Chapter 18
Full-Scale Testing and Numerical Modeling of Adhesively Bonded Hot Stamped Ultra-High Strength Steel Hat Sections

Y. B. Liu, D. Cronin, and M. Worswick

Abstract The implementation of structural adhesives to join multi-material lightweight vehicle structures requires advanced computer aided engineering (CAE) and therefore thorough material characterization and model validation at the component level. Hot stamped, 1.2 and 1.8 mm thick ultra-high strength steel hat section channels were joined to form closed tubular structures using a two-part toughened epoxy adhesive applied to the flanges, with a bondline thickness of 0.007″ (0.178 mm). The joined tubes were tested under quasi-static loading in two configurations: three-point bending to load the adhesive in shear (Mode II) and axial crush resulting primarily in Mode I loading. Finite element models of the tests were developed using previously measured material properties for the adhesive implemented using cohesive zone elements. The three-point bending response included a linear loading regime followed by localized plastic deformation of the tube and finally abrupt failure of the adhesive joint between the hat sections at an average load of 34.0 kN for the 1.2 mm tubes and 78.8 kN for the 1.8 mm tubes. The axial crush response included an initial average peak force of 260 kN followed by a local folding or global deformation mode, leading to progressive separation of the adhesive joint and an average energy absorption of 8.45 kJ. Finite element models based on published adhesive and metal properties demonstrated good correlation with experimental results in predicted peak force and overall loading response.

Keywords Structural adhesive · Material characterization · Cohesive elements · Finite element modeling · Ultra-high strength steel

18.1 Introduction and Background

Automotive manufacturers face increasing challenges to improve the fuel efficiency of their fleets to reach a Corporate Average Fuel Economy (CAFE) Standard of 54.5 mpg by 2025 [1]. This need has led to the implementation of ultra-high strength materials and the consideration of multi-material lightweight vehicle (MMLV) structures where joining of dissimilar materials may be achieved with structural adhesives. For instance, through the use of advanced adhesive and multi-material designs, a new vehicle platform was able to shed 320 kg over the previous model and saw an increase of 28% in fuel efficiency [2]. In addition to weight reduction, adhesives also improve noise, vibration and hardness (NVH) and corrosion resistance due to the formation of a continuous and sealed joint [3, 4]. The growing popularity of adhesive bonding has also increased the need for material characterization to support CAE analysis. The mechanical properties that are needed to predict the adhesive behavior in the finite element (FE) environment can be obtained with tests such as the lap shear, rigid double cantilever beam, tapered double cantilever beam and bulk adhesive testing [5]. The focus of this study was to develop a method to reliably join hot-stamped hat sections into tubes with adhesive-only joints, test the tubes in three-point bending and axial crushing under quasi-static loading rates, and then finally to assess an adhesive model developed from bulk material and coupon-level test data.

18.2 Methodology

Ultra-high strength steel (Usibor® 1500-AS, ArcelorMittal) blanks (1.2 mm thickness) were austenitized at 930 °C for six minutes and then hot stamped into hat sections 590 mm in length. A fully martensitic microstructure was achieved through

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in-die quenching. To maximize the adhesive joint strength and achieve consistent cohesive failure, the Al-Si intermetallic coating on the formed hat sections was removed by grit blasting. Immediately following the coating removal, the hat section flanges were cleaned with Methyl Ethyl Ketone to remove surface contaminates. This combination of surface preparation technique was found to optimize bond quality and reduce variability, increasing single lap shear failure strength by 4.3 MPa (19.8%) while reducing standard deviation from 1.75 MPa to 0.28 MPa. Finally, the hat sections were joined with a two-part epoxy structural adhesive (#07333 Impact Resistant Structural Adhesive, 3 M Corporation) using a bond line thickness of 0.178 mm, maintained with brass shims. A custom fixture was used to secure the hat sections while oven-curing the adhesive (80 degrees Celsius for 30 minutes). It was found that proper fixturing was important to achieve a consistent bond line thickness and to reduce variability in the component-level response of the tubes. In addition, minimizing the time between application of the adhesive and joining of the components further improved the consistency of the experimental results.

Three-point bending was used to test the adhesive in a Mode II (shear) loading condition. The test setup comprised a hydraulic load frame and an indenter attached to the piston with an outer diameter of 100 mm. The supports were spaced 375 mm apart and had an outer diameter of 50 mm. The indenter and supports were lined with Teflon to reduce friction, allowing the tube to deform freely without binding to the metal surface. Although 1.2 mm thick hat sections were the focus of the study, three preliminary three-point bend tests used 1.8 mm gauge thickness to benchmark crush response.

Mixed-mode loading was evaluated by loading the tubes in the axial direction. The tube length was reduced to 490 mm to mitigate global buckling response during the test. A fold initiator was introduced 70 mm from the top of the tube, to initiate local buckling and folding in the material.

The experimental tests were simulated using a commercial explicit finite element code (LS-DYNA R7.1.2, Livermore Software Technology Corporation). Principles of Cohesive Zone Modelling (CZM) were applied, where cohesive elements with a defined traction-separation response were connected to the hat section shell elements accounting for the shell thickness. The fixtures were modeled as rigid materials with dimensions and masses corresponding to the experimental test setup. Current models did not use failure criteria since no failure was observed in three-point bend experiments and extensive failure in axial crush could result in instability.

18.3 Experimental Results

The three-point bend test force-displacement response (Fig. 18.1) of the 1.8 mm thick specimens showed good repeatability in peak force (78.8 kN, standard deviation 0.9 kN) and displacement to ultimate load (28.2 mm, standard deviation 1.2 mm), where the adhesive joint had failed. Tests of the 1.2 mm thick specimens showed consistent peak force (34.0 kN, standard deviation 1.6 kN) but had variation in displacement to failure. This was due to an asymmetric (out-of-plane) deformation occurring in the second and third tests (3P-2 and 3P-3) (Fig. 18.1), which delayed the failure of adhesive joint considerably, thus increasing total displacement to failure.

The axial crush tests (Fig. 18.2) demonstrated good repeatability in peak force (260 kN, standard deviation 6.9 kN); however, variations in deformation after the initial peak (folding or global buckling) led to differences in total energy absorbed. Folding behavior in the first test (AX-1) was associated with higher energy absorption (10.5 kJ) compared to global buckling in the second test (AX-2) (Fig. 18.2) and the third test (AX-3) (7.26 kJ and 7.56 kJ respectively).

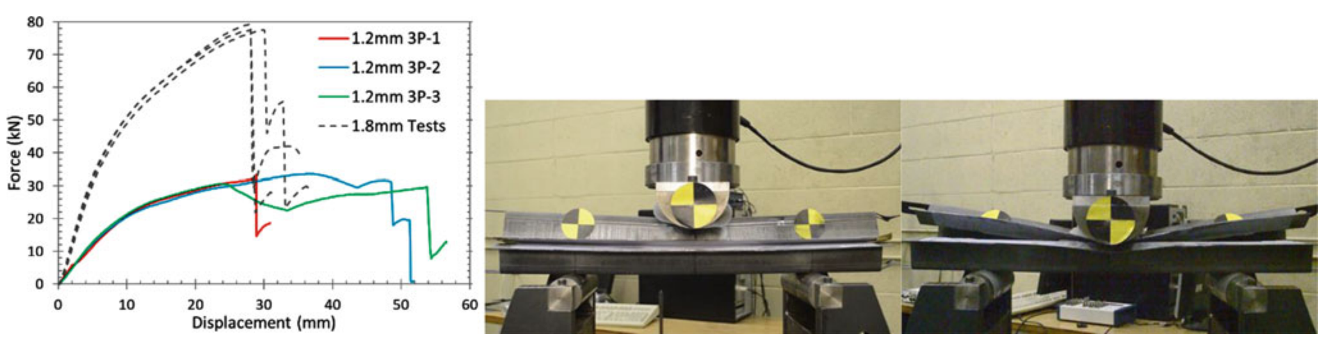

Fig. 18.1 Force displacement of three point bend tests (left), with examples of symmetric failure (center) and asymmetric failure (right)

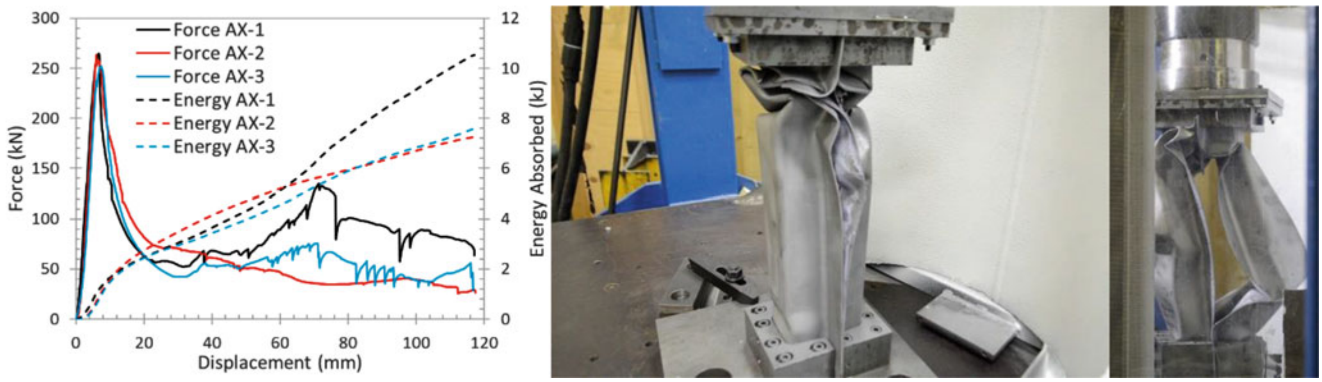

Fig. 18.2 Force displacement of axial crush tests (left), with examples of local folding mode (center) and global buckling mode (right)

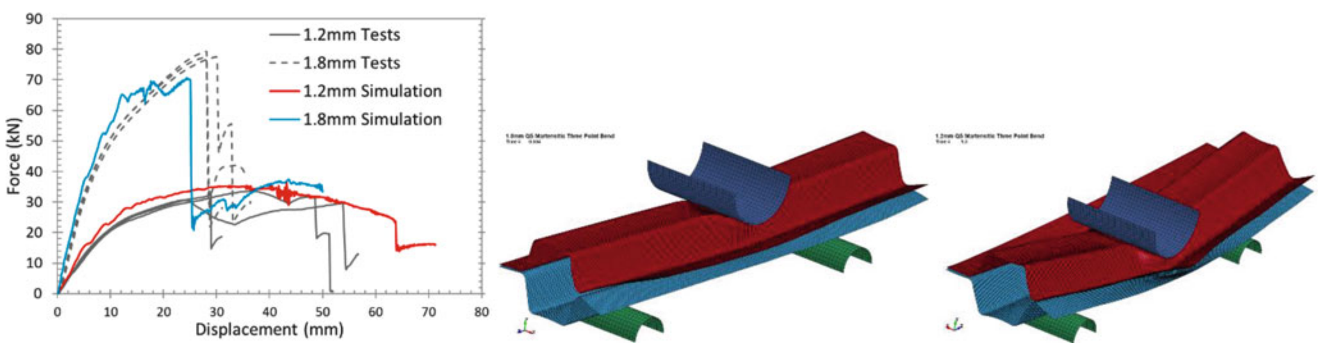

Fig. 18.3 Comparison of experimental and numerical force-displacement plots (left) and predicted separation of flange (1.8 mm center, 1.2 mm right)

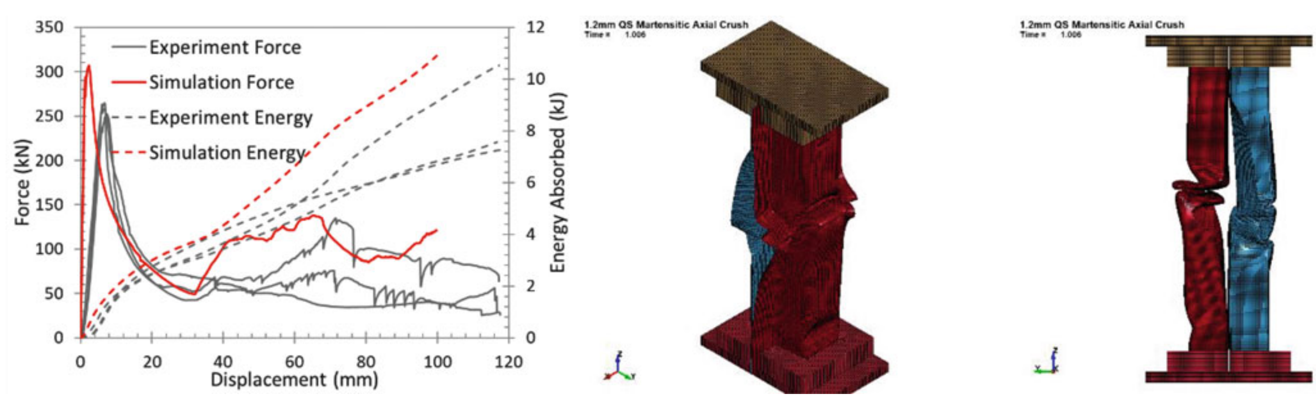

Fig. 18.4 Comparison of experimental and numerical force-displacement plots (left) and predicted global buckling deformation mode (center, right)

18.4 Numerical Results

Numerical models of three-point bending for both the 1.8 mm preliminary tests and the 1.2 mm primary tests showed good correspondence to the experimental data in loading response and peak force (Fig. 18.3). Being the thicker and thus more dimensionally stable structure, the 1.8 mm model was able to predict the onset and propagation of the adhesive failure, similar to that observed in the experiment. The 1.2 mm model predicted a response in agreement with the experiment up to the peak force, but did not predict abrupt failure of the joint until a much higher displacement value (64 mm compared to 29 mm).

The axial crush numerical model predicted a higher initial peak force (Fig. 18.4) and a stiffer response compared to the experimental data. This could be related to the need to include material thinning resulting from forming in the tube model.

Another cause could be boundary or contact conditions that did not accurately match that of the experiments. The model predicted a deformation mode (Fig. 18.4) similar to tests AX-2 and AX-3, where global buckling was prevalent over local folding.

18.5 Conclusions

Current results demonstrated that hot stamped ultra-high strength steel hat sections can be successfully joined with structural adhesives into tubes with repeatable quasi-static loading response under three-point bending and axial crush loading. The average peak loads in three-point bending loading were 34.0 kN (standard deviation 1.6 kN) for the 1.2 mm thick material and 78.8 kN (standard deviation 0.9 kN) for the 1.8 mm thick material. The peak load for axial crushing was 260 kN (standard deviation 6.9 kN) for the 1.2 mm thick material. The consistency achieved in the experiments provided reliable data for assessing the finite element model. The finite element models, including a cohesive zone adhesive model derived from coupon level and bulk material testing, demonstrated good correlation with the experiments in predicted peak force, loading response, and deformation mode.

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