ADHESIVE-BONDED SCARF AND STEPPED-LAP JOINTS

TECHNICAL REPORT

by

L. J. HART-SMITH

Prepared under Contract NAS1-11234
Douglas Aircraft Company
McDonnell Douglas Corporation
3855 Lakewood Blvd
Long Beach, California 90846

January 1973

for

Langley Research Center
Hampton, Virginia 23366

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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ABSTRACT

Continuum mechanics solutions are derived for the static load-carrying capacity of scarf and stepped-lap adhesive-bonded joints. The analyses account for adhesive plasticity and adherend stiffness imbalance and thermal mismatch. The scarf joint solutions include a simple algebraic formula which serves as a close lower bound, within a small fraction of a per cent of the true answer for most practical geometries and materials. The scarf joint solutions are believed to be the first such results ever obtained for dissimilar adherends. Digital computer programs have been developed and, for the stepped-lap joints, the critical adherend and adhesive stresses are computed for each step. The scarf joint solutions exhibit grossly different behavior from that for double-lap joints for long overlaps inasmuch as that the potential bond shear strength continues to increase with indefinitely long overlaps on the scarf joints. The stepped-lap joint solutions exhibit some characteristics of both the scarf and double-lap joints. The stepped-lap computer program handles arbitrary (different) step lengths and thicknesses and the solutions obtained have clarified potentially weak design details and the remedies. Indeed, the program has been used effectively to optimize the joint proportions.

KEYWORD DESCRIPTORS

Bonded Joints  
Adhesive Stresses and Strains  
Adherend Stiffness Imbalance  
Adherend Thermal Mismatch  
Computer Analysis Programs

Scarf Joints  
Stepped-Lap Joints  
Static Strength  
Elastic-Plastic Formulation  
Advanced Composite Joints
FOREWORD

This report was prepared by the Douglas Aircraft Company, McDonnell Douglas Corporation, Long Beach, California under the terms of Contract NAS1-11234. One summary report (NASA CR 2218) and four technical reports (NASA CR 112235, -6, -7, and -8) cover the work, which was performed between November 1971 and January 1973. The program was sponsored by the National Aeronautics and Space Administration's Langley Research Center, Hampton, Virginia. Dr. M. F. Card and Mr. H. G. Bush were the Contracting Agency's Technical Monitors.
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SYMBOLS

$A_0, \ldots A_n =$ Coefficients of power series for shear stress distribution in adhesive layer

$a, c =$ Extents of plastic stress state in adhesive at ends of bonded joint (in.)

$b =$ Extent of elastic trough in adhesive (in.)

$C, D =$ Integration constants

$CTHERM =$ Non-dimensionalized adherend thermal mismatch coefficient

$d =$ Length of elastic zone in adhesive bond (in.)

$E =$ Young's modulus (longitudinal) for adherend (psi)

$ETR =$ Adherend extensional stiffness ratio

$F_\sigma =$ Adherend allowable (or ultimate) stress (psi)

$G =$ Adhesive shear modulus for elastic-plastic representation (psi)

$\xi =$ Overlap (length of bond) (in.)

$P =$ Applied direct load on entire joint (lb in. / in.)

$SGNLD =$ Distinguisher between tensile and compressive shear loads

$T =$ Direct stress resultants in adherends (lb / in.)

$\Delta T =$ Temperature change ($T_{\text{operating}} - T_{\text{cure}}$)

$t =$ Thickness of adherend (in.)

$x =$ Axial (longitudinal) coordinate parallel to direction of load

$\alpha =$ Coefficient of thermal expansion ($^\circ F$)

$\gamma =$ Adhesive shear strain

$\gamma_e =$ Elastic adhesive shear strain

$\gamma_p =$ Plastic adhesive shear strain

$\delta =$ Axial (longitudinal) displacement of adherend (in.)

$\xi, \xi, x =$ Non-dimensionalized axial coordinates (different origin and/or sense from $x$)
\[ \eta = \text{Thickness of adhesive layer (in.)} \]
\[ \theta = \text{Scarf angle (small) (°)} \]
\[ \lambda = \text{Exponent of elastic shear stress distribution (in.}^{-1}\text{)} \]
\[ \nu = \text{Poisson's ratio for adherend(s)} \]
\[ \tau = \text{Adhesive shear stress (psi)} \]
\[ \tau_{av} = \text{Average adhesive shear stress (psi)} \]
\[ \tau_p = \text{Plastic (maximum) adhesive shear stress (psi)} \]
\[ \phi = \frac{x}{\ell} = \text{Non-dimensionalized coordinate} \]

**SUBSCRIPTS**

- \( a,c \) = Adhesive (cement)
- \( e,p \) = Elastic and plastic values
- \( i,o \) = Inner and outer adherends of symmetric bonded joint
- \( 1,2 \) = Different adherends at each end of joint
- \( 1,2,..n \) = Power series counter
SUMMARY

It has long been known that bonded scarf joints have a higher efficiency than uniform lap joints and that the latter are limited in strength and unsuitable for joining thicker sections. What has not been well understood until recently is that, in the bonding together of dissimilar adherends in a scarf joint, any adherend stiffness imbalance or thermal mismatch imposes a limitation on the joint efficiency. As a consequence the adhesive layer is not (essentially) uniformly stressed along its length as it is for a scarf joint between identical adherends. One objective of this report is to analyze and quantify these limitations on efficiency of unbalanced scarf joints. In doing so, adhesive plasticity is accounted for by the Douglas elastic-plastic model which has been demonstrated to be effective for uniform lap joints. One dominant characteristic deduced for scarf joints is that for long overlaps, regardless of any adhesive ductility and/or adherend thermal mismatch, the ratio of the average adhesive shear stress to the peak adhesive shear stress is equal to the lower ratio (<1) of the adherend extensional stiffnesses. The governing differential equations do not possess an explicit solution in terms of standard functions, so a series solution was employed. Even so, an algebraic expression was deduced for a lower bound which proved to be so close to the more precise solutions that it could be employed directly for practically all realistic joint proportions. Severe adverse effects of adherend thermal mismatch are confined to a specific overlap range. The effects decrease asymptotically to zero for very short or very long overlaps.

Stepped-lap joints represent a cross between scarf joints and uniform lap joints. The stepped-lap joint overcomes the upper limit on joint strength of uniform lap joints but retains the severe adhesive strain concentration at the end of each step. One advantage of stepped-lap joints over scarf joints is that the alignment and fit is far less critical when there are joints on more than a single interface. Another is that it is more suitable for boron-epoxy laminates than is a scarf joint because of the thick brittle filaments. This is particularly important for the titanium edge members frequently used in conjunction with boron-epoxy panels. Because the graphite fibers are so much thinner and more flexible than boron filaments, the former can take advantage of the higher efficiency of the scarf joint.
Digital computer FORTRAN IV programs are included for the iterative solutions necessary for these problems. The scarf joint solutions are in terms of non-dimensionalized parameters. The stepped-lap joint program is dimensional and permits each step to be varied independently so as to be able to identify and improve the most critical detail(s) of the joint. One key factor in the design of stepped-lap joints is that the bond load transfer is concentrated at the end of the joint from which the softer (less stiff) adherend extends. Consequently, it is necessary to restrict the length of the end step of the stiffer adherend to prevent it from being overloaded. Another characteristic of stepped-lap joints identified by the analyses is that the end three steps of the more critical end dominate the internal load distribution and effectively determine the load capacity. The steps at the less critical end are found to have practically no effect on the load capacity.
1. INTRODUCTION

It is generally recognized that, in the bonding together of thick sections, the use of either scarf or stepped-lap joints is mandatory if an acceptable structural efficiency is to be realized. References (1) and (2) explain how, for uniform lap joints, the maximum possible joint efficiency decreases with increasing thickness (extensional stiffness) of the members being bonded together. The objective of this report is to apply the elastic-plastic adhesive analysis techniques developed in References (1) and (2) to the scarf and stepped-lap joints. The approach used remains that of continuum mechanics rather than finite elements. The governing differential equations were relatively straightforward to set up but, in most cases, specific closed-form solutions could not be derived. Severe numerical accuracy problems had to be overcome in developing the FORTRAN IV digital computer programs employed and this phase of the work represented by far the bulk of the investigation. The computer programs are listed in the Appendices and representative non-dimensionalized solutions are illustrated to show the effect of the governing scarf joint parameters. Specific solutions are presented for stepped-lap joints.

This scarf joint analysis is concerned with the non-uniform adhesive shear stresses necessarily associated with the bonding together of dissimilar adherends. It is well-known that the stresses are uniform if the adherends are identical. It has only recently begun to be appreciated that the adhesive shear stresses are markedly non-uniform if the adherends are dissimilar. Indeed, the literature contains very few references to this problem. The mechanism whereby these non-uniform stresses are developed is illustrated in Figure 1 for the case of thermal mismatch between stiffness-balanced adherends. The first publication on scarf joints between dissimilar adherends appears to be that of Lubkin [Reference (3)] who, in 1957 sought the particular scarf angle associated with uniform adhesive stress for a particular ratio of adherend elastic moduli. He omitted consideration of any adherend thermal dissimilarity. Unfortunately the predictions of his equation [10] are such as to indicate the appropriate scarf angle $\theta$ is so great (typically in excess of 45 degrees) as to be of no practical interest for bonding aerospace materials together. For realistic adheresives and adherend materials, the scarf angle should be restricted to less than 4 degrees in order for the potential bond
strength to exceed the adherend strength(s). Working independently, in 1971, the present author [Reference (4)] and Erdogan and Ratwani [Reference (5)] demonstrated by calculation the non-uniform adhesive shear stress associated with scarf joints between dissimilar adherends. The former work was based on a perfectly-plastic adhesive analysis, while the latter derived from a linearly-elastic formulation. Consequently neither afforded a complete solution but both demonstrated clearly that the adhesive load transfer is concentrated at that end of the joint from which the softer adherend extends. The present solution utilizes an elastic-plastic adhesive model with linearly elastic adherends and accounts for adherend stiffness and thermal imbalances. Eccentricities in the load path are excluded and, in keeping with common design practice, the scarf angle is considered to be so small that adhesive tension (or compression) stresses may be neglected in comparison with the shear stresses.

In 1968, an elastic finite-element analysis of scarf joints was performed by Richards [see Reference (6)]. Boron/epoxy-to-boron/epoxy and boron/epoxy-to-aluminum joints were analyzed. Thermal effects were neglected. In the former case, relatively small (<4%) stress concentrations were identified in the vicinity of the ends of the scarf. Their existence had not been demonstrated prior to that investigation. In the latter case a markedly non-uniform stress distribution was deduced, with significantly more load being transferred to and from the 0° plies in the laminate than occurred with the ±45° plies. This is to be expected in view of the much lower modulus of the cross plies.

While the mathematical complexity of equations governing the scarf joint has restricted the number of solutions obtained, a number of investigations of the stepped-lap adhesive-bonded joint have been performed. Finite-element elastic solutions are reported in References (5) to (9) but none of these include any thermal mismatch effects. Reference (10) included adhesive and adherend non-linear behavior in the analysis but, for the stepped-lap joint, encountered convergence difficulties at high load levels. Grimes, Calcote, Wah, et al [Reference (10)] also performed non-linear iterative theoretical analyses of double-lap, single-lap and stepped-lap joints which they compared with their discrete element analyses, showing good agreement for the first two. They also formulated the scarf joint equations (see their Appendix A) in greater detail than is done here, but were unable to solve them. Corvelli and Saleme
[Reference (11)] developed analysis techniques for bonded joints which included analytical solutions for stepped-lap joints, but in a less comprehensive form than presented here.

Past attempts to include non-linear adhesive behavior in the analytical solutions have centered around the Ramberg-Osgood representation which has a smooth continuous characteristic. This has precluded the derivation of any explicit closed-form solutions. The present author had earlier derived such solutions for double- and single-lap adhesive-bonded joints using an elastic-plastic adhesive formulation [see References (12) and (13)]. These showed that the adhesive shear strain energy per unit bond area was the necessary and sufficient adhesive characteristic governing the potential bond shear strength. The precise shape of the stress-strain curve appeared to be unimportant. This belief was further reinforced in Reference (1) by the derivation of precisely the same potential bond shear-strength for any arbitrary bi-elastic adhesive characteristic having the same strain energy and failure stress and strain. In addition, the author's elastic-plastic solution was in good agreement with the discrete element solutions by Teodosiadis [Reference (14)], who represented the adhesive and interlaminar shear characteristics by six straight segments. The success of this elastic-plastic adhesive approach in these simpler problems led to the decision to apply the same techniques to the scarf and stepped-lap joints in this report.

The adhesive-bonded stepped-lap joint is of practical interest principally because of extensive use in the bonding of boron-epoxy to titanium edge members. The boron filaments are too thick (0.005 inch), and too hard to machine, to be as suitable for the more efficient scarf joints as the very thin graphite fibers are. In practice the stepped-lap joint contains a large number of small steps and closely approximates the behavior of the equivalent scarf joint. The only difference is marked for very brittle (high-temperature) adhesives and is the adhesive shear stress (and strain) concentrations at the ends of each step, particularly at the outermost steps. It transpired that peel stresses imposed more severe limitations for thick double- and single-lap joints than did the adhesive shear stresses [see References (1) and (2)]. In actual design practice for scarf and stepped-lap joints, the slope is small and the end step is
invariably thin so there is no way for severe peel stresses to develop. For any unusual stepped-lap joint, with a thick outer end step, the analysis in Reference (1) can be employed to assess any potential peel problem.

This report considers in turn elastic and elastic-plastic analyses of scarf and stepped-lap joints and discusses parametric effects and design procedures. The digital computer programs prepared from the analyses are recorded in the Appendices, along with brief instructions for their use.
2. ELASTIC ANALYSIS OF SCARF JOINTS

Figure 2 depicts the geometry and nomenclature for the analysis of a non-
eccentric bonded scarf joint. The diagram serves for both the elastic and
elastic-plastic solutions. In the former case, the plastic adhesive zones
should be considered removed. That is, set \( a = c = 0 \) and \( b = l \). The scarf
angle \( \theta \) is considered so small that \( \cos \theta = 1 \) and \( \theta = 0 \). In other words, the
effect of adhesive peel stresses is omitted from consideration. This is quite
legitimate for the small scarf angles associated with practical aerospace
materials.

The conditions of horizontal equilibrium for a differential element \( dx \) within
the joint are

\[
\frac{dT_1}{dx} + \tau = 0 , \quad \frac{dT_2}{dx} - \tau = 0 . (1)
\]

The stress-strain relations for the adherend materials, accounting for thermo-
elastic effects, yield

\[
\frac{d\delta_1}{dx} = \frac{T_1}{(Et)_1} + \alpha_1 AT , \quad \frac{d\delta_2}{dx} = \frac{T_2}{(Et)_2} + \alpha_2 AT , (2)
\]

in which the adherend thicknesses, as a function of the axial coordinate \( x \) are

\[
(ET)_1 = E_1t_1(1 - \frac{x}{l}) , \quad (ET)_2 = E_2t_2(\frac{x}{l}) . (3)
\]

The adhesive shear strain is taken to be uniform across the thickness of the
bond. That is

\[
\gamma = (\delta_2 - \delta_1)/n . (4)
\]

The elastic adhesive shear stress follows as

\[
\tau = G\gamma = G(\delta_2 - \delta_1)/n . (5)
\]

In solving these equations it is desirable to non-dimensionalize the solution
with respect to the peak adhesive shear stress \( \tau_p \) and the bond overlap. Thus,
introducing the non-dimensionalized axial co-ordinate

\[
\phi = x/l , (6)
\]
a series solution is sought, having the form

$$\frac{\tau}{\tau_p} = \sum_{n=1}^{\infty} A_n \phi^{n-1}.$$  \hfill (7)

We define the adherend 1 end of the joint as critical so that

$$A_1 = 1,$$  \hfill (8)

if necessary by interchange of the identifying subscripts 1 and 2. While a single non-linear differential equation has been derived from the equations above, it cannot be solved directly. This is why a series solution is employed here and, in this case, it is more straightforward to work in terms of the equations above than the derivative governing equation.

The solution proceeds from equation (7). Substitution into equation (1) yields, for the adherend forces per unit width,

$$T_1 = \tau_{av} - \tau_p \sum_{n=1}^{\infty} A_n \phi^n, \quad T_2 = \tau_p \sum_{n=1}^{\infty} A_n \phi^n.$$  \hfill (9)

Now equation (5) is differentiated.

$$\frac{d(\tau/\tau_p)}{d\phi} = \frac{G}{\tau_p \phi} \left[ \frac{d\delta_2}{d\phi} - \frac{d\delta_1}{d\phi} \right].$$  \hfill (10)

Substitution of the series (7) and (9), with the aid of equations (2), leads to the solution

$$\sum_{n=1}^{\infty} (n-1)A_n \phi^{(n-2)} = \frac{G_k}{\tau_p \phi} \left\{ \left( \alpha_2 - \alpha_1 \right) \Delta T + \frac{\tau_p \ell}{E_2 t_2} \sum_{n=1}^{\infty} A_n \phi^{(n-1)} \right\}$$

$$- \frac{\tau_{av} \ell}{E_1 t_1 (1 - \phi)} + \frac{\tau_p \ell}{E_1 t_1 (1 - \phi)} \sum_{n=1}^{\infty} A_n \phi^n \right\}.$$  \hfill (11)
Multiplication throughout by \((1 - \phi)\) converts the equation directly into a form suitable for solution by recurrence relations.

\[
(1 - \phi) \sum_{l}^{\infty} (n-1)A_{n} \phi(n-2) = \frac{G_{l}}{\tau_{p}^{n}} \left(\alpha_{2} - \alpha_{1}\right) \Delta T (1 - \phi) - \frac{G_{l}^{2} \tau_{av}}{n\tau_{p} E_{1t} \tau_{p}} + \frac{G_{l}^{2}}{n} \left[ \sum_{l}^{\infty} \frac{A_{n}}{E_{2t}} \phi(n-1) + \frac{1}{E_{1t}} \sum_{l}^{\infty} \frac{A_{n}}{\phi} \right].
\] (12)

In order to give the solution the greatest coverage with the minimum number of independent variables, certain non-dimensional parameters are introduced. The non-dimensionalized overlap is given by the square root of

\[
(\lambda E)^{2} = \frac{G_{l}^{2}}{n} \left[ \frac{1}{E_{1t}} + \frac{1}{E_{2t}} \right] = \frac{\tau_{p}^{E} G_{l}^{2}}{n\gamma_{e}} \left[ \frac{1}{E_{1t}} + \frac{1}{E_{2t}} \right],
\] (13)

the non-dimensionalized thermal mismatch term is

\[
C_{THERM}(1) = \frac{\lambda \left(\alpha_{2} - \alpha_{1}\right) \Delta T}{\tau_{p} \left(\frac{1}{E_{1t}} + \frac{1}{E_{2t}}\right)}, \quad C_{THERM}(2) = - C_{THERM}(1),
\] (14)

and the adherend stiffness ratio is

\[
E_{TR}(1) = \frac{E_{1t}}{E_{2t}}, \quad E_{TR}(2) = \frac{E_{2t}}{E_{1t}}.
\] (15)

It is interesting to note that precisely the same variables govern the double-lap joint [see Reference (1)]. Equation (12) then becomes

\[
\sum_{l}^{\infty} \left[ (n-1)A_{n} - (n-2)A_{n-1} \right] \phi(n-2) = \left(\lambda E\right) \times C_{THERM}(1) \times (1 - \phi) - \frac{(\lambda E)^{2} \tau_{av}}{[1 + E_{TR}(1)]} + \frac{(\lambda E)^{2} \times E_{TR}(1)}{[1 + E_{TR}(1)]} \sum_{l}^{\infty} \frac{A_{n}}{\phi} \phi^{n}.
\] (16)
By rearranging the limits of the series it follows that

\[
\sum_{l}^{\infty} \left[(n+1)A_{n+2} - nA_{n+1}\right] \phi^{n} = (\lambda \phi) \times \text{CTHERM}(1) (1 - \phi) - \frac{(\lambda \phi)^{2} \tau_{av}}{[1 + \text{ETR}(1)] \tau_{p}}
\]

\[
\quad + \frac{(\lambda \phi)^{2} \text{ETR}(1)}{[1 + \text{ETR}(1)]} \sum_{n=1}^{\infty} A_{n+1} \phi^{n} + \frac{(\lambda \phi)^{2} [1 - \text{ETR}(1)]}{[1 + \text{ETR}(1)]} \sum_{n=1}^{\infty} \frac{A_{n} \phi^{n}}{n}.
\]  

(17)

For large values of \(n\), on setting to zero the coefficient of the term \(\phi^{n-2}\), the recurrence relation is deduced as

\[
A_{n} = \left\{(n-2)A_{n-1} + (\lambda \phi)^{2} \left[ \frac{\text{ETR}(1)}{1 + \text{ETR}(1)} \right] A_{n-1} - \frac{1 - \text{ETR}(1)}{1 + \text{ETR}(1)} A_{n-2} \right\} / (n-1).
\]  

(18)

It remains now to establish the initial conditions by examining the coefficients of the \(\phi^{0}\) and \(\phi^{1}\) terms. From the coefficient of \(\phi^{0}\),

\[
A_{2} = (\lambda \phi) \text{CTHERM}(1) - (\lambda \phi)^{2} \left[ \frac{1}{1 + \text{ETR}(1)} \right] \frac{\tau_{av}}{\tau_{p}} + (\lambda \phi)^{2} \left[ \frac{\text{ETR}(1)}{1 + \text{ETR}(1)} \right] A_{1}
\]  

(19)

while, from the coefficient of \(\phi^{1}\),

\[
2A_{3} - A_{2} = -(\lambda \phi) \text{CTHERM}(1) + \frac{(\lambda \phi)^{2}}{[1 + \text{ETR}(1)]} \left[ [1 - \text{ETR}(1)]A_{1} + \text{ETR}(1) \frac{A_{2}}{2} \right].
\]  

(20)

It follows from equation (19) that, quite generally, for long overlaps (large values of \(\lambda \phi\)),

\[
\frac{\tau_{av}}{\tau_{p}} \rightarrow \text{ETR}(1) \leq 1.
\]  

(Interchange 1 and 2 if necessary.)

(21)

This surprisingly simple result proves to dominate the entire behavior of bonded scarf joints, even for elastic-plastic adhesives. This equation demonstrates conclusively the importance of maintaining adherend stiffness balance whenever possible. When this is maintained, in the absence of any thermal mismatch, the adhesive is essentially uniformly stressed throughout the entire overlap of any length. The only minor exception is the local end effect identified by Richards in Reference (6).
Returning now to the solution, in terms of equations (18) to (20), it follows by integrating equation (7) that

$$\frac{\tau_{av}}{\tau_p} = \sum_{n=1}^{\infty} A_n \quad .$$

(22)

In using this series it is necessary to employ two arbitrary constants to satisfy the boundary conditions. The first two are chosen. That is

$$\frac{\tau_{av}}{\tau_p} = A_1 \times \text{SIG}(3) + A_2 \times \text{SIG}(4)$$

(23)

and, because of equation (8),

$$\frac{\tau_{av}}{\tau_p} = \text{SIG}(3) + A_2 \times \text{SIG}(4) .$$

(24)

The summations SIG(3) and SIG(4) are the quantities formed by evaluating the coefficients in equation (22) by means of equations (20) and (18) after setting, in turn,

$$A_1 = 1, \quad A_2 = 0 \quad \text{for SIG}(3)$$

(25)

and

$$A_1 = 0, \quad A_2 = 1 \quad \text{for SIG}(4) .$$

(26)

The solution procedure employed in the FORTRAN IV digital computer program listed in Appendix A1 is as follows. The coefficient $A_3$ for each set of initial values (25) and (26) is evaluated in terms of equation (20). Then a number of higher order coefficients are evaluated in turn through the recurrence relation (18), the same number being evaluated for SIG(3) as for SIG(4). The results of these summations are then substituted into equation (19) which takes on the form

$$A_2 \left\{ 1 + \frac{(\lambda \xi)^2}{[1 + \text{ETR}(1)]} \text{SIG}(4) \right\} = (\lambda \xi) \text{CTHERM}(1) + \frac{(\lambda \xi)^2 \text{ETR}(1)}{[1 + \text{ETR}(1)]}$$

$$- \frac{(\lambda \xi)^2}{[1 + \text{ETR}(1)]} \text{SIG}(3) .$$

(27)
The unknown $A_2$ is then to be evaluated and substituted into equation (19) re-arranged in the form

$$
\frac{\tau_{av}}{\tau_p} = \frac{[1 + ETR(1)] \cdot \text{OTHERM}(1) \cdot [1 + ETR(1)]}{(\lambda \ell)^2} - \frac{1}{(\lambda \ell)^2} A_2 .
$$

(28)

This equation establishes the potential bond shear strength.

The detailed discussion of parametric effects is presented in Section 5 but certain features of the mathematics of the numerical solution merit elaboration at this stage. The most important feature is the decision to evaluate the terms $A_n/n$ of the average stress series (22) directly rather than the quantities $A_n$ of the series (7). To do so, equation (18) is re-organized to the form

$$
\left(\frac{A_n}{n}\right) = \frac{(n-1)(n-2)(A_{n-1})}{(n-1)} + (\lambda \ell)^2 \left[ \frac{ETR(1)}{1 + ETR(1)} \left(\frac{A_{n-1}}{n-1}\right) + \frac{1 - ETR(1)}{1 + ETR(1)} \left(\frac{A_{n-2}}{n-2}\right) \right] .
$$

(29)

The reason for this is the factor $(\lambda \ell)^2$ in equations (29) and (18). Because of this, for long overlaps, a much higher value of $n$ is needed to reach negligible values of $A_n$ from equation (18) than to reach negligible values of $A_n/n$ from equation (29). Indeed, even with the use of equation (29) rather than equation (18) it remained impossible to compute reliable internal stress distributions for long overlap joints, even with as many as 50 terms of the shear stress series because of overflow in the computer. Such a computation is of little importance, however, since the critical location must be at one end or other of the joint. In spite of this problem, however, equation (27) converges rapidly, usually within the first five successive evaluations (for progressively increasing $n$) of $\text{SIG}(3)$ and $\text{SIG}(4)$. The program in Appendix A1 used 20 terms. In addition to this, because $A_2$ is divided by $(\lambda \ell)^2$ in equation (28), an extremely reliable value of $\tau_{av}/\tau_p$ can be computed readily. The program identifies the more critical end by the simple expedient of estimating the strength starting from each end of the joint and selecting the lower value. It is obvious that a computation of $\tau_{av}/\tau_p > 1$ signifies simply that condition (8) was violated. A negative value of $\tau_{av}/\tau_p$ indicates such severe thermal mismatch between adherends that the joint will break apart prior to application of any mechanical loads.
The computation of joint strength proceeding from the other end of the joint is effected by simply interchanging the subscripts 1 and 2 on all affected quantities. With regard to adherend stiffness imbalance alone, it is always possible to identify from equation (28) that the more critical end (1) is that for which $\text{ETR}(1) \leq 1$. The possible ambiguity arises as the result of the thermal mismatch terms. Since $\text{CTHERM}(1)$ may be either negative or positive independently of whether $\text{ETR}(1)$ is less than or greater than unity, severe thermal mismatch may nullify or even overpower any stiffness imbalance effects. This possibility is evidently greatest for short overlaps because of the factor $(\lambda \varepsilon)$ in the denominator of the thermal term in equation (28). It follows that the critical end of the joint between given adherends may well change as the overlap changes and, indeed, such behavior was predicted by the computer program output.

Equations (1) and (2) have been set up for applied tensile loads in the adherends. In the event that the applied load is compressive, it can be seen with reference to Figure 2 that all quantities except the thermal strain terms will change sign. This implies that, in the absence of any thermal mismatch effects, the same end of the joint is critical for both tensile and compressive adherend loads and that the joint strength is the same. Rather than change the sign of all quantities with the exception of the thermal terms, the program merely changes the signs of $\text{CTHERM}(1)$ and $\text{CTHERM}(2)$ to account for compressive loading rather than tensile loading. It should be noted that, as a consequence, the opposite end of the same joint may be critical for a reversed load and that the strength may not be the same if there is also stiffness imbalance between the adherends. Likewise, just as for double-lap joints, if the thermal mismatch terms nullify any stiffness imbalance effects for one load direction, they must aggravate the stress concentrations for a load in the reverse direction. By analogy with the double-lap joint analyses in Reference (1), the case of in-plane shear loading is covered by the analysis above replacing $E_1$ and $E_2$ in equation (2) and those equations based on it by the shear moduli $G_1$ and $G_2$ and neglecting the thermal affects which induce bond stresses at right angles to those of concern for mechanical in-plane shear loads except at the sides of the joint. The direct adherend forces $T_1$ and $T_2$ are replaced by shear forces $S_1$ and $S_2$ per unit length. A more precise representation of thermal effects for in-plane shear loading would necessarily require a two-dimensional
analysis rather than the one-dimensional solution above and the justification for doing so is minimized by the small amount of adhesive plasticity that even the real brittle adhesives exhibit.
3. ELASTIC-PLASTIC ANALYSIS OF SCARF JOINTS

The preceding elastic analysis covers essentially the most difficult formula-
tive portions of the elastic-plastic scarf joint analysis. New numerical
difficulties of major proportions were encountered in the generation of specific
answers by the computer program, but the plastic part of the analysis is
straightforward. The necessary additional geometry and nomenclature are identified in Figure 2. Equations (1), (2) and (4) continue to apply, with the substitutions

\[ dx = \xi \, d\xi = \xi \, d\chi = \xi \, d\zeta \]  

(30)

as appropriate. Equation (5) is supplemented by the relation

\[ \tau = \tau_p \quad \text{for} \quad 0 \leq \xi \leq a \quad \text{and} \quad 0 \leq \xi \leq c. \]  

(31)

The relations (4) for the adherend stiffnesses are replaced by

\[ (Et)_1 = E_1 t_1 (1 - \xi) = E_1 t_1 (1 - \frac{a}{\xi} - \chi) = E_1 t_1 (1 - \frac{a}{\xi} - \frac{b}{\xi} - \zeta) \]  

(32)

and

\[ (Et)_2 = E_2 t_2 \xi = E_2 t_2 \left( \frac{\alpha}{\xi} + \chi \right) = E_2 t_2 \left( \frac{\alpha}{\xi} + \frac{b}{\xi} + \zeta \right) \]  

(33)

In the elastic zone, the location of which has yet to be determined, the same
power series solution is sought:

\[ \tau_p = \sum_{l}^{\infty} A_n \chi^{(n-1)} \quad \text{or} \quad \frac{\chi}{\gamma} = \sum_{l}^{\infty} A_n \chi^{(n-1)}, \]  

(34)

again with \( A_1 = 1 \) by definition of adherend 1 as the more highly loaded end of
the joint.

In the left adhesive plastic zone of the joint illustrated in Figure 2, the
adherend forces per unit width follow from equations (1) and (31) as

\[ T_1 = \tau_{av} \frac{\xi}{\tau_p} - \tau_{p} \xi \quad \text{and} \quad T_2 = \tau_{p} \xi. \]  

(35)
Substitution into equation (4), making use of equations (2), yields

\[
\gamma = \frac{\delta_2 - \delta_1}{n} = \frac{1}{n} \left[ (\alpha_2 - \alpha_1) \Delta T \xi + \int_0^\xi \frac{T_2 \xi d\xi}{(E_2)_2} - \int_0^\xi \frac{T_1 \xi d\xi}{(E_1)_1} \right], \tag{36}
\]

\[
\gamma = \frac{1}{n} \left[ (\alpha_2 - \alpha_1) \Delta T \xi + \frac{\tau_p \xi^2}{E_2t_2} + \int_0^\xi \frac{\tau_p - \tau_{av}}{E_1t_1} d\xi - \frac{\tau_p \xi^2}{E_1t_1} \right] + C, \tag{37}
\]

\[
\gamma = \frac{1}{n} \left[ (\alpha_2 - \alpha_1) \Delta T \xi + \frac{\tau_p \xi^2}{E_2t_2} \left( \frac{1}{E_2t_2} - \frac{1}{E_1t_1} \right) \xi - \frac{\tau_p - \tau_{av}}{E_1t_1} \ln(1 - \xi) \right] + C. \tag{38}
\]

The appropriate boundary conditions are that

\[
\gamma = \gamma_e + \gamma_p \quad \text{at} \quad \xi = 0
\]

and

\[
\gamma = \gamma_e \quad \text{at} \quad \xi = \alpha / \xi.
\]

Consequently, from equations (39) and (38),

\[
C = (\gamma_e + \gamma_p)
\]

so that, from equations (40) and (38),

\[
\gamma_p = \frac{1}{n} \left[ (\alpha_2 - \alpha_1) \Delta T \xi \left( \frac{a}{\xi} \right) + \frac{\tau_p \xi^2}{E_2t_2} \left( \frac{1}{E_2t_2} - \frac{1}{E_1t_1} \right) \left( \frac{a}{\xi} \right) - \frac{\tau_p - \tau_{av}}{E_1t_1} \ln \left( \frac{1 - \frac{a}{\xi}}{1} \right) \right]. \tag{40}
\]

Equation (42) may be non-dimensionalized by use of the quantities in equations (13) to (15). It then adopts the form

\[
\left( \frac{\gamma_p}{\gamma_e} \right) = \left( -\lambda \xi \right) \text{C Therm}(1) \left( \frac{a}{\xi} \right) + \left( \lambda \xi \right) \left[ \frac{1 - \text{ETR}(1)}{1 + \text{ETR}(1)} \right] + \left( \lambda \xi \right) \left[ \frac{1 - \left( \frac{\tau_{av}}{\tau_p} \right)}{1 + \text{ETR}(1)} \right] \ln \left( \frac{1 - \frac{a}{\xi}}{1} \right).
\]

\[
\tag{43}
\]

In solving for the joint strength it is necessary to maintain continuity at the transition ($\xi = \alpha / \xi$) from plastic to elastic adhesive behavior. The continuity of adherend stresses requires that there be no change in \(d\gamma/dx\).

From equations (4) and (2)

\[
\frac{d\gamma}{dx} = \frac{1}{n} \left[ (\alpha_2 - \alpha_1) \Delta T + \frac{T_2}{(E_2)_2} - \frac{T_1}{(E_1)_1} \right]. \tag{44}
\]
or, in non-dimensionalized form, for the plastic side of the transition

\[
\frac{d(\gamma/\gamma_e)}{d\xi} \bigg|_{\xi = a/l} = (\lambda \ell) \ c\text{therm}(1) - (\lambda \ell)^2 \frac{1 - \text{ETR}(1)}{1 + \text{ETR}(1)} + \frac{(\lambda \ell)^2 [1 - (\tau_{av}/\tau_p)]}{[1 + \text{ETR}(1)][1 - (a/l)]}.
\]

For the elastic side, equation (34) requires that

\[
\frac{d(\gamma/\gamma_e)}{d\chi} \bigg|_{\chi = 0} = A_2. \tag{46}
\]

Since \(A_1 = 1\), the elastic stress distribution can now be evaluated by a recurrence formula, just as in Section 2.

Under certain combinations of stiffness and thermal mismatch between adherends there will be no second plastic adhesive shear stress zone at the far end of the joint while under others there will be. In the former case, the evaluation of the elastic adhesive shear stress at \(\chi = 1 - (a/l)\) by means of the series (34) will lead to a result \(\tau_{end}/\tau_p \leq 1\). A value of this ratio greater than unity indicates a need for evaluating the affects of the presence of a second plastic adhesive zone, at the far end of the joint. Referring again to Figure 2, the adherend forces per unit width are evaluated through equations (1) and (31) as

\[
T_1 = \tau_p \ell \left(\frac{c}{\ell} - \xi\right), \quad T_2 = \tau_{av} - \tau_p \ell \left(\frac{c}{\ell} - \xi\right). \tag{47}
\]

Substitution of equations (47) and (33) into equation (44) leads to the expression

\[
\frac{d(\gamma/\gamma_e)}{d\zeta} = \frac{G}{\tau_p E_{t2}} \left(\alpha_2 - \alpha_1\right) \Delta T \ell - \frac{\tau_p g^2}{E_{t1}} + \frac{\tau_{av} g^2}{E_{t2}} - \frac{(\tau_p - \tau_{av}) g^2}{(E_{t2} + E_{t1})[1 - (c/\ell)]}. \tag{48}
\]

The transition relation at \(\zeta = 0\) follows as

\[
\frac{d(\gamma/\gamma_e)}{d\gamma} \bigg|_{\zeta = 0} = (\lambda \ell) \ c\text{therm}(1) - (\lambda \ell)^2 \frac{1 - \text{ETR}(1)}{1 + \text{ETR}(1)} - \frac{(\lambda \ell)^2 [1 - (\tau_{av}/\tau_p)]}{[1 + \text{ETR}(1)][1 - (a/l)]}. \tag{49}
\]
Equation (48) may be integrated once, yielding

\[
\left( \frac{\gamma}{\gamma_e} \right) = (\lambda \xi) \text{CTHERM}(1) \zeta - (\lambda \xi)^2 \frac{1 - ETR(1)}{1 + ETR(1)}\zeta - \\
- (\lambda \xi)^2 \frac{[1 - (\tau_{av}/\tau_p)]ETR(1)}{[1 + ETR(1)]} \ln(1 - \frac{c}{\xi} + \zeta) + C ,
\]

in which, since

\[
\gamma = \gamma_e \quad \text{at} \quad \zeta = 0 ,
\]

\[
1 = - (\lambda \xi)^2 \frac{[1 - (\tau_{av}/\tau_p)]ETR(1)}{[1 + ETR(1)]} \ln(1 - \frac{c}{\xi}) + C .
\]

Signifying by \( \gamma_{\text{max}} \) the peak adhesive shear strain at the less critical (by definition) right hand end of the joint,

\[
\left( \frac{\gamma_e}{\gamma_{\text{max}}} \right) = (\lambda \xi) \text{CTHERM}(1)\left(\frac{c}{\xi}\right) - (\lambda \xi)^2 \frac{1 - ETR(1)}{1 + ETR(1)}\left(\frac{c}{\xi}\right)\zeta - \\
+ (\lambda \xi)^2 \frac{[1 - (\tau_{av}/\tau_p)]ETR(1)}{[1 + ETR(1)]} \ln\left(1 - \frac{c}{\xi}\right) .
\]

A comparison of equations (43) and (53) shows complete consistency upon interchanging subscripts 1 and 2. While equation (53) could be employed to identify whether the left or right hand end of the joint in Figure 2 is more critical once the extent of the second plastic zone \((c/\xi)\) had been established, there is an inherent numerical difficulty in the step by step computation of the strength by the procedure outlined above. It was explained in Section 2 that, for the perfectly-elastic adhesive, only the average adhesive shear stress could be computed and not the stress distribution as a function of position along the joint. In the computer program in Appendix A3, the only reason why it proved possible to evaluate the extent of the elastic trough, for long overlaps, was the factor \([1-(a/\xi)-(c/\xi)]\)^{n-1} < 1 in equation (34). At high values of \(n\), this very small term was able to overpower the influence of the \((\lambda \xi)^2\) factor in the numerator of the recurrence formula (18). This numerical accuracy problem prevented the reliable evaluation of \(d(\gamma/\gamma_e)/dx\) at \(x = (b/\xi)\) to match boundary conditions at the transition of the second plastic adhesive zone. Consequently an iterative solution had to be employed to evaluate the maximum possible
extent of the elastic trough.

Referring to equations (45) and (46), it can be seen that, in the iterative solution process, the second term of the elastic adhesive shear stress series $A_2$ depends on the preceding estimates of both $(a/\lambda)$ and $(\tau_{av}/\tau_p)$. In the early development of the digital computer program for elastic-plastic scarf joints insurmountable convergence difficulties were encountered if the initial estimates for $(\tau_{av}/\tau_p)$ and $(a/\lambda)$ were not sufficiently close to the true values. This difficulty was eventually overcome by the following technique. Equation (43) was re-arranged to read

$$\left(\frac{\tau_{av}}{\tau_p}\right) = 1 - \frac{\left\{\frac{[1 + \text{ETR}(1)]\gamma_p}{(\lambda \varepsilon)^2} + \frac{[1 + \text{ETR}(1)]\text{CTHERM}(1)}{(\lambda \varepsilon)} - \frac{[1 - \text{ETR}(1)]\gamma_p}{(\lambda \varepsilon)}\right\}}{2\ln[1 - (a/\lambda)]}.$$  (54)

This can be differentiated with respect to $(a/\lambda)$ so that

$$\frac{d(\tau_{av}/\tau_p)}{d(a/\lambda)} = 0 \quad \text{when}$$

$$\left(1 - \frac{a}{\lambda}\right)\ln\left(1 - \frac{a}{\lambda}\right) = \frac{\left\{\frac{[1 + \text{ETR}(1)]\gamma_p}{(\lambda \varepsilon)^2} + \frac{[1 + \text{ETR}(1)]\text{CTHERM}(1)}{(\lambda \varepsilon)} - \frac{[1 - \text{ETR}(1)]\gamma_p}{(\lambda \varepsilon)}\right\}}{[1 - \text{ETR}(1)] - \frac{[1 + \text{ETR}(1)]\text{CTHERM}(1)}{(\lambda \varepsilon)}}.$$  (55)

Substitution of equation (55) into equation (54) yields, for the minimum (stationary) value of $(\tau_{av}/\tau_p)$

$$\frac{\tau_{av}}{\tau_p} = \text{ETR}(1) + \frac{[1 + \text{ETR}(1)]\text{CTHERM}(1)}{(\lambda \varepsilon)}$$

$$+ \frac{a}{\lambda} \left\{[1 - \text{ETR}(1)] - \frac{[1 + \text{ETR}(1)]\text{CTHERM}(1)}{(\lambda \varepsilon)}\right\}.  \quad \text{(56)}$$

This is evidently consistent with the elastic solution $(a/\lambda) = 0$ for large overlaps and, upon subsequent comparison with the more precisely estimated joint strengths, proved to be an extremely close lower bound for all cases of practical interest. It is significantly conservative only for very short overlaps [small values of $(a/\lambda)$] or very brittle adhesives [very small values of $(\gamma_p/\gamma_e)$]. The adhesive shear strain capacity $\gamma_p$ is involved in equation (56) implicitly through the extent $(a/\lambda)$ of the plastic zone. Equation (55)
is solved by iteration to evaluate \((a/\ell)\) and the result substituted into equation (56) or (54). Appendix A2 contains a listing of the FORTRAN IV digital computer program employed to solve equations (55) and (54), together with sample outputs and brief user instructions. The iteration technique eventually adopted proved to be quite convergent, after other re-arrangements of equation (55) demonstrated strongly divergent characteristics.

This program in Appendix A2 served to provide the initial estimates of \((a/\ell)\) and \((\tau_{av}/\tau_p)\) in the more precise solution listed in Appendix A3. The sequence of variables used in the solution is \((a/\ell)\), \((\tau_{av}/\tau_p)\) and \((c/\ell)\) after which \((\tau_{av}/\tau_p)\) is recomputed and the estimate of \((a/\ell)\) adjusted until convergence is attained. In those cases in which the critical end is not evident by inspection, the potential bond shear strength is computed from each end of the joint and the lower value adopted. Brief user instructions and sample outputs are included in Appendix A3.

The analyses above for scarf joints pertain to adhesive shear stresses and it is demonstrated that a small enough scarf angle can always be found to transfer the full adherend strength through the bond with an adequate margin. There is, of course, a potential problem with the adherend strength(s) if the scarf angle is too small. Specifically, one adherend will fail if the scarf angle \(\theta\) is so small that

\[
\theta < \frac{\tau_p}{F_u},
\]

(where \(F_u\) is the ultimate adherend stress in tension, compression, or shear, as appropriate) at the more critical end of the joint (identified by the adhesive shear stress analysis). Should this situation arise, the solution is to decrease the adherend stiffness imbalance across the joint by local reinforcement of the softer adherend. It is evident from equation (17) that this potential problem of breaking off the tip of (usually) the stiffer adherend is more likely to arise with the brittle adhesives (higher values of peak adhesive shear stress \(\tau_p\)) than with ductile adhesives. This is one important reason for preferring to effect the load transfer with a shorter overlap of ductile adhesive than with a longer overlap of brittle adhesive. The extreme case of making the overlap so extremely long that the peak adhesive shear
stress actually developed is restricted to a small fraction of its capacity when adherend failure occurs outside the joint has theoretical appeal only, frequently being quite impractical.
4. DISCUSSION OF PARAMETRIC EFFECTS

Representative solutions from Sections 2 and 3 for unbalanced bonded scarf joints are illustrated in Figures 3 through 7. Figures 3 and 4 show the separate effects of adherend stiffness and thermal mismatch, respectively, on the elastic joint strength. The deviations from unity in the \( \frac{\tau_{av}}{\tau_p} \) ratio, for a given overlap \( \lambda \ell \), are proportional to the individual imbalances. The effect of stiffness imbalance is a smooth decrease from a fully-efficient bond \( \tau_{av} = \tau_p \) to a less efficient bond \( \tau_{av} < \tau_p \) asymptoting towards the solution given in equation (21). This diagram, more than any other, characterizes the dominant feature of the scarf joint behavior. This is that the potential bond strength continues to increase indefinitely with increasing overlap. This is in marked contrast to the behavior of uniform lap joints [References (1) and (2)], which develop maximum strengths which remain effectively constant beyond intermediate overlaps. The effect of this characteristic on the potential bond strength of scarf joints is that, by making the scarf angle sufficiently small, one can always design a joint in which the potential bond strength exceeds the adherend strength by any specified factor. This is amply demonstrated by curve D in Figure 4. While adherend stiffness and thermal mismatch combine to decrease the bond efficiency below the unit value of curve A, the bond strength for long overlaps ends up being proportional to the overlap. As a consequence of this characteristic, the elastic adhesive shear stresses play a far more important role in the strength of scarf joints than they do in the case of uniform lap joints. Nevertheless, it would be erroneous to conclude that one could always design an unbalanced scarf joint within the capabilities of an elastic adhesive. The limiting problem is that, as the scarf angle becomes very small, there is a strong probability of breaking off the tip of the stiffer adherend. While not as acute a design detail problem as its counterpart for stepped-lap joints, this feature restricts the scarf angle to exceed the value

\[
\theta = \arctan\left(\frac{\tau_p}{F_u}\right) \tag{58}
\]

in which \( F_u \) is the adherend ultimate strength (in tension, compression, or shear, as appropriate for the applied load).

The effect of adherend thermal mismatch on the potential bond strength of scarf joints is shown in Figure 4. It is clear that the effects are insignificant for very short and very long overlaps, being significant only for those
overlaps of practical interest. The effects are maximum at \((\lambda \varepsilon) = 2\) for all values of the thermal mismatch coefficient CTHERM.

Figure 5 shows the interaction between adherend stiffness and thermal mismatch. Curves B, D and E represent one set of solutions, with curve B showing the effect of stiffness imbalance alone. Curve D adds the influence of compounding thermal mismatch as well. Curve E demonstrates the behavior of self-cancelling adherend imbalances at \((\lambda \varepsilon) = 3\). For values of \((\lambda \varepsilon)\) less than 3, the thermal mismatch effects dominate over those arising from stiffness mismatch and the more critical end of the joint is reversed. Curves A, C and F form another set showing how, for severe adherend thermal mismatch, there is a range of overlaps for which the residual thermal stresses are so severe that the joint will split apart without the application of any mechanical loads. Quite unlike the behavior of uniform lap joints [References (1) and (2)], this problem can be eliminated completely by sufficient extension of the overlap.

Just as is the case for uniform lap joints adhesive plasticity can increase the potential bond shear strength. The extent of this strength increase is shown in Figures 6 and 7 for stiffness and thermal mismatch, respectively. For each amount of adhesive plastic shear strain, there is an associated overlap below which the bond can be uniformly stressed. For indefinitely large overlaps the asymptotic solution (21) again holds, masking completely the influence of any adhesive plasticity. In the overlaps of practical interest, the actual amount of adhesive plasticity available from real structural adhesives can improve the potential joint strength greatly. One benefit of using a ductile adhesive of moderately high peak shear stress rather than a brittle adhesive of very high peak shear stress is that the joint is better able to withstand the variation in joint load which inevitably occurs as the result of manufacturing imperfections and non-uniform load distribution. Another benefit is that the problem of breaking off the tip of the adherend at the more critically loaded end [see equation (58)] is greatly alleviated. If the tip of the stronger adherend were allowed to be broken off, this would impose an effective net area loss on the cross-section of the weaker adherend.
5. ELASTIC ANALYSIS OF STEPPED-LAP JOINTS

The analysis for the strength of stepped-lap adhesive-bonded joints contains features of both the uniform lap joints [References (1) and (2)] and the scarf joint above. Peel stress problems are ignored on the grounds that the outermost end steps are invariably thin enough (in good design practice) not to induce significant peel stresses in the adhesive. Likewise, the small eccentricity in the load path has been ignored in the interests of obtaining a useful uncomplicated design tool.

A representative idealized stepped-lap joint is shown in Figure 8, along with the sign convention and nomenclature necessary for the analysis. Just as for the scarf joint analysis, the same diagram serves also for the elastic-plastic analysis, so it contains information not necessary for the elastic analysis. This begins with the equilibrium equations for a differential element of one of the steps.

\[
\frac{dT_o}{dx} + 2\tau = 0 , \quad \frac{dT_i}{dx} - 2\tau = 0 . \tag{59}
\]

Here the subscripts \( o \) and \( i \) refer to the "outer" and "inner" adherends, respectively, and the factors 2 in equations (59) account for the two bond surfaces surrounding the inner adherend. Consequently the adherend thicknesses \( t_o \) and \( t_i \) refer to the total cross-section and the forces \( T_o \) and \( T_i \) do likewise. The nature of the solution is such that it is, on occasions, necessary to interchange the subscripts \( o \) and \( i \) mathematically. The thermo-elastic relations for the adherends are

\[
\frac{d\delta_o}{dx} = \frac{T_o}{E_o t_o} + \alpha_o \Delta T , \quad \frac{d\delta_i}{dx} = \frac{T_i}{E_i t_i} + \alpha_i \Delta T . \tag{60}
\]

The adhesive shear strain, for tensile lap shear loading, is

\[ \gamma = (\delta_i - \delta_o) / \eta . \tag{61} \]

while the elastic adhesive shear stress is related to the shear strain by the relation

\[ \tau = G\gamma = G(\delta_i - \delta_o) / \eta . \tag{62} \]
The solution proceeds just as in Reference (1).

\[
\frac{d\tau}{dx} = \frac{G}{n} \left[ \frac{d\delta_1}{dx} - \frac{d\delta_0}{dx} \right] = \frac{G}{nE_{i1}} \left[ \frac{T_i}{E_{i1}} - \frac{T_o}{E_{o1}} + (\alpha_i - \alpha_o)\Delta T \right].
\]

(63)

\[
\frac{d^2\tau}{dx^2} = \frac{G}{nE_{i1}} \left[ \frac{2}{E_{i1}} + \frac{2}{E_{o1}} \right] \tau = \lambda^2 \tau.
\]

(64)

The solution of equation (64) is

\[
\tau = A \cosh(\lambda x) + B \sinh(\lambda x)
\]

(65)

where the integration constants \(A\) and \(B\) are to be determined by boundary conditions for each step. Substitution of equation into equation (59) yields

\[
T_o = T_{o\text{ref}} - 2 \frac{A}{\lambda} \sinh(\lambda x) - 2 \frac{B}{\lambda} [\cosh(\lambda x) - 1]
\]

(66)

and

\[
T_i = T_{i\text{ref}} + 2 \frac{A}{\lambda} \sinh(\lambda x) + 2 \frac{B}{\lambda} [\cosh(\lambda x) - 1].
\]

(67)

The values of \(T_{o\text{ref}}\) and \(T_{i\text{ref}}\) depend upon the origin of \(x\) adopted. In the solution it proves convenient to adopt the start of each step as the origin for that step. Integrating again, by means of equations (69),

\[
\delta_o = \delta_{o\text{ref}} + \alpha_o \Delta T x + \frac{1}{E_{o1}} \left[ T_{o\text{ref}} x - 2 \frac{A}{\lambda^2} \cosh(\lambda x) - 2 \frac{B}{\lambda^2} [\sinh(\lambda x) - (\lambda x)] \right]
\]

(68)

and

\[
\delta_i = \delta_{i\text{ref}} + \alpha_i \Delta T x + \frac{1}{E_{i1}} \left[ T_{i\text{ref}} x + 2 \frac{A}{\lambda^2} \cosh(\lambda x) + 2 \frac{B}{\lambda^2} [\sinh(\lambda x) - (\lambda x)] \right].
\]

(69)

In the FORTRAN IV digital computer program, listed in Appendix A4, used to solve the equations above for the elastic stepped-lap joint, the technique of solution is as follows. The solution proceeds, one joint step at a time starting with assumed values of the load and initial adhesive shear strain (or stress). The latter is set at the maximum adhesive allowable and remains so unless it is computed that the peak adhesive shear strain is greater elsewhere (most probably at the other end of the joint) in which case the initial strain is reduced as much as necessary to avoid exceeding the allowable. The key
equation in the solution is equation (65). The integration constant \( A \) is evaluated as the specified (or subsequently computed) adhesive shear stress at the start of the step under consideration.

\[
A = \tau_x = 0 .
\] (70)

The other constant \( B \) derives from equation (63), also evaluated at the start of that step. That is

\[
\frac{d\tau}{dx} = A\lambda \sinh(\lambda x) + B\lambda \cosh(\lambda x) = \frac{G}{\eta \lambda \left[ \frac{T_i}{E_{i1}} - \frac{T_o}{E_{o1}} + (\alpha_i - \alpha_o)\Delta T \right]}
\] (71)

so that at \( x = 0 \)

\[
B = \frac{G}{\eta \lambda \left[ \frac{T_i}{E_{i1}} - \frac{T_o}{E_{o1}} + (\alpha_i - \alpha_o)\Delta T \right]} \bigg|_{x = 0} .
\] (72)

The values of \( \tau, T_o, T_i, \delta_o \) and \( \delta_i \) at the end of that step then follow from equations (65), (66), (67), (68), (69) and (62), respectively. If, after one complete set of computations, the load computed to be transferred out of the far end of the joint does not match that assumed to act at the near (starting) end, the initial estimate is adjusted until the two quantities do match. At that stage, a check is made throughout the joint, step by step, to identify the most critical adhesive and adherend locations. If any negative margins are identified, the load and peak adhesive shear stress are reduced as much as is necessary to eliminate them.

While the formulation of the equations and analysis scheme above is quite straightforward, the actual numerical solution of the problem proved to be quite difficult. Even with double precision it was almost invariably impossible to compute values for all steps of the joint in a single pass, even if the initial conditions (load and peak adhesive shear stress) were precisely correct to 16 significant figures. A change of 1 in the 16th significant digit of an initial condition would frequently effect a change by a factor of up to \( \pm 10^7 \) in a quantity computed in the fourth or fifth step. This was not the result of a poorly conditioned mathematical formulation. It follows directly from strong physical characteristics of stepped-lap joints. It is the nature of stepped-lap joints, be they bonded or bolted, that any non-uniformities in the load transfer are dominated by the geometry and materials of the end three
steps. What happens in between has only negligible effect on the critical loads which almost invariably occur at one end or other of the joint. Likewise, in a uniform lap joint, practically all the load is transferred through the end three (rows of) bolts or through a narrow effective end zone of adhesive. Because of this characteristic the initial coding of the equations led to a highly accurate estimate of the load (assuming that the adhesive was critical at one end of the joint) but was unable to compute the internal loads and check on the adherend strength margin. The technique finally employed for dealing with this problem took advantage of the seemingly undesirable characteristics and is summarized as follows. By printing out intermediate computations it became clear that, if the initial load estimate on a given step was too high (even if only minutely), on the step just before computations for a subsequent step caused overflows and underflows in the computer the computations would diverge in a characteristic way, precisely the opposite of that for an initial underestimate of that load. Therefore upper and lower bounds were placed on the load estimate and the trial load was taken as the average of these. If the trial load was found to be too high, it served as the new upper bound and, were it too low, it was used to raise the lower bound. This technique was found to bring the upper and lower bounds into precise agreement rapidly. Once this had occurred the computations for the start of that step were frozen and the solution proceeded to perturb each successive step in turn, using the same convergence check above, until the load transferred out of the far end of the joint precisely equalled that input at the near end. Then a check is made, at the ends of each step, on the adhesive and adherend stresses to ensure that neither exceeds the allowable. Due allowance is made for the sign of the quantities involved. In the absence of any thermal mismatch this last operation of checking on the allowables can be performed by simple linear scaling. However, if there is any adherend thermal mismatch present, this adjustment must be performed by iteration since, as is evident from equation (62), the thermal stress terms do not scale in proportion to the adhesive and adherend stresses. A necessary check on the accuracy of the numerical processes has been accomplished by checking that precisely the same solution is obtained regardless of whether the computations commence at the more critically loaded end of the joint or at the other end.
In view of the numerical problems encountered with this analytical solution, it stands to reason that they will have their counterpart in any finite-element solution. Very fine grids would be needed in the high stress gradient areas.
6. ELASTIC-PLASTIC ANALYSIS OF STEPPED-LAP JOINTS

In addition to the equations of Section 5 for the perfectly elastic analysis of stepped-lap joints, the elastic-plastic analysis requires, instead of equation (62), that

\[ \tau = \tau_p \quad \text{for } \gamma \geq \gamma_e, \]  

(73)

and

\[ \tau = G \gamma \quad \text{for } \gamma \leq \gamma_e. \]  

(74)

The elastic-plastic solution is best carried out in terms of the adhesive shear strains rather than the shear stresses. In the plastic adhesive zones, from equations (61) and (60),

\[ \frac{d\gamma}{dx} = \frac{1}{n} \left[ \frac{d\delta_i}{dx} - \frac{d\delta_o}{dx} \right] = \frac{1}{n} \left[ \frac{T_i}{E_{it_i}} - \frac{T_o}{E_{ot_o}} + (\alpha_i - \alpha_o) \Delta T \right] \]  

(75)

whence, from equations (59)

\[ \frac{d^2\gamma}{dx^2} = \frac{2}{n} \left[ \frac{1}{E_{it_i}} + \frac{1}{E_{ot_o}} \right] \tau_p = \frac{\lambda^2}{G} \tau_p = \text{constant}. \]  

(76)

Therefore, in the plastic zone,

\[ \gamma = \frac{\lambda^2}{2G} \tau_p x^2 + Cx + D \]  

(77)

and

\[ T_o = T_{o_{ref}} - 2\tau_p x, \quad T_i = T_{i_{ref}} + 2\tau_p x \]  

(78)

while

\[ \delta_o = \delta_{o_{ref}} + \alpha_o \Delta T x + \frac{1}{E_{ot_o}} \left[ T_o x - \tau_p x^2 \right] \]  

and

\[ \delta_i = \delta_{i_{ref}} + \alpha_i \Delta T x + \frac{1}{E_{it_i}} \left[ T_i x + \tau_p x^2 \right]. \]  

(79)
In equation (77), \( D \) is set equal to \( y \) at the start of any step, since a new zero for \( x \) is chosen at that location for each step. The other constant \( c \) follows from equations (75) and (77). Thus

\[
C = \left. \frac{\text{d}y}{\text{d}x} \right|_{x=0} = \frac{1}{n} \left[ \frac{T_i}{E_{i1}} - \frac{T_0}{E_{o0}} + (a_i - a_o) \Delta T \right]_{x=0}.
\]

Very few individual steps of stepped-lap joints have fully-plastic adhesive throughout the entire joint. Any adhesive plasticity is frequently confined to the end(s) of the step(s). Therefore, in performing an elastic-plastic analysis of a stepped-lap joint, it is necessary to be able to compute the extent of the plastic zones. Therefore, beginning at the left hand end of the step element shown in Figure 8 and assuming a sufficiently high load intensity for the adhesive to be in the plastic state, the first computation is that of the maximum possible extent of the plastic zone. This is then compared with the actual extent of the step. If necessary, a second computation is performed of the maximum possible extent of the elastic trough in that same step. Starting from equation (77) with \( y = \gamma_{\text{ref}} \) at \( x = 0 \),

\[
\gamma = \frac{\lambda^2}{2G} \tau_p x^2 + Cx + \gamma_{\text{ref}}
\]

where the constant \( C \) is given by equation (80). It is necessary to find the lesser value of \( x \) for which \( \gamma = \gamma_e \). Equation (81) is re-arranged to read

\[
\frac{\lambda^2 \tau_p}{2G} x_p^2 + Cx_p + (\gamma_{\text{ref}} - \gamma_e) = 0
\]

so that the maximum extent of plastic adhesive zone is given by

\[
x_p = -C \pm \sqrt{C^2 - 2\lambda^2 \gamma_e (\gamma_{\text{ref}} - \gamma_e)}.
\]

Now, since \( C = \frac{\text{d}y}{\text{d}x} < 0 \) at \( x = 0 \) the minus sign in front of the radical holds. Once \( x_p \) has been computed, it is compared with the step length \( \ell_{\text{step}} \). If \( x_p > \ell_{\text{step}} \), that particular step is fully-plastic throughout and the values of the various quantities at the far end of the step are evaluated from equations (73) to (80). Should \( x_p \) be less than \( \ell_{\text{step}} \), the difference is examined elastically, to see whether it remains elastic throughout or becomes plastic again at the far end. For \( x_p < \ell_{\text{step}} \), the values of the various stresses, strains,
displacements and forces are evaluated in terms of equations (73) to (79) and the subscripts \( p \) serve to identify the plastic-to-elastic transition. Likewise \( e \) identifies the possible elastic-to-plastic transition at the far end of the joint. It is necessary that \( dy/dx \) be maintained at these transitions, as is evident from equation (75). The maximum possible extent of elastic trough must be deduced from equation (65). In doing so, it is mathematically far simpler to shift the \( x \) origin to the middle of the elastic trough (of extent \( 2x_e \)) so that

\[
\tau = \frac{\tau_p \cosh(\lambda x)}{\cosh(\lambda x_e)}
\]  

(84)

At the \( pe \) transition (\( x = -x_e \)) equation (62) requires that

\[
\frac{dT}{dx} = \frac{G\left[\frac{T_i}{E_{ti}} - \frac{T_o}{E_{to}} + (a_i - a_o)\Delta T\right]}{\eta_i E_{ti} - \eta_o E_{to}} = -\frac{\tau_p \lambda \tanh(\lambda x_e)}{pe}
\]  

(85)

so that the elastic trough could extend, if \( \ell_{step} \) were great enough, a distance

\[
2\lambda x_e = \tanh^{-1}\left\{ -\frac{1}{\lambda \eta_i E_{ti} - \eta_o E_{to}} - (a_i - a_o)\Delta T \right\}_e
\]  

(86)

By use of known formulas for hyperbolic functions in terms of exponentials and the interrelation between exponential and logarithmic functions, the solution (85) is more conveniently expressed as

\[
2\lambda x_e = \frac{1}{\lambda} \ln \left\{ 1 - \frac{1}{\lambda \eta_i E_{ti} - \eta_o E_{to}} + (a_i - a_o)\Delta T \right\}_e
\]  

(87)

In the event that \( x_e \) does not extend beyond the far (right hand) end of the step being analyzed, it is necessary to compute the load transferred between the adherends throughout the elastic trough. In doing so, it is quite simple to take the value of \( 2x_e \) from equation (87) and substitute it back into equations (65) to (72) for the standard elastic analysis of the preceding section. Should the elastic trough not extend to the far end of the step under analysis, equations (73) to (80) are employed for the plastic zone to the end of the step.
Equation (77) now becomes

\[ \gamma = \frac{\lambda^2r}{2G} x^2 + Cx + \gamma_{ep} \]  

(88)

with

\[ \tau = \tau_p \quad \text{for } x > x_{ep}. \]  

(89)

The constant \( C \) in equation (88) is evaluated in terms of equation (75)

\[ C = \frac{d\gamma}{dx} \bigg|_{ep} = \frac{1}{E_i t_i} \left( \frac{T_i}{E_i} - \frac{T_o}{E_o} + (\alpha_i - \alpha_o) \Delta T \right) \bigg|_{ep}. \]  

(90)

In the last steps of the joint at the far end, the adhesive may be fully plastic throughout in which case, in equation (87), \( \gamma_{ep} \) should be replaced by \( \gamma_{ref} \). Likewise, in those steps, near the middle of the joint, in which the adhesive shear strains are so small as not to reach the plastic state at either end of the step, the step will be elastic throughout and equations (65) to (72) are employed in the analysis. Towards the far end of the joint there may be a step which starts elastically and becomes plastic. In this case the actual extent of elastic behavior is determined by iteration, using equations (65) to (72) with a cut off (either positive or negative) on the shear stress.

If it should transpire that, at the end of the step, \( \gamma \) exceeds \( (\gamma_e + \gamma_{ep}) \) or \( T_i \) or \( T_o \) exceed their respective allowables, this does not cause any analytical difficulty. An iterative procedure is employed in the analysis to reduce the external load and initial adhesive strain whenever necessary. While this does not represent any analytical difficulty, one should recognize that exceeding the allowables on an inner step can occur only as the result of poor detail design. The improvement of such details can increase the potential joint strength.

No new numerical difficulties were encountered in the program listed in Appendix A5 for the elastic-plastic analysis of stepped-lap joints which did not have a direct counterpart in the perfectly elastic analysis. However, the logic associated with keeping track of the locations of the transitions between elastic and plastic adhesive behavior, and vice versa, as they moved with each successive iteration posed a formidable problem. One small computational
problem was that, if the load estimate at some early stage in the iteration sequence was too far removed from the correct value, the computer would predict physically unrealizable large negative shear strains in the adhesive. A special set of instructions was prepared for this quirk.

The computer program, as basically written, checks simultaneously for the allowable adherend and adhesive strengths at the most critical locations in each step. Since stepped-lap joints are frequently more critical in the adherend than in the adhesive, a special feature has been added to increase greatly all adherend strengths artificially in order to print out also the potential adhesive bond strength and confirm that it exceeds the adherend strength by an adequate margin.

The analysis above is presented for the case of tensile lap shear loads being positive and the sign convention is in accordance. The computer programs have been so coded that, by a single input for the variable SGNLD, the respective solutions for tensile shear loading (SGNLD = +1) and compressive shear loading (SGNLD = -1) can be printed out. In the event that there are simultaneous stiffness and thermal mismatches between the adherends, the joint strength will not be the same for each load sense. Such a situation is common in the bonding of titanium edge members to boron-epoxy panels.
7. DISCUSSION OF DESIGN OF STEPPED-LAP JOINTS

The digital computer programs developed above to analyze stepped-lap joints can serve also as a useful design tool. Three clear dominant joint characteristics have been confirmed by studies with this program. The first is that the joint load capacity is defined by the end three steps at the more critical end of the joint. If other steps have a significant influence it will be adverse and be due to poor design detailing. The second is that, once the joint is essentially well-designed, quite major changes can be made to other than the critical end three steps without any significant impact on the joint strength. Third is that, in a well-designed joint, it is the very end step that is likely to precipitate joint failure unless its length is restricted in the design process. The necessary restriction is that the product of maximum adhesive shear stress and total bond area on the end step must not exceed the product of adherend material allowable and, cross section of the end step. Consequently, a ductile adhesive with higher strain energy provides stronger joints than a brittle adhesive with higher peak stress but less strain energy. It should be noted also that minimizing adherend stiffness imbalance increases the potential bond shear strength.

Mathematically speaking, the stepped-lap family of joints represent perturbations about the scarf joint solution. These perturbations become progressively greater as the number of steps decreases until the stepped-lap solution reduces to a single-lap joint for one step. Stepped-lap joints with only two or three steps are usually confined to thin adherends for which the potential bond shear strength is far in excess of the adherend(s) strength. In such cases the added strain concentrations in the bond due to the step discontinuities are not very important. Most applications of stepped-lap joints contain a large number of steps and, with a ductile adhesive softening the most severe of the adhesive stress spikes, the behavior very closely approaches that of the scarf joint. For this reason, preliminary design of practical stepped-lap joints by means of the scarf joint solution appears to be quite realistic. In doing so, however, one should exercise caution with regard to the critical end step of the adherend. The stepped-lap joint analysis, and practical experience, have identified the end step of the stiffer adherend as a prime candidate for the most critical design detail. If the extensional modulus of a composite adherend is
significantly less than that of a metal adherend to which it is bonded, most of the shear load transfer will be concentrated at the composite end of the joint with the probable result that tip fracture of the stiffer adherend will occur. One simple remedy to this potential difficulty is to be found in the concept of the dual-slope scarf joint illustrated in the upper part of Figure 9. In this joint, in order to protect the tip of the adherend, the scarf angle $\theta_1$ is set to exceed

$$\theta_1 \text{min} = \frac{T_p}{F_u}$$

in which $T_p$ is the peak adhesive shear stress and $F_u$ is the appropriate adherend allowable stress in tension, compression, or shear as dictated by the nature of the applied load. The next step in the preliminary design process is to estimate the total scarf length necessary to effect the transfer of the entire load $P$. A reasonable approximation to this is given by the approximation

$$P = \frac{\left(\frac{T_{\text{av}}}{T_p}\right)T_p}{E_1t_1} = \frac{\left[\frac{E_1t_1}{E_2t_2}\right]}{p}$$

for the asymptotic scarf joint solution for very long overlaps, whence

$$l = \frac{P\left[\frac{E_2t_2}{E_1t_1}\right]}{T_p}.$$

The optimum location of the transition from scarf angle $\theta_1$ to $\theta_2$ can then be determined by trial and error using the stepped-lap joint computer program developed in Section 6. As a preliminary guide, it is suggested that one third of the total thickness be tried. The conversion of this conceptual scarf joint design into a practical stepped-lap joint is illustrated schematically in the lower part of Figure 9. It should be noted that the steps are thinner in the more critical load transfer region, and at the extreme opposite end for a single step to minimize potential peel stress problems. Normally peel stresses will not be a problem with stepped-lap joints for practical design configurations but the double-lap joint analysis can serve as a check if appropriate. The larger step sizes in the lightly loaded area effect an economy of fabrication which offsets the greater expense of proper detailing in the more critical areas.
For reasons evident from the discussion above, the dual-slope scarf joint has merits in its own right as well as for a model for approximate stepped-lap joint analysis. The steepening of the scarf angle at one end is particularly important for the brittle adhesives for which $\tau_p$ is much higher than for the ductile adhesives. This greater importance follows from equation (91).

One characteristic of the internal stress distribution within stepped-lap bonded joints is directly traceable to double-lap joint phenomena and has no counterpart in scarf joint behavior. This characteristic is that, once each or any step is sufficiently long to contain a fully-developed elastic trough in the adhesive shear-stress distribution, an increase in that step length does not alter the joint shear strength. Indeed, as confirmed by application of the computer programs A4EF and A4EG, the internal adherend and adhesive stresses at the ends of each and every step are invariant with respect to such step length increases, whether one, some, or all of the step lengths are increased. That this should be so follows directly from the governing equations for each step of the joint. These are precisely the same as for an unbalanced double-lap joint, the shear strength of which is independent of overlap beyond some value. The impact of this phenomenon on the design of stepped-lap bonded joints is that, if analysis indicates inadequate bond strength and the overlap is already reasonably great, no further increase in step lengths can accomplish an improvement in joint strength. It is necessary to increase the number of steps and decrease the incremental step thickness.

The technique of refining the preliminary analysis developed by the rules above is as follows. An analysis is performed, and the limiting (critical) detail identified. If this is the strength of the end step of the stiffer adherend, the appropriate procedure is to decrease this length and increase the length of the other steps. A halving of the step thickness increment and doubling of the number of steps at the more critical end of the joint will also help. This situation can be identified by a solution in which the maximum adhesive shear strain developed is less than the allowable. In rare instances it may not be the very end but one or two steps inside which are critical. The procedure for improving the joint strength is the same. Reduce the length of the critical steps and increase the others. In doing so, it should be remembered that any fully-elastic step will not transfer much more load even if its length is
increased. Furthermore, if the adhesive shear stresses at each end of the step are less than their plastic value, increasing the step length indefinitely will not introduce a plastic zone. If the adhesive shear strain is predicted to be the limiting feature rather than the adherend strength, the joint strength may be improved by increasing the number of joint steps. In doing so, steps at one end of the joint will tend to become critical and length increases in the remaining (elastic) steps will continue to increase the joint strength, but at a decreasing rate. The behavior of bonded scarf joints (Figure 6) serves to explain this approach. Since the average bond stress on a scarf joint approaches a fixed fraction of the maximum bond shear stress, an overlap sufficiently long can always be found to develop a potential strength 50 percent in excess of the adherend strength. The only inherent difficulty in this approach is the care needed not to exceed the adherend allowables near the more critical end of the joint. One may look upon an optimally designed stepped-lap joint as an approximation to a dual slope scarf joint with a small angle at the less critical end to build up the total load transferred and a steeper angle (still small) at the more critical end to prevent breaking off the tip of the adherend.

In the presence of adherend thermal mismatch (advanced composite-to-metal for example), a reversal of load direction can reverse the more critical and less critical ends of the joint. Therefore it is necessary in such cases to design for both the maximum tensile shear and compressive shear loads to be applied.

Figures 10 to 12 illustrate solutions obtained to stepped-lap bonded joint analyses using the computer programs above. The joint is drawn to scale in Figures 10 and 11 and the material properties can be found in the sample printout included in the Appendix. The brittle and ductile adhesives referred to are, respectively, Narmco Metlbond 329 and Hyso1 EA951 which have the shear characteristics illustrated in Figure 13. The elastic solutions in Figure 10 show dramatically the sharp spikes in the shear stress distribution at the ends of each step. These spikes, separated by relatively lightly-loaded troughs, represent the influence of the uniform thickness steps. It is evident also from Figure 10 that the ductile adhesive, with its lower modulus and higher elastic shear strain carries slightly more load elastically than does the brittle adhesive. Figures 10 to 12 omit the influence of thermal mismatch between adherends and, had this been included, the elastic strength disparity in
Figure 10 would have been very pronounced in favor of the ductile adhesive for a tensile shear loading. Figure 11 shows the computed bond shear stress distributions, corresponding with Figure 10, when the adhesive properties are modified to account for plasticity. As is to be expected from the adhesive characteristics in Figure 13, this modification does not increase the joint strength of the brittle adhesive sufficiently for the bond to be stronger than the weaker adherend. The ductile adhesive, on the other hand, is computed to have a potential bond strength nearly as great as the strength of the titanium outside the joint. Actually, by the time the adhesive has used up only 15 percent of its total shear strain capacity, the load level is so high as to cause the end (thin) titanium step to yield, as shown in the middle illustration of Figure 11. The ductile adhesive has a considerable strength margin over the composite adherend. Figure 12 demonstrates how the theory identifies the end metal step as being prone to fatigue failure, even though the end step had been shortened to alleviate the problem. In the static load case the theory predicts that, once the titanium has yielded locally, as shown in the second illustration of Figure 12, the load level will increase until failure occurs in the composite at the end of the joint, as shown in the fourth illustration. Figures 11 and 12 depict only the most critical conditions within each step because the computer program does not normally output a continuous solution. The adhesive shear stress distribution throughout the lightly loaded regions is not crucial to the design/analysis cycle. For illustrative purposes one can easily artificially divide each step into a number of short segments in order to avoid adding another computation sequence to the programs. This has been demonstrated to be free from convergence problems (as confirmed by Figure 10) but, naturally, takes more computer time.

The following table enumerates a number of solutions obtained with the stepped-lap joint computer programs above. The effects of thermal stresses are included, as also is the influence of the direction of the applied load. Of interest is the way in which the adherend thermal and stiffness imbalances compound to decrease the joint strengths for tensile loading while they counteract each other for the compressive loading. The failure modes predicted are identified by the comment codes 1 through 5 which are explained at the foot of the table. All cases except those for optimized step lengths have the joint geometry shown in Figure 10. In optimizing the joint proportions, the computer program
STRENGTHS OF STEPPED-LAP ADHESIVE-BONDED JOINTS

JOINTS OF TITANIUM TO ISOTROPIC HTS GRAPHITE-EPOXY

TITANIUM 0.25 IN., THICK GRAPHITE-EPOXY 0.264 IN., THICK

FAILURE LOADS (LBS/INCH)

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<th>-280°F COMPRESSION</th>
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COMMENT LEGEND:
1. TITANIUM YIELDS ON END (THIN) STEP
2. FAILURE IN COMPOSITE OUTSIDE JOINT AT 18216 LB/IN.
3. FAILURE IN ADHESIVE AT COMPOSITE END OF JOINT
4. FAILURE IN COMPOSITE ONE STEP IN FROM TITANIUM END OF JOINT
5. FAILURE IN COMPOSITE ONE STEP IN FROM COMPOSITE END

\( \Delta T \) - OPERATING TEMPERATURE - CURE TEMPERATURE OF ADHESIVE

was used to identify the most critical location and the step lengths were modified by hand for re-analysis until the minimum tensile and compressive joint strengths matched the composite adherend strength. This took only two iterations to achieve the results shown and this feature is one of the more beneficial merits of the complete internal joint analysis.

Figure 14 illustrates the bond shear stress distributions for both ductile and brittle adhesives. A comparison is effected between a joint of uniform step lengths, at left, and that with optimized lengths, at right. A small loss in elastic joint strength is incurred by shortening the end steps (and some of this could be recovered by increasing the lengths of the other steps to compensate) but the problem of yielding the end titanium step has been eliminated for the ductile adhesive. It is interesting to observe that the brittle adhesive had insufficient strain energy in shear for the problem to arise. Another important phenomenon revealed is that the ductile adhesive uses up only about a third of its ultimate shear strain capacity in breaking the composite adherend just outside the joint. This leaves a generous margin for dealing with
stress concentration due to irregularities in load intensity or bond thickness across the width of the joint. Because of these ever-present considerations, the brittle adhesive should not be expected to develop the full predicted joint strength over each inch of a wide panel. Failure would be initiated by a local effect and then be propagated rapidly.

Figure 14 omits consideration of thermal effects in order not to complicate the comparisons made. Figure 15 includes these effects for both tensile and compressive shear loading with the ductile adhesive. This figure compares the performance of the preliminary design (Figures 10 and 11) with the optimized design. Improvements in ultimate compressive strength and tensile fatigue load capacity are demonstrated.
8. CONCLUSION

This report presents elastic and elastic-plastic analysis methods for adhesive-bonded scarf and stepped-lap joints. The solutions obtained are analytic in form and the necessary digital computer FORTRAN IV programs are listed in the Appendices. These solutions are believed to be the first for such joints which account for adhesive plasticity. They include also the effects of adherend stiffness- and thermal-mismatch. While the precise solutions require iterative numerical solutions, explicit algebraic formulas are derived for a close lower-bound on the strength of scarf joints. The dominant characteristic of scarf joints is that, for long overlaps, the average bond stress asymptotes towards a fixed fraction of the peak bond stress, that fraction equalling the lesser ratio of adherend extensional stiffnesses. Unlike uniform lap joints, which reach a definite strength limit which cannot be exceeded by using longer overlaps, the potential bond strength of scarf joints increases indefinitely with overlap so that a design can always be devised in which the failure is forced to occur outside the joint. In using this approach, however, it is necessary also to check on the adherend stresses at the tip of the stiffer adherend to ensure that the scarf angle is not too small. Stepped-lap joints exhibit some characteristics of both the scarf joint and uniform double-lap joints. Those steps near the middle of a stepped-lap joint carry significantly more load than that transferred in the corresponding area of a uniform lap joint but the load so transferred is usually not a major contribution. Most of the load transfer is effected through the end three steps at one or both ends of the joint, depending on the nature of the adherend imbalances and the direction of the load. Within each step, since the governing equations are precisely the same as for an unbalanced double-lap joint, it is found that no further load can be transferred once the overlap has exceeded a determinable value. In other words, unlike scarf joints, the potential shear strength of stepped-lap joints cannot be increased indefinitely by increasing the overlap(s). The appropriate procedure is to employ more steps of finer thickness increments in order to augment the load capacity. Because scarf and stepped-lap joints can efficiently transfer load between thicker adherends than is possible with uniform double-lap joints, the latter are restricted to thinner sections in practical applications.

The inclusion of adhesive plasticity in the analysis has a marked effect on the
strength predictions. On the other hand, the elastic adhesive stresses play a far more important role in the behavior of scarf and stepped-lap joints than they do for uniform lap joints. The inclusion in the analyses of thermal mismatch effects permits their application to the bonding of titanium to the advanced composite laminates and explains how the joint strength changes with the load direction in such a situation.

The elastic-plastic analysis of the internal stresses within stepped-lap bonded joints provides sufficient information for the joint proportions to be optimized. Analyses should be performed for each load direction and at the extremes of the environmental temperature range, taking due account of material property changes with temperature, in the optimization sequence.
REFERENCES


SCARF JOINT BETWEEN DISSIMILAR MATERIALS \( (\alpha_1 > \alpha_2, E_{11} = E_{22}) \)

RESIDUAL ADHESIVE SHEAR STRESS

RESIDUAL ADHESIVE SHEAR STRAIN

ADHESIVE SHEAR STRESSES UNDER PROGRESSIVELY INCREASING TENSILE LOADS

CRITICAL SHEAR STRAIN FAILURE OF ADHESIVE

CORRESPONDING ADHESIVE SHEAR STRAINS

(NOTE THAT THE STRESSES AND STRAINS FOR PARTIAL LOADING, ABOVE, WOULD ALSO INDICATE THE BEHAVIOR UNDER STIFFNESS IMBALANCE IF \( \alpha_1 = \alpha_2 \) AND \( E_{11} > E_{22} \) BUT, WHEREAS THE CRITICAL END REVERSES WITH LOAD DIRECTION FOR THERMAL IMBALANCE, IT REMAINS THE SAME FOR STIFFNESS IMBALANCE.)

FIGURE 1. EXPLANATION OF NON-UNIFORM ADHESIVE SHEAR STRESSES IN BONDED SCARF JOINTS BETWEEN DISSIMILAR ADHERENDS
\( (\lambda)^2 = \frac{G}{\eta} \left( \frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right) t^2 \)

\( \text{ETR}(I) = \frac{E_1 t_1}{E_2 t_2} \)

\( \text{ETR}(2) = \frac{E_2 t_2}{E_1 t_1} \)

\( \text{CTHERM}(I) = \frac{(\alpha_2 - \alpha_1) \Delta T \lambda}{\tau_p \left( \frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right)} \)

\( \text{CTHERM}(2) = \frac{(\alpha_1 - \alpha_2) \Delta T \lambda}{\tau_p \left( \frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right)} \)

**Non-dimensionalized Joint Parameters**

**Figure 2. Notation and Geometry for Adhesive-Bonded Scarf Joint Analysis**
Figure 3. Effect of adherend stiffness imbalance on elastic strength of bonded scarf joints.

The graph illustrates the average adhesive shear stress as a function of the non-dimensionalized overlap \( \lambda \) and the adherend thickness (extensional stiffness) ratio \( E_{T_1}/E_{T_2} \). The graph shows how the stress changes with different values of the ratio and overlap.

The equation for the average adhesive shear stress is given by:

\[ \lambda^2 = \frac{G}{\eta} \left[ \frac{1}{E_{T_1} t_1} + \frac{1}{E_{T_2} t_2} \right] \]

where \( G \), \( \eta \), and \( \tau_p \) are material properties, and \( E_{T_1} \) and \( E_{T_2} \) are the extensional stiffnesses of the adherends.

Location A is critical for both positive (tensile lap-shear) and negative (compressive lap-shear) values of load \( P \).

The chart indicates the increasing stiffness imbalance with higher values of the ratio, affecting the stress distribution in the adhesive layer.
$\lambda^2 = \frac{G}{\eta} \left[ \frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right]$

$\text{CTHERM} = \frac{(\alpha_2 - \alpha_1) \Delta T \lambda}{\tau_p \left( \frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right)}$

$\Delta T = T_{\text{operating}} - T_{\text{stress free}}$

LOCATION A CRITICAL FOR CTHERM $< 0$ AND P $> 0$
LOCATION A CRITICAL FOR CTHERM $> 0$ AND P $< 0$
LOCATION B CRITICAL FOR CTHERM $< 0$ AND P $< 0$
LOCATION B CRITICAL FOR CTHERM $> 0$ AND P $> 0$

FIGURE 4. EFFECT OF ADHEREND THERMAL MISMATCH ON ELASTIC STRENGTH OF BONDED SCARF JOINTS
FIGURE 5. INTERACTION OF ADHEREND STIFFNESS AND THERMAL IMBALANCES FOR ELASTIC BONDED SCARF JOINTS
FIGURE 6. EFFECT OF ADHESIVE PLASTICITY IN REDUCING STRENGTH LOSS DUE TO ADHEREND STIFFNESS IMBALANCE FOR BONDED SCARF JOINTS
FIGURE 7. EFFECT OF ADHESIVE PLASTICITY IN REDUCING STRENGTH LOSS DUE TO ADHEREND THERMAL MISMATCH FOR BONDED SCARF JOINTS
FIGURE 8. NOTATION AND GEOMETRY FOR ADHESIVE-BONDED STEPPED-LAP JOINT ANALYSIS
FIGURE 9. PRACTICAL PROPORTIONING OF STEPPED-LAP JOINTS TO PROTECT AGAINST FATIGUE FAILURES AT TIP OF METAL ADHEREND
FIGURE 10. ELASTIC SHEAR STRESS DISTRIBUTIONS FOR BRITTLE AND DUCTILE ADHESIVES IN BONDED STEPPED-LAP JOINTS
FIGURE II. ELASTIC-PLASTIC SHEAR STRESS DISTRIBUTIONS FOR BRITTLE AND DUCTILE ADHESIVES IN BONDED STEPPED-LAP JOINTS
FIGURE 12. ADHEREND STRENGTHS AND INTERNAL LOADS FOR BONDED STEPPED-LAP JOINTS
FIGURE 13. COMPARISON OF SHEAR STRESS-STRAIN CHARACTERISTICS FOR BRITTLE AND DUCTILE ADHESIVES
FIGURE 14. COMPARISON BETWEEN STEPPED-LAP JOINTS WITH UNIFORM STEP LENGTHS AND WITH OPTIMIZED STEP LENGTHS
TENSION

FAILURE IN COMPOSITE AT 18216 Ib/in.

YIELD IN TITANIUM AT 11866 Ib/in.

FAILURE IN COMPOSITE AT 16997 lb/in.

COMPRESSION

NOTE THAT TITANIUM END STEPS WERE ALREADY SHORTENED DURING PRELIMINARY DESIGN. WITH UNIFORM STEPS 0.75 IN. LONG THROUGHOUT, PREMATURE FATIGUE FAILURE WOULD OCCUR AT A, FOLLOWED BY FAILURE OF COMPOSITE AT THE SAME (REDUCED) SECTION.

(A) PRELIMINARY DESIGN

SCALE

0 \hspace{1cm} 1

\( (0^\circ/45^\circ/-45^\circ/90^\circ) \) HTS GRAPHITE-EPOXY

FAILURE IN COMPOSITE AT 18180 lb/in.

6AI-4V TITANIUM

FAILURE IN COMPOSITE AT 18182 lb/in.

COMPRESSION

NO YIELDING OF TITANIUM

(B) OPTIMIZED DESIGN

DUCTILE ADHESIVE CURED AT 350°F.
STRENGTHS CALCULATED AT ROOM TEMPERATURE.
STRENGTH OF COMPOSITE ADHEREND OUTSIDE JOINT = 18216 lb/in.
POTENTIAL BOND SHEAR STRENGTH WOULD EXCEED 23257 lb/in. IN EVERY CASE SHOWN IF ADHERENDS WERE SUFFICIENTLY STRONG.

FIGURE 15. OPTIMIZATION OF DETAILS IN STEPPED-LAP BONDED JOINTS
APPENDICES

A.1 Computer Program A4EC For Elastic Strength of Bonded Scarf Joints

The FORTRAN IV digital computer program associated with the analysis in Section 2 is listed below. This program has been checked out thoroughly and sample solutions are illustrated in Section 4. Only shear stresses are considered, with the peel stresses neglected in accordance with the very small scarf angles used in practice. As discussed in Section 2, there are severe convergence problems associated with the series solution to this problem. While the average shear stresses computed are considered very reliable, no computation sequence for the stress distribution was found which was considered sufficiently accurate over the far end of the joint ($x/\lambda \approx 1$). The peak shear stress is located correctly by program A4EC at one end or other of the overlap. The only real need for a shear stress distribution is as an intermediate step in the computation of the internal adherend stresses. Since the convergence of the series was enhanced greatly by prior integration into the contributions to the average shear stress, it is recommended that any attempt to pursue the adherend stress distribution should proceed along similar lines. The adhesive shear stress distribution series can be integrated mathematically so that a more tractable series solution is obtained for the adherend stresses. The first two terms follow from the average shear stress solution and the subsequent ones would derive from recurrence formulae. The condition under which a need for such information could arise is the possible breaking off of the thin tip of the stiffer adherend for a very small scarf angle. Such a situation is unlikely for perfectly elastic adhesives because the shear stress drops off very rapidly away from the ends. A simpler procedure is available for the elastic-plastic adhesive.

The format of the input data necessary to operate the A4EC computer program is as follows:

CARD 1:

FORMAT (415)

IMAX = Number of thermal mismatch coefficients. IMAX .LE. 20.
JMAX = Number of non-dimensionalized overlaps. JMAX .LE. 40.
    (Note that this is one more than the number of overlaps to be read in. The limiting case of OL(1)=0 is set by the program.)

KMAX = Number of adherend stiffness imbalances. KMAX .LE. 10.
    (Note that this controls the number of columns of answers printed across the page and cannot be increased indefinitely.)

NMAX = Number of terms in power series. 10 .LE. NMAX .LE. 50.
    (Note NMAX = 20 is recommended.)

CARDS 2, 2A, 2B, etc.:
    FORMAT (12F6.2)
    OL(J) = Non-dimensionalized overlaps. Number restricted to 40 by dimension statement. (Note that OL(J) must be read in in ascending order and that OL(2), which is the first entry on card 2, must not exceed 0.5 because of internal computations. OL(1) = 0 is set by program as limiting case.) Values of OL(J) exceeding 50 are impractically large.

CARDS 3, 3A, 3B, etc.:
    FORMAT (10F5.2)
    ETR(K) = Adherend stiffness ratios \( \frac{E_1 t_1}{E_2 t_2} \). Number restricted to 10 by dimension statement. (Subscripts 1 and 2 must be identified so that 0 .LT. ETR .LE. 1. Array should be read in in ascending or descending order.)

CARDS 4, 4A, 4B, etc.:
    FORMAT (10F7.3)
    CThERM(I) = Adherend thermal mismatch coefficients in non-dimensionalized form. Number restricted to 20 by dimension statement. (Note that equal and opposite values must be read in consecutively to account for the difference between tensile and compressive application of the shear load. Values of up to ±5 are sufficient for the available range of adhesives. Greater values are usually associated with failure of the joint under residual thermal stresses alone.)
The complete listing follows, along with sample output pages. The output tables come in pairs with the ratio of the average to maximum adhesive shear stress \( \frac{\tau_{av}}{\tau_p} \) and the non-dimensionalized joint strength \( \frac{\tau_{av}}{\tau_p}(\lambda \lambda) \) as functions of the adherend extensional stiffness ratio \( E_{TR} = \frac{E_1 t_1}{E_2 t_2} \leq 1 \) horizontally and the non-dimensionalized joint overlap \( \lambda \lambda = \sqrt{\frac{G}{\eta} \left( \frac{1}{E_1 t_1} + \frac{1}{E_2 t_2} \right) \lambda^2} \) vertically.

Each table is prepared for a single value of thermal mismatch coefficient \( C_{THERM} = \frac{(\alpha_2 - \alpha_1) \Delta T \lambda}{\frac{1}{E_1 t_1} + \frac{1}{E_2 t_2}} \) and equal and opposite values are treated in turn to cover both tensile and compressive shear loadings.
C IDENTIFY AVERAGE THERMAL IMBALANCES ACCOUNTED FOR
C DATA PRESENTATION FOR TENSILE SHEAR LOADING
C CHANGE SIGN OF C THERM TO USE FOR COMpressive SHEAR LOADS
C SMOOTHER THAN AVERAGE THERMAL IMBALANCES (ETR(K), C THERM(I), A(N,2), TENSION(I,2),
C TAUAVG(J,K), ICRTND(J,K), STRGTH(J,K), SIG(N,2),
C DIMENSION ML(401), ETR(10), C THERM(20), A(50,2), SIG(50,2),
C READ IN ARRAY SIZES
C DIMENSION OL(20), TAUAVG(40,10), ICRTND(40,10), STRGTH(40,10)
C READ IN VON-DIMENSIONALIZED OVERLAY ARRAY
OL(1) = 0.
C OL(I,J) MUST BE IN ASCENDING ORDER
C READ (5,10) (OL(I,J); J = 2, JMAX)
C READ IN STIFFNESS IMBALANCE ARRAY
C IDENTIFY ADHEREND 1 AND 2 SUCH THAT ETR(K) = (ETR1)/(ETR2) .LE. 1.
C READ (6,70) (ETR(K), K = 1, KMAX)
C 20 FORMAT (12F6.2)
C READ IN VON-DIMENSIONALIZED THERMAL MISMATCH COEFFICIENTS
C PRINT OUT INPUT DATA
C WRITE (6,50) TMAX, JMAX, KMAX, NMAX
C 50 FORMAT (2H10, 6H1, 12H10, 9H1, 12H10)
C WRITE (6,60) (OL(I,J), J = 1, JMAX)
C 60 FORMAT (100H10, 12F6.2)
C WRITE (6,70) (ETR(K), K = 1, KMAX)
C 70 FORMAT (12H10, 6H1, 10F5.2)
C WRITE (6,80) (THERM(I), I = 1, IMAX)
C 80 FORMAT (20H10, 10F5.2)
C END OR
C SET UNIFORM STRESS FOR ZERO OVERLAP
C DO 20 K = 1, KMAX
C TAUAVG(J,K) = 1.
C 20 FORMAT (12F6.2)
C START OF COMPUTATION DO LOOPS
C DO 310 I = 1, JMAX
C DO 180 K = 1, KMAX
C 310 CONTINUE
C ESTABLISH ADHEREND 1 END OF JOINT AS REFERENCE
C SUBSEQUENTLY CHECK WHETHER ADHEREND 1 END OR ADHEREND 2 END IS CRITICAL
C NCTRTND = 1
C THERM = C THERM(I)
C VR = ETR(K) IF ( VR .NE. 1., 0.) OR (THERM .NE. 0.1) GO TO 100
C SET UNIFORM STRESS FOR BALANCED JOINTS
C TAUAVG(J,K) = 1.
C STRGTH(J,K) = OL(J)
C ICRTND(J,K) = 0
C GO TO 180
C 100 CONTINUE
C COMPUTE INITIAL TERMS OF SERIES, ASSUMING A1(1,1) = A(2,2) = 1. & A(1,2) = A(1,1)
C A(1,1) = 1.
C A(2,2) = 1.
C A(1,2) = (OLAP/6.) * (-THERM + V3*OLAP)
C A(2,1) = 0.5
C A(3,2) = (OLAP/4.) * (V2/2.1 + 1./6.)
C COMPUTE NMAX TERMS OF AVERAGE STRESS POWER SERIES
C DO 110 N = 4, NMAX
C DO 110 M = 1, 2
C 110 CONTINUE
C COMPUTE A2, THROUGH RAPID CONVERGENCE OF AVERAGE STRESS
C NOTE THAT INDIVIDUAL TERMS IN DISTRIBUTION DO NOT CONVERGE AS RAPIDLY
C SIG(3,1) = 1. + A(3,1)
C SIG(3,2) = 0.5 + A(3,2)
C DO 120 N = 4, NMAX
C SIG(N,1) = SIG(N-1,1) + A(N,1)
C SIG(N,2) = SIG(N-1,2) + A(N,2)
C 120 CONTINUE
C COMPUTE A2(MAX)
C A2SAVE = (THERM/OLAP + V2 - (SIG(NMAX,1)/V1)) / 1. ((SIG(NMAX,2)/V1) + (1./OLAP2))
C COMPUTE AVERAGE SHEAR STRESS IN BOND
C IF (NCTRTND .EQ. 2) GO TO 130
C CHECK WHICH END OF JOINT IS CRITICAL
C IF (NCTRTND .EQ. 2) GO TO 130
C IF (THERMC .LT. 0.) GO TO 130  
  NCRTND = 2  
  VR = 1. / VR  
  THERMC = - THERMC  
  GO TO 140  
  130 CONTINUE  
C IDENTIFY AVERAGE SHEAR STRESS / MAXIMUM SHEAR STRESS & CRITICAL END  
C NOTE THAT INITIAL SELECTION CRITERIA ASSUME ONE END OF JOINT CRITICAL.  
C 1 OTHER IS CRITICAL AND PRECLUDE POSSIBILITY OF MAXIMUM STRESS IN  
C 2 MIDDLE. SUBSEQUENT SEPARATE CHECK ON THIS CONDITION.  
C IF (THERMC .NE. 0.) GO TO 140  
C BOTH IMBALANCES WILL INEVITABLY COMPOUND FOR THERMC .LT. 0.  
C 1 SINCE ETTR(K) .LE. 1. HENCE NCRTND = 1  
C IF (TRATIO(J,1) .GE. 0.) GO TO 160  
C IF (TRATIO(J,1) .LT. 0.) GO TO 150  
C 140 CONTINUE  
C IDENTIFY MORE POWERFUL IMBALANCE FOR NULLIFYING BEHAVIOUR (NCRTND = 1)  
C 1 THERMC .GT. 0. AND ETTR(K) .LE. 1.  
C COVER SITUATION WHERE THERMAL IMBALANCE DOMINATES OVER STIFFNESS  
C 1 IMBALANCE. NOTE NEED DL(K) .LE. 0.9 FOR THIS CHECK.  
  NCRTND(J,K) = 2  
  IF (TRATIO(J,1) .GT. 1.) AND AND (TRATIO(J,2) .LT. 0.) GO TO 150  
C CHECK IF TWO IMBALANCES PRECISELY CANCEL  
C IF (TRATIO(J,1) .EQ. 1.) AND (TRATIO(J,2) .EQ. 1.) GO TO 160  
C CHECK IF STIFFNESS IMBALANCE DOMINATES  
  NCRTND(J,K) = 1  
  IF (TRATIO(J,1) .LE. 1.) AND (TRATIO(J,2) .GE. 0.) AND  
  1 (TRATIO(J,2) .GT. 1.) GO TO 160  
C ALL POSSIBILITIES FOR EITHER END CRITICAL CHECKED OUT  
C ONCE CRITICAL (KMAX) IS IN MIDDLE OF JOINT  
C NOTE THAT THIS PHENOMENON ARISES ONLY FOR JOINTS BROKEN WITHOUT LOAD  
C COMBINATION OF THERMAL MISMATCH AND EXCESSIVE LENGTH IS NECESSARY  
C IDENTIFY FAILURE CASES BY ASTERISKS  
  TAUAVG(J,K) = 100.  
  STRENGTH(J,K) = 1000.  
  NCRTND(J,K) = 10  
  GO TO 180  
C ZERO STRENGTH ATTAINED  
150 TAUAVG(J,K) = 0.  
  STRENGTH(J,K) = 0.  
  GO TO 180  
C ADHEREED 1 END OF JOINT CRITICAL  
160 TAUAVG(J,K) = TRATIO(J,1)  
  STRENGTH(J,K) = TAUAVG(J,K) * DL(J)  
  GO TO 180  
C ADHEREED 2 END OF JOINT CRITICAL  
170 TAUAVG(J,K) = TRATIO(J,2)  
  STRENGTH(J,K) = TAUAVG(J,K) * DL(J)  
  GO TO 180  
C 180 CONTINUE  
C IDENTIFY CRITICAL END OF JOINT FOR ZERO OVERLAP  
190 NCRTND(K) = I CRTND(J,K)  
  NCRTND = NCRTND(J,K)  
  GO TO 210  
C PRINT OUT SPECIAL HEADING FOR ZERO THERMAL MISMATCH BETWEEN ADHERENDS  
WRITE (6,2001) ETTR(K), K = 1, KMAX  
200 FORMAT (I1,1X,5X, A6,3X, A5, 1X, A15, 1X, A15)  
  A6 : TRATIO(J,1)  
  A5 : TRATIO(J,2)  
  A15 : THERMC = - THERMC  
  GO TO 230  
C PRINT OUT SPECIAL HEADING FOR ZERO THERMAL MISMATCH BETWEEN ADHERENDS  
WRITE (6,2200) ETTR(K), K = 1, KMAX  
220 FORMAT (1H1,10F7.5, 1X, A6,15F, 1X, A15, 1X, A15)  
  A6 : TRATIO(J,1)  
  15F : THERMC = - THERMC  
  GO TO 230  
C PRINT OUT SPECIAL HEADING FOR ZERO THERMAL MISMATCH BETWEEN ADHERENDS  
WRITE (6,2400) DL(J), TRATIO(J,K), ICRTND(J,K), K = 1, KMAX  
240 FORMAT (1H1, F6.2, 2X, 10F7.5, 1X, 11, 1X)  
250 CONTINUE  
C IF (THERMC .NE. 0.) GO TO 270
C PRINT OUT SPECIAL HEADING FOR ZERO THERMAL MISMATCH BETWEEN ADHERENDS A4EC1770

WRITE (6,260) (FTR(K), K = 1, KMAX)

260 FORMAT (1H1,10I7), 31X, 48ADHESIVE-BONDED SCARF JOINTS (ELASTIC A4EC1790
ANALYSIS), 39X, 31HNON-DIMENSIONALIZED FORMULATION/, A4EC1800
2 38X, 33HZERO THERMAL MISMATCH COEFFICIENT/, A4EC1810
3 68X, 29H0 = ROT EndS EQUALLY LOADED/, 29X, 72HNON-DIMENSIONALIZA4EC1820
46D STRENGTH 1 = SOFT ET END CRITICAL/, A4EC1830
5 68X, 25H2 = STIFF ET END CRITICAL/, A4EC1840
6 68X, 29H SCALED, 31X, 39HEXTENSIONAL STIFFNESS (THICKNESS) RATIO/, A4EC1850
7 7H L/T/, 7H RATIO/, 1H*, 4X, 10F10.1//, A4EC1860
GO TO 290 A4EC1870

C PRINT OUT HEADINGS

270 WRITE (6,280) C THERM(I), THERM, (FTR(K), K = 1, KMAX)

280 FORMAT (1H1,10I7), 31X, 48ADHESIVE-BONDED SCARF JOINTS (ELASTIC A4EC1900
ANALYSIS), 39X, 31HNON-DIMENSIONALIZED FORMULATION/, 17X, 31HTHERA4EC1910
2MAL MISMATCH COEFFICIENT = , F6.3, 17H FOR TENSION = , F6.3, 16H A4EC1920
3FOR COMPRESSION/, 68X, 29H0 = ROT EndS EQUALLY LOADED/, A4EC1930
4 68X, 29H SCALED, 31X, 39HNON-DIMENSIONALIZED STRENGTH , A4EC1940
5 68X, 29H SCALED, 31X, 39HSTIFF ET END CRITICAL/, A4EC1950
6 68X, 29H SCALED, 31X, 39HSTIFF ET END CRITICAL/, A4EC1960
7 68X, 29H SCALED, 31X, 39HSTIFF ET END CRITICAL/, A4EC1970
GO TO 290 A4EC1980

C PRINT OUT TABULATIONS OF NON-DIMENSIONALIZED STRENGTHS

300 FORMAT (1H1, F6.2, 2X, 10(F7.4, 1X, I1, 1X))
310 CONTINUE

320 FORMAT (1H1), 1AH PROGRAM COMPLETED//
STOP A4EC1900
END
### Adhesive-Bonded Scaffe Joints (Elastic Analysis)

**Non-Dimensionalized Formulation**

**Thermal Mismatch Coefficient**: 
- 1.000 for Tension
- -1.000 for Compression

#### Non-Dimensionalized Strength

- 0: Both Ends Equally Loaded
- 1: Stiff End Critical

#### Scaled Ratio

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#### Extended Stiffness (Thickness) Ratio

- For Compression
- For Tension
- For Adhesive-Bonded Formulation
- For Non-Dimensional Formulation
- For Any Other

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### Adhesive-Bonded Scarf Joints (Elastic Analysis)

**Thermal Mismatch Coefficient = -1.000 for Tension, = 1.000 for Compression**

Non-Dimensionalized Strength

1. Both ends equally loaded
2. Stiff end critical

#### Extensional Stiffness (Thickness) Ratio

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### Adhesive-Bonded Scarf Joints (Elastic Analysis)

Non-Dimensionalized Formulation

Thermal Mismatch Coefficient = -1.000 for Tension, = 1.000 for Compression

Average Stress / Maximum Shear Stress

1. Both ends equally loaded
2. Stiff end critical

#### Extensional Stiffness (Thickness) Ratio

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A.2 Computer Program A4ED For Lower Bound Elastic-Plastic Strength of Bonded Scarp Joints

This FORTRAN IV digital computer program covers a simple efficient approximate solution for the elastic-plastic strength of most bonded scarf joints of practical proportions and materials. Its development was needed as a sufficiently close starting point for convergence to proceed in the more precise program A4EE. It transpired, on examination of the equivalent results computed by A4EE that the quicker computations of A4ED were satisfactory as final answers provided that (1) and adhesive non-linear behavior was not negligible, i.e., that $\gamma_p/\gamma_e > 0.5$, (2) the thermal mismatch coefficient is not too high, i.e., that $\text{CTHERM} < 2$, and (3) that the stiffness mismatch between adherends be not too great, i.e., that $0.2 \leq \text{ETR} \leq 1$.

The input data for program A4ED is precisely the same as for program A4EE with the exception that $\gamma_p/\gamma_e$ for the adhesive cannot be equal to zero for A4EE. In other words, perfectly elastic adhesive behavior must be excluded from A4EE. On the other hand, the values computed by A4ED for zero adhesive plasticity are unduly conservative.

A listing of the program and sample outputs follow.
C PLASTIC ANALYSIS OF UNBALANCED SCARE JOINTS
C WARNING: ROUND ANALYSIS PROVIDED WHICH IS ACCURATE FOR DESIGN
C NON-DIMENSIONALIZED AVERAGE SHEAR STRESSES COMPUTED
C NON-DIMENSIONALIZED JOINT STRENGTHS COMPUTED
C RANGES OF ADHESIVE DUCTILITIES INCLUDED
C RANGES OF ADHESIVE STIFFNESS AND THERMAL IMBALANCES ACCOUNTED FOR
C CHANGE SIGN OF THERM TO USE FOR COMPRESSIVE SHEAR LOADS
C SET OTHERM = 0. AND REPLACE ADHEREND ET'S WITH GT'S FOR IN-PLANE
1 (EDGEWISE) SHEAR LOADING
C PRINT OUT INPUT DATA
C GPDVGE(L) MUST BE .GT. 0. FOR ELASTIC-PLASTIC ANALYSIS
C READ IN PLASTIC-TO-ELASTIC STRAIN RATIO ARRAY
C I NEED COTHERM) ARRAY TO CONTAIN BOTH POSITIVE AND NEGATIVE VALUES
C ETR(K) SHOULD INCLUDE VALUE 0., BUT MUST EXCLUDE VALUE O.
STIFFNESS RATIOS SHOULD BE
C IDENTIFY ADHERENDS
C READ IN STIFFNESS IMBALANCES ARRAY
C 10 = 
C 3L(J) MUST BE LESS THAN 0.2 FOR IDENTIFICATION OF CRITICAL END
C READ IN NON-DIMENSIONALIZED OVERLAP ARRAY
C O(1) = 0.
C OL(J) MUST BE IN ASCENDING ORDER
C OL(J) MUST BE > 0. FOR IDENTIFICATION OF CRITICAL END
C OL(J) MUST BE IN ASCENDING ORDER (LIMITING CASE)
C note: OL(J) = J = 2.
C 20 FORMAT (12F6.2)
C 50 FORMAT (515)
C 100 FORMAT (5,15)
C 60 FORMAT (5,15)
C 100 FORMAT (5,15)
C 200 FORMAT (5,15)
C 300 FORMAT (5,15)
C 400 FORMAT (5,15)
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C 600 FORMAT (5,15)
C 700 FORMAT (5,15)
C 800 FORMAT (5,15)
C 900 FORMAT (5,15)
C 1000 FORMAT (5,15)
C 1100 FORMAT (5,15)
C 1200 FORMAT (5,15)
C 1300 FORMAT (5,15)
C 1400 FORMAT (5,15)
C PRINT OUT INPUT DATA
C WRITE (6,100) (OL(J), J = 1, IMAX)
C WRITE (6,110) (OL(J), J = 1, IMAX)
C WRITE (6,120) (COTHERM) = (ETR(K))
C WRITE (6,130) (COTHERM) = (ETR(K))
C WRITE (6,140) (GPDVGE(L), L = 1, IMAX)
C START COMPUTATIONAL DD LOOPS
D = 620 L = 1, IMAX
C ENSURE EXCLUSION OF NEGATIVE PLASTICITY IN ADHESIVE ERROR IN DATA
C IF (GAMMAR .LT. 0.) GO TO 620
D = 620 L = 1, IMAX
C ENSURE EXCLUSION OF NEGATIVE PLASTICITY IN ADHESIVE ERROR IN DATA
C IF (GAMMAR .LT. 0.) GO TO 620
C SET UNIFORM STRESS FOR SHORT OVERLAPS

C I_ IV3 .LT. 0.1 .OR. |OLTRNC(I) .LE. 0.) OLTRNC(I) = 1000000. A4EDI660

C IF ICRTNO .EQ. 2 FOR SHORT OVERLAPS, OITRNT(I) WILL BE COMPUTED VERY A4EDI550

C IF NOT, OTHER END OF

C SET INFINITE TRANSITIONAL OVERLAP

C OTHER END OF JOINT

C STANDARD

C SET TRANSITIONAL OVERLAPS

C V(1) = THERMC(I) * VL(1) / (2. * VL(1))
C V2 = THERMC(2) * VL(2) / (2. * VL(2))
C V4 = V2 + GAMMA * VL(2) / (VU(2))
C V5 = V2 + GAMMA * VL(2) / (VU(2))
C ENSURE THE FOLLOWING EQUATIONS APPLY FOR TENSILE SHEAR LOADING
C IF (V4 .LT. 0.) .OR. (VLTRNC1 .LT. 0.) VLTRNC1 = 1.000000.  A4EDI460
C IF (V4 .LT. 0.) .OR. (VLTRNC2 .LT. 0.) VLTRNC2 = 1.000000.  A4EDI460
C IF (V4 .LT. 0.) .OR. (VLTRNC1 .LT. 0.) VLTRNC1 = 1.000000.  A4EDI460
C IF (V4 .LT. 0.) .OR. (VLTRNC2 .LT. 0.) VLTRNC2 = 1.000000.  A4EDI460
C SET TRANSITIONAL OVERLAPS FOR THERMAL MISMATCH ONLY
C SET INFINITE TRANSITIONAL OVERLAP TO ACCOUNT FOR THIS
C IF (V3 .LT. 0.) .OR. (OLTRNC1 .LT. 0.) OLTRNC1 = 1.000000.  A4EDI480
C IF (V3 .LT. 0.) .OR. (OLTRNC2 .LT. 0.) OLTRNC2 = 1.000000.  A4EDI480
C IF IGRTNO .EQ. 2 FOR SHORT OVERLAPS, OLTRNC1 WILL BE COMPUTED VERY A4EDI540
C C LARGE AND VICE VERSA
C C THIS IS PHYSICALLY REALISTIC AND DOES NOT LEAD TO IMPOSSIBLE COMPUTING A4EDI570
C IF BOTH V3 AND V4 ARE POSITIVE, EITHER OLTRNC1 OR OLTRNC2 WILL BE A4EDI580
C COMPUTED NEGATIVE. NEED TO PREVENT COMPUTATIONS BASED ON THIS A4EDI590
C UNREAL SITUATION. HENCE CHECKS ABOVE AND BELOW
C NEXT FOUR STATEMENTS WOULD APPLY FOR COMPRESSIVE SHEAR LOADING
C IF (V3 .GE. 0.) .OR. (VTRNC1 .LT. 0.) VTRNC1 = -V3 + SQRT(V3)
C IF (V4 .GE. 0.) .OR. (VTRNC2 .LT. 0.) VTRNC2 = -V4 + SQRT(V4)
C IF NOT, OTHER END OF JOINT CRITICAL
C OTHER END OF JOINT IDENTIFIED AS CRITICAL BY SHEAR STRAIN GRADIENT
C SET INFINITE TRANSITIONAL OVERLAP TO ACCOUNT FOR THIS
C IF (V4 .LT. 0.) .OR. (OLTRNC1 .LT. 0.) OLTRNC1 = 1.000000.  A4EDI490
C IF (V4 .LT. 0.) .OR. (OLTRNC2 .LT. 0.) OLTRNC2 = 1.000000.  A4EDI490
C 210 DO 260 NCRTN = 1, 2
C C SET UNIFORM STRESS FOR SHORT OVERLAPS
C DO 220 J = 2, JMAX
JSAVE = J
C IF (OL(1J) .GT. OLTRNT(NCRTND)) GO TO 230
C IF NOT, JOINT IS FULLY PLASTIC
220  TRATIO(J,NCRTND) = 1
C IF (JSAVE .EQ. JMAX) GO TO 260
C COMPUTE JOINT STRENGTH FOR ELASTIC-PLASTIC ADHESIVE BEHAVIOUR
C BYPASS VALUES
C IF NOT, JOINT IS FULLY PLASTIC
C COMPUTE ADVERL FOR MINIMUM VALUE OF TAUOTP BY ITERATION
C SET INITIAL ESTIMATE OF EXTENT OF PLASTIC ZONE FROM TRANSITIONAL OLAP
C ADVERL = OLTRNT(NCRTND) / OLAP
DO 240 N = 1, NMAX
C ARMOR = 1. - ADVERL
ADVERL = ARMOR * ALOG(ARMOR) + (GAMMAR / ((VU(NCRTND) / VLI(NCRTND)))
1 OLAP2 = THERMC(NCRTND) / OLAP
IF (ADVERL .GT. 0.999) ADVERL = 0.999
240 CONTINUE
C IF NOT, JOINT HAS BROKEN DUE TO THERMAL STRESSES
C COVER CASES OF ZERO SITUATION A4ED2490
3)0 CONTINUE
3_0 CONTINUE
320 TAUAVG(J,K) = TAU2
300 TAUAVG(J,K) = TAU1 - ADVERL
310 TAUAVG(J,K) = TAU2 - TAU1
C COVER SITUATION WHERE TRANSITIONAL LENGTH IS LESS THAN OL(2)
C (IF (J .EQ. 2) TRANSK) = OLTRNT(1)
GO TO 320
C BOTH ENDS OF JOINT EQUALLY CRITICAL FROM NULLIFYING (OR ZERO)
C ADHEREND IMBALANCES
300 TAUAVG(J,K) = TAU1
300 TAUAVG(J,K) = TAU1 - OLAP
ICRTND(J,K) = 1
300 TAUAVG(J,K) = TAU2
300 TAUAVG(J,K) = TAU2 - OLAP
ICRTND(J,K) = 0
C COVER SITUATION WHERE TRANSITIONAL LENGTH IS LESS THAN OL(2)
C (IF (J .EQ. 2) TRANSK) = OLTRNT(1)
GO TO 320
C ADHEREND (1) END OF JOINT CRITICAL
310 TAUAVG(J,K) = TAU1
310 TAUAVG(J,K) = TAU1 - OLAP
ICRTND(J,K) = 1
310 TAUAVG(J,K) = TAU2
310 TAUAVG(J,K) = TAU2 - OLAP
ICRTND(J,K) = 0
C COVER SITUATION WHERE TRANSITIONAL LENGTH IS LESS THAN OL(2)
C (IF (J .EQ. 2) TRANSK) = OLTRNT(1)
GO TO 320
C ADHEREND (2) END OF JOINT CRITICAL
310 TAUAVG(J,K) = TAU1
310 TAUAVG(J,K) = TAU1 - OLAP
ICRTND(J,K) = 1
310 TAUAVG(J,K) = TAU2
310 TAUAVG(J,K) = TAU2 - OLAP
ICRTND(J,K) = 0
C COVER SITUATION WHERE TRANSITIONAL LENGTH IS LESS THAN OL(2)
C (IF (J .EQ. 2) TRANSK) = OLTRNT(1)
GO TO 320
C COVER CASES OF ZERO OR NEGATIVE ESTIMATED STRENGTHS
C 320 IF (TAUAVG(J,K) .GT. 0.) GO TO 330
C IF JOINT HAS BROKEN DUE TO THERMAL STRESSES WITHOUT EXTERNAL LOAD
C TAUAVG(J,K) = 0.
C STRESS(J,K) = 0.
330 IF (TAUAVG(J,K) .LE. 1.) GO TO 340
C IF NOT, THERE HAS BEEN A COMPUTATIONAL MISTAKE
C RESTART WITH GREATER VALUE OF NMAX
C TAUAVG(J,K) = 100.
C STRESS(J,K) = 100.
340 CONTINUE
C 350 CONTINUE
C SET UNIFORM STRESS FOR ZERO OVERLAP
DO 360 K = 1, KMAX
TAUAVG(J,K) = 1.
ICRTND(J,K) = 0.
360 CONTINUE
HENCE NEED FOR DL(2) TO BE SMALL ENOUGH TO BE LESS THAN THAT AT WHICH
1 ICRTND CHANGES
END OF COMPUTATIONS. START PRINTING OUT OF TABULATED RESULTS
C PRINT OUT AVERAGE STRESS HEADING
WRITE (6,370)
370 FORMAT (1X, 5(IHO, 27X, 49HPLASTIC TO ELASTIC ADHESIVE SHEAR STRAIN RATIO), A_ED3050
   70 FORMAT (IHO, 2X, F6.2, 2X, 16X, F7.5, IX, IF), IX) A4ED3040
   460 FORMAT (IHO, 6?X, 30HO = BOTH ENDS EQUALLY CRITICAL/, 20X, A4ED2q60
   450 WRITE (6,380) GAMMAR
   380 FORMAT (1HO, 42X, 23HPURELY ELASTIC ADHESIVE) A4ED2830
   GO TO 410
390 WRITE (6,400) GAMMAR
   400 FORMAT(1HO, 27X, 49HPLASTIC TO ELASTIC ADHESIVE SHEAR STRAIN RATIO), A4ED2860
   1 = F5.2) A4ED2850
   410 IF (ICTHERM(J) .NE. 0.) GO TO 430
   420 FORMAT (1IH, 37X, 33HZERO THERMAL MISMATCH COEFFICIENT) A4ED2900
   GO TO 450
430 WRITE (6,440) THERMC(1), THERMC(2)
   440 FORMAT (1IH, 16X, 31HTHERMAL MISMATCH COEFFICIENT = , F6.3, 11TH FOR TENSION, = , F6.3, 16H FOR COMPRESSION) A4ED2930
   450 WRITE (6,460) (ETRIK), K = 1, KMAX) A4ED2940
   460 FORMAT (1HO, 67X, 30HO = BOTH ENDS EQUALLY CRITICAL/, 20X, A4ED2960
   1 72H AVERAGE SHEAR STRESS / MAXIMUM SHEAR STRESS, = = SOFT ET, A4ED2970
   2ND CRITICAL/, 6X, 25H2 = STIFF ET END CRITICAL/, A4ED2980
   3 9HO SCALING, 31X, 39HEXTENSIONAL STIFFNESS (THICKNESS) RATIO/, A4ED2990
   41H LYT, 7H RATIO, F7.1, 9F10.1, 1H ) A4ED3000
C WRITE OUT TABULATIONS OF AVERAGE BOND STRESSES
DO 480 J = 1, JMAX
   470 FORMAT (1IH, F6.2, 2X, 10(F7.5, 1X, II, 1X)) A4ED3040
   490 CONTINUE
C PRINT OUT JOINT STRENGTH HEADING
WRITE (6,490)
490 FORMAT (1IH, 5(IHO, 27X, 56HADHESIVE-BONDED SCARF JOINTS (ELASTICITY), A4ED3090
   440 FORMAT (1IH, 16X, 31HTHERMAL MISMATCH COEFFICIENT = , F6.3, 11TH FOR TENSION, = , F6.3, 16H FOR COMPRESSION) A4ED2930
   450 WRITE (6,460) (ETRIK), K = 1, KMAX) A4ED2940
   460 FORMAT (1HO, 67X, 30HO = BOTH ENDS EQUALLY CRITICAL/, 20X, A4ED2960
   1 72H AVERAGE SHEAR STRESS / MAXIMUM SHEAR STRESS, = = SOFT ET, A4ED2970
   2ND CRITICAL/, 6X, 25H2 = STIFF ET END CRITICAL/, A4ED2980
   3 9HO SCALING, 31X, 39HEXTENSIONAL STIFFNESS (THICKNESS) RATIO/, A4ED2990
   41H LYT, 7H RATIO, F7.1, 9F10.1, 1H ) A4ED3000
C WRITE OUT TABULATIONS OF JOINT STRENGTHS
DO 600 J = 1, JMAX
   500 FORMAT (1IH, F6.2, 2X, 10(F7.5, 1X, II, 1X)) A4ED3200
   600 CONTINUE
C WRITE OUT TRANSITIONAL JOINT STRENGTHS
WRITE (6,610) (TRANSL(K), K = 1, KMAX)
610 FORMAT (1HO, 67X, 30HO = BOTH ENDS EQUALLY CRITICAL/, 20X, A4ED2960
   1 72H AVERAGE SHEAR STRESS / MAXIMUM SHEAR STRESS, = = SOFT ET, A4ED2970
   2ND CRITICAL/, 6X, 25H2 = STIFF ET END CRITICAL/, A4ED2980
   3 9HO SCALING, 31X, 39HEXTENSIONAL STIFFNESS (THICKNESS) RATIO/, A4ED3000
   41H LYT, 7H RATIO, F7.1, 9F10.1, 1H ) A4ED3310
C WRITE OUT AVERAGE STRESS HEADING
WRITE (6,630)
   630 FORMAT (1IH, 18H PROGRAM COMPLETED) A4ED3430
STOP
END
### Adhesive-Bonded Joints (Elastic-Plastic Analysis) Non-Dimensionalized Formulation

**PLASTIC TO ELASTIC ADHESIVE SHEAR STRAIN RATIO = 2.0**

**THERMAL MISMATCH COEFFICIENT = -1.000 FOR TENSION, = 1.000 FOR COMPRESSION**

### Non-Dimensionalized Joint Strength

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<th>Scaled Load Ratio</th>
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<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
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### Extensional Stiffness (Thickness) Ratio

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### Adhesive-Bonded Joints (Elastic-Plastic Analysis) Non-Dimensionalized Formulation

**PLASTIC TO ELASTIC ADHESIVE SHEAR STRAIN RATIO = 2.0**

**THERMAL MISMATCH COEFFICIENT = -1.000 FOR TENSION, = 1.000 FOR COMPRESSION**

### Average Shear Stress / Maximum Shear Stress

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<th>Scaled Load Ratio</th>
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### Adhesive-Bonded Scarf Joints (Elastic-Plastic Analysis)

**Non-dimensionalized formulation**

#### Plastic to Elastic Adhesive Shear Strain Ratio = 4.0

**Thermal Mismatch Coefficient**
- 1.000 for tension
- 1.000 for compression

#### Average Shear Stress / Maximum Shear Stress
- 0 = Both Ends Equally Critical
- 1 = Soft End Critical
- 2 = Stiff End Critical

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#### Extensional Stiffness (Thickness) Ratio

**Transverse**

A.3 Computer Program A4EE For Elastic-Plastic Strength of Bonded Scarf Joints

This FORTRAN IV digital computer program provides for the precise series solution for the average shear stress on bonded scarf joints with small scarf angles. It accounts for adherend stiffness and thermal imbalance as well as adhesive plasticity. The governing analysis is presented in Sections 3 and 4. This program A4EE will not handle perfectly elastic adhesives for which the program A4EC was developed. Severe convergence difficulties were encountered in the development of the numerical program. This contributed to the omission of a solution for the adherend and adhesive shear stress distributions. Whether or not the adherend allowable stresses are exceeded can be determined simply by evaluating the ratio of the adhesive peak shear stress to the adherend allowable direct stress. If this ratio exceeds the tangent of the scarf angle, the scarf angle is too small and the tip will either break off or be yielded depending on the nature of the adherend material.

The input data required to operate program A4EE is as follows.

CARD 1:

FORMAT (515)

IMAX = Number of thermal mismatch coefficients. IMAX .LE. 20.

JMAX = Number of non-dimensionalized overlaps. JMAX .LE. 40.
(Note that this is one more than the number of overlaps to be read in. The limiting case of OL(1)=0 is set by the program.)

KMAX = Number of adherend stiffness imbalances. KMAX .LE. 10.
(Note that this controls the number of answers printed across the page and cannot be increased indefinitely for a single pass through the program.)

LMAX = Number of plastic-to-elastic adhesive shear strain ratios.
LMAX .LE. 20.

NMAX = Number of terms in power series. 10 .LE. NMAX .LE. 50.
(Note NMAX = 20 is recommended.)
CARDS 2, 2A, 2B, etc.:
FORMAT (12F6.2)
OL(J) = Non-dimensionalized overlaps. Number restricted to 40 by dimension statement. (Note that OL(J) must be read in in ascending order and that OL(2), which is the first entry on card 2, must not exceed 0.5 because of internal computations. OL(1) = 0 is set by the program as a limiting case.) Values of OL(J) exceeding 50 are impractically large.

CARDS 3, 3A, 3B, etc.:
FORMAT (10F5.2)
ETR(K) = Adherend stiffness ratios $(E_{1t1})/(E_{2t2})$.
Number of values restricted to 10 by dimension statement.
(Subscripts 1 and 2 must be identified such that $0 < ETR(K) \leq 1$. Array should be read in in ascending or descending order.)

CARDS 4, 4A, 4B, etc.:
FORMAT (10F7.3)
CTHERM(I) = Adherend thermal mismatch coefficients in non-dimensionalized form. Number restricted to 20 by dimension statement. (Note that equal and opposite values must be read in consecutively to account for the difference between tensile and compressive application of the shear load. Values up to $\pm5$ are sufficient for the available range of adhesives and adherends. Greater values are usually associated with failure of the joint under residual thermal stresses alone.)

CARDS 5, 5A, 5B, etc.:
FORMAT (14F5.2)
GPOVGE(L) = Ratio of adhesive plastic-to-elastic strain ratios. Number of entries restricted to 20 by dimension statement. (Value of zero, for elastic case, is rejected by program A4EE to prevent breakdown of the computational sequence, but accepted by A4ED.)
A complete listing and sample outputs follow. The output tables come in pairs with the ratio of the average to maximum adhesive shear stress \( \tau_{av}/\tau_p \) and the non-dimensionalized joint strength \( (\tau_{av}/\tau_p)(\lambda\lambda) \) as functions of the adherend extensional stiffness ratio \( ETR = E_{1t_1}/E_{2t_2} \leq 1 \) horizontally and the non-dimensionalized joint overlap \( \lambda\lambda = \sqrt{\frac{G}{\pi}(\frac{1}{E_{1t_1}} + \frac{1}{E_{2t_2}})}\lambda^2 \) vertically. Each table is prepared for a single value of thermal mismatch coefficient \( C_{TEMP} = \frac{(\alpha_2 - \alpha_1)\Delta T\lambda}{\tau_p\left(\frac{1}{E_{1t_1}} + \frac{1}{E_{2t_2}}\right)} \) and equal and opposite values are treated in turn to cover both tensile and compressive shear loadings. Each table is prepared for a single value of the plastic-to-elastic adhesive shear strain ratio \( \gamma_p/\gamma_e \). The quantity \( TRANS\lambda \) listed at the foot of each column of the non-dimensionalized strength table defines the transitional overlap at which the adhesive behavior changes from fully-plastic to elastic-plastic.
CDECK
C ELASTIC-PLASTIC ANALYSIS OF UNBALANCED SCARF JOINTS
C PRECISE SOLUTION, NOT LOWER ORDER
C NON-DIMENSIONALIZED AVERAGE SHEAR STRESSES COMPUTED
C NON-DIMENSIONALIZED FASTENING STRENGTHS COMPUTED
C ADDITIONAL DUCTILITIES INCLUDED
C RANGES OF ADHEREND STIFFNESS AND THERMAL IMBALANCES ACCOUNTED FOR
C DATA PRESENTATION FOR TENSILE SHEAR LOADING
C CHAIN OF THERM TO USE FOR COMPRESSIVE SHEAR LOADS
C SET THERM = 0, AND REPLACE ADHEREND ET S WITH GT'S FOR IN-PLANE
C (EDGEWISE) SHEAR LOADING
C
C DIMENSION OL(J), ETR(K), THERM(I), GPOVEG(I), TRA(T), NCR(T),
C 1 4(N), TAVAVG(J,K), STJP(H,J,K), IMCTD(J,K), THERM(J,K),
C 2 8(N), TVA(N), NCR(T), OLRN(T), NCTD(J,K),
C 3 OLRN(T), NCR(T), NCTD(J,K), OLRN(T), NCTD(J,K),
C 4 BOVERL(N)
C
C DATA PRESENTATION FOR TENSILE SHEAR LOADING
C PRINT
C READ (5,50) FORMAT (515)
DO 670 L = 1, LMAX

C IDENTIFY ADHERENDS SUCH THAT ETR(K) = (ET1)/ET2 \ LE .1,
C STIFFNESS SHOULD BE IN ASCENDING OR DESCENDING ORDER
C ETR(K) SHOULD INCLUDE VALUE 1, BUT MUST EXCLUDE VALUE 0.
C READ (5,50) ETR(K), K = 1, KMAX

C IDENTIFY ADHERENDS SUCH THAT ET1/ET2 \ LE .1,
C STIFFNESS SHOULD BE IN ASCENDING OR DESCENDING ORDER
C ETR(K) SHOULD INCLUDE VALUE 1, BUT MUST EXCLUDE VALUE 0.
C READ (5,50) ETR(K), K = 1, KMAX

C PRINT (14F5.2)
C READ IN NON-DIMENSIONALIZED THERMAL IMBALANCES
C C THERM = PROP NL.* (ALPHA(2)-ALPHA(1)) * (OPERATING TEMP. - CURE TEMP.)
C NEED THERM(I) ARRAY TO CONTAIN BOTH POSITIVE AND NEGATIVE VALUES
C READ (5,50) (THERM(I), I = 1, IMAX)

C PRINT OUT DATA
C WRITE (6,10) IMAX, JMAX, KMAX, LMAX, NMAX
C 10 FORMAT (515)
DO 70 I = 1, IMAX

C PRINT OUT DATA
C WRITE (6,10) IMAX, JMAX, KMAX, LMAX, NMAX
C 10 FORMAT (515)
DO 70 I = 1, IMAX
ESTABLISH TRANSITIONAL OVERLAPS FROM FULLY-PLASTIC TO ELASTIC-PLASTIC

SET TRANSITIONAL OVERLAPS FOR STIFFNESS IMBALANCE ONLY

IN THE ABSENCE OF THERMAL MISMATCH, SAME END IS CRITICAL FOR BOTH ADHERENDS

IF (VU(1) .GE. 0.) OLTRNC(I) = SQRT(GAMMAR*VU(2)/VU(1))
IF (VU(1) .LT. 0.) OLTRNC(I) = -VU(1) + SQRT(VU(1)*VU(2))

SET TRANSITIONAL OVERLAPS FOR THERMAL MISMATCH ONLY

IF (THERMC(1) .LT. 0.) OLTRNT(I) = -V2
IF (THERMC(2) .GE. 0.) OLTRNT(I) = GAMMAR/THERMC(2)

IF (THERMC(2) .LT. 0.) OLTRNT(I) = -GAMMAR/THERMC(1)

IF (THERMC(2) .EQ. 0.) OLTRNT(I) = LOTH

C SET INFINITE TRANSITIONAL OVERLAP FOR IDENTICAL ADHERENDS

150 OLTRNC(1) = 1000000.
OLTRNC(2) = 1000000.
OLTRNT(1) = 1000000.
OLTRNT(2) = 1000000.

IF (VU(1) .LT. 0.) OLTRNC(2) = 1000000.
IF (VU(1) .LT. 0.) OLTRNT(2) = 1000000.

C SET TRANSITIONAL OVERLAPS FOR IDENTICAL JOINTS

IF (THERMC(1) .LT. 0.) OLTRNC(I) = -V1 + SQRT(V1*V2)
IF (THERMC(2) .GE. 0.) OLTRNC(I) = GAMMAR/THERMC(2)

IF (THERMC(2) .LT. 0.) OLTRNC(I) = -GAMMAR/THERMC(1)

IF (THERMC(2) .EQ. 0.) OLTRNC(I) = LOTH

C IF NOT OTHER END OF JOINT CRITICAL

C OTHER END OF JOINT IDENTIFIED AS CRITICAL BY SHEAR STRAIN GRADIENT

C SET TRANSITIONAL OVERLAP TO ACCOUNT FOR THIS

IF (V3 .LT. 0.) OR (OLTRNT(I) .LT. 0.) OLTRNT(I) = 1000000.

IF (V4 .GT. 0.) OLTRNT(I) = V2 + SQRT(V2*V4)

C IF NOT OTHER END OF JOINT CRITICAL

C OTHER END OF JOINT IDENTIFIED AS CRITICAL BY SHEAR STRAIN GRADIENT

C SET INFINITE TRANSITIONAL OVERLAP TO ACCOUNT FOR THIS

C IF (V4 .LT. 0.) OR (OLTRNC(I) .LT. 0.) OLTRNC(I) = 1000000.

C IF NOT OTHER END OF JOINT CRITICAL

C OTHER END OF JOINT IDENTIFIED AS CRITICAL BY SHEAR STRAIN GRADIENT

C SET TRANSITIONAL OVERLAP TO ACCOUNT FOR THIS

C IF (V4 .LT. 0.) OR (OLTRNC(I) .LT. 0.) OLTRNC(I) = 1000000.

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C SET INFINITE TRANSITIONAL OVERLAP TO ACCOUNT FOR THIS

C IF (V4 .LT. 0.) OR (OLTRNC(I) .LT. 0.) OLTRNC(I) = 1000000.
DO 200 J = 2, JMAX
   JSAVE = J
   IF (A(1) .GT. OLTRAN(NCRTND)) GO TO 210
C IF A(1) IS FULLY PLASTIC
   200 IF (JSAVE.EQ.JMAX) GO TO 380
C
C COMPUTE JOINT STRENGTH FOR ELASTIC-PLASTIC ADHESIVE BEHAVIOUR

   210 DO 380 J = JSAVE, JMAX
      OLAP = OL(J)
      IF (OLAP .LE. OLAP) GO TO 230
C COMPUTE AVERAGE OF MINIMUM VALUE OF TAVOTP BY ITERATION
C SET INITIAL ESTIMATE OF EXTENT OF PLASTIC ZONE FROM TRANSITIONAL OLAP
   A4EE2210
      A4EE2250
C
   A4EE2300
C
C COMPUTE CORRESPONDING AVERAGE SHEAR STRESS
   A4EE2350
C
C THE FACTOR IS TO PREVENT DIVERGENCE IN THE SERIES COEFFICIENTS
C SET MINIMUM POSSIBLE VALUE OF ADVERL, AT WHICH TAVOTP .EQ. 1.
C TRUE EXTREM OF FINEST PLASTIC ZONE BOUNDED WITHIN AAMIN AND AREF
C minimum values of TAVOTP are now computed, these approximate the true
C solutions for all but severe overlaps or thin adherends
C IN CONJUNCTION WITH SEVERE ADHEREND MISMATCH AND/OR BRITELE
C ADHESIVES, A PRECISE ANSWER BY PRECISE SOLUTION IN POWER SERIES
C COMPUTE STRESS TERMS FOR ELASTIC-PLASTIC ADHESIVE BEHAVIOUR
   ASPEE2360
C
   230 CONTINUE
C IF TAVOTP .LT. 0.0001) ADOERL = 0.9999
   A4EE2400
C
   240 CONTINUE
C IF
      DO 280 J = 2, JMAX
         A4EE2450
C
C COMPUTE ASSOCIATED AVERAGE BOND STRESS
C
C START COMPUTING PLASTIC STRESS SERIES
C ESTABLISH A(I) AT START OF ELASTIC ZONE FROM CONTINUITY OF SHEAR
C IN ADHESIVE AT TRANSITION. THIS ENSURES ADHEREND STRESS TERMS
C 2 CONTINUITY
A4EE2470
C
C COMPUTE SUBSEQUENT TERMS FROM RECURRANCE FORMULA
   A4EE2490
C
C IF NOT, OVERFLOW IS IMMINENT, SO CUT DOWN ON NMAX
C IF NOT, HAVE IDENTIFIED EXISTENCE OF SECOND PLASTIC ZONE, AT OTHER END
A4EE2540
C
C NEED TO SELECT LOW VALUE TO IDENTIFY CRITICAL END OF JOINT
C 3SE LOWER BOUND SOLUTION IF REFINEMENT RESULTS IN STILL LOWER VALUES
AAEE3300
C IF SO, CONVERGENCE NOT ESTABLISHED AAEE3200
C IT ZONE) AAEE3200
C _SE LINEAR
C IF NOT,
C CHECK ON CONVERGENCE OF
C
C IF SO, CONVERGENCE ESTABLISHED AAEE3080
C I_ CHECK ON WHETHER COVER L IS SO LARGE THAT CRITICAL END OF JOINT
C 1 IS AT OTHER END UNTIL AFTER CONVERGENCE OF AVER L IS ESTABLISHED AAEE2900
C
C 310 SAVOTP(M) = 1,
C BOLV = A - AVER L - COV ERL
C EVALUATE AVERAGE STRESS IN TERMS OF SERIES COEFFICIENTS
C D2 30 N = 2, NMAX
C AN = N
C 320 SAVOTP(M) = SAVOTP(M) + A(N) X (BOLV X(N))
C C CHECK ON CONVERGENCE OF AVERAGE STRESS
C IF (SAVOTP(M) - ST. TAVOTP(M)) .GT. 1.1 GO TO 360
C C IF STRESS HAS NOT CONVERGED YET
C IF ( (SAVOTP(M) .LT. TAVOTP(M)) .AND. (M .EQ. 1)) GO TO 330
C C IF SO, SOLUTION IS NUMERICALLY INDISTINGUISHABLE FROM THE LOWER BOUND
C NEED TO CHECK IF EQ. 1 VALUES AND M .EQ. 2 VALUES FOR FIRST CHECK
C IF (M .EQ. 1) GO TO 360
C PROTECT AGAINST DIVISION BY ZERO
C IF (TAVOTP(M) .EQ. 0.0) AND. (SAVOTP(M) .EQ. 0.0) GO TO 340
C C IF SO, CONVERGENCE ESTABLISHED
C IF ( (SAVOTP(M) .LT. 0.00001) .AND. (SAVOTP(M) .GT. -0.00001))
C 1 RATIO = 1. + SAVOTP(M) / TAVOTP(M)
C C IF NOT, USE LOWER BOUND INTERPOLATION TO ESTIMATE AVERAGE STRESS
C USE LINEAR INTERPOLATION TO ESTIMATE AVERAGE STRESS (EXTENT OF FIRST PLASTIC
C 1 ZONE)
C IF (SAVOTP(M) .LT. TAVOTP(M)) GO TO 360
C C IF STRESS HAS NOT CONVERGED YET OR IF REFERENCE STRESSES ARE FROM SHEAR STRAIN GRADIENT
C USE LINEAR BOUND SOLUTION IF REFINEMENT RESULTS IN STILL LOWER VALUES
C 370 IF (TRATIO(J,NCRTND) .LT. TAVOTP(1)) TRATIO(J,NCRTND) TAVOTP(1)
C 2 ( (1. - TRATIO(N-1)) / (TAUEND(N1) - TAUEND(N1 -1)))
C GO TO 370
C 380 CONTINUE
C C IF REFERENCE STRESSES ARE FROM SHEAR STRAIN GRADIENT
C TR A TION(J,NCRTND) = TAVOTP(1)
C C PROTECT AGAINST ACCUMULATED NUMERICAL ERRORS
C USE LINEAR BOUND SOLUTION IF REFINEMENT RESULTS IN STILL LOWER VALUES
C 370 IF (TRATIO(J,NCRTND) .LT. TAVOTP(1)) TRATIO(J,NCRTND) = TAVOTP(1)
C 380 CONTINUE
C C CONVERGENCE OF AVER L ESTABLISHED, RECORD AVERAGE SHEAR STRESS
C VALUES COMPUTED ARE NOW STORED IN TRATIO(J,NCRTND)
C NEED TO SELECT LOWEST VALUE TO IDENTIFY CRITICAL END OF JOINT
C DD 450 J = 2, NMAX
C OLAP = OL(J)
C TAUI = TRATIO(J -1)
C TAU2 = TRATIO(J - 2)
C IF I ( (TAU1 .LT. 1.0) OR. (TAU2 .LT. 1.0)) GO TO 390
C C IF SO, JOINT IS NOT FULLY PLASTIC
C IF NOT, CRITICAL END OF JOINT FROM SHEAR STRAIN GRADIENT
C GRADNT = THERMO(J) - OLAPosed(V(1)/V(L))
IF (ICRTND .EQ. 0) MCRTND = 1
TAUAVG(J,K) = TAU1
MCRND(J,K) = OAP
IF (MCRND .EQ. 0) MCRND = 1

TRANSL(K) = OTRNT(MCRND)
G0 TO 430

390 DIFNC = IIAU - TAU2
C IF DIFNC .LT. 1., MCRND .EQ. 1
C IF DIFNC .GT. 1., MCRND .EQ. 2
C IF DIFNC .EQ. 1., MCRND = 1
IF (DIFNC)400,410,420
C ADHEREND (1) END OF JOINT CRITICAL
400 TAUAVG(J,K) = TAU1
STRGH(J,K) = TAU1 * OAP
ICRTND(J,K) = 1.
C COVER SITUATION WHERE TRANSITIONAL LENGTH IS LESS THAN OL(2)
IF (J , EQ. 2) TRANSL(K) = OTRNT(I)
GO TO 430
C BOTH ENDS OF JOINT EQUALLY CRITICAL FROM NULLIFYING (OR ZERO)
410 TAUAVG(J,K) = TAU1
STRGH(J,K) = TAU1 * OAP
ICRTND(J,K) = 0
C COVER SITUATION WHERE TRANSITIONAL LENGTH IS LESS THAN OL(2)
IF (J .EQ. 2) TRANSL(K) = OTRNT(I)
GO TO 430
C ADHEREND (2) END OF JOINT CRITICAL
420 TAUAVG(J,K) = TAU2
STRGH(J,K) = TAU2 * OAP
ICRTND(J,K) = 1.
C COVER SITUATION WHERE TRANSITIONAL LENGTH IS LESS THAN OL(2)
IF (J .EQ. 2) TRANSL(K) = OTRNT(2)
C COVER CASES OF ZERO OR NEGATIVE ESTIMATED STRENGTHS
C IF NOT, JOINT HAS BROKEN DUE TO THERMAL STRESSES WITHOUT EXTERNAL LOAD
TAUAVG(J,K) = 0.
STRGH(J,K) = 0.
GO TO 450

440 IF (TAUAVG(J,K) .LE. 1.) GO TO 450
C IF TAUAVG HAS BEEN A COMPUTATIONAL MISTAKE
C PRINT ASTERISKS TO IDENTIFY ERROR
C RERUN WITH GREATER VALUE OF NMAX
TAUAVG(J,K) = 100.
STRGH(J,K) = 1000.

450 CONTINUE

460 CONTINUE

C SET UNIFORM STRESS FOR ZERO OVERLAP
DO 470 K = 1, KMAX
TAUAVG(J,K) = 0.
STRGH(J,K) = 0.

470 IF (ICRTND(J,K) .EQ. ICRTND2(K))
C HERE WE GO FOR OL(2) TO BE SMALL ENOUGH TO BE LESS THAN THAT AT WHICH
C ICRTND CHANGES
1 NCRND CHANGES
C END OF COMPUTATIONS, START PRINTING OUT OF TABULATED RESULTS
C PRINT OUT AVERAGE STRESS HEADING
WRITE (6,490)
490 FORMAT (IH/), 5(IHO/), 27X, 56ADHESIVE-BONDED SCARF JOINTS (ELAST
1ITIC-PLASTIC ANALYSIS)/,
2. 3D, 31NON-DIMENSIONALIZED FORMULATION/)
WRITE (6,490) GAMMAR

490 FORMAT(1HO, 27X, 4HPLASTIC TO ELASTIC ADHESIVE SHEAR STRAIN RATIO)
1 = .5, .92, IF (THERMI .NE. 0.) GO TO 510
WRITE (6,500)
500 FORMAT (IH, 37X, 33ZER0 THERMAL MISMATCH COEFFICIENT)
GO TO 530
510 WRITE (6,520) THERMC(1), THERMC(2)
520 FORMAT (1H, 16X, 31THERMAL MISMATCH COEFFICIENT = , F6.3, 16H FOR TENSION,
16H FOR COMPRESSION)
530 WRITE (6,540) (THERMC(K), K = 1, KMAX)
540 FORMAT (1H, 6X, 30X = BOTH ENDS EQUALLY CRITICAL, 20X,
1. 72AVG SHEAR STRESS / MAXIMUM SHEAR STRESS, 1 = SOFT ET E64300
2ND CRITICAL, 6X, 25X2 = STIFF ET END CRITICAL,
3. RATIO SCALING, 31X, 31XEXTENSIONAL STIFFNESS (THICKNESS) RATIO/, 1
L1, 7H/7, 7H/1.1, 1H)
C WRITE OUT TABULATIONS OF AVERAGE BOND STRESSES
DO 600 J = 1, KMAX
WRITE (6,550) (TAUAVG(J,K), ICRTND(J,K)), K = 1, KMAX
550 FORMAT (1H, F6.2, 2X, 10(F7.5, 1X, 1I), 1X)
560 CONTINUE
C
C PRINT OUT JOINT STRENGTH HEADING

88
WRITE (6, 570)
570 FORMAT (1H1, 5(1HO), 27X, 569ADHESIVE-BONDED SCARF JOINTS (ELAS4EE4420
1, TIC-PLASTIC ANALYSIS/) .
2 \30X, 31WHEN-DIMENSIONALIZED FORMULATION/)
WRITE (6, 580) GAMMAR
580 FORMAT (1HO, 27X, 49HPLASTIC TO ELASTIC ADHESIVE SHEAR STRAIN RATIO
1 = _5.F5.2)
IF (THERM(1) .NE. 0.) GO TO 600
WRITE (6, 590)
590 FORMAT (1H1, 37X, 33HZERO THERMAL MISMATCH COEFFICIENT)
GO TO 620
600 WRITE (6, 610) THERMC(1), THERMC(2)
610 FORMAT (1H1, 16X, 31HTHERMAL MISMATCH COEFFICIENT = , F6.3,
1 1TH FOR TENSION, = , F6.3, 16H FOR COMPRESS.
WRITE (6, 620) (ETRI(K), K = 1, KMAX)
620 FORMAT (1HO, 67X, 30X = BOTH ENDS EQUALLY CRITICAL/, 20X,
1 72WHEN-DIMENSIONALIZED JOINT STRENGTH
1 = SOFT ET E4EE4650
2ND CRITICAL/, 69X, 25X = STIFF ET END CRITICAL/, 4
3 HO SCALED, 31X, 30X = EXTENSIONAL STIFFNESS (THICKNESS) RATIO/, 7H
4 7H L1T/7, 7H RATIO, F7.1, 0F10.1/, 1H )
C WRITE OUT TABULATIONS OF JOINT STRENGTHS
DO 650 J = 1, JMAX
WRITE (6, 640) OLC(J), (KSTP(GTH(J,K), ICRTND(J,K)), K = 1, KMAX)
640 FORMAT (1H1, 69X, 2X, 10(F7.4, 1X, 11, 1X1))
650 CONTINUE
C WRITE OUT TRANSITIONAL JOINT STRENGTHS
WRITE (6, 660) (TRANSL(K), K = 1, KMAX)
660 FORMAT (8HO TRANSL, IX, 10(F7.4, 1X))
670 CONTINUE
C
WRITE (6, 680)
680 FORMAT (1H1, 18H PROGRAM COMPLETED)
STOP
END
### Adhesive-Bonded Scarf Joints (Elastic-Plastic Analysis) - Non-Dimensionalized Formulation

**Plastic to Elastic Adhesive Shear Strain Ratio** = 5.0

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**Avera...
## Adhesive-Bonded Scarf Joints (Elastic-Plastic Analysis)

### Non-Dimensionalized Formulation

**Plastic to Elastic Adhesive Shear Strain Ratio** = 5.0

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<tr>
<th>Scaled Load Ratio</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
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### Thermal Mismatch Coefficient = -1.000 for Tension, = 1.000 for Compression

#### Average Shear Stress / Maximum Shear Stress

- **0**: Both ends equally critical
- **1**: Soft end critical
- **2**: Stiff end critical

<table>
<thead>
<tr>
<th>Scaled Load Ratio</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
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91
A.4 Computer Program A4EF For Elastic Strength of Stepped-Lap Bonded Joints

The analysis in Section 5 has been prepared as the FORTRAN IV digital computer program A4EF. The program computes the elastic joint strength of any stepped-lap bonded joint and prints out the most critical adherend and adhesive stresses for each step of the joint. In order to obtain a more complete internal stress distribution, each step can be subdivided and a series of shorter steps input instead. The input data is printed out to supplement the solution output. Eccentricities are excluded from the joint and a symmetric two-sided bonded joint is analyzed in which the thicknesses of the two outer adherends are lumped together in evaluating the joint strengths. The reason for this is the greater utilization of the back-to-back stepped-lap joint than of the single-sided joint. A single-sided joint can be analyzed with this program in one of two ways. One can add a mirror image of the actual joint and halve the strength predicted for this joint of twice the actual thickness and twice the bond area or one can change certain factors of 2, identified in the listing, to 1 for single-sided joints. The program accounts for arbitrary combinations of adherend stiffness and thermal imbalances as well as non-uniform step thickness increments and step lengths. It has been used successfully in optimizing the joint proportions in order to maximize the joint strength.

A complete listing of the program A4EF follows after the input and output have been described.

CARD 1:

FORMAT (I2)

M = Number of configurations (each requiring a complete set of data) to be solved.

CARDS 2, 2A:

FORMAT (8F10.3)

TAUMAX = $\tau_p$ = Peak adhesive shear stress.

G = Elastic adhesive shear modulus.
GAMMAX = \gamma_e + \gamma_p = Maximum adhesive shear strain. (This may be set less than \gamma_e to cover partial loads.)

GAMMAE = \gamma_e = Elastic adhesive shear strain.

ETA = \eta = Bond line thickness.

ALPHAO = \alpha_o = Coefficient of thermal expansion of outer adherend.

ALPHAI = \alpha_i = Coefficient of thermal expansion of inner adherend.

DELTMP = \Delta T = T_{operating} - T_{stress-free} = T_{operating} - T_{cure} = Temperature differential.

SGNLĐ = +1 for tensile shear load, and = -1 for compressive shear load.

ANSTEP = Number of steps in the joint. This serves to control the number of adherend property cards read in.

CARDS 3, 3A, 3B, ..etc... 3(N = ANSTEP + 1)
FORMAT (7F10.3)
THICKO(N) = Sum of thicknesses of outer adherends for nth step.

THICKI(N) = Thickness of nth step of inner adherend.

STEPL(N) = Length of nth step.

ETOTR(N) = Net extensional stiffness of outer adherends at nth step.

ETINR(N) = Extensional stiffness of inner adherend at nth step.

STROTR(N) = Net strength of outer adherends at nth step.

STRINR(N) = Strength of inner adherend at nth step.
The output is in tabular form with one row devoted to each step or step portion. Those entries not defined in the input description above are: TAU the adhesive shear stress, GAMMA the adhesive shear strain, DELTAO the displacement of the outer adherends, DELTAI the displacement of the inner adherend, with TOUTER and TINNER being the loads ($\sigma t$) in the outer and inner adherends, respectively.

The more accurate solution is obtained by starting the iterative solution from the more critically loaded end. Therefore, in those cases in which the a priori identification of the more critical end is not possible, the program outputs solutions from each end, and the second one is to be preferred. Such cases have been run and the computational procedure in double precision has been shown to be sufficiently accurate from either end. The need for this higher precision on IBM computers arises from the precision loss throughout the nested do loops in the iteration sequence. The greater number of significant digits employed by CDC machines has been found to obviate the need for this and the program can be modified to single-precision operation on CDC machines in a straightforward manner.
C PERFECTLY PLASTIC SOLUTIONS
C JOINT ANALYSIS PROGRAM
C SOLVE FOR ADHESIVE SHEAR STRESS AT JOINT
C GROUND THAT OUTER END STEP IS USUALLY SUFFICIENTLY THIN FOR
C NOTE THAT CONVERGENCE PROBLEM IS ACUTE FOR STEPPED-LAP JOINTS, EVEN
C 1 WITH DOUBLE-PRECISION, STEPS TAKEN HERE TO CONSTRAINT TENDENCY
C Note also that convergence difficulties are problem dependent, being
C 3 SUFFICIENTLY STRAIGHT THROUGH THE JOINT FROM END TO END, IN
C STRESS PROBLEMS, UP TO A DEGREE OF PROGRESS IN THE
C THE UNDERLYING DIFFICULTY IS ONE OF NUMERICAL ACCURACY LOSS IN THE
C 1 PRESENCE OF EXTREMELY HIGH ADHESIVE SHEAR STRESS GRADIENTS AT
C C BOTH ENDS OF EACH OF THE OUTER STEPS.
C C THAT PROBLEM CAN'T HANDLE A JOINT WITH SUCH HIGH
C 2 APPLICATION OF MECHANICAL LOADS, ANSWER FROM ONE END OF JOINT
C 4 WILL BE ZERO, BUT FROM OTHER END WILL BE LARGE AND POSITIVE.
C 5 ACTUALLY, THE LATTER ANSWER IS FOR A LOAD OF REVERSED SIGN, WITH
C 6 THE THERMAL STRESSES HELPING RATHER THAN HINDERING SUCH A
C 7 SITUATION CAN BE SPLIT IF THE SHEAR STRESS IN THE NERMER
C 8 SOLUTION IS NEGATIVE AT THE START OF THE JOINT
C 9 STRESS MADE TO ZERO FROM THE INTERIOR TO THE EXTERIOR
C 10 DIRECTLY IN THERMAL, THICKER, GAMMA(50), THICK(50), ETNTR(50),
C 11 ETA(N), STEP(50), THICK(50), ETNTR(50),
C 12 DOUBLE PRECISION TOLERANCE INNER, TAMMA, ETA(I), THICK(I), ETNTR(I),
C 13 TMAX, TMIN, THIC(L(N), STEPL(N), THICK(N), ETA(N), ETINR(N),
C 14 STEPL, THICK, ETA(N), ETNTR(N), THICK(N), ETNTR(N),
C 15 (THICK(N), THICK(N), STEPL(N), ETINR(N), ETINR(N),
C 16 STEP(N), STRINP(N), STRIN(N), N = 1, NSTEPS)
C CHECK ON CONSISTENCY OF ADHESIVE DATA
C VCHECK = G * GAMMAE
C IF (390.0, 390.0, GT, P) GO TO 300
C IF (GAMMAE GT, GAMMAE) GO TO 300
C TMAX, TMIN, THICK, ETA(N), ETINR(N), ETINR(N),
C C SET UP RECURRING CONSTANTS
C C FACTOR 2. ACCOUNTS FOR BONDING ON BOTH SIDES OF INNER ADHEREND.
C C REDUCE TO 1. IF JOINT HAS ONLY ONE SIDE BONDED
C C PRINT OUT INPUT DATA
C C ESTIMATE MAXIMUM POSSIBLE BOND CAPACITY FOR FULLY-PLASTIC ADHESIVE
C C NOTE FACTOR 2. INCLUDED FOR DOUBLE-SIDED JOINT
C C REDUCE TO 1. IF JOINT HAS ONLY ONE SIDE BONDED
C CONVERGENCE WILL NOT PROCEED TO FAR END OF JOINT IN SINGLE PASS
1 BECAUSE OF NUMERICAL ACCURACY PROBLEMS, REMEDY IS TO FREEZE
3 SMALLER VALUES WHICH HAVE CONVERGED AND SLIGHTLY PERTURB
5 INTERMEDIATE VALUES, AND TO CHECK FOR CONVERGENCE AT THE FAR END
A4EF2050
TMAX = TOUTERFLAG
IF (MIN.getKey(1) * TMAX = 5, * TMAX)
TOUTER(FLAG) = (TMIN + TMAX) / 2.
A4EF1900
GO TO 150
A4EF1900
GO TO 170
170 TMIN = TOUTER(FLAG)
150 CONTINUE
SCHFECK = TOUTER(FLAG)
C IF ADHERENT RATHER THAN ADHESIVE, LIMITS JOINT STRENGTH, MISO TO
C 1 BOOST LOAD IN PROPORTION TO TMAX, EVEN IF IT MEANS EXCEEDING
C 2 ADHERENT STRENGTHS IN INTERMEDIATE COMPUTATIONS, CORRECTIONS
C 3 ARE APPLIED LATER
A4EF1960
IF (MIN.getKey(1) > TMAX / 10, TMAX = 1.1 * TMAX)
A4EF2120
TOUTER(FLAG) = (TMIN + TMAX) / 2.
A4EF1900
IF (TMIN.getKey(1) > TMAX / 10, TMAX = 1.1 * TMAX)
A4EF2120
TOUTER(FLAG) = (TMIN + TMAX) / 2.
A4EF1900
GO TO 150
A4EF1900
GO TO 170
170 TMIN = TOUTER(FLAG)
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A4EF2120
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A4EF1900
IF (TMIN.getKey(1) > TMAX / 10, TMAX = 1.1 * TMAX)
A4EF2120
TOUTER(FLAG) = (TMIN + TMAX) / 2.
C USE ITERATIVE SOLUTION WHEN ADHESION THERMAL MISMATCH IS Present
C ASCERTAIN WHETHER INTERNAL LOADS ARE CRITICAL FOR ELASTIC ADHESIVE
C IF OTHER END OF JOINT IS MORE CRITICAL FOR ADHESIVE,

240 IF (PSCALE < LT, 0) PSCL = -1. * PSCL
   TAU = TAU(1) / TAU(MAX) = -1. * TAU(MAX)
   GO TO 260
N = 2, MSTOPS

C NEED TO COMPARE LOAD WITH STRENGTH ON THIN SIDE OF STEP, HENCE (N-1)
IF (RIND > LT, 0) RIND = -1. * RIND
IF (RIND > CT, PSCL) PSCL = RIND
IF (N = 50, MSTOP, GO TO 270
   S = 1. / PSCL, R = 1. / RIND
   GO TO 250

250 IF (RIND > LT, 0) RIND = -1. * RIND
   TAU = TAU(1) / TAU(MAX)
   GO TO 260

260 CONTINUE
C CHECK ON CONVERGENCE
C IF (TAU(1) > LT, 0) * TAU(1) * TAU(MAX) = 0. * TAU(1)
C IF ((1, 0, 0, 1) GT, R) AND (0, 10, 9999 , LT, R) GO TO 310
   V = 0. * TAU(1), 0. * TAU(MAX)
   IF (1, 0, 0, 1) GT, R) GO TO 310
   IF (N = 0, MSTOP, GO TO 290
   CONTINUE
C IF BOTH PSCL AND RIND ARE LT, TAU(1) MUST BE INCREASED
C IF (PSCL < LT, 0) AND (RIND < LT, 0) GO TO 300
C IF none of the three checks above is met, solution has failed to
C CONVERGE
C IF PROGRAM GIVES BEYOND PRECEDING CONTINUE STATEMENT, SOLUTION HAS NOT
C CONVERGED
C WRITE (6,330) N, STEP(N), THICK(N), THICK(N), TAU(N), GAMMA(N)
   WRITE (6,330) N, STEP(N), THICK(N), THICK(N), TAU(N)
C FOR ECA'S FIRST AND SECOND STRESS DISTRIBUTIONS
C RECOMPUTE SOLUTION FROM OTHSE END OF JOINT, IF APPROPRIATE
C MUTE THAT, IF COMPUTER PRINTS OUT TWO SOLUTIONS TO A GIVEN PROBLEM BY
C REVERSING ENDS AND RE-ANALYZING, IT IS BECAUSE THE FIRST FAILED
C TO CONVERGE, EVEN IF THE ANSWERS PRINTED SEEM TO SUGGEST
C OTHERWISE, THE SECOND SOLUTION IS TO BE PREFERRED, PARTICULARLY
C IF IT STARTS AT THAT END OF THE JOINT AT WHICH THE ADHESIVE
C SHEAR STRESS IS AT ITS HIGHEST.
C IDENTIFY CRITICAL END OF JOINT
C AVOID REVERSING ENDS BACK AGAIN
C IF (JFLAG = 2) GO TO 390
C IF (TATUMSTEPS = 1) = TAU(1) * TAU(MAX)
C IF (TATUMSTEPS = 1) = TAU(1) * TAU(MAX)
C IF SO, SOLUTION HAS FAILED TO CONVERGE, SO TRY AGAIN FROM OTHER END
C ACCURACY AT FAR END OF JOINT MAY BE BAD IF FAR END IS CRITICAL
C IF (TATUMSTEPS = 1) = TAU(1) * TAU(MAX)
C 1: (N < TATUMSTEPS) AND (TAU(MSTEPS) = GE.
C IF, AT FAR END OF JOINT, TAU(MSTEPS) GT. TAU(1) AT NEAR END.
C 2. FAILURE TO CONVERGE MAY BE SIMPLY THE RESULT OF THE FAR END
C REVERSE DATA AND RERANAYZ
360 DO 370 N = 1, MSTEPS
   STEPL(N) = STEP(IN)
   THICKN(N) = THICK(N)
   ETOUTR(N) = ETOUTR(IN)
   ETINNR(N) = ETINNR(IN)
   STRCON(N) = STRCON(IN)
370 DO 380 N = 1, MSTEPS
   STEPL(N) = STEP(MSTEPS - N)
   THICKN(N) = THICK(MSTEPS - N)
   ETOUTR(N) = ETOUTR(MSTEPS - N)
   ETINNR(N) = ETINNR(MSTEPS - N)
   STRCON(N) = STRCON(MSTEPS - N)
380 DO 390 N = 1, MSTEPS
   STEPL(N) = STEP(MSTEPS)
   THICKN(N) = 0.
   ETOUTR(N) = ETOUTR(1)
   ETINNR(N) = ETINNR(1)
   STRCON(N) = 0.
   STRCON(MSTEPS) = STRCON(1)
   V = ALPHA
   ALPHAI = ALPHA
   ALPHAI = V
   JELAG = 2
   NRVS = 0
   GO TO 50
390 CONTINUE
   STOP
   END
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**Elastic Joint Strength, Load (lbs):** 7829.0

**Alloy:** 4404 T6061 ADHESIVE SHEAR STRESS, TS MAX (psi) * 5200.0

**N = 1** for Tensile Shear and **1** for Compressive

**Temperature Differential (deg F):** 100.0

### ELASTIC JOINT STRENGTH, LOAD (LBS) = 7829.0

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<tr>
<th>N</th>
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<th>TAU</th>
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<th>STRINR</th>
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<td>0.0010</td>
<td>7829.0</td>
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**Elastic Joint Strength, Load (LBS) = 6742.0

**Alloy:** 4404 T6061 ADHESIVE SHEAR STRESS, TS MAX (psi) * 5200.0

**N = 1** for Tensile Shear and **1** for Compressive

**Temperature Differential (deg F):** 100.0

<table>
<thead>
<tr>
<th>N</th>
<th>STEPL</th>
<th>THICKE</th>
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<tr>
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<td>0.0300</td>
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A.5 Computer Program A4EG For Elastic-Plastic Strength of Stepped-Lap Bonded Joints

The elastic-plastic strength of stepped-lap joints is covered by the analysis in Section 6. The digital computer program A4EG has been prepared as a design tool for the analysis of such joints. By printing out detailed internal stresses, the program can serve to aid in design improvement by changing the joint proportions in such a manner as to reduce the load transfer in the more critical regions and to increase it in those less severely loaded areas.

In addition to those features of the elastic solution A4EF, this elastic-plastic program A4EG seeks the existence and extent of any plastic adhesive zones within any step or step portion. The convergence of the nested iterative do loops is complicated by the addition of an extra loop accounting for the maximum adhesive shear strain. This is only rarely a known quantity for ductile adhesives because the end step of the stiffer adherend is usually the most critical detail.

A complete listing of the program A4EG follows. Precisely the same input data is used as for program A4EF and the output format is the same except inasmuch as A4EG prints out separate elastic and elastic-plastic solutions.
C CHECK AEGC
C STEPPED-LAP ADHESIVE-BONDED JOINTS
C JOINT ANALYSIS PROGRAM
C JOINT DESIGN PROGRAM
C SOLUTION EXAMINES ADHESIVE SHEAR STRESS AND ADHEREND NORMAL (AXIAL)
C 1 STRESS OUTLINES CONSIDERATION OF ADHESIVE PEAK STRESS ON THE
C 2 GRADIENT AT MIDDLE END STP IS USUALLY SUFFICIENTLY THIN FOR
C 3 STRESS PROBLEMS NOT TO AFFECT
C NOTE THAT CONVERGENCE PROBLEM IS ACUTE FOR STEPPED-LAP JOINTS, EVEN
C 4 WITH DOUBLE-DIAGONAL STPS TAKEN HERE TO CONSTRAINT TANGENCY
C 5 TO AGRS (BY EQUATING SOLUTION ONE STP AT A TIME) HAVE BEEN
C 6 ADOPTED AFTER TRYING BOTH MORE AND LESS STRINGENT TECHNIQUES
C 7 MORE SEVERE END BRIEFT HIGH MODULUS) ADHESIVES, LOW MODULUS
C 8 ADHESIVES PROVED AMENABLE TO A CONVERGENT SOLUTION IN ONLY A
C 9 SINGLE PASS STRAIGHT THROUGH THE JOINT FROM END TO END, IN
C 10 single precision, WITH ONLY A SMALL LOSS OF ACCURACY IN LAST
C 11 STEPS.
C THE UNDERLYING DIFFICULTY IS ONE OF NUMERICAL ACCURACY LOSS IN THE
C 12 SPREAD OF EXTREMELY HIGH ADHESIVE SHEAR STRESS GRADIENTS AT
C 13 BOTH ENDS OF EACH OF THE OUTER STEPS.
C PROGRAM HAS BEEN ADAPTED TO RUN ON CDC COMPUTERS IN SINGLE Precision
C 14 BUT ONLY WORKS INTERMITTENTLY IN SINGLE PRECISION ON IBM MACHINES
C 15 DIMENSION TOUT(150), TINNER(150), GAMMA(150), TAU(150),
C 16 DELTA(150), DELTA(150), STEPL(50), THICK(50), HICK(50),
C 17 ETOT(50), ETAI(50), STRP(50), STRNR(50), STEP(150),
C 18 THCN(150), THCN(150), ETAU(150), ETNIN(150), STEP(150),
C 19 STRGNR(150),
C 20 DUMMY TOUT, TINNER, GAMMA, TAU, DELTA, DELTA,
C 21 MAX, MIN, A, B, C, D, F, E, F, ALAMDA, DELT, DELT, C1, C2, C3.
C 22 C4, C5, C7, C10, V, V4, V5, V6, V7, VB, V8, V9, 0, 0, 0, 0, 0, 0, 0.
C 23 TSTEP, TSTEP, TSTEP, TSTEP,
C 24 THCN, THCN, ETNIN, STRGR, STRGR, STEP, THICK
C 25 GP, ETA, ETA, ETA, ETA, ETA, ETA, ETA
C 26 GAMMA, ETA, ETA, ETA, ETA, ETA, ETA, ETA
C 27 GAMMA = LMAX + 3 * NSTEPS
C 28 NSTEPS = NSTEPS + 1
C 29 NSTEPS = NSTEPS + 1
C 30 NSTEPS = NSTEPS + 1
C 31 NSTEPS = NSTEPS + 1
C 32 NSTEPS = NSTEPS + 1
C 33 NSTEPS = NSTEPS + 1
C 34 NSTEPS = NSTEPS + 1
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C 114 NSTEPS =NSTEPS + 1
C 115 NSTEPS =NSTEPS + 1
C 116 NSTEPS =NSTEPS + 1
C 117 NSTEPS =NSTEPS + 1
C 118 NSTE
NOTE 4 BECRIFMS INDEPENDENT nF

NOTE 3 PERFECTLY-#LASTIC RPNq CAPA£1TY

NOTE ALSO OPERATE

NOTE REDUCTION

NOTE THAT, IF (HE

NOTE FACTOR 2. INCLUDED FOR DOUBLE-SIDED JOINT

NOTE THAT PROBLEM IS PREVENTED FROM HANDLING PROBLEM IN WHICH SHEAR

NOTE 2. STRESS IN ADHESIVE REVERSES SIGN, WHEN COMPUTATIONS START FROM

NOTE 1. STRESS CRITICAL END. SOLUTION IS OBTAINABLE FROM OTHER END.

NOTE 1. STRESS ALONE WITHOUT ANY EXTERNALLY APPLIED LOAD, SO NO CASES

NOTE INITIAL CONDITIONS

NOTE OPERATE ON THE LOAD LEVEL IN INTERMEDIATE LOOP

NOTE LEAVE ADJUSTMENT OF TAUMAX FOR OUTER LOOP

NOTE CONVERGENCE NEARLY ALWAYS OCCURS BETWEEN 20 AND 30 CYCLES IN TEST

NOTE CONVERGENCE, BUT THERE WERE SOME EXCEPTIONS

NOTE CHECK ON CONVERGENCE OF TOUTEP1IFLAG)

NOTE INNER LOOP COMPUTES ELASTIC JOINT STRENGTH

NOTE THAT SIGN 0 SIGNIFIES WETHER SHEAR LOAD IS TENSILE OR COMPRESSIVE

NOTE 1. IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
C NOTE THAT THESE CONVERGENCE CHECKS ARE CRITICAL
C IF THE FACTOR 2 IS TOO LARGE OR TOO SMALL, CONVERGENCE FAILS
C FACTOR 2 ACCOUNTS FOR RONNING ON BOTH SIDES OF INNER ADHESIVE
C 1. IF BOUNDED ON ONE SIDE ONLY, REDUCE TO 1.
C DELTA(I+1) = DELTA(I) + C * C * SIGMA + (TOUTER(I) - C +
C DELTA(I) / TOUTER(I)
C DELTA(I+1) = DELTA(I) + C * C * SIGMA + (TINNER(I) * C +
C DELTA(I) / TINNER(I)
C GAMMA(I+1) = GAMMA(I) / G
C 100 CONTINUE
C CHECK WHETHER OR NOT PRECISELY 100 PERCENT OF LOAD HAS TRANSFERRED
C R1 = TOUTER(I) / TINNER(I)
C CHECK ALSO WHETHER CONVERGENCE HAS BEEN OBTAINED
C 0.999999 G0.1 AND, 0.999999 WITH
C 1. (0.00001 G0.1 AND, 0.000001 G0.1) GO TO 220
C IF TOUTER(I) LT, TINNER(I) MSTEPS) GO TO 130
C IF LOAD ESTIMATE IS TOO LOW
C 100 CONTINUE
C IF LOAD ESTIMATE IS TOO HIGH
C 100 CONTINUE
C IF NOT, LOAD ESTIMATE IS TOO HIGH
C 100 CONTINUE
C IF CONVERGENCE CHECK IS NOT SATISFACTORY FOR A CONVERGENCE CHECK BECAUSE NEGATIVE VALUES OF R1 ARE OBTAINED
C 30趕 EXCESS IN UNITY
C 130 TMIN = TOUTER(I) / TINNER(I)
C TOUTER(I) = (TMIN + TMAX) / 2.
C CHECK = TINNER(I) / TOUTER(I)
C GO TO 170
C 140 TMAX = TOUTER(I) / TINNER(I)
C TOUTER(I) = (TMIN + TMAX) / 2.
C CHECK = TINNER(I) / TOUTER(I)
C GO TO 170
C NOTE THAT LABELS 26 AND 7 GOVERN FINE ADJUSTMENTS TO THE JOINT LOADS,
C 100 CONTINUE
C IF ADHESIVE, OTHER THAN ADHESIVE, LIMITS JQINT STRENGTH, NEED TO
C 1 ROU BOAD IOM IN PROPORTION TO TAIHAX, EVEN IF IT MEANS EXCEEDING
C 2 ADHESIVE STRENGTHS IN INTERMEDIATE COMPTIUTIONS, CONNECTIONS
C 3 ARE APPLIED LATER
C IF (TMIN, C, TMAX) MAX = 5, * TMAX
C TOUTER(I) = (TMIN + TMAX) / 2.
C GO TO 170
C 160 TMIN = TOUTER(I)
C 100 CONTINUE
C IF (N, EQ, NSTEPS) GO TO 210
C CONVERGENCE WILL NOT PROCEED TO FAR END OF JOINT IN SINGLE PASS
C 1 THE LIMIT OF 0.09 FOR ACCURACY PROBLEMS, 0.09 IS TO PREVENT
C 2 EARLIER VALUES, WHICH HAVE CONVERGED AND SLIGHTLY TURBID
C 3 INTERMEDIATE VALUES, AND TO CHECK FOR CONVERGENCE AT THE FAR END.
C TMIN = TOUTER(I)
C TMIN = -1, * TMAX
C GO TO 210
C IF (TOUTER(I) = 0.1, G0.1) GO TO 190
C IF (TOUTER(I) = 0.1, G0.1) GO TO 200
C TMIN = -1, * TMAX
C GO TO 210
C 190 TMAX = 1.1 * TOUTER(I)
C GO TO 210
C 200 TMIN = 0.9 * TOUTER(I)
C THE BOUNDARY VALUE IS CRITICAL IN ENSURING CONVERGENCE
C THEY MUST BE NEITHER TOO LARGE NOR TOO SMALL
C 210 CONTINUE
C 220 IF (0.000001, G0.000001) GO TO 260
C IF NOT, FIRST SOLUTION MAY BE SCALING IN THE ABSENCE OF ANY THERMAL
C 100 CONTINUE
C IF SOLUTION CAN BE REFINED BY ITERATION, SINCE THERMAL STRESS
C 1 TERMS DO NOT SCALE LINEARLY, EVEN FOR ELASTIC ADHESIVE AND
C 2 ADHESIVES
C APPLY SCALE FACTOR TO SOLUTION FOR ONLY ADHESIVE STIFFNESS IMPAIRMENT
C ASCERTAIN WHETHER INTERNAL LOADS ARE CRITICAL FOR ELASTIC ADHESIVE OR
C 2 ADHESIVES
C PROGRAM ASSUMES ADHESIVE ALLOWABLES HAVE SAME MAGNITUDE IN TENSION AS
C 1 IN COMPRESSION. DISTINCTION IS USUALLY IMPORTANT SINCE, IN
C 2 PRAC TICAL J OINTS, RESIDUAL THERMAL STRESSES ARE U NLIKELY TO
3 BREAK ADHESIVE(S) RATHER THAN ADHESIVE.

\[ \text{RS}_{\text{SCALE}} = \text{TOUTER}(1) / \text{STRIP}(1) \]
\[ \text{IF (RS}_{\text{SCALE}} \LT 0.1) \text{RS}_{\text{SCALE}} = -1. \times \text{RS}_{\text{SCALE}} \]
\[ \text{PTA}_{\text{MAX}} = \text{TATT}(1) / \text{TAMAX} \]
\[ \text{IF (PTA}_{\text{MAX}} \LT 0.1) \text{PTA}_{\text{MAX}} = -1. \times \text{PTA}_{\text{MAX}} \]
\[ \text{ON 240 N = 2, MSTEPS} \]
\[ \text{RING} = \text{TINNER}(N) / \text{STRIN}(N) \]
\[ \text{IF (RING \LT 0.1) \text{RING} = -1. \times \text{RING} \]
\[ \text{PTAU} = \text{TATT}(N) / \text{TAMAX} \]
\[ \text{IF (PTAU \LT 0.1) \text{PTAU} = -1. \times \text{PTAU} \]
\[ \text{ON 240 CONTINUE} \]

C PSCTR IS PROPORTIONAL TO CONSTANT GOVERNING ELASTIC SOLUTION.

\[ \text{IF PTA}_{\text{MAX}} \text{GT. RS}_{\text{SCALE}}, \text{ADHESIVE PLASTICITY CAN INCREASE STRENGTH.} \]

C USUALLY ADHESIVE IS CRITICAL AT ONE END OF JOINT OR OTHER, SO TAMA

\[ \text{IF } \text{GT. 1. MAY WELL JUSTIFY SIGNIFICANT END OF JOINT IS CRITICAL.} \]

C NOTE THAT PROGRAM ASSUMES THAT ANY INTERNAL ADHEREND STRESSES OF

\[ \text{IF 1. REVERSAL SIGN WITH RESPECT TO STRESS OUTSIDE THE JOINT ARE NOT} \]

\[ \text{IF 2. CRITICAL. IF THEY ARE, IT MEANS THAT THE JOINT WILL FAIL DUE} \]

\[ \text{C 3. TO RESIDUAL THERMAL STRESSES ALONE WITHOUT ANY MECHANICAL LOADS} \]

\[ \text{IF (RS}_{\text{SCALE}} \LT \text{PTA}_{\text{MAX}} \text{DSCTR} = \text{PTA}_{\text{MAX}} \]
\[ \text{ON 250 N = 1, MSTEPS} \]
\[ \text{TOUTER(N) = TOUTER(N) / DSCTR} \]
\[ \text{TINNER(N) = TINNER(N) / DSCTR} \]
\[ \text{TAINH(N) = TAINH(N) / DSCTR} \]
\[ \text{TDELTA(N) = TDELTA(N) / DSCTR} \]
\[ \text{GO TO 310} \]

C USE ITERATIVE SOLUTION WHEN ADHEREND THERMAL MISMATCH IS PRESENT.

\[ \text{IF NOT OTHER END OF JOINT IS MORE CRITICAL FOR ADHESIVE.} \]

\[ \text{ON 260 N = 0, MSTEPS} \]
\[ \text{PTA}_{\text{MAX}} = \text{TATT}(1) / \text{TAMAX} \]
\[ \text{IF (PTA}_{\text{MAX}} \LT 0.1) \text{PTA}_{\text{MAX}} = -1. \times \text{PTA}_{\text{MAX}} \]
\[ \text{ON 280 N = 2, MSTEPS} \]
\[ \text{RING} = \text{TINNER}(N) / \text{STRIN}(N) \]
\[ \text{IF (RING \LT 0.1) \text{RING} = -1. \times \text{RING} \]
\[ \text{PTAU} = \text{TATT}(N) / \text{TAMAX} \]
\[ \text{IF (PTAU \LT 0.1) \text{PTAU} = -1. \times \text{PTAU} \]
\[ \text{ON 280 CONTINUE} \]

C CHECK ON CONVERGENCE.

\[ \text{IF (TATT}_{\text{MAX}} \LT 0.1 \text{AND. (0.999999 \LT TATT}_{\text{MAX}}) \text{GO TO 330} \]
\[ \text{V = 2 \times TATT}_{\text{MAX}} \]
\[ \text{IF (0.1 \LT TATT}_{\text{MAX}} \LT 0.999999 \text{AND. (TATT}_{\text{MAX}} \LT 0.1) \text{GO TO 330} \]

C IF EITHER TATTMAX OR RSscale GT. UNITY, TATT(1) MUST BE DECREASED.

\[ \text{IF (TATT}_{\text{MAX}} \LT 1.000001 \text{AND. (RS}_{\text{SCALE}} \LT 1.000001) \text{GO TO 290} \]

C IF BOTH TATTMAX AND RSscale ARE GT. UNITY, TATT(1) MUST BE INCREASED.

\[ \text{IF (TATT}_{\text{MAX}} \LT 0.999999 \text{AND. (RS}_{\text{SCALE}} \LT 0.999999) \text{GO TO 300} \]

C IF NEITHER CHECK IS MET, SOLUTION HAS CONVERGED.

\[ \text{GO TO 330} \]
\[ \text{290 TAU}_{\text{MAX}} = \text{TATT}(1) \]
\[ \text{ON 300 TAU}_{\text{MAX}} = \text{TATT}(1) \]
\[ \text{300 CONTINUE} \]
\[ \text{C IF PROGRAM CODE BEYOND PRECEDING CONTINUE STATEMENT, SOLUTION HAS NOT} \]
\[ \text{C 1. CONVERGED} \]
\[ \text{C 2. FORMAT (1M1, 18HINCONVERGENT SOLUTION) \]
\[ \text{C 3. PRINT OUT RESULTS OF ELASTIC COMPUTATIONS} \]
\[ \text{C 330 WRITE (6,340) TATT(1), TAIMAX, SGND, Deltmph} \]
\[ \text{C 340 FORMAT (1H1, 5H0.00000, 5H0.00000) \]
\[ \text{1 39H ELASTIC JOINT STRENGTH, PLOAD (LBS) = .1,0.1/} \]
\[ \text{2 49H ALLOWABLE ADHESIVE SHEAR STRESS, TAIMAX (PSI) = .1,0.1/} \]
\[ \text{3 51H ELASTIC JOINT STRENGTH, PLP (LBS) = .1,0.1/} \]
\[ \text{4 61H JOINT SHEAR STRESS, (PSI) = .1,0.1/} \]
\[ \text{5 62H TEMPERATURE DIFFERENTIAL (DEG F) = .1,0.1/} \]
\[ \text{6 63H ELASTIC JOINT STRENGTH, PLOAD (LBS) = .1,0.1/} \]
\[ \text{7 64H 6MSTRIP 5X, 6MSTIM 5X, 6MSTRIP//} \]
\[ \text{DO 360 N = 1, MSTEPS} \]

107
WRITE (6,350) N, STEPL(N), THICKN(N), THICKI(N), TAU(N), GAMMA(N), AEG3550
2) DELTAN, DELN(A), TOUTR(N), STO(TH(N), TINHER(N), STRIN(N), AEG3560
350 FORMAT (1H, 4X, 12, 1X, 6D4, 1X, 6D4, 1X, 6D4, 1X, 6D4, 1X, 6D4, 1X, F7.1, 1X, F10.1, 1X, F10.1, 1X, F10.1, 1X, F10.1, 1X, F10.1, 1X;
2) F10.1)
360 CONTINUE
C RECOMPUTE SOLUTION FROM OTHER END OF JOINT, IF APPROPRIATE
C NOTE THAT, IF COMPUTER PRINTS OUT TWO SOLUTIONS TO A GIVEN PROBLEM BY AEG3620
C REVISE DATA AND REANALYZE IT. IT IS BECAUSE THE FIRST FAILED TO CONVERGE;
C IF CONVERGE, THEN IF THE ANSWERS PRINTED SEEM TO SUGGEST
C OTHERWISE, THE SECOND SOLUTION IS TO BE PREFERRED, PARTICULARLY
C IF IT STARTS AT THAT END OF THE JOINT AT WHICH THE ADHESIVE
C SHEAR STRESS IS AT ITS HIGHEST.
C IDENTIFY CRITICAL END OF JOINT,
C AVOID REVERSING ENDS BACK AGAIN
C IF (NVRS = EQ. 1) GO TO 370
C IF (NVRS = EQ. 0) GO TO 400
C IF 400, SOLUTION HAS FAILED TO CONVERGE, SO TRY AGAIN FROM OTHER END
C ACCURACY OF SOLUTION AT END OF JOINT MAY BE POOR IF FAR END IS CRITICAL
C IF (TAU(MSTEPS) .LE. TAU(1)) AND (TAU(MSTEPS) .GE. 1)
C IF, AT FAR END OF JOINT, TAU(MSTEPS) GT. TAU(1) AT NEAR END
C 2) OF THE JOINT BEING MORE CRITICAL THAN THE STARTING (NEAR) END
C REVERSE DATA AND REANALYZE
370 DO 380 N = 1, NSTEP
STEPL(N) = STEPL(N)
THICKN(N) = THICKN(N)
THICKI(N) = THICKI(N)
ETNTR(N) = ETNTR(N)
ETNR(N) = ETNR(N)
STORI(N) = STORI(N)
STO(N) = STRI(N)
380 CONTINUE
DO 390 N = 1, NSTP
THICKN(N) = THICKN(N)
THICKI(N) = THICKI(N)
ETNTR(N) = ETNTR(N)
ETNR(N) = ETNR(N)
STORI(N) = STORI(N)
390 CONTINUE
STEPL(MSTEP) = STEPL(MSTEP)
THICKN(MSTEP) = 0.
THICKI(MSTEP) = 0.
ETNTR(MSTEP) = 0.
ETNR(MSTEP) = 0.
STO(MSTEP) = STRI(MSTEP)
V = ALPHA
ALPHA = ALPHA
V = V
JELAC = 2
NVRS = 0
GO TO 60
C BYPASS ELASTIC-PLASTIC COMPUTATIONS IF ADHERENDS ARE MORE CRITICAL
C 1) THAN ADHESIVE
C 400 IF (PSCAL .GE. OKPUMLX) GO TO 20
C RECORD ELASTIC JOINT STRENGTH
ELSTR = TOUTR(1)
C START ELASTIC-PLASTIC SOLUTION
C ELASTIC SOLUTION CONVERGES CRITICAL END OF JOINT, AND REVISED
C ORDER OF DATA IF NECESSARY, SO THERE IS NO NEED FOR SUCH
C CAPABILITY IN THE ELASTIC-PLASTIC SOLUTION
C ADD EXTRA LIMITATIONS INSIDE STEPS TO ACCOUNT FOR POTENTIAL PLASTIC-TO-
C ELASTIC AND ELASTIC-TO-PLASTIC TRANSITIONS IN ADHESIVE
C 410 DO 420 N = 1, NSTEPS
= 3 . N
THICKN(L-2) = THICKN(N)
THICKN(L-1) = THICKN(N)
THICKI(L-2) = THICKI(N)
THICKI(L-1) = THICKI(N)
ETNTR(L-2) = ETNTR(N)
ETNTR(L-1) = ETNTR(N)
ETNR(L-2) = ETNR(N)
ETNR(L-1) = ETNR(N)
STRO(L-2) = STRI(N)
STRO(L-1) = STRI(N)
STRI(L-2) = STRI(N)
STRI(L-1) = STRI(N)
AEG4110
AEG4120
AEG4130
AEG4140
AEG4150
AEG4160
AEG4170
AEG4180
AEG4190
AEG4200
AEG4210
AEG4220
AEG4230
AEG4240
AEG4250
AEG4260
AEG4270
AEG4280
AEG4290
AEG4300
AEG4310
AEG4320
AEG4330
AEG4340
AEG4350
AEG4360
AEG4370
AEG4380
AEG4390
AEG4400
108
PROCEDURE FOR

C Henr

C CHECK CONVERGENCE OF MIDDLE LOOP

C SET INITIAL CONDITIONS

C IF ADHERENTS, IF BONDER ON ONE SIDE ONLY, REDUCE TO 1.

C TMAX = TMAX

C TMXP, FULLY-PLASTIC JOINT STRENGTH

C TMIN, PERFECTLY-PLASTIC JOINT STRENGTH

C ICHECK = 0

C I CHECK = 10

C 1. EQUAL TO EITHER 1 OR 2

C THIS INSTRUCTION PRINTS OUT SOLUTION FOR POTENTIAL BOND SHEAR STRENGTH

C MAX = TMXP

C TMN = TMIN

C GAMMA(1) = (GAMMPR + GAMMLR) / 2.

C IF (KADFQV .EQ. 1) AND (J , GT. 1) GO TO 770

C IF (ICHECK .NE. JCHECK) GO TO 450

C IF NOT, ICHECK = 2 AND LOAD HAS BEEN TOO HIGH FOR TWO CONSECUTIVE ITERATIONS

C 1. ITERATIONS

C GAMMA(1) = (GAMMA(1) + GAMMLR) / 2.

C ICHECK = 2

C GO TO 450

C IF ICHECK = 1, LOAD HAS BEEN TOO LOW FOR TWO CONSECUTIVE ITERATIONS

C 430 GAMMA(1) = (GAMMA(1) + GAMMPR) / 2.

C ICHECK = 1

C GO TO 450

C SET INITIAL CONDITIONS

C 450 TMNX = (TMXP + TLOWF) / 2.

C TINNPF(1) = 0.

C TAU(1) = TAUMAX

C DELTAM(1) = 0.

C DELTAM(1) = 0

C DO 700 IFLAG = 1, NSTEP

C J1 = 3

C IF IFLAG .LT. NSTEP, ICHECK .EQ. 2 GO TO 670

C J2 = J1 + 3

C SCHEP = 100000000000000000.

C DO 650 NCHECK = 1, 650

C P USUALLY 20 CYCLES PER ITERATION WERE SUFFICIENT AT THIS POINT

C MIDDLE LOOP ADJUSTS LOAD LEVEL

C CHECK ON CONVERGENCE OF TMNX(1)

C IF IFLAG .EQ. 2 AND LOAD HAS BEEN TOO HIGH FOR TWO CONSECUTIVE ITERATIONS

C 430 GAMMA(1) = (GAMMA(1) + GAMMPR) / 2.

C ICHECK = 1

C GO TO 450

C INNERMOST LOOP COMPUTES JOINT STRENGTH

C I = 3

C NSTEP = -2

C STEP(1) = STEP(N)

C STEP(1) = 0.

C IF ADOHESIVE IS NOT LOADED INTO PLASTIC ZONE IN LATER STEPS OF JOINT

C 1. ADOHESIVE IS LOADED INTO PLASTIC ZONE AND PROCEED TO PERFECTLY-ELASTIC SOLUTION

C VR = GAMMA(1)

C IF (VR .LT. GAMMA(1) AND VR .GT. 0.1) GO TO 510

C IF IFLAG .EQ. 1 GO TO 510

C SOLVE FOR MAXIMUM POSSIBLE EXTENT OF PLASTIC ADHESIVE ZONE

C IF BONDER ON ONE SIDE OF JOINT ONLY, DIVIDE A BY 2.

C B = (CS * SGNL - VR / V6 + V7 / V5) / ETA

C NOTE THAT B SHOULD BE NEGATIVE AT AND NEAR CRITICAL END OF JOINT

C ENEED FOR BROKEN ADHESIVE SOLUTION TO IDENTIFY CRITICAL END

C IF (VR .LT. 0.1) GO TO 510

C PROCEDURE FOR POSITIVE PLASTIC ADHESIVE SHEAR STRAINS

C (V8 .LT. 0.1) GO TO 47
C IF SQ. PLASTIC ZONE IS UNREDUCED, AS AT FAR END OF J0NT
XP = (-1. * B - DSOPT(D1)) / (2. * A)
GO TO 470
C IF SQ. PLASTIC ZONE IS UNREDUCED, AS AT FAR END OF J0NT
V0 = (V1 - DSOPT(D1)) / (2. * A)
470 IF (V0 .GE. V0) GO TO 440
C IF SQ. PLASTIC ZONE IS FULLY PLASTIC THROUGHOUT THAT STEP
IF NOT, BREAK UP STEP INTO PLASTIC AND ELASTIC PORTIONS
MFLAG = 1
STEP(1) = XP
STEP(+1) = V0 - XP
V0 = XP
C MAY HAVE TO DECREASE STEPS(3*N-1) AND ADD TO STEPS(3*N) LATER
C PROCEDURE FOR FULLY-PLASTIC STEP OR STEP PORTION
C THIS SERIES OF EQUATIONS HOLDS REGARDLESS OF SIGN OF SHEAR STRESS
C L GRADIENT AT START OF STEP
480 DELT = 2. * TAU(L) * V0
C THE USE OF TAU(L) INSTEAD OF TAU(MAX) COVERS REVERSAL OF SIGN
C FACTOR 0. ACCOUNTS FOR ROUNDOFF ON BOTH SIDES OF INNER ADHEREND
L = 1 + 1
TOUTER(L1) = TOUTER(L)
TOUTER(L2) = TOUTER(L)
TINNER(L1) = TINNER(L)
TINNER(L2) = TINNER(L)
TAU(L1) = TAU(L)
TAU(L2) = TAU(L)
DELTA(T1) = DELTA(T)
DELMA(L1) = GAMMA(L1)
DELMA(L2) = GAMMA(L2)
DELTA(T2) = DELTA(T)
DELTA(T1) = DELTA(T)
DELTA(T2) = DELTA(T)
1 = (V0**2) / 2.1 / V4
DELTA(T1) = DELTA(T)
DELTA(T2) = DELTA(T)
C NOTE THAT USE OF TAU(L) INSTEAD OF TAU(MAX) AUTOMATICALLY ACCOUNTS FOR
C SIGN OF ADHESIVE SHEAR STRESS
490 IF (N .EQ. NSTEPS) GO TO 500
IF (TOUTER(L) .LT. V10) GO TO 620
IF TINNER(L) .LT. V10) GO TO 610
C NOTE THAT THESE CONVERGENCE CHECKS ARE CRITICAL
C IF NOT, STEP IS PLASTIC THROUGHOUT
L1 = L + 1
L2 = L + 2
TOUTER(L1) = TOUTER(L)
TOUTER(L2) = TOUTER(L)
TINNER(L1) = TINNER(L)
TINNER(L2) = TINNER(L)
TAU(L1) = TAU(L)
TAU(L2) = TAU(L)
DELTA(T1) = DELTA(T)
DELMA(L1) = GAMMA(L1)
DELMA(L2) = GAMMA(L2)
DELTA(T2) = DELTA(T)
DELTA(T1) = DELTA(T)
DELTA(T2) = DELTA(T)
C IF NOT, STEP SIZE IS EXCESSIVE, REDUCE BY ITERATION
C IF NOT, ELASTIC STEP SIZE IS EXCESSIVE, REDUCE BY ITERATION
C PROCEDURE FOR PERFECTLY-ELASTIC ZONE
C IDENTIFY WHETHER STEP IS ELASTIC-PLASTIC OR FULLY ELASTIC THROUGHOUT
C 510 K = L - 1 * N + 2
C K .EQ. 0 CORRESPONDS TO NO PLASTIC ZONE AT NEAR END OF JOINT
C SET INITIAL CONDITIONS AT START OF STEP
V6 = EFDTR(N)
V5 = EFTINP(N)
V6 = TOUTER(L)
V7 = TINNER(L)
ALAMDA = DSOPT(C2 * (1. / V4 + 1. / V5))
C IF RANDON ON ONE SIDE ONLY, REDUCE TO 1
C COMPUTE VALUES AT FAR END OF ELASTIC ZONE
A = TAU(L)
B = V5 - V6 / V4 + C5 * SGNL(N) * C1 / ALAMDA
C NOTE THAT SGNL(N) SIGNIFIES WHETHER SHEAR LOAD IS TENSILE OR COMPRESSIVE
C STEPI(L)
D = ALAMDA * C
E = DSTDH(N)
F = EGCASH(D)
TAU(L+1) = A * F + B * E
IF (TAU(L+1) .GE. TAIAX) .AND. (TAU(L+1) .GE. C10) )
1 GO TO 540
C IF NPT, THEN 10 (SPCQN n) PLASTIC Zn N p AT
C
C
C THIS IS NOT APPROPRIATELY COMPUTED TO LAST SUBDIVISION IN STEP
C
C IF NOT, THEN THERE IS NO (SECOND) PLASTIC ZONE AT FAR END OF STEP
L1 = L + 1
TOUTER(11) = TOUTER(L)
TINPER(11) = TINPER(L)
TAU(11) = TAU(L)
GAMMA(11) = GAMMA(L)
DELTA(11) = DELTA(L)
IF (K = FQ, 1) GO TO 550
C IF NOT, THEN THERE IS NO (FIRST) PLASTIC ZONE AT NEAR END OF JOINT
L2 = L + 2
TOUTER(12) = TOUTER(L)
TINPER(12) = TINPER(L)
TAU(12) = TAU(L)
GAMMA(12) = GAMMA(L)
DELTA(12) = DELTA(L)
550 IF (N = FQ. 1STEPS) GO TO 560
IF (TOUTER(11) .LT. V10) GO TO 620
IF (TOUTER(11) .LT. V10) GO TO 620
IF (TOUTER(11) .LT. V10) GO TO 620
C NOTE THAT THESE CONVERGENCE CHECKS ARE CRITICAL
C IF V10 IS EITHER TOO LARGE OR TOO SMALL, CONVERGENCE FAILS
560 IF (L = FQ, 1) GO TO 570
GO TO 590
C
C PROCEDURE FOR (SECOND) PLASTIC ZONE AT FAR END OF STEP
570 VO = TOUTER(L)
DELT = 2. * TAU(L) * V9
C FACTOR 2 ACCOUNTS FOR BONDING ON BOTH SIDES OF INNER ADHEREND.
C IF BONDED ON ONE SIDE ONLY, REDUCE TO 1.
C
C SET INITIAL CONDITIONS AT START OF STEP
V4 = F(Material)
V5 = ETINPER(N)
V6 = TOUTER(L)
V7 = TINPER(L)
L = L + 1
TOUTER(L) = V6 - DELT
TINPER(L) = V7 + DELT
TAU(L) = (TOUTER(L) - V6 + TINPER(L) - V7) / (V5 - V6 + V7 - V4)
C NOTE THE USE OF TAU(L-1) INSTEAD OF TAU(MAX) IN ORDER TO ACCOUNT
C AUTOMATICALLY FOR THE SIGN OF THE SHEAR STRESS
C IF BONDED ON ONE SIDE ONLY, DIVIDE A BY 2.
B = (C5 * SGNLD - V6 / V4 + V7 / V5) / ETA
GAMMA(L) = GAMMA(L-1) + R * V9 + A * (V9**2)
TAU(L) = TAU(L-1)
DELTA(L) = DELTA(L-1) + C3 * V9 + SGNLD * (V6 * V9 - TAU(L))
1 (V9**2) / 2. * V9
DELTA(L) = DELTA(L-1) + C4 * V9 + SGNLD * (V7 * V9 - TAU(L))
1 (V9**2) / 2. * V9
C IF THERE HAS BEEN NO PLASTIC ZONE AT START OF STEP, TRANSFER VALUES
C IF THERE HAS BEEN PLASTIC ZONE ACROSS TO LAST SUBDIVISION IN STEP
C THIS IS NECESSARY TO PROVIDE INPUT DATA FOR START OF NEXT STEP
IF (K = FQ, 1) GO TO 580
L = L + 1
TOUTER(L) = TOUTER(L)
TINPER(L) = TINPER(L)
TAU(L) = TAU(L)
GAMMA(L) = GAMMA(L)
DELTA(L) = DELTA(L)
DO 620 TMIN = (TMAX + TMIN) / 2.
TO 660

C CONVERGENCE WILL NOT PROCEED TO END OF JOINT IN SINGLE PASS
C BECAUSE OF NUMERICAL ACCURACY PROBLEMS. REMEDY IS TO FREEZE
C INTERMEDIATE VALUES, AND TO CHECK FOR CONVERGENCE AT THE FAR END.

TMAX = TUPPER
TMIN = -1. * TMAX
GO TO 700

670 IF (TOUTER(J2) .GT. 0.) GO TO 680
IF (TOUTER(J2) .LT. 0.) GO TO 690
TMAX = TOUTER(J1) / 10.
TMIN = -1. * TMAX
GO TO 700

680 TMAX = 0.9 * TOUTER(J2)
TMIN = 0.9 * TOUTER(J2)
GO TO 700

690 TMAX = 0.9 * TOUTER(J2)
TMIN = 1.1 * TOUTER(J2)
GO TO 700

C THE BOUNDS ABOVE ARE CRITICAL IN ENSURING CONVERGENCE
C THEY MUST BE NEITHER TOO LARGE NOR TOO SMALL
700 CONTINUE
C
C ASCERTAIN WHETHER INTERNAL LOADS ARE CRITICAL FOR ELASTIC-PLASTIC
C 1 ADHESIVE

710 PScale = TOUTER(1) / STAGEP(1)
IF (PScale .LT. 0.2) PScale = -1. * PScale
PGMAX = GAMMA(1) / GAMMAX
IF (PGMAX .LT. 0.) PGMAX = -1. * PGMAX
DG 730 N = 2 * PScale
RINP = TINNER(N) / STAGRM(N-1)
RINO = TINNER(N) / STAGRM(N-1)
IF (RINO .GT. 0.) RINO = -1. * RINO
IF (RINO .LT. 0.) RINO = RINO
IF (RINP .LT. 0.) RINP = RINP
IF (RINP .LT. 0.) RINP = RINP
R720 PGMAX = GAMMA(1) / GAMMAX
IF (PGMAX .LT. 0.) PGMAX = -1. * PGMAX
IF (PGMAX .LT. 0.) PGMAX = PGMAX
730 CONTINUE
C
C IN CASE UPPER AND LOWER BOUNDS ON JOINT LOAD HAVE COALESCED,
C NO MORE CONVERGENCE IS POSSIBLE. PRINT OUT RESULTS.

740 IF (1.000000001 * LT. R) AND (-0.999999999 * LT. R) GO TO 770

C ADJUST MAXIMUM ADHESIVE SHEAR STRAIN IF ADHESIVE STRENGTH GOVERNS OVERALL THERMAL
C STRESS CONSIDERATIONS

750 IF (PScale .LT. 1.001) OR (PGMAX .LT. 1.001)

770 CONTINUE
1. GO TO 740
   IF 1 (RESCALE .LT. 0.9999) AND. (PGAMAX .LT. 0.9999) 1
   GO TO 750
C IF NEITHER ONE OF THESE CHECKS IS MET, SOLUTION HAS CONVERGED. PRINT OUT.
A4EG7930
A4EG7940
A4EG7950
750 IF NOT, REPEAT
A4EG7960
740 GAMMA = GAMMA(1)
    TUPPER = TUPPER(1)
    JCHECK = 2
    GO TO 760
750 GAMMA = GAMMA(1)
    TUPPER = TUPPER(1)
    JCHECK = 1
    GO TO 760
C IF PROGRAM GOES PAST THIS CONTINUE STATEMENT, CONVERGENCE HAS FAILED
760 CONTINUE
A4EG7970
A4EG7980
A4EG7990
770 IF PRINT OUT RESULTS OF ELASTIC-PLASTIC COMPUTATIONS.
A4EG8000
A4EG8010
780 FORMAT (141, 6(140/1), 1D16.14)
790 FORMAT (141, 6(140/1), 1D16.14)
800 CONTINUE
A4EG8020
A4EG8030
A4EG8040
A4EG8050
A4EG8060
A4EG8070
A4EG8080
A4EG8090
A4EG8100
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A4EG8370
A4EG8380
A4EG8390

113
### Input Data

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### Elastic Joint Strength

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### Elastic-Plastic Joint Strength

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114
## INPUT DATA

### ELASTIC JOINT STRENGTH, PLOAD (LBS) = 10730.1

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### ALLOWABLE ADHESIVE SHEAR STRAIN, GAMMA = 0.17

### ALLOWABLE ADHESIVE SHEAR STRESS, TAUMAX (PSI) = 6000.0

### ALLOWABLE TENSILE SHEAR AND -1 FOR COMPRESSION

### TEMPORATURE DIFFERENTIAL (DEG F) = -280.0

### DELTAP = -28°C (DEG. F)