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Optimization of a B-Pillar Undergoing Roof Crush Using HEEDS COMPOSE

N. Chase and R. Sidhu
Red Cedar Technology, Inc.

1. Introduction

Executing full vehicle finite element analyses can be time consuming and expensive. Compound this with the fact that crash optimization problems require a large number of evaluations (due to the complicated design landscape), and optimization of full vehicle crash simulations becomes computationally costly and difficult. An ideal solution is to reduce the full vehicle model down to a manageable sub-model that can be analyzed much more quickly, while maintaining the boundary constraints as if using the full vehicle model. The optimization process can then be managed with this sub-model while significantly reducing the computational requirements.

This paper will demonstrate how to optimize the A-pillar, B-pillar, roof rail, rocker, front header, and roof bow components of a car for roof crush, utilizing ultra-high-strength steel. In addition to the gauge of the individual structural components, a soft zone trigger and its location within the B-pillar are introduced as design variables. LS-DYNA [1] is utilized as the simulation tool with the COMPOSE (**COMP**onent **O**ptimization in a **S**ystem **E**nvironment) module for HEEDS MDO used to perform the optimization.

COMPOSE enables the use of a sub-model for optimization in a way that significantly reduces the overall optimization time. Using COMPOSE, the majority of the evaluations during the optimization are performed using the sub-model, while only a handful of full model evaluations are performed to maintain the coupling between the two models.

2. Challenges of System Design Optimization

The objective of a system design optimization is to find the design that behaves the best in a given environment under a set of prescribed conditions. However, design optimization of automotive systems undergoing roof crush requires many large-scale, nonlinear finite element simulations. Often it is not practical to perform design optimization on large automotive structures, due to the analysis time required to perform so many design evaluations. The introduction of COMPOSE makes these complex optimizations feasible in a realistic timeframe. [2]

The use of sub-models is not a new concept. But, because the performance of the sub-system relies on the boundary conditions from the global system model, the optimization process needs to identify both the sub-system design that is optimal under certain conditions and the boundary conditions that allow the sub-system to behave optimally.

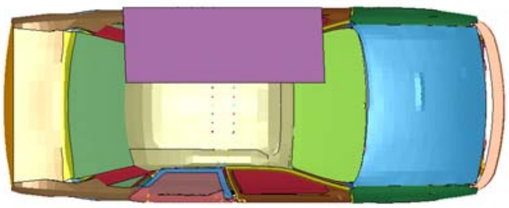
This creates a challenge because the optimal design boundary conditions are not known *a priori*. Thus, they cannot be found until the design approaches its optimal form. Often a sub-system design will look great following a sub-system optimization process, only to perform poorly when used in the global system model. Simply because the sub-system design is optimal for a given set of boundary conditions doesn’t imply that it works well for all boundary conditions.

The COMPOSE module for HEEDS MDO is a direct iterative approach to solving these types of problems without the need for sensitivity derivatives.

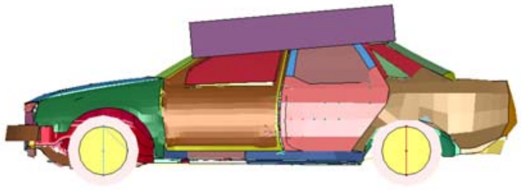
3. Global Roof Crush Analysis and Design Models

A Ford Taurus-V2 LS-DYNA model [3] was adapted for use as the global model in this roof crush application (shown in Figure 1).

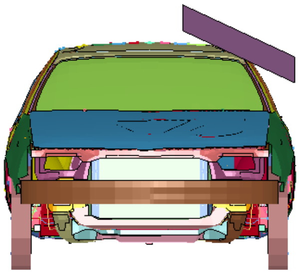
The gross vehicle weight (GVW) of the car being designed was 19.708 kN. The baseline simulation model had a total structural mass of 1.392 tonnes. The roof crush simulation was a 75 ms event that utilized a rigid impactor to crush the roof on the driver’s side of the vehicle, as shown in Figure 1, with a constant velocity of 2 m/s, normal to the impactor. The vehicle was constrained with DOF 12456 at the vehicle hubs and DOF 3456 on the rockers, as shown in Figure 2.



a. Top view of global roof crush model.



b. Side view of global roof crush model.



c. Front view of global roof crush model.

Figure 1. *Global LS-DYNA roof crush model.*

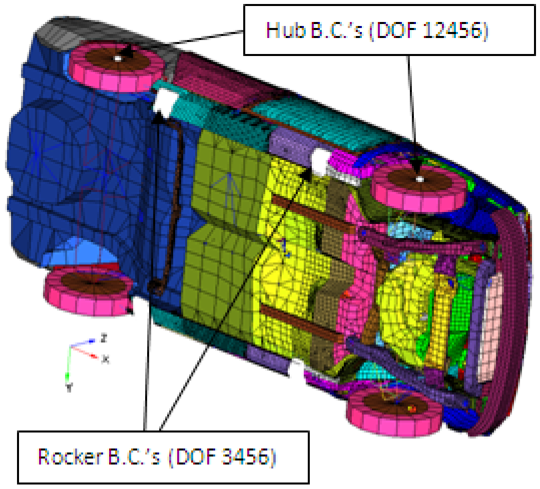


Figure 2. *Highlighted boundary condition locations at the hubs and rockers (symmetric cross-car).*

The material and gauge for most of the car components were the same as the Taurus-V2 model. The components integral to roof crush (A-pillar, B-pillar, roof rail, rocker, front header, and roof bow components, as shown in Figure 3) were changed to ultra-high-strength materials. These components were modified during optimization to improve crash performance and decrease mass.

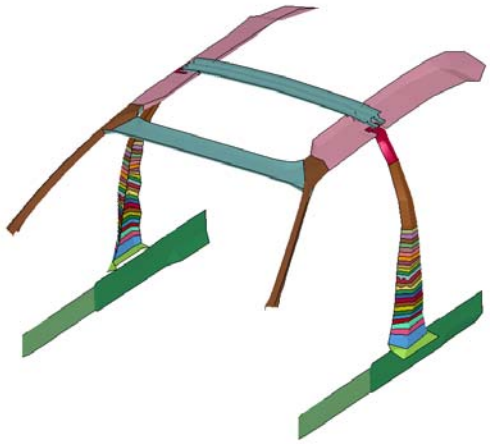


Figure 3. *Components made from Ultra High Strength materials in the automotive structure.*

The parts of the structure that used ultra-high-strength materials were hot-stamped, boron-alloyed steels. Hot-stamped parts tend to provide better formability at higher temperatures, with the added bonus of no spring back on the final part [4].

Before hot-stamping, the base material in hot-stamped boron-alloy steels has a tensile strength of approximately 600 MPa. After a part is hot-stamped, its strength can increase by up to 250 percent; the hot-stamping process transforms the base material from a ferritic-pearlitic microstructure to a martensitic microstructure [5].

The example in Figure 4 compares the stress-strain curves of a typical high grade steel with that of a typical boron-alloyed steel that has been hot-stamped.

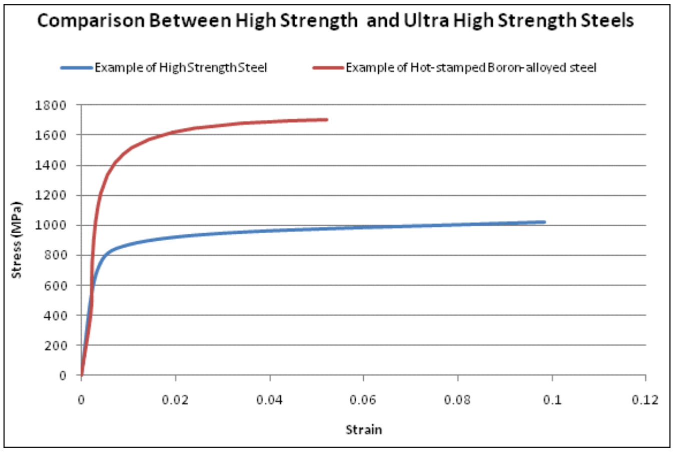


Figure 4. *Comparison of typical stress-strain curves for high strength steel and hot-stamped boron-alloyed steel.*

4. Roof Crush Sub-Model for Use with COMPOSE

The speedup in the optimization runtime achieved by COMPOSE is highly dependent on the ratio of the time it takes to run the global model to the time it takes to run the local model. The higher this factor, the larger the speedup you can expect with COMPOSE. As a result, the selection of the sub-model is an important step.

The sub-model is a smaller model (in spatial or time domain) that contains the variables to be optimized. The regions where parts are deleted to create the sub-model from the global model are called *interface boundaries*. The sub-model is analyzed by imposing the boundary conditions from the global model at the interface boundaries of the sub-model. The boundary conditions are imposed by prescribing displacements on the interface nodes directly in the input file.

Since sub-models have fewer elements than global models, they typically run much faster than the global models. Therefore, as long as the boundary constraints for a given sub-model match the global design, a representative solution can be found in less time by analyzing the sub-model instead of the global model.

The issue, of course, is that the boundary constraints on the sub-model cannot be guaranteed to match that of the global model without actually running the global model. If the boundary constraints applied to a given design are no longer valid when a modification is made that alters the design (such as during optimization), then the sub-model no longer represents the global model solution. However, there's no way to know whether the boundary constraints are still valid until the new global analysis is performed. This is the dilemma COMPOSE helps to overcome.

To create a sub-model, a boundary cut is typically made to the global model outside the critical region of interest. Figure 5 shows the boundary cut made to the global roof crush model used in this study.

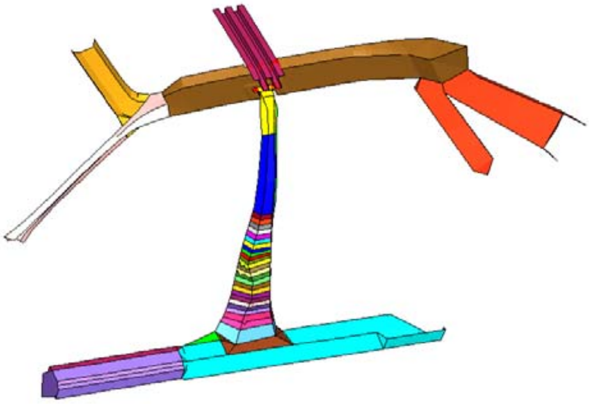


Figure 5. *Roof crush sub-model.*

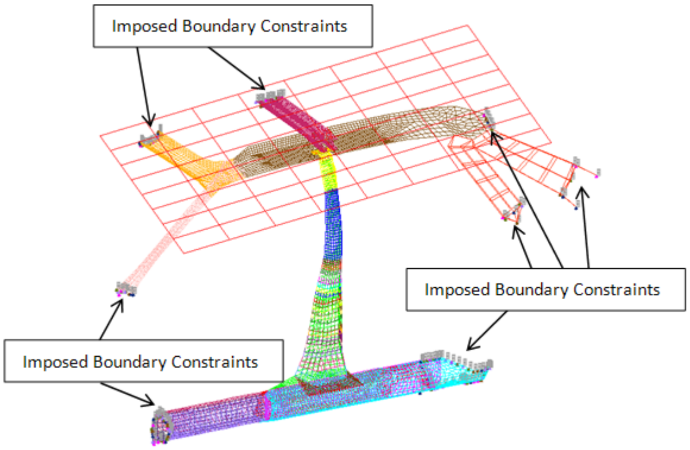


Figure 6. *Roof crush sub-model with boundary constraints highlighted. Cuts were made along the rocker, A-pillar, front header, C-pillar, roof rail, and roof bow components, as shown.*

Since it is known that the primary structural members around the roof (A-pillar, B-pillar, C-pillar, roof rail, rocker, front header, and roof bow components) have the greatest influence on the roof crush performance, the boundary cuts are made such that the important parts of these components are included in the sub-model.

In order for the boundary constraints to be extracted from the global model and imposed in the sub-model, node sets need to be created that contain the boundary cut edges in both the global and local models. The displacements and rotations of the nodes in these sets then need to be extracted from the global model. The sub-model can then have these displacements and rotations applied to the nodes located in its boundary cut node sets. Note that COMPOSE automates this boundary constraint mapping from the global to the sub-model with the process discussed in the next section. Figure 6 shows the sub-model with the boundary constraints imposed for the roof crush study.

5. The COMPOSE Module

The optimization process with COMPOSE is broken down into four basic steps. First, the global system is evaluated using initial values of design variables to determine the boundary conditions at the boundary cut edges. Second, the boundary conditions found in the first step are applied to the sub-system model. Third, the sub-system optimization uses the updated boundary conditions. The optimization contains constraints specific only to the decomposed sub-system. The values of the subsystem design variables will ultimately change, which will strongly affect the overall system if large coupling exists. Finally, the global system is evaluated and a new set of boundary conditions is extracted.

This process is repeated until convergence between the sub-system and global system results is obtained and an optimized global design is found. Figure 7 shows the process COMPOSE uses in the roof crush optimization.

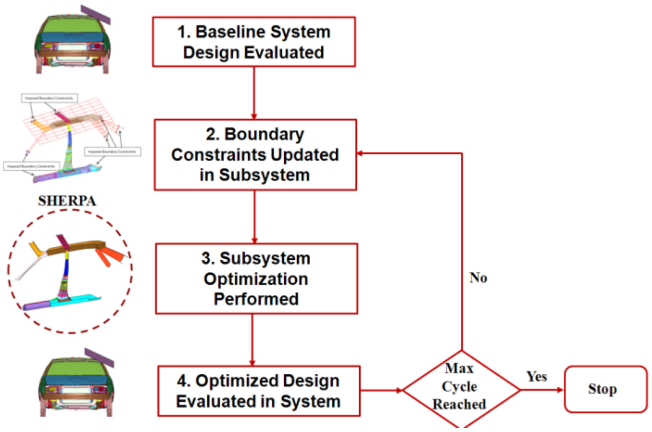


Figure 7*. COMPOSE flowchart for the roof crush optimization.*

6. Roof Crush Optimization Problem Description

The goal of the roof crush optimization was to minimize the mass of the vehicle while satisfying a constraint such that the reaction force was greater than 3.5 times the gross-vehicle weight of the vehicle. This was to be achieved by varying the thicknesses of the critical boron-alloyed steel structural components (A-pillar, B-pillar, roof rail, rocker, front header, and roof bow as shown in Figure 3), as well as the length and location of the non-geometric trigger in the B-pillar.

The optimization problem statement for the roof crush optimization performed in this study can be written as follows:

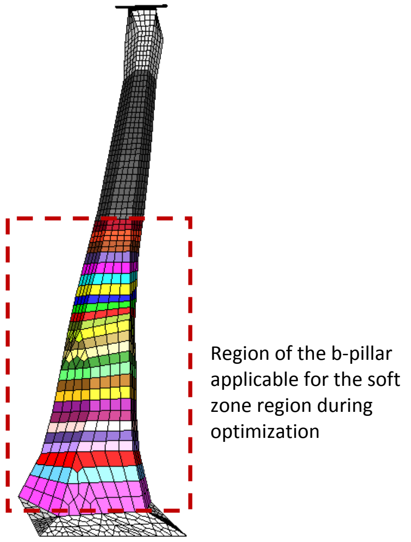
Objective: Minimize *Mass*

Such That: *Reaction Force* ≥ 68.98 kN

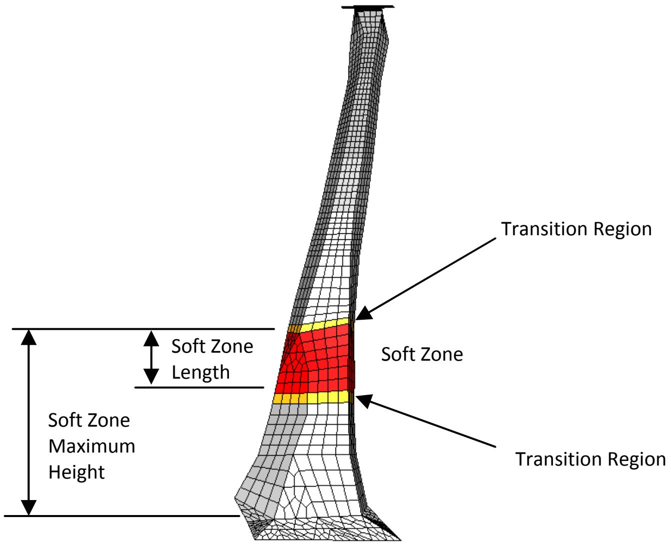
By Varying:
50 mm ≤ *Soft Zone Length* ≤ 200 mm
100 mm ≤ *Soft Zone Max. Ht.* ≤ 575 mm
1.0 mm ≤ *A-pillar Thickness* ≤ 3.0 mm
1.0 mm ≤ *B-pillar Top Thick.* ≤ 3.0 mm
1.0 mm ≤ *B-pillar Thickness* ≤ 3.0 mm
1.0 mm ≤ *Roof Rail Thickness* ≤ 3.0 mm
1.0 mm ≤ *Front Header Thick.* ≤ 3.0 mm
1.0 mm ≤ *Roof Bow Thickness* ≤ 3.0 mm
1.0 mm ≤ *Rocker Thickness* ≤ 3.0 mm

With hot-stamped boron-alloyed steel parts, a soft region can be strategically placed in the part, where the material properties of that region are significantly degraded (or softened). By designing the location and length of this soft region in a B-pillar, a non-geometric trigger can be created to increase performance in the vehicle by forcing desired deformations in the B-pillar. Along with the soft zone, a transition zone exists where the material properties are between the base material and the soft zone in the part. The transition zone in this study was assumed to be a constant 25 mm, and the material properties of this zone were set to the average of the soft zone and the ultra-high-strength zone.

Figure 8 shows the B-pillar utilized in this study and how the soft zone was designed. Along the length of the B-pillar, multiple parts (components) were created, each with a length of roughly 20 mm. Based upon the location and length of the soft zone, the appropriate material property was assigned to the given B-pillar part.



a. B-pillar model used for the roof crush optimization.



b. Example of the soft zone and transition zones that were designed during optimization.

Figure 8. *B-pillar soft zone design technique to introduce a non-geometric trigger.*

7. Optimization Results Using COMPOSE

COMPOSE was used to optimize the B-pillar in the manner described previously. The HEEDS MDO optimization was set up such that 120 sub-system evaluations were performed for every 1 system level evaluation, utilizing the COMPOSE module and SHERPA as the search method. Five such cycles were performed during the optimization, for a total of 6 global system-level evaluations and 600 sub-system evaluations.

After the first cycle (1 system evaluation and 120 sub-system evaluations), the optimized design found by the sub-system search had a 3.4 % reduction in mass over the baseline design. When this sub-system optimized design was substituted into the system analysis, it performed as intended, satisfying the reaction force constraint criteria. Table 1 shows the performance of the optimized sub-system designs when substituted back into the global system analysis model by COMPOSE, compared with the baseline design.

Table 1. *Performance of the optimized sub-system designs when put back into the global system level analysis model.*

Cycle Iteration	Designable Mass (kg)	Reaction Force (kN)	Mass Reduction
Baseline	22.61	76.0	-
1	21.84	74.8	3.4 %
2	22.61	73.85	0.0 %
3	22.18	75.91	1.9 %
4	20.33	75.05	10.1 %
5	19.55	75.33	13.5 %
6	21.37	69.87	5.5 %

After 5 cycles, a feasible design with a 13.5 % reduction in mass was obtained. Figure 9 shows the roof crush deformation for this design compared with the baseline design, while Figure 10 shows a comparison between their reaction force profiles.

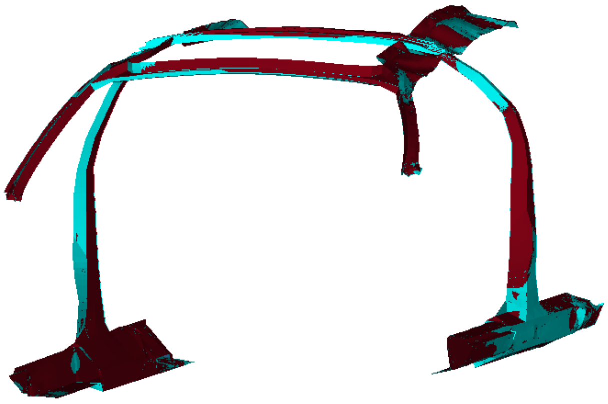


Figure 9. *Comparison of the crush characteristics for the baseline design (lighter cyan color) and the optimized design found utilizing COMPOSE (cycle iteration 5) (darker maroon color). These superimposed deformations are at 60 ms of the global system level roof crush event (with the non-designable components turned off for visualization purposes).*

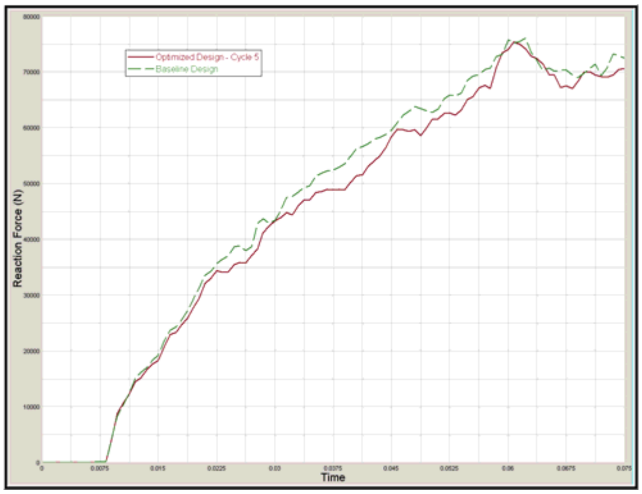


Figure 10. *Comparison of the baseline design roof crush reaction force profile (green) with that of the optimized design found using COMPOSE (red, cycle iteration 5).*

Table 2 gives the design variable values for this optimized design. The non-geometric trigger location was significantly altered, and the mass distribution was altered such that a similar deformation mode could be maintained with an overall lighter design.

Table 2. *Optimized design variable values for the optimized design from cycle 5, compared to the baseline design.*

Design Variable	Baseline (mm)	Optimized (mm)
Soft Zone Length	61	65.79
Soft Zone Max Height	486	271
A-pillar Thickness	1.3	1.1
B-pillar Top Thickness	1.9	2.0
B-pillar Thickness	2.8	2.3
Roof Rail Thickness	1.0	1.0
Front Header Thickness	2.0	1.7
Roof Bow Thickness	1.9	1.3
Rocker Thickness	1.0	1.0

Conclusions

It was shown here that the use of COMPOSE can yield high-performing designs for roof crush optimization in a way that can significantly reduce the overall optimization time while allowing the interactions of the optimal subsystem with the global system to be maintained. COMPOSE makes it possible to optimize large system models. In the past, these models would have required an impractical amount of compute resources and time.

References

[1] LS-DYNA (Version 971) [Computer software]. Livermore, CA: Livermore Software Technology Corporation.

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[3] National Crash Analysis Center. Ford Taurus, Modified Model (28,400 elements). http://www.ncac.gwu.edu/vml/models (accessed January 23, 2012).

[4] Center for Precision Forming, The Ohio State University. 2007. Hot-stamping boron-alloyed steels for automotive parts. *Stamping Journal* January 2007: 14-15. Available online: http://nsmwww.eng.ohio-state.edu/Jan07RDUpdate.pdf (accessed January 23, 2012).

[5] Merklein, M., Lechler, J., and Geiger, M. 2006. Characterisation of the Flow Properties of the Quenchenable Ultra High Strength Steel 22MnB5. *Annals of the CIRP* Vol. 55.