Modelling of deformation and failure of crash toughened adhesive bonded lap shear joints

L. Lu[1], H. Y. Zhao*[1], Z. P. Cai[1], P. C. Wang[2] and John Fickes[3]

With an increase in the use of advanced high strength steels in vehicle architectures, materials joining issues have become increasingly important. Among the various joining methods, adhesive bonding is increasingly used in automobile manufacturing. Successful implementation of adhesive bonding to improve structural crashworthiness and reduce vehicle weight requires the knowledge of issues related not only to processing but also to joint performance. In this study, a new anisotropic yield criterion which is determined from tensile and shear tests, is developed and incorporated into a finite element model to predict the static load displacement curves of various adhesive bonded steel joints. In the developed model, when the calculated plastic strain of bonded steel joint reaches the equivalent plastic strain of the adhesive the joint is regarded as failed. Modelling results have been validated by the experimental data. Since the model covers different steel grades, gages, and overlap distances, the model can be used to predict the static strengths of adhesive bonded assemblies. Finally, the model is employed to evaluate the effect dissimilar steel grades and sheet gages on the joint strength of lap shear bonded steel joints. The results show that for the joints made of dissimilar steel grade and sheet gage, the stiffness (i.e. strength and thickness) of the two adherends should be balanced to obtain the optimum joint strength.

Keywords: Yield model, Adhesive-bonded, Lap-shear, FEA

Introduction

With an increase in the use of advanced high strength steels in vehicle architectures, materials joining issues have become increasingly important. Among the various joining methods, adhesive bonding is increasingly used in automobile manufacturing.[1] Successful implementation of adhesive bonding to improve structural crashworthiness and reduce vehicle weight requires the knowledge of issues related not only to processing but also joint performance.

Recently, there has been a considerable amount of work directed toward understanding the factors controlling the mechanical performance of adhesive bonded sheet steels. The studies basically can be divided into two categories: experimental testing,[2–5] and predictive approach.[6–8] Owing to the difficulties in conducting lengthy and costly testing, a predictive modelling is often desired. So far, although a number of models have been developed to predict the joint strength of adhesive bonded steel none of them have shown effectively for joints using toughened epoxy adhesive.

[1]Department of Mechanical Engineering, Tsinghua University, Beijing, 100084, China; Key Laborotory for Advanced Materials Processing Technology, Ministry of Education, China
[2]R & D Center, General Motors Corporation, Warren, MI 48090, USA
[3]Body Center, General Motors Corporation, Warren, MI 48090, USA

*Corresponding author, email hyzhao@tsinghua.edu.cn

In this study, a predictive modelling methodology has been demonstrated for adhesive lap joints. The lap shear joint shown in Fig. 1 is commonly found in automotive construction. It is subjected to a lap shear loading. An anisotropic yield criterion is developed and incorporated into a finite element model to predict the load displacement curve of adhesive bonded steel joints. Results from these tests are compared with experimental results to assess the predictive accuracies of the models and to explore the validity of criteria for the onset failure in the adhesive. Finally, the model is employed to assess the effect of dissimilar materials and sheet gage on the static strength of bonded steel joints.

Computational model

Material model

Low carbon steel (GMW2), high strength low alloy steel (HSLA340), DP600 and DP780 were used in this study as substrate. Chemical composition and mechanical properties of the steels are shown in Table 1 and Fig. 2 respectively.

The adhesive used in this study was a toughened epoxy. Figure 3 shows the static stress–strain properties of epoxy adhesive.

Yield criterion of adhesive

It is shown in Fig. 3, tests under tension and compression on bulk adhesive show that yielding in toughened

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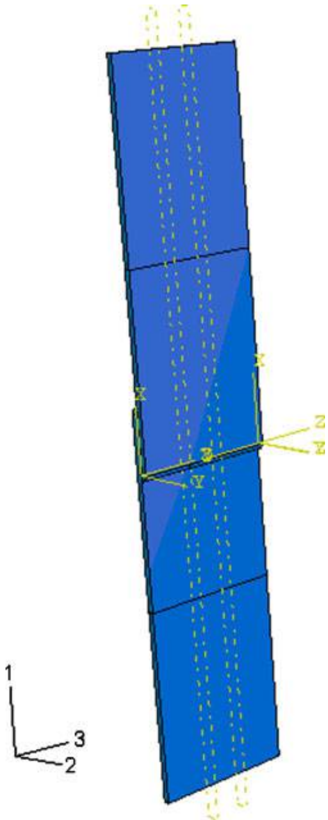
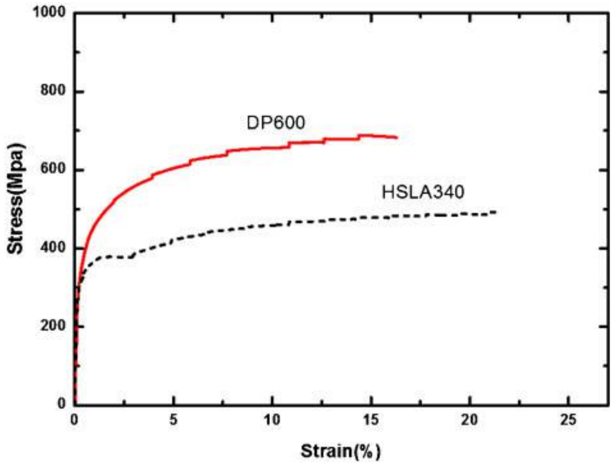
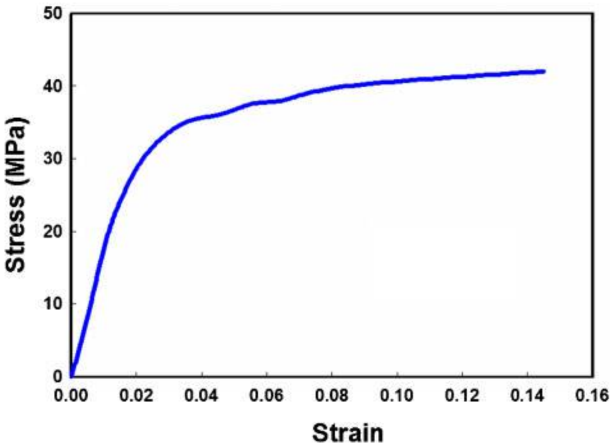


1 Lap shear adhesive bonded joints



2 Stress–strain properties of HSLA340 and DP600 steels



3 Stress–strain properties of epoxy adhesive

epoxy is quite different. This implies that the von Mises yield criterion is unsatisfactory for toughened adhesive and a new criterion is needed. Thus, an expansion of von Mises criterion is used here in this study. By referring to Hill's secondary yield criterion, which is an expansion of the von Mises criterion, the anisotropic yield criterion is shown

$$\begin{bmatrix} F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+ \\ H(\sigma_{11}-\sigma_{22})^2+2L\sigma_{23}^2+2M\sigma_{31}^2+2N\sigma_{12}^2 \end{bmatrix}^{1/2} \leqslant \sigma_0 \quad (1)$$

where F, G, H, L, M and N are expressed as below respectively

$$F=\frac{(\sigma^0)^2}{2}\left(\frac{1}{\overline{\sigma}_{22}^2}+\frac{1}{\overline{\sigma}_{33}^2}-\frac{1}{\overline{\sigma}_{11}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{22}^2}+\frac{1}{R_{33}^2}-\frac{1}{R_{11}^2}\right)$$

$$G=\frac{(\sigma^0)^2}{2}\left(\frac{1}{\overline{\sigma}_{22}^2}+\frac{1}{\overline{\sigma}_{33}^2}-\frac{1}{\overline{\sigma}_{11}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{22}^2}+\frac{1}{R_{33}^2}-\frac{1}{R_{11}^2}\right)$$

$$H=\frac{(\sigma^0)^2}{2}\left(\frac{1}{\overline{\sigma}_{11}^2}+\frac{1}{\overline{\sigma}_{22}^2}-\frac{1}{\overline{\sigma}_{33}^2}\right)=\frac{1}{2}\left(\frac{1}{R_{11}^2}+\frac{1}{R_{22}^2}-\frac{1}{R_{33}^2}\right)$$

$$L=\frac{3}{2}\left(\frac{\tau^0}{\overline{\sigma}_{23}}\right)^2=\frac{3}{2R_{23}^2}$$

$$M=\frac{3}{2}\left(\frac{\tau^0}{\overline{\sigma}_{13}}\right)^2=\frac{3}{2R_{13}^2}$$

$$N=\frac{3}{2}\left(\frac{\tau^0}{\overline{\sigma}_{12}}\right)^2=\frac{3}{2R_{12}^2}$$

where $\overline{\sigma}_{\mathrm{ii}}$ is the measured yield stress of ii direction when the material is under a single axis tensile stress, σ^0 is the defined corresponding yield stress, and $\tau^0=\sigma^0/3^{1/2}$. R_{ij} is the yield stress ratios, which are defined as below

$$R_{11}=\frac{\overline{\sigma}_{11}}{\sigma^0},\ R_{22}=\frac{\overline{\sigma}_{22}}{\sigma^0},\ R_{33}=\frac{\overline{\sigma}_{33}}{\sigma^0},$$

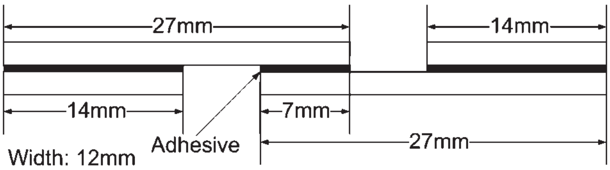
$$R_{12}=\frac{\overline{\sigma}_{12}}{\tau^0},\ R_{23}=\frac{\overline{\sigma}_{23}}{\tau^0},\ R_{13}=\frac{\overline{\sigma}_{13}}{\tau^0}$$

And previous study shows that adhesive is not a typical anisotropic material, the relationships for R_{ij} should be as below

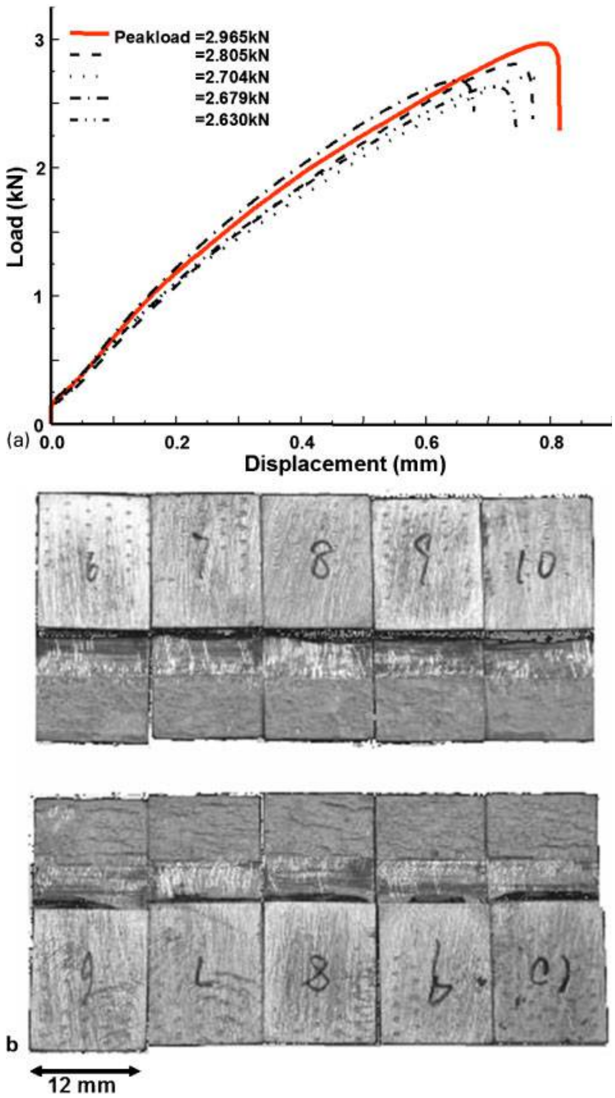
$$R_{11}=R_{22}=R_{33}=R,\ R_{12}=R_{23}=R_{13}=r$$

Table 1 Chemistry (wt-%), coating and sheet gage for low carbon and high strength steels

Steel	C	Mn	P	Si	Ni	S	Al	Cr	Ca	Ti	Gage, mm
HSLA340 (HDG60)	0·15	1·2	–	–	0·2	0·035	–	0·15	–	0·3	1·40 2·25 3·50
DP600 (HDG60)	0·08	1·14	–	0·97	–	0·003	0·03	0·1	0·0014	–	0·75 0·50 2·25



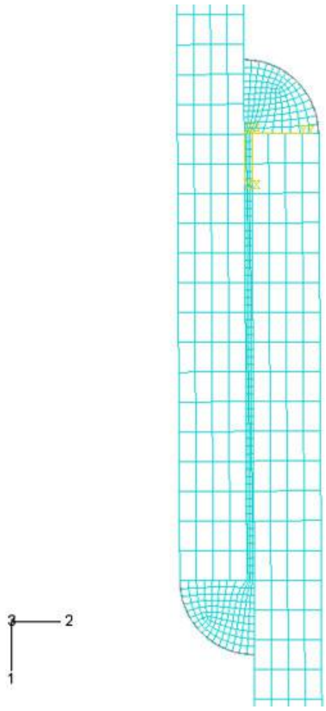
4 Joints used for determining shear strength of adhesive



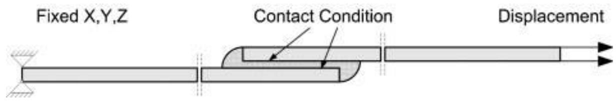
5 *a* load displacement for lap shear testing of adhesive bonded joint and *b* broken adhesive bonded joints

By substituting these relationships into equation (1), the yield criterion for adhesive can be obtained as

$$\left[\frac{1}{2R^2}\left[\begin{array}{l}(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+\\(\sigma_{11}-\sigma_{22})^2\end{array}\right]+\frac{3}{r^2}\left(\sigma_{23}^2+\sigma_{31}^2+\sigma_{12}^2\right)\right]^{1/2}\leqslant\sigma_0 \qquad (2)$$



6 Plane strain model (partial)



7 Boundary conditions for finite element modelling

where R and r are yield stress ratio for normal tensile and shear respectively and σ^0 is the defined corresponding yield stress. The values for R, r and σ^0 can be determined from experimental result.

To determine the shear strength of the adhesive, the specimen configuration shown in Fig. 4 is designed and fabricated using 1·7 mm thick DP780 steel. Quasi-static tests were performed and test results are shown in Fig. 5. From the results in Fig. 5, the values for R, r and σ^0 can be determined and shown in Table 2.

Failure criterion

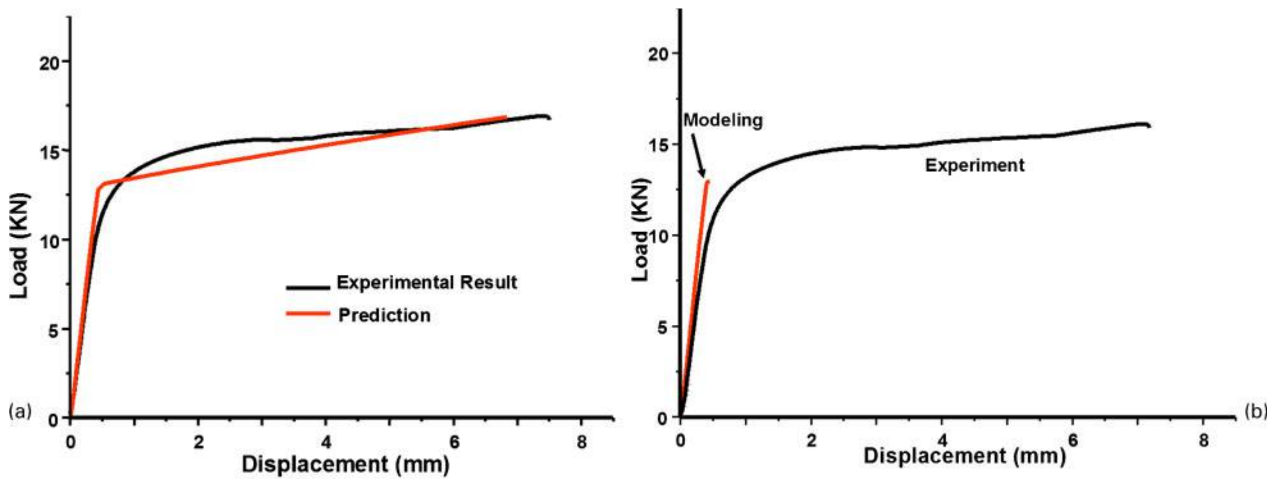
By comparing the crack initiation site in the experiments and finite element calculations, it was found that the site having the maximum equivalent plastic strain in the calculation is where the crack initiates in the experiments. Thus, equivalent plastic strain (PEEQ) is used as the failure criterion for toughened epoxy adhesive. From the stress–strain curve of toughened adhesive, as shown in Fig. 3, the maximum equivalent plastic strain (PEEQ) of the adhesive can be found to be the fracture strain of the adhesive.

Model geometry and boundary conditions

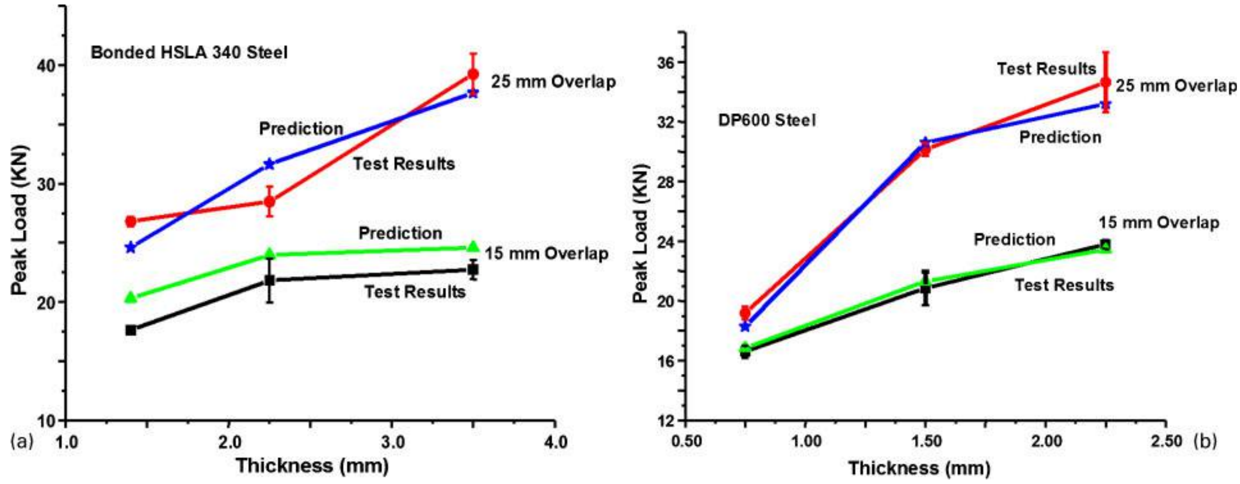
In applying the finite element method to the stress analysis of adhesive bonded lap shear joint, the whole

Table 2 Material parameters for adhesive

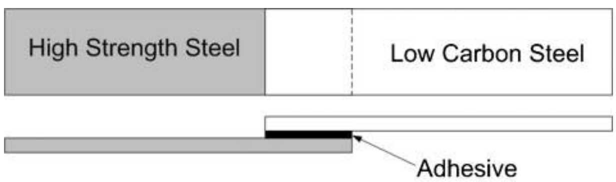
Young's module	Poisson's ratio	Corresponding yield stress σ^0	Ultimate tensile stress	Maximum plastic strain	R_{11}, R_{22}, R_{33} (R)	R_{12}, R_{23}, R_{13} (r)
1500 MPa	0·4	35 MPa	35 MPa	12%	1	1·7



8 Comparison of model calculations and experimental results use *a* proposed model and *b* von Mises yield criterion



9 Comparison of calculated peak loads and experimental results for bonded *a* HSLA340 and *b* DP600



10 Schematic of adhesive bonding of low carbon and high strength steels (DP600)

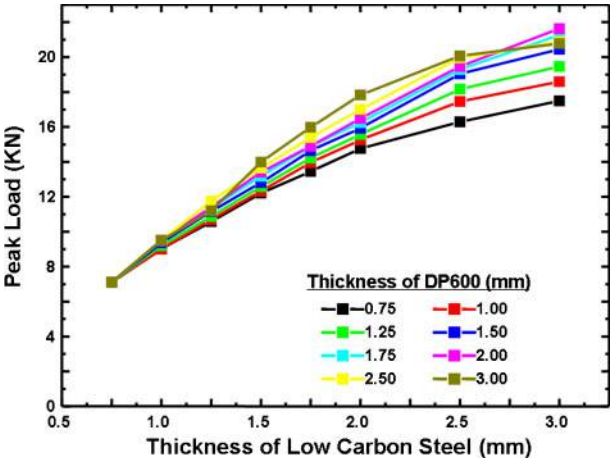
geometry is represented by a two-dimensional model shown in Fig. 6. Since the joints can be seen as symmetric along the width direction, a two-dimensional plane strain model is employed. As more attention should be paid to adhesive layer, the adhesive layer is meshed into a fine gird of 0·1 mm, while the grid size for coupon is ~0·25 mm. The coupons and adhesive layer are combined together by using a tie constrain, which can be defined in ABAQUS codes.[9] In the finite element model, adhesive squeeze-out is also considered.

Figure 7 shows the boundary conditions for the joint with 15 mm overlap as shown in Fig. 1. As in the experiments, the joints are fixed at one end, and a displacement is added to the other end. The model has 1702 elements (i.e. plane strain CPE4R) and 2029 nodes. The detail of this element is described in Ref. 9. The analysis is carried out by ABAQUS.[9] Tensile loads are applied at both ends of the specimen. The material properties of DP600 steel shown in Fig. 2 are used for analysis. Elastic–plastic calculations were performed. The calculations were performed on a PC computer with P4 3·0 GHZ CPU. The computing times were 179 s.

Comparison of modelling and experimental results

As mentioned in the introduction section, mechanical testing of adhesive bonded steel joints is a lengthy and costly process. Here the authors use the aforementioned yield and failure criteria and finite element method to predict the static strength of bonded steel joints.

Figure 8*a* compares the load displacement curve obtained from a bonded 0·75 mm thick DP steel joint under a tension with the curve predicted by finite element analysis using the new yield and failure criteria. As shown, the calculated results are consistent with the experimental measurements. It can be noted that there are wide differences between measured and predict results, as shown in Fig. 8*b*, using the von Mises yield criterion.



11 Predicted effect of dissimilar sheet gage on static strength of bonded steels

A variety of quasi-static testing and load displacement for each set of test have been recorded. For the purpose of conducting detailed comparison, two examples are selected from these results, namely HSLA 340 steel and DP600 steels. For each steel grade, three sheet gages and two overlap distances are studied. These results are compared with the calculated static strengths using the aforementioned model:

(i) HSLA 340 steel: Fig. 9*a* shows the comparison of predicted static strength with the measurements. As shown, the model predicts the strength for 25 mm overlap but overestimates the static strengths for 15 mm overlap

(ii) DP600 steel: Fig. 9*b* compares the peak loads obtained from bonded DP600 steel joints with the results predicted by the aforementioned model.

Application of model: dissimilar steel grade and sheet gage

With an increase in the use of various high strength steels in vehicle architectures, joining of dissimilar steel grades and gages has become common. Successful implementation of adhesive bonding to improve structural performance and reduce vehicle weight requires the knowledge of issues related not only to processing but also to joint performance.[10]

To see the effect of dissimilar steel gages and grade, as shown in Fig. 10, on joint strength, DP600 and low carbon (SAE1008) steels with various sheet gages were modelled and predicted results are shown in Fig. 11. As shown in Fig. 11, for a given sheet thickness of DP600 steel, the joint strength increases with increasing sheet gage of SAE1008 steel. Similarly, an increase in the gage of DP600 resulted in an increase in joint strength for a given sheet gage of GMW2. However, the increase is more pronounced for the former case. These results suggest that for a given adhesive, the weaker adherend determines the joint strength. To optimise the joint strength, it is necessary to balance the strength and gage of the adherend to obtain the optimum joint strength.

The present investigation clearly demonstrated the usefulness of the computation model, which can provide the designers with a tool for estimating the effects of steel grades, and various geometrical (e.g. steel gage) on the static strengths of adhesive bonded steel joints. However, the results and model presented here are only for joints under a lap shear loading configuration, whereas the adhesive bonded vehicle components are designed with various loading conditions. Since the analyses agree with experimental results, the authors believe that the same approach can be used for coach peel and other joint configurations.

Conclusions

1. A model has been developed to predict the static strength of adhesive bonded lap shear steel joints. Quantitative agreement between the measured and calculated static strengths has been demonstrated for HSLA340 and DP600 steels with various sheet gages.
2. An anisotropic yield criterion for toughened epoxy adhesive has been proposed. The use of this yield criterion along with the plastic equivalent strain of the bulk adhesive as the failure criterion, the peak load of adhesive bonded lap shear steel joints can be predicted.
3. Based on the above model, the effects of various geometric variables on the static strengths of adhesive bonded lap shear steel joints are predicted. For the joints made of dissimilar steel grade and sheet gage, the stiffness (i.e. strength and thickness) of the two adherends should be balanced to obtain the optimum joint strength.

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