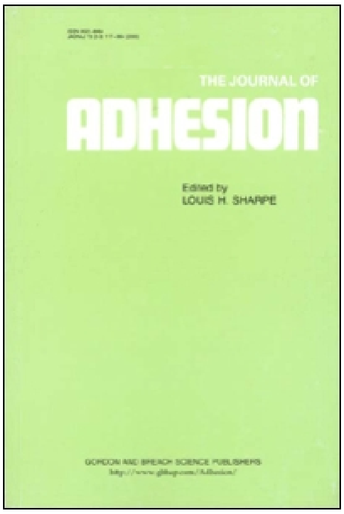


The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

Stress Analysis of Adhesively Bonded Electroprimed Steel Lap Shear Joints

David W. Schmueser[a]; Nancy L. Johnson[a]; Robert T. Foister[b]
[a] Engineering Mechanics Department, [b] Polymers Department, General Motors Research Laboratories, Warren, Michigan

To cite this Article Schmueser, David W. , Johnson, Nancy L. and Foister, Robert T.(1987) 'Stress Analysis of Adhesively Bonded Electroprimed Steel Lap Shear Joints', The Journal of Adhesion, 24: 1, 47 — 64

To link to this Article: DOI: 10.1080/00218468708075415

URL: http://dx.doi.org/10.1080/00218468708075415

J. Adhesion, 1987, Vol. 24, pp. 47–64
Photocopying permitted by license only

Printed in the United Kingdom

Stress Analysis of Adhesively Bonded Electroprimed Steel Lap Shear Joints

DAVID W. SCHMUESER and NANCY L. JOHNSON
Engineering Mechanics Department

and

ROBERT T. FOISTER
Polymers Department, General Motors Research Laboratories, Warren, Michigan

(Received October 11, 1986; in final form February 13, 1987)

Structural applications for adhesive bonding have been increasing in recent years due to improvements in the types of adhesives available and in improved knowledge of bonding procedures. Consequently, there exists a demand for precise numerical modeling of adhesive joint behavior, particularly along bondline interfaces where low surface energy adhesives contact high surface energy metallic oxides. The purpose of the present study is to determine the effect of electrodeposited organic paint primer (ELPO) on the stress and strain distributions within an adhesively bonded single-lap-shear joint. Initial experimental studies have shown that bonding to ELPO-primed steel adherends has enhanced strength and durability characteristics compared to conventional bonds to unprimed steel surfaces. Recent studies based on finite element analysis of varied single-lap-shear joint moduli and thicknesses, and subsequent testing of joints with two different adhesive moduli, have indicated the mechanisms involved in this phenomenon. The presence of the ELPO-primer reduced peak peel and shear stresses and allowed for more uniform stress distribution throughout the joint.

KEY WORDS Single-lap-shear joint; finite element method; peel stress; shear stress; lap-shear strength; bondline interface

---

Corresponding Author: David W. Schmueser, Engineering Mechanics Dept. RMB-256, General Motors Research Laboratories, Warren, MI 48090-9055, U.S.A.

INTRODUCTION

In recent years, adhesive bonding has become of more interest for structural applications due to improvements in the types of adhesives available and in improved knowledge of bonding procedures. However, before bonding of primary structural automotive components can be achieved with adequate strength and durability, the problem of poor bonding resulting from surface contamination of metallic adherends must be overcome. Even when cleaning procedures are used to remove greases, oils, and lubricants from metallic substrates, there still is an inherent weakness in a "clean" metal-to-adhesive bond. This weakness is related to interfacial conditions where a low surface energy adhesive contacts a high surface energy metallic oxide. It has been shown[1,2] that even when initial strengths of metal-to-metal adhesively bonded joints are very high, the inherent instability of the metallic oxide/adhesive interface, particularly in the presence of moisture, leads to strength degradation during the service life of a joint.

Recently, as a result of this problem in bonding metal-to-metal substrates with structural adhesives, alternatives to bonding directly to cleaned or oiled steel substrates have been examined. As a first alternative, adhesively bonding ELPO-primed steel surfaces has been investigated.[3] The priming process consists of first depositing a thin (~0.6 μm) layer of zinc phosphate crystals on the steel ferric oxide surface (Figure 1). A layer of organic primer is then deposited onto the zinc phosphate. The primer surface formed in this manner is referred to as an "ELPO" surface, the term "ELPO" referring to the electrodeposition of organic primer. When using a properly

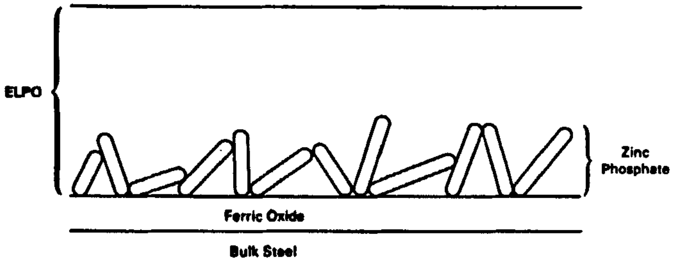


FIGURE 1 Schematic of ELPO/zinc phosphate/steel interphase bond.

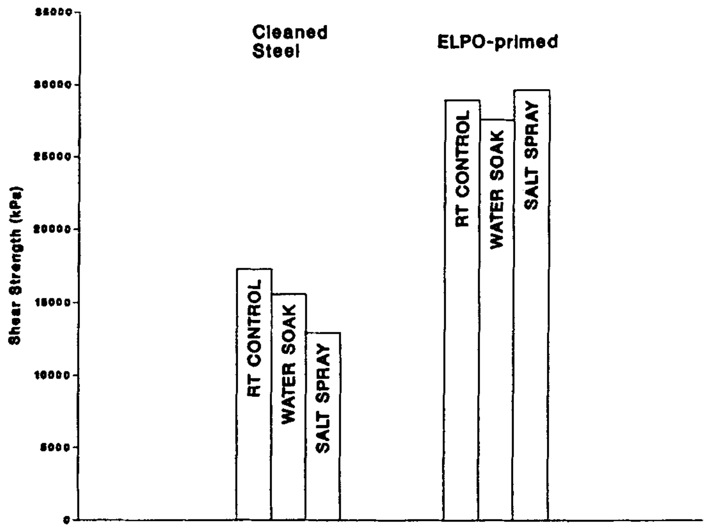


FIGURE 2 Lap shear strengths for EA2 adhesive[3] on steel primed with Uniprime 3043 electrodeposited primer.

formulated adhesive, strengths for single-lap-shear (SLS) joints showed increases of up to 88% (Figure 2) on ELPO-primed steel compared to results obtained using an identical adhesive on unprimed steel.[3] The failure surface of an adhesive/ELPO-primer joint (Figure 3) shows the failure to be solely within the phosphate/primer region. A scanning electron micrograph of this failure surface (Figure 4) shows that fracture actually occurs within the ELPO/zinc phosphate coating interphase region.

The purpose of the present study was to determine if the large and unexpected increases in strength for ELPO-primed steel substrates could be explained by differences in the stress and strain distributions attributable to the presence of the primer. A large-deformation finite element analysis has been completed to investigate the effect of the ELPO primer. A parametric computational study was conducted to determine the effects which adhesive thickness and adhesive moduli have on the joint stress and strain distributions. Static shear strength tests were also conducted to quantify the numerical results.

The following sections of the paper discuss general adhesive

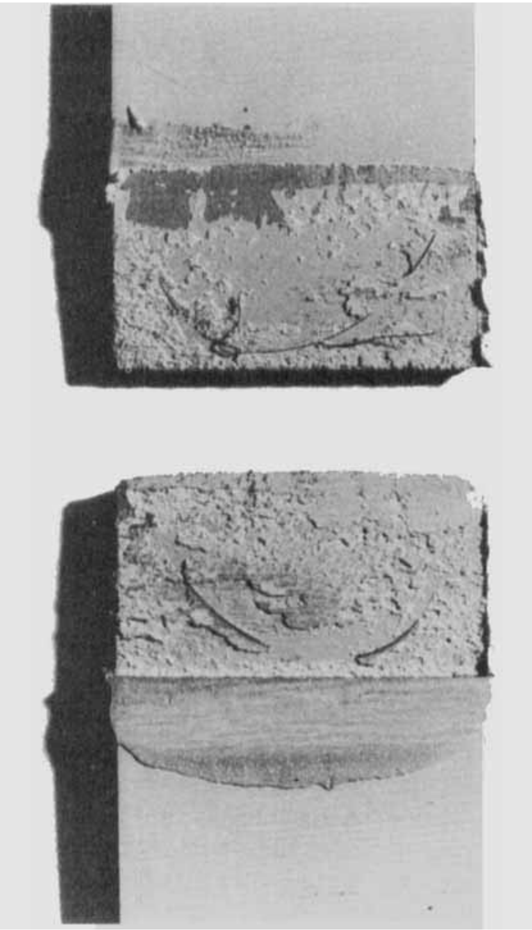


FIGURE 3 Failure surface for single-lap-shear specimen.

bonding analysis procedures, describe finite element modeling procedures for the SLS joint, present the results of the parametric computational study, and describe experimental results which substantiate the finite element analysis.

ADHESIVE BONDING ANALYSIS PROCEDURES

Commercial development of adhesive bonding techniques has evolved essentially by trial and error. Such a process is costly,

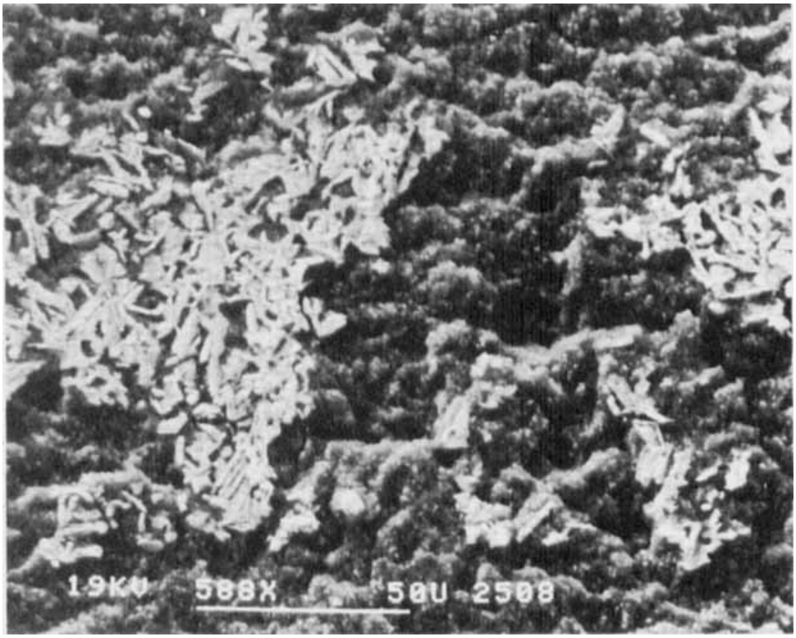


FIGURE 4 Scanning electron micrograph of the single-lap-shear failure surface.

particularly when different adherend and adhesive systems are involved. As a result, an analytically or numerically-based methodology becomes desirable to allow for a more economical approach to bonding technology. In response to this need, several stress analysis techniques have been developed. In the following, two types of stress analysis procedures are reviewed:

1) Analytical (closed-form) methods
2) Numerical methods

Analytical (closed-form) methods

One type of closed-form bond strength analysis is based on membrane approximations which neglect the effect of bending or peel stress distributions within a joint. The analysis of Volkersen[4] is typical of this type of approximation. This formulation is based on the joining of two adherends (in a lap or butt joint) and on submitting that system to an inplane load. The load at failure in relation to the bond area gives an average failure stress as a measure of bond strength, provided the same joint geometry and adherend materials are used. Since this type of analysis ignores nonuniform stress distributions throughout the joint, the more detailed Strength of Materials Analysis was formulated.

For the Strength of Materials approach, strains are averaged over the bondline thickness, but allowances are made for variations of this average strain along the bondline. Elastic deformation of thin adherends is also approximated. The analysis of Goland and Reissner[5] is of this type. Hart-Smith[6] further extended the Strength of Materials approach by allowing for "nonlinear" adhesive behavior. Both of these analysis procedures assume that the bond interface remains intact and that the adhesive is the "weak link" in the joint. The methods are, therefore, unable to characterize stress distributions near or at the adherend-adhesive interface.

Since most bonds fail by propagation of cracks through the bondline, a thickness-averaged procedure based on fracture mechanics concepts was formulated. This method identifies the entire bondline as the "weak link" in the bond system. By assuming that the bondline is infinitesimally thin compared to the adherends, joint strength determination is reduced to the equivalent problem of a continuous body with a weak plane in which the crack propagates. Thus, the thickness-averaged fracture mechanics approach neglects the details of the fracture process within the adhesive region. However, there are many phenomena which occur within the adhesive layer or at the adhesive-adherend interface that are important to the process of bond failure. The question as to whether failure occurs at the interface or through the middle of the bond cannot be answered by the thickness-averaged fracture mechanics approach.

Numerical methods

Since the closed-form solution techniques described above cannot be used effectively to model interfacial phenomena at the bondline, numerical techniques have been developed to investigate bondline strength more accurately. Finite difference methods, based on the solution of fundamental continuum mechanics equations expressed in explicit form, were first applied to bonding problems. However, because of the explicit formulation of this method, the cost of executing finite difference analyses was excessive. Therefore, in recent times, the finite element method has been used very extensively to model bonded joints.

The finite element method has been applied to characterize the stress concentrations which occur at free edges in joints. The method has also been used to compute fracture mechanics parameters which characterize the bond strength at an interface by adhesion energy per unit of bond area. These parameters provide a unifying link between bonding mechanical loads, bond geometry, adherend and adhesive material properties, and interface conditions.

The work described in the following sections uses the finite element method to determine stress distributions and stress concentrations in the middle of the adhesive layer and at the adhesive-ELPO interface. This allows for accurate assessment of stresses through the adhesive thickness and along the interfaces. Thus, a qualitative description of the failure characteristics of a single-lap-shear joint can be determined.

FINITE ELEMENT MODELING PROCEDURES

The single-lap shear (SLS) joint has been used in previous studies[3] to examine the feasibility of bonding to ELPO-primed steel surfaces. Applying this joint geometry to experimentally evaluate adhesive strength is difficult for two reasons. First, testing of the joint gives little information on the deformation within the adhesive layer. Secondly, the bonded joint is in a three-dimensional state of stress. Shear, peel, and axial stress components are present and are not constant along the bondline or through the adhesive layer. As illustrated in Figure 5, the discontinuities in the joint geometry make it extremely difficult to compute stress distributions along the free edge of the adhesive.[7] For this reason, a very fine finite element mesh with small aspect ratios must be used in the vicinity of the corners.

Figure 6A shows the boundary conditions used for the finite element model, while Figure 6B shows the position of the steel,

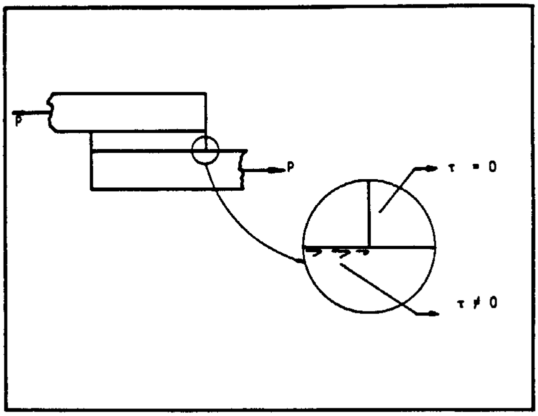
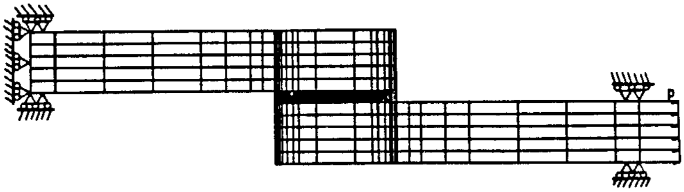
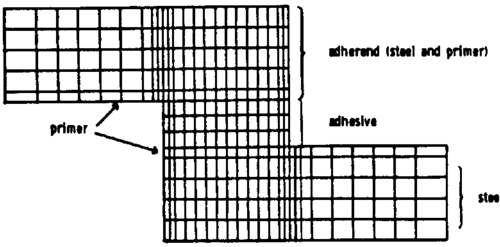


FIGURE 5 Discontinuity in shear stress at joint free edge.



(a) Model for Boundary Conditions

Section of Single-Lap Joint Model



(b) ELPO and Adhesive Layer Locations

FIGURE 6 Finite element model for single-lap-shear joint.

TABLE I
Adhesive and ELPO moduli used for parametric stress analysis

Material	Modulus (GPa)
Adhesive	2.8
ELPO Primer	1.0 ("Stiff" primer) 0.1 ("Soft" primer)

adhesive, and ELPO layers. The material properties used for the adherend, adhesive, and ELPO materials are listed in Table I. For the finite element analysis, stiff and soft moduli representing bounds on available estimates were used. An eight-node isoparametric finite element having 16 degrees of freedom was used for the analysis. Four elements were used across the thickness of each adherend, while three elements were used across the thickness of the adhesive. One element was used to model the ELPO layer thickness. Thirty-two elements were used along the length of the bonded overlap region, while sixteen elements were used along the length of the unbonded adherends. The aspect ratio of the smallest element was 2.0. A static, generalized plane strain stress analysis was completed with small strain and large displacement approximations.

SINGLE-LAP-SHEAR STRESS ANALYSIS

Parametric studies were made using the SLS joint to determine which configuration provided the minimal stresses while remaining within the constraints of possible material characteristics and deformation.

The effect of including a layer of ELPO primer between the adhesive and adherend sections of the SLS joint was initially investigated. A 0.0254 mm thick layer of ELPO was placed along each adherend as shown in Figure 6B. For this portion of the study, two different possible values of elastic ELPO moduli were used: 1.0 GPa and 0.1 GPa. This range of elastic moduli represents typical property values of thermoset polymers above and below the glass transition temperature, Tg.[8] The ELPO Poisson's ratio was assumed to be equal to that of the adhesive (0.34). The peel and shear stress distributions along both the centerline of the adhesive and the ELPO-adhesive interface are plotted in Figures 7 through 10 as a function of distance from the bond centerline. The distances were normalized by dividing by half the bond length, C, and the stresses by dividing by the average applied stress, $\sigma_0 = P/A$. As exhibited by these stress distribution curves, the addition of the ELPO layer improved the stress distribution by reducing the peak stresses and making the distribution more uniform.

Although a given SLS joint geometry may appear to have enhanced performance based on stress distributions, the resulting deformation of the joint may be too excessive. Figure 11 shows the portion of the joint at the edge of the adhesive in a deformed state. When bonding directly to the steel, the adhesive exhibits a large amount of deformation including rotation. However, when including the layer of ELPO primer, there is very little rotation and the ELPO deforms greatly in shear. Using the lower modulus of elasticity (0.1 GPa) for the ELPO gives some further reduction in stresses, but large deformations within the ELPO layer.

The effect of varying thicknesses of the adhesive and ELPO primer layers was also determined. Thicknesses of 0.013, 0.025 and

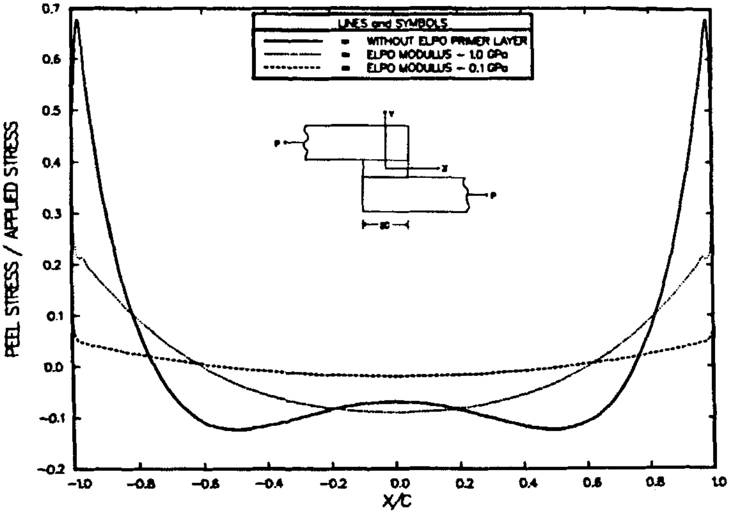


FIGURE 7 Peel stress distribution along bond centerline.

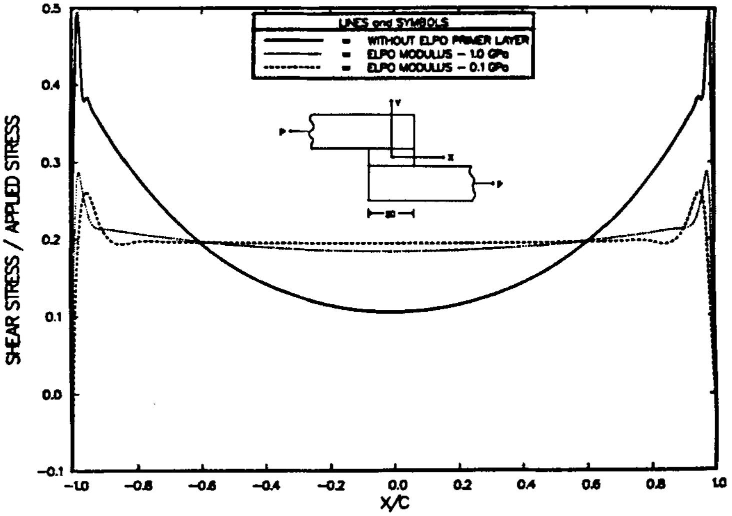


FIGURE 8 Shear stress distribution along bond centerline.

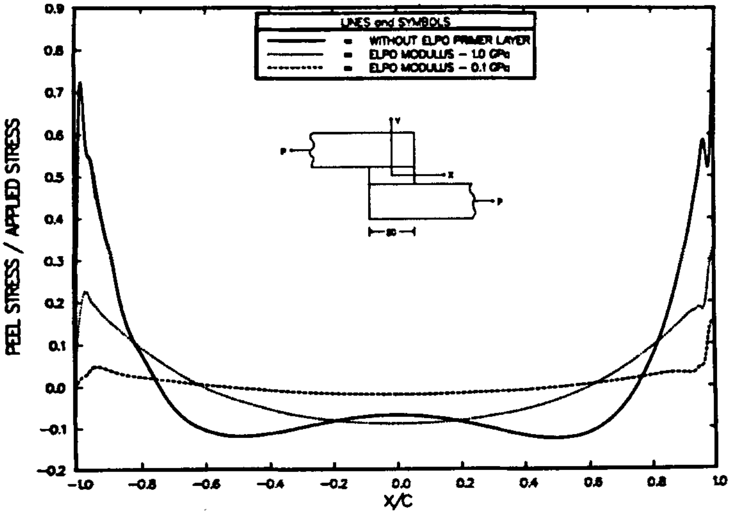


FIGURE 9 Peel stress distribution along ELPO-adhesive interface.

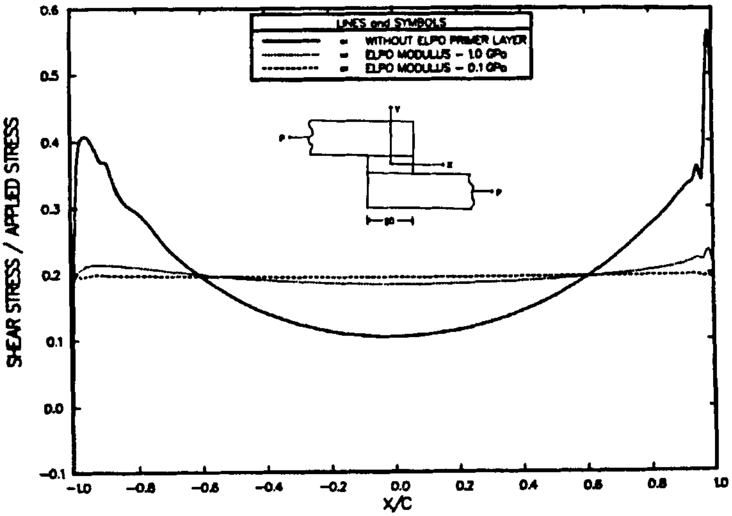


FIGURE 10 Shear stress distribution along ELPO-adhesive interface.

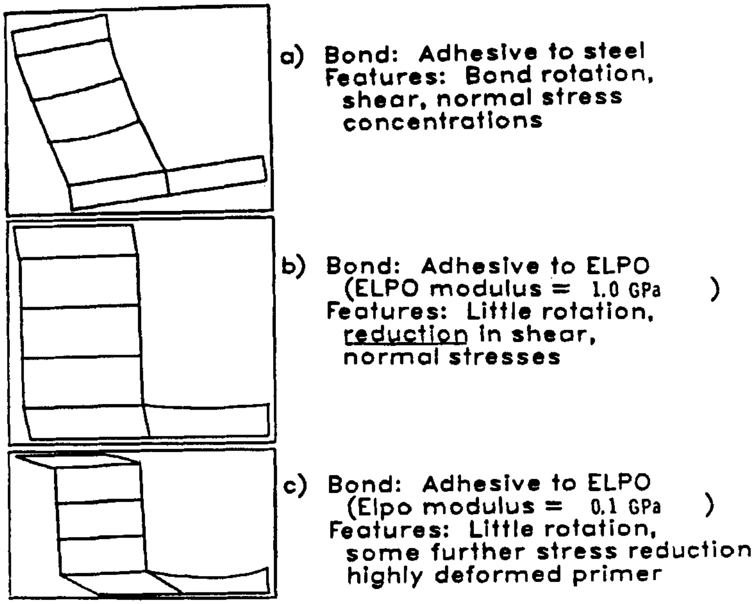


FIGURE 11 Bond deformations for ELPO-primed and unprimed joint surfaces.

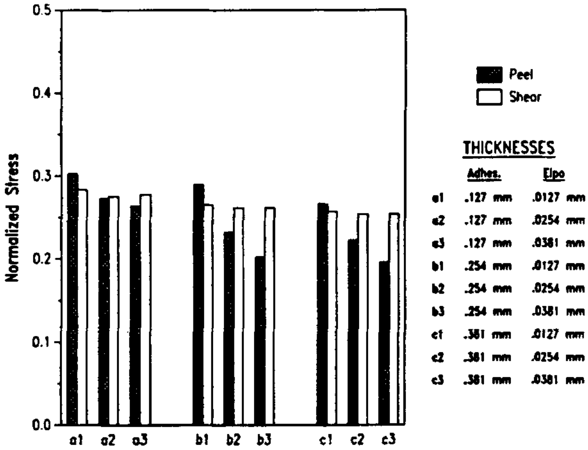


FIGURE 12 Effects of adhesive and ELPO thicknesses on peak stresses at the adhesive centerline.

0.038 mm were used for the ELPO while thicknesses of 0.127, 0.254, and 0.381 mm were used for the adhesive. These thickness ranges represent typical values in test samples. The maximum stresses along the adhesive centerline and ELPO-adherend interface for the nine possible thickness combinations are shown in Figures 12 and 13. For these cases, the modulus of elasticity for the ELPO and adhesive are 1.0 GPa and 2.8 GPa, respectively.

As exhibited by the bar graphs, the greatest reduction in peak stresses occurred along the centerline of the adhesive for peel stress. A 26 percent reduction occurred when the ELPO thickness was varied from 0.013 mm to 0.038 mm for a joint with an adhesive thickness of 0.381 mm. Overall, the stress distributions were insensitive to changes in the adhesive and ELPO thicknesses. On the average, peak peel stresses showed a 16 percent change, while peak shear stresses showed a 3 percent change.

Varying the elastic moduli of the adhesive and ELPO-primer layers had a greater influence on the stress distributions than did varying the layer thicknesses. Figures 14 and 15 show that a lower modulus of elasticity for either the ELPO primer or adhesive decreases the maximum stress and improves the stress distribution.

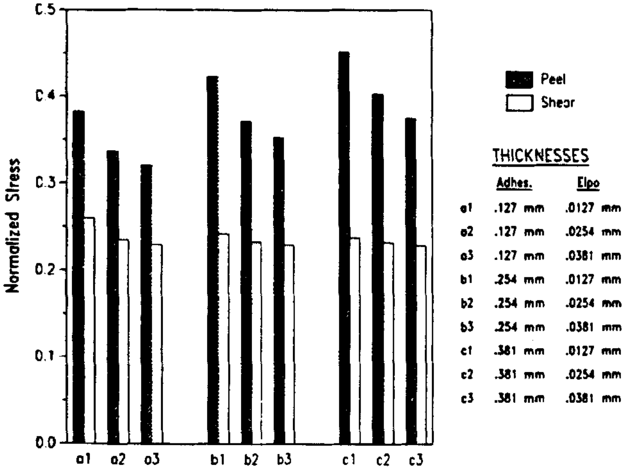


FIGURE 13 Effects of adhesive and ELPO thicknesses on peak stresses at the ELPO-adhesive interface.

A parametric study for determining the influence of both moduli on joint stress distributions is summarized in the following.

First, the elastic modulus of the ELPO primer was kept constant at 1.0 GPa and the elastic moduli of the adhesive were varied according to E_a/E_e, the ratio of the adhesive modulus to the ELPO

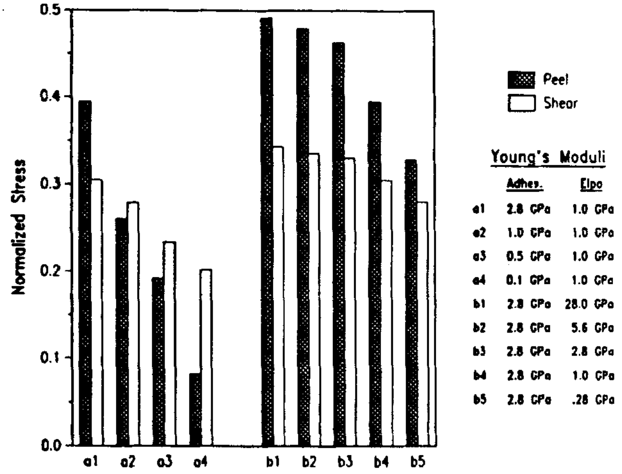


FIGURE 14 Effects of adhesive and ELPO moduli on peak stresses at the adhesive centerline.

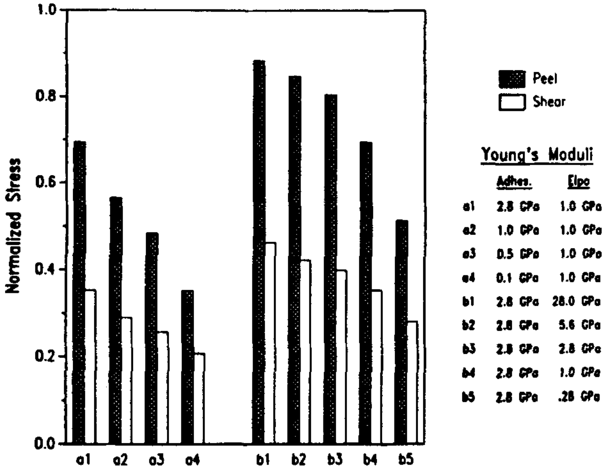


FIGURE 15 Effects of adhesive and ELPO moduli on peak stresses at the ELPO-adhesive interface.

modulus. The first four bars (a1 to a4) in Figures 14 and 15 represent E_a/E_e ratios ranging from 0.1 to 2.8 with the ELPO modulus fixed at 1.0 GPa. The remaining five bars (b1 to b5) represent E_a/E_e ratios ranging from 0.1 to 10.0 with the adhesive modulus fixed at 2.8 GPa.

As shown by these results, a lower value of an elastic modulus for either the ELPO primer or the adhesive reduces the maximum stresses in both peel and shear. A reduction of 80 percent was exhibited in the peel stresses along the adhesive centerline as the E_a/E_e ratio varied from 2.8 to 0.1. As the moduli of the adhesive and ELPO were decreased, average reductions for peak shear and peel stress components were 46 and 63 percent, respectively.

EXPERIMENTAL SINGLE-LAP-SHEAR BOND STRENGTHS: EFFECTS OF MODULUS RATIO

Two different two-part epoxy adhesives were evaluated for their bonding characteristics to ELPO primed steel and cleaned mild steel. One of these adhesives, "125", was an unfilled, laboratory formulation consisting of 75 parts per hundred resin (phr) D.E.N. 431 epoxy novolac (Dow Chemical Co.), 100 phr Epi-rez 5048

TABLE II
Measured adhesive and ELPO moduli from correlative SLS experiments

Material	Modulus (GPA)	Adhesive/ELPO modulus ratio	Poisson's ratio
2-Part epoxy (125)	3.2	2.5	0.34
2-Part epoxy (2216)	1.4	1.1	0.34
ELPO primer (ED3150A)	1.4	—	0.34

(Celanese, Inc.), and 8.5 phr imidazole curing agent. The second adhesive used was 3M Company's #2216 two-part epoxy.

Tensile specimens, cut from cast sheets of the adhesives or from sheets of the ELPO primer removed from the steel surface, were used to characterize the material properties for the adhesives and ELPO primer. The specimens were prepared and tested at room temperature in accordance with ASTM D638, using either an Instron Model TTC testing machine or an Instron Model 1125 Universal Tester at a crosshead speed of 5 mm/min. Moduli for adhesive specimens, as well as thin ELPO films, were calculated from initial slopes of load *vs.* elongation curves. Table II summarizes moduli values and Poisson's ratios for the adhesives and ELPO film.

Lap shear specimens were prepared in accordance with ASTM Standard D1002. An evaluation of various adhesive test methods has been presented by Anderson, *et al.*[9] "Cleaned Steel" coupons (101 × 25.4 × 2.21 mm) were degreased in trichloroethane and vapor-blasted with a suspension of Novacite 200 in water at 550 kPa. Also, ELPO-primed steel coupons (101 × 25.4 × 2.21 mm) were used as bonding substrates. ELPO-priming was preceded by deposition of a zinc-phosphate conversion coating (Chemfil 168). The ELPO primer (Uniprime 3150A, PPG Industries) is a proprietary formulation used in GM Manufacturing facilities.

After surface preparation, adhesive was applied to a 1.27 × 2.54 cm bond area, and a small piece of copper wire was used as a spacer to maintain a bond thickness of 0.127 mm. SLS specimens were placed in a special fixture prior to cure. The specimens were tested on an Instron Model TTC testing machine at a crosshead speed of 1.3 mm/min. Lap shear strengths are reported in Table III as the maximum load reached prior to bond rupture.

Table III shows that while the mean lap shear strength for the

TABLE III
Shear strengths for correlative SLS experiments

Adhesive/substrate	Strength (kPa)	% Increase over cleaned steel
125/ED3150A	2.57×10^4 2.2×10^3	13 ± 2.0
2216/ED3150A	1.63×10^4 4.3×10^2	30 ± 6.1
125/Cleaned steel	2.28×10^4 2.2×10^3	—
2216/Cleaned steel	1.25×10^4 2.5×10^3	—

lower modulus adhesive (2216), on both cleaned and ELPO-primed steel, is less than the corresponding values for the higher modulus adhesive (125), there is a thirty percent increase in strength for 2216 on primed compared to unprimed steel. For the 125 adhesive, on the other hand, there is only a thirteen percent increase over primed steel. However, the Adhesive/ELPO modulus ratio for the 125 adhesive is 2.5, while that for the 2216 adhesive is 1.1 (Table II). Thus the trend predicted on the basis of the analysis above, namely that lower modulus ratios correspond to greater reductions in peak stresses, is borne out by the experimentally observed improvements in lap shear strength.

SUMMARY

Based on parametric finite element analyses of single-lap-shear joints of varied adhesive modulus and thickness, and subsequent testing of joints with two different adhesive moduli, it has been shown that adhesive bonding to ELPO-primed steel has enhanced strength characteristics compared to conventional bonding of unprimed steel-to-steel surfaces. The parametric study showed that the presence of the ELPO layer reduced peak peel and shear stresses along the bond centerline and along the ELPO-adhesive interface. Decreasing the adhesive modulus relative to the ELPO modulus reduced peak stress components along the centerline and along the primer interface. Subsequent single-lap-shear tests verified the numerical results by showing greater increases in bondline strength for joints with the lower adhesive-to-ELPO modulus ratios. Thus, the finite element analyses have provided a qualitative explanation for the enhanced strength characteristics of ELPO-primed joints.

Acknowledgment

The authors acknowledge Patricia A. Madsen of the GMR Polymers Department for conducting the materials characterization tests for the adhesive and ELPO primer.

References

1. R. A. Gledhill and A. J. Kinloch, *J. Adhesion* **6,** 315 (1974).
2. J. Comyn, *Developments in Adhesives*—2 (Applied Science Pulbishers, London, 1982), p. 279.
3. R. T. Foister, R. K. Gray, and P. A. Madsen, "Structural Adhesive Bonds to Steel Electrodeposited with a Primer", *J. Adhesion,* in press.
4. O. Volkersen, *Luftfahrtforschung* **15,** 41 (1938).
5. M. Goland and E. Reissner, *J. Appl. Mechanics* **11,** A17 (1944).
6. L. J. Hart-Smith, "Adhesive-Bonded Single-Lap Joints", NASA CR-11236, (January 1973).
7. G. P. Anderson, S. J. Bennett, and K. L. DeVries, *Analysis and Testing of Adhesive Bonds* (Academic Press, New York, 1977).
8. A. J. Kinloch and R. J. Young, *Fracture Behavior of Polymers* (Applied Science Publishers, London, 1983), p. 25.
9. G. P. Anderson, K. L. DeVries, and G. Sharon, "Evaluation of Adhesive Test", in *Adhesive Joints,* K. L. Mittal, Ed. (Plenum Publishing Co., New York, 1984), p. 269.