

Development of New Structural Optimization Methodology for Vehicle Crashworthiness

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ABSTRACT

The automotive industry continues to face the challenge of developing efficient side body structures that help to reduce the risk of injury to occupants in collisions. The B-pillar, Roof, and Side Sill are key structural members that help reduce the risk of injury to the occupants during a side impact crash event. This study used a simulation-based global optimization method to find optimum thickness for the B-pillar, Roof, and Side Sill components considering baseline material specification and vehicle performance in the IIHS SICE (Side Impact Crashworthiness Evaluation) and FMVSS 216 (Roof Crush Resistance) safety tests.

Fifteen design variables were defined by selecting structural members from a unibody vehicle design. The objective of the optimization was to find the most efficient distribution of mass for the structural members that are vital for the occupant safety. Automated simultaneous simulations were conducted using a global optimization method called Self-Adaptive Evolution. This methodology resulted in a 11% increase in occupants survival space (or decrease in occupant compartment intrusion), and 1.7% reduction in total mass compared to the baseline structure. Also this optimization result met the FMVSS 216 roof crush resistance requirement.

1. Introduction

Government and insurance institutions have introduced many safety standards with the intent to help reduce the risk of serious and fatal injuries to occupants during side impact crashes. To achieve a desired crashworthiness, the auto industry focuses on developing better vehicle side body structures that help reduce the risk of injury to occupants in collisions. When considering safety standards in development, available design and test technologies only allows the engineer to design and tune the vehicle side structure to each test mode separately. However, this can be inefficient and somewhat imprecise since it requires a lot of design time and experience to find an appropriate strength and balance for the side structure. Still the engineer may not find the optimum structure respect to weight and strength.

A new simulation-based structural optimization method was developed to help design the structure more efficiently considering the crash modes simultaneously. This method was validated during the initial phase of side structure development for 2011 Odyssey. The objective was to find the optimum thickness for the side structural members that would

help to reduce the risk of injury to occupants in collisions and meet the requirements of the Side Impact Crashworthiness Evaluation (SICE) and Federal Motor Vehicle Safety Standard (FMVSS) No. 216, Roof crush resistance modes. These modes were selected since they are the most dominant for side impact crashes.

The numerical optimization method used was Self Adaptive Evolution (SAE). This is a global optimization algorithm⁽¹⁾ in which the results are not dependent on a starting point, such as it is in the gradient-based methods.

Furthermore, iterations are calculated in parallel and tend to converge to a global optimum.

Generally, global optimization methods require a large number of simulations and dedicated computer resources. To facilitate this, computer resources at the Ohio Supercomputing Center (OSC) were used.

2. Side Impact Crash Modes

Roof crush resistance and SICE simulation models were used simultaneously to find the optimum gauges for the side structure (Fig. 1).

Total mass of these parts, shown in Fig. 2, was

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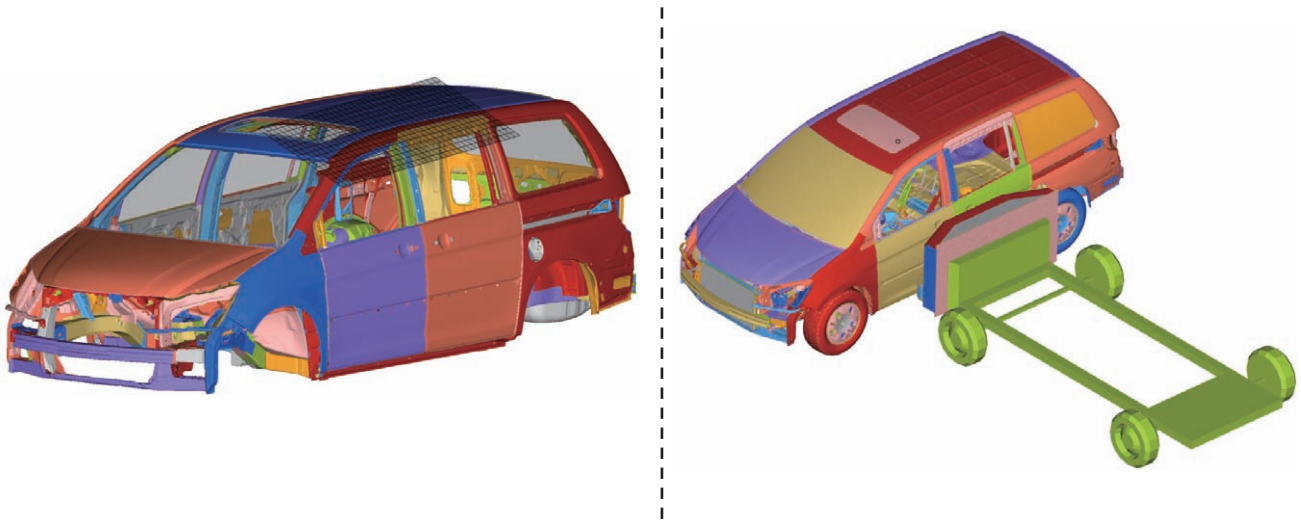


Fig. 1 Simulation models

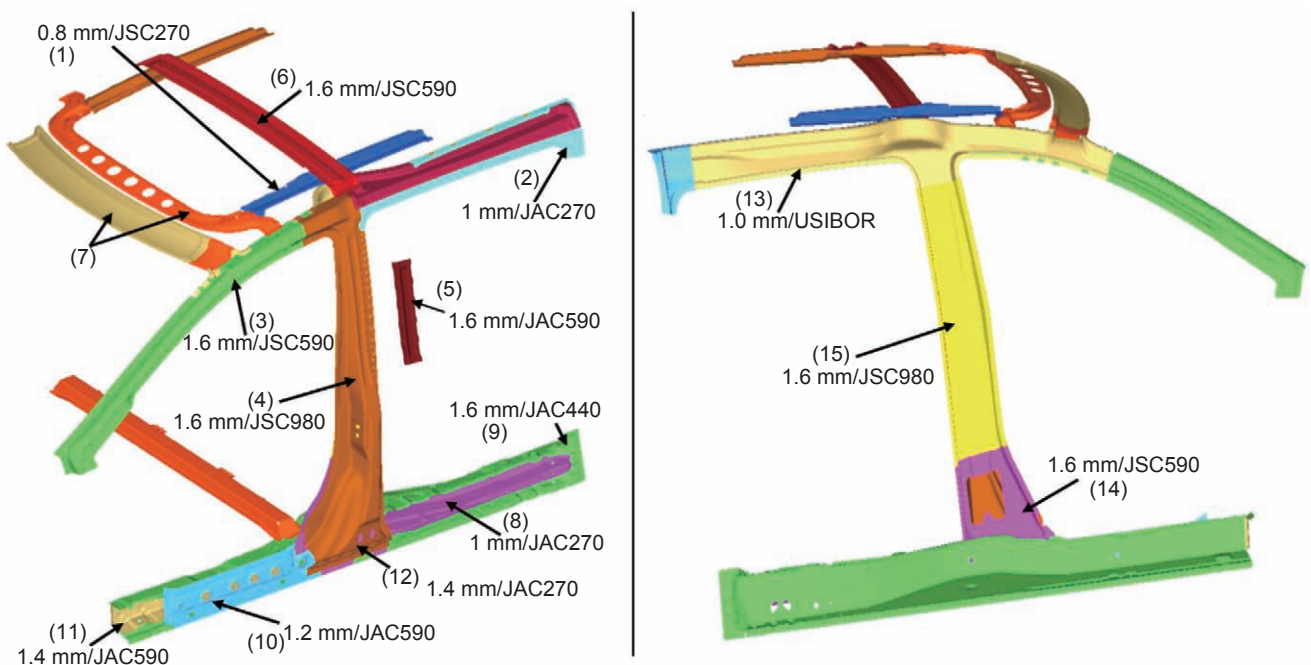


Fig. 2 Side structural members selected for optimization

36.93 kg. These parts were selected primarily based on their direct contribution to withstand the side crash modes. Part size was a secondary factor since more mass can be taken out from larger structural members. The objective of this study was to find the optimum thickness to the structural members that would meet the target force level and occupant survival space for roof crush resistance and SICE crash modes respectively.

3. System Workflow

Figure 3 shows the optimization workflow⁽²⁾ that was developed using OPTIMUS software. This is a fully automated workflow that varies the thickness of

the side structure, simulates the two crash modes, and extracts the roof crush resistance force and survival space.

Using this workflow, many simulations were run successfully. OPTIMUS easily interacts with other software that control the simulation submission process and can incorporate user scripts, which is essential since some of the simulations required extracting complex results. For this study, a separate script was written to extract the occupant survival space from the SICE simulation. All the simulations were done using LS-DYNA⁽³⁾ software. The OSC was used to process the 200-plus simulations that were needed to complete this optimization.

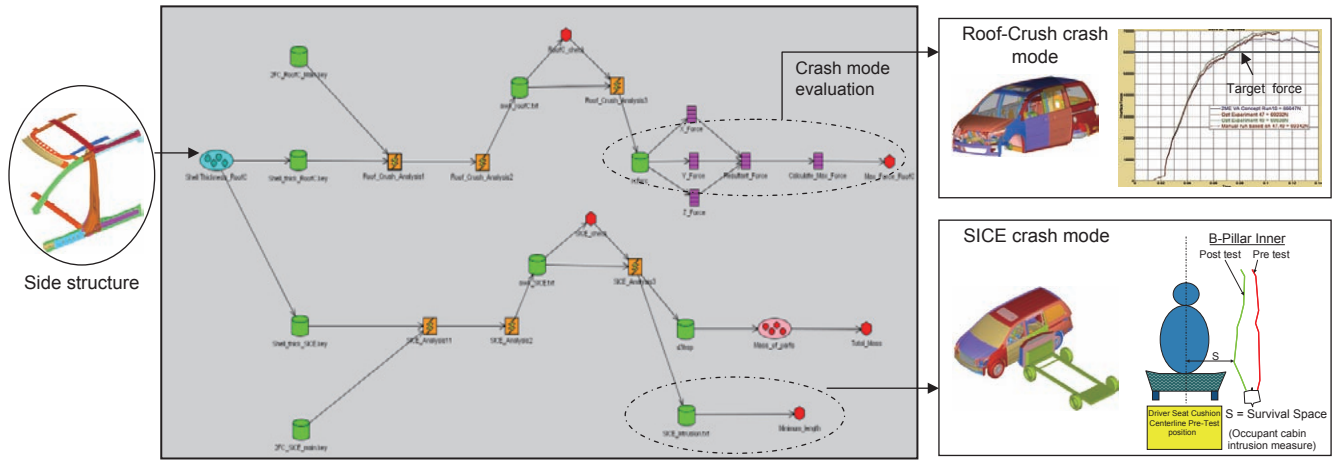


Fig. 3 Optimization workflow

Table 1 Baseline (first design milestone) simulation results

	Roof-crush force (N)	Survival space (mm)	Total mass (kg) [Comps for optimization]	Total mass (kg) [Comparing the both sides of the car]
Target	66400	116	Reduce mass	Reduce mass
Baseline run	73414	117	36.9	69.5

4. Optimization

The noisy, non-linear nature of crash analysis reduces the use of gradient-based optimization methods; therefore, a global optimization method called SAE was selected to drive the optimization. The SAE strategy is directly based on absolute valued vectors when dealing with continuous parameter optimization studies. The algorithm is a multi-recombinant scheme based on a population of designs and its strategy is to imitate biological mutation and selection⁽⁴⁾. Designs with the best fit from the current total population will be selected as the parents for the next generation. The multi-recombinant method used here selects multiple parents to generate one offspring, and mutation is independently applied to each design so the old generation produces a new generation. The new generation's fitness is then calculated and new offspring are made. The algorithm has convergence criteria and, for certain ranges, algorithm parameter values have been determined for improved performance.

Objective: Minimize total mass of the selected parts.

Constraint 1: Roof crush resistance force has to be greater than 66400 N

Constraint 2: Distance from center of the vehicle to B-Pillar Inner has to be greater than 551 mm for SICE.

Occupant survival space is calculated as $551 - 435 = 116$ mm

Where 435 mm is the distance from center of the vehicle to the center of driver seat cushion, which is a constant.

Thickness of the parts varies between 0.7 and 2.3 mm.

Number of Simulations required is calculated as

Number of Load Cases (Roof-Crush and SICE)

$\times$ *Population Size* (number of simulations for each generation)

$\times$ *Number of generations*,

Therefore total number is $2 \times 15 \times 8 = 240$ simulations.

Table 1 shows the baseline results compared to the target.

5. Optimization Results

Table 2 shows the results of the first 22 simulations. In the OPTIMUS workflow, Max_Force_RoofC refers to Constraint 1 and Minimum_length refers to Constraint 2. It is observed that when going from one generation to the next, the optimization algorithm finds more feasible solutions in allocating less mass to the structural members.

Figures 4 and 5 show the behavior of total mass respect to the two constraints. It is clear from Fig. 5 that the efficient mass distribution among the structural members can give better roof crush resistance force and survival space. It is also evident that SICE or Minimum_length is the driving constraint for the optimization.

Table 3 shows the best mass distribution among the structural members found through this optimization study.

As shown in Table 4, simulations 76 and 114 show better roof crush resistance force and better survival space with same or less mass compared to the baseline.

Table 2 Optimization results

Ex.	Sill_Stf_11	Sill_Mid_Gusset_12	Roof_Rail_Mid_13	B_Piv_Innr_Lower_14	B_Piv_Innr_15	Max_Force_RoofC	RoofC_check	SICE_check	Minimum_length	Mass	Mass_Roof_Pnl_Stfa_1	Mass_Roo...
1	1.4	1.4	1	1.6	1.6	73414.05988	1	1	551.80119	0.03693	0.00067	0.00142
2	2.17527	1.07986	0.9259	1.8068	0.82217	74098.89675	1	1	480.71187	0.04024	0.0015	0.00149
3	2.26034	1.45738	1.13839	1.58647	1.26983	83555.64269	1	1	522.36654	0.04132	0.00096	0.00298
4	0.73922	1.02046	1.26649	2.14818	1.03945	72408.99837	1	1	487.86479	0.0398	0.00079	0.00189
5	0.9197	1.72167	0.73424	1.63261	1.99598	83279.00918	1	1	552.16775	0.04573	0.00167	0.00236
6	1.23412	1.75231	2.21306	1.08029	1.35413	81371.44184	1	1	562.77054	0.04604	0.0011	0.00143
7	1.52989	2.08538	1.44351	1.01872	1.44085	79934.56033	1	1	562.73009	0.04241	0.00128	0.00318
8	2.01739	1.27882	2.18121	1.34793	2.22882	86990.55015	1	1	539.72879	0.04652	0.0016	0.0018
9	1.08419	1.92358	1.83202	1.23219	1.75651	74629.93174	1	1	483.58532	0.0339	0.00183	0.0029
10	1.81663	0.91657	1.94495	1.84493	1.52692	82692.24098	1	1	526.78253	0.04378	0.00193	0.00224
11	1.32462	2.28692	1.586	0.73092	0.7034	76685.33638	1	0	0	0	0	0
12	1.62001	2.05898	1.7118	0.88489	1.87067	74045.01601	1	1	497.4169	0.04211	0.00064	0.00254
13	1.00175	1.16911	0.97682	2.05075	1.63053	80076.50215	1	1	506.12295	0.03863	0.00139	0.0021
14	1.89399	1.53783	1.36992	1.42941	2.16825	68574.24987	1	1	544.5277	0.02591	0.00101	0.00104
15	1.43257	0.75562	2.06329	2.2798	1.15273	83475.05342	1	1	478.04627	0.04159	0.00077	0.0027
16	1.52574	1.46687	2.15844	1.32224	2.23749	87324.91362	1	1	575.81261	0.04727	0.00157	0.00108
17	1.91985	1.46763	0.78527	1.50638	1.98987	76008.33082	1	1	550.23227	0.04088	0.00131	0.00247
18	0.8661	1.38715	2.00255	1.54866	2.1108	85255.95634	1	1	566.1369	0.04411	0.00087	0.0028
19	1.22032	0.88859	1.55661	1.13431	1.46839	79604.92029	1	1	535.50341	0.04416	0.00098	0.00207
20	1.47562	2.01973	0.98894	1.4871	1.38109	77435.46488	1	0	0	0	0	0
21	2.28307	1.35723	1.30305	1.04271	2.1189	72373.9723	1	1	546.67652	0.04379	0.00101	0.00134
22	1.91869	1.77888	0.72418	1.45207	2.00793	77133.49329	1	1	546.38456	0.04377	0.00166	0.00239

Move towards a feasible region (s)

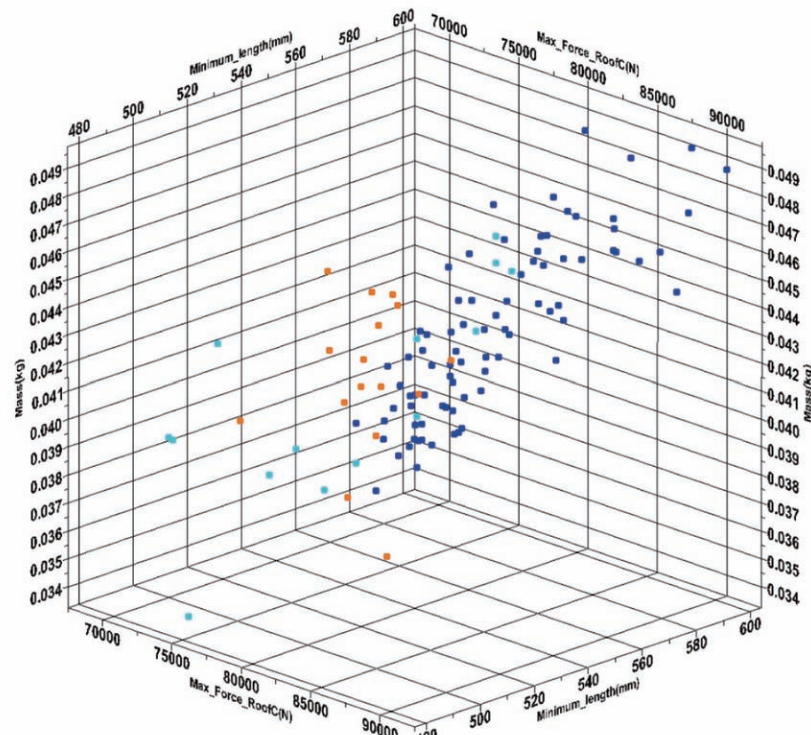


Fig. 4 Mass versus Roof crush force, Minimum_length

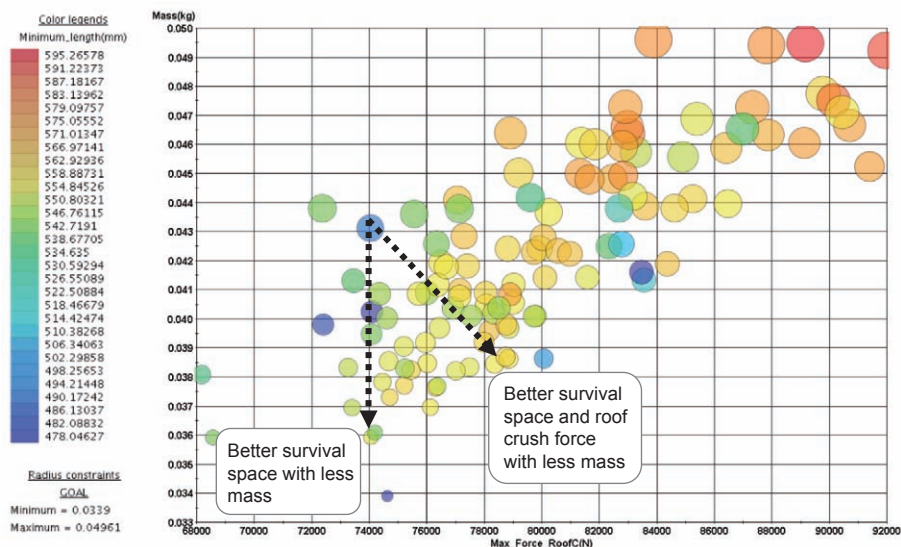


Fig. 5 Mass versus roof crush resistance force

Table 3 Optimization results with efficient mass distribution

Exp. Num.	Iter	B_Plr_Innr_15	Max_Force_RoofC	RoofC_check	SICE_check	Minimum_length	Mass
1	0	1.6	73414.05988	1	1	551.80119	0.03693
61	4	2.06459	76316.01867	1	1	565.17467	0.03762
76	5	2.10386	74064.04847	1	1	555.82743	0.03591
110	7	2.09286	76131.41799	1	1	560.37781	0.03695
114	7	2.19667	74716.40748	1	1	564.97335	0.0373

Table 4 Simulations 76 and 114 compared with baseline

	Roof-crush force (N)	Survival space (mm)	Total mass (kg) [Comps for optimization]	Total mass (kg) [Comparing the both sides of the car]
Target	66400	116	Reduce mass	Reduce mass
Baseline run	73414	117	36.9	69.5
Run 076	74064	121	35.9	-
Run 114	74716	130	37.3	-

6. Refinement of the Optimization Results

It is essential that optimization results should be analyzed further as global optimization methods will require many more number of simulations to converge to an optimized single solution. Because of the limitation on the computer resource availability this many simulations were not feasible. As already large numbers of simulations were completed and a good scatter was available for the responses (mass,

constraints), these results were analyzed based on the Design of Experiments (DOE) principle.

Based on correlation values in Fig. 6, optimization results were further refined.

Correlation value table gives information about the level of correlation between the design variables (thickness of structural members) and the responses. The correlation value is always between +1 and -1. A correlation value closer to +1 or -1 signifies that responses and corresponding design variables are

	Roof_Pnl_Stfa_1	Roof_Rail_Sidef_2	Stf_Aplr_3	Stf_Ctr_Plr_4	Floor_Cmbr_5	Roof_Pnl_Stfba_6	Roof_Pnl_Stffc_7	Sill_RR_Rail_8	Sill_Inside_9	Sill_Rntmnt_10	Sill_Stf_11	Sill_Mid_Gusset_12	Roof_Rail_Midl_13	B_Plr_Innr_Lower_14	B_Plr_Innr_15	Max_Force_RoofC	Minimum_length	Mass
Roof_Pnl_Stfa_1	1.00	-0.19	0.10	0.11	-0.11	-0.01	0.11	0.08	0.08	0.27	0.10	0.10	0.06	0.01	0.17	0.27	0.19	0.29
Roof_Rail_Sidef_2	-0.19	1.00	0.02	0.04	0.07	0.02	-0.03	0.16	-0.32	-0.16	-0.08	0.15	-0.10	0.00	-0.16	0.05	-0.08	-0.09
Stf_Aplr_3	0.10	0.02	1.00	-0.03	-0.02	0.08	-0.15	-0.08	-0.03	0.03	0.05	-0.06	0.11	0.02	-0.13	0.23	0.02	0.12
Stf_Ctr_Plr_4	0.11	0.04	-0.03	1.00	-0.08	0.02	0.02	0.06	0.04	0.11	0.16	0.02	0.01	-0.11	-0.00	0.21	0.48	0.33
Floor_Cmbr_5	-0.11	0.07	-0.02	-0.08	1.00	0.00	-0.01	0.02	-0.07	-0.06	0.02	-0.12	0.21	0.03	-0.25	0.02	-0.05	-0.00
Roof_Pnl_Stfba_6	-0.01	0.02	0.08	0.02	0.00	1.00	-0.20	-0.16	0.10	-0.00	0.23	-0.08	0.02	0.09	-0.06	0.16	-0.01	0.16
Roof_Pnl_Stffc_7	0.11	-0.03	-0.15	0.02	-0.01	-0.20	1.00	-0.02	0.11	0.12	0.06	-0.14	0.12	0.09	-0.01	0.66	0.00	0.49
Sill_RR_Rail_8	0.08	0.16	-0.08	0.06	0.02	-0.16	-0.02	1.00	-0.15	-0.11	-0.27	0.01	-0.07	-0.15	0.13	-0.03	0.15	0.01
Sill_Inside_9	0.08	-0.32	-0.03	0.04	-0.07	0.10	0.11	-0.15	1.00	0.23	0.22	0.10	0.13	-0.11	-0.00	0.27	0.22	0.69
Sill_Rntmnt_10	0.27	-0.16	0.03	0.11	-0.06	-0.00	0.12	-0.11	0.23	1.00	0.29	0.06	0.08	-0.01	0.01	0.23	0.15	0.41
Sill_Stf_11	0.10	-0.08	0.05	0.16	0.02	0.23	0.06	-0.27	0.22	0.29	1.00	0.11	-0.07	-0.04	-0.36	0.10	-0.18	0.37
Sill_Mid_Gusset_12	0.10	0.15	-0.06	0.02	-0.12	-0.08	-0.14	0.01	0.10	0.06	0.11	1.00	-0.01	-0.37	0.14	-0.08	0.16	0.06
Roof_Rail_Midl_13	0.06	-0.10	0.11	0.01	0.21	0.02	0.12	-0.07	0.13	0.08	-0.07	-0.01	1.00	-0.08	0.20	0.50	0.36	0.42
B_Plr_Innr_Lower_14	0.01	0.00	0.02	-0.11	0.03	0.09	0.09	-0.15	-0.11	-0.01	-0.04	-0.37	-0.08	1.00	-0.19	0.13	-0.24	-0.05
B_Plr_Innr_15	0.17	-0.16	-0.13	-0.00	-0.25	-0.06	-0.01	0.13	-0.00	0.01	-0.36	0.14	0.20	-0.19	1.00	0.12	0.66	0.06
Max_Force_RoofC	0.27	0.05	0.23	0.21	0.02	0.16	0.66	-0.03	0.27	0.23	0.10	-0.08	0.50	0.13	0.12	1.00	0.40	0.78
Minimum_length	0.19	-0.08	0.02	0.48	-0.05	-0.01	0.00	0.15	0.22	0.15	-0.18	0.16	0.36	-0.24	0.66	0.40	1.00	0.43
Mass	0.29	-0.09	0.12	0.33	-0.00	0.16	0.49	0.01	0.69	0.41	0.37	0.06	0.42	-0.05	0.06	0.78	0.43	1.00

Fig. 6 Correlation value table

Table 5 Thickness values for simulations 76a, 114a were based on 76,114

	Roof_Rail_SideF_2	Floor_Cmbr_5	Roof_Pnl_Stiffb_6	Sill_Stf_11	B_Plr_Innr_Lower_14	B_Plr_Innr_15
1	1.00	1.60	1.60	1.40	1.60	1.60
76	0.82	0.77	1.00	0.91	1.66	2.10
114	1.91	1.77	1.01	0.73	1.40	2.20
76a	0.82	0.67	0.80	0.81	1.50	2.10
114a	1.01	1.60	1.01	0.73	1.40	2.20

Table 6 Manual Simulations 76a and 114a compared with baseline

	Roof-crush force (N)	Survival space (mm)	Total mass (kg) [Comps for optimization]	Total mass (kg) [Comparing both sides of the car]
Target	66400	116	Reduce mass	Reduce mass
Baseline run	73414	117	36.9	69.5
Run 076	74064	121	35.9	-
Run 076a	68760	120	35.0	66.5 (3.0) ↓
Run 114	74716	130	37.3	-
Run 114a	71692	130	36.0	68.3 (1.2) ↓

mostly linearly-related, while a value closer to zero indicates that they are fairly independent.

The high correlation value of 0.66 indicates that the B-pillar inner (part 15) is the most important for SICE. This is very much in line with the design experience.

Negative correlation values for parts 2, 5, 6, 11, and 14 indicate that they are not significant for SICE. Therefore, thickness for these can be reduced and still provide the same occupant survival space. To further reduce mass, the thickness of these parts was reduced and new simulations, called 76a and 114a, were run manually. Thickness comparison is shown in Table 5.

Table 6 shows the results for simulations 76a and 114a compared with optimization results.

Simulation 76a shows that mass can be reduced by about 3 kg per vehicle and still provide more occupant survival space and roof crush resistance force compared to the baseline. Simulation 114a shows a survival space improvement of 13 mm over the baseline condition and with a reduction in mass of about 1.2 kg less per vehicle. Figures 7 and 8 show comparison of the baseline to the simulations 76a and 114a with respect to roof crush resistance force and SICE.

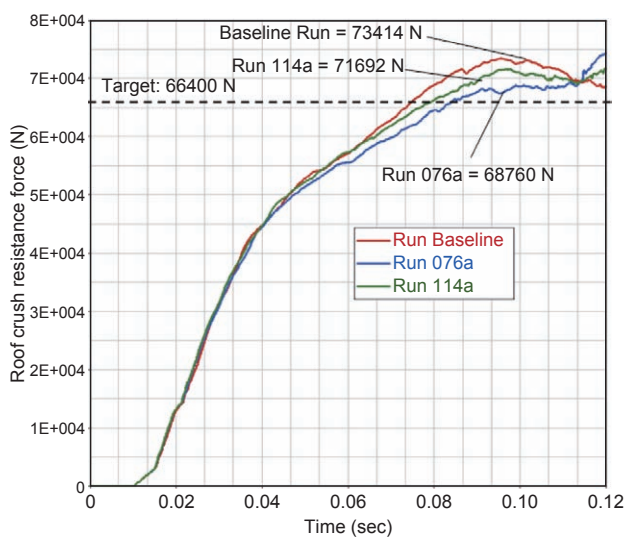


Fig. 7 Roof Crush force

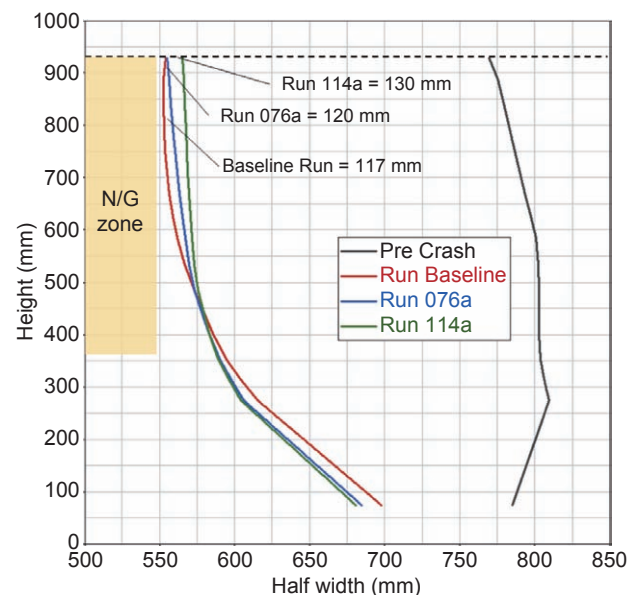


Fig. 8 Occupant survival space for SICE

7. Conclusion

- (1) The global optimization simulation method used in this study can be applied to similar situations where a structure is designed using several test modes. In this study, the number of simulations required was a major challenge since each one required approximately 20 hours to complete. This required a parallel processing environment with many available CPUs. To use these computer resources efficiently, only the most dominant test modes were considered for the optimization workflow.
- (2) During optimization, 7 out of 240 simulations did not complete correctly due to numerical instabilities caused by the unbalanced structure. When the optimization process assigned thickness, in extreme situations the structure became severely unbalanced and led to numerical instabilities in the simulation. This was an unavoidable situation that was considered in the planning stages of the study by having few additional simulations than required and also designing the optimization workflow to ignore such results.
- (3) The optimization results in Table 5 show thickness of the B-pillar inner to be 2.1 mm. This may be infeasible to manufacture as a single part. Therefore, consideration is made to apply reinforcement to the B-pillar inner so that the combined thickness gives a similar strength as 2.1 mm B-pillar inner.

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