

Efficient Approximate Methods for Predicting Behaviors of Steel Hat Sections Under Axial Impact Loading

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ABSTRACT

Hat sections made of steel are frequently encountered in automotive body structural components such as front rails. These components can absorb significant amount of impact energy during collisions thereby protecting occupants of vehicles from severe injury. 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 peak load, mean load, energy absorption, or total crush, or a combination of these parameters. Such a goal can be accomplished if efficient and reliable data-based models are available for predicting the performance of a section of given geometry as alternatives to time-consuming and detailed engineering analysis typically based on the explicit finite element method. In the present study, the effectiveness of data-based approaches based on polynomial hyper-space, radial basis function and a generalized regression neural network is studied for predicting peak and mean loads for steel hat sections subjected to axial impact. Additionally, the first two approaches are applied to the prediction of time history of axial impact load. The database used in the formulation of the stated models has been generated with the aid of a validated finite element modeling procedure for explicit analysis using a standard code.

INTRODUCTION

Hat sections made of steel are frequently encountered in automotive body structural components such as front rails of unibody cars. These components can 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 single and double 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 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. et Sato 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.

Stander et al. [8] compared the use of metamodeling techniques for multidisciplinary optimization in vehicle design. They considered polynomial response surface, artificial neural network (ANN) and Kriging methodologies for different case studies relating to (i) front impact and NVH performance, (ii) head impact and (iii) pedestrian impact. These authors [8] have also reported other studies in which some of the above data-based techniques have been applied to vehicle structural design. Lanzi, Bisagni and Ricci [9] used neural networks to predict the response histories of structural components made of aluminium alloys subject to impact loads.

The discussion above provides an overview of selected relevant work for the current area of interest i.e. prediction of the behavior of spot-welded steel hat sections under axial impact loading employing data mining approaches which can also be viewed as metamodeling techniques. Although such techniques have been widely applied to the optimization of full or sub-system level vehicle body structures, their usage for the prediction of key structural components of unibody vehicles appears to be missing. Thus, in the present study, the predictive abilities of interpolations based on polynomial hyper-space (PHS), radial basis function (RBF) and ANN are compared against simulation results obtained with LS-DYNA using a validated modeling procedure. To the authors' best knowledge, RBF has not been used in the past for the prediction of impact behavior of structural components. Additionally, it is shown for the first time that PHS and RBF are capable of predicting not just indicative performance parameters (such as peak and mean loads) but also the entire time history of impact load for a given case of axial impact of a steel hat section. It may be noted that the data mining approaches mentioned are empirical in nature; however, once formulated, fast estimates of impact performance can be made with these tools compared to detailed numerical simulations commonly carried out with nonlinear finite element modeling and analysis.

MODELING PROCEDURE FOR PREDICTION OF HAT-SECTION IMPACT PERFORMANCE

One of the most powerful tools currently available for realistic prediction of dynamic response histories in axial impact loading of thin walled tubes is explicit finite element analysis accounting for geometric and material nonlinearities including contact forces developed during impact. For the development of the data mining techniques discussed in the ensuing sections, recourse is taken to axial impact data generated within a given design space for a steel hat section using an explicit LS-DYNA solver. However, in order to have confidence on the envisaged data, it is imperative that the modeling procedure is validated by comparing analysis results against physical (i.e. experimental) trends.

As mentioned earlier, the problem of dynamic axial loading of top-hat sections had been considered by Sato et al. [7] experimentally and numerically. The latter authors had studied hat sections made of four different grades of steel identified by their tensile strengths. In order to arrive at a validated modeling procedure which can be used for building the necessary database for the current study, the experimental load-time response for a top-hat section component made of the 300 MPa steel grade considered in [7] is chosen. A line diagram indicating the sectional shape and geometric dimensions is given in Fig. 1. The specimen has a length of 200 mm and the thickness of the constituent plates in Fig. 1 is 1.6 mm. A finite element model representing the tested component is shown in Fig. 2. The material behavior of the component plates is modeled by material type 24 (*MAT_PIECEWISE_LINEAR_PLASTICITY) in LS-DYNA. The plastic behavior after yielding is described by a series of effective stress-effective plastic strain curves for different strain rates [7] shown in Fig. 3. Corotational Belytschko-Lin-Tsay shell elements are chosen for the finite element model in Fig. 2. Each spot-weld was modeled with a cluster of rigid elements joining nodes on overlapping plates in the flanges. The distance between the centers of two consecutive welds was maintained at 45 mm [7]. Analysis was carried out for meshes of different element sizes; a uniform element size of 2.5 mm appeared to yield the best correlation of computed response with the experimentally obtained result presented in [7]. This comparison of load-displacement responses is given in Fig. 4 where the initial peak as well as the subsequent lower peaks are seen to match closely. Interestingly, the computed response curve shown in Fig. 4 is for a model in which sharp corners in the section were assumed; this response led to a better correlation with test dynamic response as compared to the model in which corner radiuses were accounted for. The authors in [7] also found that ignoring corner radiuses in the finite element model of Fig. 2 led to a mean axial load that was closer to the test value vis-à-vis a geometrically more accurate

representation of the section profile. This unexpected behavior may have resulted from not accounting for the effects of forming on the spatial variation of material properties in the relevant top-hat section plate.

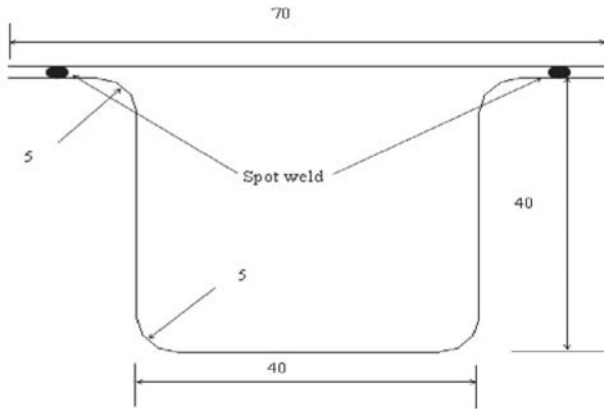


Fig. 1. Schematic view of top-hat section (all dimensions are in mm)

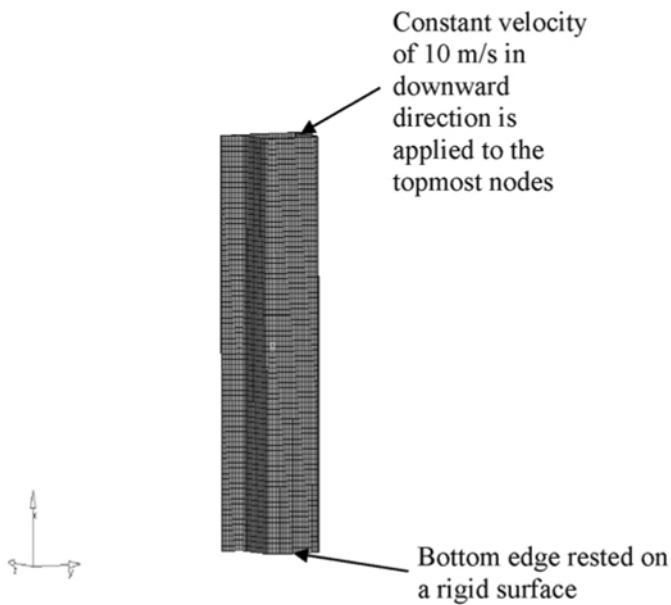


Fig. 2. Finite element model of the top-hat section component

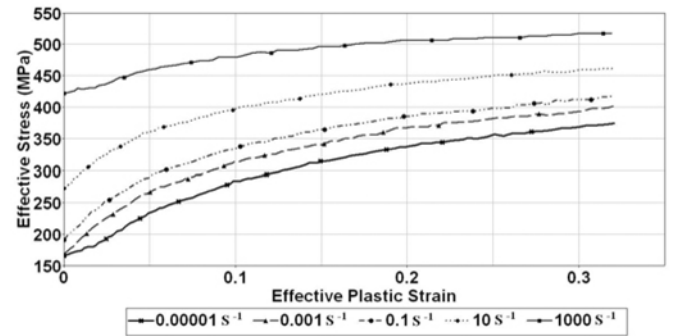


Fig. 3. True effective stress versus true effective plastic strain curves at indicated strain rates obtained from [7]

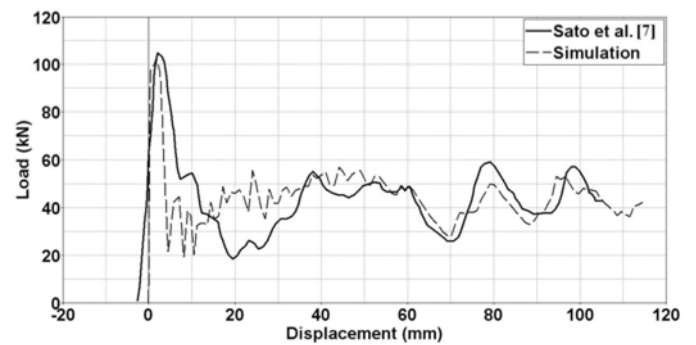


Fig. 4. Comparison of simulation and experimental load-displacement curves

It is noted that the interface option *CONTACT_AUTOMATIC_GENERAL in LS-DYNA has been activated in the present study. As per the test reported in [7], the analysis of axial crushing of the top-hat section specimen has been carried out for an axial shortening of 100 mm. It has often been found that there may be considerable variation in experimental load time histories of similar specimens subjected to same conditions of impact. Thus, it may be worthwhile to define a 'gross correlation index' (GCI) by including parameters (such as mean load and energy absorption) which are expected to be more consistent for similar specimens as given below:

$$GCI = 1 - \left[\frac{1}{3} \left\{ \frac{(P - P_{Test})^2}{P_{Test}^2} + \frac{(M - M_{Test})^2}{M_{Test}^2} + \frac{(E - E_{Test})^2}{E_{Test}^2} \right\} \right]^{\frac{1}{2}} \quad (1)$$

where,

P, P_{Test} = predicted and experimental values respectively of peak load;

M, M_{Test} = predicted and experimental values respectively of mean load; and

E, E_{Test} = predicted and experimental values respectively of energy absorption.