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MECHANICAL BEHAVIOR OF MULTIMATERIAL COMPOSITE SYSTEMS

INTERLAMINAR BEHAVIOR

Final Technical Report (Third Research Year)

by

Ori Ishai, Dan Peretz and Shiomit Gali

October 1977

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MECHANICAL BEHAVIOR OF MULTIMATERIAL COMPOSITE SYSTEMS

Interlaminar Behavior

- I -

O. Ishai*, D. Peretz** and S. Gali***

ABSTRACT

Interlaminar stress characteristics within a bonded doubler model were evaluated. The study covered the inelastic range of the adhesive up to initiation of its visco-plastic flow. The analytical solution was derived by an iterative procedure, using a linear FEM program which follows a non-linear effective stress-strain relationship. This relationship was based on uniaxial test results of the bulk adhesive, which were found to correlate with the corresponding in-situ characteristics of the adhesive.

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MECHANICAL BEHAVIOR OF MULTIMATERIAL COMPOSITE SYSTEMS

Interlaminar Behavior

- II -

TABLE OF CONTENTS

1.	Introduction	. 1
2.	Adhesive Bulk Characteristics	, 3
3.	Mechanical Characterization of Adhesive Layer in-situ under Combined Load	. 7
4.	The Effect of Hygrothermal Conditions on Mechanical Behavior of the Adhesive Layer	. 9
5.	Interlaminar Stress Distribution within Adhesive	10
	Layer at the hon rinear hange	, 10
6.	Summary and General Conclusions	. 13
	Literature Cited	. 14
	Glossary	. 16
	Figures	. 18
	Appendix 1	

LIST OF FIGURES

- Fig. 1 Typical stress-strain curve and the related Poisson Ratio for bulk epoxy resin under uniaxial tension.Fig. 2 Tensile stress-strain curves of epoxy resin at different strain rates.
- Fig. 3 The effect of strain rate on proportional stress, maximum stress and initial Young's modulus of bulk epoxy resin.
- Fig. 4a Photograph of tubular epoxy specimen with special device for measuring angular displacement under torsional loading.
- Fig. 4b Illustration of tubular epoxy specimen with special device for measuring angular displacement under torsional loading.
- Fig. 5 The effect of specimen length on torsional deformation procedure for correcting shear stress-strain relationship.
- Fig. 6 Procedure of deriving "true" shear stress-strain relationship based on torsional test of tubular specimens of different gauge lengths.
- Fig. 7 Effective stress-strain relationship and related properties for epoxy resin used as adhesive layer.
- Fig. 8 The effect of strain on the variation of Poisson's Ratio tangent and secant moduli of epoxy resin used for adhesive layer.
- Fig. 9 Typical shear stress-strain curves for the adhesive layer in-situ compared with its bulk epoxy reference (Fig. 6).
- Fig. 10 The effect of adhesive layer thickness on initial shear modulus compared with its bulk epoxy reference.
- Fig. 11 The effect of adhesive layer thickness on ultimate shear strength compared with its bulk epoxy reference.
- Fig. 12a Illustration of device for combined loading of adhesive layer in-situ.
- Fig. 12b Photograph of device for combined loading of adhesive layer in-situ.
- Fig. 13 Typical shear stress-strain curves of adhesive layer in-situ under combined shear and axial normal loading.

- Fig. 14 Failure envelope for adhesive layer in-situ (loaded under combined shear and axial normal stress).
- Fig. 15 The effect of hygrothermal history on adhesive stress-strain behavior.
- Fig. 16 Symmetrical doubler model.
- Fig. 17 Illustration of IAL network at the boundary zone used for finite element non-linear stress analysis.
- Fig. 18 Comparison of plane stress vs plane strain solutions for interlaminar shear-stress (τ_{xz}) distribution at the boundary zone (linear range).
- Fig. 19 Comparison of plane stress vs plane strain solutions for interlaminar lateral normal stress (σ_z) distribution at the boundary zone (linear range).
- Fig. 20 Plane strain solution for interlaminar transverse normal stress (σ_v) distribution at the boundary zone.
- Fig. 21 Flow chart for stress analysis of interlaminar adhesive layer at the non-linear range.
- Fig. 22 Illustration of FEM procedure for stress analysis of IAL at the non-linear range.
- Fig. 23 Convergence of the FEM iteration procedure to the exact solution.
- Fig. 24 The effect of central loading on effective stresses at the critical points in the boundary zone of the IAL.
- Fig. 25 The effect of central loading on effective strain at the critical points in the boundary zone of the IAL.
- Fig. 26 The effect of central loading on shear and normal stresses at the critical points in the boundary zone of the IAL.
- Fig. 27 Shear stress distribution at the boundary zone of the IAL (non-linear range).
- Fig. 28 Lateral normal stress distribution at the boundary zone of the IAL (non-linear range).
- Fig. 29 Effective stress distribution along the IAL (non-linear range).
- Fig. 30 Effective stress distribution at the IAL boundary zone (non-linear range).

- Fig. 31 The effect of central loading on effective stresses at the critical point in the boundary zone of the IAL (plane strain, simplified elasto-plastic vs non-linear solutions).
- Fig. 32 The effect of central loading on effective strains at the critical point in the boundary zone of the IAL (plane strain, simplified elasto-plastic vs non-linear solutions).
- Fig. 33 Shear stress distribution at the boundary zone of the IAL (plane strain, simplified elasto-plastic vs non-linear solutions).
- Fig. 34 Lateral normal stress distribution at the boundary zone of the IAL (plane strain, simplified elasto-plastic vs non-linear solutions).
- Fig. 35 Convergence of the FEM iteration procedure to the exact solution (non-linear vs simplified elasto-plastic solutions).

Appendix 1: Print-out of typical finite element program for stress distribution in an interlaminar adhesive layer within a doubler model.

- V -

1. INTRODUCTION

Most modern structural adhesives are designed for high toughness and therefore exhibit highly non-linear inelastic characteristics. Hence, a non-linear program is essential for predicting structural performance of a bonded system.

Due to the complex visco-elastic-plastic nature of the IAL even at low stress levels, rigorous analytical formulation of its mechanical behavior up to failure is impossible, especially when time- and environmental factors are taken into account. Thus, comprehensive empirical information is necessary on the inelastic stress-strain relationship of the adhesive as a function of time, temperature and such factors as moisture content.

Bulk data on the adhesive may suffice so long as stress distribution and cohesive failure within the bond are concerned. However, when failure initiates or propagates close to the adhesive-adherend interfacial zone, in-situ characteristics must be taken into account and correlated with the bulk properties. Accordingly, a series of tests on the in-situ mechanical behavior of an adhesive, for different loading modes, geometries and strain rates, was conducted with a view to correlating the findings with the behavior of the bulk adhesive under uniaxial load. This goal was partly achieved and results are described in the present report which deals with three main subjects:

- (a) The mechanical characteristics of the bulk epoxy used in the adhesive layer.
- (b) The in-situ mechanical characteristics of the adhesive layer.
- (c) The two-dimensional stress distribution (analytically solved) within the IAL at the non-linear range of the adhesive.

Preliminary tests on the in-situ hygrothermal behavior of the adhesive will be reported briefly in conjunction with a future research program.

The following is a list of reports related directly or indirectly to the output of the three-year research activity sponsored by the U.S. Army; they have either been published or submitted for publication.

- 1 -

List of Publications Related to Research Project on MECHANICAL BEHAVIOR OF MULTIMATERIAL COMPOSITE SYSTEMS

Interlaminar Behavior

- Ishai, O., Peretz, D. and Gali, S., "Direct Determination of Interlaminar Stresses in Polymeric Adhesive Layer," Experimental Mechanics, 17(7), 265-270, July 1977.
- Ishai, O. and Gali, S., "Two-Dimensional Interlaminar Stress Distribution within the Adhesive Layer of a Symmetrical Doubler Model," J. Adhesion, 8, 301-312, 1977.
- 3. Peretz, D., "Interlaminar Behavior of Bonded Bimaterial Systems," Composites, July 1977.
- Steg, I.D. and Ishai, O., "The Effect of Lateral Constraint on the Strength of a Single Lap Joint," J. Adhesion, 8, 263-273, 1977.
- 5. Ishai, O. and Girshengorn, T., "Strength of Bonded Aluminum-CFRP Single Lap Joint," Presented at the 9th National SAMPE Technical Conference, Atlanta, GA, Oct 4-6, 1977. Materials & Processes - In Service Performance, Vol. 9, National SAMPE Technical Conference Series.
- 6. Peretz, D., "Shear Stress-Strain Characteristics of Adhesive Layers," to be published in the Journal of Adhesion.
- 7. Gali, S. and Ishai, O., "Interlaminar Stress Distribution within an Adhesive Layer in the Non-Linear Range," submitted for publication.
- 8. Peretz, D. and Ishai, O., "Mechanical Characterization of Thin Adhesive Layer in-situ Under Combined Load," submitted for publication.

2. ADHESIVE BULK CHARACTERISTICS

2.1 Introduction

Bulk epoxy characteristics under different loading modes and testing conditions are currently obtained using standard experimental facilities such as the Instron tester. A ductile type of epoxy-versamid system, which was previously investigated [1-4], was selected to serve as representative for structurally tough adhesives throughout the present investigation. Most of the data is available for uniaxial tension. The purpose of the present test series was to relate this data to other loading modes such as shear. This relation will enable the prediction of the general stress-strain behavior of bulk epoxy from the elastic stage through the inelastic one up to failure, under a combined state of stress.

2.2 Specimen Fabrication

The material tested consisted of Shell epoxy epon 815 and General Mills versamid V-140 in the ratio of 70:30. The mixture was cured for 24 hours at room temperature followed by postcuring of 6 hours at 80°C.

For the tensile test, dog-bone specimens were cut from the cast plates according to ASTM D638-64T. For the shear test, thin-walled tubes were prepared and machined to have thinner thickness along the gauge length. Special metal grips were prepared and bonded to the specimens as shown in Fig. 4.

2.3 Uniaxial Tension Loading

The specimens were loaded in the Instron tester under uniaxial tension at various strain rates ranging from $15 \times 10^{-4} \text{min}^{-1}$ 38×10^{-2} at room temperature (about 22°C). A typical stressstrain curve is shown in Figure 1. The general trend for all curves shows a short linear portion beyond which a non-linear curve terminates in a stress plateau.

Other specimens were similarly loaded in uniaxial tension, and transverse strain was recorded simultaneously with longitudinal strain by means of a special extensometer. The ratio of transverse to longitudinal strains provides the Poisson ratio, v, which is plotted as a function of uniaxial strain in Figure 1. The strain-rate effect can be evaluated from the family of stressstrain curves obtained under different strain rates (Fig. 2). The major effect is on the maximum stress plateau, S_f, which can be defined as yield stress, and shows an increase in linearity with log strain-rates [1] (Fig. 3). The effect on initial Young's modulus and proportional limit is less pronounced (Fig. 3).

2.4 Shear Loading

Tubular specimens were mounted on an Instron tester and loaded in torsion. A device was designed to measure change of torsional angle, using the regular Instron extensometer (Fig. 4). overall torsional deformation of the specimens consists of an unknown displacement at the grip region which is difficult to estimate. In order to obtain the net shear deformation along the uniform gauge length, the following procedure was carried out: Tubular specimens of different lengths, ranging from 40 to 110 mm, were loaded in torsion up to failure. Torsional displacement at each torsion moment level was plotted as a function of specimen length. These plots show a series of lines (Fig. 5) which can be extrapolated to intersect the zero length axis at different torsional displacement levels. The extrapolated shear strain at zero length, as a function of the respective shear stress (calculated from the respective torsional moment) provides the correction curve (Fig. 6). By subtraction of the correction curve from the overall shear stress-strain curve, the "true" shear stress-strain relationship can be obtained as shown in Figure 6.

2.5 Effective Stress-Strain Relationship

An effective stress-strain relationship (Fig. 7, solid curve) was derived from the uniaxial-tensile stress (Fig. 1) for the representative epoxy resin. The effective stresses and strains are related to their respective stress components by using the von Mises' deviatoric-energy yield criterion [5] as follows:

$$s = C_{1} [\sigma_{x} - \sigma_{y})^{2} + (\sigma_{y} - \sigma_{z})^{2} + (\sigma_{z} - \sigma_{x})^{2} + 6(\tau_{xy}^{2} + \tau_{yz}^{2} + \tau_{zx}^{2})]^{1/2}$$
(1)

$$e = C_{2} [\varepsilon_{x} - \varepsilon_{y})^{2} + (\varepsilon_{y} - \varepsilon_{z})^{2} + (\varepsilon_{z} - \varepsilon_{x})^{2} + 6(\varepsilon_{xy}^{2} + \varepsilon_{yz}^{2} + \varepsilon_{zx}^{2})]^{1/2}$$
(2)

$$C_{1} = \frac{\sqrt{2}}{2} \qquad C_{2} = \frac{\sqrt{2}}{2(1+y)} \qquad \varepsilon_{1,1} = \frac{\gamma_{1,1}}{2}$$

In the case of uniaxial tension test data, the effective stress-strain curve is identical to the respective uniaxial tensile stress-strain curve of Figure 1. In order to calculate the effective stress-strain relation from the shear tests data (Fig. 6) the following relations are used:

$$s = \sqrt{3} \tau_{xz} \qquad e = \frac{\sqrt{3}}{2} \frac{\gamma_{xz}}{1+\nu}$$
(3)

It has to be noted that in order to compare shear data with respective tensile data, one must use the same effective strain rate, i.e.,

$$\dot{\gamma}_{xz} = (1+\nu)\frac{2}{\sqrt{3}}\dot{\epsilon}_{x}$$
 $\dot{\gamma}_{xz} \sim \sqrt{3}\dot{\epsilon}_{xy}$ (4)

where $\tilde{\gamma}_{XZ}$ and $\tilde{\epsilon}_{X}$ are the shear and tensile strain rates respectively.

The plots of shear and tensile tests data in terms of the effective stress-strain relationship in Figure 7 exhibit good agreement. This supports the effective stress-strain concept used in the present study.

The analytical solution for inelastic stress distribution in the adhesive within the doubler model necessitates the derivation of the adhesive moduli as well as Poisson Ratio at the different strain levels.

The variations of effective tangent (E_t) and secant (E_s) moduli, as well as effective Poisson ratio, v, as functions of effective strain, are shown in Figure 8. Three regions may be distinguished along the stress-strain curve, namely:

- an almost linear region up to the proportional limit (S₀) through which v is almost constant;
- 2. a non-linear, probably viscoelastic range, characterized
 by an increase in v, up to the "yield plateau" level
 (S_f);
- 3. a macro-plastic flow range beyond which stresses are almost constant and even tend to drop at higher strain levels. v is almost invariant at this range. By substraction of the elastic components of axial and transverse strains, the "non-elastic Poisson ratio" may be derived. At the "yield plateau" its value tends to approach 0.5, which is the theoretical limit based on the assumption of incompressible flow.

All the characteristics described in Figures 7 and 8 are functions of loading strain rate and temperature. The present study, however, will be confined to the reference strain rate and temperature specified in Figures 1 and 7 which are considered to be typical and representative for similar "non-linear" adhesive materials.

2.6 Bulk Characteristics Compared with Adhesive In-Situ Data

In a previous report and subsequent publication [6] an investigation of shear stress-strain relationship of a similar epoxy adhesive in-situ was reported. The study was concerned with the effect of adhesive layer thickness on its mechanical characteristics. The main objective was to compare the behavior of the adhesive layer in-situ with its bulk reference.

Stress-Strain Behavior

Shear stress-strain curves for adhesives of different thickness compared with the bulk references are shown in Figures 6 and 9, The similarity of bulk to in-situ behavior is evident at the linear elastic range up to the initiation of the yield plateau level.

Adhesive Shear Elastic Modulus

The effect of in-situ adhesive layer thickness on its shear modulus is shown in Figure 10. The level of bulk modulus seems to be approximately the same as the thick adhesive layer. It may be concluded that no significant variation in modulus is apparent for adhesive layers of thicknesses above 0.3mm.

Adhesive Shear Strength

The effect of in-situ adhesive layer thickness on its shear strength is shown in Figure 11. The shear strength of the bulk epoxy seems to be on a slightly lower level compared with that of the adhesive in-situ. It may be concluded that for epoxy adhesive thickness above 0.15mm, shear strength is almost invariant with adhesive thickness. Hence, bulk shear data can be used for a first estimation of bond strength as long as failure is of the cohesive type within the adhesive layer.

3. MECHANICAL CHARACTERIZATION OF ADHESIVE LAYER IN-SITU UNDER COMBINED LOAD

3.1 Introduction

Knowledge of the mechanical properties of adhesives in a combined state of stress is essential in engineering applications of structural bonded joints in which the adhesive layer undergoes a complex state of stress even under simple loading.

Unfortunately, experimental data in this content is very scanty. Early studies of the single-lap joint model [7] tended to oversimplify the problem by assuming pure shear; subsequently, the more sophisticated closed-form solution of Goland and Reissner [8] envisaged a lateral normal stress component, the so-called "peel stress", while more recent experimental work deals mostly with cases of pure shear [6] or tension [9].

The investigation reported here was conducted using a torsiontension apparatus to measure the mechanical properties of thin adhesive layers in-situ. Some preliminary results are presented, indicating the suitability of the method for the purpose in question.

3.2 Testing Apparatus (Figs. 12a,b)

The test specimen consists of a pair of 2025 aluminum flanged cylinders (adherends) a. The loading device consists of a torsion arm, b, operated from any conventional loading tester (e.g. Instron), and a spring operated axial loading post, c, capable of applying tension or compression.

3.3 Procedure

The test adhesive was composed of Shell epoxy resin 815 and General Mills versamid V-140 in the ratio of 70:30. The adherends were aligned on a special fixture with a controlled gap of 1mm, into which the resin was poured. The joint was cured for 24 hours at room temperature, plus 6 additional hours at 60°C. The specimens were then tested on a conventional Instron machine at different constant shear-strain rates and under different axial load levels.

For calibration, shear displacements of specimens with "zero adhesive thickness" were recorded and deducted from the overall shear displacement of the bonded specimens. The shear strains and stresses are computed from recorded moment-displacement curves.

3.4 Results

Typical shear stress-strain curves in Figure 13 indicate that normal uniaxial load has a clear-cut effect on the inelastic behavior of the adhesive. Axial tension tends to reduce the initial modulus, shear strength and ultimate strain, while axial compression tends to increase them. However, because of the lower in-situ tensile strength of the adhesive-adherend interface and its brittle mode of failure under tension load, the range of applicability is limited. Stiffness and level of yield plateau seem to be lower with the reduction in strain rate. In-situ stress-strain relationship shows fair agreement with reference bulk data. Failure under combined load may be described by means of the apparent ultimate-stress combination plotted in the shear-normal axial stress plane (Fig. 14). The failure envelope thus obtained also shows reduction of the shear strength with increasing tensile load, and increase under compression.

It may be concluded that the above methodology for adhesive in-situ characterization under combined loading can provide useful data for failure analysis of bonded systems.

- 8 -

4. THE EFFECT OF HYGROTHERMAL CONDITIONS ON MECHANICAL BEHAVIOR OF THE ADHESIVE LAYER.

The above topic was scheduled to be initiated only at an advanced stage of the research due to its complexity and the need for adequate experimental and analytical basic substrate. It is aimed to achieve a more realistic picture of IAL behavior under external conditions, and also to provide some information on the long-term durability of structural adhesive joints.

At the present preliminary stage, the effect of hot water immersion on the adhesive layer was investigated and compared with an oven dried counterpart. Preliminary results (Fig. 15) indicate a significant change in the shear stress-strain characteristics. The presoaked adhesive specimen showed lower stiffness, strength and ultimate strain compared to its previously dried reference.

The next step will be a more comprehensive investigation of adhesive specimens exposed to different hygrothermal conditions and tested in shear and tension in wet and dry conditions. The long range scheme is to measure hygrothermal effects on interlaminar stress and strain distributions within a doubler specimen by utilizing the method described in the Final Technical Report of the second year. The experimental results will be compared with the analytical FEM solution and will take into account the hygrothermal effects on the adhesive stress-strain relationship.

5. INTERLAMINAR STRESS DISTRIBUTION WITHIN ADHESIVE LAYER AT THE NON-LINEAR RANGE.

5.1 Introduction

Numerous publications are available on the analytical solution for stress distribution within the adhesive layer of a structural bonded joint model. Most of the earlier works [8,10-13] are based on certain assumptions such as uniform shear and normal stress distribution through the adhesive thickness which enable the derivation of a closed form solution. These simplifications, which provide only the average stress data, lead also to certain inconsistencies in the equilibrium equations and violate boundary conditions at the edges.

More recent works deal with the analytical complexity of the problem by applying numerical methods such as finite difference [14] and finite element [15-18] and provide the twodimensional stress distribution within the adhesive layer for various bonded joint models of isotropic [15,16] and orthotropic [17,18] adherends. These solutions are in agreement with equilibrium and boundary conditions of the structural model but are limited to the elastic-linear stress-strain relationship.

Unfortunately, the polymeric adhesive layer commonly used is characterized by a non-linear stress-strain behavior, even at a relatively low stress level. This non-linearity is more pronounced at high stresses, reaching a stress plateau which may be defined as "macro-plastic" yielding (see Fig. 7). Another approach to represent this mode of behavior is by a simplified elastic-plastic model [18-20] which may provide an approximate upper bound for the real solution. Such a solution is insufficient considering the fact that under service load, the material is not allowed to approach this "yield point" and that at the critical region of the adhesive, the stress level is mainly at the non-linear range, beyond the elastic limit but below the yield plateau.

The viscoelastic-plastic nature of the polymeric adhesive, which is reflected in its sensitivity to temperature and its dependence on time [3,4], also contributes to the complexity of the problem. The present work attempts to provide the first step towards the solution of the problem. It is confined, however, to the two-dimensional case and to constant temperature and strain rate loading conditions.

5.2 Model Representation

Interlaminar adhesive layer (IAL) behavior is most conveniently represented by the symmetrical doubler model shown in Figure 16 and fully described in Reference 16. Reference 16 also provides the two-dimensional linear elastic solution for stress distribution of this model. The corresponding FEM network is shown in Figure 17. The analysis is focused on the "boundary" edge zone where stresses attain their critical value.

5.3 Plane Stress vs. Plane Strain Solutions

Plane stress and plane strain states may be considered as two bounds for the three-dimensional solution. They represent the situation close to the free edges $(y = \pm b)$ and along the midsection (y = 0) respectively. Stress distributions based on assumptions of plane stress and plane strain for the linear range are shown in Figs. 18 and 19. Comparison of the $\tau_{\chi Z}$ and σ_{χ} distributions in the two cases indicated only minor variations. It may be concluded that the two-dimensional solution is not affected significantly by the unknown stresses acting along the third direction. The σ_{χ} distribution along y derived from the plane strain solution (Fig. 20), (which may provide the upper bound for the actual three-dimensional state of stress) attains its maximum at the center line (y = 0). Generally it seems that the worst condition for failure would be at the corners $(y = \pm b, x = \pm c)$.

5.4 Analytical Proceudre at the Non-linear Range

The procedure for determining the stresses at the different locations within the adhesive boundary zone under a given external uniaxial load will follow the flow chart given in Figure 21 and includes the following steps:*

- 1. Apply predetermined external σ_{c} level at the central adherend.
- Calculate effective strains and stresses of the different elements in the FEM network using the linear FEM program and assuming the same initial effective modulus for all elements.
- Determine the specific secant modulus at each element based on the experimental relationship given in Figures 7 and 8 according to the respective effective strain calculated in step 2.
- 4. Rerun the linear program with the modified modulus at each element according to step 3.
- 5. Compare the calculated stress S_k at each element as derived in step 4 with the stress S_k obtained from the experimental effective stress-strain curve for the respective calculated strain.

A full printout of a representative FEM program is given in Appendix 1.

6. Repeat steps 3-5 up to the stage where the difference between the calculated and "empirical" stresses is less than 2% of the final stress value.

The different steps are illustrated in Fig. 22 for a representative element k. The level of convergence was achieved by significantly fewer iterations in the case of plane strain compared with the plane stress solution (Fig. 23).

5.5 IAL Stress Distribution at the Non-linear Range

The results were focused on stress distribution at the boundary zone. The effect of axial external stress σ_c (applied to the central adherend) on the effective stress and strain at the critical point (located close to the IAL edge) is shown in Figures 24 and 25. The difference between linear and nonlinear solutions is pronounced, especially in the plane stress case.

Lower effective stress and strain were found in the case of plane strain compared with plane stress. The reverse trend was found for the shear (τ_{ZX}) and lateral normal (σ_Z) stresses as a function of axial external stress (Figure 26): namely, higher stresses in the case of non-linear solution of the plane strain state. In the case of the linear solution, no significant difference is shown for the two plane states.

Shear stress distribution at the boundary zone for $\sigma_{\rm C}=53.3~{\rm kg/mm}^2$ is shown in Fig.27. Here again no significant difference can be distinguished between plane stress and plane strain solutions, except at the critical location close to the lower edge corner (see Fig. 17). Similar trends were found for the two-dimentional lateral normal stress (Fig. 28).

In most cases, the effective stress tends to level off and even drop faster in the plane stress state.

The effective-stress distribution at the boundary zone (Figures 29, 30) permit evaluation of the ductile failure process of the IAL. The region of "viscoplastic flow" may comprise the elements where the effective stress or strain exceed their prespecified limit* as shown in Fig. 8. For the specific load level of the present case, this region is located close to the lower edge of the IAL (Fig. 17).

5.6 Comparison with Simplified Elasto-Plastic Solution

A simplified elasto-plastic model of the stress-strain relationship (Figure 7) has substantial advantages over the more realistic non-linear one, in that it reduces the parameters for describing the complex inelastic process to two the initial elastic modulus E_0 , and the yield-stress plateau S_f .

This limit may be defined as the level where initiation of residual deformation was detected (Ref. [21]).

It may also permit inclusion of the strain-rate and temperaturedependence in the analysis, provided their effect on the above parameters is available [3]. The respective stress distributions based on this model (Figures 31-34) show that while there is no significant deviation from the exact solution at the critical location, there is some farther away from the edges. More iterations are needed for convergence of the elasto-plastic solution compared with the more exact non-linear one (Figure 35).

6. SUMMARY AND CONCLUSIONS

The present report comprises two main parts, the first of which deals with bulk and in-situ characterization of an adhesive material and provides the empirical basis for the second part, devoted to analytical solution of the stress distribution in the IAL at the non-linear range. The following conclusions may be drawn:

(a) The stress-strain relationship of the bulk adhesive under a combined state of stress may be derived from the stressstrain relationship obtained under uniaxial loading. This follows the "effective" stress-strain approach and von Mises' criteria for inelastic behavior.

(b) The shear stress-strain relationship of the adhesive in-situ, its Young's modulus and ultimate strength, may be roughly considered as invariant for thicknesses about 0.2mm; in these circumstances, bulk data provide the basic parameters for a preliminary assessment of the relevant mechanical behavior of the adhesive within a bonded structure.

(c) The finite-element method was found to be adequate for determining the stress distribution of the IAL at the nonlinear range. At high external loading levels, non-linear behavior was found to predominate in narrow boundary zones close to the IAL edge, whereas most of the IAL remains at the elastic (linear) range.

(d) The non-linear FEM solution serves for assessment of IAL failure. The latter is manifested by initiation of plastic flow of the adhesive, which can be related to a specific limit point on the effective stress-strain curve. Under a given external load, a "visco-plastic" state prevails in the boundary zone of the IAL with stresses in all elements exceeding the above limit.

The present study is the first step towards more general non-linear analysis and empirical investigation of bonded structural systems. Future research will involve time-dependent non-linear stress analysis of the IAL with reference to the viscoelastic-plastic nature of the polymeric adhesive; another phase will cover the influence of environmental factors (temperature, moisture) on the above time-dependent mode of behavior.

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-	16	-

GLOSSARY

b	-	half IAL width
с	-	constant
с	-	half IAL length
Εo	-	initial Young's modulus
E _s	-	secant modulus
Et	-	tangent modulus
е	-	effective strain
ė	-	effective strain rate
h	-	thickness
h ₀	-	adhesive thickness
n	-	number of iterations
S	-	effective stress
т	-	temperature
x,y,z	-	axial, transverse and lateral coordinates respectively
γ	-	shear strain
Ŷ	-	shear strain rate
ε		normal strain
ε _c	-	uniaxial external strain
ε	-	axial strain rate
ν	-	Poisson ratio
τ	-	shear stress
σ	-	normal stress
σc	-	uniaxial external stress
$\chi = \frac{x}{c}$	-	nondimensional axial coordinate

IAL	- interlaminar adhesive layer
CAL	- central adherend layer
EAL	- external adherend layer
FEM	- finite element method

- 17 -















- 24 -



- 26 -300 0.5 MODULI (kg/mm²) 100 m 100 m 2 0.4 PLO v <u>secant modulus (E</u>s) tangent modulus (Et) POISSON 0 0.2 6 Sf 5 prespecified viscoplastic limit EFFECTIVE STRESS s (kg/mm²) $\dot{e} = 0.0385 \text{ min}^{-1}$ 1 01 2 e1 3 5 6 4 er EFFECTIVE STRAIN (%) e FIG. 8

G. 8 THE EFFECT OF STRAIN ON THE VARIATION OF POISSON'S RATIO, TANGENT AND SECANT MODULI OF EPOXY RESIN USED FOR ADHESIVE LAYER.




- 28 -



















- 37 -



- 38 -



- 39 -



FLOW CHART











44 --



- 45 -



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46 -



LATERAL NORMAL STRESS DISTRIBUTION AT THE BOUNDARY ZONE OF THE IAL (NON-LINEAR RANGE).







- 50 -





52 --



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- 53 -



- 54 -

APPENDIX 1

PRINT-OUT OF TYPICAL FINITE ELEMENT PROGRAM FOR STRESS DISTRIBUTION IN AN INTERLAMINAR ADHESIVE LAYER WITHIN A DOUBLER MODEL.

- 56 - BEST AVAILABLE COPY

VV	73)	CS7360 FORTRAN H	
11 5	D OPTICAL	S - NAME- MATA CRI-00.1 INFONT=60.517F-0000K.	
1.0	-R Grillen	SOURCE - FRONTC - NOLIST - NODECK - LCAD - NOMAP - NOFELT - TD - NOXPER	
c			00011000
c	THO FINE	NSTON PLAN STRAIN/STRESS FINITE ELEMENT PROGRAM	00052000
C	FCR GENER	RAL MATERIAL	00053000
C	i de location		20004000
C	REAL	*A TTTIF(5)	0000=000
	COMM	ON UNP.NEL.NMAT.NSLC.NCFT.NPODY.NTYP.IE(200.5).RO(10).TH(10).	00000000
	1FT(1)	0), UT(10), GGT(10), F1T(10), F2T(10), U12T(10), U21T(10), G12T(10),	00007000
	26613	• 3) • 0 ^w (3 • 3 • 10) • E • U • 66 • E 1 • E 2 • U 12 • L 21 • 6 12 • 607 (3 • 3 • 10) •	00007500
	3x(20)	0),Y(200),ULX(200),VLY(200),KODE(200),JSC(20),JSC(20),	00030000
	4SURT	RX(20,2),SURTRY(20,2),EP(10)	00005000
	CCMM	DN/ONE/CK(10+10)+G(10)+E(2+10)+C(3+3)+PT(3+6)+X3(5)+YG(5)	00010000
	CCMM	DN /TWO/ JBANC.NEG. R(400), AK(400.50)	00011000
	CATA	MAXEL. MAXNP, MAXMAT, MAXEW. MAXSLC	00012000
	1	/ 200, 200, 10, 50, 20/	00013000
•	9999 READ	100 • NPROF • (TITLE(I) • I=1 • 9)	00017000
		IF(MPROP.LE.O) GO TO 999	00018000
:	1020 PRIN	[200.NPRCB.(TITLE(I).I=1.9)	00019000
	(CALL DATAIN (MAXEL, MAXAP, MAXMAT, MAXSLC, TSTOP)	00020000
		MAXNCF = 2*MAXNP	00021000
		MAXCIF = 0	00024000
	l	00 1 T=1.NEL	00055000
	I	JC J J=1.4	00026000
	l	JC 1 K=1,4	00027000
		LL = IABS(IF(J,J) - IF(I,K))	00022000
		$IF(LL \cdot G \cdot FAX UIF) FAXUIF = LL$	00024000
	1 (00020000
		$\frac{1840L}{1840L} = 2 \pm (FAX01F \pm 1)$	00032000
		TELTRAND CT. MAYDLA CO TO SOO	00033000
		TELISTOP CT. 0) CC TO 999	00034000
			00035000
		TE (ISTOP.CT.O) CO TO SSS	00036000
		CALL RANSCI (1.AK.R.NEC.TRAND.MAXEOF.NAXRW)	00035000
	(CALL PANSCI (2. AK.R. NEC. IPAND. MAXECE. MAXBW)	00042000
	PRTN	T 300. (T.R(2+T-1).R(2+T).T=1.NNF)	00043000
	(CALL STRESS	00045000
	(30 TO 9995	00047000
	900 FRI'	901. TPAND. MAXEW	00048000
	GO TO	9499	00045000
	100 FCRM	AT(15+3X+9A8)	00050000
	200 FORM	AT (/8H1PROBLEM, 15, 3H , SAR)	00051000
	300 FCR'1/	AT (37H10UTPUT TABLE 1 MCCAL DISPLACEMENTS //	00052000
	1	13X.4HNODE. 9X. 11HL = X-DISP9X.11HV = Y-CISP./	00053000
	2	(5×+112+2E20.8))	00054000
	901 FCRM	AT(///12H BANGWIDTH =. 14.25H EYCEEDS MAY. ALLOWARLE =. 14//	00055000
	1 301	GO ON TO NEXT PROBLEM)	00056000
	999 STCP		00057000
	ENC		00058000

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- 57 -

ILER CPTICHS - NAME MATA, CPT=02.LINECHT=60.SIZE=0000K. SOURCE, FRODIC, NOLIST, NODECK, LOAD, NOMAP, NOEDIT, ID, NOXPER SUBROUTINE MATERP 00001000 COMMON NNP.NEL .NMAT. NSLC .N CET. NBODY . MTYP. TE (200.5) .RO(10) .TE (10) . 00002000 1ET(10), UT(10), GGT(10), E1T(10), E2T(10), U12T(10), U21T(10), C12T(10), 00003000 266(3,3), 0M(3,3,10), F, U, 66, E1, F2, U12, L21, 612, 607(3,3,10), 00004000 3x(200),Y(200),ULX(200),VLY(200),KODE(200),ISC(20),USC(20), 00075000 4SURTRY (20.2). SURTRY (20.2). EF (10) 00006000 CO 250 IMAT=1.NMAT 10007000 E=ET(IMAT) 00090000 L=LT(IMAT) 00005000 00010000 GG=GGT(IMAT) E1=E1T(IMAT) 00011000 E2=E2T(IMAT) 00012000 00013000 U12=U12T(IMAT) U21=U21T(IMAT) 00014000 G12=G12T(IMAT) 00015000 00016000 CO 350 I=1.3 CO 350 J=1.3 00017000 350 GG(I.J)=0GT(I.J.IMAT) 00018000 IF (E .EQ. 0. . AND.GG .EC. 0.) GO TO 500 00019000 IF (E .EQ. 0.) GO TO 300 00020000 IF (U .EG. 0.) GC TO 200 00021000 IF (GG .EG. 0.)GG = E+0.5/(1.+U) 00022000 GC TO 400 00023000 200 IF (GG .NE. 0.) U = 1. - E+0.5/GG 00024000 CC TO 400 00025000 300 IF (U .EQ. 0.) GC TO 400 00026000 E = 2.*(1.+U)+GG 00027000 400 IF (NOPT.EG.1)60 TC 450 00035000 00029000 GG(1,1) = E/(1.-U*U)CC(2.1) = U*CC(1.1) 00020000 GG(3,3) = GG 00031000 GG(2.2) = OG(1.1)00032000 GC TC 1000 00022000 450 GC(1+1)=E*(1+L)/((1+U)*(1-2*U)) 00024000 GC(2.1)=E*U/((1+U)*(1-2*U)) 00035000 GC(2.2)=00(1.1) 00036000 GG(3.3)=GG 00037000 GO TO 1000 00032000 500 IF (E1 .E9. C. .AND. E2 .E0. 0.) GC TC 1000 IF (U12 .EG. 0.) GC TC 700 IF (U21 .EG. 0.) U21 = U12*E2/E1 00025000 00040000 00041000 GO TO 800 00042000 700 L12 = U21*E1/F2 00042000 800 GG(1.1) = E1/(1.-U12+U21) 00044000 GG(2.1) = U21+00(1.1) 00045000 GG(2.2) = E2/(1.-U12+U21) 00046000 GC(3.3) = G12 00047000 1000 DC 1200 I=1.3 00048000 00045000 CC 1200 J=1.1 GM(I.J.IMAT)=60(I.J) 00050000 GM (J.I.IMAT)=GO(I.J) 00051000 00052000 1200 CONTINUE 00053000 SEU CONTINUE 00054000 RETURN 00055000 ENC

JAN	73)	C	51360	FORTRAN H	
FTIF	R OF	TICHS - NAME - MAIN .CPT=02.	TAFON	T=60.SIZE=0000K.	
		SOURCE . FRCCTC . LOLIS	T.NODE	CK.LCAD.NOMAP.NOECIT.ID.NCXPEF	
		SUPROUTINE DATAIN(MAX	FI . MAX	NP. MAXMAT. MAMSLC. ISTCP)	00011000
		COMMON NNP .NEL .NMAT .NSI C .NC	FT.NRO	DY. MTYP. IE (200.5) . RO(10) . TH(10).	00002000
	1	FT(10).UT(10).GGT(10).F1T(1	0).F2T	(10).U12T(10).U21T(10).G12T(10).	00053000
	2	GG(3,3), GM(3,3,10), E.U.GG.E	1.E2.U	12.L21.G12.COT(3.3.10).	00002500
		X(200) . Y(200) . ULX(200) . VLY(20C).K	ODE (200) . ISC (20) . JSC (20) .	00004000
	L	SURTRX (20.2) . SURTRY (20.2) . F	F(10)		0007=000
c					00006000
•		ISTOP = 0			00007000
		READ 1. NNP . NEL . NMAT . NSLC . NC	FT.NRO	DY	00093000
c					00025000
•		PRINT 100 . NNF . NEL . NMAT . NSLC	.NCPT.	NBOCY	00010000
		IF (NNP.LE.MAXNE) GO TO	201		00013000
		ISTOF = ISTOP + 1			00014000
		PRINT 251. MAXNP			00015000
	201	IF (NEL.LE.MAXEL) GO TC	202		00016000
		ISTOF = ISTOF + 1			00017000
		PRINT 252. MAXEL			00018000
	202	IF (NMAT.LE.MAXMAT) GO T	C 203		00019000
		ISTOF = ISTOP + 1			00020000
		PRINT 253. MAXMAT			00021000
	203	IF (NSLC.IE.MAXSLC) GO T	C 204		00055000
		ISTOF = ISTOF + 1			00023000
		PRINT 254. MAXSLC			00024000
	204	IF(ISTOP.EQ.0) GC TO 20	5		00025000
		PRINT 255. ISTOP			00026000
		STCP			00027000
С					00056000
	205	READ 2. (RO(I).TH(I).I=1.NM	AT)		00052000
		FRINT 101			00020000
		PRINT 51. (I.FO(I).TH(I).I=	1 . NMAT)	00031000
		READ 10.(ET(I).UT(I).GCT(I)	+E1T(I).E2T(I).U12T(I).U21T(I).	00031010
	1	G12T(I) • I=1 • NMAT)			00031050
		FRINT 80. (I.ET(I).UT(I).GG	T(I),E	1T(I),E2T(I),U12T(I),U21T(I),	00031040
	:	G12T(I) • I=1 • NMAT)			00031050
		CC 150 IMAT=1.NMAT			00031110
		CO 150 I=1.3			00031120
		READ 11. (GGT(I.J.IMAT).J=1	• 3)		00031130
		PRINT 81, (OCT(I,J,IMAT),J=	1.3)		00031140
	1:0	CONTINUE			00021150
		CALL MATERP			00021500
		CC 550 IMATE1 . MMAT			00021510
		CC 550 1=1.3			00021520
		PPINI 82. (QM(1.J.IMAT).J=1	• • • •		00021530
	220	CONTINUE			00021540
		PRINI 105			00024000
					00035000
	5	READ 3. MIROLE(M). X(M). T(M)	.ULX(M). (()	00022000
		COINT SOL M			00027000
	4	CDINT 52-N-KOFF/ML V/PL V	N	(M) - VI V (N)	00022000
		TETOR - TETOR IS	HI TULX		00000000
					00041000
	7				00041000
	'		r		00042000
			c		00044000
		KODE (1)-0	r	and the second	00045000
	0				00042000

- 58 -

X(N) = X(N-1) + RX00046000 Y(N) = Y(N-1) + RY00047000 ULX(N)=0.0 00046000 VLY(N)=0.0 00045000 6 PRINT 52.N.KOLE(N).X(N).Y(N).LLX(N).VLY(N) 00050000 000-1000 N=N+1 IF (M-N)9.6.8 00052000 9 IF (N.LE.NNP) GC TO 5 00053000 FRINT 106 00056000 13 L=000057000 14 READ 15. M. (IE(M.T).I=1.5) 00052000 16 L=L+1 00055000 IF (M-L) 117, 17, 18 00060000 117 PRINT 118.M 00061000 PRINT 53. M. (IE(M.I). I=1.5) 00062000 ISTOF=ISTCP+1 00053000 GC TO 14 00064000 18 IE(1.1)= IF(L-1.1)+1 00065000 IE(L.2)= IF(L-1.2)+1 00066000 IE(L.3)=IE(L-1.3)+1 00067000 IE(L+4)=JE(L-1+4)+1 00033000 IE(L.5)=TE(L-1.5) 00065000 17 FRINT 53. L. (IE(L.I).I=1.5) 00070000 IF(M-L)20,20,16 00071000 20 IF (NEL-L)21.21.14 00072000 CONTINUE 21 00073000 IF (NSLC.EG.0) GO TO 31 00076000 30 PRINT 108 00077000 DC 40 L=1.NSLC 00038000 READ 41.ISC(L).JSC(L).SURTRX(L,1).SURTRX(L,2).SURTRY(L,1). 00075000 1 SURTRY(L.2) 00024000 40 PRINT 42.ISC(L).JSC(L).SURTRY(L.1).SURTRX(L.2).SURTRY(L.1). 00021000 1 SURTRY(L.2) 00053000 IF(ISTOP.EQ.D) GC TO 999 31 00053000 PPINT 900. ISTOP 00064000 00023000 1 FCRMAT(615) 00086000 100 FORMAT(35HOINFUT TARLE 1.. PASIC PARAMETERS 11 00087000 00093000 1 2 00023000 3 00020000 5X. 40H NUMBER OF SURFACE LOAD CARDS. IF/ 00051000 5X, 40F 1 = PLANE STRAIN, 2 = PLANE STRESS. . .. IF/ 00052000 5 5X, 40F RODY FORCES(1 = IN -Y DIREC., 0 = NONE), 15) 00053000 6 251 FORMAT (////33+ TOC MANY NOCAL POINTS, MAXIMUM =, IE) 00094000 252 FORMAT (////30F TOC MANY ELEMENTS, MAXIMUN = . IS) 00055000 253 FORMAT(////30F TOC MANY MATERIALS, MAXIMUM =, 15) 00056000 254 FORMAT(////40F TOO MANY SURFACE LOAD CARES. MAYIMUM = . 15) 00057000 255 FORMAT(////28F EXECUTION HALTED BECAUSE CF. 15.13H FATAL FRECES/) 00032000 2 FORMAT(2E10.3) 00022000 101 FORMAT (36HOINFUT TARLE 2.. MATERIAL FROPERTIES // 0010000 10H MATERIAL. 5X. 10HMOCULUS OF. 6X. 9HPOISSON'S. 7X. 00101000 1 00102000 28+MATERIAL , 7X. SHMATEPIAL / 34X.6HNUMBER.5X.10HELASTICITY.FX.7H RATIC. PX.7HDENSITY.6X. 00103000 00104000 49HTHICKNESS) 00105000 51 FORMAT(110.2E15.4) 00105010 10 FCRMAT(BE10.3) 20 FCRMAT(110.8F15.4) 00105020

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11 FORMAT(3E10.3)	00105030
81 FORMAT(3E10.3)	00105040
82 FORMAT(3E10.3)	00105050
103 FORMAT(34H1INFUT TABLE 3., NOCAL POINT DATA //	00106000
1 5X,5HNCDAL,4AX,7HX-CISF,4X,7HY-DISF./	00107000
25X,5HPOINT,6X,4HTYPE,14X,1HX,14X,1HY,8X,7HOR LOAD,8X,7HOP LCAC)	00108000
3 FORMAT(215.4F10.3)	00105000
105 FORMAT(5X,17HERROR IN CARE NO.,15/)	00110000
52 FORMAT(2110,4E15,4)	00111000
106 FORMAT(34H1INFUT TARLE 4., ELEMENT DATA //	00112000
1 11X, 31+GLOPAL INDICES OF ELEMENT NODES/3X, 7+ELEMENT,	00113000
27X+1H1+7X+1H2+7X+1H3+7X+1H4+2X+8HMATERIAL)	00114000
118 FORMAT(5X, 25HERRCR IN ELEMENT CARD NO., 15)	00115000
15 FORMAT(615)	00116000
53 FORMAT(110+478+110)	00117000
108 FORMAT(37H1INFUT TAPLE 5 SURFACE LCADING DATA //	00118000
117X, 33HSURFACE LOAD INTENSITIES AT NODES/	00115000
24X,6HNODE I.4X,6HNCDE J.10X,2FXI,10X,2HXJ,10X,2FYI,10X,2FYL)	00120000
41 FORMAT(215,4E10.3)	00121000
42 FORMAT(2110,4E12,4)	00122000
900 FORMAT(///45H ASSEMBLY AND SOLUTION WILL NOT BE PERFORMEDIS.	00123000
121H FATAL CARD ERRORS)	00124000
999 RETURN	00125000
END	00126000

PILER OPTICNS - NAMF = MAIN.CPT=02.LINFCNT=60.SIZE=000CK. SOURCE.EBCCIC.NOLIST.NODECK.LCAD.NOMAP.NOECIT.ID.NCXREF 000C1000 SUEPOLTINE GFCMBC(L.N) 000C2000 CCMMON/TWC/ IFAND.NFG.E(400).AK(400.50) 000C2000 C THIS SUBROUTINE MODIFIES THE ASSEMPLAGE STIFFNESS AND LCADS FCR THE COUC3000 00100 M=2.IBAND C FRESCRIBED DISPLACEMENT U AT DEGREE OF FREEDOM N. EQ.(6-18B). (REF.1)000C4000 000C6000 C IO 100 M=2.IBAND 000C6000 K = N - M + 1 000C6000 DO 100 M=2.IBAND 000C6000 K = N - M + 1 000C6000 DO 100 M=2.IBAND 000C6000 K = N + M + 1 000C6000 DO 100 K = R(K) - AK(K.M)*U 000C6000 AK(K.M) = 0.0 0001000 R(K) = R(K) - AK(N.M)*U 00012000 AK(N.M) = 0.0 00013000 AK(N.1) = 1.0 00014000 R(N) = U 00017000 RETURN 00017000 FUE 00017000	JAN 73)	CS/360 FORTRAN H	
SOURCE + EBCCIC + NOLIST + NODECK + LCAD + NOMAP + NOECIT + ID + NCXREF SUEPOLTINE GFCMBC(L,A) 00001000 CCMMON/TWC/ IFAND + NEG + E(400) + AK (400 + 50) 00002000 C THIS SUBROUTINE MODIFIES THE ASSEMPLAGE STIFFNESS AND LCADS FCR THE COOC3000 00000000 C PRESCRIBED DISPLACEMENT U AT DEGREE OF FREEDOM N + EQ. (6-188) + (REF + 1)00000000 000000000 DO 100 M=2 + IBAND 00000000 K = N + M + 1 00000000 IF(K + LE + 0) CO TO 50 00000000 AK(K + M) = 0.0 00000000 SOURCE + EMCLARED GO TO 100 M = 2 + IBAND 00000000 K = N + M + 1 00000000 IF(K + LE + 0) CO TO 50 00000000 AK(K + M) = 0.0 00000000 AK(K + M) = 0.0 00000000 IF(K + GT + R(K) - AK(N + M) + U 00012000 AK(N + M) = 0.0 00013000 AK(N + 1) = 1.0 00012000 AK(N + 1) = 1.0 00012000 RETURN 00012000 RETURN 00012000	PILER OPTICHS - NAME MAIN.CPT=0	D2+LINECNT=60.SIZE=0000K.	
SUPPOLTINE GFCMBC(L,N) 00001000 COMMON/TWO/ IFAND.NEG.E(400). AK(400.50) 0002000 C THIS SUBROUTINE MODIFIES THE ASSEMPLAGE STIFFNESS AND LCAPS FCR THE C0002000 C FRESCRIBED DISPLACEMENT U AT DEGREE OF FREEDOM N. EQ.(G-18B). (REF.1)00004000 D0 100 M=2.JBAND 00000000 K = N + M + 1 00000000 K(K) = R(K) - AK(K.M)*U 00000000 AK(K.M) = 0.0 00000000 K = N + M + 1 00000000 AK(K.M) = 0.0 000000000 K = N + M + 1 00000000 AK(K.M) = 0.0 00000000 IF(K.GT.NEQ) GO TC 100 0001000 R(K) = R(K) - AK(N.M)*U 00012000 AK(N.M) = 0.0 00012000 AK(N.M) = 0.0 00012000 AK(N.M) = 0.0 00012000 AK(N.1) = 1.0 00012000 RETURN 00012000 RETURN 00012000 RETURN 00012000	SOURCE . EBCCTC . NOL	IST NODECK , LCAD , NOMAP , NOEDIT , ID , NOXREF	
$\begin{array}{c} \mbox{COMMON/TWO/ IFAND:} \mbox{Ke}(400), \mbox{AK}(400, \mbox{EQ}) & 00002000 \\ \mbox{C} THIS SUBROUTINE MODIFIES THE ASSEMPLAGE STIFFNESS AND LCADS FOR THE COOC3000 \\ \mbox{C} C FRESCRIBED DISPLACEMENT U AT DEGREE OF FREEDOM N. EQ.(6-18B). (REF.1)00004000 \\ \mbox{DO 100 M=2:IBAND} & 0000000 \\ \mbox{DO 100 M=2:IBAND} & 0000000 \\ \mbox{K = N - M + 1} & 0000000 \\ \mbox{C} (K) = R(K) - 000 TO 50 & 0000000 \\ \mbox{AK}(K,M) = 0.0 & 0000000 \\ \mbox{SO K = N + M - 1} & 00000000 \\ \mbox{SO K = N + M - 1} & 00000000 \\ \mbox{SO K = N + M - 1} & 00000000 \\ \mbox{SO K = N + M - 1} & 00001000 \\ \mbox{IF}(K.GT.NEQ) GO TO 10 C 100 & 00012000 \\ \mbox{AK}(N,M) = 0.0 & 00012000 \\ \mbox{AK}(N,M) = 0.0 & 00012000 \\ \mbox{AK}(N,M) = 0.0 & 00012000 \\ \mbox{AK}(N,1) = 1.0 & 00012000 \\ \mbox{AK}(N,1) = 1.0 & 00012000 \\ \mbox{AK}(N,1) = 0 & 00012000 \\ \mbox{AK}(N,1) = 0 & 00012000 \\ \mbox{AK}(N,1) = 0 & 0 & 00012000 \\ \mbox{AK}(N,1) $	SUPPOLTINE GECMBC(L.N)	0.0	001000
C THIS SUBROUTINE MODIFIES THE ASSEMPLAGE STIFFNESS AND LCADS FOR THE COOC3000 C PRESCRIBED DISPLACEMENT U AT DEGREE OF FREEDOM N. EQ.(6-18B). (REF.1)00004000 DO 100 M=2.IBAND K = N - M + 1 00000000 K = N - M + 1 00000000 R(K) = R(K) - AK(K.M) * U 00000000 50 K = N + M - 1 00000000 F(K.GT.NEQ) GO TO 100 $R(K) = R(K) - AK(N.M) * U00011000R(K) = R(K) - AK(N.M) * U00012000100 CONTINUE00012000AK(N.M) = 0.0100 CONTINUE00012000R(N) = URETURNEND$	COMMON/TWO/ IFAND .NEG . R (4	+00) • AK(400.50) 00	002000
C PRESCRIBED DISPLACEMENT U AT DEGREF OF FREEDOM N. EQ.(6-18B). (REF.1)00004000 DO 100 M=2.IBAND K = N - M + 1 IF(K.LE.0) CO TO 50 R(K) = R(K) - AK(K.M) * U AK(K.M) = 0.0 50 $K = N + M - 1$ IF(K.GT.NEQ) CO TC 1CO R(K) = R(K) - AK(N.M) * U OOOC5000 ICO CONTINUF AK(N.M) = 0.0 ICO CONTINUF R(N) = U R(N) = U R(N) = 0 R(N) =	C THIS SUBROUTINE MODIFIES THE	E ASSEMPLAGE STIFFNESS AND LOADS FOR THE CO	000500
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	C PRESCRIBED DISPLACEMENT U AT	T REGREF OF FREEDOM N. EQ. (6-188). (REF.1)00	004000
K = N + M + 1 0000000 IF(K.LE.0) CO TO 50 00007000 R(K) = R(K) - AK(K.M)*U 0000000 AK(K.M) = 0.0 00005000 50 K = N + M - 1 0001000 IF(K.GT.NEQ) CO TC 100 00012000 R(K) = R(K) - AK(N.M)*U 00012000 AK(N.M) = 0.0 00012000 AK(N.M) = 0.0 00012000 AK(N.M) = 0.0 00012000 R(K) = R(K) - AK(N.M)*U 00012000 AK(N.M) = 0.0 00012000 AK(N.M) = 0.0 00012000 NC 00012000 RETURN 00012000 NC 00012000	DO 100 MESTBAND	0.0	005000
$IF(K \cdot LE \cdot 0) CO TO EC 00007000 R(K) = R(K) - AK(K \cdot M) *U 0000000 AK(K \cdot M) = 0.0 00005000 50 K = N + M - 1 0001000 IF(K \cdot GT \cdot NEQ) CO TC 100 00012000 R(K) = R(K) - AK(N \cdot M) *U 00012000 AK(N \cdot M) = 0.0 00012000 100 CONTINUE 00014000 AK(N \cdot 1) = 1.0 00015000 R(N) = U 00017000 00017000 00017000$	K = N - M + 1	00	000330
$R(K) = R(K) - \Delta K(K, M) + U$ $D0002000$ $\Delta K(K, M) = 0.0$ $E0 K = N + M - 1$ 0001000 $IF(K.GT.NEQ) GO TC 1C0$ $R(K) = R(K) - \Delta K(N, M) + U$ 00012000 $\Delta K(N, M) = 0.0$ 00012000 $\Delta K(N, M) = 0.0$ 00012000 $R(N, M) = 1.0$ $R(N) = U$ 00012000 $R(N) = U$ 00012000 $RETURN$ 00012000 00012000 $RETURN$ 00012000 00012000 00012000 $RETURN$ 00012000	TE(K.LE.C) CO TO	n 50 00	007000
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	R(K) = R(K) - AK	K(K.M)*II 00	000930
50 $K = N + M - 1$ 0001000 IF(K.GT.NEQ) GO TC 1C0 00011000 R(K) = R(K) - AK(N,*)*U 00012000 AK(N,*M) = 0.0 00013000 100 CONTINUE 00014000 AK(N,1) = 1.0 00015000 R(N) = U 00016000 RETURN 00017000 NC 00012000	AK(K.M) = 0.0	00	000200
IF(K.GT.NEQ) GO TC 1CO 00011000 R(K) = R(K) - AK(N,*)*U 00012000 AK(N,*M) = 0.0 00013000 1CO CONTINUE 00014000 AK(N,1) = 1.0 00015000 R(N) = U 00015000 RETURN 00017000 00017000 00017000	50 K = N + M - 1	00	010000
R(K) = R(K) - AK(N, M) * U $AK(N, M) = 0.0$ 100 100 CONTINUE $AK(N, 1) = 1.0$ $R(N) = U$ 00012000 0000 00000 00000 00000 00000 00000 0000	TE(K.GT.NEQ) CO	TC 100 00	011000
AK(N+M) = 0.0 00013000 100 CONTINUE 00014000 AK(N+1) = 1.0 00015000 R(N) = U 00016000 RETURN 00017000 END 00018000	$R(K) = R(K) - \Delta K$	((012000
100 CONTINUE 00014000 AK(N+1) = 1.0 0015000 R(N) = U 00015000 RETURN 00017000 00017000 00018000	AK (NI-M) = 0.0	00	013000
AK(N+1) = 1.0 R(N) = U RETURN END RETURN	100 CONTINUE	0.0	014000
R(N) = U 0016000 RETURN 00017000 D0018000	AK(N(.1) = 1.0	00	015000
RETURN 00017000 00018000	P(N) = II	0.0	016000
00018000	RETURN	00	017000
	ENC	0.0	018000

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ILER	OPTICNS - N	AME = MAIN.CPT=02	+LINECNI	=60.SIZE	=0000K, NOMAP,NOEDIT,ID,NCXREF	
	SUBROLTIN	E ASEMBL(ISTOP)				00001000
	COMMON NN	P . NFL . MMAT . NSLC . N	CFT . NBOD	Y. MTYP. I	[F(200.5),RO(10).TF(10).	00002000
	1ET(10),UT	(10).GGT(10).E1T(10).E2T	10).0127	(10), U21T(10), C12T(10),	00053000
	266(3.3).6	M(3,3,10) • E • U • GG •	E1.E2.U1	12.121.01	12.007(3.3.10).	00003500
	3x(200),Y(200).ULX(200).VLY	(20C) .KC	DDE(200).	ISC(20).JSC(20).	00004000
	4SURTRX (20	.2).SURTRY(20.2).	EF(10)		DT/T () VOIEL VOIEL	00005000
	COMMON/ON	E/ QK(10,10),Q(10) + H (3 + 1((3 + 2)	+HI (3+6) +XG (5) + TG (5)	00012000
	CUP MUN/TW	ID I DICANDANEGAR (41)	UI. ARTA	00.507		00000000
c	UTPENSION					000022000
L	PELIND 1					00010000
	NEWING I	ISTOF = 0				00012000
		BT(1,4) = 0.0				00014000
		BT(1.5) = 0.0				0015000
		BT(1.6) = 0.0				00016000
		BT(2.1) = 0.0				00017000
		BT(2.2) = 0.0				00018000
		BT(2.3) = 0.0				00019000
	D0 2	I=1.NEQ				00026000
		R(I) = 0.0				00027000
	, DC 2					00022000
	2 00 10	M-1 NEI				00025000
	TEITE	(M.5) GT 0) GO TC	11			00022000
	1. (11	ISTOF = ISTOP + 1	11			00035000
	GC TC	10				00036000
	11 CALL	GUAD (M+AREA)				00037000
	IF (AR	EA.61.0.0) GO TO	16			00035000
		ISTOF = ISTOP + 1				00055000
	PRINT 20.	M				00040000
	16 IF(IE	(M.3).EQ.IE(M.4))	EO TO 2	26		00044000
	DO 31	$J = 1 \cdot 2$				00045000
						00046000
		IK= IJ+I				00047000
	00 30	FIVUT = GR(Ir + IR)				00042000
	00 52	$E = CK(IK \cdot K)/DIVC$	т			00049000
	•	GK(IK .K)=F				00051000
	DC 33	J=K.IJ				00052000
		QK(J+K)=QK(T+K)-	F*OK(I.)	IK)		00053000
	23	$OK(K \cdot I) = OK(I \cdot K)$				00054000
	22	0(K) =0(K)-CK(IK.	K)*C(1K))		00055000
	31	O(IK) = O(IK) / bivc	T		1	00056000
	26 KPITE (1)	((OK(I,J),J=1,1))).1=9.10)) · C(3) ·		00061000
	1((6(1.)),	J=1,10,1=1,3),((((1.)).	J=1.2).1=	=1.3).xQ(=).+Q(=)	00062000
	1-11	LIP-8	1 TN - 6	4		00062000
		T=2.1 TM.2	L)	,		00068000
	00 10	$I_{I} = I/2$				00065000
		LP(I-1) = 2+IE(M.	1.) - 1			00070000
	40	LP(T) = 2*TE(".I.	1			00071000
	DO 50	LL=1.LTM				00072000
		I = LP(LL)				00073000
		R(I) = R(I) + O(L	L)			00074000
	D0 50	MM=1.LIM				00075000
		J = LP(MM) - I +	1			00076000

IF (J.LE. 0) GO TO 50 00077000 AK(I.J)= AK(I.J)+ GK(LL.MM) 00037000 50 CONTINUE 00075000 10 CONTINUE 00080000 DO 55 N=1.NNP 00053000 IF (KODE (N) . EQ.3) GO TO 55 00084000 K=2*N 00023000 IF(KODE(N).EG.1) GO TC 57 00086000 R(K-1) = R(K-1) + ILX(N)00079000 IF (KODE (N) .NE.0) GO TO 55 000996000 57 R(K) = R(K) + VLY(N)00029000 55 CONTINUE 00050000 IF (MSLC.FG.0) CO TO 60 00054000 DO 61 L = 1.NSLC00055000 I = ISC(L)00056000 J = .SC(L)00057000 TI=2+I 00092000 JJ=2+J 00099000 DX = X(J) - X(T)0010000 CY = Y(J) - Y(T)00101000 EL = SORT(DX+DX + CY+DY) 00102000 PXT=SURTRX(L+1)*FL 00103000 PXJ=SURTRX(L+2)*EL 00104000 PYT=SURTRY(L.1)*FL 00105000 PYJ=SURTRY(L+2)*FL 00106000 R(II-1) = R(II-1) + FXI/3.0 + PXJ/6.000107000 R(JJ-1) = R(JJ-1) + FXI/6.0 + PXJ/6.0001020100 R(TJ)=R(TI)+ PY1/3.9 + PYJ/6.0 00105000 R(JJ) = R(JJ) + PYI/6.0 + PY./3.0 00110000 CONTINUE 61 00111000 DC 70 M=1.NNP En 00116000 IF (KOCE(M).GE.O.AND.KCCE(M).LE.3) GO TO 72 00117000 ISTOF = ISTOP + 100112000 GC TO 70 00115000 72 IF (KODE (M).EQ.0) GO TO 70 00120000 IF (KODE (M) . EQ. 2) GO TO 71 00121000 CALL GEOMEC(ULX(M), 2*M-1) 00122000 IF (KODE (M) .EQ.1) GO TC .70 00123000 71 CALL GEOMEC(VLY(M), 2*M) 00124000 CONTINUE 00125000 70 ENCFILE 1 00126000 IF(ISTOP.FO.0) SC TO 81 00127000 PRINT 100, ISTOP 00122000 20 FORMAT(/5X.17F AREA OF FLEMENT , 15.14H IS MEGATIVE /) 00125000 100 FORMAT (////42+ SOLUTICE WILL NOT BE FERFORMED DECAUSE OF .15. 00130000 1 15H DATA ERRORS 00121000 1) P1 RETURN 00132000 00133000 ENC
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CS/360 FORTRAN H IN 73) LER OPTIONS - NAME _ MAIN. OFT=02.LINECNT=60.SIZE=0000K. SCURCE, FBCCIC, NOLIST, NODECK, LOAD, NOMAP, NOEDIT, ID, NCXRFF SUBROUTINE QUAD (M. TOTALA) 000010000 CCMMON NNP.NFL.NMAT.NSLC.NCFT.NRODY.MTYP.IF (200.5).RC(10).TH(10). 00002000 1ET(10),UT(10),GGT(10),E1T(10),E2T(10),U12T(10),U21T(10),E12T(10), 00053000 266(3,3), QM(3,2,10), E, U, GG, E1, E2, U12, L21, G12, QOT(3,3,10), 00003500 3x(200),Y(200),ULX(200),VLY(200),KODE(200), ISC(20), USC(20), 00004000 4SURTRX(20.2).SURTRY(20.2).EF(10) 00005000 COMMON/ONE/ QK(10,10),G(10),P(3,10),C(3,3),PT(3,6),XG(5),YG(5) 00000000 CCMMON/TWO/ IEAND.NEG.R(400). AK(400.50) 00077000 00030000 С I= IE (M.1) 00009000 J= IF (M,2) 00010000 K= IE (M.3) 00011000 L= IE (M,4) 00012000 MTYP = IE(M,5)00013000 00014000 TOTALA = 0.0 IF (NMAT.EQ.1.AND.M.GT.1) CC TC 5 00019000 C(1.1)=OM(1.1.MTYP) 00020000 C(1.2)=QM(1.2.MTYP) 00021000 C(1.3)=QM(1.3.MTYP) 00022000 C(2.1)=QM(2.1.MTYP) 00023000 00024000 C(2.2)=QM(2.2.MTYP) C(2,3)=QM(2,3,MTYP) 00025000 C(3.1)=QM(3.1.MTYP) 00026000 C(3.2)=QM(3.2.MTYP) 00027000 C(3.3)=QM(3.3.MTYP) 00032000 5 LIM = 400022000 IF (K.EQ.L) LIM = 3 00034000 00035000 XQ(5) = 0.0YQ(5) = 0.0 00036000 DO 10 N=1.LIM 00037000 $NN = IE(M \cdot N)$ 00032000 XQ(N) = X(NN)00025000 YQ(N) = Y(NN)00040000 XQ(5) = XQ(5) + X(NN)/FLOAT(LIM)00041000 10 YG(5) = YG(5) + Y(NN)/FLOAT(LIM) 00042000 00045000 DC 13 II =1.10 Q(II)=0.0 00046000 DO 12 JJ = 1.10 00047000 00042000 12 OK(II.1)=0.0 DC 13 JJ=1.3 00045000 $B(JJ \cdot II) = 0.0$ 00050000 13 IF (K.NE.L) GO TO 15 00051000 00052000 CALL CST(1.2.3.TOTALA) GC TO 999 00053000 15 CALL CST(1.2.5. AREA) 00054000 TOTALA = TOTALA + ARFA 000==000 20056000 CALL CST(2.3.5.AREA) TOTALA = TOTALA + ARFA 00057000 00055000 CALL CST(3.4.5.AREA) 00055000 TOTALA = TOTALA + AREA CALL CST(4.1. F. AREA) 00060000 TOTALA = TOTALA + AREA 00061000 999 RETURN 00063000

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	CUD	001.71	SUURI	E · E HIII	ADEA	21.00	COL		UAN	• 100	- AF	•		• 10 •	NU ARTI	•	00001000
	SUE	MON		STIL OF	CIC.	OFT			TVD	TE	120					••	00001000
	157/	101 1	T(10)	- GGT (10	FIT	101	FOT	101		TI	101	.1.2	17/1	01.0	101/1		00002000
	2001	3. 3.	ON 13.	7.101.5	U.GG.	F1.5	2.11	12.1	21.1	12	.00	T (3	. 7 . 1	0	161(1)		000025000
	ZVID	001	(1200)		11.WI V	1200	· · · ·	DEI	200	1.T	SCI	201		1201			000000000
	4010	TOVIS	20.21.	CUDTRY	11.01	FELS	101	100.1	ena			.01	- Cat	1201	•		00005000
	CON	MONIC	NIE / C	K(10.10	.0(10	1.9	12.11	1	13.	2).	DTO	3.6		151.	YC (5)		00006000
	CON	MON /1		FAND AF	- PILO		AKI	100.	501	- / .							00007000
	PINI	FNST	IN CR	12.6).10	61.11	(3).	TKI	5.61	201								000010000
r	LIFE							,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,									00005000
c			1.1.1	11= T													00010000
			IT(S														00011000
			1 1 1 1	5)= K													00012000
			BT(1	1.1)= YO		(K)											00015000
			PT(·2)= YO	(K) -YG	(1)											00016000
			RT(1	1.3) = Y	2(T)-Y	GIN											00017000
			PT(2	-4)=XG(1	() - XQ (1)											00012000
			BT(2	2.5) = X	(I)-	XGIN	()										00019000
			ETIZ	2.6) = X	- (1)	XGI	i										00020000
			BT(3	3.1)=PT()	.4)												00021000
			BT(?	1.2) = R	1(2.5)												00022000
			BT(3	3.3) = B	(2,6)												00023000
			BT (?	x.4) = 8	(1.1)												00024000
			BT(3	3.5)= PT	(1.2)												00025000
			BT (3	3.6)= ET	(1.3)												00036000
			ARE	A =(BT(2	4)*B1	111.3	!) -	BTI	2.5) * P	T(1	.1))/2.	0			00027000
		DC 1	10 IT=	=1.3													0000:0000
		00 1	1011 =	= 1.6													00021000
			CB(1	= (LL.II	0.0												00055000
	00	10 KH	< = 1.	• 3													00055000
	10		CB()	II.JJ) =	CB(II) + (I'KI	K)*	BT (KK.,	JJ)				00024000
		DC 1	15 11	= 1.6													00037000
		DC 1	15 JJ	= 1.6													00035000
			TK(11.77)=0	.0												00032000
		DC :	12 KK	=1+3			-										00040000
	12		TK()	11.JJ)=	TK()	T.J.	.)+B	TIKK	•11)*C	P(K)	K . J.	()				00041000
		DO :	15 II:	=1.3													00046000
			LCO	IT) = 2*	T(II)		I										00047000
	15		LCI	11+51 =	2*LI()	(1)											00042000
		00 3	50 1 (=	=1.6													00049000
																	000-0000
			FR =		U*ARF	A)											00051000
				- 2.0+FR													00052000
		00 4	NM -														00054000
	20		OKI	- LC(00) -	0K (1 1			TKII	T		THU	TY	-)*	K			00055000
	• 0	00 3	30 .1.1	= 1.3	ANTEL	•			140				· - r				00056000
	20	00	PI.I.	1.11) =			DT.	1.1.1.		+FR							00057000
		TEI	IBCDY	FQ.01 G	TO	ge											00060000
			TROP	TYF = A	REA* F	CIMI	YPI	* T	HIM	TYP	1						00061000
			BODY	YF = -T	PCCYF	1.0											00063000
		00 3	35 TT:	=1.3													00063000
			1.1=	2* 1717	1)												00064000
	25		011	J)= 0(JJ	+ -	YF											00023000
g	SA PET	IRN															00066000
	ENC																00067000

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- 65 -

ILER OPTICNS - NAME = MAIN, CPT=02, LINECNT=60, SIZE=0000K,	
SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID,NCXR	EF
SUBROUTINE STRESS	00001000
COMMON NNP+NEL+NMAT+NSLC+NOPT+NBODY+MTYP+IE(200+5)+RO(10)+TF(10), 00002000
1ET(10),UT(10),GGT(10),E1T(10),E2T(10),U12T(10),U21T(10),G12T(10), 00003000
200(3,3),0M(3,3,10),E,U,66,E1,E2,U12,L21,612,00T(3,3,10),	00003500
3X(200),Y(200),ULX(200),VLY(200),KODE(200),ISC(20),JSC(20),	00004000
4SURTRX(20+2)+SURTRY(20+2)+EF(10)	00050000
COMMON/ONE/ QK(10+10)+Q(10)+B(3+10)+C(3+3)+BT(3+6)+XQ(5)+YG(5) 00006000
COMMON/TWO/ IEAND,NEG,R(400), AK(400,50)	20007000
DIMENSION SIG(6)	000630000
C	00000000
REWIND 1	00010000
PRINT 300	00011000
NOLINE = 47	00012000
DO 5 M=1+NEL	00016000
READ(1) $((QK(I,J),J=1,10),I=1,2), Q(9), Q(10),$	00017000
1 ((B(I,J),J=1,10),I=1,3), ((C(I,J),J=1,3),I=1,3), XC,YC	00016000
LIM = 4	00021000
IF(IE(M,3),EG,IE(M,4)) $LIM = 3$	00022000
DO 10 I=1.LIM	00023000
II = 2*I	00024000
$JJ = 2 * IE(M \cdot I)$	00025000
$G(II \cdot I) = R(JJ - I)$	00026000
$10 \qquad \qquad G(II) = R(JJ)$	00027000
IF(LIM.EQ.3) GO TO 16	00020000
DC 15 K=1.2	00021000
JK = K + 8	00032000
IK = JK - 1	00022000
DO 15 L=1.1K	00024000
$15 \qquad Q(JK) = Q(JK) - GK(K,L) * Q(L)$	00022000
LIM = 10	00032000
FAC = 0.25	00025000
GC 10 17	00040000
$16 \qquad \Box I = 6$	00041000
FAC = 1.0	00042000
	00043000
	00044000
D(2) = J = J + L + P	00042000
	00042000
50 - 1 - 1 + 3	00049000
	000-1000
	00052000
SP = (STG(1) + STG(2))/2 0	000=4000
$S_{m} = (S_{m}(1) - S_{m}(2))/2 = 0$	00055000
DS = SORT(SM SM + SIG(3) + SIG(3))	000 - 6000
SIG(4) = SP + DS	00057000
SIG(F) = SP + DS	00052000
SIG(f) = 0.0	00055000
IF(SIG(3).NE.0.0.AND.SM.NE.0.0) SIG(6) = 28.648*ATAN2(SIG	(3), 00060000
1	SM) 00061000
IF (NOLINE.GT.0) GC TO 54	00063000
PRINT 1000	00064000
NOLINE = 49	00055000
54 NOLINE = NOLINE - 1	00066000
5 PRINT 1010. M.XC.YC. (SIG(1), J=1.6)	000€7000
ENCFILE 1	00093000

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300 FORMAT (47H10UTPUT TABLE 2.. STRESSES AT ELEMENT CENTROIDS // 00065000 11X. 7HELEMENT. 5X. 1HX. 9X. 1HY. 4X. 8HSIGMA(X). 4X. 8HSIGMA(Y). 4X. 00070000 28HTAU(X.Y).4X.8HSIGMA(1).4X.8+SIGMA(2). 7X.5HANGLE) 00071000 1000 FORMAT(1H1. 7HELEMENT.9X.1HX.9X.1HY.4X8HSIGMA(X).4X.8HSIGMA(Y). 00072000 14X.8HTAU(X.Y).4X.8HSIGMA(1).4X.8HSIGMA(2). 7X.5HANGLE) 00073000 1010 FORMAT(18, 2F10.2.1P6E12.4) 00074000 RETURN 00075000 END 00076000

CS/160 FORTRAN H

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ILI	ER O	PTT	CNS	s -	AVIA	F=	MAT	N.C	PT=0	2.11	NECI	NT=E	0.51	ZE=	= 0 0 0	nK.						
					SOL	IRCE	.FBC	CIC	.NOL	IST.	NODE	ECK.	LCAD	NC	MAP	.NOF	CIT	. 10		CXRE	F	
		SU	BRO	JUT	INE	RAN	SOL (KKK	. AK .	RINF	G . I	BAN			TIM	1						00001000
С	SYM	MET	RIC	CB	AND	MAT	RIX	EQU	ATIO	N 50	LVER	R.	(REF	. 2	2)							000030000
с																						00053000
c	KKK	=	1 1	TRI	ANGL	LAR	IZES	TH	E PA	NC M	ATR	IX A	K. E	G.	(2-	21						00004000
С	KKK	=	2 5	SOL	VES	FOR	RIG	HT.	HAND	SID	ER	. 50	LUTI	ICN	RET	URNS	IN	R.	E	6.12	-3)	00055000
С																						00006000
		CI	MET	ISI	ON /	KIN	DIM.	MUI	M).	R(1)												00007000
					NF	= 25	NEG	-	1													00030000
					NF	2 =	NEQ															00005000
			1	IF (FKK.	EQ.	2) G	CT	0 20	0												00010000
			1	00	120	N=	1 . NR	S														00011000
					M =	- 11 -	1															00012000
					MF	=	MINO	(TP	AND .	NR-M)											00013000
					PI	TOVI	= A	KIN	.1)													00014000
			[00	120	1=2	. MR															00015000
					CF)= A	KIN.	L11	PIVO	T												∩001€000
					I	= M	+L															00017000
					J	= C																00012000
			[00	110	K=L	.MR															00015000
					J	= .	+ 1															00030000
	110				AF	(11.	J)=	AK (1.1)	-CP	*AK	(N.K	()									00021000
	120				14	(1.1.	L) =	CP														00055000
			(GC	10 4	100																00053000
	500		[DC	250	N=1	. MRS															00024000
					M =	= N•	1															00025000
					ME	= \$	MINO	(IE	AND.	NR-M	1											00056000
					CF	P= F	(11)															00027000
					R	(N)=	CP/A	K(V	•1)													00035000
			(00	550	1=	2 . MR															00052000
					I	= M	+ L															00030000
	220				R	(1)=	RI) -	AK (V.F)	*CP											00031000
					R	NR)	= R	(NR)/AK	(NR.	1)											00055000
			1	00	320	I =	1 . N	RS														00052000
					N =	N'R	- I															00034000
					M =	- M -	1															00035000
					MA	2 =	MINO	(TE	AND.	VB-N)											00036000
			C	00	350	K =	5.4	R														00077000
					L	= ٣	+K					-										00035000
C	ST	ORE	CC	DWP	UTED	נחו	SPLA	CEM	ENTS	IN	LOAD	D VE	CTOR	R								00052000
	320				R	('A	PIN)-	VKIN	.K)*	F(L)										00040000
	400	RE	TUF	N																		00041000
		EN	C																			00042000

3