Impact Performance of Advanced High Strength Steel Thin-Walled Columns

Portillo Oscar, Romero Luis Eduardo

Abstract— **The crashworthiness performance of spot-welded columns fabricated with advanced high strength steels is evaluated using finite element (FE) analysis. A failure criterion for the spot-welds is implemented into the FE model to predict accurately the progressive axial collapse of the columns. The behavior of two Dual Phase (DP) steels and a High Strength Low Alloy (HSLA) steel are compared by examining the mean crushing force, peak load and crushed column length for single-hat and double-hat configurations, both experimentally and numerically. Numerical results of the developed FE model correlate favorably available experimental data for different impact conditions.**

Index Terms — **Dynamic collapse, High-strength steel, Impact absorption energy, Spot-welded columns.**

I. Introduction

A worldwide trend in steel making for the automotive industry is the development towards higher strength grades in order to achieve greater structural strength and enhance lightweight structure design. The extensive use of advanced high strength steels (AHSS) in transportation systems provides a motivation for studying the crashworthiness properties of energy absorber elements. These elements are design to absorb large amounts of impact energy, while collapsing progressively in a controlled manner, providing the strength and rigidity needed for passenger compartment integrity. Axial crushing of metallic kinetic-energy absorbing components has been the subject of extensive studies over the past decades [1, 2]. A second motivation of this research arises from the fact that the various types of hat cross-section column members are extensively used in vehicle applications and play a significant role in absorbing crush energy during a collision [3, 4]. Generally, the car front rails are single-hat elements and the door pillars are typically double-hat elements. Also, cross-members are commonly hat-like structures. Therefore, it is vital to understand their dynamic axial crushing behavior for the effective structural design of a vehicle and ultimately to reduce the likelihood of passenger death or serious injury in an accident.

Crashworthiness performance of hat-type columns fabricated from DP and HSLA steels is investigated in this work. One major characteristic that is shared among the family of AHSS is the positive strain rate performance. That is to say, at higher rates of strain commonly observed in crashworthiness events (strain rates can reach levels of 500 s^{-1}), the AHSS steels have higher strength increases. Consequently, the combination of strength, ductility, strain-rate sensitivity, rapid strain hardening characteristics and formability of AHSS materials reflects their higher capacity to absorb energy during crashes than conventional low-carbon steels or crashworthy structures made of aluminium, while reducing the overall weight of the automobile [5]. One of the most common automotive applications of DP steels comprises the fabrication of front and rear rails. These elements are very important because they control the spatial distribution of impact forces. HSLA materials are typically found on passenger-car applications such as door-intrusion beams, B/C pillar reinforcements, cross-members and bumpers.

Numerous researchers have investigated the quasi-static and dynamic axial crush behavior of several crashworthy components having square, rectangular, square top-hat, rectangular top-hat and multi-corner cross sections [3,4,6,7]. They have examined experimental collapse profiles, force-deformation histories and crush displacements. Some authors have proposed approximate theoretical models based upon generalized superfolding elements to determine the mean crush load for hat-type thin-walled columns [4]. Spot-welds in structural members frequently fail under combined loads during a car crash impact. Consequently, a failure criterion for spot welds is helpful for the structural integrity design of the vehicle. Failure of spot-welds is linked to many variables such as residual stresses, material inhomogeneity, welding parameters, nugget size, thickness, material properties of the heat affected zone and the base metal. Numerous efforts have been devoted to estimating the strength of spot-welds [8].

The impact absorbing properties of spot-welded single-hat and double-hat columns made from DP and HSLA steels were recently investigated by F. Ben-Yahia and J.A. Nemes [9]. Reasonable agreement between the experimental results and the FE predictions was observed. This work was further extended by O. Portillo and J.A. Nemes [10, 11] where they studied the effects of spot-weld failure in the crashworthy columns. The researchers implemented two FE models for simulating the crush behavior of hat-type cross-sectional steel columns undergoing dynamic axial impacts using the ABAQUS-v.6.4 mesh independent spot-weld Fastener interaction and the element connection type-Weld method. Based on test results and numerical simulations, they found that the DP steels exhibit better energy absorption efficiency

Manuscript received March 6, 2008. This work was supported in part by the CONACYT and SEP, Mexico.

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than the HSLA steel for both hat-type geometric configurations. In the present work, breakable spot welds are modeled in ABAQUS/Explicit-v6.7 using the BOND modeling technique [12]. This modeling capability simulates the spot weld failure under relatively monotonic straining such as presented in a car impact. For simplicity, a limit time to force-based failure criterion for spot-welds is implemented into the finite element model, the adopted failure criterion simulates interfacial separation as a function of the normal force. Numerical results of the FE model are intended to provide design guidance to further optimize the performance of the structures.

II. Finite Element Modeling

A. Materials

Two types of DP grade are considered in this study, having yield strengths of 400MPa and 300MPa respectively. The other high-strength material selected for this investigation is an HSLA steel. The mechanical properties of these steels are given in Table I.

Table I. Static mechanical properties of steels examined (after [9]).

STEEL	STATIC MECHANICAL PROPERTIES			
Label	YS (MPa)	TS (MPa)	El (%)	n-value
DP600/400	400	620	23	0.13
DP600/300	300	620	25	0.15
HSLA	360	430	35	0.20

B. Constitutive Model

The plastic behavior of the selected AHSS steels is characterized by the Johnson-Cook constitutive model [13], which aims to predict material behavior subjected to large strains and high strain rates such as high velocity impacts. The constitutive model is expressed as:

$$\sigma = [A + B\varepsilon_p^{n'}][1 + C\ln\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_\circ}][1 - (\frac{T - T_0}{T_{melt} - T_0})^{m'}] \qquad (1)$$

were σ is the equivalent stress, ε_p is the equivalent plastic strain, $\dot{\varepsilon}_o$ is the reference strain rate (taken to be 1 s^{-1}), $\dot{\varepsilon}_p$ is equivalent strain rate, T is the temperature of the specimen and T_{melt} and T_o are the melt and reference temperatures. The Johnson-Cook parameters of the steels considered in this study are listed in Table II.

Table II. Johnson-Cook parameters of steels examined (after [9]).

STEEL	JOHNSON-COOK PARAMETERS				
Label	A (MPa)	B (MPa)	C	n´	m´
DP600/400	300	630	0.030	0.30	1.0
DP600/300	270	875	0.080	0.36	1.0
HSLA	344	200	0.025	0.33	1.0

C. Geometry of the hat-type steel columns

The single-hat column comprises a hat cross-section component welded to a closing plate, whereas the double-hat column consists of two hat cross-section welded units. Details of the geometry and spot-weld arrangement are illustrated in Fig. 1.

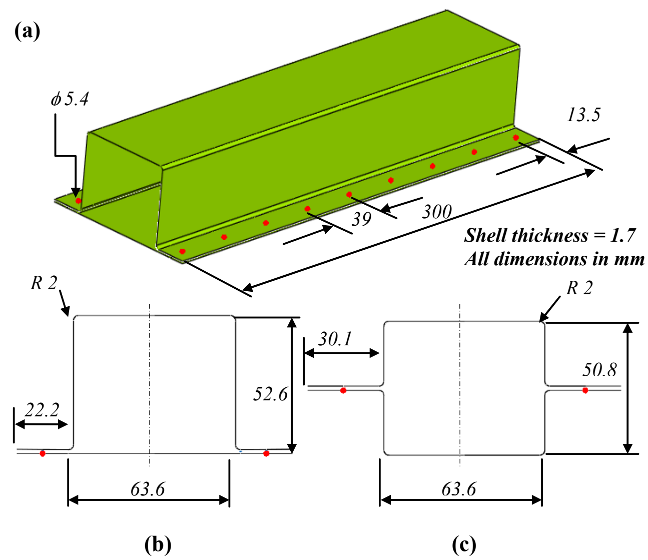


Figure 1. Geometrical configuration of the columns. (a) Spot-weld arrangement demonstrated in a single-hat specimen. (b) Single-hat cross-section. (c) Double-hat cross-section. (after [11]).

D. Test Setup and Procedure

Dynamical axial crush testing was conducted in a drop weight testing machine. Direct data acquisition included load and time. Details of the experimental setup can be found in [10]. Two impact loading conditions were considered. In the first, the single and double hat columns are struck by an impactor mass of 148.2 kg travelling at a velocity of 9.2 m/s. This will be referred to as *impact condition I*. In the second case, the double-hat column is impacted by a striking mass of 181.4 kg travelling at 7.6 m/s, referred to here as *impact condition II*.

E. Finite Element Model Configuration

The crush simulation model involves two FE analyzes with essentially the same model definition. A linear perturbation analysis is run in ABAQUS/Standard to obtain the ten first eigenmodes of the hat-type columns. Subsequently, ABAQUS/Explicit is used to determine the postbuckling behavior of the columns. Geometric imperfections are incorporated into the computer model using the results from the eigenvalue static buckling analysis. The initial geometric imperfections are introduced into the perfect geometry by choosing a set of scale factors that superimpose only the first symmetric mode shapes (the largest scale factor was taken to be 1% of the shell thickness and the subsequent scaling factors monotonically decrease as the mode number increases). Computer results of the buckling prediction on the single and double hat geometries are depicted in Fig. 2.

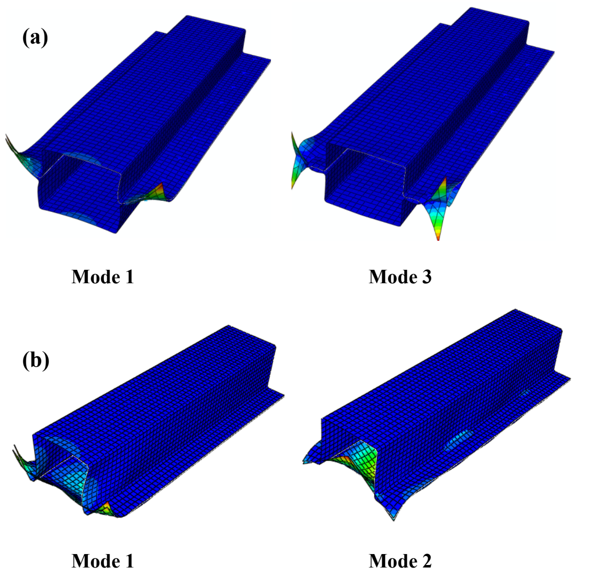


Figure 2. First symmetric buckling modes. (a) Double-hat column. (b) Single-hat column.

Fig. 3 illustrates the explicit finite element model. It comprises a fixed non-deformable plate, the hat-type column, and a moving rigid plate (striker). The initial velocity and mass of the striker is assigned to the moving plate through its reference node using a point mass element. The momentum generated by this initial velocity will cause the striker plate to impact the column which will ultimately crush against the fixed rigid plate. Both single-hat and double-hat columns are modeled as a shell structures. The finite element model of the single-hat column consist of 3960 S4RSW elements (doubly curved shell hourglass control elements) and the double-hat column comprises 4320 S4RSW elements. The spot-welds are implemented using the mesh independent spot-weld Fastener modeling method during the buckling analysis (ABAQUS/Standard) and the BOND capability is used during the post-buckling analysis (ABAQUS/Explicit). A contact interaction between the hat part - plate interface (or both hat parts in the case of the double-hat column) is defined using the automatic surface-to-surface contact algorithm. The spot-welds (bonds) are located at the nodes of the slave surface of the contact pair. The general contact algorithm is applied between the other components of the assembly, including self-contact in deformable bodies (hat component and closing plate). Spot-weld failure is incorporated into the numerical model by considering a 10kN limit force needed to cause interfacial separation in mode-I loading (tension). The separated spot-welds are then gradually switched off and a time to failure model of 2 ms is adopted to characterize their post-yield response. The model simulates the deterioration process of the spot-welds after failing by assuming that the maximum forces that they can bear decay linearly to zero during 2 ms.

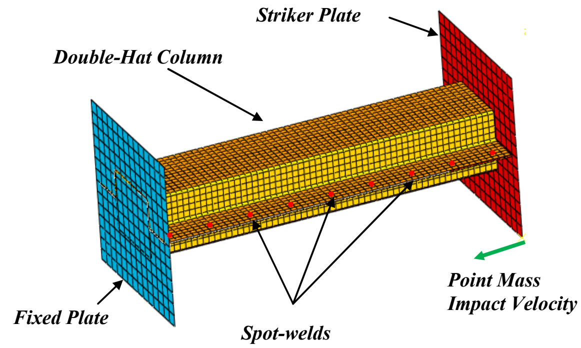


Figure 3. FE element model demonstrated in a double-hat column.

III. Results

To evaluate and compare the structural efficiency of the hat-type columns, the computer simulated impact test and experimental results are compared in terms of load-displacement history curve, final collapse length, peak load and mean crushing load. Two groups of FE simulations were carried out. First, numerical simulations were conducted by modeling rigid spot-welds on the columns, referred to here as *FE-Model I*. The second group of simulations were performed by modeling breakable spot-welds (assuming a 10kN failure load in tension) referred to as *FE-Model II*.

Fig. 4 shows a comparison of force-axial deformation curves between FE predictions and experimental results for selected materials and impact conditions. Very good agreement can be identified in most cases despite of some variation in the initial phase of the axial shortening response, this behavior is actually expected from test specimen to test specimen since the end caps of the fixture do not provide total fixity to the columns ends. Nevertheless, the instantaneous load-deformation curves agree reasonably well after the peak load, especially for the FE-Model II.

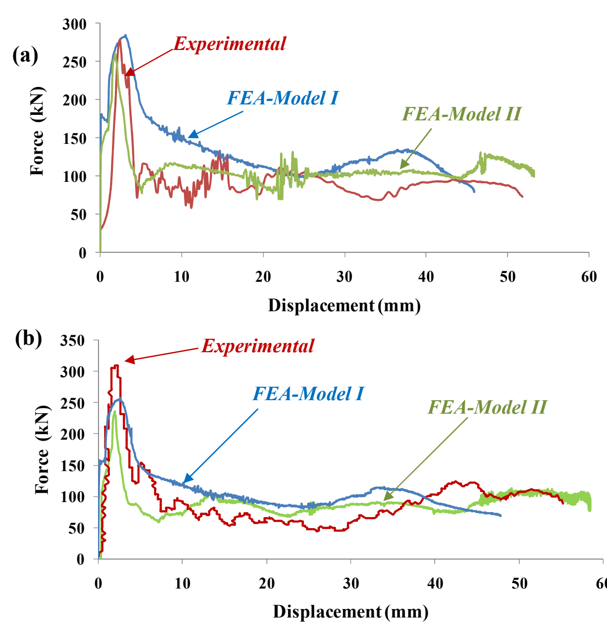
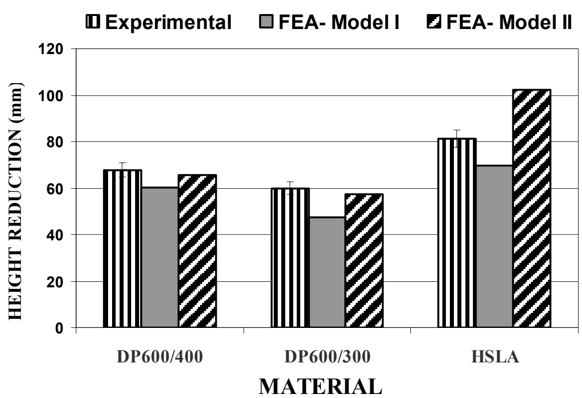


Figure 4. Force-displacement history for single-hat columns.
a) Impact condition I, material DP600/300. b) Impact condition II, material DP600/400. (Experimental data courtesy of Stelco [10]).

The comparison of the permanent axial deformation between available experimental data and generated numerical results are shown in Fig. 5. It can be seen that the crush length predictions of the FE-model II are above the FE-Model I numerical estimations as result of reduction of structural strength due to spot-weld failure. It is found that the FE-Model I predictions slightly underestimate the high reduction of the columns measured manually in most cases. Visual examination of the crushed specimens revealed that one to four out the eighteen spots-welds exhibited significant nugget pullout failures. Ductile failure of the material was also observed in some test samples. Occurrence of spot-weld and material failure was seen more often for the DP600/400 steel, [10]. In the case of the impact condition I, inclusion of spot-weld failure into the FE model results in better predictions for the DP materials but significantly overestimates the crush length for the HSLA steel. This over-prediction of the FE-Model II for the HSLA is also observed in the case of the impact condition II. Analysis of numerical simulations for the HSLA material shows that six spot-welds presented failure, such number of spot-weld failure does not correlate with test observations and explains the discrepancy between the experimental and predicted height reduction.

(a)



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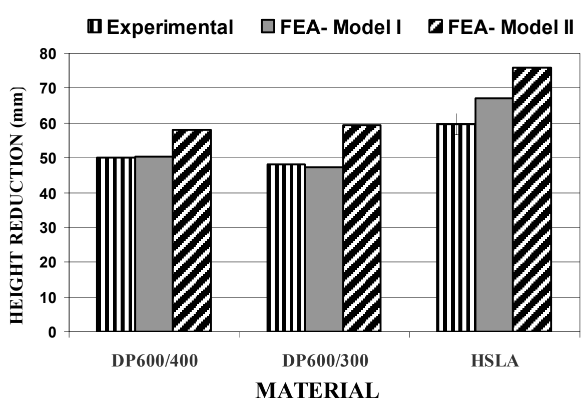
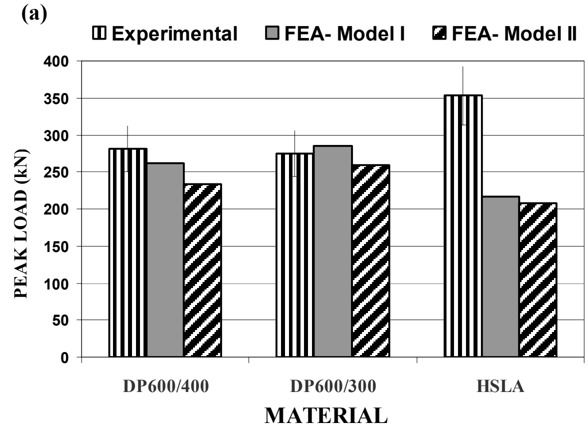


Figure 5. Height reduction for single-hat columns. a) Impact condition I. (b) Impact condition II.

Numerical estimations of the unbreakable spot-weld FE code compare closely with the experimental measurements for the DP steels subjected to the second impact condition. In this case, the presence of breakable spot-welds in the model results in a slight over prediction of the crush length as a consequence of spot-weld failure, resulting in unnecessary excessive axial deformation.

Although the predicted peak load lies in the lower range of its experimental equivalent for DP specimens subjected to the impact condition I, it is generally found that this crashworthiness parameter is underestimated by the numerical simulations, Fig. 6. Despite such discrepancy, the mean crushing force is estimated with satisfactory accuracy, Fig. 7. It is observed that the mean load is lower in the HSLA than the DP steels. It is also seen that the mean load of the DP and HSLA steels becomes shorter as the crash energy is reduced (the impact energy of the impact condition I is higher than the impact condition II).

(a)



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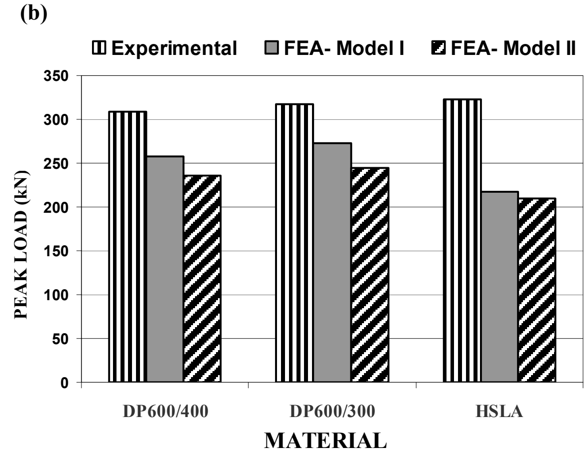


Figure 6. Peak load for single-hat columns. a) Impact condition I. (b) Impact condition II.

In integrity vehicle design, the ultimate objective is to fabricate a crashworthy structure that will deform in a controlled manner absorbing a certain amount of energy in a shorter crush displacement to provide occupant compartment space protection. Structural comparison of the high strength steels can be assessed by examining the end-shortening characteristic for the same input mass and impact velocity. From Fig. 6 and 7 is noted that the crush displacement of the single-hat column made from HSLA is longer than that for the columns fabricated with DP steels, which indicates better energy absorption performance of the DP grades. Also, it can be observed that the DP600/300 steel exhibits the shortest height reduction which points toward a greater structural efficiency for both impact conditions. The better crashworthiness performance of the DP600/300 material in comparison with the DP600/400 steel can be directly attributed to its superior work hardening and greater strain-rate sensitivity properties.

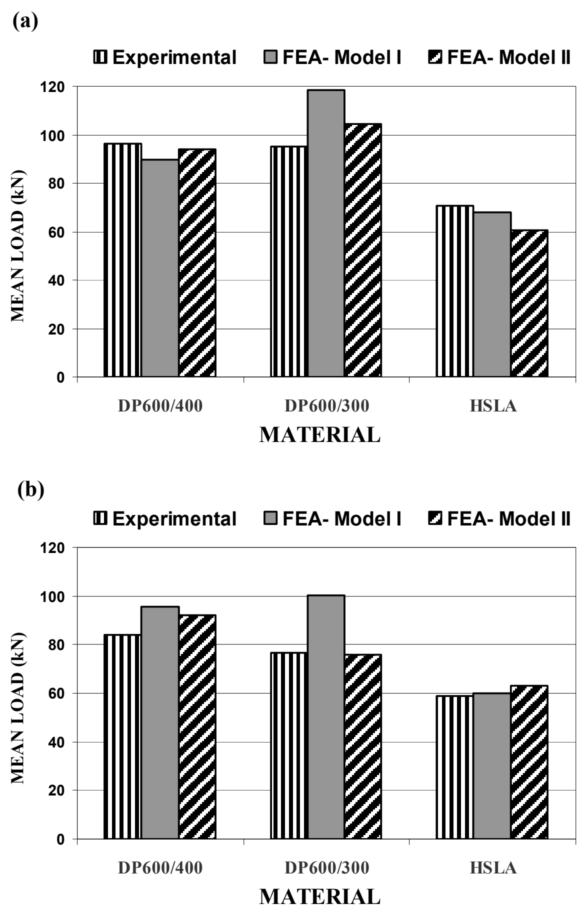


Figure 7. Mean load for single-hat columns. a) Impact condition I. (b) Impact condition II.

Numerical simulation results and available experimental data for double-hat columns subjected to the impact condition I are shown in Table III. It can be seen that there is a significant overestimation in the computed crush length for the DP600/400 material. Nonetheless, the numerically calculated mean force shows good agreement with the experimental value. It is also observed that the column height reduction is lowest for the DP600/300 material indicating again its better energy absorption capacity. This finding correlates with the results of the single-hat geometry.

A comparison of the permanent axial shortening between the single and double hat columns points toward greater energy absorption properties of the double-hat geometry, see Fig. 8. The crush length of the double-hat columns is significantly less than the single-hat and consequently better in terms of crashworthy performance. However, the peak and mean load are lower for the single-hat columns which is more desirable in terms of safety engineering design. It should be noted that the mass of the double-hat specimen is approximately 8% higher than the single-hat.

Table III. Experimental and numerical results for double-hat columns, impact condition I. Test data courtesy of Stelco [10].

Material		Peak Load (kN)	Height Reduction (mm)	Mean Load (kN)
DP600/400	Experimental	313.6	31.5	125.5
	FEA-Model I	242.3	45.8	140.4
	FEA-Model II	243.7	46.9	126.5
DP600/300	Experimental	N/A	N/A	N/A
	FEA-Model I	268.3	42.3	145.5
	FEA-Model II	269.6	43.5	143.9
HSLA	Experimental	N/A	N/A	N/A
	FEA-Model I	232.4	57.5	99.5
	FEA-Model II	206.5	57.9	102.1

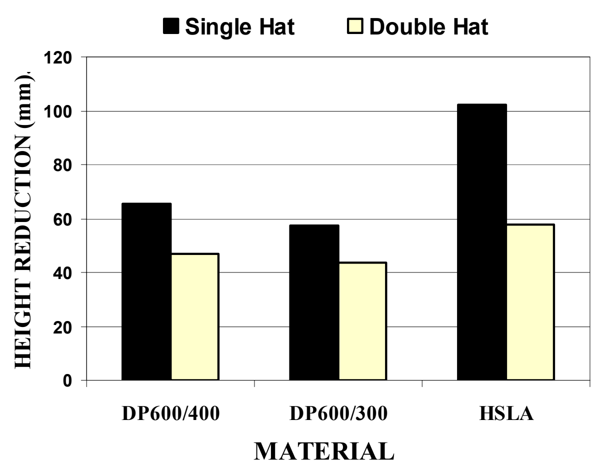
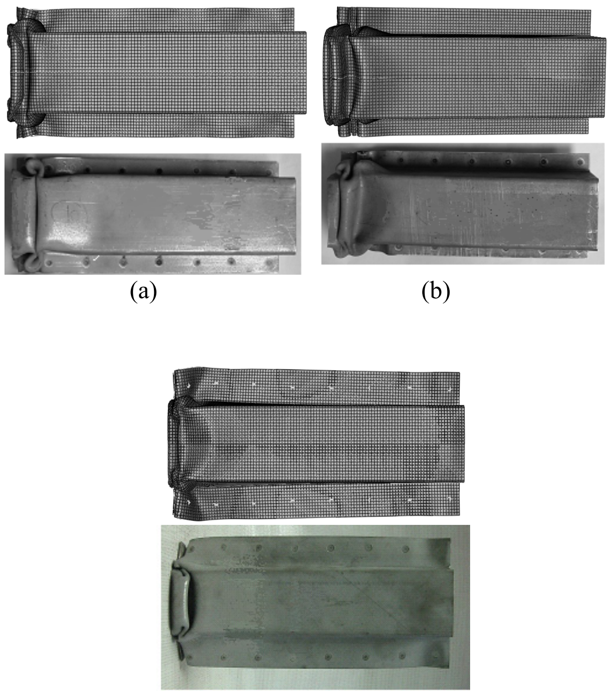


Figure 8. Height reduction for hat-type columns, impact condition I.

Comparisons of the final deformed shape between FE predictions and drop-weight test results for selected steel columns are shown in Fig. 9. The folding pattern of the hat-type columns shows very close similarity between the computer simulation and the actual experiment.

It should be mentioned that predictions of the FE model could be improved if a material failure criterion is incorporated into the code in order to account for ductile material failure as observed experimentally.



(a) (b)

(c)

Figure 9. Deformation pattern of hat-type columns. a) Single-hat column made of DP600/300 steel subjected to the impact condition II. b) Single-hat column fabricated with HSLA steel subjected to the impact condition II. c) Double-hat column made of DP600/400 steel subjected to the impact condition I.

IV. Conclusion

Axial crushing behavior of hat-type spot-welded columns has been studied numerically. Computer simulation results of the developed FE models and the drop-weight experimental results are found to be in good agreement in terms of force-deformation curve, axial shortening, peak load, mean crushing force and folding deformed column shape. Based on test results and FE simulations, it can be concluded that the DP steels exhibit greater energy absorbing properties than the HSLA steel for both hat-type configurations. It was also found that the DP600/300 material exhibits better crashworthiness efficiency than the DP600/400. A simple limit normal force failure criterion was implemented into the FE code to investigate the effects of spot-weld failure. Permanent crush length estimations of this model are larger than the numerical predictions using rigid spot-welds, indicating the decrease of structural integrity of the column. The robust numerical model can be effectively used to predict the crashworthiness efficiency of hat-type column specimens prior to conducting the actual axial crush test.

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