

Cross-Section Optimization for Axial and Bending Crushes Using Dual Phase Steels

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ABSTRACT

To achieve optimal axial and bending crush performance using dual phase steels for components designed for crash energy absorption and/or intrusion resistance applications, the cross sections of the components need to be optimized. In this study, Altair HyperMorph™ and HyperStudy® optimization software were used in defining the shape design variables and the optimization problem setup, and non-linear finite element code LS-DYNA® software was used in crush simulations. Correlated crash simulation models were utilized and the square cross-section was selected as the baseline. The optimized cross-sections for bending and axial crush performance resulted in significant mass and cost savings, particularly with the application of dual phase steels.

INTRODUCTION

Dual phase (DP) steels, especially DP590 with a minimum tensile strength of 590 MPa, have been widely implemented recently in the automotive industry to improve vehicle crash energy management. Over the next few years, higher strength dual phase steel grades like DP780 and DP980 will be implemented by North American automakers to help meet upcoming more stringent side impact and roof crush rollover standards where intrusion into the passenger compartment is further limited [1]. To meet the new crash standards while maintaining or reducing vehicle weight, somewhat unique architectures will need to be derived along with the applications of DP780 and DP980 steels.

While axial crash mode can only be achieved in direct frontal/rear or slightly off-angle impacts to absorb the kinetic energy of the vehicle, bending mode is dominant in side impact and roof crush, where the crash resistance or strength to maintain passenger compartment integrity is the major concern. Generally, most of the structural members, including front/rear end structures, are subject to mixed crash modes comprised of axial collapse and bending in a real crash event.

Therefore, improving bending crush performance for components such as A-pillar, B-pillar, roof rail, rocker, cross-member, etc., is also critical for occupant safety by reducing intrusion into the passenger compartment.

In a previous study [2], manual shape optimization was performed to search for optimal cross-sections for axial and bending crush modes with the use of correlated crush simulation models and DP780 and DP980 steels. The manual optimization is a very time-consuming process since the design needs to be modified and re-meshed for every iteration and extensive experience is necessary for designs with complex geometry and multiple load cases. With the advancement in Computer-Aided Engineering (CAE) technology in recent years, especially the progress in design optimization software, the development of the commercially available optimization tools have become more robust and efficient, and lend themselves to the solving of more complicated design optimization problems.

In this study, verified crush simulation models developed using LS-DYNA® were used together with HyperMorph™ and HyperStudy® software to define the shape design variables and set up the optimization problem. Optimal cross-sections were automatically searched for improved axial and bending crush performance and mass reduction potentials using DP780 and DP980 steels. It is the objective of this paper to offer guidelines to the design-engineering community for applications of innovative cross-sections using DP780 and DP980 for crash-critical components.

MATERIALS

Three dual phase (DP) steels, i.e. DP590, DP780 and DP980, specified by the minimum tensile strength in MPa, were used in this study to replace conventional high strength low alloy steel (HSLA350) for mass reduction. When compared to HSLA steels with similar yield strength, dual phase steels have higher initial work hardening and higher tensile to yield strength ratio.

which enable the manufactured parts to have significantly better energy absorption capability.

Figure 1 shows the quasi-static stress strain curves for each of the dual phase steels and HSLA350, and Table 1 lists their typical mechanical properties. DP590 steel has significantly higher tensile strength than HSLA350 although the yield strength is similar. Unlike HSLA350, the dual phase steels show no yield point elongation (YPE). The low yield strength increase for HSLA350 is caused in part by its large YPE value.

For the 48 km/hr (30 mph) axial crush simulations, strain-rate sensitivity is considered and the strain rate properties for DP590 and DP780 used in the simulations are shown in Figure 2.

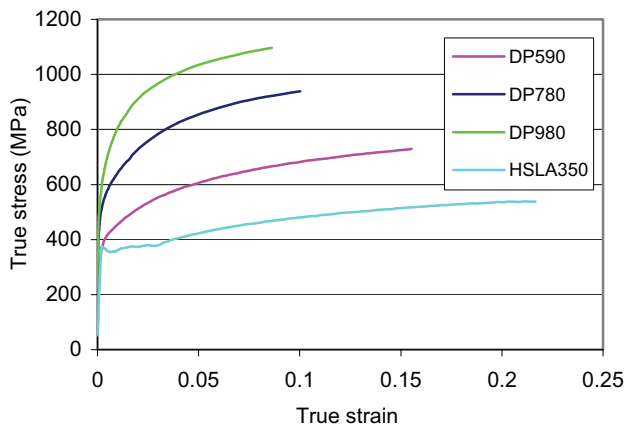
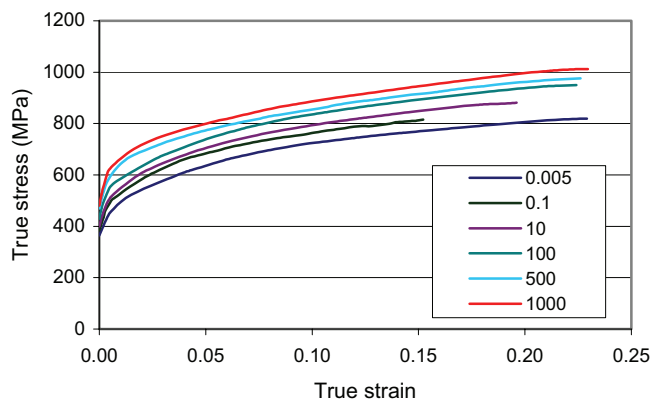


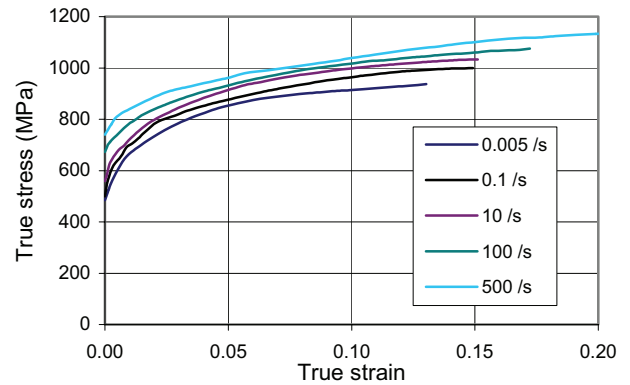
Figure 1. True stress-true strain curves

Table 1. Typical mechanical properties

Grade	Yield strength (MPa)	Tensile strength (MPa)	TEL (%)	n value
HSLA350	372	487	28.7	0.16
DP590	390	634	23.7	0.16
DP780	457	836	17.9	0.12
DP980	573	1003	15.1	0.10



2(a) DP590



2(b) DP780

Figure 2. Strain-rate curves for DP590 and DP780

CRUSH SIMULATION MODELS

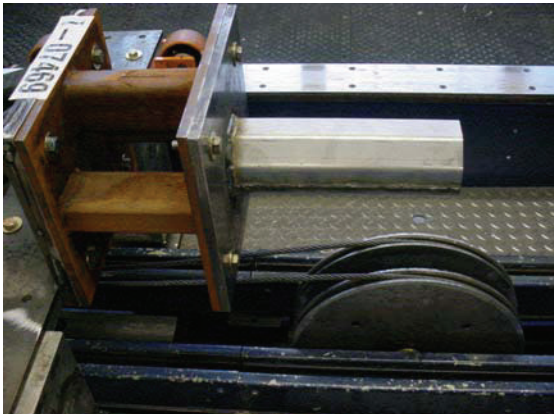
Crush simulation models were developed using non-linear finite element code LS-DYNA® to simulate the actual testing scenarios. Belytschko-Tsay (type 2) shell elements were used instead of the fully integrated shell elements (type 16) in LS-DYNA®. A previous study shows that slightly better simulation results can be achieved with fully integrated shell elements (type 16), but the computational time is about three times more than that of using Belytschko-Tsay (type 2) elements [3]. The element size is about 3.0 mm.

The set-up for the 48 km/hr (30 mph) axial crush is shown in Figure 3(a). The test sample was welded to a plate and placed on a VIA sled vehicle. The sled vehicle was accelerated to 48 km/hr before crashing into a concrete wall. The total weight of the sled-vehicle is about 249 kg. All the crush energy is expected to be absorbed by the crush sample.

The set-up for the quasi-static bending is shown in Figures 3(b) and 3(c). The span length between two supports is about 560 mm. A punch with a diameter of 50.8 mm hits the sample at the center. The reaction forces were measured with three load cells located at the punch and each support.

The FEA models for axial and bending crushes are shown in Figures 4 and 5, respectively. An explicit scheme was used for both dynamic and quasi-static crush simulations. When using the explicit code for the quasi-static bending tests, the mass density used in the model was reduced by a factor of 100 to eliminate the dynamic effect so that a relatively higher impact velocity could be utilized to reduce computational time [4]. A comparison study showed that the simulation results using both explicit and implicit schemes for the quasi-static bending tests were almost the same, but using the explicit scheme avoided the potential convergence problem for the implicit scheme.

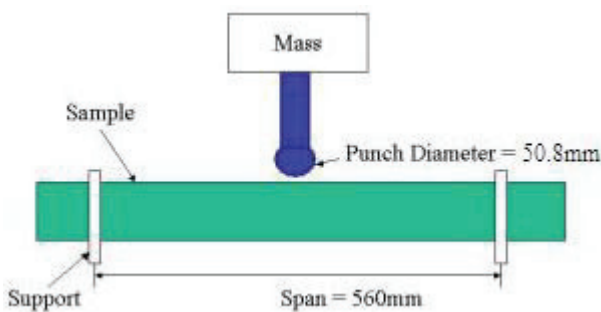
Correlation of crush simulation models to the physical crush tests was conducted in a previous research study on axial and bending crushes of DP590 columns with hexagonal and octagonal cross-sections [2,5,6]. The correlated simulation models with the same numerical model parameters as well as mesh topology and crash speed etc. were applied for subsequent cross-section optimization studies to improve axial and bending crush performance using DP780 and DP980 steels. The same scenarios of 48 km/hr (30 mph) axial crush and quasi-static bending crush were used as the two load cases for the optimization study.



3(a) Axial crush



3(b) Bending crush



3(c) Dimensions for bending crush

Figure 3. Axial and bending crush test set-up

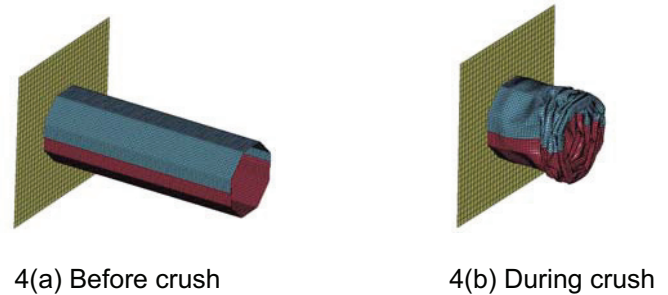


Figure 4. FEA axial crush model



Figure 5. FEA bending crush model

OPTIMIZATION METHOD

Optimization is a process to find the parameter setting of a model that minimizes or maximizes a particular objective function subject to a number of constraints. An optimization study can be described as follows:

- A baseline design to be used as the starting point and served as a reference for comparison.
- A set of design variables that can change within the pre-defined ranges in the baseline design.
- An objective to evaluate the performance of a design, where the objective is the attribute to be maximized or minimized.
- One or more constraints to be satisfied during the optimization process.

The design that maximizes or minimizes the objective while still satisfying the constraints is chosen as the optimal design. A design that simply satisfies all of the constraints, regardless of how well it meets the objective, is a feasible design. Usually, there are many feasible designs that are not optimal.

Altair HyperStudy® and HyperMorph™, members of the Altair HyperWorks® suite of software products, were used in this study to automate the search for the optimal design within a given design space. HyperStudy® is software to perform Design of Experiments (DOE), optimization and stochastic studies in a CAE environment. The optimization can be applied to any one or more analysis codes and helps can be multi-disciplinary for different attributes of a design. In the

current study, non-linear dynamic solver LS-DYNA® was utilized for the simulations of axial and bending crushes.

Aside from the typical definition of solver input data as design variables, the shapes of finite element model geometries can also be parameterized using Altair HyperMorph™ module. These morphed shapes can then be saved as HyperStudy® shape design variables to evaluate their effect on design performance in the non-linear analyses. In this study, shapes that control the cross-section geometry, steel sheet gauge, and steel grades were defined as the design variables.

Adaptive Response Surface Method [7,8,9] (Altair HyperOpt®) was used to search for the optimal designs because of its algorithm efficiency and robustness compared to other optimization methods currently available in HyperStudy®. In this approach, the objective and constraint functions were approximated in terms of design variables using a second order polynomial. The polynomial coefficients were determined using a least squares fit of the functions onto the previous design points obtained from actual non-linear crush simulation results. The optimization procedure is described as follows:

1. Analyze the initial design and n perturbed designs (n is the number of design variables);
2. Use the least squares fit technique to determine the polynomial coefficients for the objective and constraint functions;
3. Solve for the approximate optimum design using mathematical programming. The best optimization method is selected automatically;
4. Analyze the approximate optimum design;
5. If the designs have converged according to the user-defined convergence criteria and have not violated the constraints, then stop;
6. If the designs have not converged, go to step 2 and repeat until convergence.

CROSS-SECTION OPTIMIZATION STUDY

In the following optimization study, a square cross-section with a width of 84 mm made of 1.55 mm thick DP780 steel was chosen as the baseline. Using the finite element model of the square cross-section as the reference, eight shape variables were defined using HyperMorph™, as illustrated in Figure 6. The details of the shape variables are described in Table 2. Initial values of zero for all eight-shape variables mean that the optimization starts at the square cross-section. Manufacturing feasibility was considered in defining the range or maximum distance for each shape variable.

Variable *Shape1* moves simultaneously in the diagonal directions at the four corners for corner control. Variables *Shape2* – *Shape6* control bead depth and width at the central portions of the side, top and bottom walls, respectively. Variables *Shape7* and *Shape8* change the whole cross-section width and depth, respectively.

Two independent load cases, i.e., 48 km/hr (30 mph) axial crush and quasi-static bending crush, were applied for the optimization models to automatically search for the optimal cross-sections for axial and bending crushes, respectively.

AXIAL CRUSH – In the cross-section optimization for axial crush, the objective was to minimize the total crush distance since the total crush energy was constant, and the constraint was the mass of the optimized design not exceeding that of the baseline part with a square cross-section.

The optimization history for the axial crush is shown in Figure 7. As shown in Figure 7(a), the optimal design was achieved at Iteration #52, where the objective of the crush distance was at the minimum and the mass constraint was not violated, i.e. the mass of the optimized design did not exceed the mass of the baseline design. Figure 7(b) shows the history of the shape design variables during the optimization. The variable *Shape1* proved to be the most crucial parameter for axial crush performance improvement by increasing the number of corners of the cross-sections. When *Shape1* increased at the early stage of the iterations, the crush distance decreased quickly, as shown in Figure 7(a). Variables *Shape7* and *Shape8* changed simultaneously with *Shape1* in order to meet the mass constraint.

The optimized design for axial crush at Iteration #52 is a 12-sided cross-section as shown in Figure 8(a) and its crush mode is shown in Figure 8(b). This is consistent with the manual optimization results reported in a previous paper [2]. The axial crush performance of the optimized cross-section in terms of crush force and energy absorption is compared with that of the baseline square cross-section, and the comparisons are shown in Figure 8(c).

The total crush distance of the 12-sided cross-section was only half that of the square cross-section when all the crush energy is absorbed. In other words, the energy absorption capability is doubled for the 12-sided cross-section when crushed at the same distance. For example, at the same crush distance of 125 mm, the square cross-section absorbs 10 KJ of crush energy, while the 12-sided cross-section absorbs more than 21 KJ of crush energy. The superior axial crush energy absorption capability of the 12-sided cross-section offers great mass reduction opportunities through the downgauging of the components designed for axial crush energy management.