Moisture and Temperature Effects on the Instability of Cylindrical Composite Panels

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An analytical investigation was performed to evaluate the stability characteristics of cylindrical, composite panels subject to axial loading. These composite panels were eight-ply graphite/epoxy (AS/3501-5) laminates. The three laminate ply orientations considered were $[0, +45, -45, 90]_s$ $[90, +45, -45, 0]_s$, and $[45, -45]_{2s}$. The analysis evaluated the influence of several different panel radii, two sets of panel boundary conditions, and three sets of moisture conditions. The influences of moisture and temperature were investigated by degrading the transverse elastic modulus E_2 and the shear modulus G_{12}, based upon test data for the AS/3501-5 system. Each ply orientation was evaluated at 20 time/temperature conditions that ranged from 80 to 300°F, and moisture concentrations ranging from a zero moisture content to an equilibrium moisture distribution. The bifurcation loads were determined using the STAGS-C1 finite element analysis program. The bifurcation analysis mode, with a prebuckled linear displacement option, was used for this analysis. Moisture and temperature were found to cause a reduction in the panel's bifurcation load ranging from 21.3% for the $[0, +45, -45, 90]_s$ laminate to 42.7% for the $[+45, -45]_{2s}$ laminate.

Introduction

THE use of polymer matrix composites in aircraft structural applications requires a careful evaluation of the effects of environmental exposure on the material properties. The influences of the common environmental mechanisms of moisture and temperature have been found to significantly degrade the matrix-dominated mechanical properties. In order to evaluate the influence of moisture and temperature upon the stability characteristics of composite panels, an analytical investigation was performed. A square, cylindrical panel was chosen for this analysis. Such a panel is representative of skin panels found in a fuselage or wing. The panel was loaded in axial compression. The variation of the panel's bifurcation load, due to degradations in certain elastic moduli, was evaluated using the STAGS-C1 finite element shell analysis program. The AS/3501-5 graphite/epoxy composite system was used in this analysis.

Moisture and Temperature Effects on Composites

While composites have many superior properties compared to metals, the commonly used epoxy composite systems are significantly affected by environmental exposure to an agent such as water, which is absorbed by the polymer resin, and to thermal conditions which are near or exceed the polymer's glass transition temperature. The fibers, which are typically graphite or boron, are not affected by either water or the moderate temperatures encountered during normal aircraft service. Thus only the resin-dominated material properties are significantly affected.

Whitney and Ashton[1] reported that the environmental factors which influence the resin's properties were 1) increases in temperature, 2) resin absorption of a swelling agent such as water vapor, and 3) the sudden expansion of gases absorbed in the resin. It was noted that resin swelling alone, due to moisture and temperature effects, could cause a flat composite plate to buckle.

Temperature and moisture act on the polymeric resin to cause dimensional changes and variations in the mechanical properties. Increasing temperatures and absorbed water vapor cause the resin to swell. This water-induced swelling is believed to be due to the water molecules bonding to the hydroxyl groups in the epoxy polymers.[2] Matrix swelling and rapid heating may lead to surface crazing and surface cracking which will affect the resin's mechanical properties.[3,4]

Temperature and moisture also act together to cause reductions in the temperature range over which the resin's mechanical properties are fairly stable. Epoxy resins have a temperature range below which the resin is essentially brittle and above which the resin behaves rubbery. Usually, this temperature range is fairly narrow and the midvalue of this range is referred to as the resin's glass transition temperature, T_g. As increasing concentrations of moisture are absorbed in the resin, the T_g is continually lowered until moisture equilibrium is reached. Once equilibrium is reached, the T_g remains constant. The means by which moisture causes this change in the T_g is discussed in Ref. 5.

These physical changes in the resin have been found to result in decreases in the tensile properties[6] and reductions in the transverse and shear modulus[4,7,8] of the composite. A slight increase in the longitudinal elastic modulus was reported in Ref. 4. As noted in Ref. 3, these changes in the composite's mechanical properties may be grouped into two general classifications: 1) those changes due to moisture-induced plasticization which reduce the temperature range over which the material properties are relatively stable, and 2) those losses due to mechanical damage from moisture-induced swelling and rapid heating which affect the mechanical properties below the T_g.

Prediction of Absorbed Moisture

The absorption of water vapor into the resin is through diffusion. Fick's second law of diffusion[9] has shown good correlation with test data[4] at predicting the rate of moisture weight gain in a polymeric resin and in the composite. Fick developed this equation in 1855 by drawing an analogy between heat conduction in a solid and diffusion through a

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solid. The Fick equation is

$$\frac{\partial C}{\partial t}=K\frac{\partial^2 C}{\partial Z^2}$$

where C is the concentration of moisture through the thickness of the laminate as a function of time and distance through the thickness, Z the space coordinate measured normal to the surface, K the diffusion constant, and t the time. C is expressed as a ratio of the gain in the weight of the laminate due to the absorption of moisture divided by the original weight of the laminate.

The solution of this partial differential equation with boundary and initial conditions pertinent to the problem is shown below. This series solution in a slightly different form is found in Sec. 4.3.3 of Ref. 9.

$$C(Z,t)=C_1+(C_2-C_1)\frac{Z}{h}+\frac{2}{\pi}\sum_{n=1}^{\infty}\frac{C_2\cos n\pi-C_1}{n}\sin\frac{n\pi Z}{h}$$
$$\times\exp\left[\frac{-Kn^2\pi^2 t}{h^2}\right]+\frac{4C_0}{\pi}\sum_{m=0}^{\infty}\frac{1}{2m+1}\sin\frac{(2m+1)\pi Z}{h}$$
$$\times\exp\left[\frac{-K(2m+1)^2\pi^2 t}{h^2}\right] \tag{1}$$

where C is as previously defined, C_0 the initial, uniform moisture concentration through the thickness of the laminate, C_1 and C_2 the moisture concentration boundary conditions at the surface of the laminate, and h the thickness of the laminate.

Using this series solution with a known diffusion constant and prescribed initial conditions, the moisture concentration distribution through the thickness can be determined. With the assumption that the effective moisture concentration of each ply can be approximated by the calculated moisture concentration at the middle of the ply, the reduced mechanical properties of each ply can be determined from appropriate test data.

This series solution is seen to represent the summation of a time-independent moisture distribution, represented by the first and second terms, and a transient moisture distribution that is a function of time, represented by the last two terms. The influence of the transient terms decreases with increasing time. The accuracy of this series approximation is dependent upon the number of terms used in the two summations. To insure an accurate solution to Eq. (1), the summations were carried out until there was no change in the value of the calculated solution to 14 significant digits of accuracy. As an example, for the value of T^* shown later in Table 3, the values of n and m for $T^*=0.001$ are 227 and 112, and for $T^*=0.5$, are 11 and 4, respectively.

There are limitations on the application of Fick's equation. The series solution was determined with the assumption that the moisture diffusion coefficient K is constant. K is actually a function of the temperature of the resin. However, since moisture diffusion is a relatively slow process, with many months or years required before the moisture concentration distribution through a typical laminate achieves equilibrium, the diffusion process, in simple cases, may be assumed to take place at a constant temperature. Bergmann and Nitsch[2] have noted that K also varies with the laminate's moisture concentration, generally increasing with increasing moisture concentration levels.

The accuracy of Fick's equation is also affected by rapid temperature changes. Rapid thermal heating of the laminate (perhaps due to flight at supersonic speeds), where the laminate is heated to temperatures near the material's T_g, has been found to increase the rate of moisture weight gain above that predicted by the Fick equation.[3,4,7,10] This increase is believed due to the development of surface crazing and cracking brought about by rapid heating and resin swelling.[4]

With the restrictions of no rapid heating and no surface crazing or cracking, and assuming that K is constant, Fick's equation has been generally accepted as a good initial approximation of the moisture concentration distribution for simple cases.[2,4,7,11,12]

AS/3501-5 Mechanical Properties

The STAGS-C1 shell analysis program requires, as input parameters, the composite's longitudinal modulus E_1, the transverse modulus E_2, the shear modulus G_{12}, and Poisson's ratio ν_{21}. Poisson's ratio ν_{12} relates the strain in direction 2 to the strain in direction 1 when stressed in direction 1. Experimentally measured data for a graphite/epoxy system, AS/3501-5, from Fig. 8.18 of Ref. 13, were used in the determination of the elastic moduli as a function of temperature and moisture concentration. The units of stress in GPa and temperature in degrees Kelvin are converted to psi and degrees Fahrenheit. The values of E_2 and G_{12} used in this work are shown in graphical form in Fig. 1.

The moisture and temperature influences on the transverse and shear moduli are clearly evident in the experimental data for AS/3501-5 shown in Fig. 1. The transverse modulus E_2 shows degradation both at room temperature and at elevated temperatures, while the shear modulus G_{12} only shows degradation at elevated temperatures. The moisture-caused change in the T_g and the resulting plasticization of the resin is shown by the increased degradation in the moduli with increasing moisture concentration at each elevated temperature. This is consistent with the previously noted expected changes in the elastic moduli. The longitudinal modulus E_1 is dominated by the fiber stiffness and, hence, is not significantly influenced by changes in moisture and temperature as are the matrix-dominated E_2 and G_{12} moduli.

The value of ν_{12} used in this analysis was taken from Table 1.9 of Ref. 13. The value of ν_{12} used is 0.30, which is a representative value for AS/3501-5 composites. Examination of the test data[4] upon which the material in Ref. 13 was based shows that ν_{12} does vary with temperature and moisture concentration. The range of variation was from 0.36 to 0.46. The sensitivity of the analytical results to this variation in ν_{12} was found to be very small.

Finite Element Bifurcation Analysis

The STAGS-C1 program has been specifically developed to perform a collapse analysis of general stiffened and unstiffened shells. The program has several operating modes. Among these are a linear or geometric nonlinear static analysis, a bifurcation analysis with a linear or nonlinear stress state, and a small vibration analysis with either a stress-free, linear, or nonlinear stress state. The program is capable of handling both isotropic or layered orthotropic materials. See Ref. 14 for a comprehensive review of the capabilities of this program and Ref. 15 for an explanation of the program's input parameters.

Limitations of Classical Laminated Plate Theory

The restrictions and assumptions of classical laminated, thin plate theory are stated in Ref. 17. The assumption that the transverse shear strains may be assumed to be zero results in the neglect of the transverse shear stresses. However, in addressing the problem of environmental degradation in composites, this assumption may not be valid. Flaggs and Vinson[18] have developed a general buckling theory for flat plates which accounts for the moisture and temperature effects and includes transverse shear, normal deformation, and bending-extension coupling. The flat plate finite elements currently available in the STAGS-C1 program do not include a transverse shear capability.

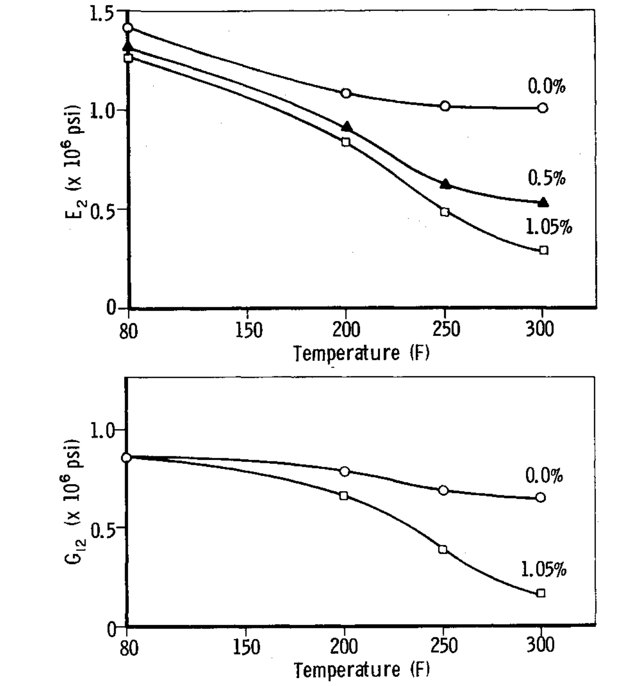

Fig. 1 E_2 and G_{12} degradation vs temperature at constant values of moisture concentration.

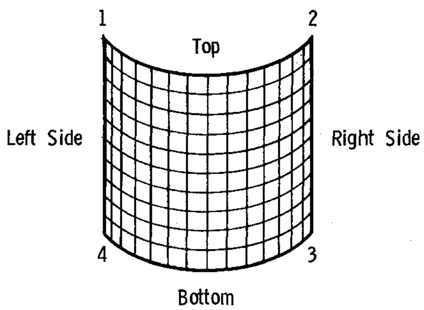

Fig. 2 Finite element model.

Because of the apparent need for a transverse shear-capable element to totally address the moisture and temperature effects, the study of these effects will be limited to the degradations in elastic moduli due to moisture and temperature. Dimensional changes due to resin swelling, either due to moisture absorption or temperature-induced expansion, will not be included.

Another restriction needed to use STAGS-C1 is that each layer's material properties are assumed to be constant across the layer's thickness and throughout that layer. In the calculation of the degraded moduli, each layer was assumed to have a uniform moisture concentration equal to the value calculated at the ply's midsurface. In the determination of the temperature degradation, the entire laminate was assumed to be at the specified temperature.

With these additional restrictions and assumptions, the STAGS-C1 program should adequately predict the panel's critical load. By limiting the problem to only changes in elastic moduli, the influence of these moduli degradations can be addressed separately. Also, the problem of modeling the laminated panel is simplified.

Finite Element Model

This paper will evaluate the stability of cylindrical, composite panels subject to axial compression. A typical composite fuselage skin panel with backup structure is used as the basis for the development of the finite element model shown in Fig. 2. The STAGS-C1 cylindrical shell geometry is shown in Fig. 3.

Table 1 Panel boundary conditions

	Fixed (first set)						Simple (second set)					
	U	*V*	*W*	*RU*	*RV*	*RW*	*U*	*V*	*W*	*RU*	*RV*	*RW*
Top	1	0	0	0	0	0	1	0	0	0	0	0
Right side	1	0	0	0	0	0	1	0	0	1	0	0
Bottom	0	0	0	0	0	0	0	0	0	0	0	0
Left side	1	0	0	0	0	0	1	0	0	1	0	0

The composite panel consists of eight plies. Each ply is assumed to be 0.05 in. thick with a laminate thickness of 0.40 in. Three ply orientations are evaluated to determine the influence of the ply stacking sequence on the stability behavior of the panel. These ply orientations are $[0, +45, -45, 90]_s$, $[90, +45, -45, 0]_s$ and $[+45, -45]_{2s}$. The relationship of these three orientations to the STAGS-C1 cylindrical panel coordinate system is shown in Fig. 4.

The panel is square, with the panel height and circumferential width being 12 in. Such a panel is defined as having an aspect ratio of 1. The finite elements also are square with an aspect ratio of 1. The aspect ratio is equal to the height divided by the circumferential width for both panels and elements. The elements are 0.857×0.857 in. in size. The finite element model of this panel has a mesh of 14×14 elements with a total of 196 elements and 225 nodes.

The SH410 finite element was used in this model. This element is a four-noded, flat quadrilateral element with 24 degrees of freedom, three translational and three rotational displacements at each node. References 16, 19, and 20 contain a more thorough discussion of the development and application of this element in the modeling of curved surfaces.

The boundary conditions used in the evaluation of the moisture and temperature effects were selected to represent those of a typical backup structure rather than the standard simple or fixed boundary conditions. Two sets of boundary conditions were chosen. The first set of conditions assumes that the backup structure's ring frames and longerons are effective in restraining out-of-plane deflections (W) and rotational movement (RU, RV, RW). The top frame and side longerons are assumed not to be effective in resisting the axial compressive load, but do resist in-plane displacements in the circumferential direction (V). The second set of boundary conditions is identical to the first, with the exception that the longerons are assumed to have no torsional stiffness and, hence, cannot resist a torsional rotation. In the first set, the longerons were assumed to be closed sections and, hence, effective in resisting torsion. In the second set, the longerons were assumed to be open sections which have little effective torsional resistance. The boundary conditions are summarized in Table 1, where 0 represents a fixed displacement and 1 represents a free displacement along the panel's edges.

The loads applied to the panel represent axial compression loading. This load is assumed to act uniformly across the top of the panel and is reacted across the bottom of the panel.

Bifurcation Analysis Method

STAGS-C1 has two buckling analysis modes. One uses a linear prebuckled state and is referred to in the STAGS-C1 manual as the bifurcation analysis with a linear stress state. The second method uses a geometric prebuckling nonlinear displacement calculation and is referred to as the bifurcation analysis with a nonlinear displacement state. As noted in Ref. 16, the SH410 element has not produced good results using the nonlinear mode in predicting postbuckling modes. The bifurcation analysis with a linear displacement state prior to bifurcation will be used. This method will calculate the prebuckling displacements and rotations, stress resultants, strains, and stresses as desired. It also predicts the bifurcation eigenvalue and the shape of the eigenvector. It does not yield any postbuckling information.

Moisture and Temperature Conditions Evaluated

Moisture Conditions

Test data[4] for the AS/3501-5 graphite/epoxy system, which included the degradation in the transverse and shear moduli, were available for a saturation moisture concentration up to 1.05%. The moisture concentration is measured as a percentage of original weight gained through moisture absorption. To determine the moisture concentration through the laminate thickness as a function of time, the series solution of the Fick equation was used. The coefficients C_1 and C_2, representing the moisture concentration at the surface of the laminate, were selected to be representative of actual moisture conditions a laminate may be exposed to. To evaluate the influence of the moisture as it is absorbed into the laminate, the solution to the series solution was evaluated at several times. In this evaluation of the moisture and temperature effects, three surface moisture conditions were investigated at each of five times. These moisture conditions are shown in Table 2.

The coefficient C_0 represents the initial moisture concentration in the laminate. For the cylindrical panel being investigated, C_1 is the moisture concentration on the inside $(-Z)$ surface, and C_2 is the moisture concentration on the outside $(+Z)$ surface. Conditions 1 and 2 will result in an unsymmetric degradation of the E_2 and G_{12} moduli, resulting in an unsymmetric laminate. This will introduce bending-extension coupling. Condition 3 is symmetric and will not produce any bending-extension coupling.

The five times evaluated are expressed as a dimensionless time T^* (where $T^* = Kt/h^2$). This expression for T^* comes from the exponential term in the series solution. It is a convenient way of expressing large values of actual time and comparing laminates with different thicknesses and moisture diffusion constants. The dimensionless times used in this analysis are 0.0, 0.001, 0.01, 0.1, and 0.5. Table 3 shows the correspondence between real time and T^*.

These times were calculated using $K = 0.52537 \times 10^{-10}$ (in.^{2}/s) for an eight-ply, 0.40-in.-thick, AS/3501-5 laminate. The parametric equation used to determine K was taken from Ref. 13. This equation is

$$K = 6.51 \exp(-5722/T)(0.03937)^2$$

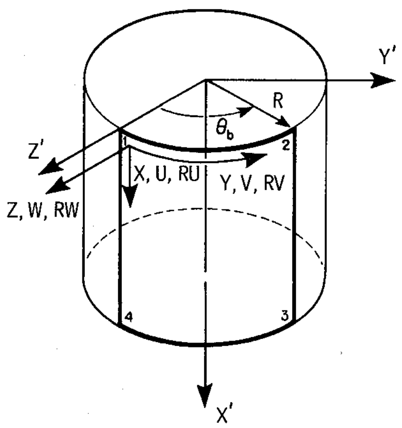

Fig. 3 STAGS-C1 cylindrical shell geometry.

Table 2 Moisture conditions

Condition No.	C_0	C_1	C_2
1	0.00	0.00	0.0105
2	0.00	0.0105	0.00
3	0.00	0.0105	0.0105

where T is the laminate temperature in degrees Kelvin, and K is as defined previously. For the purpose of the calculation of K, the laminate temperature was assumed to be 80°F (300 K).

The moisture distribution through the thickness, using Eq. (1), for moisture conditions 1 and 3 and the five time values are shown in Fig. 5. A T^* of 0.5 represents the steady-state distribution. The moisture distributions in Fig. 5 are shown as continuous functions. As was noted above, the degraded moduli values, used in the finite element analysis, are based upon the value of the moisture concentration at the center of each ply of the laminate.

Temperature Conditions

The test data in Ref. 4 were taken at four temperatures: 80, 200, 250, and 300°F. Because a thin laminate reaches temperature equilibrium very quickly when compared with the time to reach moisture equilibrium, the laminates were assumed to be at a constant temperature. These four temperatures were used to evaluate the temperature's influence.

Calculation of Moduli Degradations

For each ply's calculated moisture concentration and the laminate's specified temperature, the reduced E_2 and G_{12} values were calculated from the data shown in Fig. 1. A linear interpolation between the moduli values at known moisture concentrations was used to calculate intermediate values. In

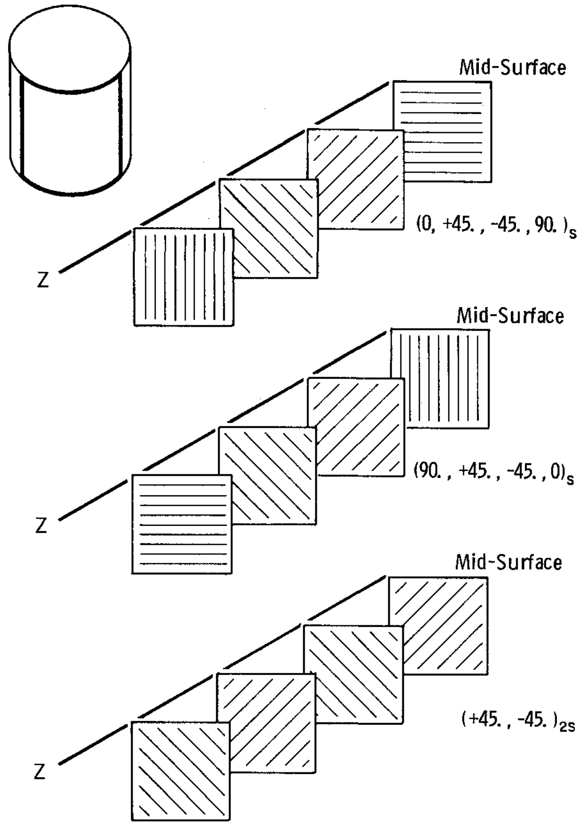

Fig. 4 Laminate ply orientations.

Table 3 Relation between real and dimensionless time

Dimensionless time, T^*	Real time, s	Real time, days
0.0	0.0	0.0
0.001	3.045×10^4	0.35
0.01	3.045×10^5	3.52
0.1	3.045×10^6	35.24
0.5	1.527×10^7	176.24

this manner, the E_2 and G_{12} values for each ply were determined.

Once the value of E_2 was calculated, the corresponding value of ν_{12} was calculated using the relationship:

$$\nu_{12}/E_1 = \nu_{21}/E_2$$

As noted previously, both E_1 and ν_{12} were assumed to be constant. However, they do actually vary with moisture concentration and temperature. E_1 increases by about 10% and ν_{12} varies from 0.36 to 0.46. Using the STAGS-C1 program, the increase in E_1 resulted in approximately an 8% increase in the bifurcation load. Variations in the Poisson's ratio, ν_{12}, did not significantly influence the bifurcation load, with changes of less than 2%. Since E_1 caused an increase in the bifurcation load, it was decided not to include this modulus change in the case studies because it would make an evaluation of the effects of reductions in the other two moduli more difficult to assess.

STAGS-C1 Cases

The combination of three moisture conditions, four temperatures, and five times generates a matrix of 60 cases for each laminate per boundary condition set. These 60 cases were broken into three sets of 20 cases (20 cases for each moisture condition). Because of the large number of cases to be evaluated, all 60 cases were run for only the boundary condition with the fixed vertical edges. Only 20 cases, for the first moisture condition, were run for the boundary condition with the simple-supported vertical edges to evaluate the influence of the change in edge support conditions. The matrix of case numbers, moisture and boundary conditions, and laminate orientations is shown in Table 4. These cases were all run for 12×12-in. panels with a panel radius of 12 in. Two additional sets, identical to cases 1-20, were run with panel radii of 24 and 48 in. to evaluate the influence of panel radius on the stability degradation characteristics.

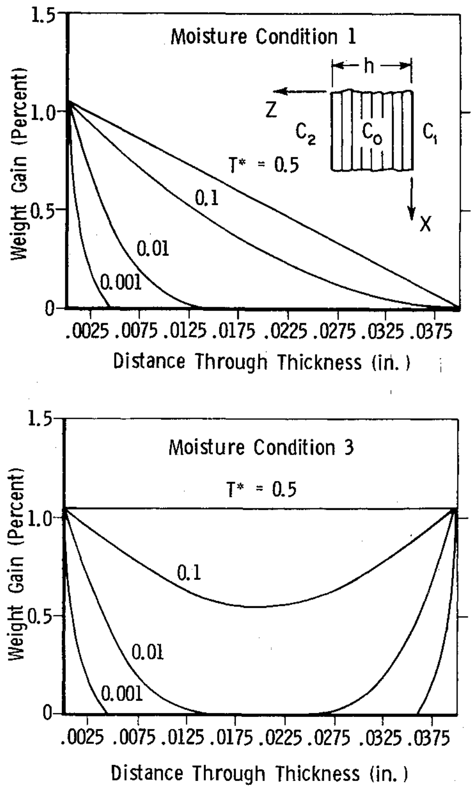

Fig. 5 Moisture concentration distribution for moisture conditions 1 and 3.

Results and Discussion

The moisture- and temperature-induced degradations in the E_2 and G_{12} moduli resulted in reductions in the panels' bifurcation loads. The results of the STAGS-C1 cases for the three panels with the fixed boundary condition are shown in Figs. 6-8. In these plots $\bar{N}_{X_{orig}}$ represents the bifurcation load for the room temperature condition at $T^* = 0.0$. This condition is unaffected by either temperature or moisture degradations. These results are for the 12×12-in. panels with a radius of 12 in.

As was expected, the panel bifurcation load decreased with increasing temperature and absorbed moisture. At the highest temperature and moisture concentration, this reduction was significant: ranging from 21% for the $[0, +45, -45, 90]_s$ laminate to 43% for the $[+45, -45]_{2s}$ laminate. These reductions are especially significant considering that dimensional changes due to resin swelling were not included and the longitudinal modulus was held constant. A summary of the maximum reduction in $\bar{N}_X$ for each laminate and moisture condition is shown in Table 5. These results are for the fixed boundary condition.

The change in the panel's edge boundary conditions did not significantly change the bifurcation loads. Comparisons of

Table 4 STAGS-C1 cases evaluated

Case No.	Moisture condition	Boundary condition	Laminate
1-20	1	Fixed	$[0, +45, -45, 90]_s$
21-40	1	Fixed	$[90, +45, -45, 0]_s$
41-60	1	Fixed	$[+45, -45]_{2s}$
101-120	1	Simple	$[0, +45, -45, 90]_s$
121-140	1	Simple	$[90, +45, -45, 0]_s$
141-160	1	Simple	$[+45, -45]_{2s}$
201-220	2	Fixed	$[0, +45, -45, 90]_s$
221-240	2	Fixed	$[90, +45, -45, 0]_s$
241-260	2	Fixed	$[+45, -45]_{2s}$
401-420	3	Fixed	$[0, +45, -45, 90]_s$
421-440	3	Fixed	$[90, +45, -45, 0]_s$
441-460	3	Fixed	$[+45, -45]_{2s}$

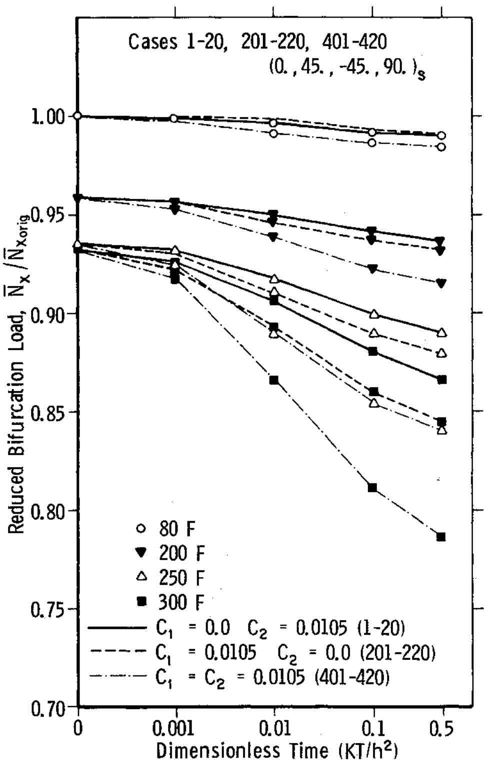

Fig. 6 Degradation in $\bar{N}_X$ for the $[0, +45, -45, 90]_s$ laminate.

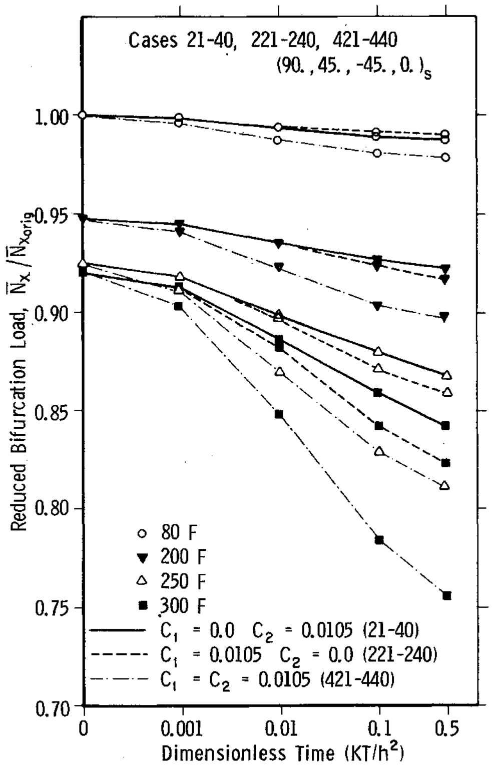

Fig. 7 Degradation in $\bar{N}_X$ for the [90, +45, −45, 0]$_s$ laminate.

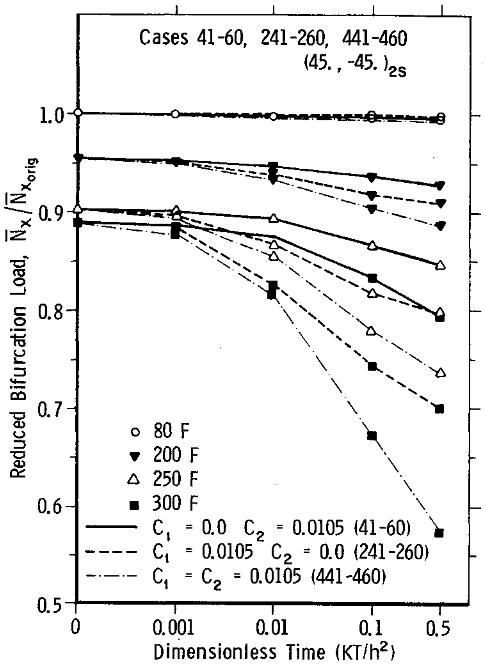

Fig. 8 Degradation in $\bar{N}_X$ for the [+45, −45]$_{2s}$ laminate.

Table 5 Percent reduction in bifurcation load at 300°F and $T^* = 0.5$

Laminate	Moisture condition 1	2	3
[0, +45, −45, 90]$_s$	13.4	15.5	21.3
[90, +45, −45, 0]$_s$	15.9	17.7	24.5
[+45, −45]$_{2s}$	20.6	29.9	42.7

Table 6 Change in $\bar{N}_X$ due to changing boundary conditions

Laminate	Boundary fixed	$\bar{N}_X$ Condition simple	Percent reduction
Moisture condition 1, $T^* = 0.0$, 80°F			
[0, +45, −45, 90]$_s$	514.8	502.8	−2.33
[90, +45, −45, 0]$_s$	446.0	444.1	−0.43
[+45, −45]$_{2s}$	428.9	421.6	−1.63
Moisture condition 1, $T^* = 0.5$, 300°F			
[0, +45, −45, 90]$_s$	445.9	434.6	−2.53
[90, +45, −45, 0]$_s$	375.3	373.5	−0.48
[+45, −45]$_{2s}$	340.4	328.9	−3.78

the calculated $\bar{N}_X$ for the two boundary conditions are shown in Table 6. These results are shown for the original room temperature values and the worst case values.

Moisture conditions 1 and 2 cause the initially symmetric laminate to become unsymmetric. This unsymmetry introduces bending-extension coupling. If this coupling caused a significant variation in the bifurcation load, then a significant difference in the laminate's $\bar{N}_X$ for moisture conditions 1 and 2 would be expected. This is because these two conditions produce unsymmetry in the laminate which is opposite to each other. The influence of this coupling can be seen in Figs. 6-8. For the [0, +45, −45, 90]$_s$ laminate and the [90, +45, −45, 0]$_s$ laminate, there is very little difference in the $\bar{N}_X$ values for the two moisture conditions. At most, there was only a 3% difference between the two moisture conditions for these two laminates. The difference between the two conditions for the [+45, −45]$_{2s}$ laminate is 10% at 300°F and a time of 0.5. The influence of the unsymmetry is greater for this laminate because the magnitudes of the bending-extension coupling stiffnesses are greater for this laminate than they were for the other two laminates.

To evaluate the influence of panel radius on the moisture- and temperature-caused reductions in $\bar{N}_X$, the 20 cases for moisture condition 1 for the [0, +45, −45, 90]$_s$ panel were rerun with radii of 24 and 48 in. As expected, the panel's original $\bar{N}_X$ reduced with increasing radius. $\bar{N}_X$ changed from 514.8 lb at a 12-in. radius to 290.8 lb at a 24-in. radius and to 170.3 lb at a 48-in. radius. However, the percentage reduction in these original $\bar{N}_X$ values with increasing moisture concentrations and temperatures did not significantly change. Thus panel radius does not significantly influence the moisture- and temperature-caused degradation characteristics within the limits of a shallow shell.

Conclusions

On the basis of the finite element analysis, the following conclusions can be made for cylindrical, composite panels subject to moisture exposure and elevated temperatures and loaded in axial compression:

1) The bifurcation load of a composite panel, with a resin material whose elastic moduli are reduced by absorbed moisture and elevated temperatures, will degrade with increasing moisture concentrations and temperatures.

2) The extent of the degradation in the bifurcation load is influenced by the degree of moisture concentration, the temperature, and the panel's ply orientations. At 300°F and a maximum moisture weight gain of 1.05%, the [0, +45, −45, 90]$_s$ panel experienced a 21.3% degradation; the [90, +45 −45, 0]$_s$ panel experienced a 24.5% degradation; and the [+45, −45]$_{2s}$ panel experienced a 42.7% degradation.

3) A change in the rotational restraints of the vertical, straight sides, from fully fixed to simple-supported, did not significantly reduce the bifurcation load or change the moisture- and temperature-induced degradation characteristics for a panel aspect ratio of 1.

4) Increasing the cylindrical panel's radius decreased the panel's bifurcation load but did not significantly change the moisture- and temperature-induced degradation characteristics.

5) The bending-extension coupling resulting from the unsymmetric moisture concentration distributions, which resulted in an unsymmetric laminate, did not significantly influence the bifurcation load.

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