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Designing for Fiber Composite Structural Durability in Hygrothermomechanical Environments

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DESIGNING FOR FIBER COMPOSITE STRUCTURAL DURABILITY IN HYGROTHERMOMECHANICAL ENVIRONMENTS

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ABSTRACT

An available methodology (developed at Lewis Research Center) is described which can be used to design/analyze fiber composite structures subjected to complex hygrothermomechanical environments. This methodology includes composite mechanics and advanced structural analysis methods (finite element). Select examples are described to illustrate the application of the available methodology. The examples include (1) composite progressive fracture, (2) composite design for high cycle fatigue combined with hot-wet conditions, and (3) general laminate design.

INTRODUCTION

A major concern in the fiber composite community has been the prediction, or even a reasonable approximation, of the structural durability of fiber composite structures in service environments. Service environments which fiber composite structures need to be designed to resist include: mechanical load (static, cyclic, impact), thermal, moisture, and combinations or hygrothermomechanical (HTM). The general procedure for designing fiber composites for HTM environments is to use empirical data to select laminate configurations for the component and validate them through the preliminary design phase. Subsequently, a variety of tests are conducted in the specified HTM environments. The results of these tests are, then, used to reconfigure the laminates to meet the design requirements. This procedure, though robust (successful) is cumbersome because it is costly, time consuming, and needs to be repeated for each new design. This cumbersome procedure can be circumvented to a large extent by a methodology for predicting the structural durability and, therefore, service life of fiber composites in HTM environments. The objective of this proposed report is to describe a predictively correct methodology for the HTM effects on fiber composite stiffness and strength which thereby can be used to design fiber composite structural components for structural durability.

The methodology to be described evolved at NASA Lewis Research Center over the past seven years. It began with the development of an integrated theory for predicting the hygrothermal effects on fiber composites (fall 1977) and has culminated into three major computer programs: (1) CODSTRAN (Composite Durability Structural Analysis), (2) INHYD (Intraply Hybrid-Composite Design), and (3) ICAN (Integrated Composite Analyzer). These programs collectively provide analyses required to design for structural durability.

In this report, first the fundamental aspects comprising the methodology are briefly summarized. These fundamental aspects include: (1) hypotheses for HTM effects, (2) functional relationships for HTM behavior, and (3) possible generalizations. Second, the incorporation of these fundamental aspects into the computer programs CODSTRAN, INHYD, and ICAN are summarized. This has been mainly accomplished by developing the upward integrated top-down traced methodology structure. Third, the application of this methodology to predict the structural durability of select fiber composite structural components is presented. Typical results are shown and discussed to illustrate the effectiveness of the methodology.

HYGROTHERMOMECHANICAL THEORY

There are two fundamental concepts, which underlie the hygrothermomechanical (HTM) theory developed at Lewis Research Center. These are (1) the hygrothermal (hot-wet) environment degrades <u>only</u> the resin matrix properties, and (2) the degraded resin matrix properties contribution to the corresponding laminate (composite) properties degradation can be accurately predicted (within acceptable engineering accuracy) by using composite mechanics. Composite mechanics as used herein includes composite micromechanics, composite macromechanics, combined stress failure criteria, and laminate theory. The hygrothermal environment degradation on resin properties is predicted by empirical equations of simple form.

The various assumptions, justifications, and correlations with measured data are described in the original papers (1,2). Here, we briefly summarize these equations in order to: (1) identify the significant variables which contribute to the matrix property degradation, and (2) expedite the description on how this property degradation effects composite properties, composite structural response, and composite structural design. A similar but more detailed discussion is given in Ref. (3). Step-by-step procedures for using these equations are described in Refs. (4) and (5).

The empirical equation for predicting the hygrothermal degradation effects on resin matrix mechanical properties is given by

$$\frac{P_{MD}}{P_{MO}} = \left[\frac{T_{GW} - T}{T_{GD} - T_0}\right]^{1/2} \tag{1}$$

where P_{MD} is the degraded mechanical property (modulus or strength), P_{MO} is the same property at reference conditions (normally room temperature dry), T_{GW} is the glass transition temperature of the wet resin, T is the use temperature at which P_{MD} is desired, T_{GD} is the glass transition temperature of the dry resin and T_0 is the reference temperature (normally room temperature) at which P_{MO} was determined. In Eq. (1) the degraded property is expressed as a ratio of known or determined temperature differences. The glass transition temperature of the dry resin is normally supplied by the material supplier while T_{GW} is either determined by measurement or predicted using the empirical equation (4,5).

$$T_{QW} = (0.005\ M^2 - 0.1\ M + 1)\ T_{GD} \qquad (M \leq 10 \text{ percent}) \tag{2}$$

where M is the weight percent moisture in the resin.

It is seen from Eqs. (1) and (2) that the use temperature (T) and the moisture pickup M are the two important environmental variables for the design. The resin matrix material characteristic is T_{GD}. A matrix with high T_{GD} will yield a composite with greater resistance to hygrothermal degradation as is expected.

APPLICATION OF HYGROTHERMOMECHANICAL THEORY

Static Load

The procedure for applying the HTM theory for design/analysis of statically loaded structures is accomplished by using the following steps: (1) select a laminate configuration (number of plies and orientation); (2) predict the hygrothermal degradation effects of the resin matrix using Eqs. (1) and (2); (3) predict the unidirectional composite (ply) properties using composite micromechanics with the specified fiber and the degraded matrix properties from step 2; (4) transform the ply unidirectional properties from step 3 along the composite structural axes using composite macromechanics; (5) predict the ply uniaxial strengths using combined strength failure criteria; (6) predict composite properties using laminate theory; (7) predict composite structural properties using structural mechanics; (8) model composite structural part; (9) predict the structural response and compare with structural response design allowables (displacements, frequencies, buckling loads, other); (10) predict ply stresses and interply delamination using laminate theory, apply ply combined strength criteria using predicted ply stresses and ply strength allowables, and compare margins; (11) three alternatives are possible: (i) steps 9 and 10 satisfied with acceptable margins - satisfactory design, stop, (ii) steps 9 and 10 satisfied with large positive margins - laminate is over-designed decrease number of plies and repeat steps 2 to 11, (iii) steps 9 or 10 not satisfied (negative margins) - increase number of plies and repeat steps 2 to 11.

The procedure is illustrated schematically in Fig. 1. It is best performed by computerized capabilities which couple composite mechanics (6) with a general purpose finite element code (7) as described in Ref. (8).

Cyclic Load

For the case of cyclic load (fatigue), the ply uniaxial strengths predicted in step 5 above are modified according to the equation

$$\frac{S_{\ell N}}{S_{\ell}} = 1.0 - B \text{ Log } N \tag{3}$$

where $S_{\ell N}$ is the ply cyclic uniaxial strength which survives N cycles, S_{ℓ} is the uniaxial strength predicted in step 5 which includes the hygrothermal degradation, and B is an empirical constant with the following values (9): 0.02 for graphite-fiber/epoxy-matrix composites, 0.05 for Kevlar-fiber/epoxy-matrix composites, and 0.15 for glass-fiber/epoxy matrix composites. The values of $S_{\ell n}$ predicted from Eq. (3) are used in step 10 to predict the ply combined strengths margins. All other steps remain the same.

Combined Static and Cyclic Loads

The ply uniaxial strengths and the predicted ply stresses for this combined load case are determined from the following equation:

$$\left(\frac{\sigma_{\ell}}{S_{\ell}}\right) = \left(\frac{\sigma_{\ell st}}{S_{\ell}} + \frac{\sigma_{\ell cyc}}{S_{\ell N}}\right) \tag{4}$$

where $\sigma_{\ell st}$ is the static load ply stress and $\sigma_{\ell cyc}$ is the cyclic load ply stress prior to substitution in the combined strength failure criteria step 10 above. All other steps remain the same. Application of this approach is described in detail in Ref. (10).

PLY STRESS INFLUENCE COEFFICIENTS

The ply stress influence coefficients provide a direct means for sizing laminates, for determining ply stresses due to combined load and for assessing laminate behavior in general. Explicit equations are available (11) for ply stress influence coefficients for the case of predominant in-plane loads. These equations are as follows (refer to Fig. 2 for notation):

Ply longitudinal stress ($\sigma_{\ell 11}$)

$$\sigma_{\ell 11} = \left(\frac{E_{\ell 11}}{E_{cxx}}\right)\left(\cos^2\theta - \nu_{cxy}\sin^2\theta\right)\sigma_{cxx} + \left(\frac{E_{\ell 11}}{E_{cyy}}\right)\left(\sin^2\theta - \nu_{cxy}\cos^2\theta\right)\sigma_{cyy}$$

$$+ \frac{E_{\ell 11}}{2G_{cxy}}\left[\left(1 - \nu_{\ell 21}\right)\sin 2\theta\right]\sigma_{cxy} \tag{5}$$

Ply transverse stress ($\sigma_{\ell 22}$)

$$\sigma_{\ell 22} = \left(\frac{E_{\ell 22}}{E_{cxx}}\right)\left[\left(\nu_{\ell 12} - \nu_{cxy}\right)\cos^2\theta + \left(1 - \nu_{cxy}\nu_{\ell 12}\right)\sin^2\theta\right]\sigma_{cxx}$$

$$+ \left(\frac{E_{\ell 22}}{E_{cyy}}\right)\left[\left(1 - \nu_{cxy}\nu_{\ell 12}\right)\cos^2\theta + \left(\nu_{\ell 12} - \nu_{cxy}\right)\sin^2\theta\right]\sigma_{cyy}$$

$$- \left(\frac{E_{\ell 22}}{2G_{cxy}}\right)\left[\left(1 - \nu_{\ell 12}\right)\sin 2\theta\right]\sigma_{cxy} \tag{6}$$

Ply intralaminar shear stress ($\sigma_{\ell 12}$)

$$\sigma_{\ell 12} = -\left(\frac{G_{\ell 12}}{E_{cxx}}\right)\left[\left(1 + \nu_{cxy}\right)\sin 2\theta\right]\sigma_{cxx}$$

$$+ \left(\frac{G_{\ell 12}}{E_{cyy}}\right)\left[\left(1 + \nu_{cxy}\right)\sin 2\theta\right]\sigma_{cyy} + \left(\frac{G_{\ell 12}}{G_{cxy}}\right)\left(\cos 2\theta\right)\sigma_{cxy} \tag{7}$$

The generic notation in Eqs. (5) to (7) is as follows: σ is the stress, E and G are moduli, ν is the Poisson's ratio, θ is the ply orientation angle. The numerical subscripts and ℓ refer to ply properties along its material axes (1, 2, 3, Fig. 2). The lettered subscripts and c refer to composite or laminate properties (x, y, z, Fig. 2).

Several significant observations can be made about composite behavior by examining Eqs. (5) to (7). For example:

(1) The ply longitudinal stress ($\sigma_{\ell 11}$) Eq. (5), will increase in combined load cases where the composite properties (E_c, G_c, ν_c) degrade at a faster rate than $E_{\ell 11}$. This is a very good composite self-adjusting behavior since stress is transferred from a weaker to a stronger material.

(2) The ply transverse and intralaminar shear stresses ($\sigma_{\ell 22}$, Eq. (6), and $\sigma_{\ell 12}$, Eq. (7)) decrease in combined load cases where the matrix dominated properties (E_{ℓ} and G_{ℓ}) degrade at a faster rate than the composite properties (E_c, G_c, ν_c). This also is a self-adjusting beneficial behavior since the degraded material can sustain lower stresses. It is both of these observations that provide fiber composites with the desirable characteristics such as: notch insensitivity, good fatigue resistance, high damping, and good resistance to hygrothermal environments for properly designed laminates. The reader can make additional observations by studying Eqs. (5), (6), and/or (7).

SELECT APPLICATIONS

Select, but representative, applications of composite analysis/design are described to illustrate what can be done with this available methodology.

Composite Progressive Fracture

One of the most interesting aspects of composite analysis/design is to be able to predict defect growth and fracture. At Lewis Research Center, this is done using an integrated computer program CODSTRAN (Composite Durability Structural Analysis, (8)). The types of loadings that can be analyzed/designed are depicted schematically in Fig. 3. Typical results obtained and comparisons with measured data are summarized in Fig. 4. The significant conclusion is that this complex composite fracture behavior is effectively modeled by using CODSTRAN.

Composite Fan Exit Guide Vanes (FEGV)

These types of structures are mainly designed to resist high cycle fatigue (12). A schematic of a typical FEGV is shown in Fig. 5. Design criteria for different materials, different design concepts, and different hygrothermal environmental conditions are summarized in Fig. 6. The significant conclusion is that composite structural components can be designed to successfully resist complex hygrothermomechanical loadings (hot, wet, high-cycle fatigue).

Composite Windmill Blades

Composite windmill blades (Fig. 7) made using transverse filament tape is an effective use of glass-fiber/epoxy composite. These types of blades are mainly designed to survive 30 yr of service at very high cyclic fatigue. Several laminate configurations have been investigated and their high cycle fatigue life successfully predicted using the HTM theory described previously (13). Typical predicted results and comparisons with measured data are shown in Fig. 8. The significant conclusion is that the high cycle fatigue of fiber composites in different environments can be predicted by the available methodology.

Composites Laminates in General

All of the previous three examples are designed/analyzed at the laminate level. Laminate analysis/design is generic to all composite structural analysis/design. This can be performed most effectively using computerized capabilities (6) as previously mentioned. It can also be performed using step-by-step procedures described in Ref. (14). The results of designing a laminate subjected to combined loads (Fig. 9) are summarized in Tables I and II illustrate that fiber composite laminates can be designed to resist combined loads and meet practical, diverse design requirements.

CONCLUSIONS

The methodology is available for the design/analysis of fiber composite structures subject to complex hygrothermomechanical environments. This methodology is most effectively used in computer code form; however, step-by-step procedures can also be used. The step-by-step procedures have the added advantage of providing instantaneous feedback of the design procedures. The methodology has evolved to the extent that (1) composite progressive fracture can be predicted, (2) composite structural parts can be designed for high cycle fatigue combined with hot-wet conditions, and (3) general laminates can be designed to meet a variety of combined loads and design requirements. Confidence in fiber composite design/analysis is progressively improving as more field data are accumulated and as more knowledge in composite behavior is gained by using the design/analysis procedures as described herein.

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TABLE I. - DESIGN RESULTS SUMMARY

[Laminate Configuration: $[\pm 45/0/90/0]_{2S}$ AS/E; t_c = 0.10 in.]

Margins of Safety (M.O.S.) for:									
Displacement		Ply stresses				Buckling			
Type	M.O.S.	Ply	M.O.S.			Case, ksi			M.O.S.
			$\sigma_{\ell 11}$	$\sigma_{\ell 22}$	$\sigma_{\ell 12}$	σ_{cxx}	σ_{cyy}	σ_{cxy}	
u/a	0.43	---							-----
v/b	1.94	0	2.77	0.61	1.30	0	0	20	-0.74
Δθ	.33	+45	0.7[illegible]	∞	∞	40	20	20	3.35
	----	-45	4.43	[a].27	∞	----	----	----	-----
	----	90	6.00	.12	1.30	----	----	----	-----

[a]At specified load (at design load M.S. = 0.38).

TABLE II. - SUMMARY OF PLY STRESS ANALYSIS FOR COMBINED LOAD, ($[\pm 45/0/90/0]_{2S}$ AS/E ANGLEPLIED LAMINATE)

Load condition /strength /M.O.S	Ply/ply-stress/strength (ksi), MOS-ratio											
	0°-Ply			+45°-Ply			-45°-Ply			90°-Ply		
	$\sigma_{\ell 11}$	$\sigma_{\ell 22}$	$\sigma_{\ell 12}$	$\sigma_{\ell 11}$	$\sigma_{\ell 22}$	$\sigma_{\ell 12}$	$\sigma_{\ell 11}$	$\sigma_{\ell 22}$	$\sigma_{\ell 12}$	$\sigma_{\ell 11}$	$\sigma_{\ell 22}$	$\sigma_{\ell 12}$
N_{cxx}	77.1	-.7	0	25.8	3.5	-2.8	25.8	3.5	2.8	-25.4	7.6	0
N_{cyy}	-18.1	5.6	0	19.1	2.6	2.0	19.1	2.6	-2.0	56.9	-0.5	0
N_{cxy}	0	0	4.3	78.0	-6.5	0	-78.0	6.5	0	0	0	-4.3
SUM	58.3	5.0	4.3	122.9	-0.5	-0.7	-33.0	12.6	.8	31.5	7.1	-4.3
S_ℓ	220.0	8.0	10.0	220.0	8.0	-10.0	-180.0	8.0	10	220.0	8.0	-10.0
M.O.S	2.77	0.61	1.30	0.79	∞	∞	4.43	[a]-0.36	∞	6.00	0.12	1.30

[a]At specified load this is +0.27.

Notation:
- N_c panel in-plane loads
- S_ℓ ply strength
- σ_ℓ ply stress
- M.O.S margin of safety

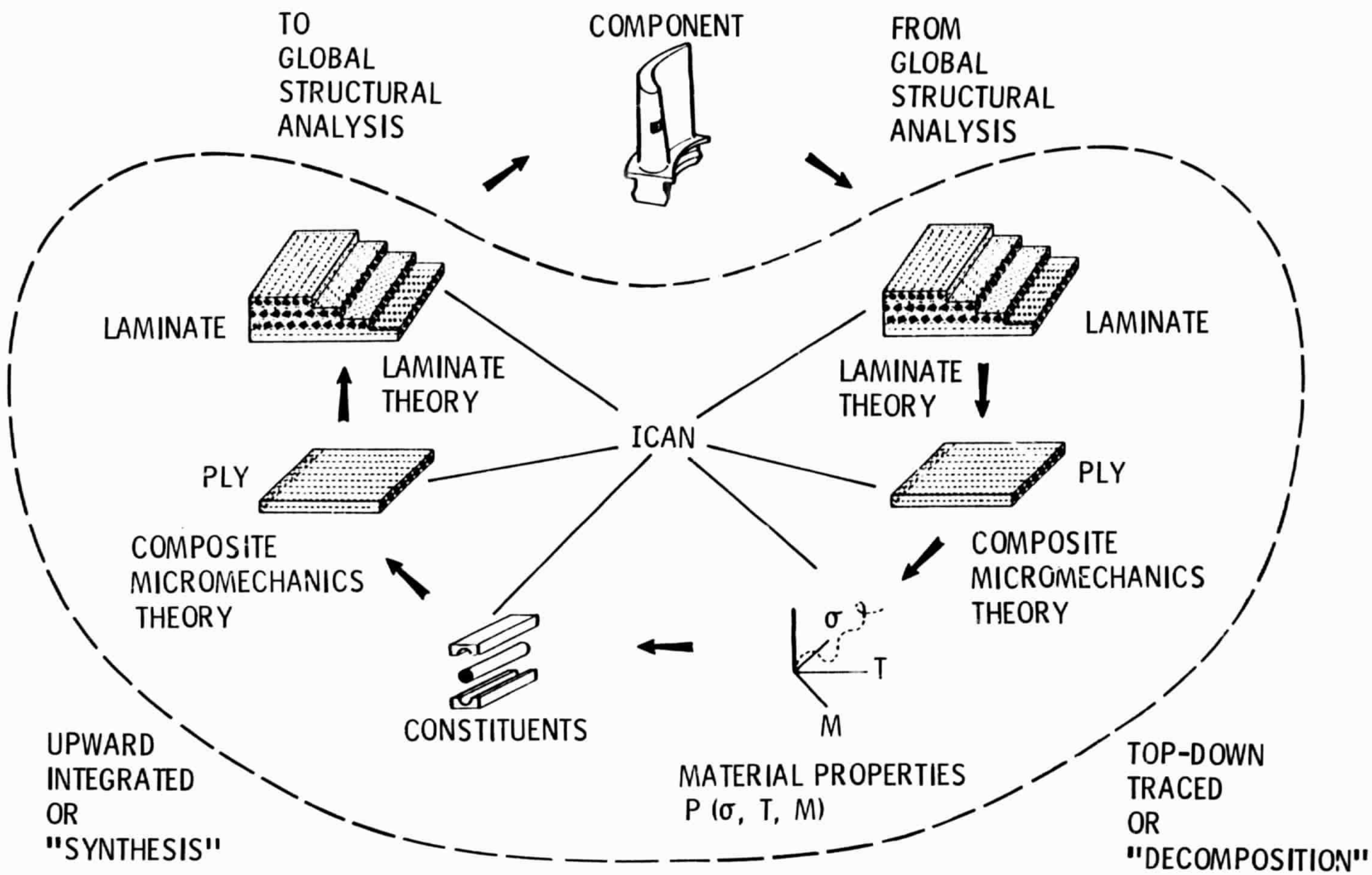
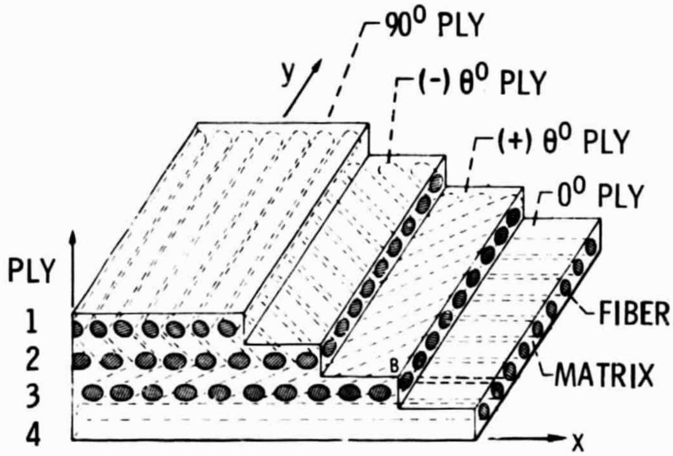
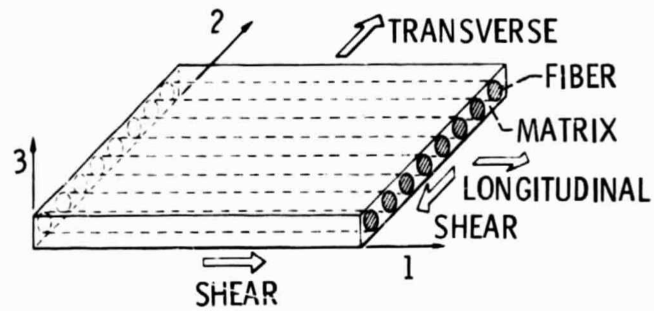


Figure 1. - ICAN: Integrated composites analyzer.



(a) Angleplied laminate.



(b) Ply.

Figure 2. - Typical fiber composite geometry.

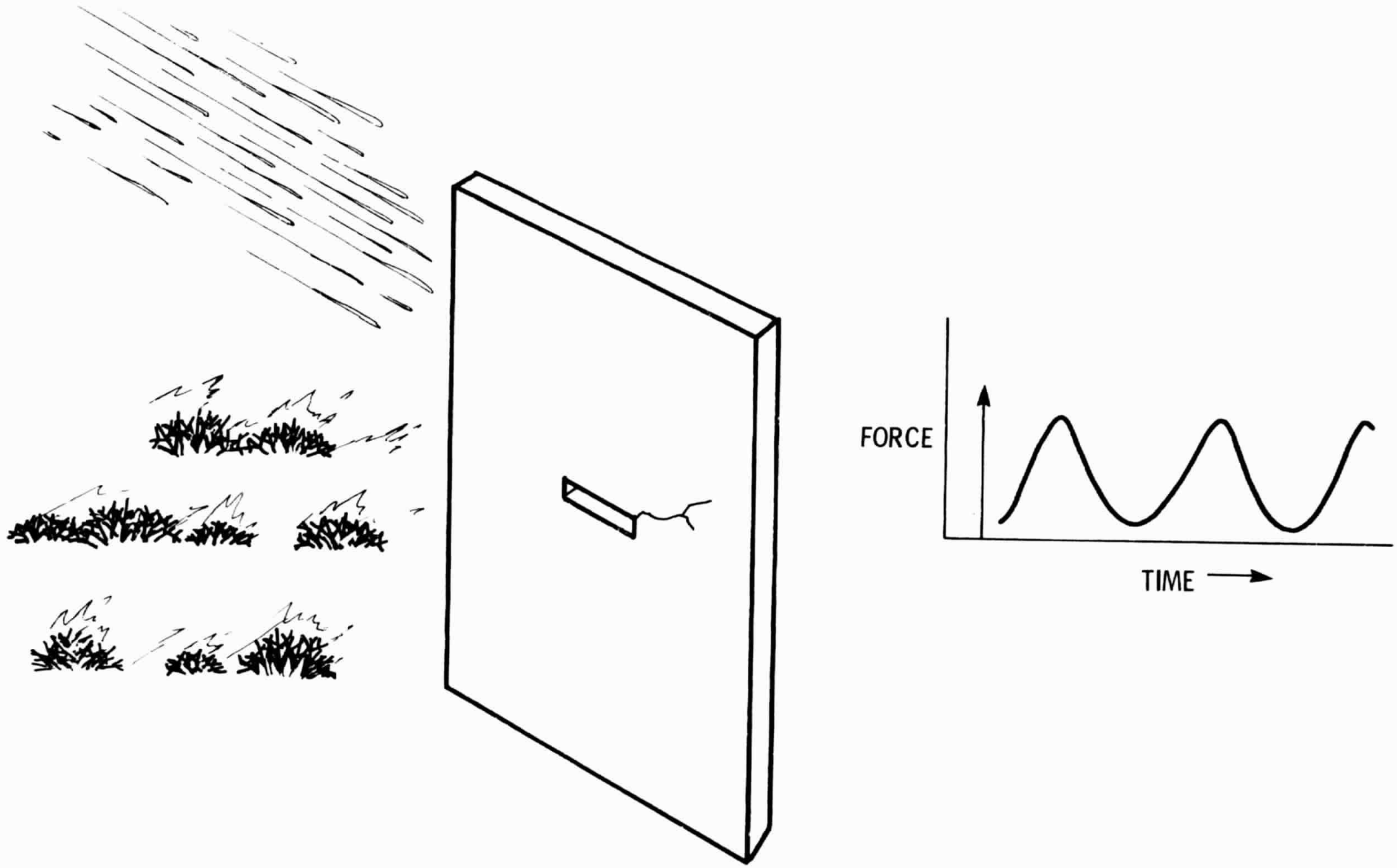


Figure 3. - Environmental effects on defect growth in composite materials.

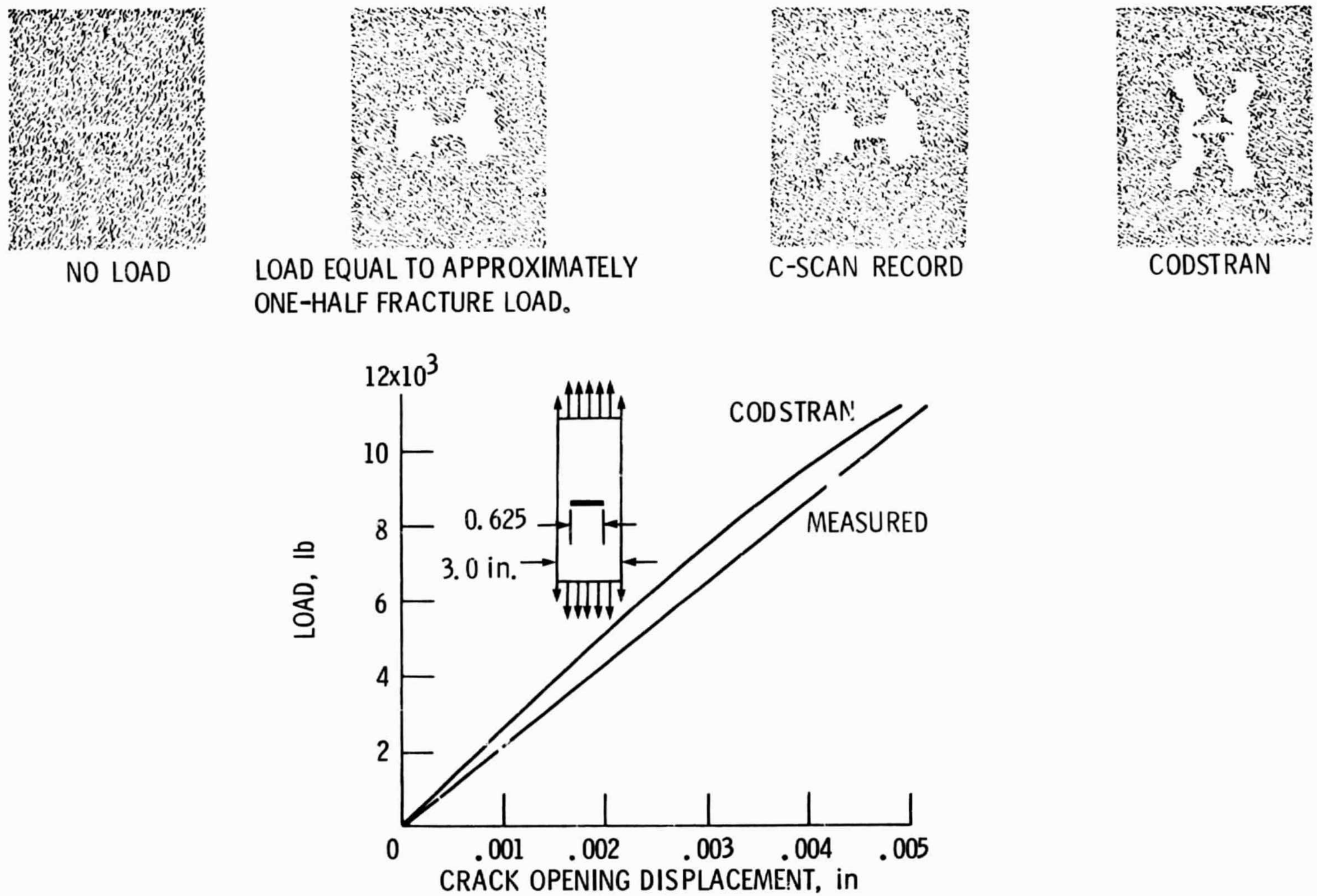


Figure 4. - Composite progressive fracture - CODSTRAN-predicted results compared with experimental data. (Crack opening displacement measured between A and B.)

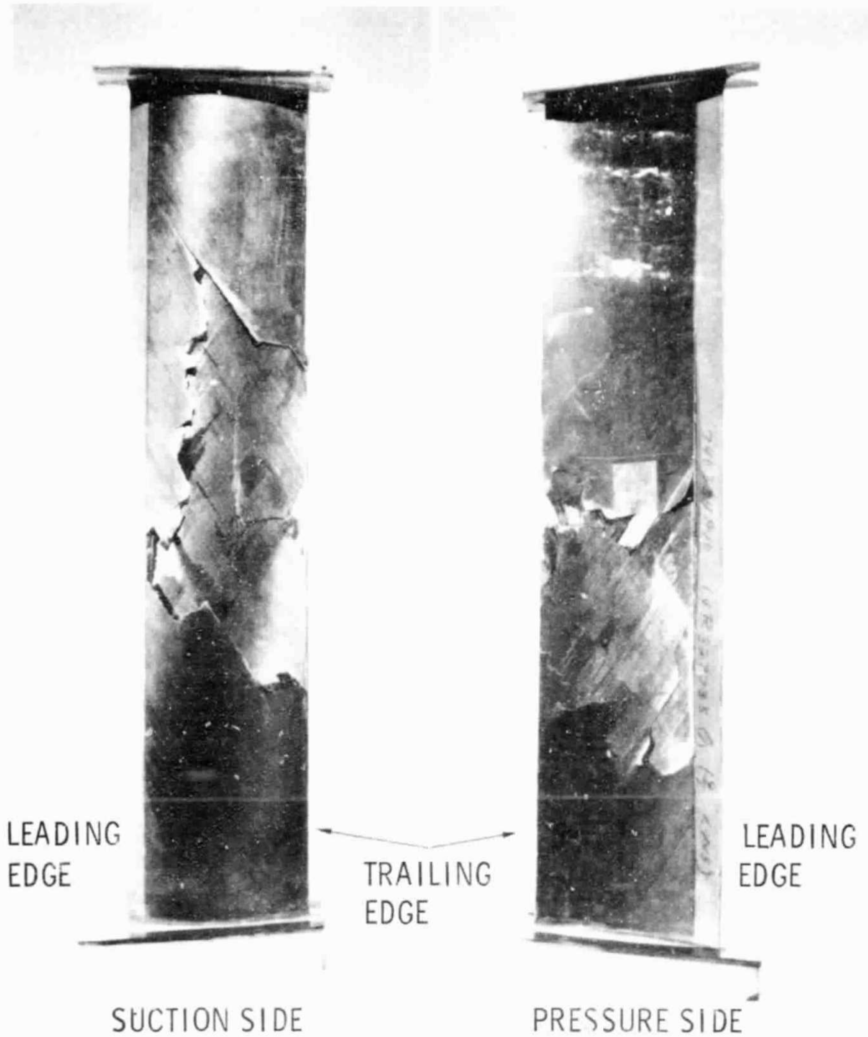


Figure 5. - Composite fan exit guide vanes.

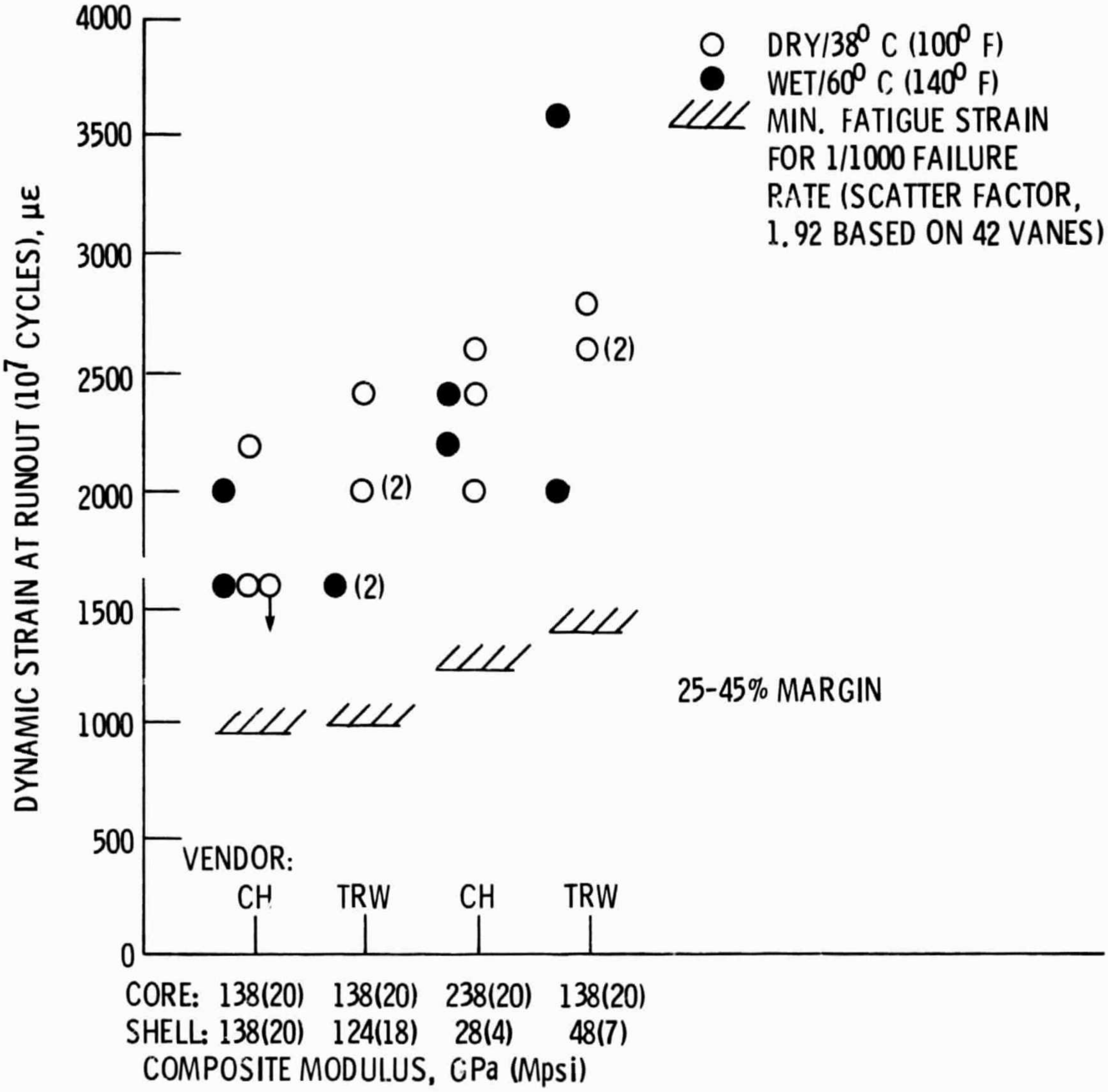


Figure 6. - Strain allowables for hygrothermomechanical designs of fan exit guide vanes with core/shell configuration.

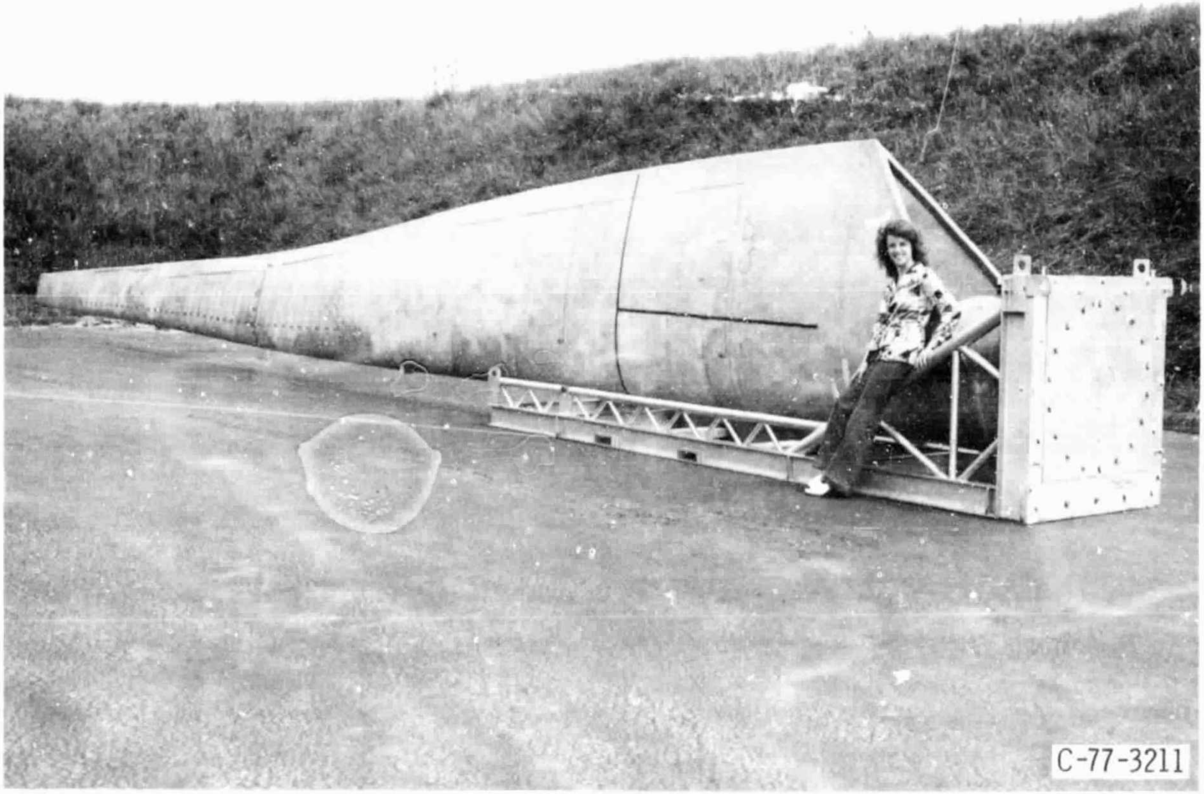


Figure 7. - Composite windmill blade.

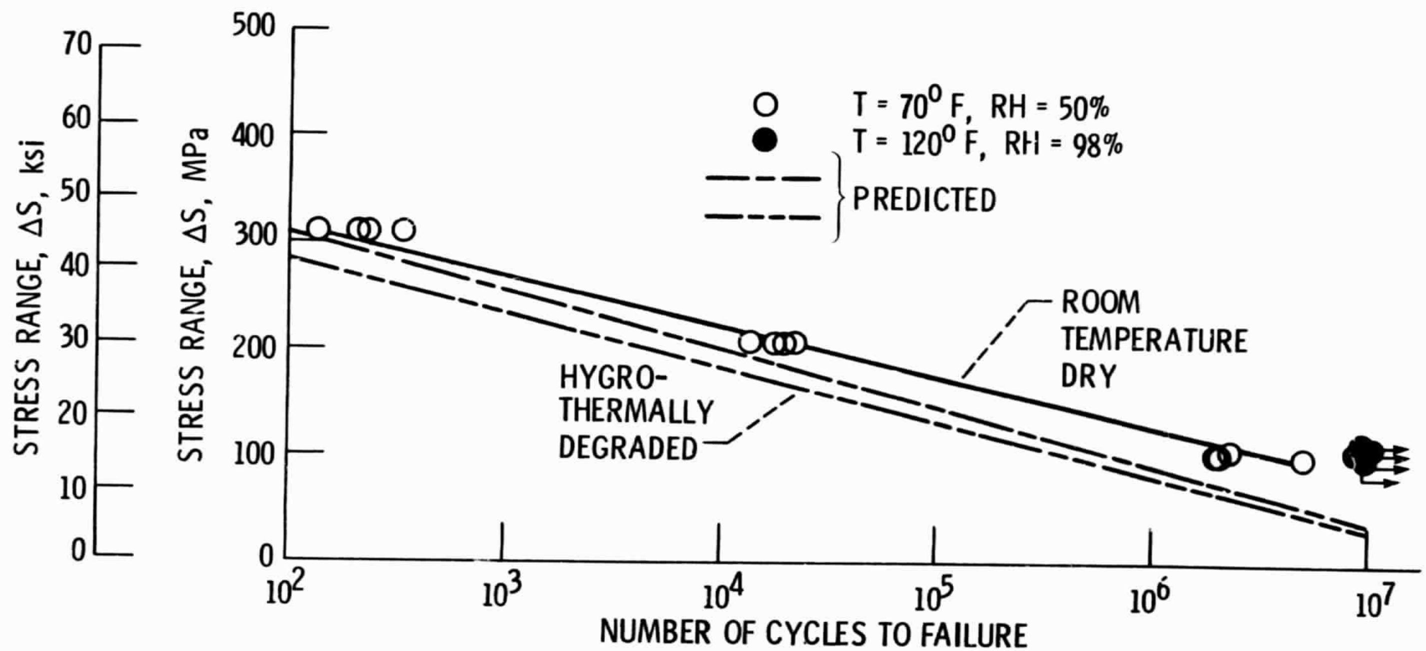


Figure 8. - Comparison of S-N fatigue life diagrams - winding pattern of two TFT/epoxy composites (R = 0).

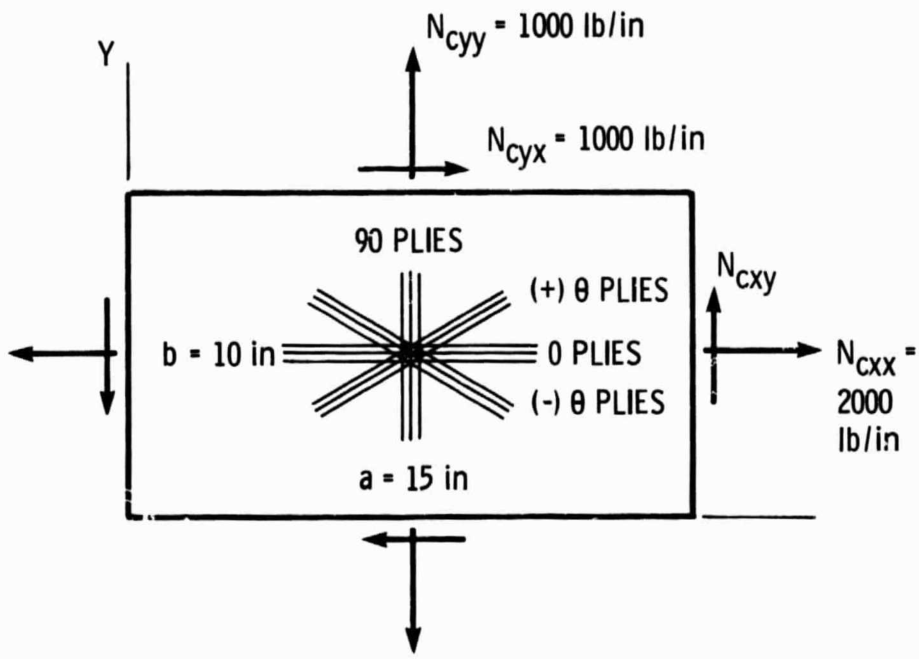


Figure 9. - Composite panel subjected to in-plane combined loads with the following design requirements: displacement limits, 0.5% times a or b; shearing angle 1°; safety factor, 2.0 on specified load (load factor); composite system, AS/E, about 0.6 FVR.

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