Improving Stiffness-to-weight Ratio of Spot-welded Structures based upon Nonlinear Finite Element Modelling

Shengyong Zhang
Department of Mechanical and Civil Engineering, College of Engineering and Sciences, Purdue University Northwest, USA
syzhang@pnw.edu

Abstract. Spot welding has been widely used for vehicle body construction due to its advantages of high speed and adaptability for automation. An effort to increase the stiffness-to-weight ratio of spot-welded structures is investigated based upon nonlinear finite element analysis. Topology optimization is conducted for reducing weight in the overlapping regions by choosing an appropriate topology. Three spot-welded models (lap, doubt-hat and T-shape) that approximate “typical” vehicle body components are studied for validating and illustrating the proposed method. It is concluded that removing underutilized material from overlapping regions can result in a significant increase in structural stiffness-to-weight ratio.

1. Introduction
Most automobiles and light trucks have their body-in-white (BIW) structures comprised of stamped or bonded panels connected with combinations of mechanical fasteners, resistance welds and bonding. Due to its advantages of high speed and adaptability for automation, resistance spot welding is conventionally the dominant joining technology for assembled vehicle construction. A modern automobile may contain 3000 to 4000 spot welds in its sheet metal structure. Over the last few years low density material (e.g. aluminium and magnesium alloys) has been suggested to substitute carbon steels for fabricating vehicle BIW. Again, it is noted that assembly of aluminium sheets is still dominated by resistance spot welding [1]. The integration of spot welds determines the overall body assembly stiffness and has an influence on the associated noise, vibration and harshness (NVH) characteristics.

Much of the recent research in the automotive industry has been motivated by the need to improve fuel economy and dynamic performance. One way to achieve such an improvement is to reduce BIW weight. The BIW typically represents about 30 percent of the total weight of a vehicle and is therefore a prime target for weight reduction. Among the strategies employed for lightweight BIW design are (1) low-density material substitution (aluminium and magnesium alloys are the most common candidates)[2, 3]; (2) manufacturing process improvement (an array of new manufacturing techniques are being adopted by the automotive industry, such as hydro-forming, stamping of Tailor-welded blankets, etc.)[4, 5]; and (3) design architecture optimization (FE and sensitivity based optimization provides a promising way to reduce BIW weight, for example)[6-9]. The availability of advanced high-strength steel (AHSS) is emphasized as an emerging technology that would help reduce vehicle weight by allowing the use of reduced-gauge underbody parts. Reference [10] studies the microstructure and mechanical properties of spot weldments in various grades of AHSS and proposes a formula for measuring the effect of carbon and alloying elements on weld fusion zone hardness.
This study focuses on improving the effectiveness of material in the overlap regions of spot-welded structures (e.g. automotive BIW). Nonlinear FEA and topology optimization are employed to locate and remove underutilized material for maximizing the structural stiffness-to-weight ratio. Three spot-welded models with sections found commonly in vehicle body structures are examined as validation case studies to evaluate the proposed weight-reducing design.

2. Nonlinear FE model and topology optimization

2.1 Nonlinear FE model of a welded specimen

Figure 1 shows the configurations and dimensions of the considered specimen. The specimen is composed of two sheets assembled using resistance spot welding. The sheets are made of A366 steel (Young’s modulus $E=190$ GPa, Poisson’s ratio $\nu=0.25$). Each sheet is 120 mm long, 15 mm wide and 1 mm thick. The spot weld is at the centre of the overlap zone and has a diameter of 6 mm. Elastic material properties of the spot nugget are set to be $E=200$ GPa and $\nu=0.2$. A gap of 0.02 mm between the two sheets is assumed in the overlap zone. Finite element model of the specimen is shown in Figure 2. Three-dimensional body elements are used in the discretization. The spot nugget in the specimen is meshed with layers of hexahedral elements by using volume sweeping, a technique with which one can fill an existing unmeshed volume with elements by sweeping the mesh from a source area to a target area throughout the volume. One end of the specimen is subjected to uniform loading, while the other end is clamped. Due to the symmetry in the structural geometry, external loading and boundary conditions about the specimen’s longitudinal axis, only half of the specimen is modelled. Symmetric boundary conditions are applied to the plane of symmetry for restricting out-of-plane displacements and in-plane rotations.

Linear FE analysis is conducted to investigate the specimen responses to the above prescribed loadings and constraints. It is found that contact and interference have occurred between the two sheets in the overlap zone. Ignoring the effects of contact and interference in the FE modelling will lead to incorrect predictions of the specimen compliance and other structural parameters. Contact problem has nonlinear behaviour involved and is regarded as a boundary nonlinear process. Because of the inherent complexities, it is difficult to develop analytical models to assess the contacting process. Most researches on this nonlinear behaviour focus on FE-based numerical approaches. In FE models various contact elements are utilized to simulate the contacting surfaces. Elements TARGE170 and CONTA173, for example, are a contact pair developed in ANSYS: element CONT173 describes the boundary of a deformable body and are potentially in contact with target surface defined by TARGE170. In this study 3-D surface-to-surface contact pairs are applied to the contact zone between the two sheets. Both the contact elements and target surfaces are defined as flexible bodies in the FE model. Figure 3 shows the deformed specimen in which surface contact is avoided due to the application of the contact pairs.

Geometric nonlinearity is another consideration in the modelling of this specimen for more accurate predictions. Geometric nonlinearity primarily refers to stiffness changes related to geometry constraints or the magnitude of strains. Unlike material nonlinearity, geometric stiffening has no hard transition marker. However, large displacement is an indicative of the transition from linear to
nonlinear behaviour. In this study, the onset of geometric nonlinearity is assumed when displacement exceeds one-third of the sheet thickness, see Figure 3.

2.2 Material removal for improving stiffness-to-weight ratio

From material saving perspective, spot welded structures should be designed to have as less material as possible in the overlap zone. Stiffness-to-weight ratio is a measure of the effects of weight reduction efforts on the assembly stiffness of spot welded structures. Assembly stiffness is defined to be the quotient of an applied force and corresponding deformation of the structure at the same location. The weight used in calculating the stiffness-to-weight ratio refers to the mass of material contained in the overlap zone in this study. One objective of this research focuses on maximizing the assembly stiffness under specified amount of weight reduction in the overlap zone. Nonlinear FE analysis is conducted. Figure 4 shows the resulting von Mises stress distribution in the overlap zone when the lap-welded specimen is subjected to the above prescribed external loading and boundary constraints. The nonuniformities of the stress distributions are a result of the inherently non-uniform internal load distributions required for static equilibrium constraints, providing guidance for evaluating the effectiveness of material in a loaded structure. Low stressed material is deemed to be underutilized. Removing or eliminating regions that contain relatively low levels of stress in the structure results in a near uniform stress distribution by reducing the stress variation. Fully stressed design, for example, is one optimum design methodology based on this criterion to distribute a limited amount of material in the design domain. Figure 5 shows the path plots of von Mises stresses calculated on the symmetry plane across the overlap zone. The two peaks on the plots correspond to the maximum stresses at either side of the nugget along the path. The stress concentrations shown in Figure 5 suggest that failures of spot welded structures most likely occur at the interception of the nugget boundary with the interface of the welded sheets.

Figure 4. Nonuniform von Mises stress distribution in the overlap zone.

Figure 5. Path plot of von Mises stress across the overlap zone.

2.3 Topology optimization

Topology optimization is a form of shape optimization. The goal of topology optimization is to find the best use of material for a body such that an objective criterion (structural stiffness in this study) takes on a maximum value subject to given constraints (weight reduction in this study). Existing topology optimization routines work by removing materials based upon strain energy density or von Mises stress distributions in the design domain. In this study stiffness-based optimization is performed in order to reduce the specimen’s weight and increase material effectiveness. Reducing weight is achieved by removing material from the sheets in the overlap zone. However, such material removal will result in a decrease in the structural stiffness. Optimization analysis aims to minimize the adversely influence of this effort. The objective function in this study is defined to be the specimen’s compliance, because minimizing structural compliance is equivalent to maximizing the structural stiffness. The overlap zone of the welded sheets is to be optimized for improving material effectiveness. A 20% reduction of the volume in the optimized region is specified as the constraint, which means that 20% of the material in the overlap zone is to be removed in a manner that maximizes the stiffness with the given load configuration. Figure 6 plots the material density of each finite element in the design domain, ranging from 0 to 1. Material density distributions provide an approach for determining material configuration in the most
effective way: if the density of an element is lower than user-specified threshold, the element is identified to be less stressed and can be eliminated from the design domain with negligible influence on the objective function. Figure 7 shows the optimum result with rough surfaces. Less stressed elements are invisible. The rough surfaces can be smoothed using appropriate algorithm based on geometries and results for better visualization. Optimum results provide the designer an insight from which regions the material can be removed for improving structural stiffness-to-weight ratio.

**Figure 6.** Distribution of density functions.  
**Figure 7.** Elimination of less stressed material

3. Case studies

Three spot-welded models (lap, double-hat and T-shaped) are studied for validating the above-mentioned optimum design. The optimum process is illustrated by taking a lap model as an example. The baseline lap model is composed of two flat sheets assembled using multiple resistance spot welds with a pitch of 30 mm. Each sheet is 60 mm in length, 90 mm in width and 1 mm in thickness. Both contact nonlinearity and geometric nonlinearity are involved in the FE modeling. Topology optimization is performed when the lap model is subjected to a tensile load shown in Figure 8(a). The volume of material in the overlap zone is to be optimized for maximizing the model’s stiffness-to-weight ratio. Figures 8(b) and 8(c) show the optimization results and demonstrate the regions where the material is not efficiently utilized. Modified lap model shown in Figure 8(d) is formed by removing material from these regions. Figures 8(e) and 8(f) plot the respective deformations of the baseline and modified lap models subject to a given set of forces and boundary constraints. The applied forces and corresponding deformations permit calculations of the assembly stiffness, which in turn are used to calculate the stiffness-to-weight ratio. Comparison results are reported in Table 1. The above optimization is based upon structural stiffness. The considered lap model can also be optimized for minimizing maximum stress. The overlapping width (W) and spot weld spacing (S) are defined as two design variables in this study. W is assumed to range from 15 to 30 mm and S from 20 to 40 mm. Optimization of these design variables is performed for maximum von Mises stress minimization. Similar analysis is conducted for the double-hat model and T-shaped model separately. Results are shown and compared in Figures 9 and 10 and in Table 1. It is found that the assembly stiffness-to-weight ratio of each modified model has been improved significantly compared to that of the corresponding baseline model.

4. Conclusions

Most BIW structures are comprised of panels assembled by resistance spot welding. Reducing BIW weight has been an effective way for improving fuel economy and dynamic performance. Design architecture optimization has been employed to achieve such a weight reduction because it can provide internal force management that yields an optimized structure with equivalent stiffness at low BIW weight.

A FEA-based method is investigated to reduce the weight of spot-welded structures without a significant decrease in structural stiffness. Contact and geometric nonlinearities involved in the structure responses are simulated in the FE models for more accurate numerical predictions. Topology optimization is conducted to identify less stressed material in the overlapping regions. The identified material has low effectiveness and can be eliminated without significant influence on the structural stiffness. Finally, three types of spot-welded models with sections found commonly in vehicle body structures are analyzed and optimized to validate the proposed method for designing architecture with optimum structural stiffness-to-weight ratios.

| Table 1. Increases in the stiffness-to-weight ratio of the modified models |
|--------------------------|------------------|------------------|
|                         | Lap              | Doubt-hat        | T-shape          |
| Stiffness-to-weight ratio| 1.24             | 1.25             | 1.22             |
Figure 8. FE analysis and optimization of lap model. (a) baseline lap model; (b) distribution of variable density; (c) optimum results after removal of underutilized material; (d) modified lap model; (e) deformation of the baseline lap model; and (f) deformation of the modified lap model.

Figure 9. FE analysis and optimization of double-hat model. Baseline one and modified one.

Figure 10. FE analysis and optimization of T-shaped model. Baseline one and modified one.

Reference
[1] Gould, J.E. 2012 Joining Aluminum Sheet in the Automotive Industry—A 30 Year History Welding Journal, 91, 23s–34s.
[2] Chung, Y-D., Kang, H., and Cho, W-S. 2000 The Development of Lightweight Vehicle using Aluminum Space Frame Body. Proceedings of the FISITA World Automotive Congress Seoul, Korea, 12-15 Jane 2000, paper number F2000G361.
[3] Hirsch, J. 2011 Aluminum in Innovative Light-Weight Car Design Materials Transactions 52, pp 818–824.
[4] Kreis, O. and Hein, P. 2001 Manufacturing System for the Integrated Hydroforming, Trimming and Welding of Sheet Metal Pairs Journal of Materials Processing Technology, 115, pp 49-54.
[5] Kükü, U. 2013 Investigation into the Formability of Al-1050 Tailor-Welded Blanks with Antilock Braking System International Journal of Advanced Manufacturing Technology. 66, pp 221–229.
[6] Patton, R., Brehob, E., State, M., Furman, V., Geck, P. and Cummins, M. 2000 Advanced Material Technologies for 21st Century Trucks SAE paper no. 2000-01-3124.
[7] Baskin, D., Reed, D., Seel, M., Takacs, Z. and Vollmer, A.B.2008 A Case Study in Structural Optimization of an Automotive Body-in-White Design SAE Technical Paper 2008-01-0880.
[8] Christensen, J., Bastien, C., Blundel, M.V., etc. 2012 Generation of Optimized Hybrid Electric Vehicle Body in White Architecture from a Styling Envelope. Global Journal of Researchs in Engineering Automotive Engineering, 12(1), Version 1.0, pp 1–7.
[9] Li, Z. and Mei, J. 2012 A Lightweight Optimization Method of Vehicle Body Structure Design Proc. of FISITA 2012 World Automotive Congress, paper number F2012-E09-026, pp 1063–1074.
[10] Khan, M.I., Kuntz, M.L. etc. 2008 Microstructure and Mechanical Properties of Resistance Spot Welded Advanced High Strength Steels Materials Transactions. 49(7), pp 1629–1637.