

Fatigue Based Lightweight Optimization of a Pickup Cargo Box with Advanced High Strength Steels

Guofei Chen
United States Steel Corp.

Mingchao Guo and Weidong Zhang
Chrysler Group LLC

ABSTRACT

Advanced high strength steels (AHSS) offer a good balance of strength, durability, crash energy absorption and formability. Applications of AHSS for lightweight designs of automotive structures are accelerating in recent years to meet the tough new CAFE standard for vehicle fuel economy by 2025. At the same time, the new generation pickup cargo box is to be designed for a dramatic increase in payload. Upgrading the box material from conventional mild steels to AHSS is necessary to meet the conflicting requirements of vehicle light weighting and higher payload. In this paper, typical AHSS grades such as DP590 and DP780 were applied to selected components of the pickup cargo box for weight reduction while meeting the design targets for fatigue, strength and local stiffness. An automatic gauge optimization process was developed using HyperStudy®, in conjunction with NX™ Nastran for stress analysis and FE-Safe® for multi-axial duty-cycle parent metal fatigue analysis under a measured full durability schedule of proving ground loads. A fatigue life design target (or the calculated fatigue lives at critical locations in the baseline design if they did not meet the target) was applied as the optimization constraints. A total of 7% weight reduction was achieved with the application of AHSS without deteriorating the fatigue, strength and stiffness performance of the cargo box.

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INTRODUCTION

Due to a good balance of strength, durability, crash energy absorption and formability, advanced high strength steels (AHSS) have been widely accepted as one of the material choices in the automotive industry to reduce overall vehicle weight and improve vehicle structural performance. According to a study on North American light vehicle metallic material trends by Ducker Worldwide [1], AHSS will grow 10% annually and reach over 204 kg per vehicle by 2020. It is expected that AHSS will be used approximately 3 times more frequently than current levels by 2020 in North American light vehicle body structures.

The U. S. automotive companies are currently facing a challenge to meet the tough new CAFE standard for vehicle fuel economy (an average 54.5 mpg for passenger car and an average 40 mpg for light truck) by 2025. At the same time, the vehicles are to be designed with improved structural performance and functionality for better customer satisfaction. For example, the new generation pickup cargo box is to be designed with a dramatic increase in payload without sacrificing its durability performance and fuel economy.

Upgrading the box materials from the conventional mild steels to AHSS is necessary to meet the conflicting requirements of vehicle light weighting and higher payload.

With the advancement in Computer-Aided Engineering (CAE) technology in recent years, especially the progress in design optimization software, the commercially available optimization tools have become more robust and efficient, lending themselves to solving more complicated design optimization problems. As an example, by using the structural design optimization techniques [2], the FutureSteelVehicle (FSV) program recently developed by WorldAutoSteel featured optimized AHSS body structures for compact electrified vehicles in the 2015 to 2020 model-year.

Because of the difficulty integrating the duty cycle fatigue life requirements into the design optimization process, stress is usually used as the design constraint. However, the stress-based optimization may not be able to meet the fatigue life target because the fatigue life is affected by other factors such as stress combination (critical plane, von Mises or principal stress, etc), multi-axial stress, mean stress, durability exponent and surface roughness, etc.  **Documents**
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Fatigue Life Equivalent Stress (TFLES) was introduced based on the fatigue life requirement and then used as a design constraint in the shape optimization process [3]. With the advancement in design optimization software and computer hardware, fatigue based optimization is preferred because the fatigue lives are directly used as the design constraints in the optimization process. Recently, fatigue based shape optimization was successfully performed to optimize a cylinder head design using two different optimization software: TOSCA® and HyperStudy® [4].

In this study, typical AHSS grades such as dual phase (DP) steels DP590 and DP780 were applied to selected components of a pickup cargo box for weight reduction, while meeting the fatigue performance target for increased payload. Gauge optimization was performed for duty-cycle loads using an optimization engine in HyperStudy® interacting with stress analysis software NX™ Nastran and fatigue analysis software FE-Safe® to automatically search for the optimal gauges of the selected components under the constraints of target parent metal fatigue life.

LIGHTWEIGHT OPTIMIZATION STRATEGY

As shown in Figure 1, the cargo box is comprised of several major structural components: box inner and outer panels, floor and cross members, front panel, front side panel and reinforcements, wheel house inner and outer, D-pillar inner and outer panels, and tailgate. The cross members underneath the floor include four regular cross members and two touch-down cross-members. The four regular cross-members are bolted to the frame rails, while the two touch-down cross-members have no mechanical connections to the rails. When the floor moves down, the touch-down cross-members are in contact with the rails to transfer loads. A mild steel is used for almost all the components in the baseline design.

To meet the lightweighting and increased payload capacity requirements, an optimization strategy was set up and described as follows:

- Calibrated the CAE durability model by correlation studies with test results under proving ground (PG) loads to ensure accuracy of the analyses.
- Conducted geometry/shape optimization of components with considerations of cargo box usage and manufacturing feasibility.
- Selected components that met stamping requirements as materials were changed from mild steel to typical AHSS grades such as DP590 and DP780 without significant tooling changes.
- Ran one-step forming analyses to evaluate the formability of the selected components with the material upgrade.
- Performed gauge optimization of the cargo box package consisting of DP590, DP780 and mild steel with constraints on parent metal fatigue life under PG loads.

- Evaluated the package from the gauge optimization for spot weld fatigue under the same PG loads, global bending and torsion stiffness and local load cases such as heel load and cement bag drop on the floor.
- Verified the optimized package for other PG loads to take into account vehicle configurations such as 4×2 and 4×4 wheel drive and powertrain type variations.
- Modified the design locally to meet all the requirements. If spot weld fatigue became a concern for an AHSS component because of the downgauging, adhesive was applied at the locations.

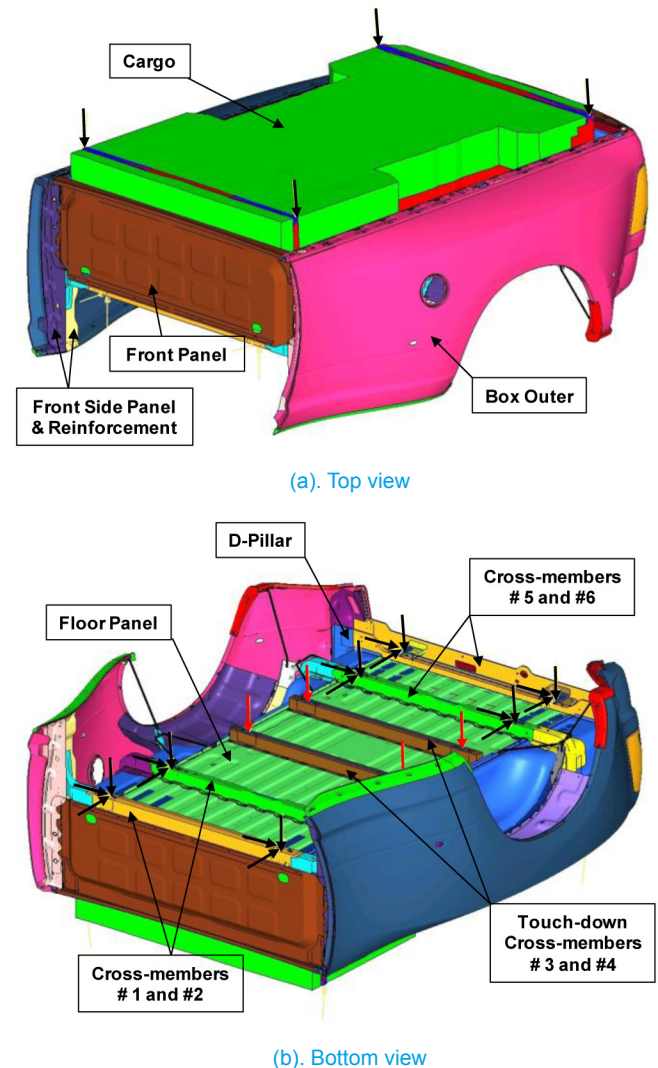


Figure 1. Finite element model of the pickup cargo box

This paper focuses on the gauge optimization process and results. Examples of one-step forming simulation and heel load analyses are also included.

MATERIAL UPGRADE

A conventional mild steel was used in the baseline design for almost all the components in the cargo box. To meet the fatigue life design target for a higher payload while light-

weighting the cargo box, both the part geometry optimization and material upgrades from the mild steel to higher strength steels for critical components were necessary. The geometry optimization was done previously based on the cargo box usage requirements and manufacturing feasibility. In this study, the material was upgraded from mild steel to DP590 and DP780 for some major structural components without geometry and tooling changes.

Table 1 compares the typical mechanical properties for mild steel, DP590 and DP780. Generally, the total elongation as a measure of the material ductility decreases when the material strength increases. DP steels consist of a soft ferrite matrix and a hard martensitic second phase in the form of islands. When DP steels deform, strain is concentrated in the lower-strength ferrite phase surrounding the islands of martensite, resulting in relatively high work-hardening rates compared to conventional high strength low alloy (HSLA) steels. As shown in Table 1, DP590 and DP780 steels maintain a good balance of strength and ductility, making them excellent candidate materials for load-carrying structural members with relatively complex design geometries.

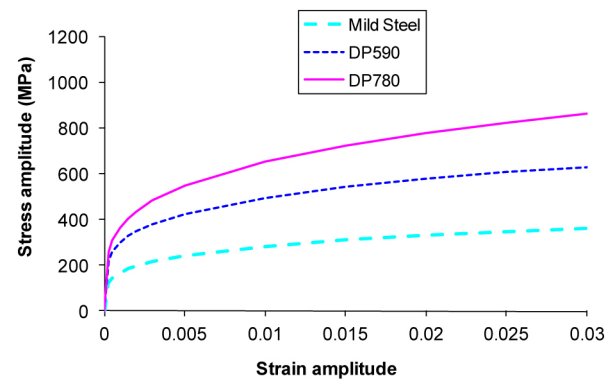
Figure 2 shows the cyclic stress-strain curves and strain-life curves of mild steel, DP590 and DP780. Improved fatigue performance of DP590 and DP780 over mild steel offers a good opportunity for downgaging the structural components while meeting the durability design target.

One-step forming analyses were performed to evaluate the formability of the components with the material upgrade. One-step forming analysis is widely used at the early design stage for quick evaluation of manufacturing feasibility without detailed tooling information. As an example, Figure 3 shows the formability contour of the D-Pillar Inner for the cargo box with DP590, which confirms good formability for this part as the forming strains are well below the forming limit curve (FLC) of DP590. The wrinkle tendency can be eliminated by applying draw beads and blank-holder forces during the stamping process.

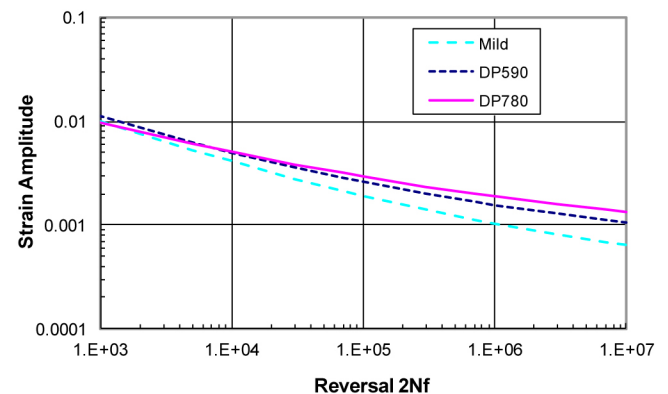
As shown in Table 2, DP590 and DP780 were applied for seven selected components based on the considerations of formability and impact on potential weight savings. DP780 was applied to the touch-down cross-members #3 and #4 and their reinforcements with a relatively simple U-channel cross-section.

Table 1. Typical mechanical properties of steels

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)
Mild Steel	162	308	22.6	44.2
DP590	408	615	14.9	25.2
DP780	507	859	12.6	16.9



(a). Cyclic stress-strain curves



(b). Strain-life curves

Figure 2. Cyclic stress-strain curves and strain-life curves of mild steel, DP590 and DP780

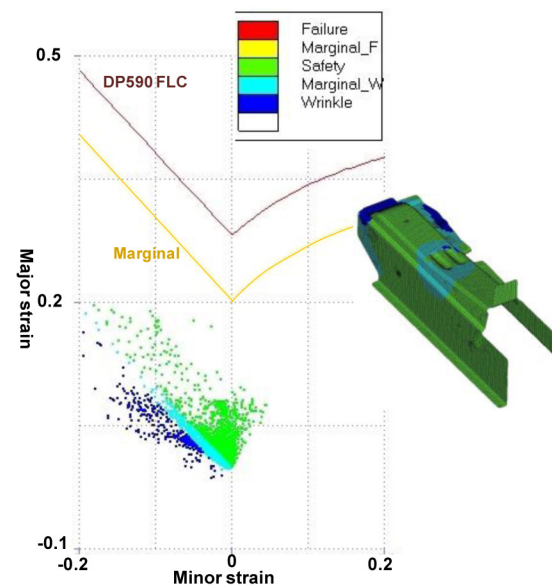


Figure 3. Forming analysis of D-Pillar inner with DP590