

A Comparison of the Behaviors of Steel and GFRP Hat-Section Components under Axial Quasi-Static and Impact Loading

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ABSTRACT

Hat-sections, single and double, made of steel are frequently encountered in automotive body structural components. These components play a significant role in terms of impact energy absorption during vehicle crashes thereby protecting occupants of vehicles from severe injury. However, with the need for higher fuel economy and for compliance to stringent emission norms, auto manufacturers are looking for means to continually reduce vehicle body weight either by employing lighter materials like aluminum and fiber-reinforced plastics, or by using higher strength steel with reduced gages, or by combinations of these approaches. Unlike steel hat-sections which have been extensively reported in published literature, the axial crushing behavior of hat-sections made of fiber-reinforced composites may not have been adequately probed. In the current study, the performance of double hat-sections made of a glass fiber-reinforced plastic (GFRP) is compared with steel hat-sections of similar size under axial quasi-static and impact loading conditions. It has been found that during quasi-static testing, despite the occurrence of multiple brittle failure modes in GFRP-based hat-section components, the overall response displays an extremely healthy trend with progressive crush and a comparable mean load vis-à-vis its mild steel counterpart which undergoes well-known progressive dynamic buckling. The overall load-displacement response of GFRP components under quasi-static loading appears to suggest both failures associated with fiber-reinforced composites as well as geometry-driven instability of local buckling resulting in alternate crests and troughs in load-displacement curve following the initial peak load. When subjected to axial impact loading, the GFRP components gave rise to relatively flat but lower mean loads when compared with corresponding quasi-static response. However, the impact response of a given GFRP component has been found to be stable with respect to the entire range of displacement/shortening and although the load oscillates more rapidly as compared to the load response of a steel hat-section under similar impact condition, the deformed GFRP components appear to exhibit progressive fold formation due to local buckling which is the primary failure mode in steel components. Catastrophic failure modes were not encountered in the tested GFRP specimens which is reassuring in terms of seriously considering such lightweight fiber-reinforced composites for vehicle crash safety design.

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INTRODUCTION

Hat-sections, single and double, made of steel are frequently encountered in automotive body structural components such as rails, rockers, etc. an example of which is shown in [Figure 1](#). In the event of a crash, these are crucial energy-absorbers and protect the occupants from severe injury. However, with the need for higher fuel economy and lesser carbon footprint, auto manufacturers are looking for means to continually reduce vehicle body weight either by employing lighter materials like aluminum and fiber-reinforced plastics, or by using higher strength steel with reduced gages, or by combinations of these approaches. Unlike steel hat-sections which have been extensively reported in published literature, studies on

axial crushing behavior of hat-sections made of fiber-reinforced materials appear to be limited. As such 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, theoretical as well as semi-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 and Jones [2] and White, Jones and Abramowicz [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 sections 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. An approximate method to predict mean crushing strength of closed-hat-section members was presented in [8]. The approximate method was used to predict energy absorption capacity of closed hat-section members under quasi-static axial loading. Recently, Haorongbam, Deb and Chou [9] numerically predicted the behavior of steel hat-sections under different axial loading conditions. They also carried out a study on steel double hat-sections under eccentric impact load. However, investigations on fiber-reinforced composite hat-sections under axial loading appear to be rather scanty. A study relevant to the current work is by Yang et al. [11] who experimentally compared the behaviors of single hat-sections made of steel and carbon fiber-reinforced plastic under quasi-static axial loading. It would appear to the present authors that the behaviors of double hat-sections based on a glass fiber-reinforced plastic (GFRP) have not been reported yet. In the current work, a comparative study has been done on the performance of steel and GFRP-based double hat-sections of similar size under axial quasi-static and impact loading conditions. In addition to comparing load-displacement curves, comparisons are carried out on specific energy absorption attributes and collapse modes of the hat-sections made of vastly different materials. In the limited number of tests, quasi-static as well as impact dynamic, carried out on GFRP double hat-section components, catastrophic failures were not observed. This is reassuring from the viewpoint of adopting these lightweight components in real-world vehicle body design. Characteristic experimental responses obtained for steel hat-sections are verified

against theoretical predictions, and the load-displacement curves obtained from axial quasi-static and impact tests are used for correlating numerical predictions using LS-DYNA, which by itself is a daunting task.

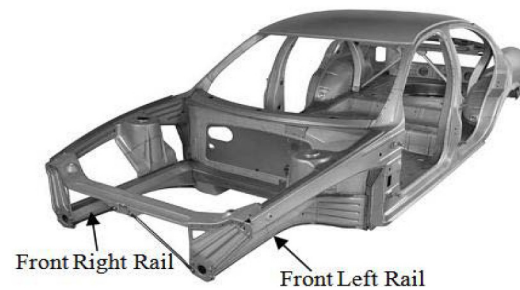


Figure 1. A typical body-in-white of a unitized body car [10]

PREPARATION OF GFRP COMPOSITE DOUBLE HAT-SECTIONS

E-glass fiber-based Woven Roving Mat (WRM) of weight 360 gsm (grams per square meter) shown in Figure 2 is used as reinforcement for fabricating GFRP double hat-sections using hand lay-up technique. General purpose polyester (GPP) resin along with required quantities of chalk powder, hardener, and accelerator are mixed together to formulate the matrix. Depending upon the required thickness, resin dipped glass fiber plies are laid on half dies in the shape of two hats of a double hat-section. Here, a total number of twelve plies i.e. six plies on each die are used to obtain a thickness of 2 mm. It is noted that the plies are arranged with the same orientation of orthogonal fibers along the axis of a hat-section and in the transverse direction. A mandrel with a through hole was placed between the two-half dies. The dies are then held together using C-clamps. Later, a steel rod is inserted through the hollow interior of the mandrel. The clamped dies are rotated at a low speed until the resin sets properly. This rotation is performed to ensure proper spreading of resin in the fibers due to centrifugal action.



Figure 2. A bidirectionally woven glass fiber mat



Figure 3. Untested double hat-sections made of (a) mild steel, and (b) GFRP

In Figures 3(a) and 3(b) are shown two untested steel and GFRP composite double hat-sections respectively. Schematic views of the cross-sections of this specimen are given in Figure 4. Numerical details of the sections are given in Table 1. Both mild steel and GFRP-based double hat-section components are 250 mm in length. However, in order that GFRP components behave in a stable manner, their wall thickness is made twice that of steel specimens. It is noted that the pitch of the spot-welds in the steel double hat-sections is 45 mm.

Table 1. Details of steel and GFRP double hat-sections

Test Specimen Type	a (mm), b (mm), f (mm), t (mm) in Figure 4
Mild Steel	60, 60, 25, 1
GFRP	63, 63, 27, 2

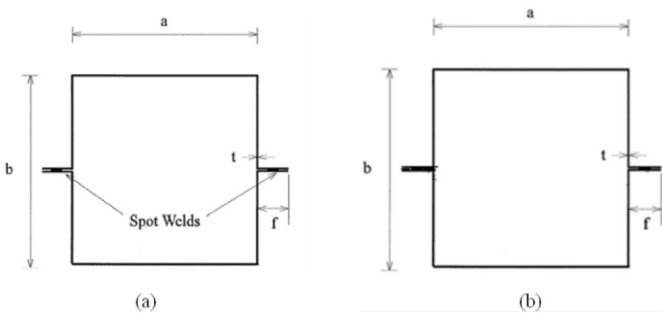


Figure 4. Schematic views of (a) mild steel, and (b) GFRP double hat-sections

MATERIAL PROPERTIES OF STEEL AND GFRP DOUBLE HAT-SECTION COMPONENTS

For determination of material properties of mild steel-based test components, coupon specimens conforming to the relevant ASTM standard for tensile testing were cut from the flat faces of unused components as shown in Figure 5. These coupons were extracted using a wire-cutting EDM (Electric Discharge Machining) facility. In Figure 6 are shown three coupon specimens on completion of tensile tests in a UTM at a constant cross-head speed of 1 mm/min.



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



Figure 6. Tested dog bone shaped specimens

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 Figure 7.

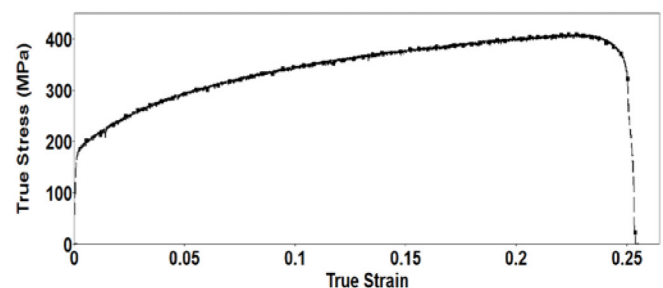


Figure 7. Experimental true stress versus true strain curve obtained from uniaxial tensile testing of a coupon specimen