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Paper

Interlaminar Normal Stress Effects in Cylindrical Tubular Specimens of Graphite/Epoxy $[\pm 45]_s$ Composites

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ABSTRACT: The thin-walled cylindrical tubes are frequently used for the evaluation of fatigue property of composites. But the curvature of the tubular specimen induces interlaminar normal stress which may affect the fatigue property. In this paper interlaminar normal stress effect on the fatigue behaviour of thin-walled graphite/epoxy tubes $[\pm 45]_s$ composites was studied experimentally. It was concluded that the interlaminar normal stress induced by the curvature of the cylinder has no discernible effect on the fatigue life. But excessive internal pressure can produce the stiffness increase and this affects the fatigue life of the cylindrical tubular composite.

Key Words: Fatigue, Graphite/Epoxy Composite, Interlaminar Normal Stress, Cylindrical Tubular Specimen

1. INTRODUCTION

The evaluation of the fatigue property of epoxy matrix composites is traditionally performed using coupon test specimens. They are easy to make, and valuable fatigue data have been generated with it. However, substantial loading in compression will cause buckling of coupon specimens and very little fatigue data are available for negative R-ratios. R-ratio is defined as

$$R-ratio = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{1}$$

where $\sigma_{\min}$ and $\sigma_{\max}$ are the minimum stress and maximum stress during a cycle, respectively. Moreover, the use of coupon specimens restricts the loading to uniaxial conditions and no possibility exists to ascertain the biaxial fatigue performance of the composite materials. In the future, composites are expected to replace conventional materials in high performance and other applications. Because of this trend, there will be an increasing need for fatigue data involving negative R-ratios and/or biaxial loading. Consequently, considerable effort have been expended to design and construct a tubular specimen and associated fixtures. With tubular specimens we obtain experimental results of the mechanical behaviour of fatigue performance of $[\pm 45]_s$ graphite/epoxy [1]. Because the curvature in the tubular specimens may promote interlaminar normal stress which can contribute to the delamination, resulting in the deterioration of fatigue resistance [2]. Therefore, material properties obtained with the tubular specimen would be those of the material/tube configuration rather than the desired material properties. One of the great difficulties with composite materials is the establishment of "true material properties." Even the widely accepted coupon specimen is prone to edge effects, and material data obtained with this specimens is tainted by such a possible effect whose influence on fatigue performance is very hard to quantify.

It was felt that the criticism brought forward in curvature of specimen effect was valid and deserved the separate investigation. We used a rubber bladder to apply air pressure inside the specimen to eliminate the internal normal stress induced by the curvature of the cylindrical specimen. If the excessive pressure is applied the compressive internal normal stress can be produced. But in addition to this normal stress the stiffness of the specimen is also increased. To investigate this effects we installed two types of metal mandrels inside the tubes. Experimental investigation of the effect of insertion of metal mandrels are studied.

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2. INTERLAMINAR NORMAL STRESSES IN CYLINDRICAL SPECIMEN

Fig. 1 shows the specimen used in the investigation.

For the present investigation, Graphite/Epoxy with a $[\pm 45]_s$ lay-up was used. Materials used in this study include Fiberite Hy-E 1048 A1E, 3048 A1k, and 1248 A1F unidirection- al prepreg tapes. According to the specifications of these Fiberite prepregs, the only difference between those materials is the volume percentage of the resin content. It varies from 39% for Hy-E 1248 A1F to 41% for Hy-E 1048 A1E. Mechanical properties of Hy-E 3048 A1K unidirectional composites are listed in Table 1.

From the analysis of strength of materials, the interlaminar normal stress σ_3 at the interface between the first and second plies (Fig. 2) can be expressed as:

$$\sigma_3 = \frac{\sigma_1(\cos^2\theta)t}{r} \tag{2}$$

where σ_1 is the stress in the fiber direction, $\theta = \pi/4$ is the angle between the fiber and cylinder axis, $t = 0.15$ mm, is the thickness of the ply, and $r = 12.7$ mm is the inside radius of the cylinder. In the testing of $[\pm 45]_s$ specimens, the axial strength was in the order to 150 MPa so that the calculated maximum normal interlaminar stress is less than 0.69 MPa.

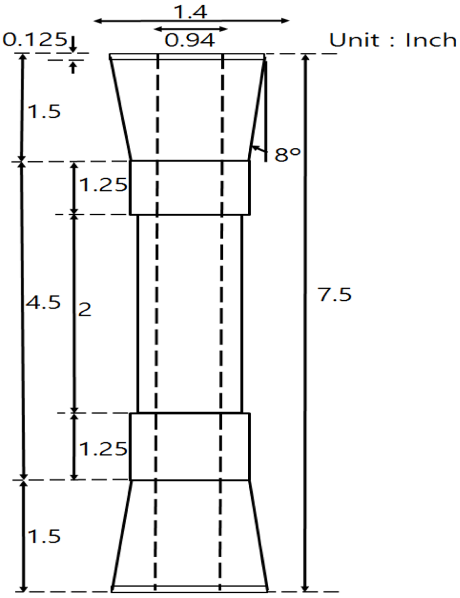

Fig. 1. Thin-walled tubular specimen

Table 1. Mechanical Properties of Fiberite Hy-E 3048A1K

σ_{1f}	1.345 GPa (195 ksi)
σ_{2f}	30 MPa (4.35 ksi)
E_1	133.8 GPa (19,400 ksi)
E_2	8.464 GPa (1,230 ksi)
G_{12}	4.997 GPa (725 ksi)
ν_{12}	0.294
ν_{21}	0.024
t_{ply} (thickness)	0.15 mm (0.0058")

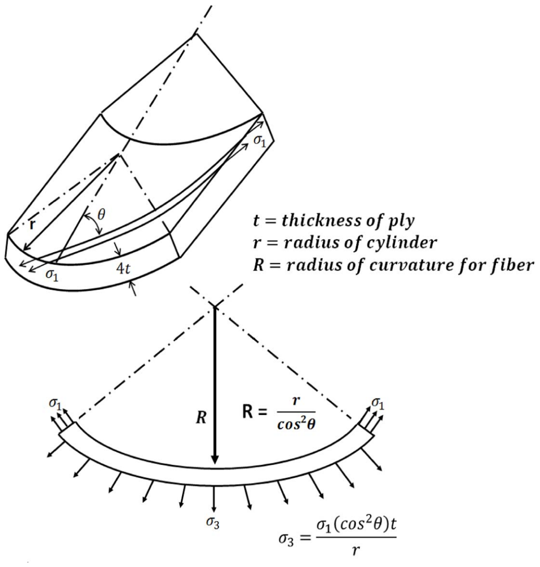

Fig. 2. Estimation of interlaminar normal stress

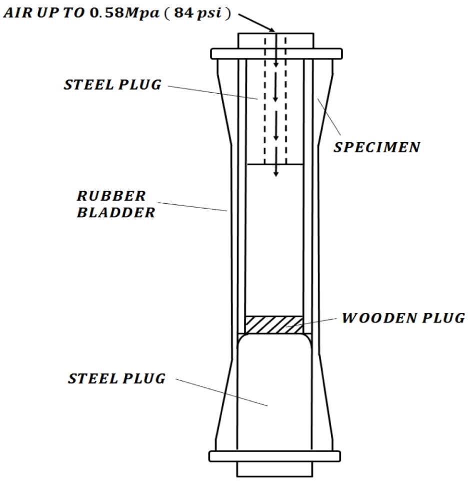

Fig. 3. Internally pressurized specimen, showing the rubber bladder and plugs

Because of the magnitude of this interlaminar normal stress, the shop air pressure was sufficient for compensating the interlaminar normal stress, and it was decided to build an internal pressurization equipment with this pressure source. Fig. 3 schematically shows the specimen with rubber bladder.

3. EXPERIMENTAL INVESTIGATION

3.1 Static Tests

The testing machine is computer-controlled axial-torsion servo-hydraulic system (MTS 809.10). For the determination of ultimate tensile strength, σ_u, and shear strength, τ_u, load

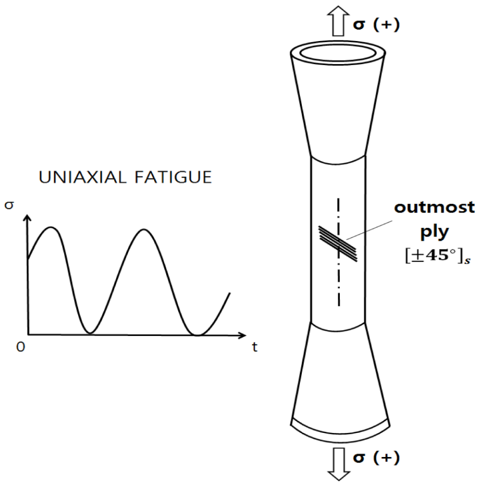

Fig. 4. Fatigue test conditions for composite tubes

control was used. A since wave of 0.01 Hz with maximum load of 8.9 KN in axial tests and a maximum torque of 226 N-m in torsional tests are employed, respectively. Experimental results are listed in Table 2.

The sign convention in torsional tests is shown in Fig. 4. All the static results are similar to those obtained by Niu and Ayar [5,6].

3.2 Test Results

A static test with an internal pressure of 0.55 MPa was performed and the ultimate tensile strength was 135 MPa. This value was below the average of previously tested unpressurized specimen (see Table 2). As part of this test the stiffness of the specimen with and without internal pressure was measured and the results were found to be unchanged.

Table 2. Uniaxial Fatigue Test Results for $[\pm 45]_s$ Gr/E $R = 0$ at 5 Hz

Specimen Number	Amplitude S (%)*	Fatigue Life $\log N_f$	Internal Pressure P_i (psi)
A-11-11	21.43	$\succ 6$	52
A-11-11	21.43	$\succ 6$	0
A-11-10	24.72	4.59	0
A-11-3	24.72	5.03	0
A-11-8	24.72	5.51	0
A-11-2	24.72	5.6	0
A-11-12	24.72	5.75	0
A-11-6	24.72	4.75	60
A-11-4	24.72	5.41	60
A-11-9	24.72	5.69	60
A-11-5	24.72	5.55	60
A-11-13	26.79	4.73	0
A-11-14	26.79	3.59	65
A-11-7	26.79	5.02	65
B-4-3	26.79	5.62	0
B-4-2	26.79	5.75	65
A-11-1	30.00	4.29	73

* Stress amplitude (σ_a)/Ultimate tensile strength (145 MPa) × 100%

All fatigue tests were performed at a frequency of 5 Hz under zero-to-tension axial load-controlled conditions ($R = 0$). Total of sixteen specimens were tested with and without constant internal pressure. The purpose of the test with internal pressure was to compensate for the maximum interlaminar tensile stress predicted by Eq. (2). Therefore, tests with internal pressure can be thought of as having no interlaminar tensile stress. The test results showing the nondimensional stress amplitude, the internal pressure, and the fatigue life are presented in Table 2. It is evident that the internal pressurization has no discernible effect on the fatigue life.

4. EFFECT OF LATERAL RESTRAINT ON TUBULAR SPECIMENS

It is shown that no direct influence of internal pressure on the fatigue life is evident. An elementary analysis and test results show that the addition of internal pressure does not change the stiffness of the tube.

However, the stiffness can be appreciably changed if the lateral movement of the tube is restrained during the test by inserting the metal mandrel inside the tube. The relationships between the stress resultants and in-plane laminate strains are

$$\begin{aligned} N_1 &= A_{11}\varepsilon_1^0 + A_{12}\varepsilon_2^0 + A_{16}\varepsilon_6^0 \\ N_2 &= A_{21}\varepsilon_1^0 + A_{22}\varepsilon_2^0 + A_{26}\varepsilon_6^0 \\ N_6 &= A_{61}\varepsilon_1^0 + A_{62}\varepsilon_2^0 + A_{66}\varepsilon_6^0 \end{aligned} \tag{3}$$

Here, we denote the axial direction as 1, and the circumferential direction as 2. A_{ij} are the components of the stiffness matrix of the composite laminate [3].

As an approximation, it can be assumed that the hoop strain is nearly zero in this case. An elementary analysis shows that the ratio of the axial strain under uniaxial loading with and without mandrel can be expressed as:

$$\frac{\varepsilon_{1without}}{\varepsilon_{1with}} = \frac{1}{1-a^2} \tag{4}$$

where, $a = (A_{12}A_{21}/A_{11}A_{22})^{1/2}$. Substitution of material properties of a graphite/epoxy in Table 1 gives the ratio 2.39.

The static tensile and fatigue tests were performed for the tube with the mandrel inside the tube. The results are shown in Table 3. It is evident that the insertion of the mandrel has made a significant improvement in the static and the fatigue strength. This result shows that the restraint of the lateral movement causes beneficial effects which are not attributed to the elimination of the interlaminar tensile stress. The com-

Table 3. Test results with and without lateral restraint

Static Tension

Condition	Ultimate Tensile Strength MPa
Al (Aluminium) Mandrel (B-6-9)	196
Al Mandrel (B-6-9)	200
Steel Mandrel (B-6-17)	235
No Mandrel (B-6-7)	117
No Mandrel (B-6-4)	125
No Mandrel (B-6-5)	145

Fatigue $R = 0$, 5 Hz

Condition	Stress Amplitude MPa	Fatigue Life Cycles
Steel Mandrel (B-6-3)	94	4×10^5
No Mandrel (B-6-11)	87	4×10^3

pressive stress developed between the mandrel and the innermost ply of tube will help to eliminate the interlaminar tensile stress. Rather, the significant effects are the reduction of lateral movement and the increase in axial stiffness which reduces the axial strain by a factor of 2.39.

If it is assumed that the strain is the controlling factor for fatigue, then the stiffness increase attributes to the increase in fatigue life, which was observed at the same stress amplitude.

5. CONCLUSION

1) Based on the experimental results, it is concluded that interlaminar tensile stresses do not affect the fatigue life in the $[\pm 45]_s$ Graphite/Epoxy tubular specimen.

2) Restraint of the lateral motion by inserting a metal mandrel into the tube noticeably increased the static and fatigue strengths.

ACKNOWLEDGEMENTS

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