

Numerical Prediction of Dynamic Progressive Buckling Behaviors of Single-Hat and Double-Hat Steel Components under Axial Loading

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ABSTRACT

Hat sections, single and double, made of steel are frequently encountered in automotive body structural components such as front rails, B-Pillar, and rockers of unitized-body cars. These components can play a significant role in terms of impact energy absorption during collisions thereby protecting occupants of vehicles from severe injury. Modern vehicle safety design relies heavily on computer-aided engineering particularly in the form of explicit finite element analysis tools such as LS-DYNA for virtual assessment of crash performance of a vehicle body structure. There is a great need for the analysis-based predictions to yield close correlation with test results which in turn requires well-proven modeling procedures for nonlinear material modeling with strain rate dependence, effective representation of spot welds, sufficiently refined finite element mesh, etc. Although hat sections subject to axial loading have been studied widely in published literature, it is difficult to come across detailed information on modeling that can lead to sound correlation of CAE predictions with experimental results even for quasi-static conditions. In the current study, both single-hat and double-hat components made of mild steel are at first tested under axial loading in a UTM and the resulting load-displacement responses are predicted accurately through explicit finite element analysis carried out with LS-DYNA. Mean loads from theoretical predictions are then compared with the experimentally obtained results. Furthermore, studies are conducted for different impact conditions and the modeling procedures such as for definition of elasto-plastic material behavior are discussed in detail. The simulation-based impact dynamic responses including crash performance parameters such as mean load and total crush are found to compare well with corresponding experimental results. For generality and for relevance to practical impact scenarios, eccentrically loaded double hat-sections are tested and reasonably good numerical predictions of their behaviors are presented, perhaps for the first time in published literature.

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INTRODUCTION

Hat sections made of steel are frequently encountered in automotive body structural components such as front rails and rockers of unitized-body cars an example of which is shown in Fig. 1. Both single- and double-hat sections are common. These components absorb significant amount of impact energy during front collisions and thus are indispensable countermeasures in ensuring vehicle crashworthiness and occupant safety. In the initial phase of vehicle design, it will be prudent to incorporate the sectional details of such a component based on an engineering target

such as energy absorption, mean load or total crush or a combination of these parameters. There has been a considerable interest in studying the axial crush behaviors of thin-walled structural components such as box and hat sections through experimental, semi-analytical, empirical, and numerical means. Mahmood and Paluszny [1] presented semi-empirical relations for the prediction of average load-carrying capacities of closed rectangular box sections subjected to progressive local buckling under quasi-static axial compressive loads. Comparisons with experimental results were also given for steel columns with geometric aspect ratios relevant to automotive body applications such as

front rails. White, Jones and Abramowicz [2], and, White and Jones [3] discussed simplified theoretical and empirical procedures for predicting the performance of top-hat (i.e. single-hat) and double-hat sections under quasi-static and dynamic axial loading conditions leading to progressive collapse. A detailed experimental study on progressive collapse behavior of thin-walled closed-section structural components made from high-strength steels under quasi-static and impact axial loads was reported by Schneider and Jones [4]. The latter authors made a comparison with theoretical formulas which had been used successfully for predicting the behavior of mild steel thin-walled structures. Peixinho, Jones and Pinho[5] studied axial crushing of top-hat and hexagonal tubes made of dual-phase and TRIP (transformation induced plasticity) steels, and compared the test results with their numerical simulation results. Trigopula et al. [6] performed quasi-static and dynamic axial crushing tests on thin-walled square tubes and spot-welded top-hat sections made of high-strength steel of grade DP800. The authors compared test results with analytical predictions as well as detailed numerical simulations carried out with LS-DYNA by accounting for effects of elevated strain rates on material dynamic yield strength. Additionally, the validated numerical model was used to study the dependence of specific energy absorption on yield strength, sheet thickness, flange width and spot-weld spacing. Sato et al. [7] performed dynamic axial tests on spot-welded top-hat sections made of four grades of steel (300-590 MPa). The authors also carried out finite element-based studies by accounting for strain rate effects on material plasticity, and compared the predicted dynamic responses with experimental results.

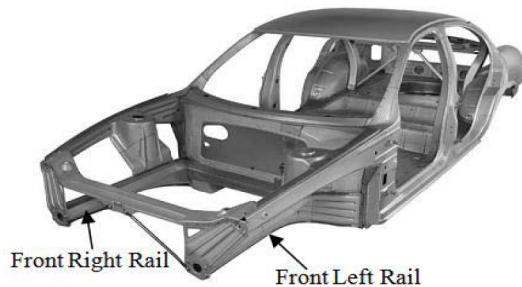


Fig. 1. A typical body-in-white of a unitized body car [10]

In the current study, both single-hat and double-hat components made of mild steel are tested under axial loading in a UTM (Universal Testing Machine) and the resulting load-displacement responses are predicted satisfactorily through explicit finite element analysis carried out with LS-DYNA. The studies are conducted for quasi-static and impact loading conditions, and the modeling procedures such as for definition of elasto-plastic material behavior with strain rate effects are discussed in detail. For generality and for relevance to practical impact scenarios, eccentrically loaded hat-sections are tested and predictions of their behaviors presented for the first time. Mean loads predicted using analytical relations are compared with experimentally

obtained results. Responses (load-displacement curves in quasi-static tests and load time-histories in impact tests) obtained through numerical simulation are compared with corresponding experimental responses. Additionally, peak load, mean load, energy absorption and total crush obtained through numerical analysis are compared against experimental results. It is seen that in most cases the numerical predictions of these parameters correspond extremely well with experimental results.

EXPERIMENTAL STUDIES ON THE BEHAVIOR OF SINGLE-HAT AND DOUBLE-HAT COMPONENTS UNDER AXIAL QUASI-STATIC LOADING

The behavior of single and double-hat section components under quasi-static compressive loading was studied initially in a servo-hydraulic UTM in CAR (Creative Automotive Research) Laboratory, CPDM, Indian Institute of Science. The details of section geometry of single and double-hat section components are given in [Table 1](#).

Table 1. Details of single-hat and double-hat sections

Test Specimen Type	Section Details a (mm), b (mm), f (mm), t (mm)	Spot-weld Pitch (mm)
Single-Hat	60, 60, 25, 1	45
Double-Hat	60, 60, 25, 1	45

Quasi-static tests were conducted on pairs of single-hat and double-hat sections and the load-displacement responses are presented in [Figs. 3\(a\)](#) and [3\(b\)](#) respectively. All quasi-static tests were carried out at a cross-head speed of 1mm/min. The tests were carried out for a total axial displacement of 100 mm in each case. It is seen from both these figures that the responses for these sections are quite similar to each other. Thus, a high degree of confidence can be placed on the experimentally-obtained loading responses. Three relevant parameters for judging crash performance of a vehicular structural component or subsystem are peak load, mean load and impact energy absorbed. For each pair of tests conducted, these parameters are compared in [Tables 2](#) and [3](#) and the close correlation for a given type of section is a further attestation of the consistency of the test results.

For a given crush length of 100 mm, about 76-78% higher energy absorption is observed for double-hat sections as compared to single-hat sections though both of these components have similar cross-sectional areas. The load-displacement curves of [Fig. 3](#) are compared in [Fig. 4](#) and the higher load response of double-hat components is clearly seen. The reason for the superior performance of the double-hat section component studied is likely to be the higher number of “corners” present in the formed plates relative to

the single-hat section component (i.e. 8 in double-hat versus 4 in single-hat).

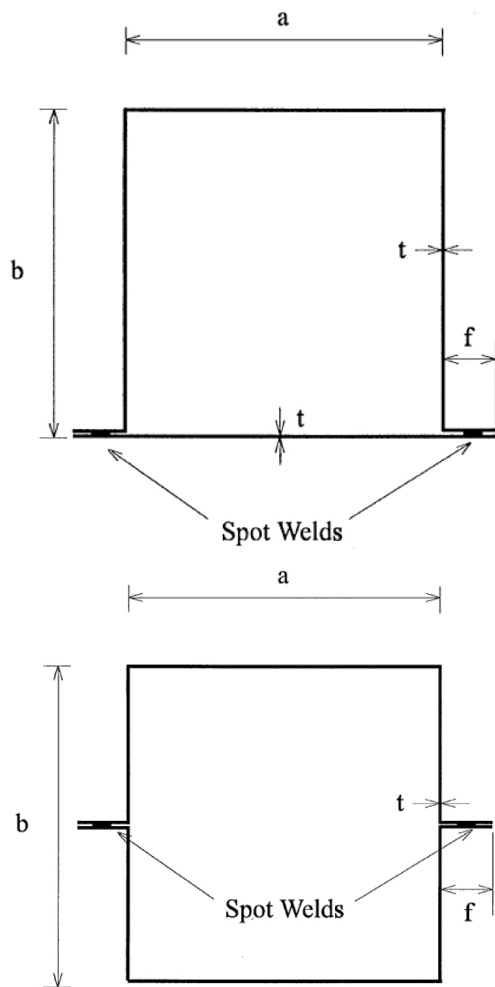


Fig. 2. Schematic views of single-hat (top) and double-hat (bottom) sections

Table 2. A comparison of results obtained from quasi-static axial crushing of single-hat sections

Case	Peak Load (kN)	Mean Load (kN)	Energy Absorption (J)
SHQ1	31.14	13.11	1311.41
SHQ2	34.21	12.88	1288.38

Table 3. A comparison of results obtained from quasi-static axial crushing of double-hat sections

Case	Peak Load (kN)	Mean Load (kN)	Energy Absorption (J)
DHQ1	52.16	23.35	2334.89
DHQ2	49.16	22.66	2266.52

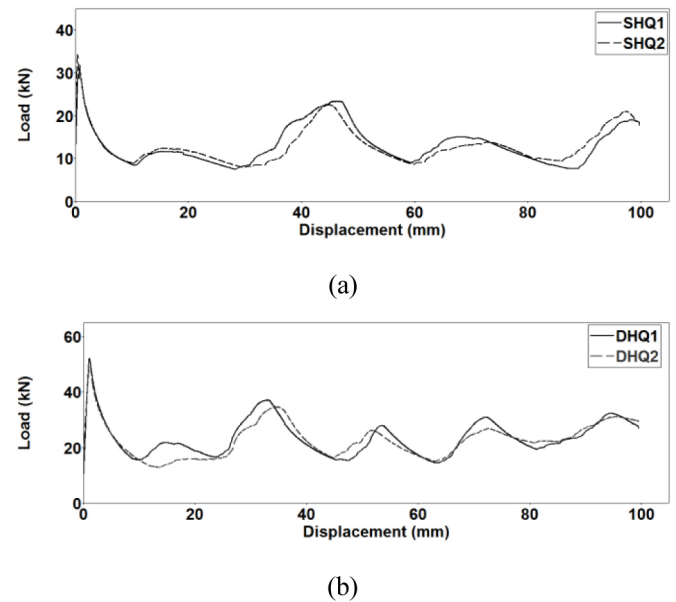


Fig. 3. Load-displacement responses obtained through quasi-testing of (a) single-hat, and (b) double-hat section components

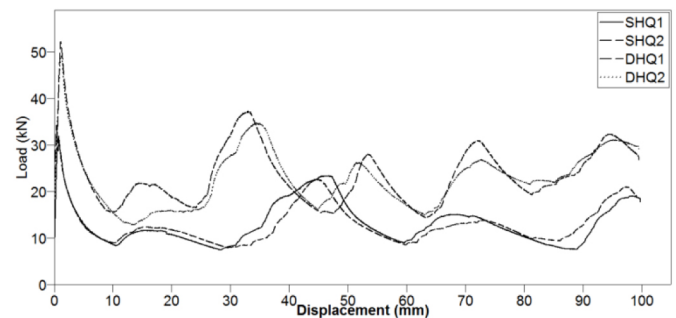


Fig. 4. Comparison of load-displacement responses of single-hat and double-hat section tests

Material Properties of Steel Sheet Metal in Hat Section Components

For determination of material properties of the mild steel used in the fabrication of the test components, coupon specimens conforming to the relevant ASTM standard for tensile testing were cut from the flat faces of the hat-shaped sheet metal of unused single-hat or double-hat components as shown in Fig. 5. These coupons were extracted using a wire-cutting EDM (Electric Discharge Machining) facility. In Fig. 6 is shown three coupon specimens on completion of tensile tests in the UTM mentioned earlier at a constant cross-head speed of 1 mm/min.



Fig. 5. Formed double-hat face from which a tensile test coupon specimen is extracted



Fig. 6. Tested dog bone shaped specimens

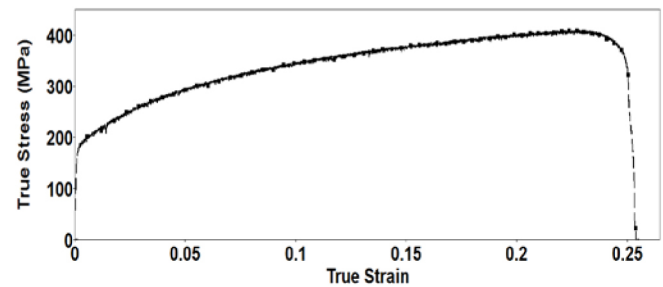


Fig. 7. Experimental true stress versus true strain curve obtained from uniaxial tensile testing of a coupon specimen

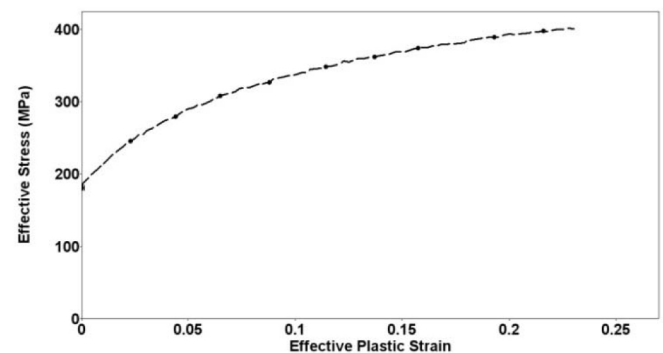


Fig. 8. Effective stress versus plastic strain curve used in finite element analysis

By performing quasi-static tensile tests as mentioned, true stress versus true strain curves were obtained. These were found to be repetitive for different samples of coupon specimens. A typical true stress-strain curve is shown in Fig. 7. For constitutive modeling in LS-DYNA, it is necessary to extract from the latter curve the true stress (which can be interpreted as effective or Von Mises stress) versus true plastic strain curve which is shown in Fig. 8.