

Optimized Design Solutions for Roof Strength Using Advanced High Strength Steels

2010-01-0214

Published
04/12/2010

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ABSTRACT

In August 2005, National Highway Traffic Safety Administration (NHTSA) proposed to increase the roof strength requirement under Federal Motor Vehicle Safety Standard (FMVSS) 216 from 1.5 to 2.5 times unloaded vehicle weight (UVW). To meet the new requirement with a minimum impact on vehicle weight and cost, the automotive community is working actively to develop improved roof architectures using advanced high strength steels (AHSS) and other lightweight materials such as structural foam. The objective of this study is to develop an optimized steel-only solution with low material and part-manufacturing costs.

Since the new regulation will present a particular challenge to the roof architectures of large vans, pickup trucks and SUVs due to their large mass and size, a validated roof crush model on a B-Pillar-less light truck is utilized in this study. Optimized steel-only solutions are investigated with the application of CAE optimization technology and AHSS including dual phase (DP) steels up to 980 MPa tensile strength and boron steel for hot stamped parts. HyperStudy® optimization software and LS-DYNA® nonlinear finite element software are utilized together to search for the optimal design. Steel inserts are designed and added at critical locations to improve the load-carrying capacity. Material and gauge optimizations are also performed on key roof components to minimize the vehicle weight while meeting the enhanced roof crush load requirement. The optimized steel-only solutions are compared to the alternative designs using nylon inserts.

INTRODUCTION

Roof strength is regulated in the United States by the FMVSS 216 standard, *Roof Crush Resistance*, and was adopted on September 1, 1973. This standard establishes strength

requirements for the roof structure over the front occupants. The purpose of this standard is to reduce injuries and fatalities due to crushing of the roof into the passenger compartment when the roof strikes the ground during rollover crashes.

Roof strength is evaluated through a static roof crush test, as shown in [Figure 1](#). The load is applied to the forward edge of a vehicle's roof through a rigid rectangular plate at the size of 762 mm × 1829 mm. The FMVSS 216 standard currently requires that within 127 mm (5 inches) of load platen travel, a vehicle's roof must be able to withstand a load of 1.5 times UVW and up to a maximum of 22.24 kN (5000 lbs). It currently applies to passenger cars and to multipurpose passenger vehicles, trucks and buses with a gross vehicle weight rating (GVWR) of 2722 kg (6000 lbs) or less.

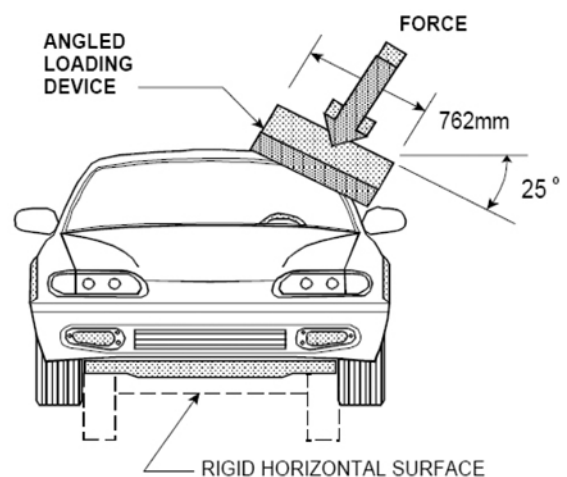


Figure 1. Static roof crush test

In August 2005, NHTSA issued a notice of proposed rulemaking (NPRM) to upgrade the FMVSS 216 to better



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address fatalities and injuries occurring in roof-involved rollover crashes. NHTSA's proposed rulemaking increases the strength requirement to 2.5 times UVW with the platen travel limited by the contact with the head of a 50th percentile male dummy. The new regulation also extends the application of the standard to vehicles with a GVWR up to 4536 kg (10000 lbs).

In addition to the much stricter occupant safety regulation, the increased new fuel economy standard and cost pressure are prompting automakers for solutions to decrease the mass of vehicle structures. This presents a challenge to the automotive industry for meeting the increased roof load requirements with minimum weight and cost penalties.

Recently, the automotive industry gradually recognized that advanced high strength steels could be effectively utilized for vehicle weight reduction while maintaining or improving safety, durability and NVH performance [1]. The DP590 grade with a minimum tensile strength of 590 MPa has been one of the most popular AHSS used in the majority of newly designed vehicles due to a combination of high strength and good formability [2, 3]. Over the next few years, higher strength dual phase steel grades like DP780 and DP980 and hot-stamped boron steel will be implemented to help meet upcoming more stringent side impact and roof crush standards that call for further limitations on passenger compartment intrusion [4, 5].

The objective of this study is to develop an optimized steel-only solution by taking advantage of steel's low material and part-manufacturing costs. The optimized steel only solutions are accomplished with the application of CAE optimization technology and AHSS, including dual phase steels up to 980 MPa tensile strength and boron steel for hot stamped parts. HyperStudy® optimization software and LS-DYNA® crush simulation software are utilized together to automatically search for the optimal design. Steel inserts are designed and added at critical locations to improve load-carrying capacity. Material and gauge optimizations are also performed on key roof components to minimize the vehicle weight while meeting the enhanced roof crush load requirement. The optimized steel-only solutions are compared to the alternative designs using nylon inserts [5, 6].

ROOF CRUSH CAE MODEL

Since the new regulation would present a challenge particularly to the roof architectures of vans, pickup trucks and SUVs due to their large mass and size, a validated roof crush model on a B-Pillar-less light truck cab was utilized in this study, as shown in Figure 2. The model was initially developed in phase 1 of Auto/Steel Partnership (A/SP) Mass Efficient Architecture for Roof Strength (MEARS) project [5]. Figure 3 shows the final optimal design achieved in phase 1 with AHSS and nylon inserts. Nylon inserts were

placed at A-Pillar, Roof Rail Front and Rear, and C-Pillar to increase load carrying capability and reduce the mass of the roof structures.

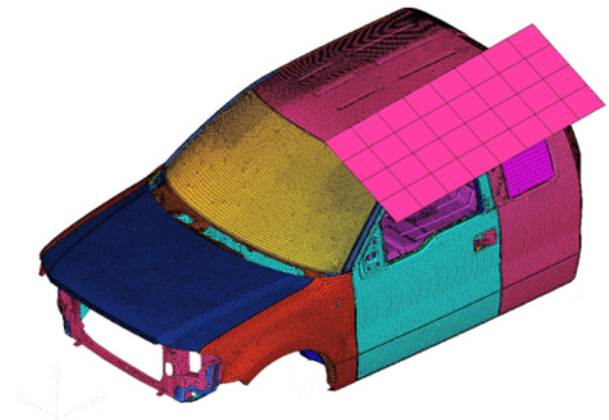


Figure 2. Roof crush CAE model for a B-Pillar-less pickup truck

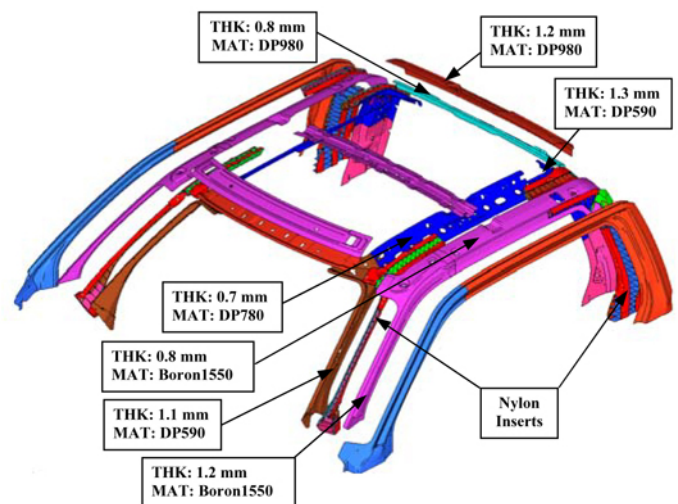


Figure 3. Optimized design with nylon inserts

In addition to the nylon inserts, the phase I final design used a lot of AHSS, such as DP980 for the Rear Header and boron steel for the A-Pillar Reinforcement and Roof Rail Outer. The cab mass of the nylon insert design is about 500 kg, which is 1.2 kg heavier than the original donor vehicle model with mild steels and conventional high strength steels for the roof components. But the normalized roof crush load increased significantly from 1.8 of the original donor vehicle to 3.05 of the nylon insert design.

The model with nylon inserts was used to build the current baseline CAE model for the subsequent optimization study, and LS-DYNA® non-linear finite element software was utilized for the roof crush simulations. After removing the nylon inserts and unnecessary contact definitions, increasing

time step from 1.0 μ s to 1.3 μ s and the moving speed of the rigid plate from 1 m/s to 3 m/s, the modified model is much faster with the CPU time decreasing from 15 hours to 3 hours, which allowed running the optimization simulations more efficiently since a lot of iteration runs are needed for the optimized solutions. The modified model sacrificed only a little bit of accuracy due to the increased dynamic effect, as shown in [Figure 4](#).

In the optimization simulation, the target is set to achieve the roof strength of 3.0 times UVW within 114 mm (4.5 inches) of load platen travel. The 3.0 times load target, instead of 2.5, has a 20% safety margin over the new roof strength requirements to account for potential numerical errors and the test-to-test variability. The target displacement criterion of 114 mm load platen travel is based on the interior package space of vehicle used in this study.

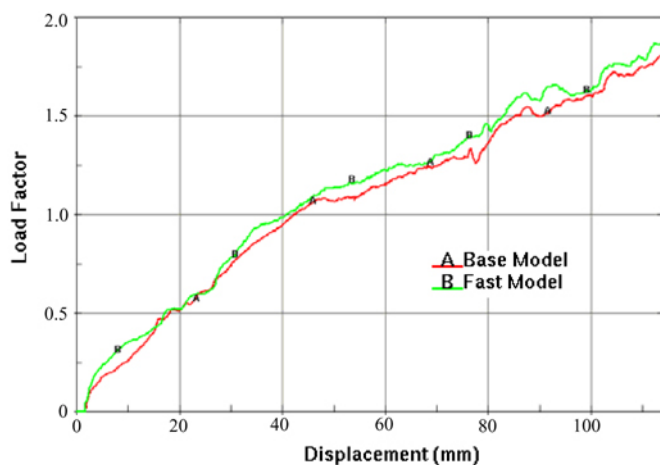


Figure 4. Results comparison after model modifications

OPTIMIZATION

The optimization study of roof structures has been conducted in other studies [7, 8] using the manual optimization approach such as the sensitivity analysis method. With the advancement in design optimization software in recent years, the commercially available optimization tools have become more robust and efficient, and are capable of solving more complicated design optimization problems. In this study, HyperStudy® optimization software and LS-DYNA® non-linear finite element software were utilized together to automatically search for the optimized steel-only design solutions. The Adaptive Response Surface Method [9, 10, 11] (Altair HyperOpt® StudyWizard) was used to search for the optimal designs because of its algorithm efficiency and robustness when compared to other optimization methods currently available in HyperStudy® software. The details of the optimization algorithm can be found in a previous study on cross-section optimization for axial and bending crushes [12].

The steel grades used in the optimization include HSLA350, DP590, DP780, DP980, and Boron1550 for hot stamped parts. [Figure 5](#) shows the stress-strain curves of these steels used in the crush simulations. Although only dual phase steels are used for the crush simulation and optimization, transformation induced plasticity (TRIP) steels with similar strength levels may be used in the final design for components difficult to be stamped with dual phase steels, since at the same strength level TRIP steels have better formability and similar crash performance as the dual phase steels.

A total of 13 parts contributing to the roof strength were selected for material and gauge optimization, as listed in [Table 1](#). The gauge is allowed to change within the range of 0.6 and 2.2 mm in the optimization. The optimization objective is to minimize the mass of the cab and the constraint is to maintain the roof crush load factor above 3.0.

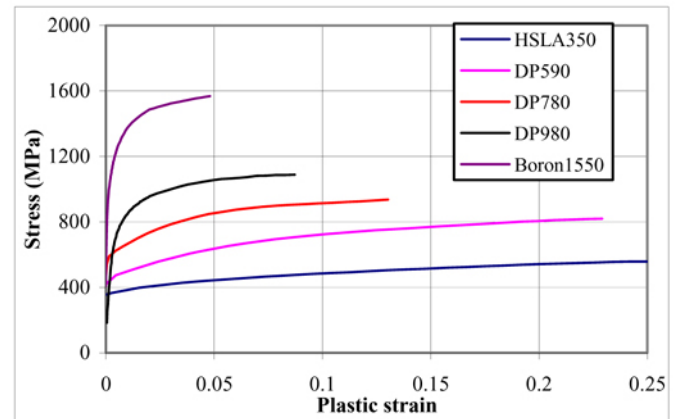


Figure 5. Stress-strain curves

Table 1. Material and gauge variables

Part Name	Material	Gauge Range (mm)
A-Pillar Inner	HSLA350 – Boron1550	0.6 – 2.2
A-Pillar Reinforcement	HSLA350 – Boron1550	0.6 – 2.2
BSO_A-Pillar	HSLA350 – Boron1550	0.6 – 2.2
BSO_C-Pillar	HSLA350 – Boron1550	0.6 – 2.2
C-Pillar Upper	HSLA350 – Boron1550	0.6 – 2.2
C-Pillar Lower	HSLA350 – Boron1550	0.6 – 2.2
Header Front Upper	HSLA350 – Boron1550	0.6 – 2.2
Header Front Lower	HSLA350 – Boron1550	0.6 – 2.2
Header Rear Upper	HSLA350 – Boron1550	0.6 – 2.2
Header Rear Lower	HSLA350 – Boron1550	0.6 – 2.2
Roof Bow	HSLA350 – Boron1550	0.6 – 2.2
Roof Rail Inner	HSLA350 – Boron1550	0.6 – 2.2
Roof Rail Outer	HSLA350 – Boron1550	0.6 – 2.2

If material cost is not considered as a constraint in the optimization process, the steel grade with the highest strength (or Boron1550 in this study) will always be selected for all 13 parts. Therefore, a relative cost function shown in [Table 2](#) was introduced to estimate the relative cost of different steel