

Axial Crash Testing and Finite Element Modeling of A 12-Sided Steel Component

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Guofei Chen, Todd M. Link and Ming F. Shi
United States Steel Corporation

Tau Tyan and Ruth Gao
Ford Motor Company

Paul M. McKune
Noble International

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ABSTRACT

To improve the energy absorption capacity of front-end structures during a vehicle crash, a novel 12-sided cross-section was developed and tested. Computer-aided engineering (CAE) studies showed superior axial crash performance of the 12-sided component over more conventional cross-sections. When produced from advanced high strength steels (AHSS), the 12-sided cross-section offers opportunities for significant mass-savings for crash energy absorbing components such as front or rear rails and crush tips. In this study, physical crash tests and CAE modeling were conducted on tapered 12-sided samples fabricated from AHSS. The effects of crash trigger holes, different steel grades and bake hardening on crash behavior were examined. Crash sensitivity was also studied by using two different part fabrication methods and two crash test methods. The 12-sided components showed regular folding mode and excellent energy absorption capacity in axial crash tests. In general, the simulation results correlated well with the tests in terms of crash mode, crash force, crash distance and energy absorption.

INTRODUCTION

During a vehicle front or rear crash, it is important for the front/rear end structures, particularly the longitudinal rails, to absorb a significant amount of kinetic energy within a predetermined crash distance. It is usually desirable for the longitudinal rails to collapse axially and progressively in a predetermined mode during a crash. While the axially

progressive folding mode is generally considered to be the most effective mechanism of energy absorption, it is also the most difficult one to achieve in real structures with thin-walled sections [1, 2]. The objective in designing longitudinal rails is to identify an optimal combination of cross-section geometry, steel grade and thickness to achieve the maximum energy absorption capacity while satisfying constraints on mass and the allowable axial crash force.

In a previous study [3], shape optimization was performed to search for optimal cross-section geometries for axial and bending crash modes with the use of correlated crash simulation models and AHSS, especially dual phase (DP) steels. Verified crash simulation models developed using LS-DYNA® Nonlinear Finite Element Analysis (FEA) Software were used with HyperMorph® and HyperStudy® Design Optimization Software to define the shape design variables and to set up the optimization problem. Starting from a square cross-section, optimal cross-sections were automatically searched for improved axial and bending crash performance. It was found that the 12-sided cross-section was superior in an axial crash and was a great candidate to be applied for axial crash critical components to improve energy absorption and reduce mass and costs with the use of DP steels.

In the present paper, physical component crash tests and CAE modeling were conducted on tapered 12-sided samples fabricated from high strength low alloy (HSLA), DP and 590R (ferrite-bainite) steels. The effects of bake hardening, crash trigger holes and different steel grades on crash

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behavior were investigated. Crash sensitivity was also studied using two different part fabrication methods and two crash test methods to examine potential variations in crash behavior and to gain confidence in the 12-sided design for potential implementation in future vehicles.

PART GEOMETRY AND FABRICATION

Based on the optimization results for an axial crash in a previous study [3], a tapered part with a 12-sided cross-section was designed as shown in Figure 1. The tapered 12-sided component is 300 mm long and has a wall width of 22 mm at the front and 34 mm at the back, resulting in a longitudinal taper angle of approximately 4.0 degrees. The tapered design was chosen for improved stability and better progressive crash mode during axial crushing. 1.5-mm DP590 steel with yield strength of 381 MPa and tensile strength of 630 MPa was used to fabricate the components.

Laser welding and press-forming processes were used to fabricate the components, as shown in Figure 2. Starting from a developed blank, a conical tube was press formed and laser seam welded. Then the tube was placed outside of a mandrel die with the same shape as the tapered 12-sided components. As the press closed, four identical punches simultaneously closed around the mandrel to form the 12-sided shape. Finally, the 12-sided components were trimmed at both ends to meet the specified dimensions.

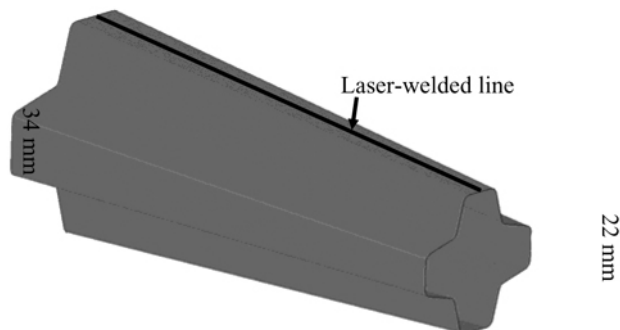


Figure 1. Geometry of the tapered 12-sided part

AXIAL CRASH TESTS

Dynamic axial crash tests were conducted at two velocities - 24 km/hr (15 mph) and 48 km/hr (30 mph). Quasi-static axial crash tests were also performed at a velocity of 0.42 mm/sec (1.0 in/min).

The set-up for the dynamic axial crash test is shown in Figure 3. The test sample was welded to a 5 mm thick steel plate and attached to a VIA sled vehicle. The sled vehicle was accelerated on the track to reach the predetermined crash velocity before crashing into a concrete wall. The total weight

of the sled-vehicle was about 1376 kg for the 24-km/hr crash test and 252 kg for the 48-km/hr crash test. Actual test velocities ranged from 24.3 to 24.7 km/hr and 48.1 to 48.6 km/hr, respectively, which yields a maximum variance of 0.9%. All the crash energy is expected to be absorbed by the crash sample. The acceleration and crash forces of the sled vehicle were measured during the crash tests using load cells and sensors placed on the rigid wall and the sled vehicle. The measured crash forces were then processed using SAE Class 180 and 300 filters for the 24 km/hr and 48 km/hr crash tests, respectively, to reduce dynamic noise in the test data.

The quasi-static axial crash tests were performed on a Tinius Olsen machine with a load capacity of 260 kN. The test sample was fully fixed at one end and crushed at the other end at a constant speed of 0.42 mm/sec (1.0 in/min). The test was stopped after the sample was crushed to approximately 25% of its original length. A load cell in the table measured the crush force, while a string potentiometer measured the displacement.

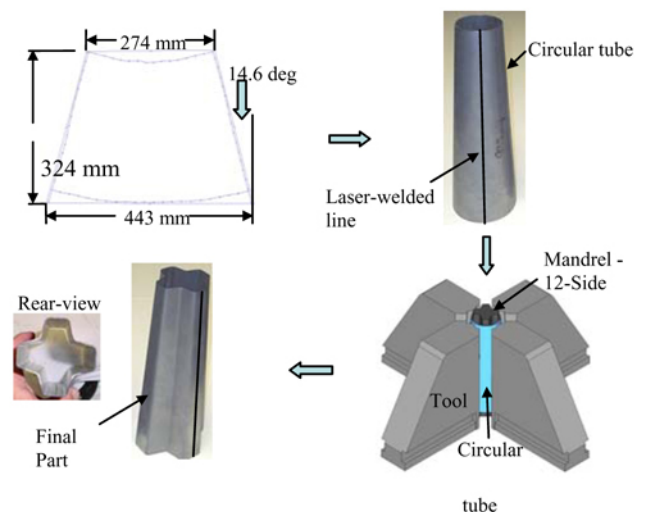


Figure 2. Press-forming process

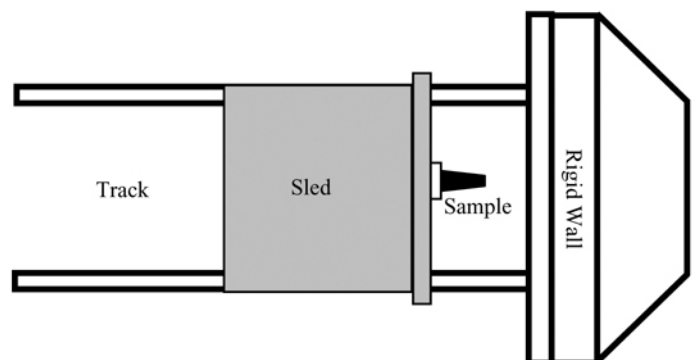


Figure 3. Schematic of the dynamic crash test

Four replicate 12-sided samples were tested for each velocity. For each test condition, one conical tube was also tested for comparison. Although the conical tubes have a circular cross-section, the mass and front/rear perimeters (line lengths) are identical to those of the 12-sided components.

The typical crash deformation modes for the axial crash tests are shown in [Figure 4](#). During the dynamic sled crash tests, the samples all deformed in stable and progressive folding modes as shown in [Figures 4\(a\)](#) and [\(b\)](#), although some cracks developed at the later stage of the crash. However, in the quasi-static crash tests, only one sample deformed in the stable and progressive folding mode (see [Figure 4\(c\)](#)), and the other three samples all collapsed in an unstable and irregular mode (see [Figure 4\(d\)](#)). The unstable buckling mode was initiated in the middle of the sample before moving to the top of the sample in a non-progressive manner.

One possible reason that the unstable collapse mode was observed in the quasi-static crash tests may be that because the samples deform so slowly (0.42 mm/sec), there is more time available for slight tolerance imperfections in the component to have an impact on the test results. The unstable collapse mode increases the variation in crash behaviors among replicate samples and makes it more difficult to predict the crash performance. Therefore, in the subsequent sensitivity study, crash trigger holes were added to control this unstable crash behavior.

<[figure 4](#) here>

The axial crash test results in terms of crash force and energy absorption as a function of displacement are shown in [Figures 5, 6, 7](#) for the different test rates.

The results for the four replicate samples in dynamic crash tests ([Figures 5](#) and [6](#)) are very consistent because of the stable and progressive crash mode. With the same mass as the circular tube, the 12-sided cross-section samples demonstrate higher crash forces, significantly shorter crash distance and approximately 45% more energy absorption capability. This phenomenon could be explained by the plate buckling theory [[2](#), [4](#)] that the buckling wavelength is proportional to the side-width of the thin-walled columns under an axial compressive loading. With small side-widths ranging from 22 to 34 mm, the 12-sided samples have relatively shorter buckling wavelengths. Therefore, at the same crash distance, more folds were developed in the 12-sided samples, encouraging a greater volume of material to participate in energy absorption during the crash.

As shown in [Figure 7](#), the test data for the four replicate samples in the quasi-static crash tests are not consistent because of the unstable crash mode. However, for the sample with the stable and progressive folding mode in test #3, the 12-sided component showed higher crash forces and energy

absorption capability than the other three replicate 12-sided samples and the conical tube. The three 12-sided samples with unstable and irregular collapse modes in tests 1, 2 and 4 showed similar crash performance to that of the conical tube.

<[figure 5](#) here>

<[figure 6](#) here>

<[figure 7](#) here>

FEA MODELING AND CORRELATION

Crash simulation models were developed using LS-DYNA® Nonlinear FEA Software to simulate the actual testing at three crash velocities. An explicit scheme was used for the dynamic crash, and an implicit scheme was used for the quasi-static crash simulations. Belytschko-Tsay (type 2) shell elements with a size of 3.0 mm were utilized in all simulations.

A correlation study between the crash simulation models and physical crash tests was conducted in previous studies on axial and bending crashes of DP590 columns with hexagonal and octagonal cross-sections [[5](#), [6](#)]. The correlated simulation models with the same numerical model parameters were used in the current modeling of the crash tests on the tapered 12-sided samples.

For the dynamic axial crash simulations, the strain-rate sensitivity was considered. The strain rate dependent stress strain curves for the 1.5-mm DP590 steel were obtained in previous simulation studies [[3](#), [5](#)]. The same material properties were used in the current simulations.

Comparisons of the crash deformation modes, the axial crash force-displacement and energy absorption-displacement characteristics for the 12-sided samples and the circular tube are shown in [Figures 8, 9, 10, 11](#), respectively, for the 48-km/hr and 24-km/hr axial crash tests. The crash deformation modes obtained from simulation matched those observed in the tests. Since no material failure models were considered in the simulations, cracks observed on the 12-sided samples in the later stage of the dynamic tests were not predicted in the simulations.

<[figure 8](#) here>

<[figure 9](#) here>

<[figure 10](#) here>

<[figure 11](#) here>

Other than the magnitude of the initial force peak, the simulated force-displacement curves agreed fairly well with the test results including peak load locations, mean crash force, and total crash distance, and even better agreement was achieved in energy absorption-displacement curves. This suggests that cracks observed in the later stage of the tests had negligible effect on energy absorption capacity.

Comparisons of the crash deformation modes, the axial crash force-displacement and energy absorption-displacement characteristics for the quasi-static crash tests are shown in [Figures 12](#) and [13](#) for the 12-sided samples and the conical tube. Since geometric imperfections inherent in the fabricated component were not included in the simulation, the FEA model deformed in stable and progressive folding mode, which agreed well with that observed in test #3 for the 12-sided samples. Correspondingly, the simulated force-displacement and energy-displacement curves agreed well with the results for test #3 except for the magnitude of the initial force peak.

In summary, other than the magnitude of the initial force peak, the simulation results correlated well with the tests for all three crash velocities. Since the initial force peak is associated with significant dynamic noise in both the tests and simulations, it is inherently difficult to achieve good correlation on the magnitude of the first force peak load in axial crash tests.

<[figure 12](#) here>

<[figure 13](#) here>

SENSITIVITY STUDY

In the previous test results, unstable collapse mode was observed, especially in the quasi-static tests. In the following studies, crash trigger holes were added as a solution to control the unstable crash behavior [7, 8]. Using the same correlated FEA models, the trigger hole configuration, including the hole size and locations, was determined, and the optimized trigger geometry is shown in [Figure 14](#). Three rows of circular trigger holes with a diameter of 6.5 mm were mechanically drilled on every other convex corner of the 12-sided samples. Therefore, each row had four trigger holes. The distances from the front end to the first hole and between the holes in the middle were 15 mm, 70 mm, and 78 mm, respectively.

AHSS can exhibit significant bake hardening responses in uniaxial tension tests, e.g., an increase in yield strength after a simulated paint baking thermal cycle [9, 10]. Such changes in mechanical properties after baking may have the potential to affect the crash performance. To understand the effect of paint baking on the axial crash performance, 12 samples were baked at 177°C for 30 minutes prior to testing to simulate an

automotive paint baking cycle. Three sample conditions - 1) baking only, 2) trigger-holes only, and 3) baking & trigger-holes - were tested at the three crash velocities again with two replicates for each test velocity. The new results are to be compared with the previous test results on the original samples.

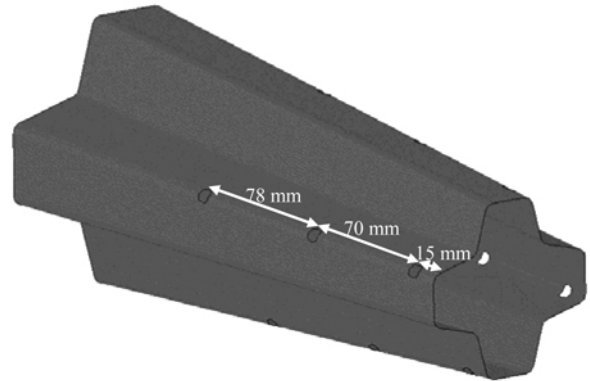


Figure 14. 12-sided samples with circular trigger holes

[Figures 15](#) and [16](#) show the crash deformation modes after 24-km/hr sled crash tests and quasi-static tests, respectively. Similar results were observed for 48 km/hr-sled crash tests and were not reported in this paper. The crash modes for the baked samples without trigger holes were very similar to those of the original samples shown in [Figures 4\(b\)](#) and [\(d\)](#). [Figure 16\(a\)](#) shows that the baked samples still exhibited unstable and irregular collapse mode in the quasi-static tests. With crash trigger holes, the crash deformation process was better controlled, resulting in more stable and regular folding modes, as shown in [Figures 15\(b\)](#) and [\(c\)](#). The effect of trigger holes on the crash mode for the quasi-static tests is shown in [Figures 16\(b\)](#) and [\(c\)](#).

The effects of baking and crash trigger holes on axial crash performance are summarized in [Figures 17](#) and [18](#) for the 24-km/hr sled test and the quasi-static test, respectively. Overall, the first peak load increases slightly for the baked samples, while crash trigger holes decrease the first peak load by 10-15%. Baking has no significant effect on the average crash force as the baking treatment itself does not change the crash deformation behavior. The samples with trigger holes exhibit slightly lower average crash force in the 24-km/hr sled crash tests and substantially higher average crash force in the quasi-static tests. This is because the trigger holes help the samples crush in stable and regular folding modes in the quasi-static tests.

In general, the current results agree with our previous studies on crash trigger holes [7, 8] and other studies on baking effects [9, 10] on axial crash behaviors.