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A STUDY OF INTERPLY LAYER EFFECTS ON THE FREE-EDGE STRESS FIELD OF ANGLEPLIED LAMINATES

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SUMMARY

The general-purpose finite-element program MSC/NASTRAN is used to study the interply layer effects on the free-edge stress field of symmetric angleplied laminates subjected to uniform tensile stress. The free-edge region is modeled as a separate substructure (superelement) which enables easy mesh refinement and provides the flexibility to move the superelement along the edge. The results indicate that the interply layer reduces the stress intensity significantly at the free edge. Another important observation of the study is that the failures observed near free edges of these types of laminates could have been caused by the interlaminar shear stresses.

INTRODUCTION

Preliminary Remarks

Free edges in composite laminates often promote complex three-dimensional stress fields with steep gradients. This phenomenon has been studied both experimentally and analytically to a considerable depth during the last 15 years. It is thought that delaminations and matrix microcracking occurring near free edges are due to the steep interlaminar stress gradients in the free-edge region. However, much controversy still exists regarding the nature and magnitude of the interlaminar free-edge stresses. The free-edge region of a composite laminate is usually modeled as homogeneous anisotropic layers sharing common boundaries between them. In reality, however, a thin, soft matrix layer exists between the plies. The effect of such a layer on the free-edge stress field must be considered in order to completely describe the stress field as the free edge is approached and also to better understand the apparent singular behavior of some of the stresses near a free edge. The singularities are inherent to the formulations when there is an abrupt change of material properties across the common boundary as when the interply layer is neglected. Furthermore, singularity is only a mathematical concept and not a realistic issue in practical problems.

Background

Numerous papers pertaining to the free-edge stress have been published during the last 15 years. A brief description of the literature on the subject is given in order to provide the background and impetus leading to this investigation.

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The problem of finite-width laminate under uniform extensional strain was first analyzed by Pipes and Pagano (ref. 1). The formulation was based on anisotropic elasticity, and the solution was obtained using a finite-difference scheme. A number of investigations have subsequently been conducted on this problem with a fairly wide range of approaches. Quasi-three-dimensional finite-element approaches which use plane-strain plate elements can be found in references 2 to 4. Hsu and Herakovich (ref. 6) obtained a solution using a perturbation technique. Singular hybrid-stress finite-element models were employed by Spilker and Chou (ref. 6) and Wang and Yuan (ref. 7). The latter work is based on the theory of anisotropic elasticity and Lekhnitskii's stress potentials (ref. 8). A fully three-dimensional formulation with a three-dimensional finite-difference solution scheme is given in reference 9. Recently, a global-local laminate variational model has been proposed by Soni and Pagano (ref. 10). A review of the free-edge stress problem with a comparative assessment can be found in references 4 and 11 to 13.

Approximate procedures, which assume specific form for the stress distributions near the free edge and use elastic equations of equilibrium, have also been employed with some success (refs. 14 to 16). The main intention of these works is to present procedures to design laminate with appropriate stacking sequence such that the resulting laminate is less likely to develop high interlaminar stresses and subsequent failures in the free-edge region.

Synopsis

A survey of the literature on the free-edge stress problems leads to the following important conclusions/issues:

(1) A fully, three-dimensional finite-element analysis or elasticity solution is not available at the present time.

(2) The interply layer of finite thickness has not been considered in the solution available to date.

(3) Much controversy exists regarding the nature and magnitude of the interlaminar stresses near the free edge.

(4) The free-edge region has been customarily modeled as dissimilar anisotropic layers sharing common interfaces. Consequently, stress singularities are inherent to such formulations.

Present Investigation

This investigation is directed toward addressing the previous issues with the aid of a finite-element analysis. In a typical solution scheme of finite-element or finite-difference type, the layers are divided into a fine mesh. The mesh size near the interface is usually of the order of the dimensions of the fiber and the interfiber spacing. Therefore, a more realistic approach from the micromechanics viewpoint would be to provide a thin interply layer at the interface as illustrated in figure 1. In this analysis, a thin, soft, isotropic matrix layer is provided at the interface. This layer is referred to as the interply layer in this discussion. A fully, three-dimensional finite-element analysis is carried out using 20-node isoparametric brick elements that are available in the general-purpose finite-element code MSC/NASTRAN. Another feature unique to the present study is the use of a special free-edge superelement which allows the free-edge region to be analyzed as a substructure. This feature has the added advantage of remeshing and reanalyzing the free-edge region to the extent of detail desired without solving the primary structure every time. The analysis is conducted on the complete structure. The dimensions of the laminate are chosen to reflect a realistic plate type structure (28 in. by 7 in. by 0.0202 in.).

ANALYSIS

In this section, the specimen geometry, the finite-element idealization of the primary and the superelement structures, and the cases investigated are described.

Specimen Geometry

The geometry of the laminated plate under study is shown in figure 2. As shown in the figure, the length of the plate is 28 in., the width 7 in., and the thickness 0.0202 in. The plate is composed of seven layers (four plies and three interply layers). The plies are arranged symmetrically to form a $(\pm\theta)_s$ type angleplied laminate. The coordinate axes are as shown.

Finite-Element Modeling

Figures 3 and 4 give the details of the finite-element mesh employed in the present analysis for the primary and the superelement structures, respectively. One element is used through the thickness of each layer. There are 7 elements across the plate width and 28 elements along the plate length. A total of 1365 brick elements are used to model the primary structure. The superelement contains 224 elements with progressively decreasing mesh size toward the free edge. With this type of arrangement, the center of an element nearest to the edge is 1/512 in. from the edge. The boundary conditions imposed are such that along the edge $x = 0$ every node in the midplane is constrained from displacement in x-, y-, and z-directions. Also, the rest of the nodes along the edge $x = 0$ are constrained from displacement in the x-direction. Along the edge $x = 28$ in. a uniform stress of magnitude unity is prescribed.

Cases Investigated

The types of laminates investigated in the present study are $(\pm 10)_s$ through $(\pm 80)_s$ at 10° intervals. The $(\pm 45)_s$ laminate is also studied as a special case since it has been given substantial attention in the literature. The interply layers are assumed to be isotropic with $E = 0.5$ mpsi and $\nu = 0.35$. These are representative properties of an epoxy matrix. The thickness of the interply layer is taken as 0.000067 in. The plies are assumed to be homogeneous and orthotropic. The material properties chosen for the plies are typical of an AS-graphite fiber/epoxy composite system. The stress-strain relation for the material is given by

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} & G_{14} & G_{15} & G_{16} \\ & G_{22} & G_{23} & G_{24} & G_{25} & G_{26} \\ & & G_{33} & G_{34} & G_{35} & G_{36} \\ & & & G_{44} & G_{45} & G_{46} \\ & \text{symmetric} & & & G_{55} & G_{56} \\ & & & & & G_{66} \end{bmatrix} \times \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \delta_{12} \\ \delta_{23} \\ \delta_{31} \end{bmatrix} \qquad (1)$$

The NASTRAN input data material properties for a 0°, 0.005-in.-thick ply are as follows (units are in mpsi):

$G_{11} = 19.4$ $G_{12} = 0.5164$ $G_{13} = 0.5164$ $G_{22} = 1.384$

$G_{23} = 0.4473$ $G_{33} = 1.483$ $G_{44} = 0.6667$ $G_{55} = 0.3974$

$G_{66} = 0.6667$

The rest of the G values are zero.

These properties are calculated using ICAN, a resident composite mechanics computer program with a data base of fiber and matrix properties (ref. 17). In addition to the previous cases, a limited study is also conducted where the thickness of the plate is varied from 1/7 through 1/40 of the width.

RESULTS AND DISCUSSION

Free-Edge Stresses

In order to study the three-dimensional stress behavior near the straight free edge, a small region close to edge is isolated and modeled as a substructure (superelement). In this region, the element size is decreased progressively as the free edge is approached. With this type of mesh, increasing levels of mesh refinement can be obtained as illustrated in figure 5. The results shown in this section were obtained by employing a mesh refinement such that the center of the element closest to the free edge was 1/512 in. from the free edge. The six stresses, which were obtained near the free-edge region, are summarized in figures 6 to 14. These results are plotted against a length parameter X_f along a central line perpendicular to the free edge. The length parameter X_f is related to the distance from free edge L_f by

$$X_f = 1 - L_f \qquad (2)$$

In these figure the dashed lines represent the stress computed at the center of (+Θ) ply elements. The solid lines represent the stress computed at the center of the interply layer between (+Θ) and (-Θ) layers. The stresses are normalized with respect to the applied stress $\sigma_{xx\infty}$. The classical laminate analysis predictions for these normalized stresses are

$$\sigma_{xx}/\sigma_{xx\infty} = 1$$

$$\sigma_{yy}/\sigma_{xx\infty} = 0 \tag{3}$$

The inplane shear stress σ_{xy} is a function of ply angle Θ. The variation of σ_{xy} in the +Θ ply as a function of ply orientation is shown in figure 15. The general behavior of the stress field as the free edge is approached is now summarized.

<u>Inplane stresses σ_{xx}, σ_{xy}, and σ_{yy}.</u> - The inplane stresses σ_{xx}, σ_{xy}, and σ_{yy} approach classical laminate theory predictions in the interior of the ply. Close to the free edge, however, significant changes in these stresses are clearly seen. The maximum change in the magnitude of σ_{xx} is 30 percent greater than that predicted by theory (CLT).

The transverse normal stress σ_{yy} in the +Θ layer appears to be negligible. However, it does not vanish because of the presence of the interply layer. The maximum σ_{yy} observed in the +Θ layer is less than 10 percent. In the interply layer, σ_{yy} is significant for layups $(\pm 30)_s$ to $(\pm 80)_s$ with magnitudes ranging from 10 to 20 percent of the applied stress. Also, the sign of σ_{yy} changes for $(\pm 70)_s$ and $(\pm 80)_s$ laminates.

The σ_{xy} stress in the interply layer is negligible and can not be seen distinctly in figures 6 to 14. Both σ_{xy} and σ_{xx} in the +Θ layer are seen to approach a finite value near the edge. A sign reversal is observed for these stresses in the case of $(\pm 10)_s$ laminate.

<u>Interlaminar stresses σ_{xz}, σ_{zz}, and σ_{zy}.</u> - The interlaminar shear stress σ_{xz} has the greatest magnitude among these stresses in the laminates range $(\pm 30)_s$ through $(\pm 60)_s$. A steep increase in magnitude is seen near the free-edge zone. The stress magnitude in the interply is higher than that of the +Θ layer. A maximum of 28 percent of the applied stress is seen in the interply layer of the $(\pm 40)_s$ laminate.

The interlaminar normal stress σ_{zz} appears to be of minor significance. However, it does have a definite trend. Two sign reversals are clearly noted. It starts as compressive stress in the interior of the ply or the interply layer, becomes tensile stress for a short distance closer to the edge, and then reverts to compressive stress near the edge. The maximum σ_{zz} observed is about 3 percent of the applied stress.

On the basis of these results, it can be concluded that σ_{xz} is the only interlaminar stress that could initiate delamination at a free edge in angleplied laminates, specifically in the sensitive range of Θ = 30° through Θ = 60°. The interlaminar stress σ_{zz} by virtue of its magnitude and sign (compressive in a major portion of the free edge region) does not appear likely to initiate peeling-off-type delaminations near the free edge. The interlaminar shear stress σ_{zy} is the least significant of these stresses throughout the range considered. It can be neglected for all practical purposes.

Effect of Ply Angle on Free-Edge Stresses

The peak values (computed 1/512 in. from the free edge) of the interlaminar stresses σ_{xz} and σ_{zz} and the inplane stress σ_{yy} in the interply layer between $+\theta$ and $-\theta$ plies are shown graphically in figures 16 to 18 plotted against the laminate type. As seen in figure 16, σ_{xz} appears to be very sensitive in the range $(\pm30)_s$ through $(\pm60)_s$. The trend appears to be similar to the functional behavior of σ_{xy} stress shown in figure 15. The maximum σ_{xz} is observed for the $(\pm45)_s$ laminate (about 28 percent of the applied stress).

The σ_{zz} peak distribution indicates that for a large range of θ's the stress is compressive. The dashed line in the figure refers to stress computations 3/512 in. from the free edge. The solid line refers to stress computations 1/512 in. from the free edge. The maximum magnitude of σ_{zz} (about 3 percent of the applied stress) is observed for $(\pm70)_s$ laminate.

The σ_{yy} stress appears to have a definite trend with maxima at $(\pm40)_s$ and $(\pm80)_s$. The maximum value of σ_{yy} is about 15 percent of the applied stress.

Influence of Progressive Mesh Refinement on Interlaminar Stress Distribution

A (±30) symmetric laminate is chosen for this study. The mesh progressive refinement shown in figure 5 is employed to achieve three levels of fineness. The centers of the element closest to the free edge are 1/32, 1/64, and 1/128 in. from the edge for levels 1, 2, and 3, respectively. The interlaminar stresses σ_{zz} and σ_{zy} are selected for the following discussion, and the results appear in figures 19 and 20. Both stress distributions indicate stable, converged behavior except for the region close to the edge. The interlaminar shear stress σ_{zy} distribution, however, shows much higher noise near the edge though the magnitudes are negligible. It is known from the laminate equilibrium consideration that σ_{zy} should be zero on the edge.

Effect of Width to Thickness Ratio on Interlaminar Stress Peaks

A limited study with (±45) symmetric laminate has been conducted to assess the effect of width to thickness ratio on the interlaminar stress peaks. The stresses σ_{xz} and σ_{zz} are selected for the study because they appeared to be the only significant interlaminar stresses. The results are shown in figure 21. The stresses are computed 3/512 in. from the free edge. Four ratios of W/h, where W is the width and h the thickness, are chosen in the study. The results show significant sensitivity to the W/h ratio. Both stresses appear to have substantial magnitudes for the laminate with $W/h = 20$. As the laminate becomes thinner, however, σ_{zz} appears to reach a zero value while σ_{xz} continues to have a significant magnitude.

SUMMARY OF RESULTS

The significant results from the present investigation are now summarized.

1. The major stresses in the free-edge region are the inplane stresses σ_{xx}, σ_{yy}, and σ_{xy}. The inplane stresses σ_{xx} and σ_{xy} increase above the CLT predicted values by as much as 30 percent of the applied stress in the $+\theta$ layers. The inplane stress σ_{yy} is nontrivial because of the presence of the interply layer. A maximum of 15 percent of the applied stress is observed in the layers of $(\pm 40)_s$ and $(\pm 80)_s$ laminates.

2. The interlaminar stresses σ_{xz}, σ_{zz}, and σ_{zy} are of second order compared to σ_{xx} in general. However, the interlaminar shear stress σ_{xz} could become substantial in the interply layer free-edge region depending on the configuration of the angleply laminate. The range of laminates from $(\pm 30)_s$ through $(\pm 60)_s$ are likely to develop relatively high σ_{xz} stress magnitudes that may initiate edge delaminations.

3. The peeling off stress σ_{zz} is not significant, and it is not likely to initiate edge delaminations in $(\pm\theta)_s$ angleplied laminates.

4. Progressive mesh refinement is an effective way to describe the behavior of the interlaminar stresses as the free edge is approached. The results indicate stable convergence of these stresses with some noise as the free edge is approached.

5. The magnitudes of the interlaminar stress peaks are sensitive to the width to thickness ratio of the laminate. Results obtained from relatively narrow specimens are not indicative of practical laminate behavior.

6. The interply layer appears to alter the apparent singular behavior of the free-edge stresses. The present study indicates finite magnitudes for all the stresses as the free edge is approached. Another effect of the interply layer is to induce transverse normal stresses σ_{yy} in the laminate.

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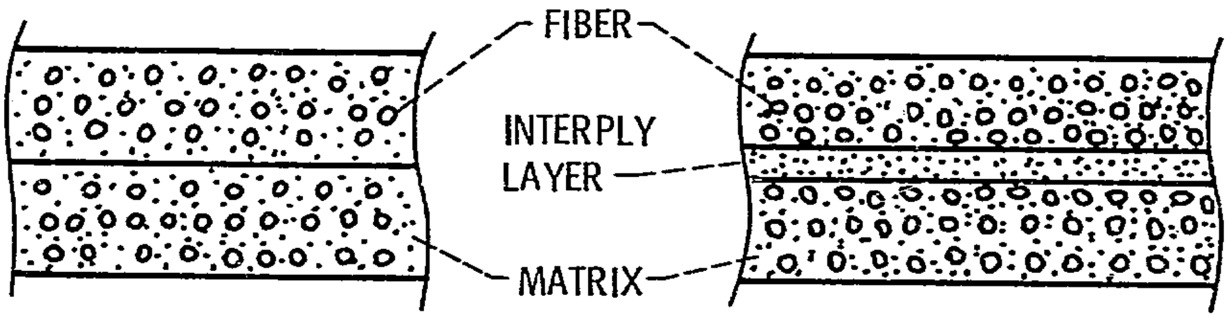

Figure 1. - Illustration of interply layer.

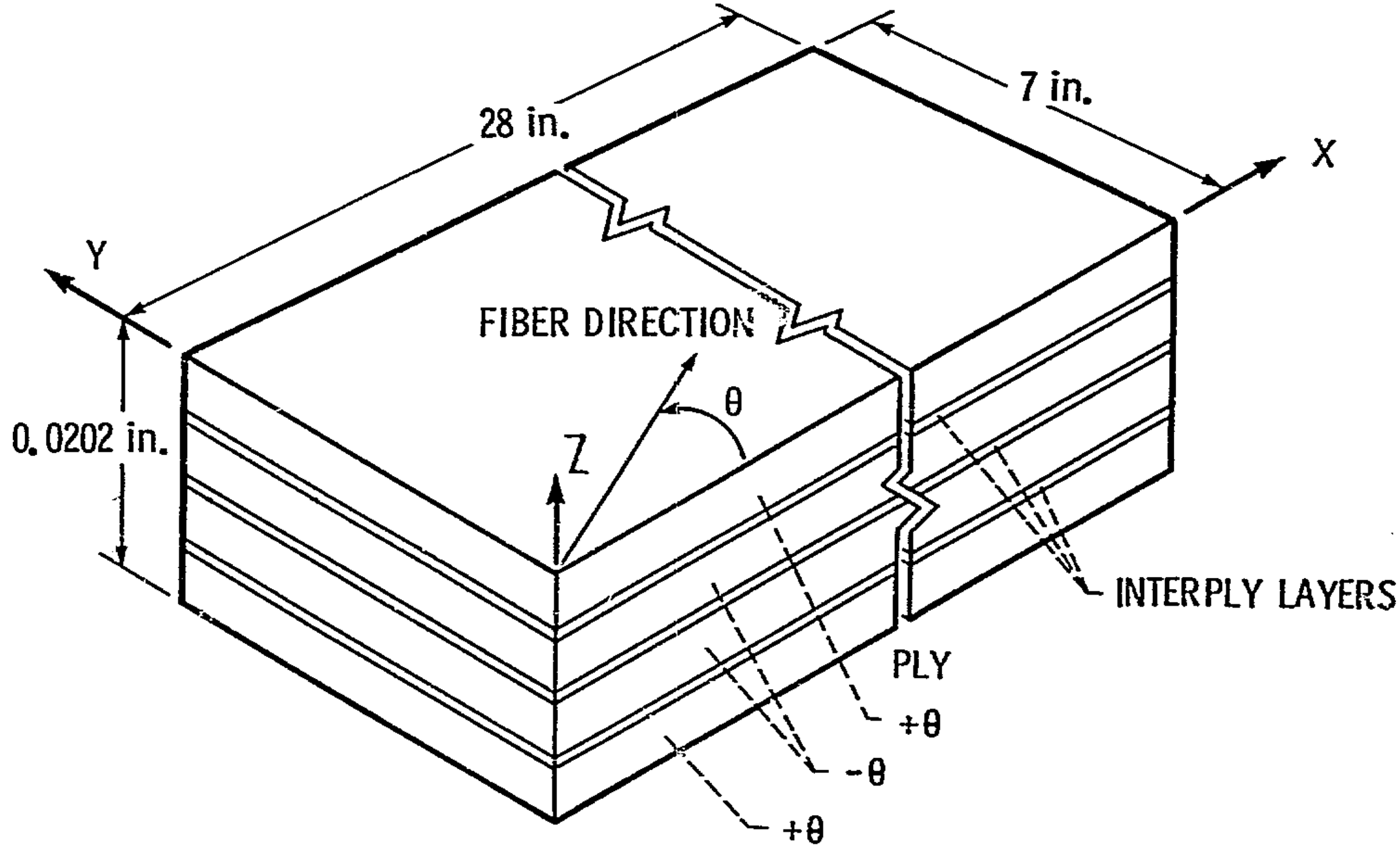

Figure 2. – Symmetric angleplied laminate of $(\pm\theta)_s$ type with interply layers.

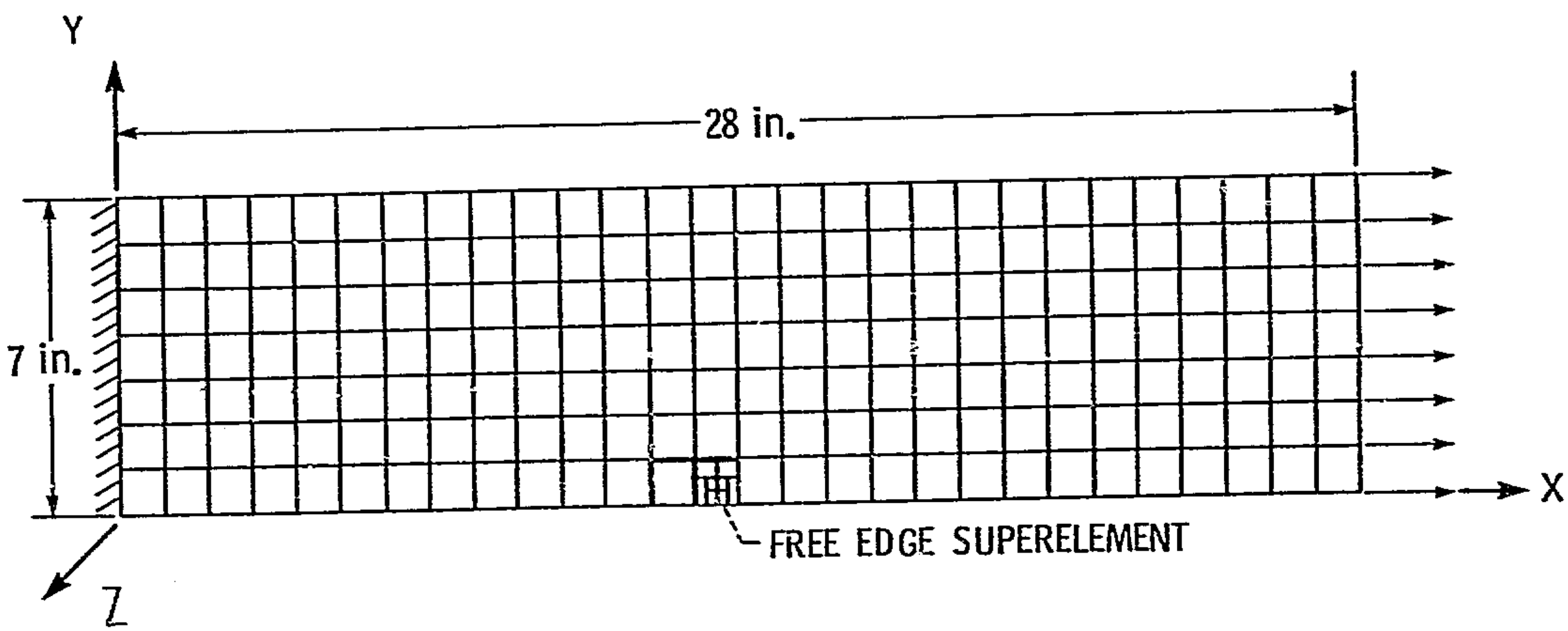

Figure 3. - Angleplied laminate under uniform extensional stress.

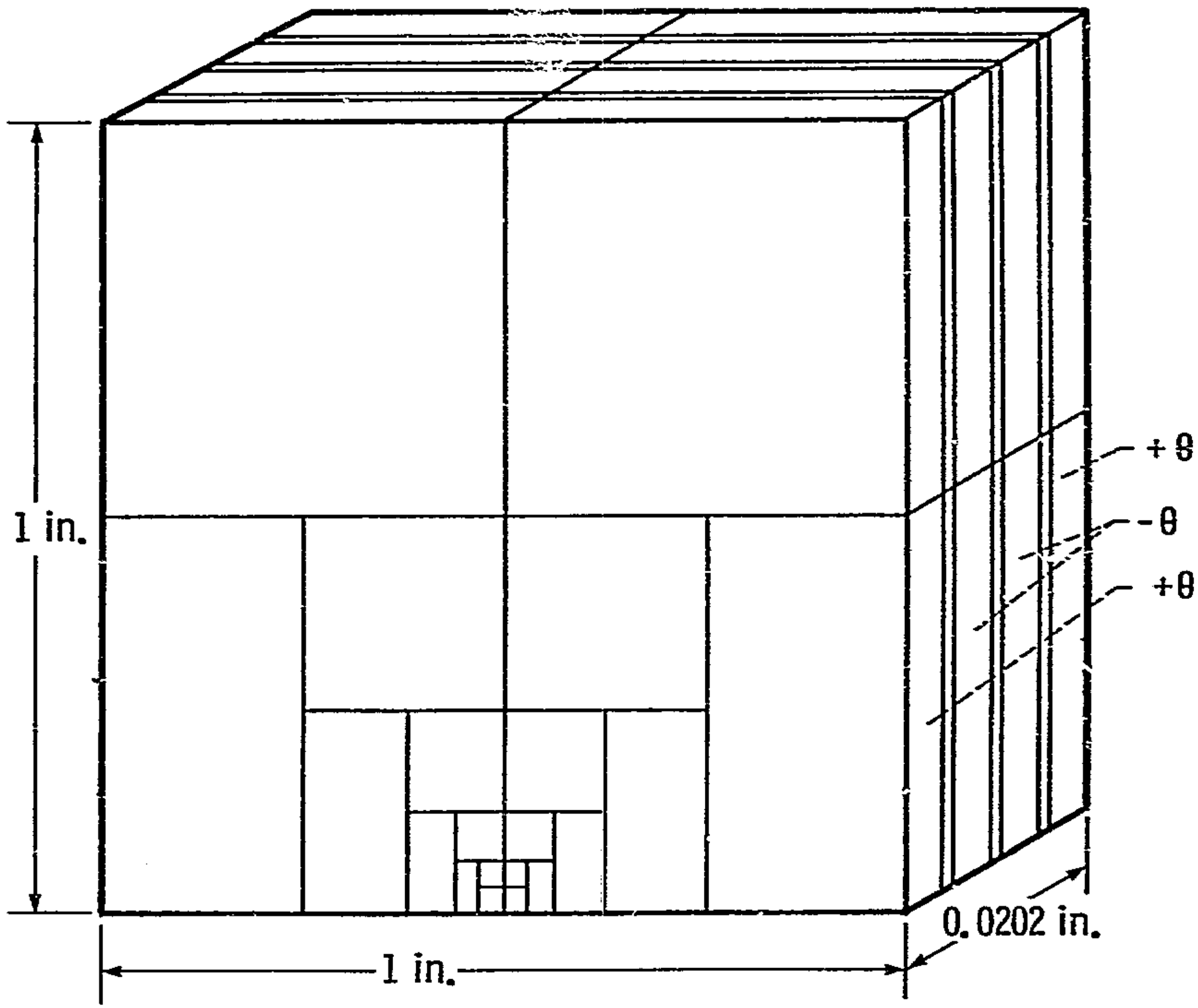

Figure 4. - Free-edge superelement.

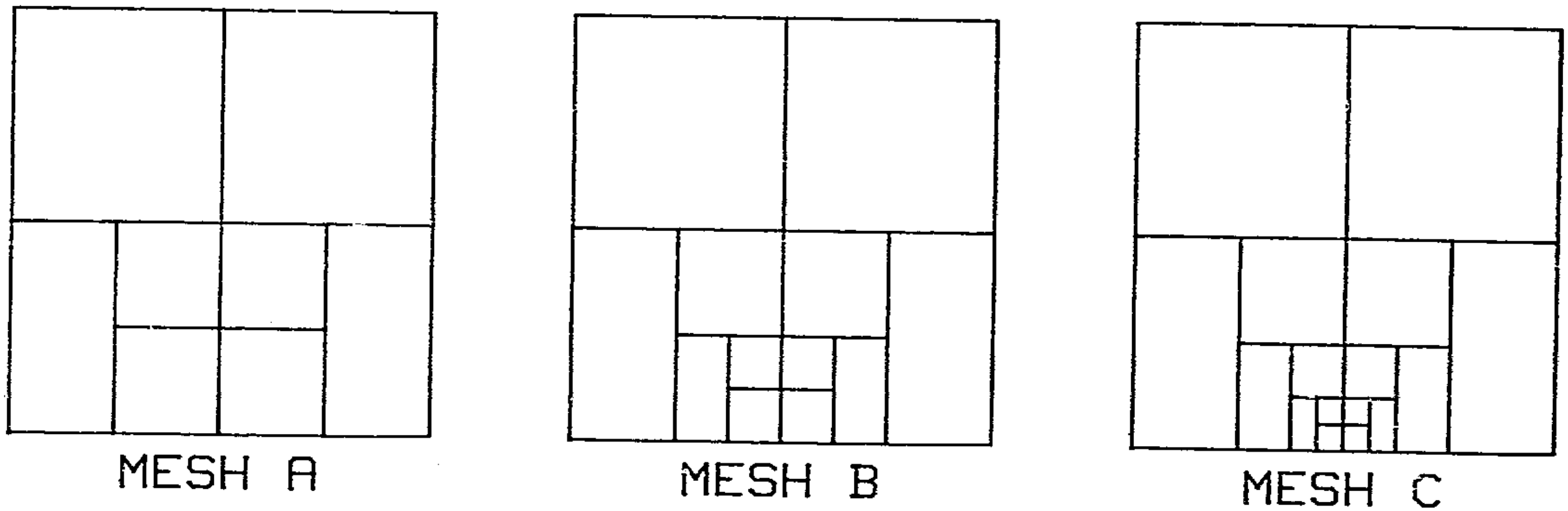

Figure 5. - Illustration of progressive mesh refinement.

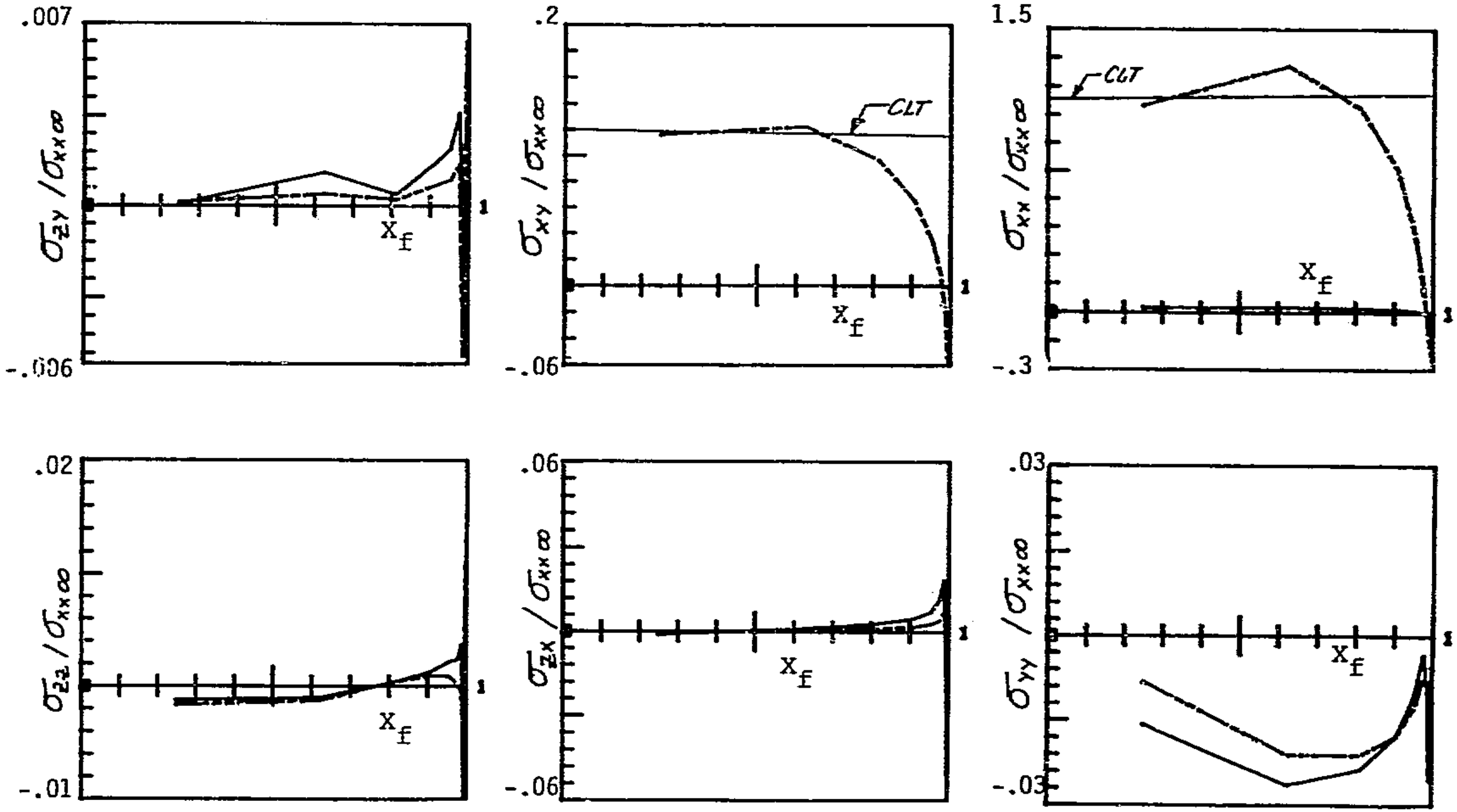

Figure 6. – Free-edge stresses in +10° and interply layers of $(\pm 10)_s$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

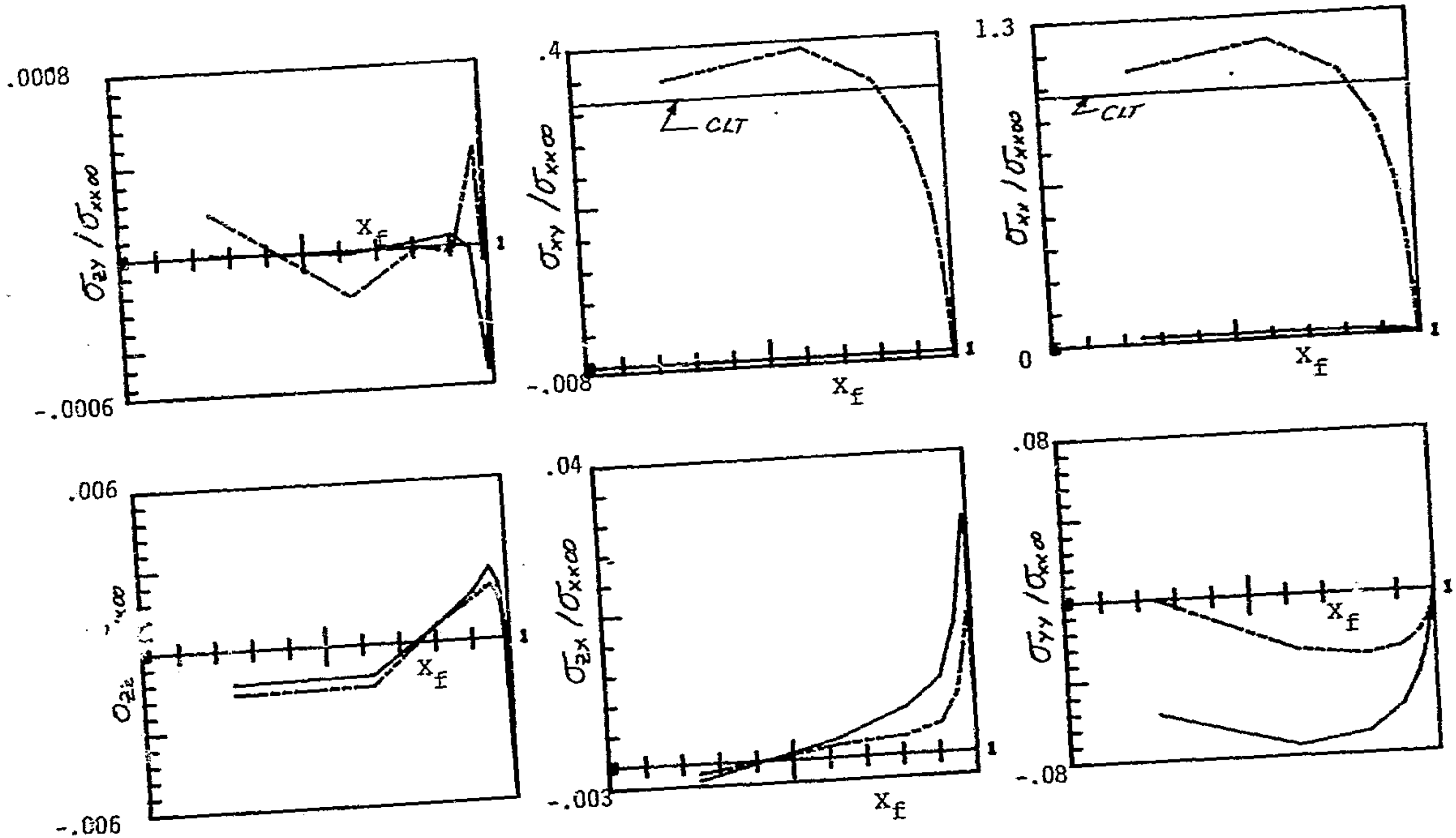

Figure 7. - Free-edge stresses in +20° and interply layers of $(\pm 20)_s$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

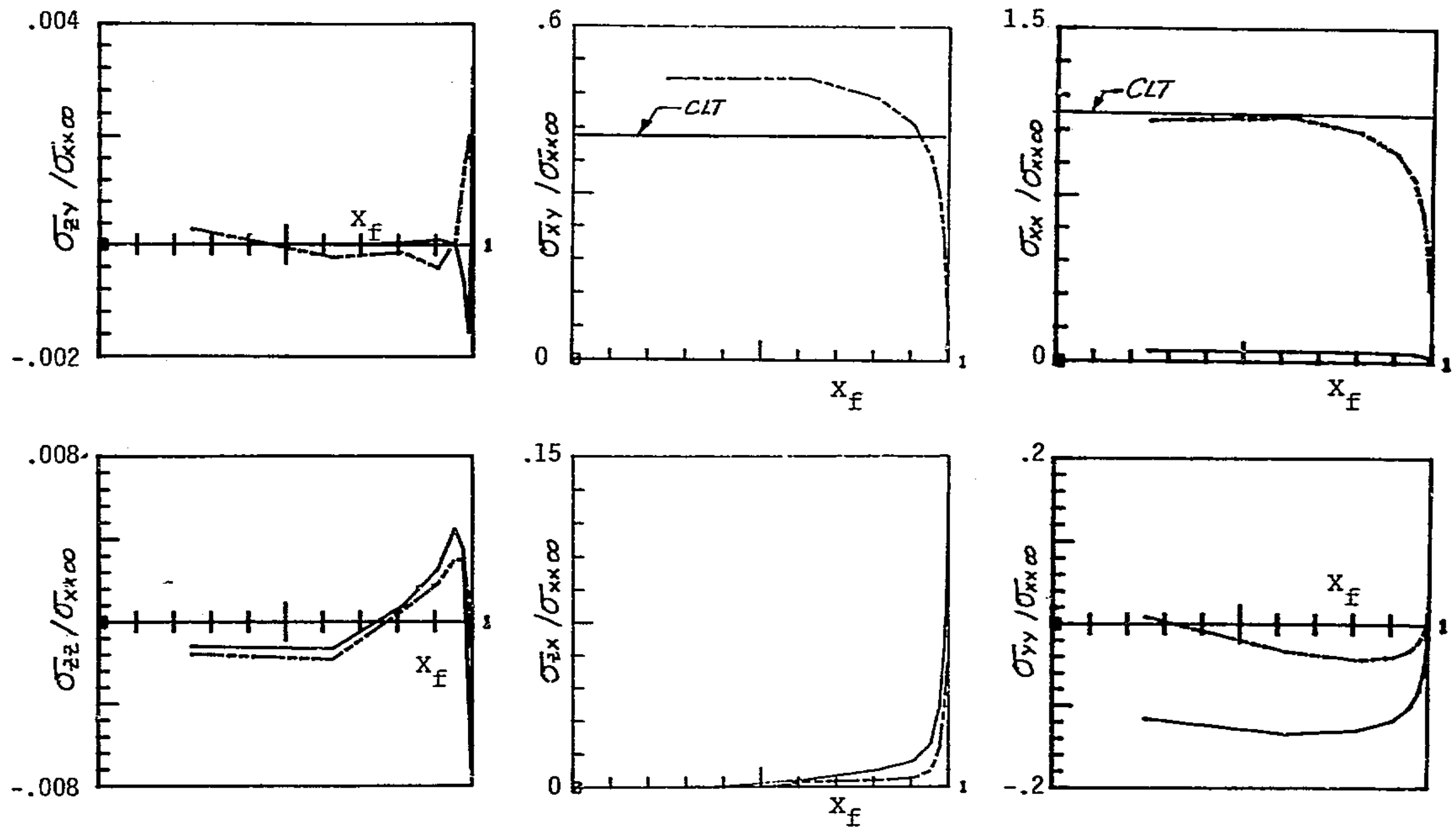

Figure 8. - Free-edge stresses in +30° and interply layers of $(\pm30)_s$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

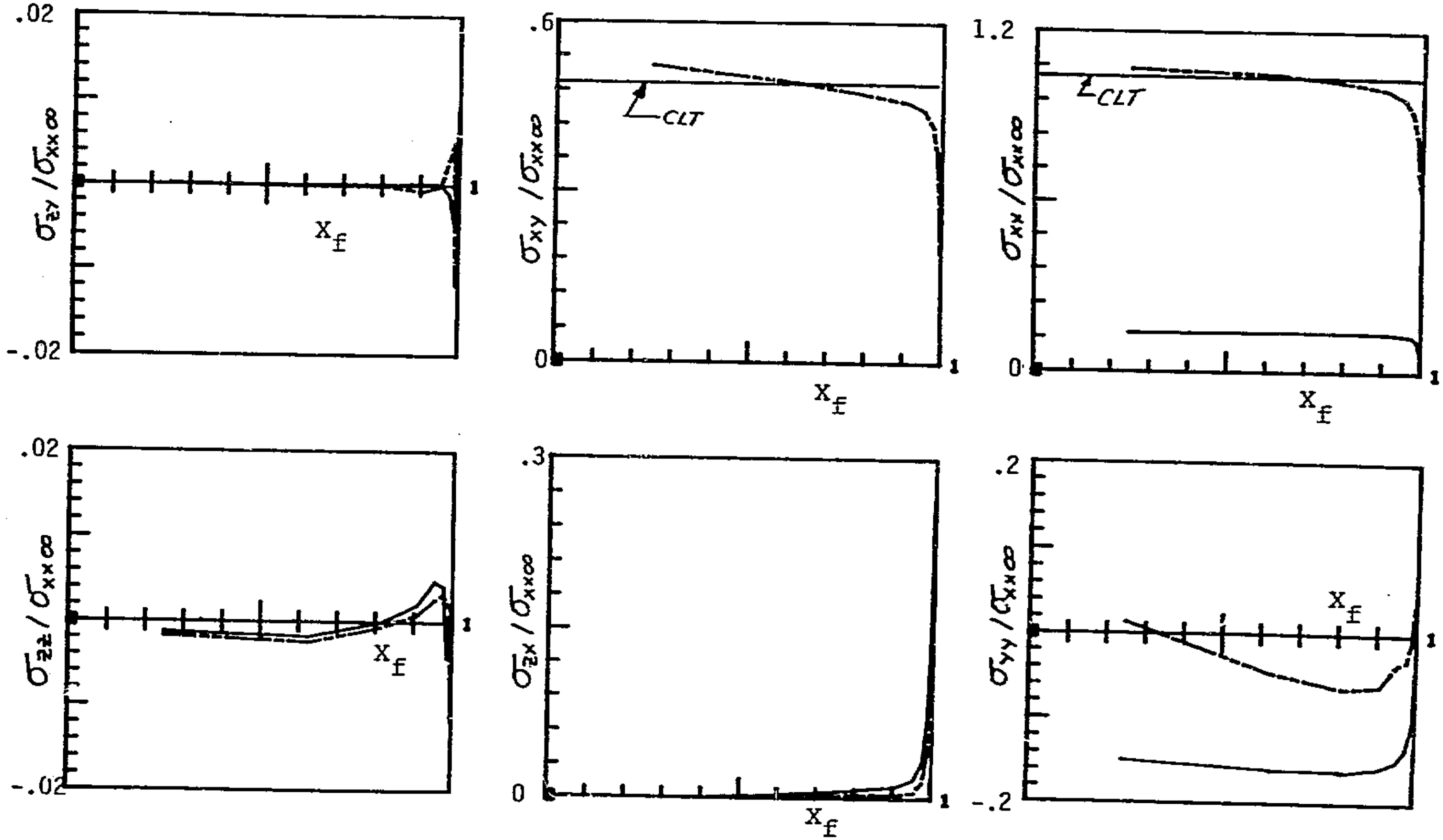

Figure 9. - Free-edge stresses in +40° and interply layers of $(\pm 40)_s$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

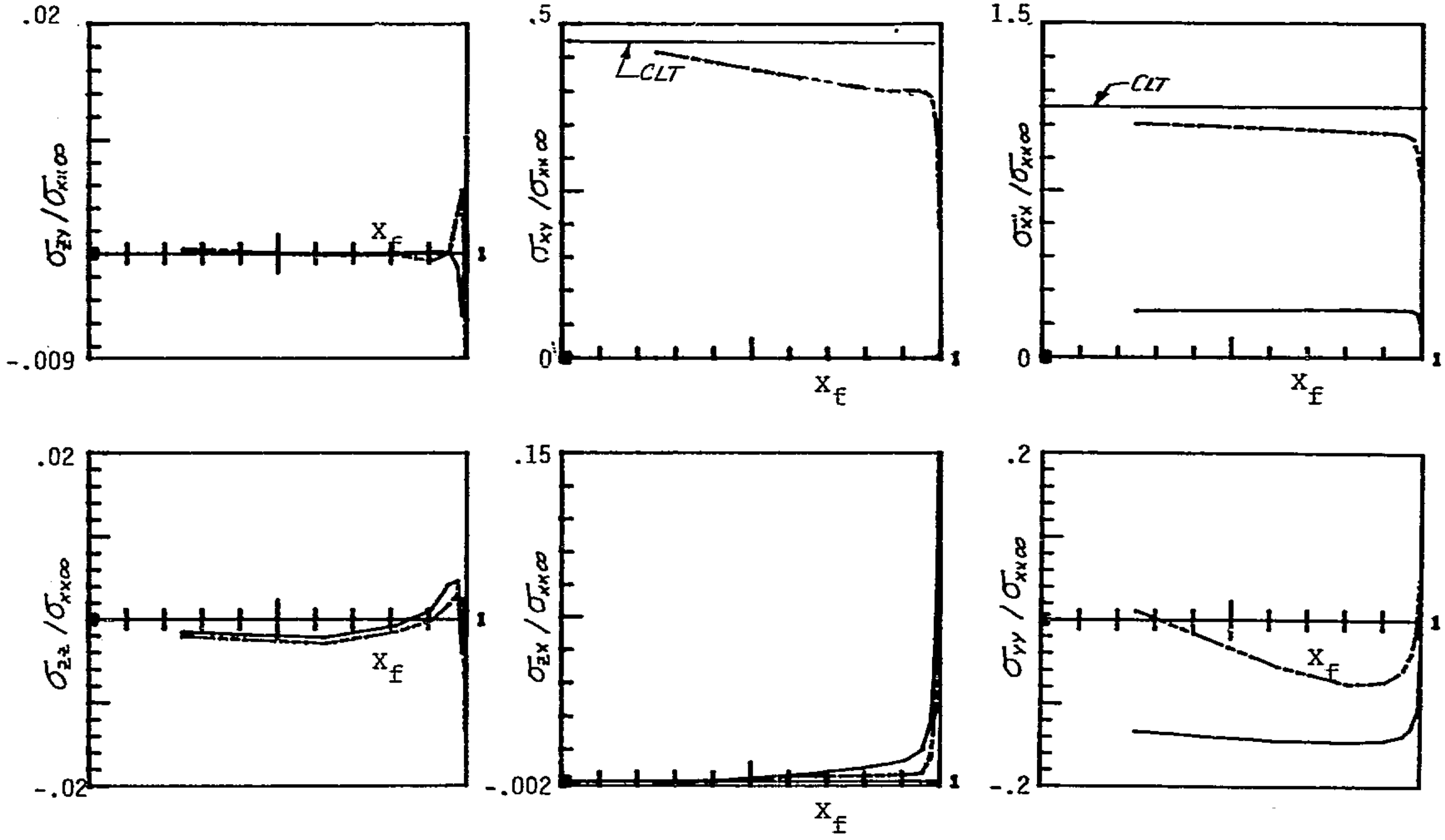

Figure 10. – Free-edge stresses in +45° and interply layers of $(\pm45)_S$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

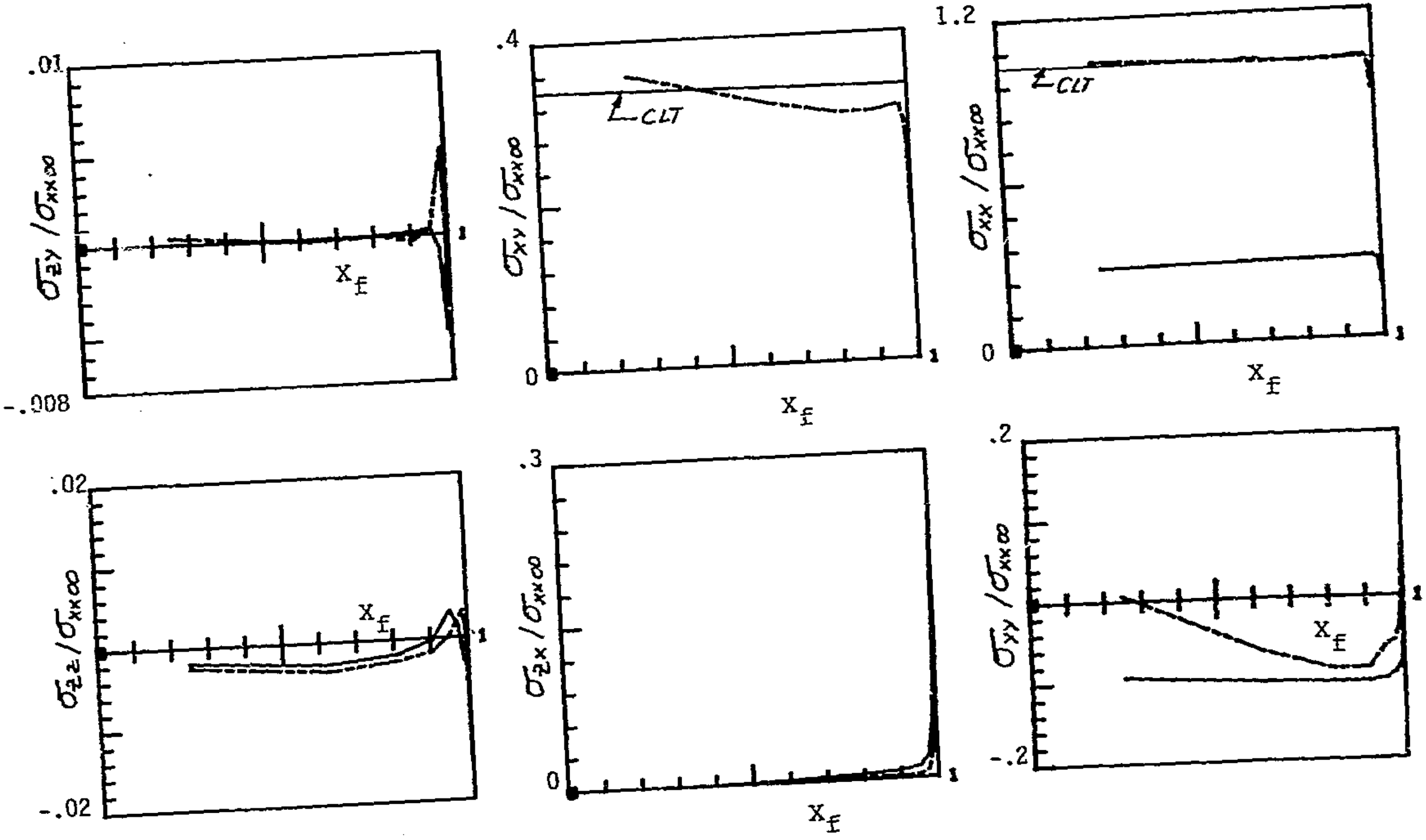

Figure 11. - Free-edge stresses in +50° and interply layers of $(\pm 50)_s$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

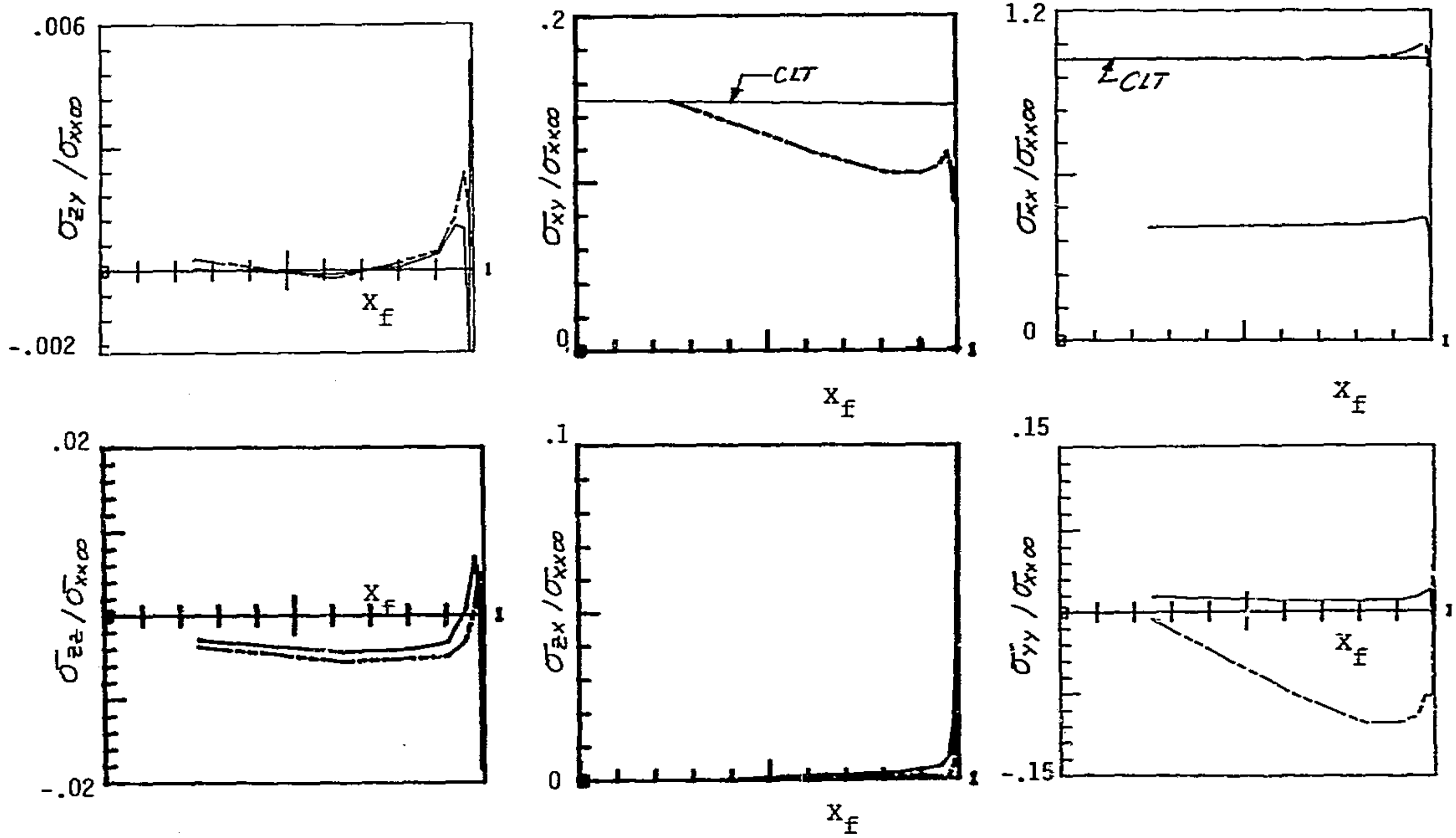

Figure 12. - Free-edge stresses in +60° and interply layers of $(\pm 60)_s$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

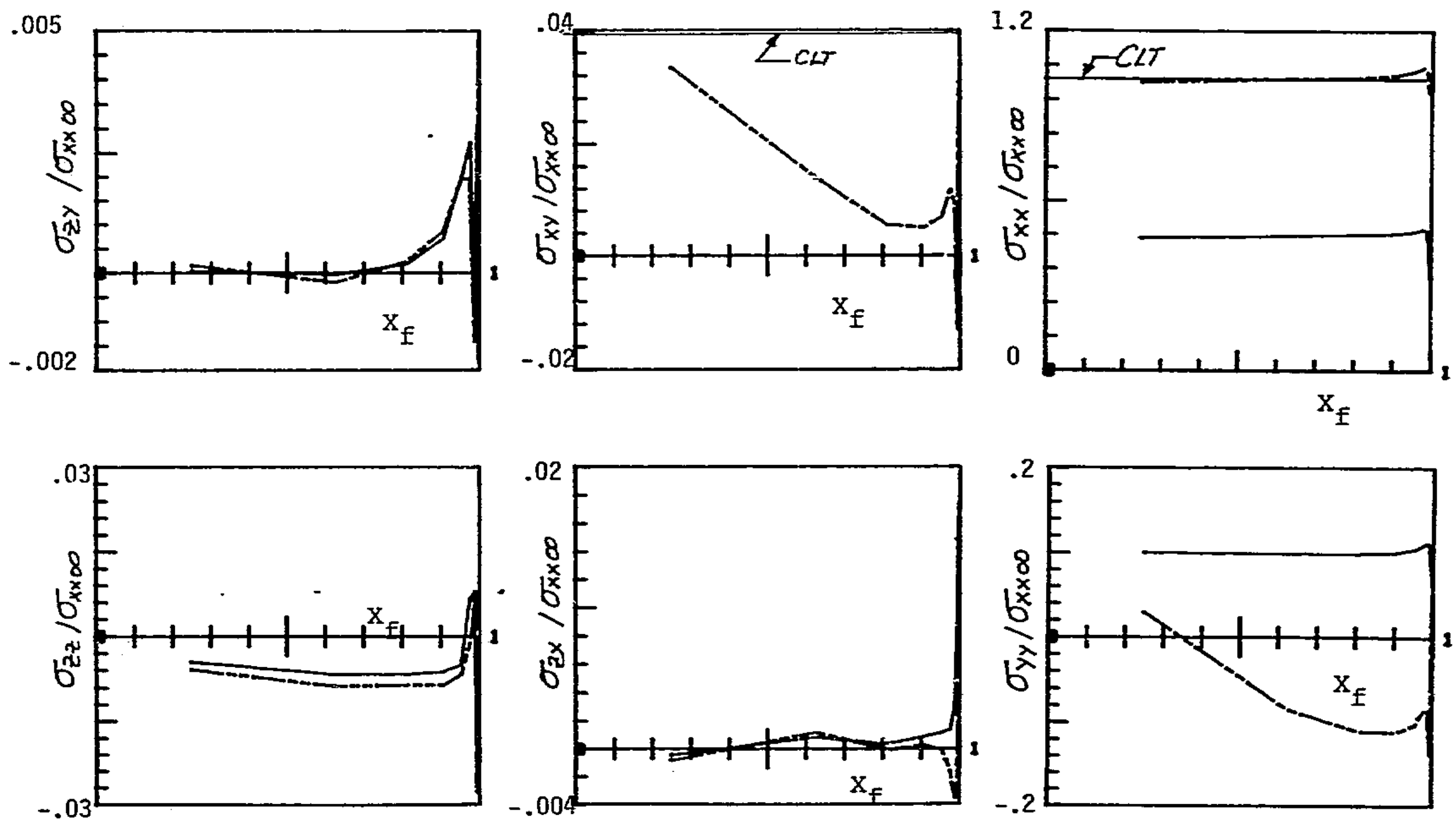

Figure 13. - Free-edge stresses in +70° and interply layers of $(\pm 70)_s$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

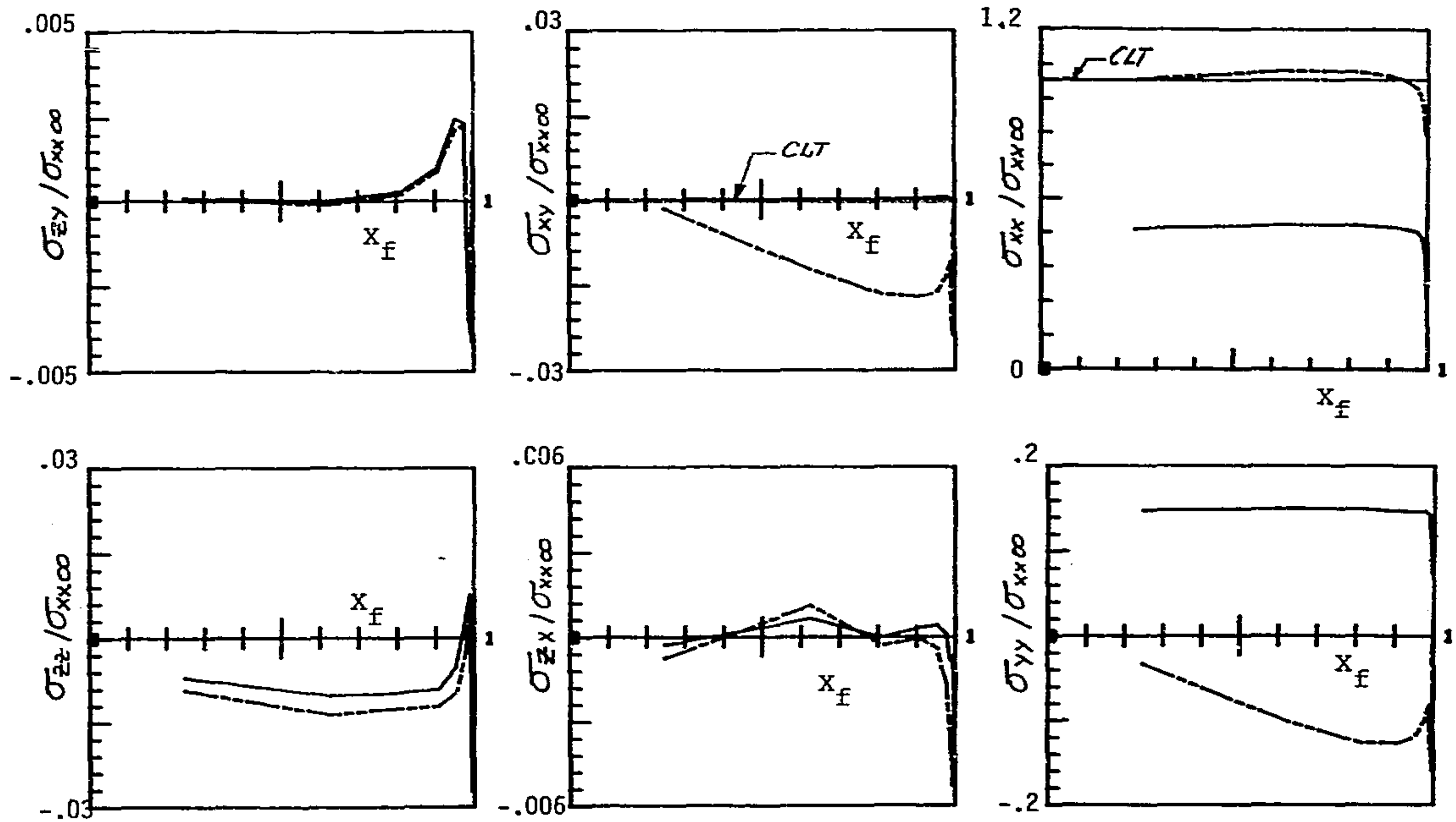

Figure 14. – Free-edge stresses in +80° and interply layers of $(\pm 80)_s$ laminate. (Solid curve, interply layer; dashed curve, center of ply.)

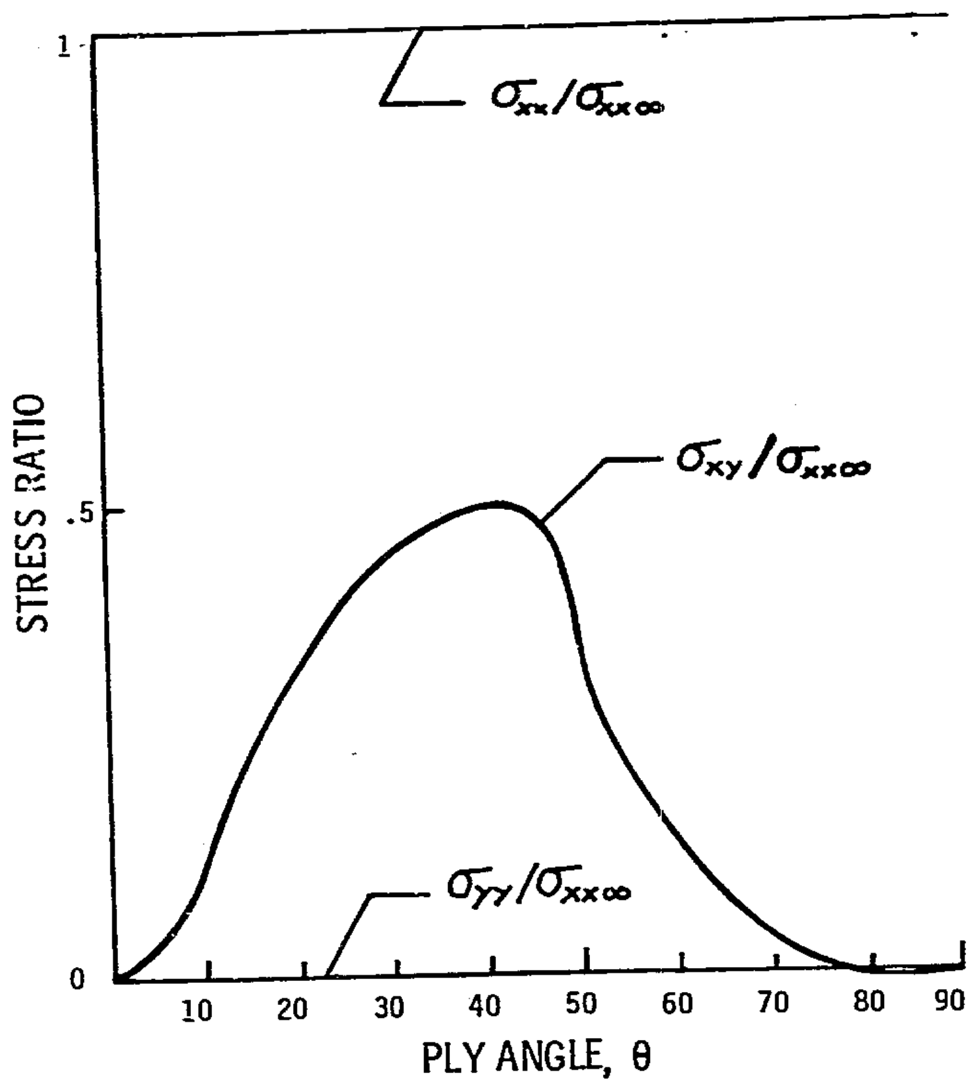

Figure 15. – Variation of inplane stresses with ply angle predicted by classical laminate theory.

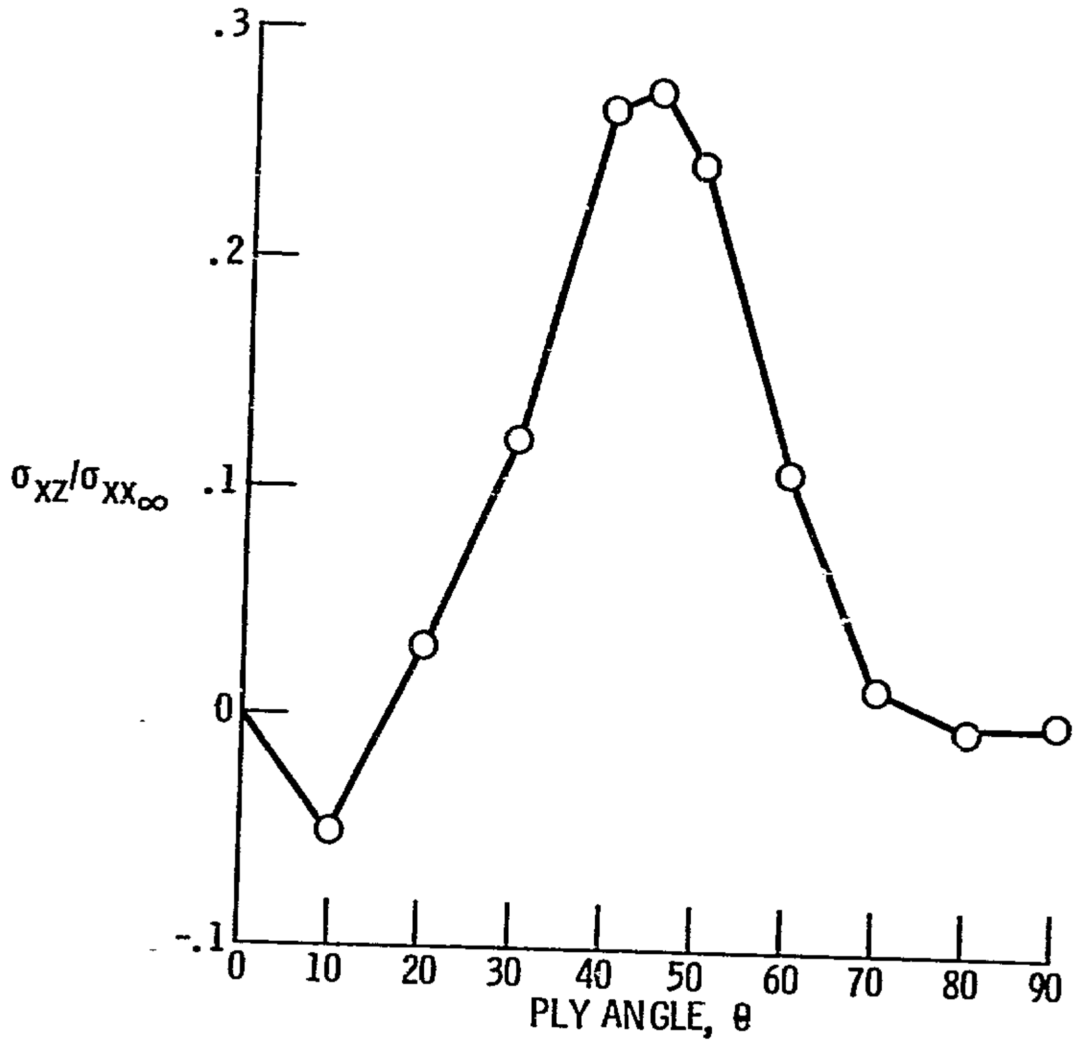

Figure 16. - Influence of ply angle on interlaminar shear stress near free-edge region of interply layer.

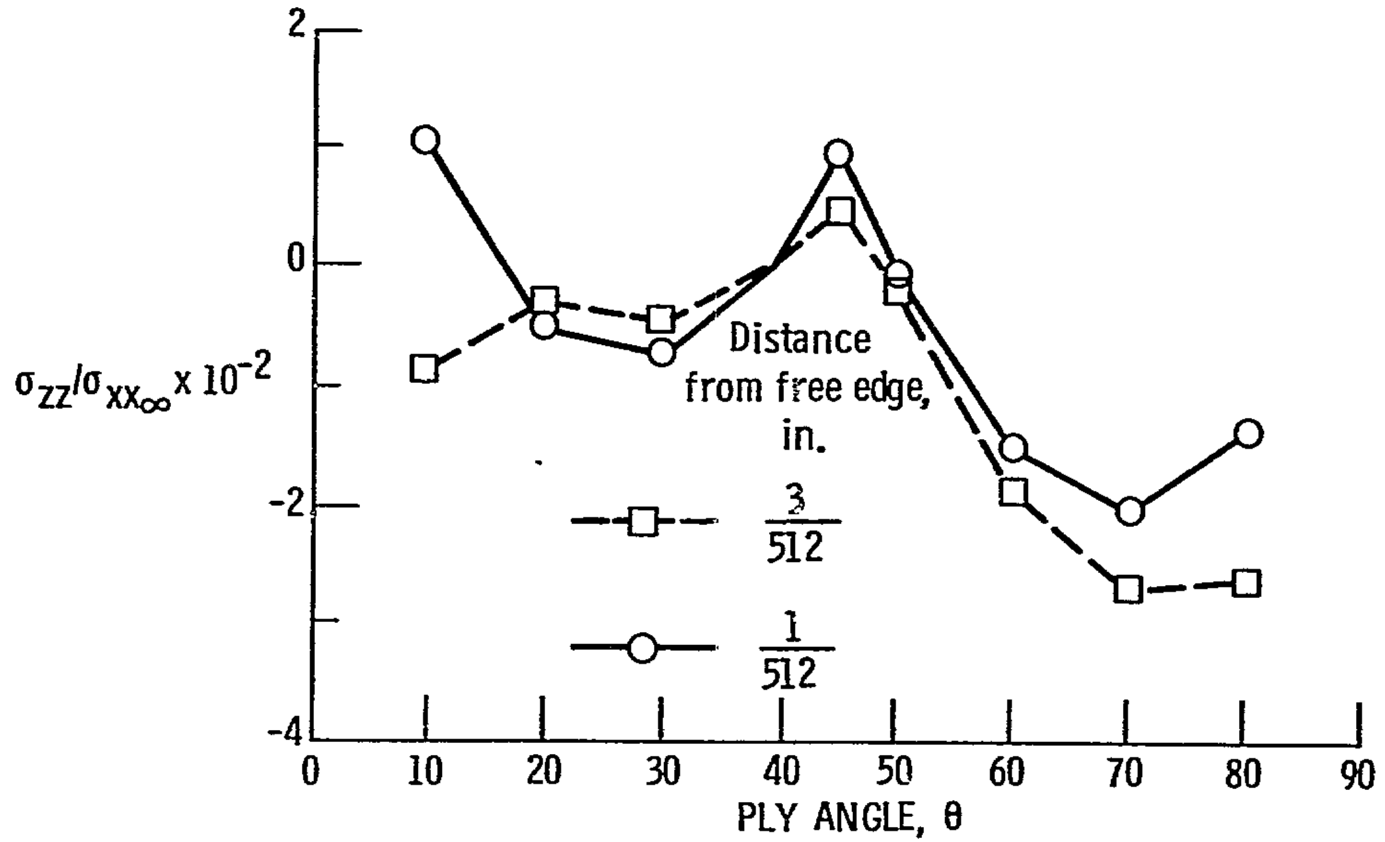

Figure 17. - Influence of ply angle on interply normal stress near free-edge region.

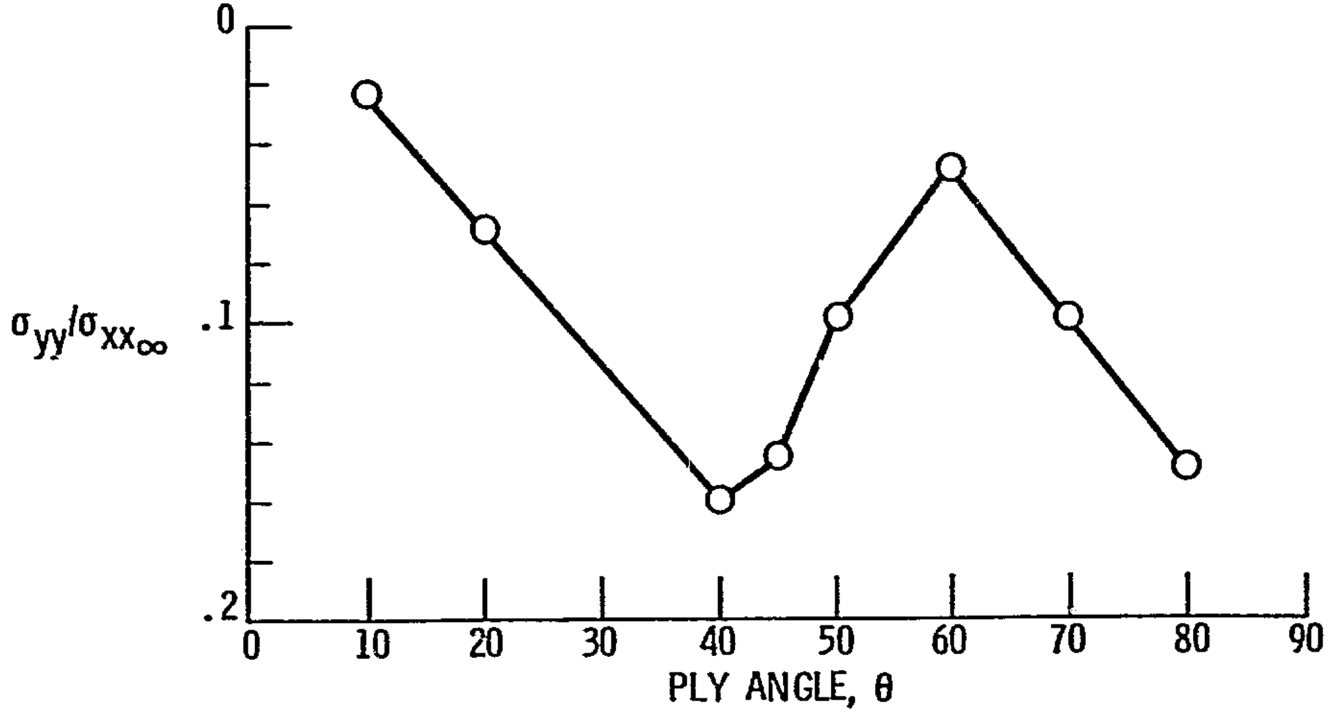

Figure 18. – Influence of ply angle on transverse normal stress (σ_{yy}) of interply layer.

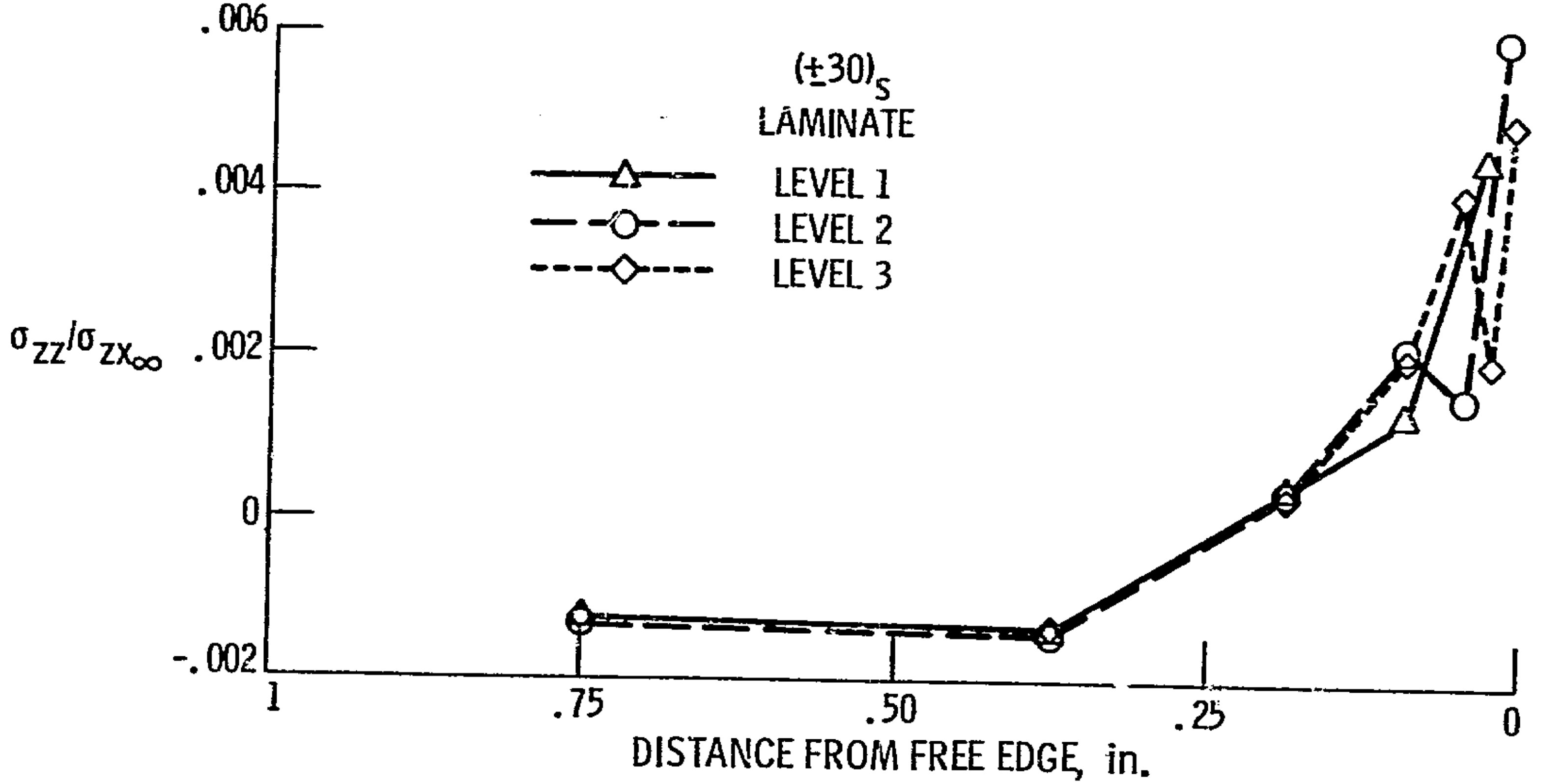

Figure 19. – Behavior of interlaminar normal stress σ_{zz} as free edge is approached in interply layer of $(\pm 30)_s$ laminate.

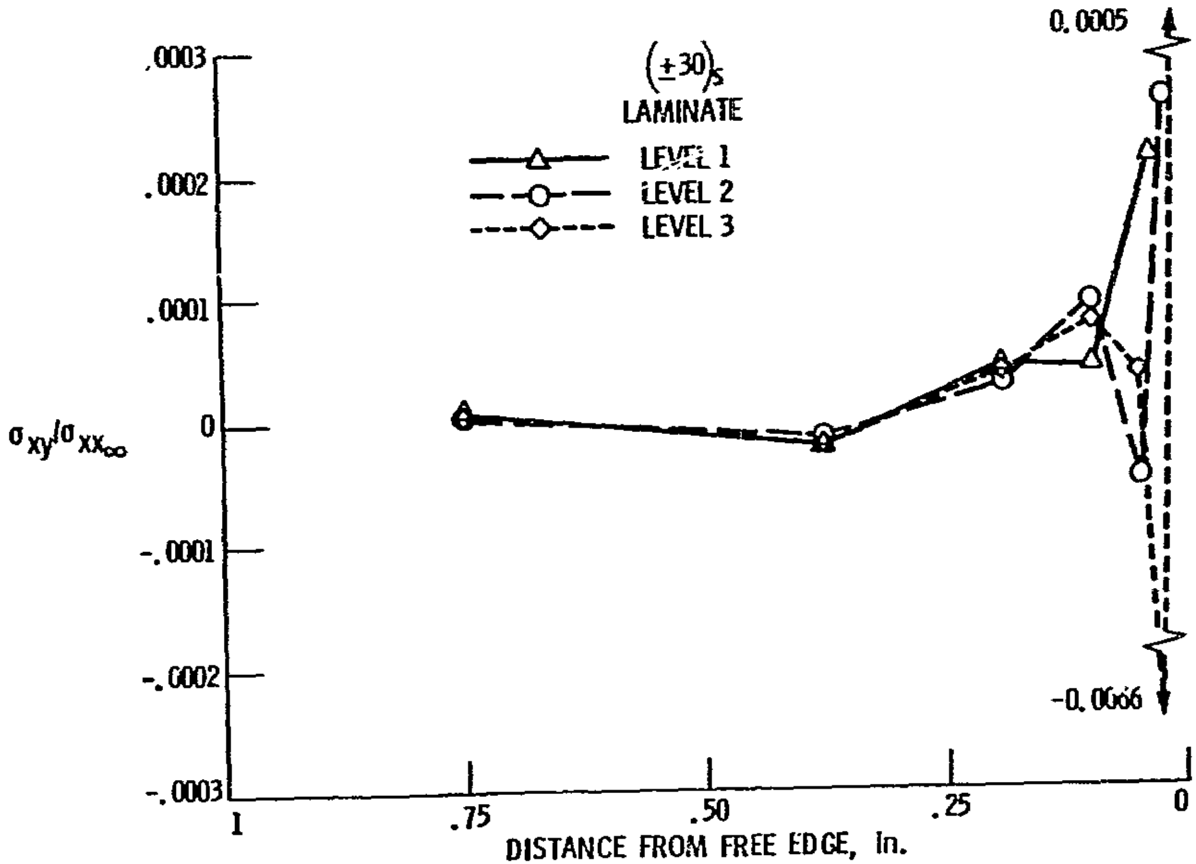

Figure 20. – Behavior of transverse shear stress σ_{zy} as free edge is approached in interply layer of $(\pm 30)_s$ laminate.

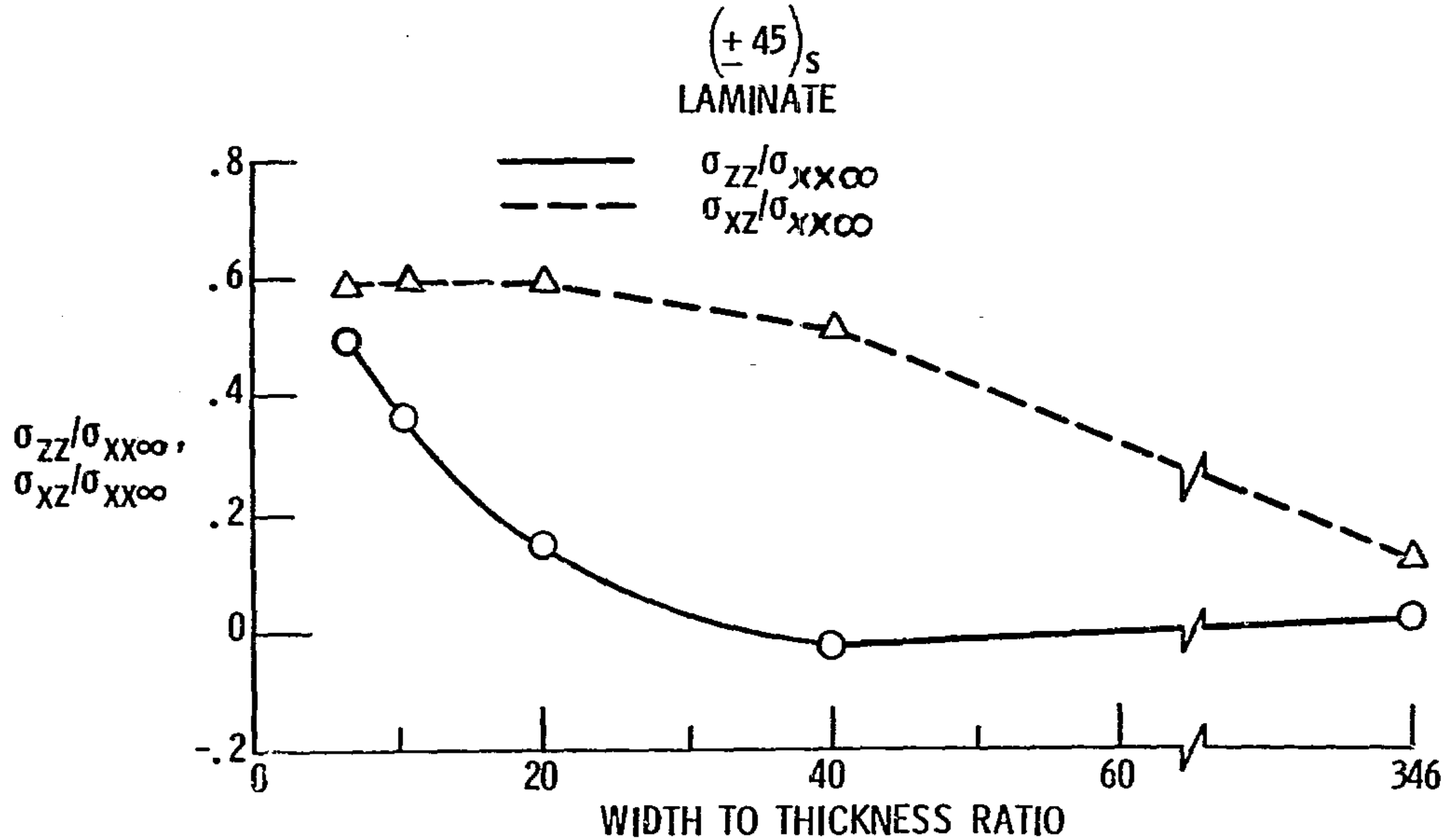

Figure 21. - Influence of width to thickness ratio on interlaminar normal and shear stress behavior at free edge in interply layer of $(\pm45)_s$ laminate.