Experimental Investigation of Strains in Fabric under Biaxial and Shear Forces

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The paper defines the experimental phase of an objective to obtain the mechanical characteristics and coefficients required by the generalized form of Hooke's law for nylon-polyurethane-coated fabric. Test specimens were cylindrical fabric sleeves and were loaded in axial tension by an Instron, in hoop tension by pressurizing, and in shear by a torquing fixture. An extensive amount of strain data is included for a wide combination of the three membrane loads. The tests indicate highly nonlinear stress-strain characteristics of the fabric and a strong dependency on all three membrane loads.

Nomenclature

C_{ij} = the measured circumference of the test specimen for the ith value of $\sigma_w t$ and the jth value of τt, in.
C_o = the initial circumference of the test specimen for a given circumferential stress and for the axial stress ($\sigma_w t$) and shear stress (τt) equal to zero, in.
D = reference diameter of the unstrained specimen, in.
t = thickness of membrane, in.
γ = shear deformation, radians
$\varepsilon_f, \varepsilon_w$ = strain in the fill and warp direction, respectively, unitless
$\varepsilon_{fw}, \varepsilon_{wf}$ = strain in the fill direction due to normal strain in the warp direction, and strain in the warp direction due to normal strain in the fill direction, respectively, unitless $[\varepsilon_{fw} = (C_{ij} - C_o)/\pi D]$
$\sigma_f t$ $\sigma_w t$ = membrane force in the fill and warp directions, respectively lb/in.
τt = membrane shear force, lb/in.

Introduction

THE subject paper is the first of two related papers that are an outgrowth of a government contractual responsibility to furnish test data and derived mechanical characteristics of nylon-polyurethane-coated fabric for use in a structural analysis of a parawing. This paper deals explicitly with the experimental phase and presentation of these test data. In a future issue of this journal, the processing of these test data into the elastic constants of the generalized form of Hooke's law is described and the data are provided.

Fabrics are being used widely as structural materials in the aerospace field in such forms as parachutes, decelerators, balloons, light planes, ballutes, inflatable satellites, and so forth. Hence, the engineer is faced with the problem of structural design, deformations, and stress analyses which intimately involve the fabric mechanical properties. The availability of the required mechanical constants for fabrics is exceedingly poor in comparison with the current situations for the common structural materials. Furthermore, the mechanical characteristics of woven fabrics are generally nonlinear and are found to be strongly dependent upon the combination of biaxial normal stresses and the accompanying shear stresses.

Freeston, Platt, and Schoppee[1] list the outstanding mechanisms involved in the deformations of biaxially stressed fabrics as crimp interchange, change in the angle between the fill and warp yarns, yarn bending, yarn flattening, yarn extension, friction between filaments and yarns, yarn nesting at crossover, yarn swelling, and yarn and fabric rupture. In addition to these factors, the loading sequences, history, and loading rate and magnitude influence the deformation.

Stress-strain behavior of fabrics under two-dimensional loading has been considered by a number of other investigators. Zender and Deaton[2,3] used the concept of a pressurized fabric cylinder for determining the stiffness characteristics of a nylon-neoprene-coated fabric. Their test setup was restricted to a fixed relationship between the axial and circumferential loading; these loads resulting from the pressurization only. The shear loading was independently variable.

In this paper, the test apparatus and test procedures are discussed in detail for testing fabric under the combination of biaxial normal stresses and accompanying shear stresses. The nonlinear tristress dependent strain data are presented for practical ranges of stress.

Test Apparatus

The test apparatus was developed around a standard Instron uniaxial loading machine. The biaxial loading capability with accompanying shear required additions to the standard machine. The complete loading apparatus is shown in Fig. 1, with an enlargement of the central features given in Fig. 2. The test specimen is a cylindrical fabric sleeve and is seen centered in the Instron load frame. The normal stress parallel to the cylindrical axis of the sleeve is generated as a standard function of the Instron. The orthogonal normal stress is the hoop stress in the cylinder generated by pressurizing the fabric sleeve. Along with these normal stresses, a shear stress is imposed by rotating the upper drum of the sleeve through a system of cables, pulleys, and weights.

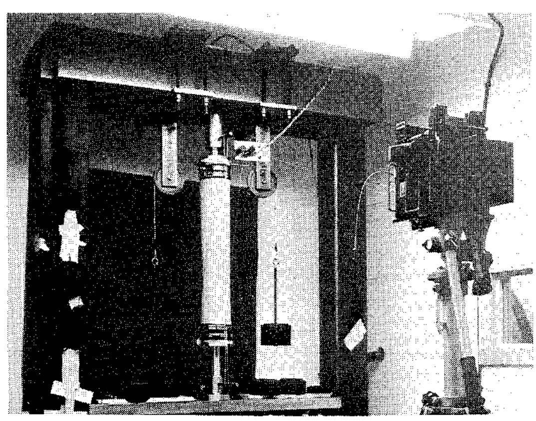

Fig. 1 The load apparatus and recording equipment.

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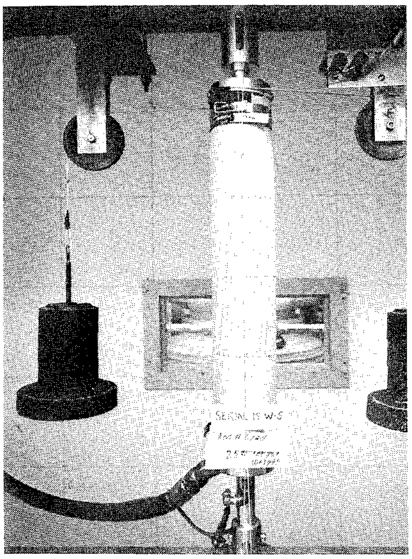

Fig. 2 Cylindrical fabric sleeve showing torquing device, shear grid, and air supply hose.

Sleeve Assembly

The parts comprising the cylindrical sleeve assembly pictured in Fig. 2 are shown in detail in Fig. 3. Head and base blocks are provided to which the fabric sleeve specimen is secured with commerical heavy-duty hose clamps (two at each end). The base block is rigid against rotation and secured in the standard Instron fitting. The head block is made to rotate freely under axial load having a maximum frictional torque of about $\frac{1}{2}$ in.-lb under an axial load of 1000 lb. The head and base blocks are maintained concentric by an internal sleeve and shaft guide. These fit together with 0.020 diametrical clearance on teflon sleeve bearings.

The fabric sleeve specimen is constructed of two halves sewn together with two longitudinal "French fell seams," diametrically opposed. The assembly is designed to take 4-in.-diam sleeves. In order to minimize end effects, the sleeves are fabricated for active lengths of four diameters or greater. A grid system is drawn with ink on the unstrained fabric specimen for purposes of measuring shear deformation. The shear deformation is readily observed and measured from this grid as seen in Fig. 2 for the fabric under biaxial and shear stresses. The sleeves are secured to the head and base blocks by using adhesive between the sleeves and the aluminum blocks. Double layers of 0.035-in.-thick rubber gripping pads were used on the external sleeve surfaces to avoid chafing by the hose clamps.

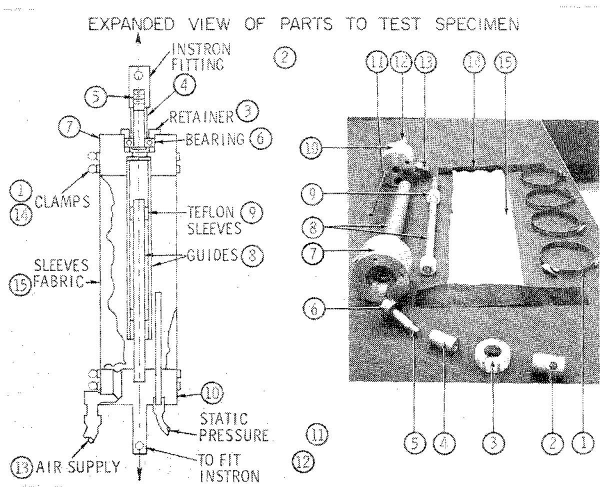

Fig. 3 Expanded view of parts to test specimen.

The internal pressurization is obtained by an air supply entering through an orifice in the base block. A 90-psi air supply is available through a 1-in. air supply line and with a minimum orifice existing at the $\frac{5}{8}$-in. discharge hole in the base block.

Recording Equipment

The shear deformations were recorded by a Polaroid camera as shown in Fig. 1. The axial deformations load applied to the specimen were recorded on the strip chart that is standard equipment on the Instron. Circumferential deformation was measured manually for incremental loading by use of a calibrated tape.

A Bourdon tube pressure gage of $\frac{1}{100}$ psi accuracy was used to read the stagnation pressure in the sleeve. The pressure was sensed through a pipe extension attached to the base block of the sleeve assembly. The free end of the pipe was sufficiently above the inlet to the air supply to assure static pressure conditions.

Test Procedures

The basic testings consisted of applying a constant axial load and pressure, and varying torque incrementally. An attempt was made to maintain a fairly consistent rate of loading to avoid large effects of relaxation and creep. Since the torque was applied manually, a constant rate of loading was only approximated. A single sleeve specimen was used for a combination of constant axial loads with incremental variations in torque. Successive sets of measurements were taken on axial elongation, circumferential dimension, and shear deformation for combinations of axial load, internal pressurization, and torque. Also, careful observations were made to identify the buckling bounds for the combined loading. Test data were recorded for the uploading phase of the load cycle only. A single initial load cycle was given each specimen before acquiring the permanent data. The material of the fabric test specimen is a 2.25-oz nylon-polyurethane-coated fabric identified as S/155 sailcloth procured from the Lamport Sail Co., Ltd. The weave characteristics are recorded on Fig. 4 for the purpose of making these tests applicable to other materials of similar geometry.

Output Data

The fundamental test results for determining the shear strains were recorded as Polaroid plates. Figure 2 is a typical example of Polaroid data from which the shear deformation can be measured directly. The axial elongation was manually recorded and tabulated from the output of the strip chart of the Instron. The circumferential deformation was manually determined by direct measurement of the girth of the specimen.

From these data, graphs are constructed of axial, circum-

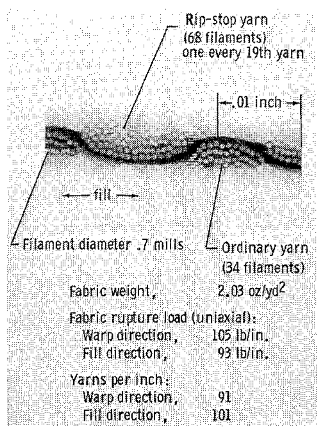

Fig 4. Geometric characteristics of rip-stop weave polyurethane-coated nylon fabric.

ferential, and shear strains as functions of the three independent stresses. After fairing by curve-fitting techniques, these data are furnished as Figs. 5–7 for a wide range of test values.

Discussion of Test Efforts and Data

It should be appreciated that the determination of stress-strain characteristics for a fabric is destined to have inaccuracies and a lack of repeatability between tests by virtue of a number of causes. Such effects are creep, incomplete buckling, sequence of loading, rate of loading, the material load history, the energy losses due to friction, the sensitivity to humidity, the initial tolerances in yarn spacing, initial crimp, and the presence of pulls and wrinkles in an assembled test specimen. However, duplicate tests were performed for identical load conditions for all test combinations and the results were found to have surprisingly good repeatability. As a result of the many factors affecting accuracy, the fairing of test data was a necessity.

Discussion of Test Problems

The characteristics furnished in this report are valid for the uploading cycle and would be somewhat different for downloading. The uploading characteristics are felt useful for applications such as decelerator initial inflation, the deployment of inflatable structures, or single shock loading of fabrics. To treat the cyclic load problem, the stress-strain characteristics become explicitly dependent upon the preceding history of the loading and their determination is an effort of an order of magnitude greater than that required for the initial uploading characteristics.

In addition, the material specimens used in these tests were not virgin materials for each test. For example, the specimen was loaded with a fixed normal stress and then uploaded progressively with shear stress. Then the same process was repeated on the same specimen for different normal stresses. Thus, the second and subsequent tests in a series were not on a virgin (or unstretched) material.

In this effort, the rate of loading was not representative of

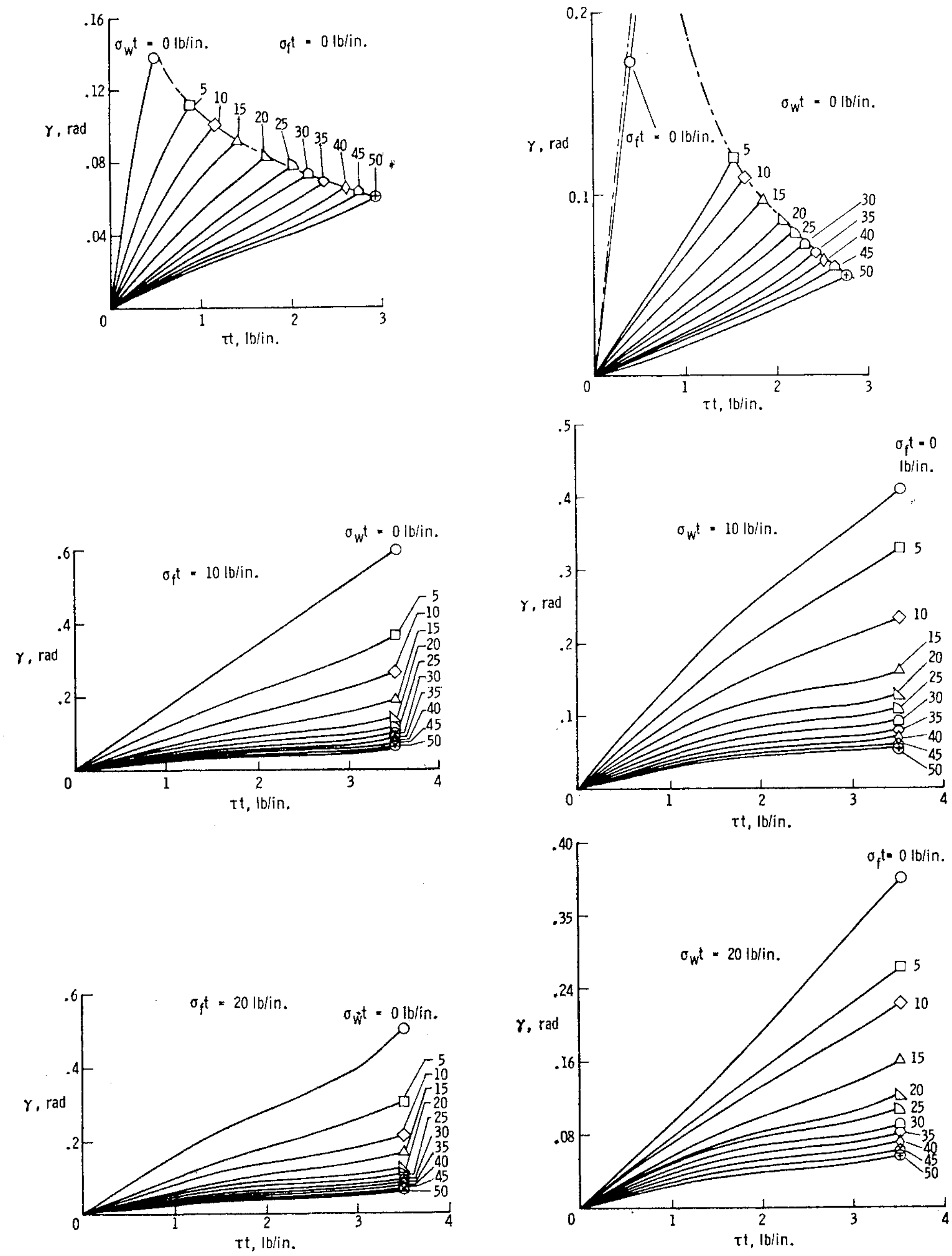

Fig. 5 Shear strain.

the load onset rates experienced in decelerator deployments and shock loadings. The testing facility did not permit high load rates but an effort was maintained to achieve approximately constant load rates even though they were at very low rates (i.e., 20 in./min max.). If the loading was not applied in a steady and uniform manner, the influence of relaxation or creep was apparent.

Considerable difficulty was experienced in obtaining consistent and rational results in the initial data and related processed data for low values of axial loading. This was generally the result of incipient buckling that was not always consistent in the mode of buckling or in the rate of onset. This difficulty is reflected in the wide excursions of the strain data for small axial loads as compared to those for high levels of axial load.

The acoustical disturbance due to escaping air through the porous material was sufficiently severe that it was declared a health hazard. As a result, a sound enclosure for the test apparatus was required. Early in the experimentation it was discovered that the major source of air leakage was around the stitched seams in the test specimens. With a 90-psi air supply and a $\frac{3}{8}$-in.-diam. minimum constriction, the initial specimen could be pressurized to 15 psi, which degenerated to as low as 5 psi for high axial loads. By sealing the stitched seams with silicone rubber sealant (RTV-102), a maximum constant pressure of 10 psi could be maintained throughout the test period and range of applied loads. Furthermore, after approximately 10 cycles of axial loading with various levels of constant shear loading, the porosity of the specimens was increased to the point where 10 psi pressure could not be maintained. Under all test conditions, the leak rate was a function of the stress level, and modulation of the flow rate to maintain constant pressure was a necessity. Two rows of stitching $\frac{1}{4}$ in. apart and with $\frac{1}{8}$ in. stitches could not provide the structural integrity needed. It was experienced, with an ordinary lapped seam, that pressurization to 10 psi could not be accomplished without the sleeve exploding. It was necesary to use a "French fell seam" to achieve the desired strength, although this provided a local band of stiffness to the specimen that originally it was felt desirable to avoid. These diametrically

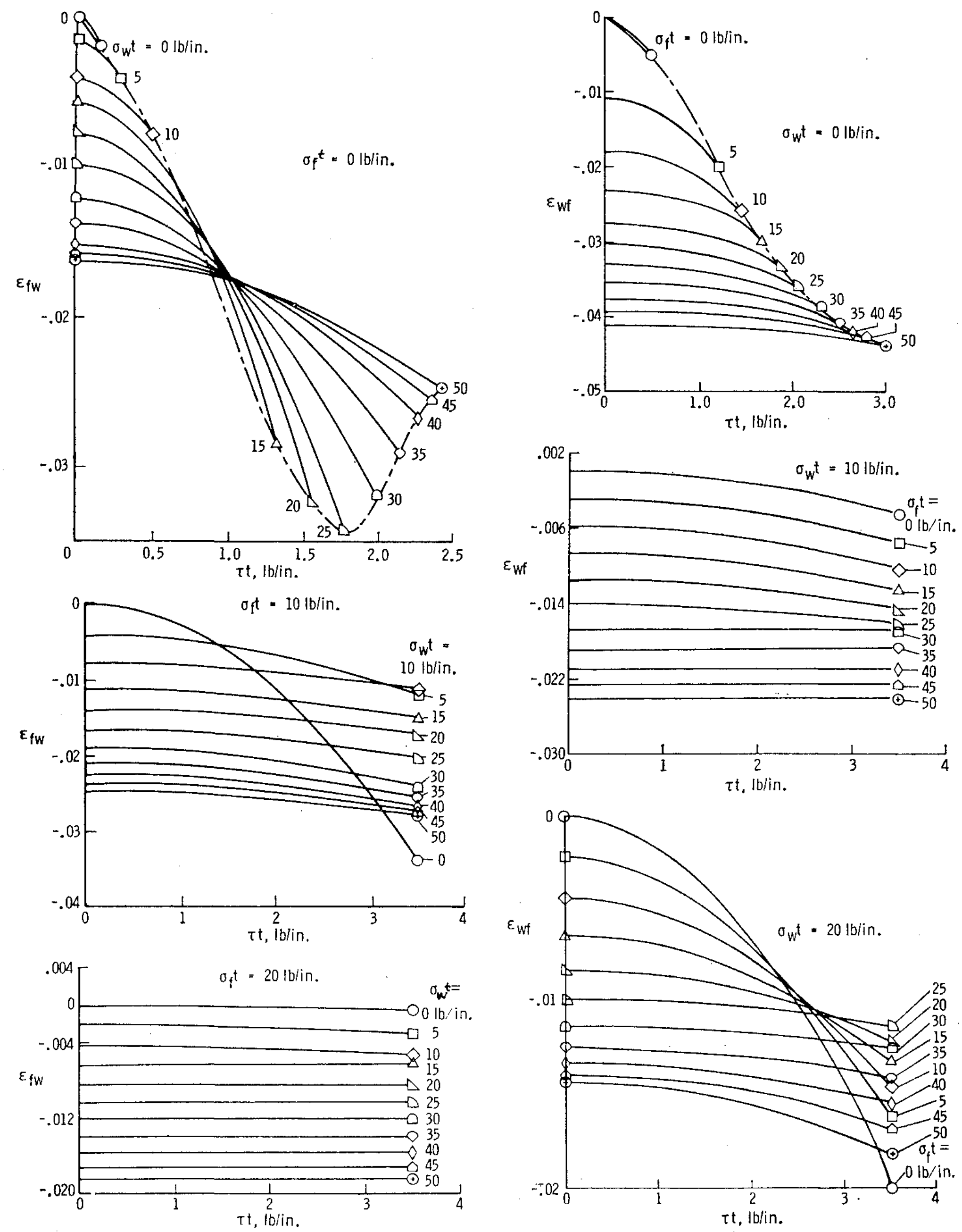

Fig. 6 Normal (circumferential) strains.

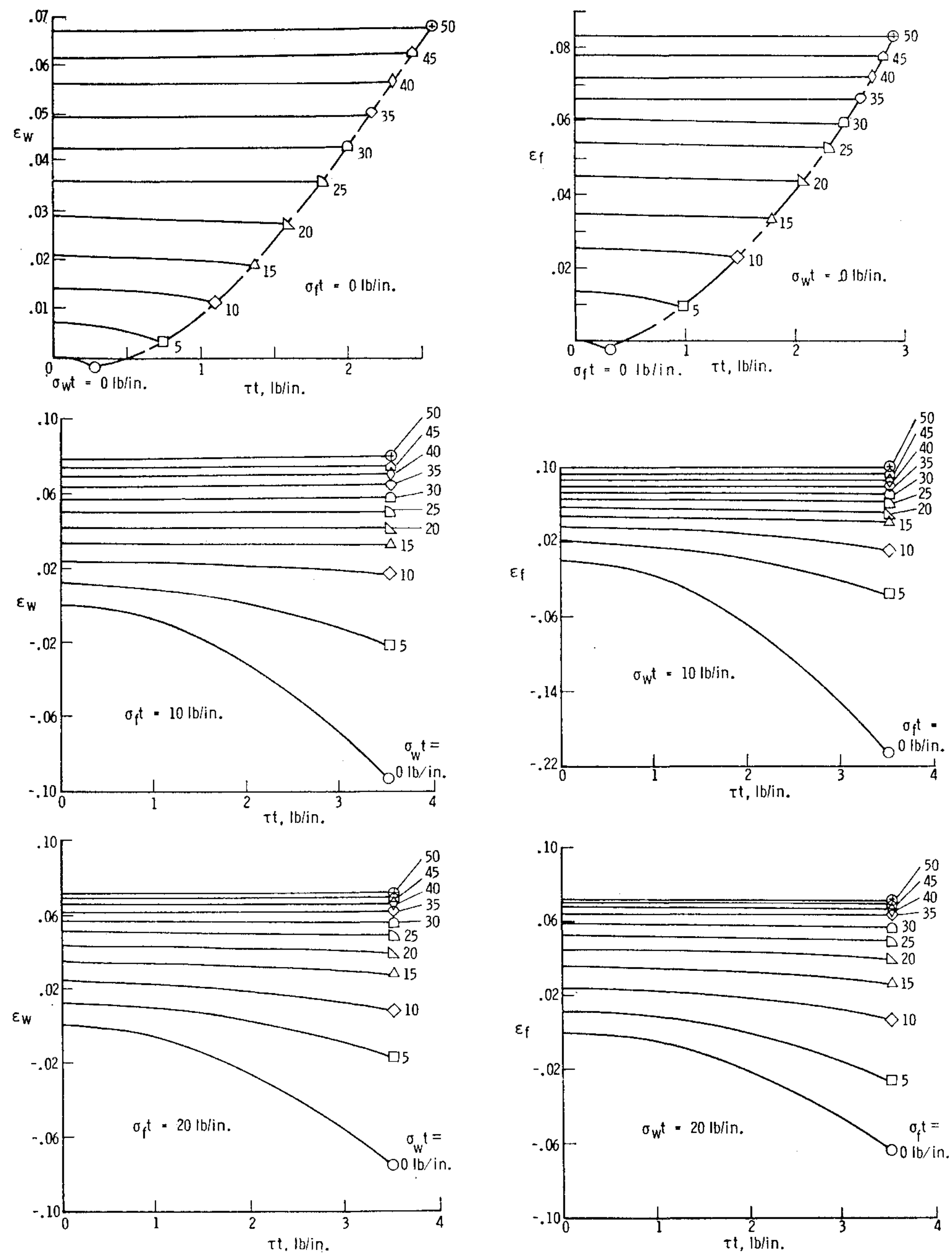

Fig. 7 Normal (axial) strains.

opposite bands were ignored in the determination of the stresses and uniformity of stress fields. It is believed that a uniform biaxial stress field was achieved throughout the majority of the test specimen. The circumferential expansion was essentially constant over 90% of the length of the cylinder.

With the fill specimens, a difficulty was encountered in clamping the specimens to the head and base blocks. Slippage occurred at axial load in excess of 35 lb/in. and could not be prevented by use of plybond adhesives, rubber gripping pads, and maximum clamp pressures. As a result, some of the data ε_f and ε_{wf} for an axial membrane load of 35 lb/in. or greater were affected and estimated corrections to these values were necessary. Rubber gripping pads were found essential to prevent local overstressing at the edges of the clamps which initially resulted in premature failure of the fabric specimens.

The shear was limited to approximately 3.5 lb/in. membrane loading. For the zero circumferential load case, this limitation was a direct result of torsional buckling. For the nonzero circumferential load cases, the 3.5 lb/in. limit was justified by virtue of the large associated strains. Application of these strain data to structural analyses have shown that, as a result of the low shear stiffness, only small shear stresses can be generated.

Buckling is dependent upon whether the loading proceeded from an unbuckled state to a buckled state or conversely. The buckle bounds given in this paper were established in accordance with the former. The mode of buckling was generally a set of wrinkled helices. For near zero axial loads, an unstable column mode of failure occasionally was observed along with the torsional mode. For light axial loads, a combination of the column and torsional modes, wrinkles associated with pulls in the specimen and large shear strains made identification of buckling indecisive.

The determination of the ε_{fw} and ε_{wf} data by direct measurement of the girth of the specimen was particularly difficult and of low accuracy. Furthermore, in the range of low-axial loads difficulties were compounded as a result of the usual unstable torsional behavior around zero axial load along with a cylindrical mode of oscillation that developed via internal pressure and escaping air.

Further Research

Further testing is seen necessary to control strain rates, develop a meaningful plan for justifying and the quantization of such strain rate control, and improve accuracy of the acquired data. The two-dimensional problem has indicated that similar efforts should be considered for three-dimensional anisotropic filamental materials. Also, a more definitive buckling criterion is desirable and the appropriateness of the cylindrical test specimen for acquiring two-dimensional data needs further study.

Conclusions

An experimental investigation is documented on the stress-strain characteristics of a 2.25-oz nylon fabric with polyurethane coating. The stress-strain relationships are found to be nonlinear functions of the biaxial normal membrane forces and accompanying shear forces. The use of an Instron uniaxial loading machine with a pressurized cylindrical sleeve test specimen with a torquing fixture provided an effective apparatus for testing fabric under simultaneous biaxial and shear loading. Stress-strain curves are provided for shear strain, axial strain, and the introduction of orthogonal plane strains. These data are shown for combinations of shear membrane forces between 0 and 3.5 lb/in., axial membrane forces between 0 and 50 lb/in., and circumferential membrane forces from 0 to 20 lb/in.

This experimental effort indicates the need for further research into fabric mechanical behavior with emphasis given to more careful control of strain rates, improvement in accuracy, and extension of multiloading testing to three-dimensional anisotropic filamental materials. In a future issue of this journal, the processing of these test data into the elastic constants of the generalized form of Hooke's law is documented in detail.

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