# THE EFFECTS OF MICROCRACKING ON
# THE THERMAL EXPANSION OF GRAPHITE-EPOXY COMPOSITES

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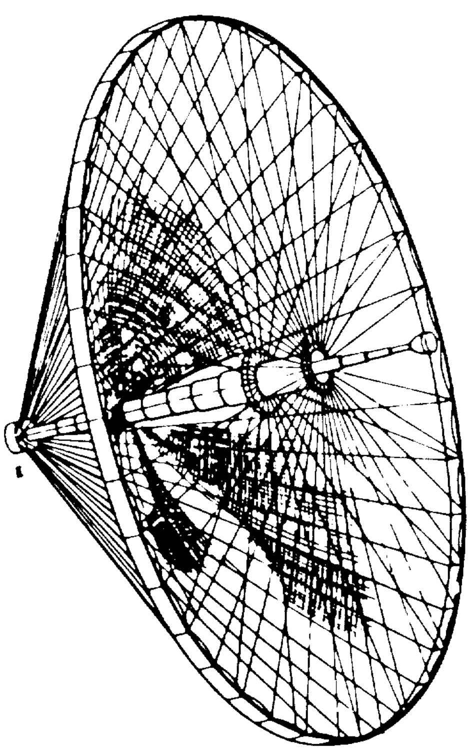
The performance characteristics of many large space structures are dependent upon their dimensional stability. One example of this is a space communications antenna, as shown in figure 1, in which small dimensional changes may cause a defocusing of the antenna and a corresponding loss in efficiency. The materials to be used in these structures include graphite cables, organic matrix composites, and metal-matrix composites. Composites are selected because of their inherent dimensional stability (high stiffness, low CTE) and their light weight. The primary factors controlling the dimensional stability of these materials are listed in the figure. For organic-matrix composites, microcracking is one of these primary factors. Permanent changes in the thermoelastic properties and/or permanent residual strains can result from this type of damage. The present research was concerned with the effect microcracking has on the thermal expansion of graphite-epoxy composites.

## DIMENSIONAL STABILITY OF SPACE STRUCTURES



HOOP/COLUMN ANTENNA

### FACTORS CONTROLLING DIMENSIONAL STABILITY

- CABLES
  - THERMAL CYCLING
  - MECHANICAL LOADING
- ORGANIC MATRIX COMPOSITES
  - MOISTURE DESORPTION
  - THERMAL CYCLING
  - MECHANICAL LOADING
  - MICROYIELDING (CAUSED BY MATRIX MICROCRACKING)
  - RADIATION
- METAL MATRIX COMPOSITES
  - THERMAL CYCLING
  - MECHANICAL LOADING

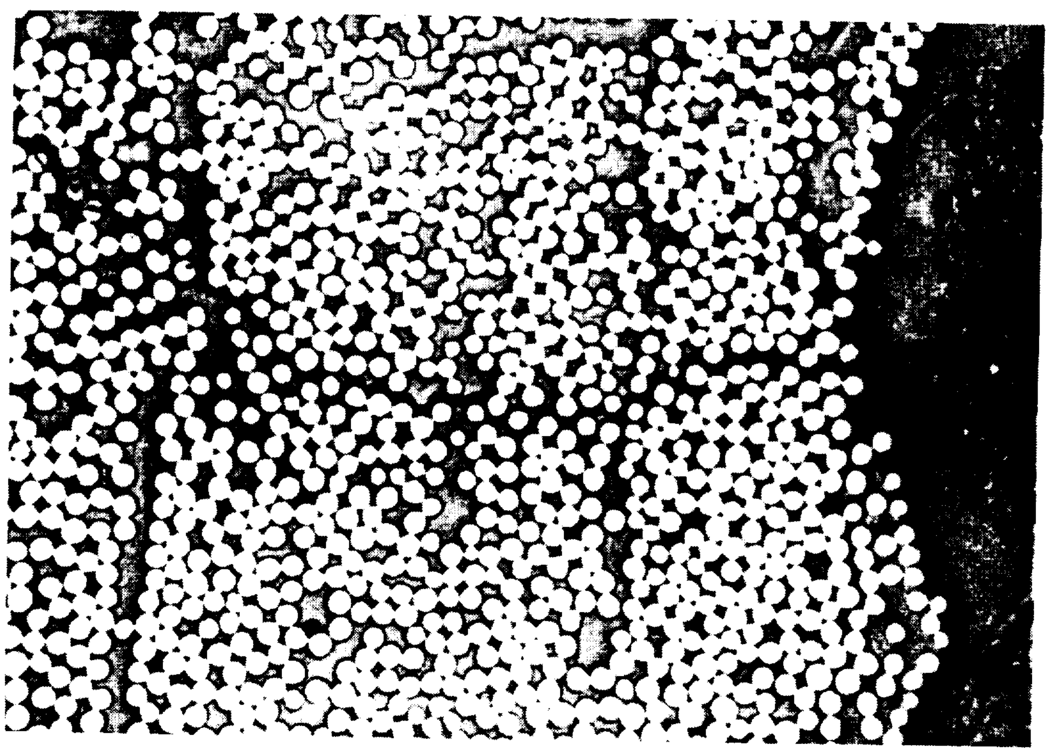
Figure 1

MICROCRACKING IN COMPOSITES

Microcracks in organic-matrix composites are small cracks in the matrix material which extend parallel to the fiber direction. They occur when the internal stresses exceed the transverse strength of an individual lamina. The two primary causes of microcracking are mechanical and thermal loads.

A limited amount of research has been conducted concerning the causes and effects of microcracking in composites. Repeated thermal cycling has been shown to cause microcracking in graphite-epoxy laminates which causes the CTE to approach that of the unidirectional material (ref. 1). A typical example of this thermal microcracking is shown in figure 2. Research has also shown that residual strains, due to microcracking, of up to 20 $\mu\varepsilon$ may develop in graphite-epoxy during the first cooling cycle to 130 K (ref. 2). What has been lacking in past research is a quantitative relationship between the amount of microcracking and changes in CTE. This was the main focus of the current research.

## MICROCRACKING DUE TO THERMAL CYCLING IN GRAPHITE-EPOXY



(REF. 1) ├─ 75 μm ─┤

Figure 2

## RESEARCH OBJECTIVE AND APPROACH

The objective of this research was to study the effect of microcracking on the CTE of graphite-epoxy. To accomplish this objective, the approach outlined in figure 3 was used. Specimens from two quasi-isotropic ($[0/\pm45/90]_s$ and $[0/90/\pm45]_s$) laminate configurations were mechanically loaded in static tension to produce varying amounts of microcracking in selected plies. The loading direction was perpendicular to the 90° plies. Mechanical loading was selected as the method for producing microcracks in the specimens because the amount of damage could be easily controlled. The amount of microcracking was characterized by computing an average crack density in the damaged plies. CTE measurements were then made on the damaged specimens to correlate CTE values with crack density. An analysis was also proposed and implemented to model the effect.

# RESEARCH PROGRAM

OBJECTIVE -
- STUDY THE EFFECT OF TRANSVERSE MATRIX MICROCRACKING ON THE CTE OF GRAPHITE-EPOXY

APPROACH -
- PRODUCE VARYING AMOUNTS OF MICROCRACKING WITH STATIC TENSION TESTS ON TWO QUASI-ISOTROPIC LAMINATES ($[0/\pm45/90]_S$ AND $[0/90/\pm45]_S$)
- CHARACTERIZE THE AMOUNT OF DAMAGE IN TERMS OF CRACK DENSITY
- CORRELATE THE AMOUNT OF MICROCRACKING WITH THE CHANGE IN CTE
- PROPOSE ANALYSIS TO MODEL THE EFFECT

Figure 3

MECHANICALLY INDUCED MICROCRACKING

A photomicrograph of a typical microcracking pattern in one of the mechanically loaded specimens is shown in figure 4. For this particular specimen, cracks formed in the central 90° plies as well as the adjacent 45° plies. Loading was at 73% of ultimate in a direction perpendicular to the 90° plies. Microcrack patterns were recorded while under load using an edge replication technique. From previous research, it was found that microcracks formed in this fashion did extend through the entire width (25 mm) of the specimen and therefore, damage viewed along the edge was representative of the entire specimen. Crack densities were computed by observing the edge replica in a standard microfiche card reader and counting the number of cracks in a particular ply over a 25 mm length. Loads varied from 0 to 82% of ultimate to produce specimens with crack densities ranging from 0 to 2.0 cracks per mm.

## TYPICAL MICROCRACKING DUE TO MECHANICAL LOADING

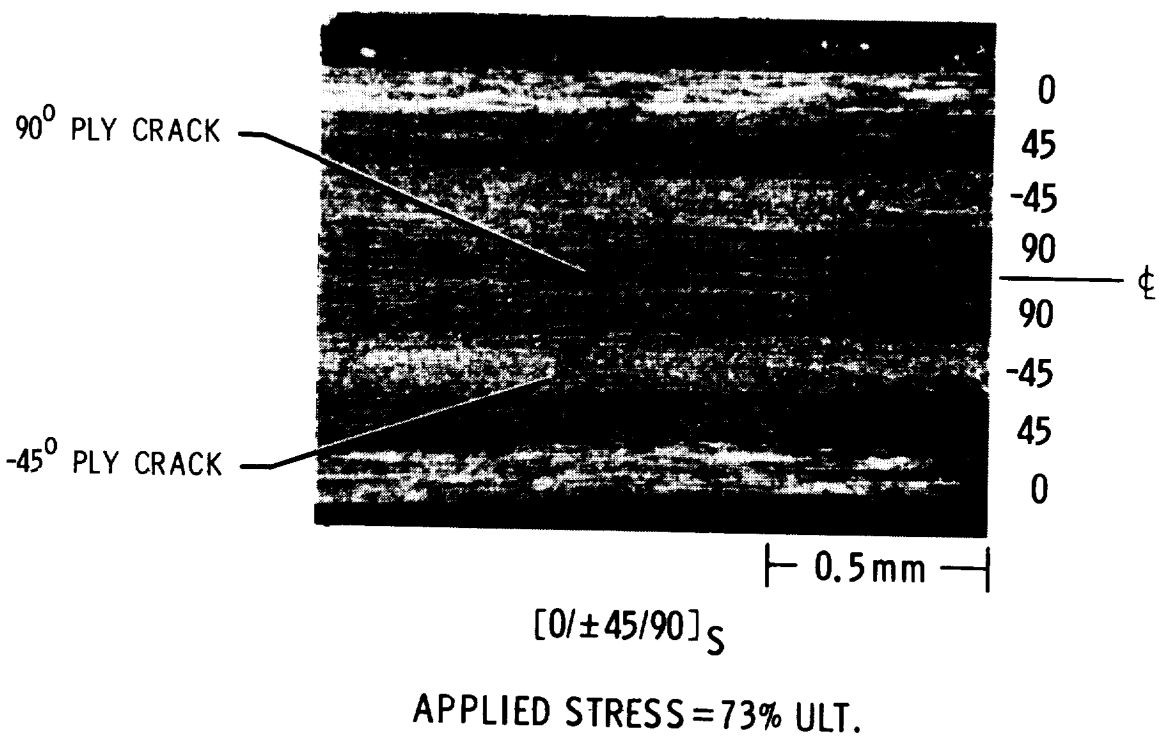



Figure 4

## CTE MEASUREMENTS

CTE measurements were made using a moire interferometry technique, the details of which may be found in reference 3. A schematic diagram of the experimental arrangement is shown in figure 5. This is an optical interference technique in which thermal strain values are determined by computing the change in the number of interference fringes over a 25-mm gage length between any two temperatures. Thermal strain measurements were taken for each specimen between room temperature and 422 K. All specimens were conditioned at 422 K for 18 hours prior to testing to remove any moisture.

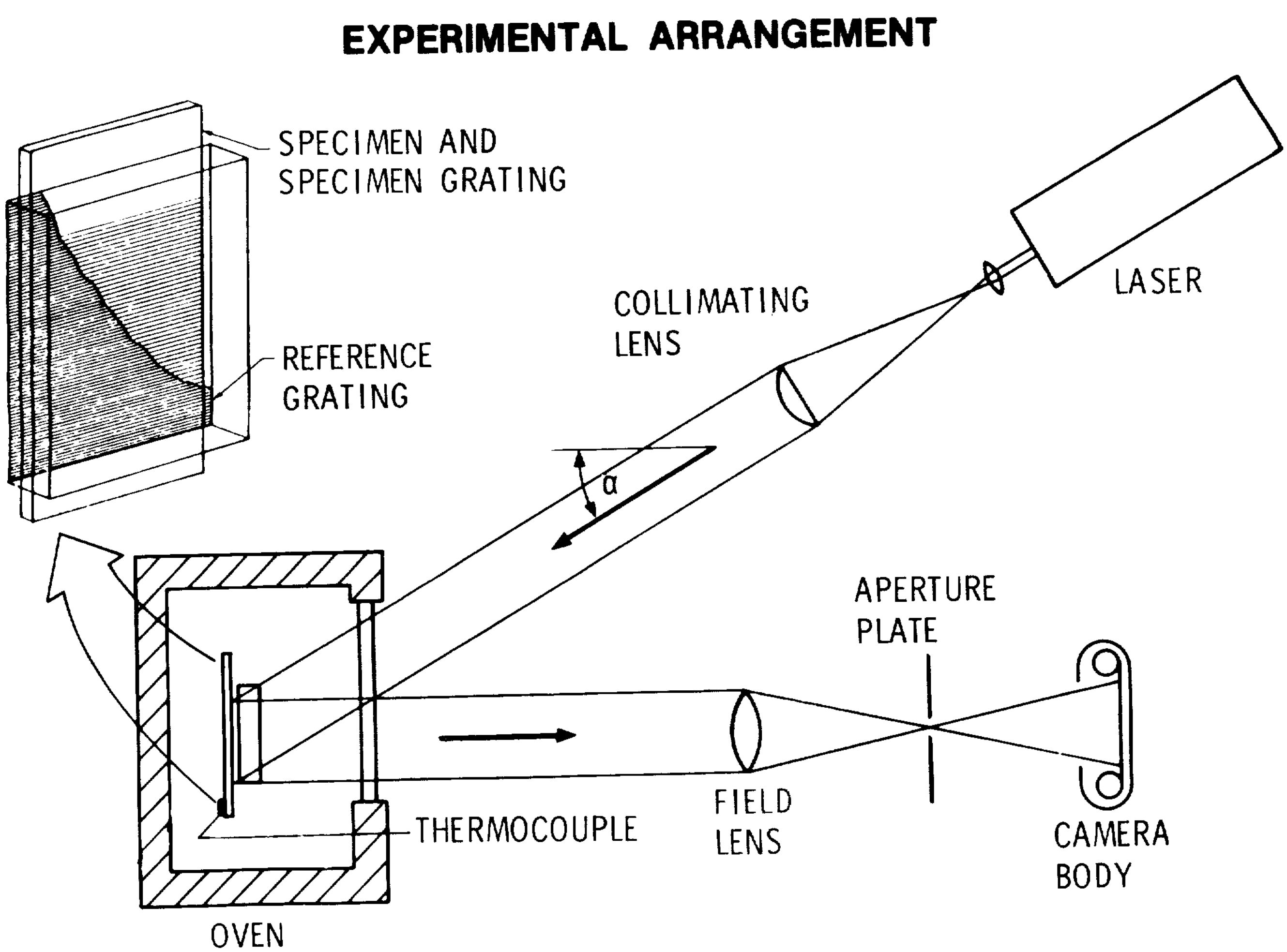



Figure 5

TYPICAL THERMAL EXPANSION DATA

A typical thermal expansion curve is shown in figure 6. These data represent both heating and cooling data for one cycle between 300 and 422 K. No differences were observed between heating and cooling or from cycle to cycle. CTE values are not directly obtained from the measurements but are computed from the slope of the $\Delta L/L$ versus temperature curve. All of the specimens exhibited a slightly nonlinear thermal strain response. A 2nd order least-squares polynomial was found to fit the data and an average CTE was computed for the entire temperature range by computing the slope at the average temperature (360 K). This average CTE value will be used in all subsequent discussions.

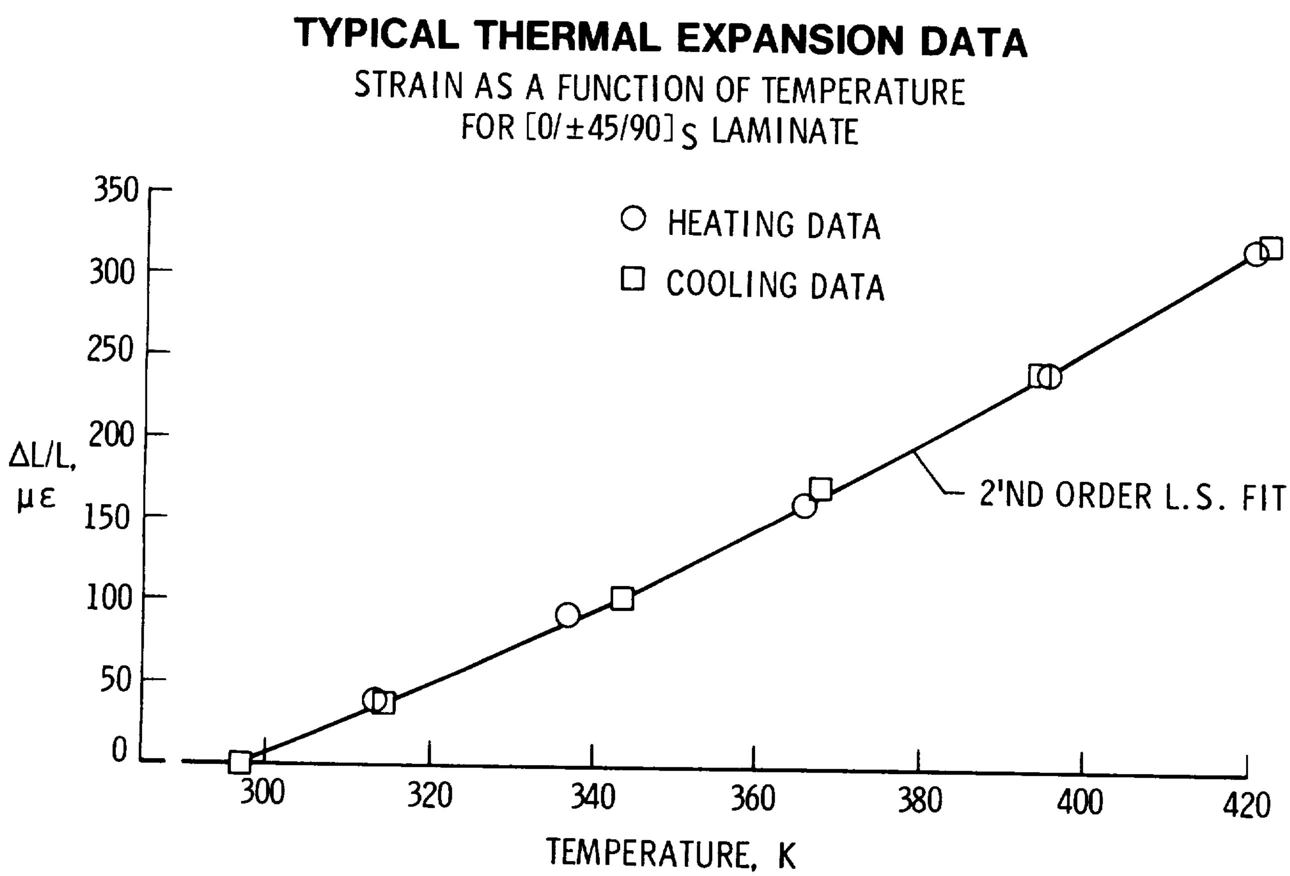



Figure 6

EXPERIMENTAL RESULTS

The results of CTE measurements plotted as a function of crack density in the 90° plies are shown in figure 7. An explanation for the scatter in CTE values for the $[0/90/\pm45]_s$ laminate at zero crack density is that only the data point with the largest CTE truly represents zero crack density since it had no load applied. The other two data points represent specimens that had loads applied. Although no cracks were visible, some small amount of damage was thought to exist. Maximum reductions in CTE of 21 and 25% occurred in specimens with crack densities of 1.10 and 2.05 $mm^{-1}$, respectively. These two specimens had been loaded to 73 and 82% of ultimate, respectively, with some microcracks forming in the adjacent 45° plies as well as the 90° plies.

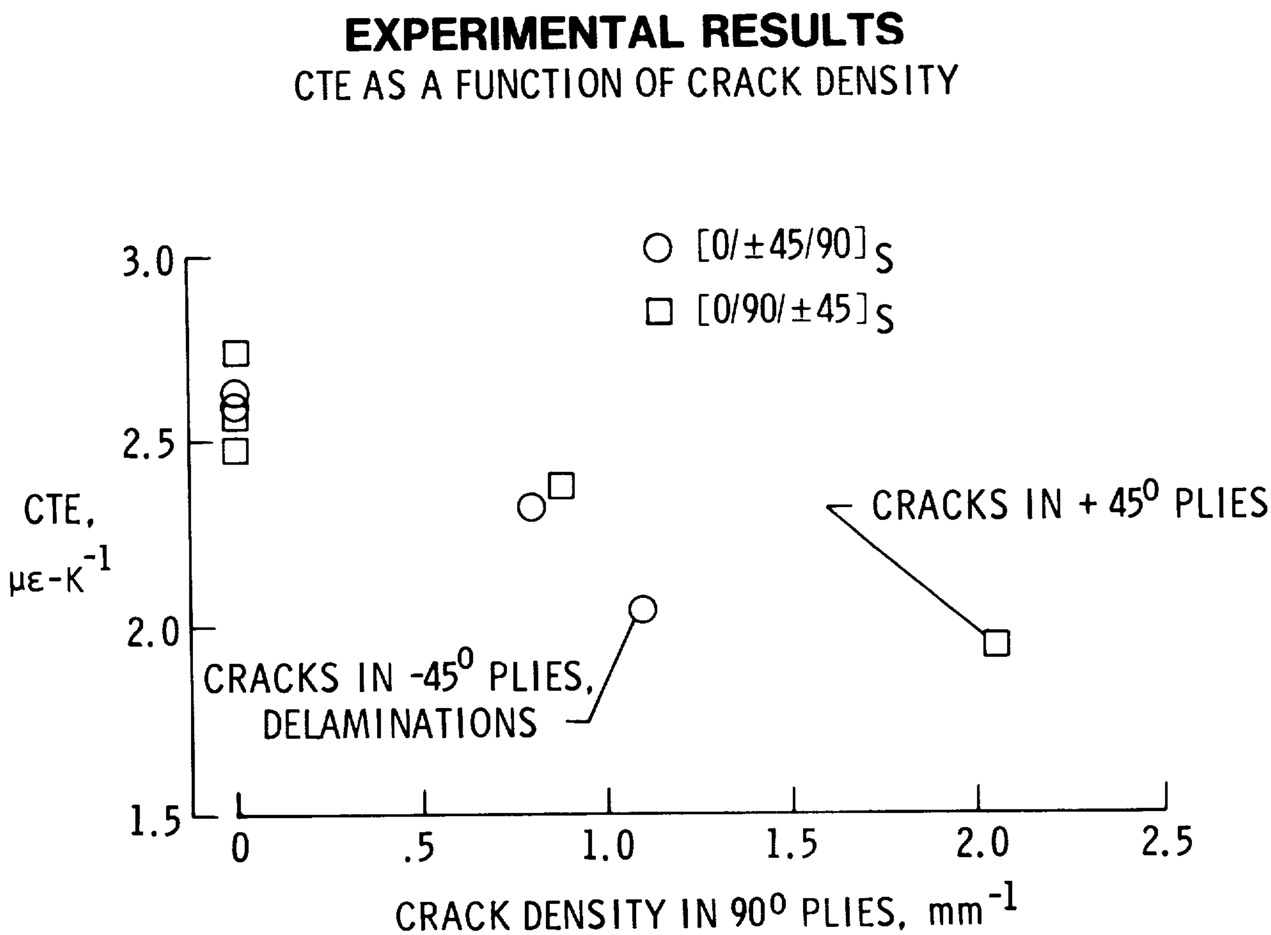



Figure 7

## LAMINATE ANALYSIS

Laminate analysis is a useful tool for predicting the inplane CTE of composite laminates. It has been suggested (ref. 2) that laminate analysis may also be suitable for predicting the CTE of composites when microcracks are present, if appropriate modifications are made. These modifications include reducing the transverse stiffness, $E_2$, the transverse CTE, $\alpha_2$, and the shear modulus, $G_{12}$, of the cracked plies. These reduced values are then used as input parameters to the laminate analysis. The effect of reducing $E_2$ by various amounts on the laminate CTE of a quasi-isotropic configuration is shown in figure 8. If $E_2$ is reduced by 100% in all plies, the laminate CTE approaches the value for the unidirectional ([0]) laminate in the fiber direction. A similar effect on the laminate CTE would result if $\alpha_2$ were reduced from its original value. For this particular laminate configuration, $[0/\pm45/90]_s$, a reduction in $G_{12}$ has negligible effect on CTE.

### LAMINATE ANALYSIS TO INCLUDE EFFECT OF MICROCRACKING

LAMINATE CTE AS A FUNCTION OF LAMINA TRANSVERSE STIFFNESS, $E_2$, FOR $[0/\pm45/90]_S$ LAMINATE

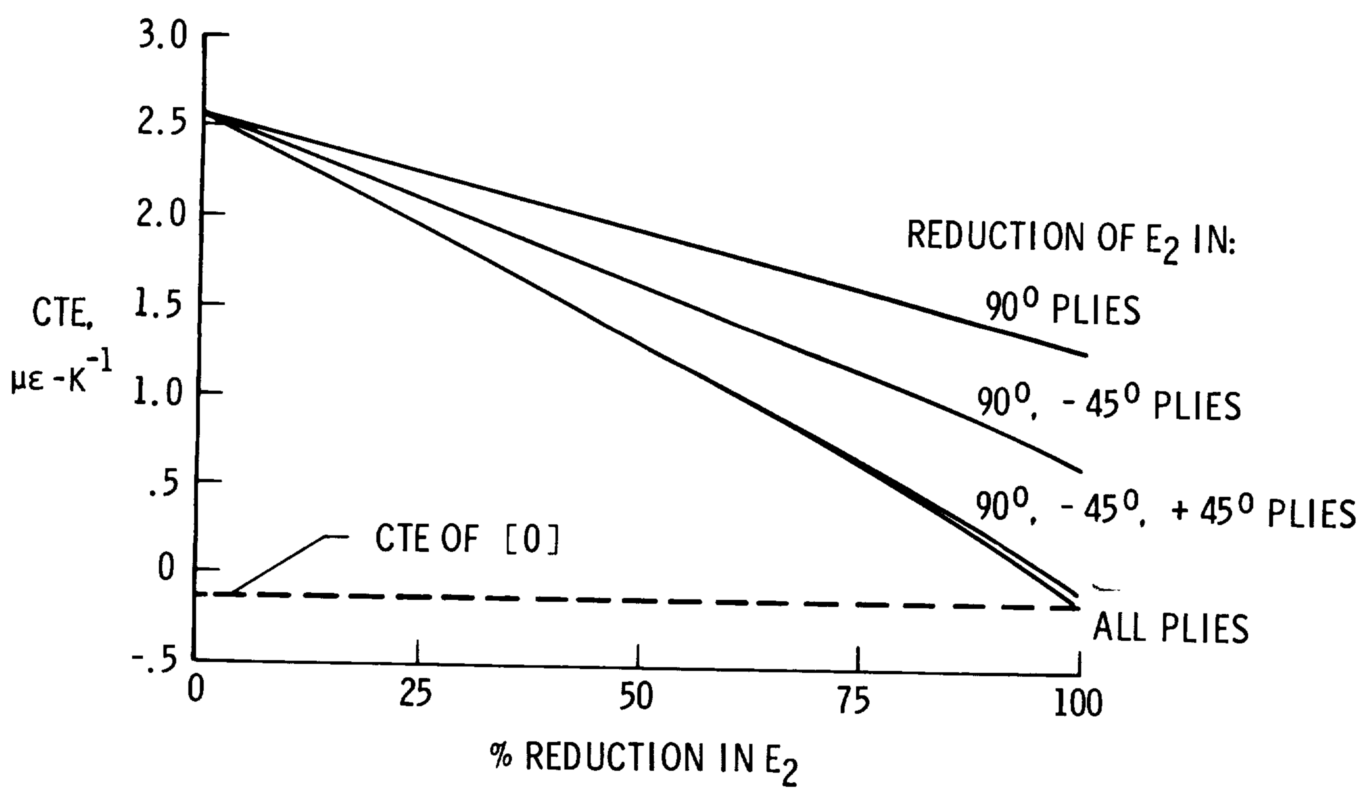



Figure 8

## RELATIONSHIP BETWEEN CRACK DENSITY AND REDUCTION IN LAMINA PROPERTIES

The relationship between crack density and reduction in lamina properties must be known in order to use laminate analysis to predict the effect of microcracking on the CTE. Lockheed under NASA contract NAS1-16406 (ref. 4) has been studying the effect of microcracking and delamination on laminate stiffness reduction. In the course of their research, they developed a relationship between crack density and the reduction in lamina transverse stiffness, $E_2$. A finite element analysis was used to first determine the effect of crack density on laminate stiffness reduction. Then simple laminate analysis was used to determine the amount of reduction in lamina stiffness needed to account for the reduction in laminate stiffness. From these two analyses, the relationship between crack density and reduction in lamina $E_2$ was determined. A plot of this relationship is shown in figure 9. For the maximum crack densities produced in the current research, the reduction in $E_2$ was approximately 35%.

## MASTER CURVE FOR REDUCTION IN LAMINA VALUES OF $E_2$

REDUCTION IN $E_2$ AS A FUNCTION OF CRACK DENSITY

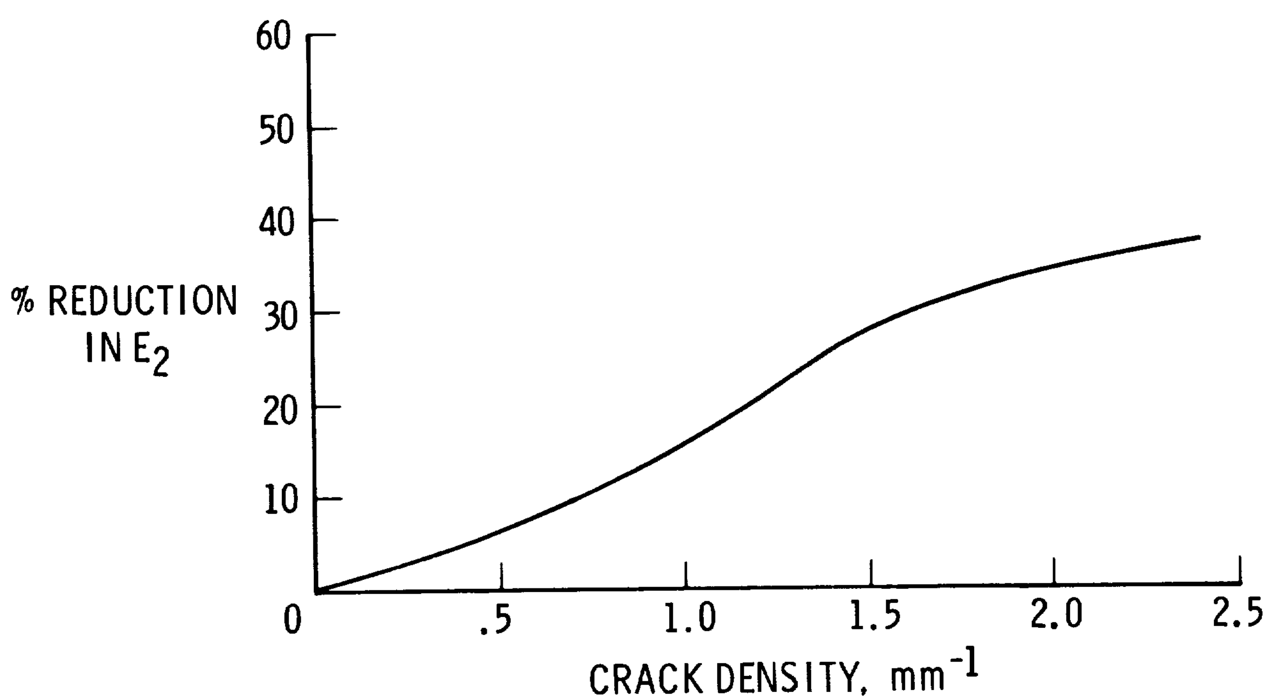



Figure 9

## COMPARISON OF EXPERIMENTAL RESULTS AND ANALYTICAL PREDICTIONS

A comparison of the experimental data with the analytical predictions based on the approach previously described is shown in figure 10. The predictions for zero crack density agree well with the measured values. Two different schemes were used to account for microcracks. The first consisted of reducing only $E_2$ of the cracked plies. In the second, both $E_2$ and $\alpha_2$ of the cracked plies were reduced. The correlation between crack density and the amount of reduction in $E_2$ to be used in the laminate analysis was determined from the plot in figure 9. For the scheme where both $E_2$ and $\alpha_2$ were reduced, the amount of reduction in each property was assumed to be the same. The dashed lines, shown in the plot below at crack densities of 1.10 and 2.05 $mm^{-1}$, are the predictions including the effect of cracks in the 45° plies. In general, there is good agreement between the prediction using reduced values of both $E_2$ and $\alpha_2$ and the experimental results.

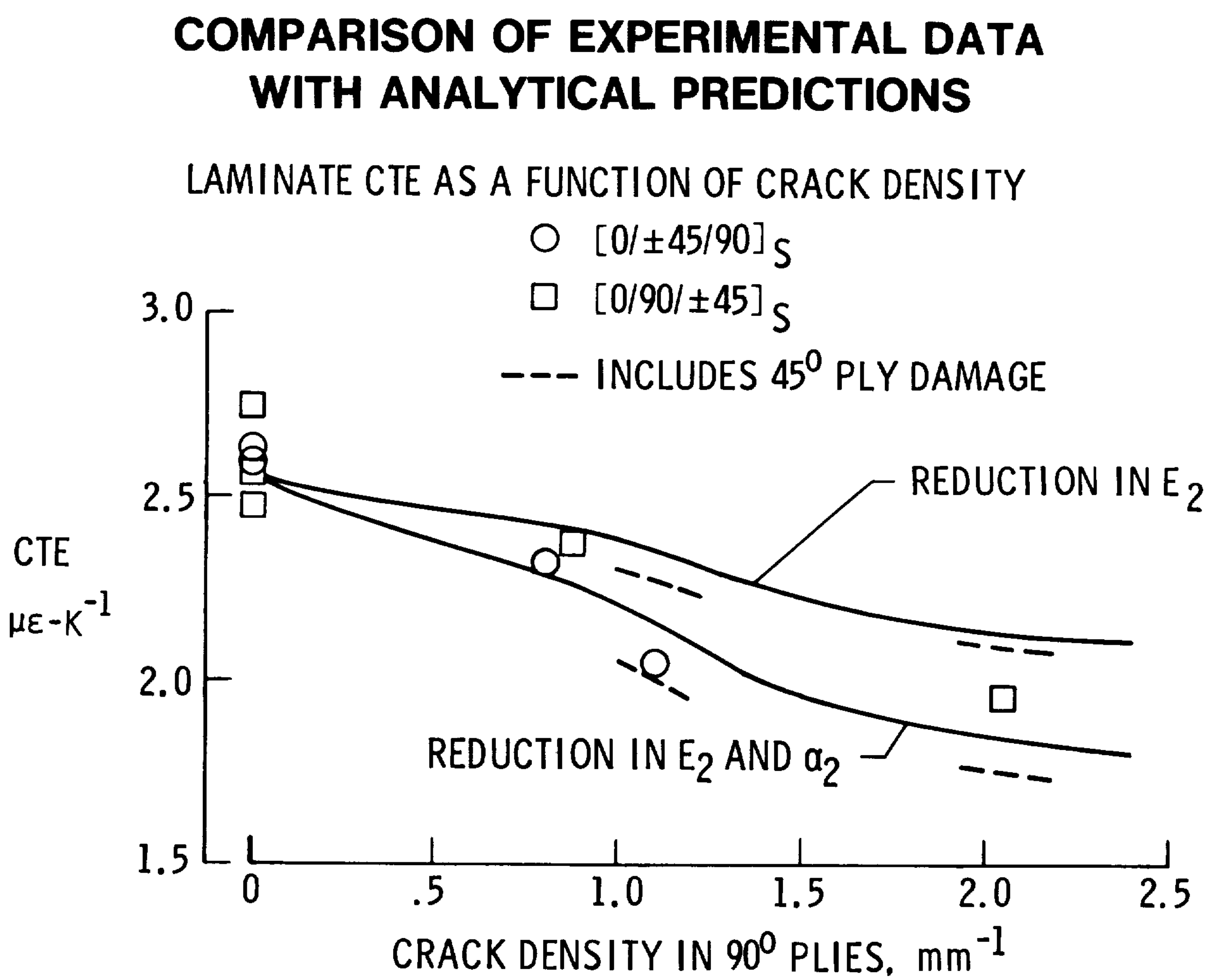



Figure 10

## CONCLUSIONS AND FUTURE WORK

The results of this research indicate that microcracking does affect the CTE of composite laminates. The amount of reduction in CTE was a function of the crack density. A maximum reduction of approximately 25% occurred in a quasi-isotropic specimen with a crack density of 2.05 $mm^{-1}$ in the 90° plies. Also laminate analysis with appropriate reductions in $E_2$ and $\alpha_2$ of the damaged plies appears to be capable of modeling the observed change. These conclusions are summarized in figure 11.

Future work will include characterizing the amount of microcracking due to thermal loads (i.e. thermal cycling) and measuring the effect on CTE, both above and below room temperature. Work will also continue in improving the modeling capability to predict CTE degradation due to damage formation.

### CONCLUSIONS

- MICROCRACKING DOES AFFECT THE CTE OF THE COMPOSITES TESTED
- EXPERIMENTAL DATA SHOWS THAT THE CHANGE IN CTE IS A FUNCTION OF CRACK DENSITY
- LAMINATE ANALYSIS WITH A REDUCTION IN $E_2$ AND $\alpha_2$ OF THE DAMAGED PLIES APPEARS TO BE CAPABLE OF MODELING THIS OBSERVED CHANGE

### FUTURE WORK

- STUDY THE EFFECT OF MICROCRACKING ON THE CTE BELOW ROOM TEMPERATURE
- IMPROVE ANALYSIS TO RELATE THE AMOUNT OF MICROCRACKING TO CHANGES IN LAMINA THERMOELASTIC PROPERTIES AND LAMINATE CTE
- STUDY THE EFFECT OF THERMALLY INDUCED MICROCRACKING ON CHANGES IN CTE

Figure 11

## REFERENCES

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