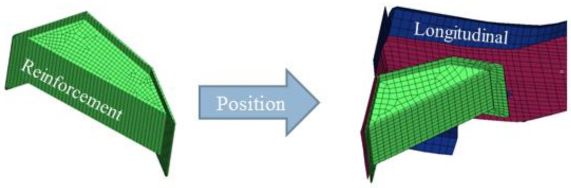


Fig. 7 The sample shapes of longitudinal reinforcement model

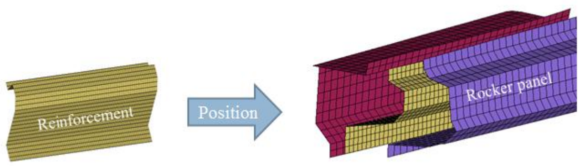


Fig. 8 The sample shapes of rocker panel reinforcement model

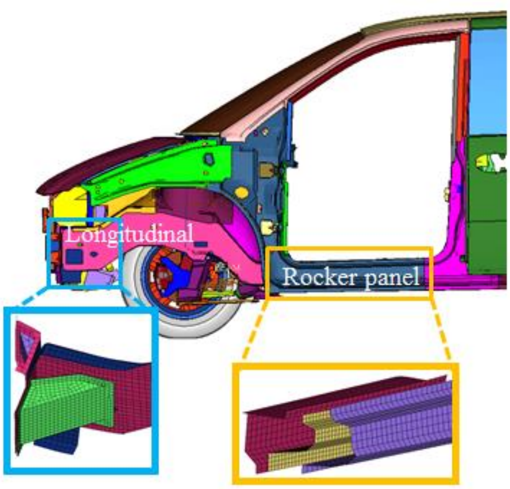


Fig. 9 The position of longitudinal and rocker panel reinforcements in vehicle model

2.4. Small-Overlap Crash Test Model Measurement and Constraints. In this paper the small-overlap crash simulation model was set to follow the actual IIHS crash test conditions. The vehicle model collides on the right edge of the barrier model at 64 km/h with 25% overlap.

Figure 10 shows the measurement points for measuring vehicle intrusion. According to [34, 35], 18 points were used for measurement. The purpose of this study was improving the vehicle structure in the event of a SOFI, so only nine points were used to measure deformation: the lower (three points) and upper (three points) hinge pillar, and the rocker panel (three points). The reference point R (red) will be taken on the vehicle structure on the nonstruck (right side) rear door frame.

The calculation of the intrusion dimensions can be explained such as: there are three measure points of each component (rocker panel, lower hinge pillar, and upper hinge pillar) only intrusions of moving direction are measured. The maximum values are used for calculation. In case of rocker panel the average of intrusion is used as shown in figure 11.

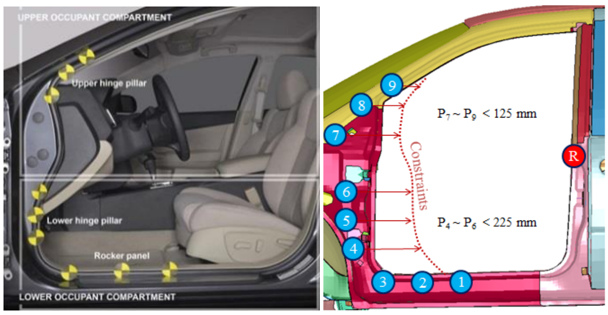


Fig. 10 Measurement points and constraints of hinge pillar

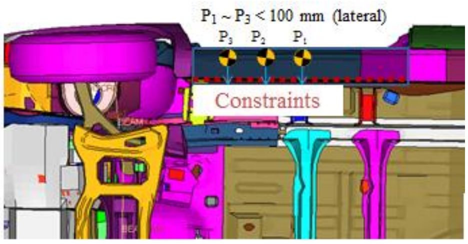


Fig. 11 Measurement points and constraints of rocker panel

3. SMALL-OVERLAP TEST SIMULATIONS

3.1. Analysis of Frontal Structure Models in SOFI Simulation and Overall Structural Rating. The frontal structures of vehicle model as shown in Figure 12. In small overlap frontal crash, the collision area is approximately a quarter of the full width of the vehicle model. So that the occupant compartment is seriously damaged during the collision such as hinge pillar, rocker panel and A-pillar in case longitudinal missed. Figure 13 shows the resulting damage to the frontal structures of the vehicle model in the 25% overlap impact to rigid barrier model.

The intrusion of the frontal door structures such as hinge pillar upper, lower and rocker panel were selected as the parameter for measuring the damage severity. In small-overlap frontal crash test, the left longitudinal rail was generally undamaged. In this case, the main load was attacked outside the longitudinal structures to others components such as the rocker panel and hinge pillar as shown in Figure 13.

The rating of this study follows IIHS rating [35]. The initial structural rating is based on a comparison of the measured intrusion with the rating guidelines, as shown in Figure 14. This rating may then be modified on the basis of additional observations about the structural integrity of the safety cage. According to [1, 2], the structure is rated based on sub-ratings for both the lower and upper occupant compartments. The measured intrusions in the lower and upper compartments falling in the "good" zone receive a structural sub-rating of "good" if no additional observations lead to a downgraded rating. Similarly, vehicles with all intrusion measures falling into one of the other three zones shown in Figure 14 receive sub-ratings of "acceptable," "marginal," or "poor." When intrusion measurements fall in different rating bands, the sub-rating generally reflects the band with the most measurements. However, the sub-rating cannot be more than one rating level better than the worst measurement.

The overall structural rating takes the worse of the lower and upper occupant compartment sub-ratings if no additional observations lead to a downgraded rating. For example, a vehicle with a lower occupant compartment sub-rating of acceptable and upper occupant compartment sub-rating of marginal receives an overall structural rating of marginal.

Based on [1, 2], the results obtained in this study were rated as shown in Figure 14.

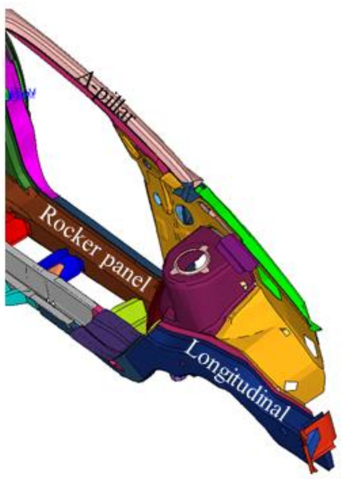


Fig. 12 The frontal structures of vehicle model

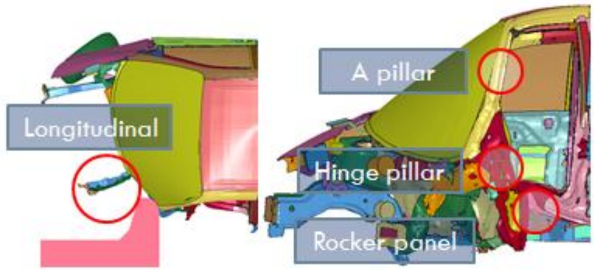


Fig. 13 Top and right views for intrusion of full original model

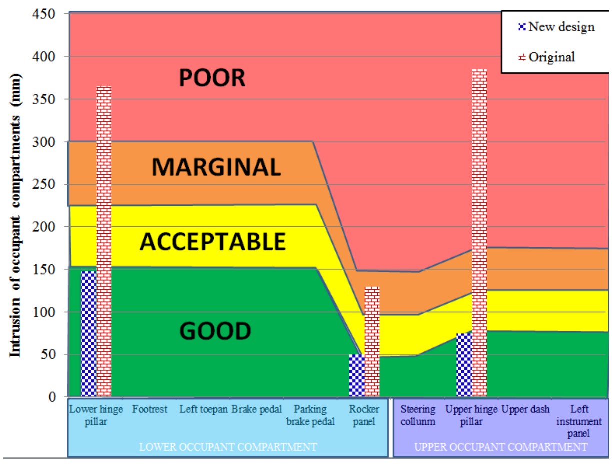


Fig. 14 Guidelines for rating occupant compartment intrusion [35]

3.2. Optimal Vehicle Structure Design Model

3.2.1. Optimization Algorithm Overview. The object function was used to solve the following optimization problem: minimize **f(x)**; subject to **g(x)**<0; $\mathbf{x}_{min} < \mathbf{x} < \mathbf{x}_{max}$; where **f(x)** is a function of the design objectives to be minimized (e.g., structural weight), **g(x)** is constraint (e.g., intrusion, energy), and $\mathbf{x}_{min}$ and $\mathbf{x}_{max}$ are the minimum and maximum bounds for the vector of design variables **x**, which has a number of design variables.

3.2.2. The sensitive part analysis. To analyze the main intrusion of structures in the SOFI, nine major variables were designed as shown in Figure 15: longitudinal reinforcement (X_1), longitudinal outer (X_2), longitudinal inner (X_3), rocker panel inner (X_4), rocker panel outer (X_5), and rocker panel reinforcement (X_6), A-pillar inner (X_7), A-pillar reinforcement (X_8) and A-pillar outer (X_9) which were the values of current point added by 20% as shown in Table 4. In view of structural safety and economy, all responses should be taken into account, in which the total mass should be small to ensure the economy, and the reduction of intrusion is used to guarantee the occupant survival space.

Table 4. Range of design thickness variables

Var	Components	Base	lower	upper
X_1	Longitudinal reinf	2.0	1.6	2.4
X_2	Longitudinal outer	2.1	1.7	2.5
X_3	Longitudinal inner	2.1	1.7	2.5
X_4	Rocker panel inner	1.4	1.1	1.7
X_5	Rocker panel outer	1.3	1.0	1.6
X_6	Rocker panel reinf	2.0	1.6	2.4
X_7	A-pillar inner	1.9	1.5	2.3
X_8	A-pillar reinforcement	1.9	1.2	2.2
X_9	A-pillar outer	1.2	1.0	1.4

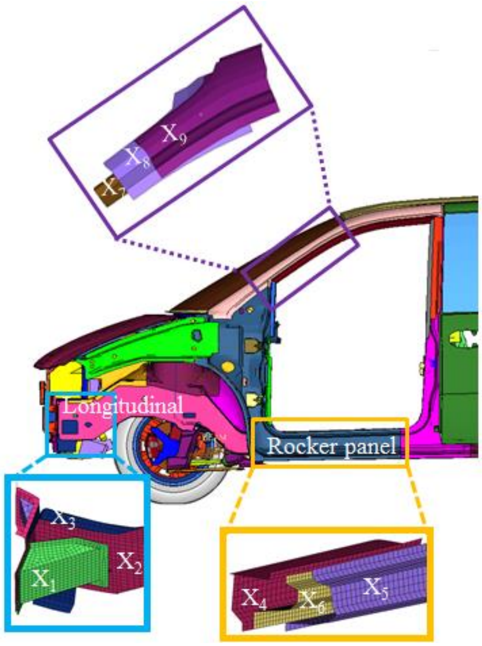


Fig. 15 Illustration of design variables for vehicle structure

To reduce the case of study, the sensitive parts were analyzed. The nine variables stand for nine parts of vehicle model. The sensitive part results were shown in Figure 16. Based on the results, the sensitive variables were rank from 1 to 9 such as X_8, X_7, X_9, X_6, X_1, X_4 X_2, X_5, and X_3

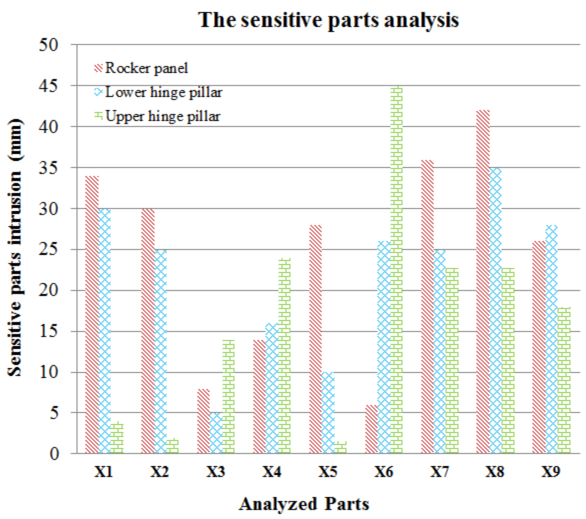


Fig. 16 Illustration of design variables for vehicle structure

In this study the sampling frequency decrease from 130 to 54 by chosen 6 sensitive parts such as A-pillar reinforcement, A-pillar inner, A-pillar outer, Rocker panel reinforcement, longitudinal reinforcement and rocker panel inner. The optimal solution was compared to the original model in Table 5. Typical deterministic optimization formula is described as follows:

Find: $X = (x_1, x_2, x_3, x_4, x_5, x_6)^T$

With $X_L < X < X_U$

To minimize: mass, intrusion

Subject to: R - 50 < 0; L - 150 < 0; U - 75 < 0.

In this paper, the functional connection between deformation and the thicknesses of rocker panel, absorbed crash energy and the thicknesses of longitudinal, and the stiffener can be calculated by response surface method function (RSM). The quadratic polynomial is assumed as follows:

$$Y(x) = 2 + 6\,10^{-3}x_1 + 5\,10^{-3}x_2 + 6\,10^{-4}x_3 + 2\,10^{-3}x_4 - 10^{-3}x_5 - 7\,10^{-3}x_6 - 7\,10^{-4}x_1^2 + 10^{-3}x_2^2 + 3\,10^{-4}x_3^2 + 2\,10^{-3}x_4^2 + 4\,10^{-4}x_5^2 + 5\,10^{-3}x_6^2 + 2\,10^{-19}x_1x_2 + 8\,10^{-4}x_1x_3 - 2\,10^{-3}x_1x_4 - 3\,10^{-16}x_1x_5 - 2\,10^{-3}x_1x_6 - 2\,10^{-3}x_2x_3 + 2\,10^{-18}x_2x_4 - 4\,10^{-4}x_2x_5 + 2\,10^{-3}x_2x_6 - 3\,10^{-16}x_3x_4 - 3\,10^{-3}x_3x_5 + 10^{-3}x_3x_6$$

Where, Y(x) is the optimal target which is mass in this paper. R, L, and U stand for the intrusion of rocker panel, lower hinge pillar, and upper hinge pillar, respectively. X_L and X_U are the lower and upper bounds of design variables shown in Table 4.

3.2.3. Optimal Vehicle Structure Model Results. This paper studied on frontal structure optimal design such as A-pillar, longitudinal and rocker panel to improve vehicle structure in the SOFI test. The response surface method was applied for the optimal design solution. When considering the safety and economy in conformity with the original weight, optimal solution is chosen as follows in Table 5, 6 and 7.

Figure 14 shows the results of the new model in SOFI test simulation and compares the intrusion in the occupant compartments with the original model using the Flat 150 (the flat barrier with 150 mm radius at the corner and 25% overlap).

The results in Figure 17 to 19 demonstrate that the rating for the occupant compartment intrusion can be improved by optimizing the frontal structures of vehicle model. In this research, the thickness optimization method was applied to modify the vehicle structure stiffness by changing the thicknesses of the A-pillar, longitudinal, rocker panel and reinforcements.

Table 5. Optimized design variables (mm)

Var	Components	Original model	New design
X_1	Longitudinal reinforce	NONE	1.7
X_2	Longitudinal outer	2.1	2.1
X_3	Longitudinal inner	2.1	2.1
X_4	Rocker panel inner	1.4	1.4
X_5	Rocker panel outer	1.3	1.3
X_6	Rocker panel reinforce	NONE	1.6
X_7	A-pillar inner	1.9	2.1
X_8	A-pillar reinforce	1.9	2.0
X_9	A-pillar outer	1.2	1.1

Table 6. Comparison results of RSM function and simulation (mm, tons)

Intrusion	RSM	Simulation	Error%
R	52	50	4
L	150	148	1
U	74	75	1
Mass	2.029	2.033	0.2

Table 7. Comparison results of original model and optimal model (mm, joule, tons)

Intrusion	Original	New design	% Change
R	130	50	-61
L	365	148	-59
U	385	75	-80
Energy	9.5E+6	2.5E+7	163
Mass	2.028	2.033	0.2

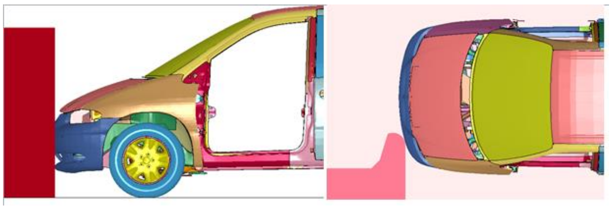
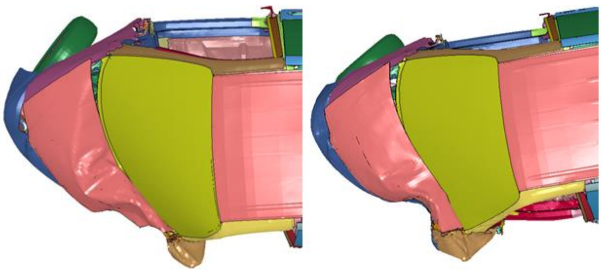


Fig. 17 The SOFI full vehicle model pre-crash



a. Original model **b. Optimal model**

Fig. 18 The comparison of the deformation of full vehilce model post-crash in top view

a. Original model **b. Optimal model**

Fig. 19 The comparison of the deformation of full vehilce model post-crash in right view

4. CONCLUSION

In this paper, a vehicle FE model was used to analyze the frontal structure of vehicle performance in the event of a small-overlap frontal crash with 25% overlap. The new design model simulation results were compared to the original with the same condition by using the Flat 150 (the flat barrier with 150 mm radius and 25% overlap). The frontal structures were optimal design to improve the rating in SOFI IIHS test. The result shows that the upper occupant compartment was the most deformed over the limitation rate which made the overall structural rating was downgraded. The optimization results showed that the overall structural rating improved which displayed below:

The results displayed the most serious intrusion; the rocker panel and lower hinge pillar showed the most deformation. In addition, the A-pillar was bent and moved upward. The left wheel was severe damage. With the new design, the overall structural evaluation for SOFI was upgraded to "good."

Future extensions of this research could include improving the upper occupant compartment such as upper hinge pillar which led the overall structural rating was downgraded. Based on the drawbacks of thickness optimization method, future work will involve improving the vehicle structure for SOFI tests by changing the shape of the A-pillar, rocker panel, and longitudinal rail.

ACKNOWLEDGMENT - This work was supported in part by the research program 2015 of Kookmin University in Korea.

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