ANALYSIS OF VEHICLE BODY WITH SMALL-OVERLAP FRONTAL IMPACT ON VARIOUS BARRIERS

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ABSTRACT

This paper presents an analysis of the vehicle structure in the event of a small-overlap frontal impact (SOFI) on various barriers based on a computer crash simulation model. Three barrier models were developed for SOFI simulation based on real test conditions: Flat 50, Flat 150, and Pole 250. The simulation models were developed using HyperMesh and LS-DYNA software. 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. The parts sensitive to a small-overlap crash were confirmed. Thickness optimization was conducted to strengthen the rocker panel, A-pillar, and lower hinge pillar in order to improve the vehicle structure in the event of a SOFI. The best values among the variables were chosen for the new design. The crash analysis using finite element models showed that the most serious damage to the vehicle structure occurred when the minivan model collided with Flat 50 at 20% overlap. In this study, the grade of the overall structure was changed from "poor" to "acceptable" in the case of Pole 250.

Keywords: *small-overlap, crashworthiness, frontal impact, vehicle structure, barrier design, crash test.*

1. INTRODUCTION

The Insurance Institute for Highway Safety (IIHS) introduced the small-overlap frontal impact (SOFI) test in 2012 in order to consider one of the most serious crash scenarios and difficult engineering challenges [1-3]. During the experiment, the vehicle hits a rigid wall at 64 km/h with 25% of the front bumper making contact with the barrier. A real-life comparison may be a vehicle colliding with a pole or flat object but only making contact with the center-line of the headlight [4].

In small-overlap frontal crashes, the crash forces are applied outboard of the vehicle's longitudinal frame rails [5]. In addition, forces are concentrated on the front suspension, at the firewall, and at the base of the A-pillar. These areas not traditionally designed to absorb and dissipate crash forces [6 - 8].

In recent studies on small-overlaps, two vehicles have been developed with different types of rail cross-sections along the longitudinal direction. Finite element (FE) analysis was performed to characterize the frontal pole impact compared to the full-frontal rigid barrier test and IIHS 40% offset frontal impact test. Hong et al. found that the rails absorbed over 50% of the crash energy in the IIHS test [9]. Park et al. suggested that the offset-frontal crash test can be used to complement the full-frontal crash test [10].

2. SMALL-OVERLAP MODELING

2.1. Description and validation of vehicle FE model

A minivan FE model was used in this study for experiments based on updates to the IIHS small-overlap research program. The FE model from the National Crash Analysis Center library contains of 333,455 elements without interior components or restraint systems. The detailed FE model was constructed of parts broken down into elements [11].

The FE model was verified and validated in several ways to ensure that it was an accurate representation of the actual vehicle. These efforts included checking for the completeness of elements and adequacy of the connection details. This model was validated by comparing the test and simulation results for the acceleration and energy absorption of the vehicle according to.

Figure 1 plots the global energy from the simulation. The energy was balanced throughout the simulation. 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.

The curve shapes and peak value of the model showed good and consistent correlation with. The agreement with regard to the acceleration (Figure 2), energy curve (Figure 1) and velocity (Figure 3) meant that this FE model could be assumed to be valid.

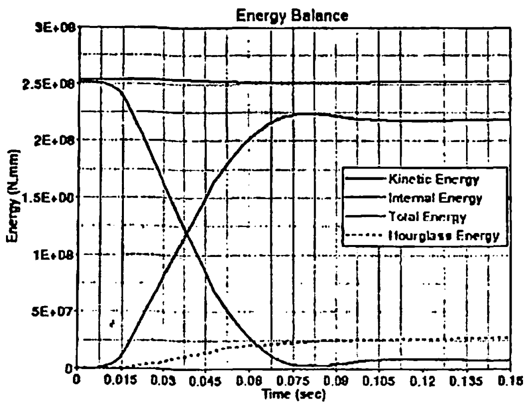


Figure 1. Simulation energy balance analyses

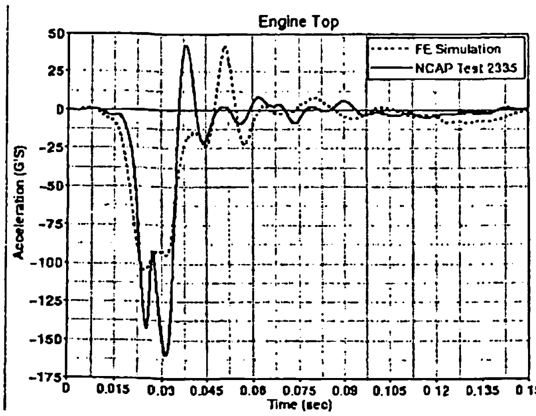


Figure 2. Test and simulation results for engine top acceleration vs time curve

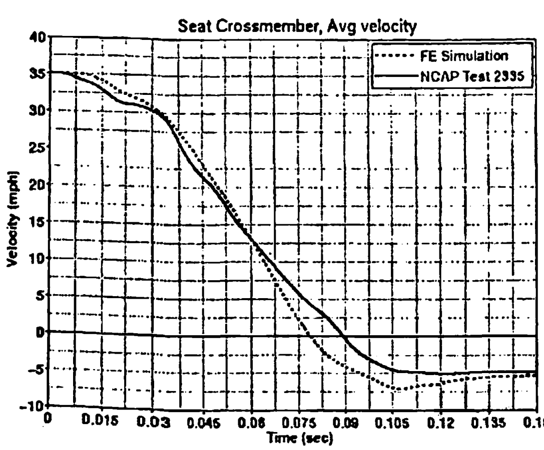


Figure 3. Test and simulation results for seat cross member average velocity curve

2.2. Barrier model designs

In this study, three barrier types were designed, as shown in Figure 4: Flat 150 was a flat barrier with a 150 mm radius and 25% overlap [1], Flat 50 was a flat barrier with a 50 mm radius and 20% overlap [2]; and Pole 250 was a pole with a 250 mm radius and 25% overlap [2].

The two proportions to the vehicle width modes were 20% and 5%, as shown in Figure 5. Most of the barriers for the experiments were made using the CATIA software. HyperMesh was then used to derive their FE models. As shown in Figure 6, these two modes were used to develop three FE simulation models.

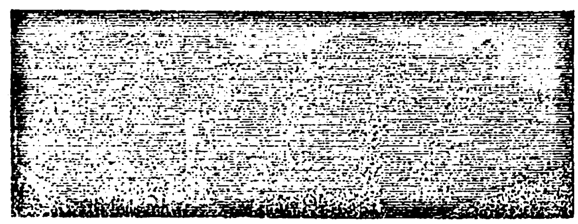


Figure 4. (a) Flat 50 (b) Flat 150 (c) Pole

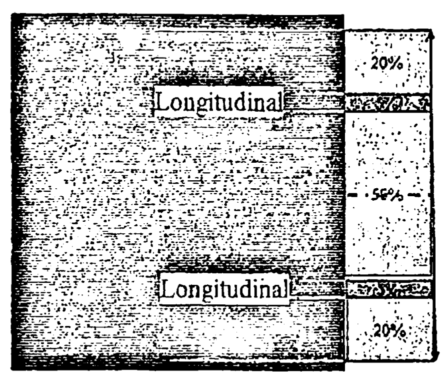


Figure 5. Vehicle width ratio and structure of minivan model

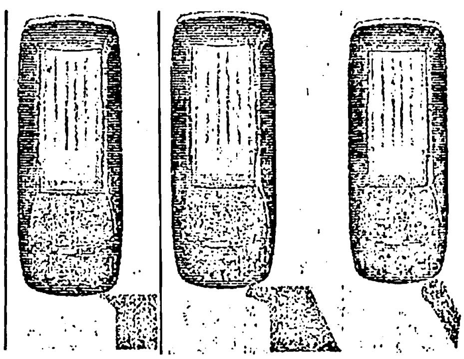
2.2 Small-overlap crash test model

The small-overlap crash examination model was set to follow the actual IIHS crash test conditions. The right edge of the barrier model face was offset to the left of the vehicle centerline by 20% or 25% depending on the type of barrier and the minivan model hit it at 64 km/h.

Figure 7 shown the measurement points to mearsure vehicle intrusion. Following [2], 18 points were measured. The scope of this study was improving the frontal 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 hinge pillar was measured at the inner-most surface of the door opening; this was typically on the pinch weld.

The vertical coordinates for the three lower points were obtained by adding 0 cm (lower hinge pillar point 1), 7.5 cm (lower hinge pillar point 2), and 15 cm (lower hinge pillar point 3) to the brake pedal reference point. The upper points were obtained by adding 45 cm (upper hinge pillar point 1), 52.5 cm (upper hinge pillar point 2), and 60 cm (upper hinge pillar point 3).

The rocker panel was also measured at the inner-most surface of the door opening; this was typically on the pinch weld. The longitudinal coordinates were obtained by adding 20 cm (rocker panel point 1), 35 cm (rocker panel point 2), and 50 cm (rocker panel point 3) to the brake pedal reference point.



(a)Flat 50 (b) Flat 150 (c) Pole 250
Figure 6. FE simulations models for three barriers

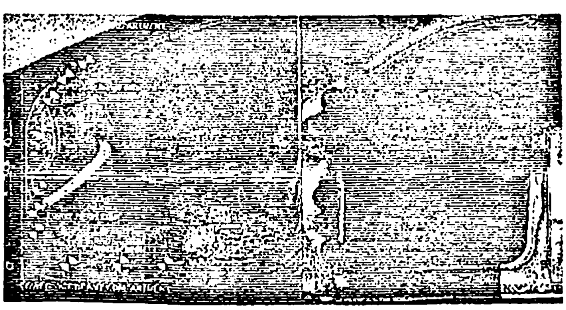


Figure 7. Measurement points in occupant

3. SMALL-OVERLAP TEST SIMULATIONS

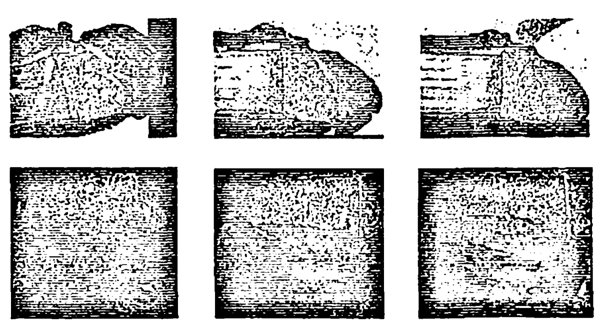
3.1. Frontal crash simulation of full vehicle model

The contact area in a small-overlap crash is tiny compared with the full width of the car model; thus, the body is serious damaged during the impact. Figure 8 shows the resulting damage to the frontal structure of the vehicle models in the three impact modes.

The intrusion of the frontal compartments was selected as the parameter for measuring the damage severity.

With Flat 50, the left longitudinal rail was largely undamaged. This means that the majority of the loading was outside longitudinal structures such as the rocker arm and hinge pillar. Figure 10 shows that the upper hinge pillar was the most deformed part in this case. The red dotted line in Figure 13 shows that the main longitudinal rail was missed. The wheel was directly loaded and pushed rearward into the toepan. The hinge pillar, rocker panel, and upper structures experienced additional loading. This loading pattern led to significant intrusion of both the lower and upper regions of the occupant compartment, as shown in Figure 9. In this case, the wheel suffered from the load; this caused distortion and a rotation 90°, which caused nearly the whole body of the vehicle to twist. The second mode was Flat 150; the result was shown in Figure 11. In this case, the main longitudinal rail was not missed, so the left wheel was not directly loaded. This was why Flat 150 received less damage than Flat 50. The blue line in Figure 13 show the path load; the upper hinge pillar was the most deformed, as shown in Figure 9.

The last mode was Pole 250; the result was shown in Figure 12. In this case, the same situation as for Flat 150 occurred; this was shown by the gold line load path in Figure 13. The vehicle model tended to rotate and slide sideways during this type of collision; this can move the driver's head outboard away from the protection of the front airbag. In this mode, the vehicle model quickly moved out to the side; thus, it received less damage than in the other modes.



(a) Flat 50 (b) Flat 150 (c) Pole250
Figure 8. Top and back views for intrusion of three impact modes.

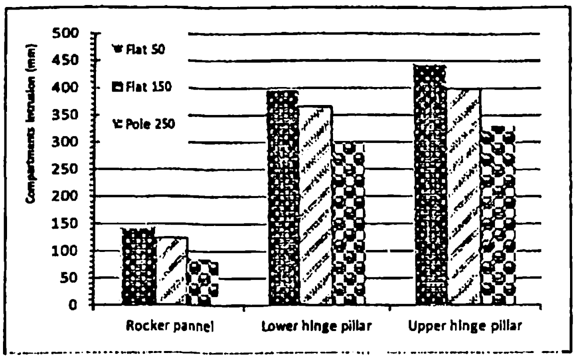


Figure 9. Comparison of occupant compartments in three modes

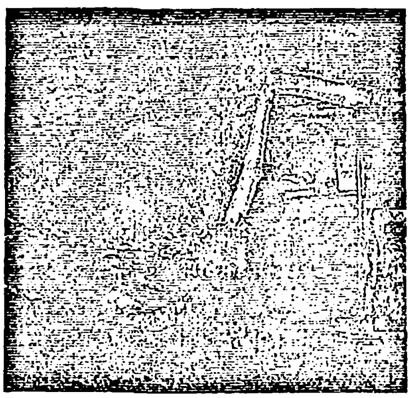


Figure 10. Vehicle deformation with Flat 50

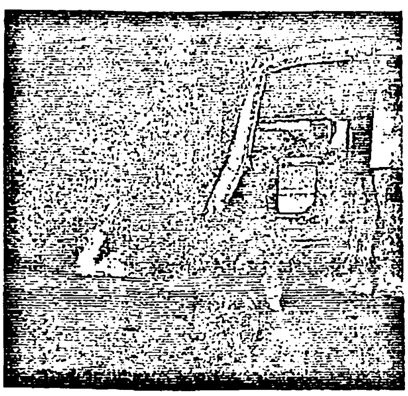


Figure 11. Vehicle deformation with Flat 150

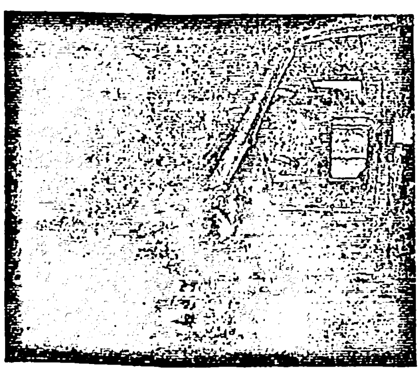


Figure 12. Vehicle deformation with Pole 250

3.2. Small-overlap rating

According to [3], the initial structural rating is based on comparing the measured intrusion with the rating guidelines, as shown in Figure 15. This rating may then be modified on the basis of additional observations about the structural integrity of the safety cage. Following [3] 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 15 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 is not more than one rating level better than the worst measurement.

3.3. Load path

The vehicle deformation and load path in Figure 13 are based on the values in Table 1. Despite the differences in test configurations (crash partner, barrier geometry, barrier type) compare to [4], the load paths and deformation patterns showed differences depending on if the main longitudinal rail was missed (i.e., Flat 50 mode with 20% overlap) or not. If the main longitudinal rail was missed, the wheel was directly loaded and pushed rearward into the toepan/hinge pillar/-rocker panel, and the upper structures received additional loading. This loading pattern led to significant intrusion of both the lower and upper regions of the occupant compartment. When the main longitudinal rail was not missed, the upper hinge pillar received the most deformation, as shown in Figure 8.

Table 1. Intrusion of occupant compartments in three modes (unit: mm)

Components	Pre-crash	Post-crash Flat 50	Intrusion	Post-crash Flat 150	Intrusion	Post-crash Pole 250	Intrusion	Note
Rocker pannel 1	838.419	753.071	85.348	736.532	101.887	760.166	78.253	
Rocker pannel 2	944.33	803.388	140.942	842.595	101.735	859.886	84.444	
Rocker pannel 3	1027.21	826.769	200.441	861.11	166.1	935.391	91.819	
Lower hinge pillar 1	1044.33	650.408	393.922	728.952	315.378	746.002	298.328	
Lower hinge pillar 2	1037.52	641.279	396.241	673.356	364.164	788.296	249.224	
Lower hinge pillar 3	1007.28	631.512	375.768	649.543	357.737	746.518	260.762	
Upper hinge pillar 1	1108.32	759.48	348.84	710.069	398.251	779.035	329.285	
Upper hinge pillar 2	1039.12	597.225	441.895	656.424	382.696	798.479	240.641	
Upper hinge pillar 3	967.053	658.669	308.384	693.952	273.101	675.828	291.225	
Rocker pannel			142.2437		123.241		84.83867	Average
Lower hinge pillar			396.241		364.164		298.328	Max
Upper hinge pillar			441.895		398.251		329.285	Max

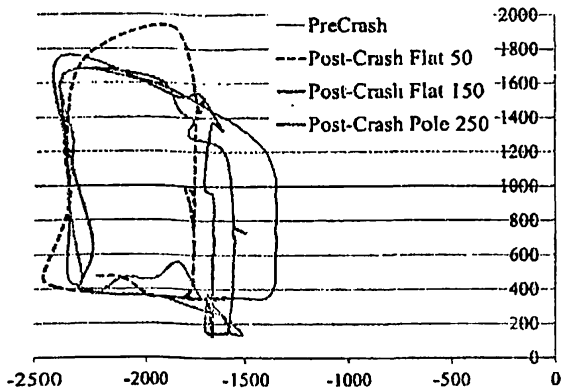


Figure 13. The vehicle deformation and load path

These vehicle damage patterns were similar to those seen in real-world studies; occupant compartment intrusion has been identified as the primary injury mechanism in real-world crashes.

3.4. Optimal design vehicle structure model

The most commonly employed optimization process for a highly nonlinear problem with several design variables is to construct a multidimensional response surface as accurately as possible and seek an optimum solution on this surface. In this study, the design variables were chosen according to the design of experiments (DOE) method.

The algorithm was used to solve the following optimization problem:

Design objective: Min Y(x).

Design constraints:

$R - 150 < 0$; $L - 250 < 0$; $U - 180 < 0$.

Design variables: $X_{lower} < X < X_{upper}$

with $X = (x1, x2, x3, x4, x5, x6)^T$

Design factors: thicknesses of outer A-pillar (x1), A-pillar reinforcement (x2), inner A-pillar (x3), door frame (x4), rocker panel (x5), and lower hinge pillar (x6), as shown in Figure 14.

Table 2. Range of design variables (unit: mm)

Variable	Components	Nodes	Base	Lower	Upper
x1	A pillar outer	2000052	1.2	0.96	1.44
x2	A pillar reinforce	2000054	1.86	1.488	2.232
x3	A pillar inner	2000080	1.88	1.504	2.256
x4	Door frame	2000078	1.43	1.144	1.716
x5	Rocker pannel	2000107	1.32	1.056	1.584
x6	lower hinge pillar	2000046	1.33	1.064	1.596

where R, L, and U stand for the rocker panel, lower hinge pillar, and upper hinge pillar, respectively. X_{lower} and X_{upper} are the minimum and maximum values in the for the variable in the design range.

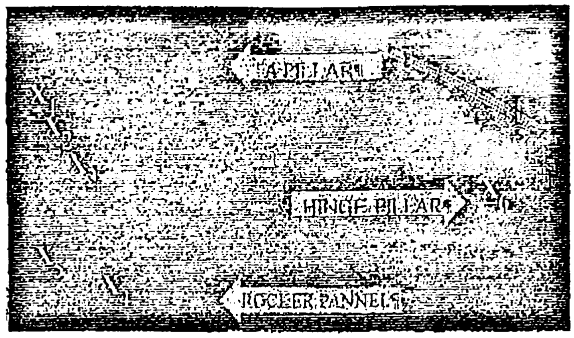


Figure 14. Illustration of design variables for vehicle structure

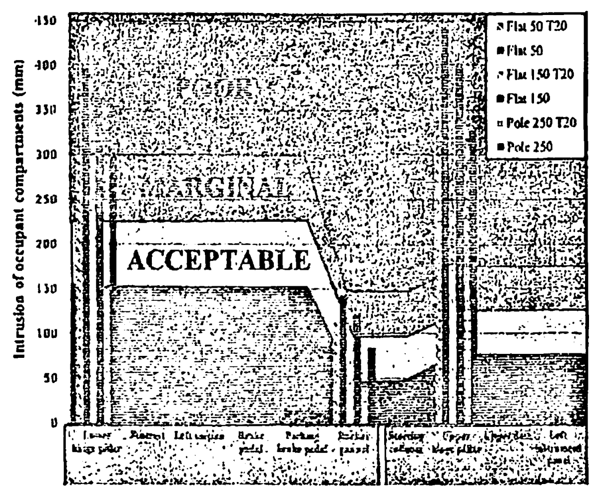


Figure 15. Guidelines for rating occupant compartment intrusion with different modes

4. CONCLUSION

In this study, a minivan FE model was used to analyze the vehicle body in the event of a small-overlap frontal crash with three types of barriers. The simulation results of the original and new design model were analyzed in three modes: Flat 50, Flat 150, and Pole 250.

The Flat 50 mode 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 turned 90° with severe damage. The overall structural evaluation for this mode was "poor."

The Flat 150 mode showed the second most serious intrusion; the rocker panel was bent, and the A-pillar moved backward. In this mode, the overall structural rating was upgraded to "marginal."

The Pole 250 mode showed the least serious intrusion; the rocker panel became bent, the A-pillar moved backward, and the vehicle model sliced out of the barrier. In this mode, the overall structural rating was upgraded to "acceptable."

The poor results indicate that most vehicles are just not designed for small-overlap impacts with rigid barriers. Traditional crash absorption structures are completely bypassed during the event, which exposes the vehicle safety structure to greater deformation and the occupant to stronger deceleration.

At present, most vehicles are designed to use the entire front end to absorb an impact, and crash testing has focused on only the driver's side. This is why almost all cars currently available commercially are rated as "poor" or "marginal" by the IIHS.

Future extensions of this research could include improving the front side member via various barriers in the event of a SOFI. The limitations of the thickness optimization method do not satisfy the requirements for the three barrier types with small overlap. Based on the drawbacks of this method, future work will involve improving the vehicle structure for SOFI tests with various barriers by optimizing the cross-section design of multiple components such as the A-pillar, rocker panel, and longitudinal rail. A new active frame rail will be proposed to engage the barriers and other reinforcements in the key cross members.

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