Early Fatigue Damage Detection in Composite Materials

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ABSTRACT

Detection of early fatigue damage in composite materials by non-destructive inspection (NDI) techniques has been demonstrated for ±45° Glass/Epoxy, and ±45°/0° Graphite/Glass/Epoxy. Dynamic axial modulus and temperature were monitored continuously with a correlation between temperature rise and modulus decrease observed. The modulus decrease and temperature rise are indicative of irreversible damage in these materials.

Torsional modulus measurements and coin tap tests were performed at 0, 10^6, 5×10^6, and 10^7 cycles, on all fatigue specimens. Other NDI procedures including holographic interferometry, ultrasonics, penetrant, and X-Ray radiography were performed on two specimens of each material to evaluate their effectiveness in detecting fatigue damage. Ultrasonics and holography proved to be effective; however, at this time, no clear quantitative correlation between structural properties and NDI measurements has been determined.

SCOPE

FATIGUE BEHAVIOR OF filamentary composites differs considerably from that of metals in that they exhibit several modes of failure [1]. These include matrix crazing, delamination, fiber failure, fiber/matrix interfacial bond failure, void growth, and cracking. Damage may be due to one or a combination of these modes of failure.

One major difference between the behavior of composites and metals in fatigue is the change in stiffness which can occur continuously over a large portion of fatigue life to fracture. This phenomenon has been observed in fatigue testing of glass (Figure 1), graphite, and boron reinforced epoxy, glass reinforced polyester and polypropylene, and boron reinforced aluminum [1–11].

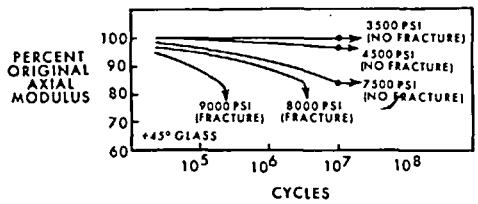

Figure 1. Composites exhibit measurable fatigue damage in the form of stiffness change early in the total life to fracture. After Salkind, Ref. 28.

Heat generation due to fatigue damage of composites is a phenomenon which has been observed by many investigators [1, 4–8, 10–12]. Heat generation is both a consequence of and a contributing factor to fatigue damage. Damage such as delamination and cracking results in significant local internal friction which generates heat. The heat in turn raises the temperature of the structure and reduces its resistance to fatigue. In addition, if stiffness monitoring is utilized for measuring fatigue damage, the temperature rise alone reduces the stiffness thus making the damage appear greater. A critical experiment was performed by Cessna, et al [5] which separated these phenomena. They conducted constant deflection cantilever beam fatigue tests of glass reinforced thermoplastics, monitoring both load decay (proportional to stiffness change) and temperature. Tests were conducted both at isothermal conditions and with no temperature control. The isothermal tests isolated the stiffness change due to fatigue damage alone (without heating effects) and resulted in increases in both the onset of stiffness change and fracture life of 20 to 100 times. The phenomenon of heat generation due to fatigue damage allows consideration of the use of thermography as an in-service damage detection technique. Temperature sensitive strips or coatings could be placed on the structure to give a visual indication of damage.

There is a need to detect defects in composites non-destructively for both manufacturing quality control and for determining structural damage in service. Non-destructive inspection methods which have been investigated to detect damage in composites include visual, ultrasonics, X-Ray, holography, acoustic emission and thermography.

Visual inspection is widely used for both quality control and service damage detection. G. Epstein [13] has listed the possible types of defects that can be

observed. The defects most commonly seen during fatigue testing are resin crazing, cracks, and delaminations. Manufacturing defects which can be detected visually which can directly cause the onset of fatigue damage are scratches, dents, pitting, porosity, voids, and delaminations.

Ultrasonic inspection has been used by many investigators as a method of detection for flaws such as disbonds, large voids, and interlaminar cracks located both on the surface and below it [14–20]. A problem with ultrasonic inspection is the noise and attenuation present due to the scattering and deflection of the signal by the many interfaces in the composites. This noise makes interpretation of the received signal very difficult. Flaws which are small (less than .61 cm (¼")) or not close to the surface are difficult to detect because there is not enough energy deflected from the flaw to clearly distinguish it from the noise. Rose, et al [17] suggest the use of ultrasonic spectroscopy, using frequency signatures, where signal attenuation is great.

Radiography has been evaluated for both metal and non-metal matrix composites [13–14, 18–20]. Radiography is useful in detecting large voids and cracks with "soft", low power X-Rays in non-metal composites. In metal-matrix composites filament anomalies can be detected with good resolution. Cook, et al [21] investigated ultrasonic and radiographic inspection of B-staged material in an attempt to predict flawed areas in cured composites, however, they could not relate suspected flawed areas in the B-staged material with flawed areas which were found in the cured composites.

Burchett and Irwin [22], McCaughey, et al [23], and Aas, et al [24] have investigated the use of laser holography as an inspection tool for resin matrix composites. Anomalies and bond failures were easily found with this method. Burchett and Irwin used tubular specimens in their investigation noting that eventual fractures in their specimens were located at anomalies or bond failures. They also noted that evaluation of fringe patterns for these tubular specimens was very difficult due to fixturing and geometry.

Acoustic emission shows promise as a damage indicator of fiber breakage for static and fatigue tests. Fitz-Randolf, et al [25] have demonstrated a good correlation between acoustic emission and fiber breakage, the dominant failure mode in their unidirectional boron/epoxy specimens. Williams and Reifsnider [26] were able to show a correlation between total acoustic emission and fatigue damage in boron/aluminum and boron/epoxy.

A common damage detection method is the sonic or coin tap technique which utilizes the human ear to detect differences in sound transmission through a structure. Lucien and Standart [27] report success in detecting large cracks in composite structures with this technique by replacing the human ear with a microphone.

The purpose of this investigation was to quantitatively correlate changes in structural properties of composites due to fatigue damage with measurable observations made by non-destructive inspection. Torsional and axial modulus measurements and residual tensile strength measurements were employed to characterize

fatigue damage quantitatively. Observations of heat generation, coin tap, penetrant, X-Ray radiographic, ultrasonic, and, halographic interferometry inspection where conducted to characterize the structural damage. This approach is aimed at demonstrating the feasibility of using NDI procedures as fatigue damage indicators for structures in service in order to improve structural reliability by detecting the on-set of fatigue damage.

CONCLUSION

It appears that there are many indicators of early fatigue damage in composites which can be exploited to develop in-service detection schemes. Permanent changes in stiffness have been detected at *less than 1%* of total life to fracture. Temperature monitoring, ultrasonics, and holography have also proved to detect damage at these early stages. Although each of these techniques is technically and economically feasible for in-service damage detection, their effectivity depends to a large extent on defining a quantitative data base relating indications to residual strength and life. This research has laid the foundation for developing that data base, but extensive additional testing is needed. The behavior of different materials and laminate orientations should be defined in detail for all stages of fatigue life to provide a valid design data base.

It should be noted that this type of research, which is material oriented, can provide only a part of the required design data base for safe design of composite structures. There are other configuration-sensitive aspects which should be explored by complementary research efforts. These include such aspects as the fatigue behavior of bonded and mechanically fastened joints, the understanding of fatigue damage initiation and propagation, and the applicability of damage detection schemes to such joints.

SUPPLEMENTAL INFORMATION

Experimental Approach

Two laminates, using non-woven glass and graphite filaments pre-impregnated with epoxy resin, were selected for this investigation. The two systems chosen were an *E*-Glass/Epoxy laminate (±45°) (4 plies DM-501) and a Graphite/Glass/Epoxy laminate $(\pm 45^\circ/0^\circ/\mp 45^\circ/0^\circ)_T$, 75% ±45° graphite (4 plies DM-101) with 25% 0° *E*-Glass, (2 plies DM-500).[1] Thirteen tubular specimens of each laminate were fabricated having an ID of 1½″ and a 5″ gage length.

Three specimens of each laminate were tested statically to determine axial modulus, E, and ultimate tensile strength, F_{tu}. The remaining ten specimens of each laminate were tested in axial fatigue on a Sonntag SF-1-U constant load fatigue machine at an $R = 0.1$, (R = min/max stress), and a speed of 30*Hz*

[1] DM501 – Reliabond resin designation 350° F Cure
DM500 – Reliabond resin designation 250° F Cure
DM101 – Reliabond resin designation 250° F Cure

(1800 *cpm*). Residual strength and static modulus were obtained for all specimens run to 10^7 cycles. During fatigue testing, the average specimen stiffness was monitored continuously using a specially designed displacement monitoring device. The device consists of two flexure arms which are strain gaged to detect total deflection of the specimen over the entire gage length.

Temperature was continuously monitored on the surface of all fatigue specimens using both thermocouples and irreversible indication temperature sensitive coatings and strips. Static torsional modulus calibrations and coin tap tests were conducted at 0, 10^6, 5×10^6, and 10^7 cycles.

Fluorescent penetrant inspection was also used as a test for surface damage. Ultraviolet light was used to cause fluorescence of entrapped penetrant.

Two of the ten fatigue specimens from each group underwent additional nondestructive evaluation to detect fatigue damage. Ultrasonics, holographic interferometry, and X-Ray radiography tests were performed at 0, 10^6, 5×10^6, and 10^7 cycles for specimens that survived that long in fatigue.

Results and Discussion

The main objective of this investigation was the evaluation of methods of detecting damage in composites and relating measurements to structural properties. Static tensile tests were initially performed on three specimens of each laminate. The results are contained in Figure 2 along with residual static properties after fatigue testing. During static testing acoustic emission was detected. For the $(\pm 45^\circ/0^\circ/\mp 45^\circ/0^\circ)_T$ graphite/glass specimens, audible sound accompanied by a change in stiffness was detected at approximately half of ultimate load at which point a secondary linear modulus was evident (Figure 3). By contrast, the $(\pm 45^\circ)_S$ glass specimens exhibited linear stress-strain behavior and did not emit audible sound until approximately 90% of maximum load. It is believed that the sound emission in the first laminate was due to 0° fiber breakage and fiber/matrix debonding. This hypothesis is supported by the fact that the pure ±45° laminate, which would experience only matrix failure until near fracture, did not emit noise until near fracture. The audible noise is an indication that irreversible damage is being caused in the specimen. This statement is verified from observations of residual strength static tensile tests performed on $(\pm 45^\circ/0^\circ/\mp 45^\circ/0^\circ)_T$ specimens which had been fatigued to 10^7 cycles. These specimens did not emit audible sounds until 90% to 95% of their maximum load was reached but did exhibit measurable reductions in both axial modulus and strength indicating that some of the 0° fibers had fractured and debonded from the resin previously in fatigue. The stress vs strain relationship of one such specimen appears in Figure 3. Note that the curve exhibits a single linear portion. The slope of this portion falls between the primary secondary linear moduli of a previously untested specimen.

Residual static modulus and strength of the runout fatigue specimens at 10^7 cycles are seen in Figure 2 compared with the ultimate strength of virgin specimens. It should be noted that the specimens containing 0° fibers experienced a greater

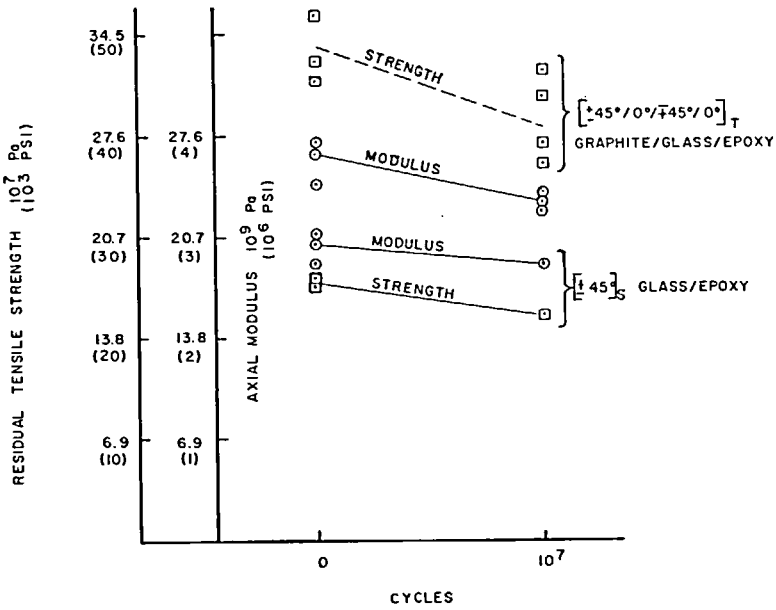

Figure 2. Fatigue damage reduces axial residual strength and stiffness.

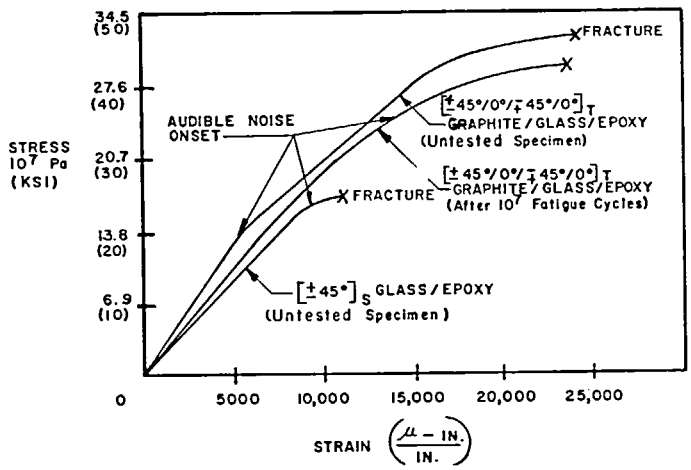

Figure 3. Accoustic emission occurs at lower fraction of ultimate strength for laminates with 0° fibers.

reduction in both strength and stiffness which is probably related to the breakage and debonding of 0° fibers discussed above.

Ten specimens of each laminate configuration were tested in axial fatigue. Fatigue results are summarized in Figure 4. Dynamic axial modulus and temperature were continuously monitored during all fatigue tests. Static torsional modulus, coin tap tests, and visual observations were made at 0, 10^6, 5×10^6, and 10^7 cycles. Fatigue tests were stopped at these times in order to complete these measurements. The relationships among dynamic axial modulus, temperature, and static torsional modulus, as a function of cycles are summarized in Figures 5 and 6.

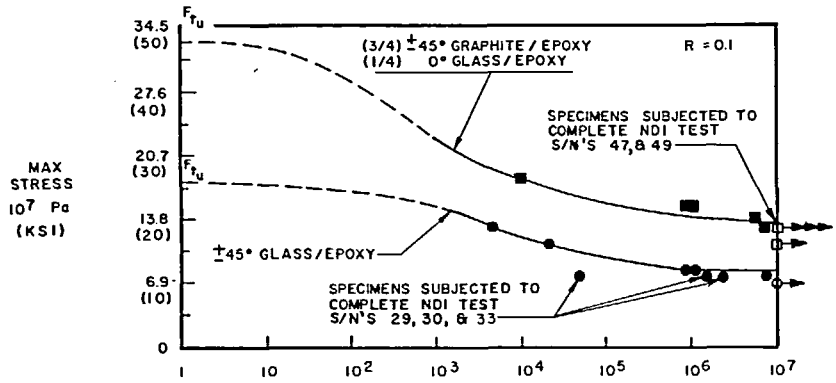

Figure 4. Fatigue behavior of E-glass/epoxy and graphite/E-glass/epoxy laminates.

The damage observed by axial modulus decrease is irreversible damage. This conclusion is drawn by analyzing the temperature data. We can see an initial drop in modulus along with an initial rise in temperature. The tests were then stopped for calibration at 10^6 and 5×10^6 cycles for a minimum of four hours and in most cases twenty to twenty-four hours. At these times the specimens quickly cooled to ambient temperature. Upon restart of the tests, the temperature returned quickly to the preceeding high temperature attained before. This indicates that the damage was irreversible because the frictional heating caused by the damage reached the same level. If the damage were not irreversible, the specimen would have heated more slowly, as the untested specimens did.

The rate of temperature rise and modulus decrease changed concurrently during the fatigue tests as seen in Figures 5 and 6. This is evidence that both are indicating the same phenomenon, to wit, the rate of accumulation of fatigue damage. It should be noted that most fatigue specimens which fractured exhibited a rise in temperature just prior to fracture even when they had previously exhibited a leveling off of temperature. This observation is consistent with a more rapid accumula-

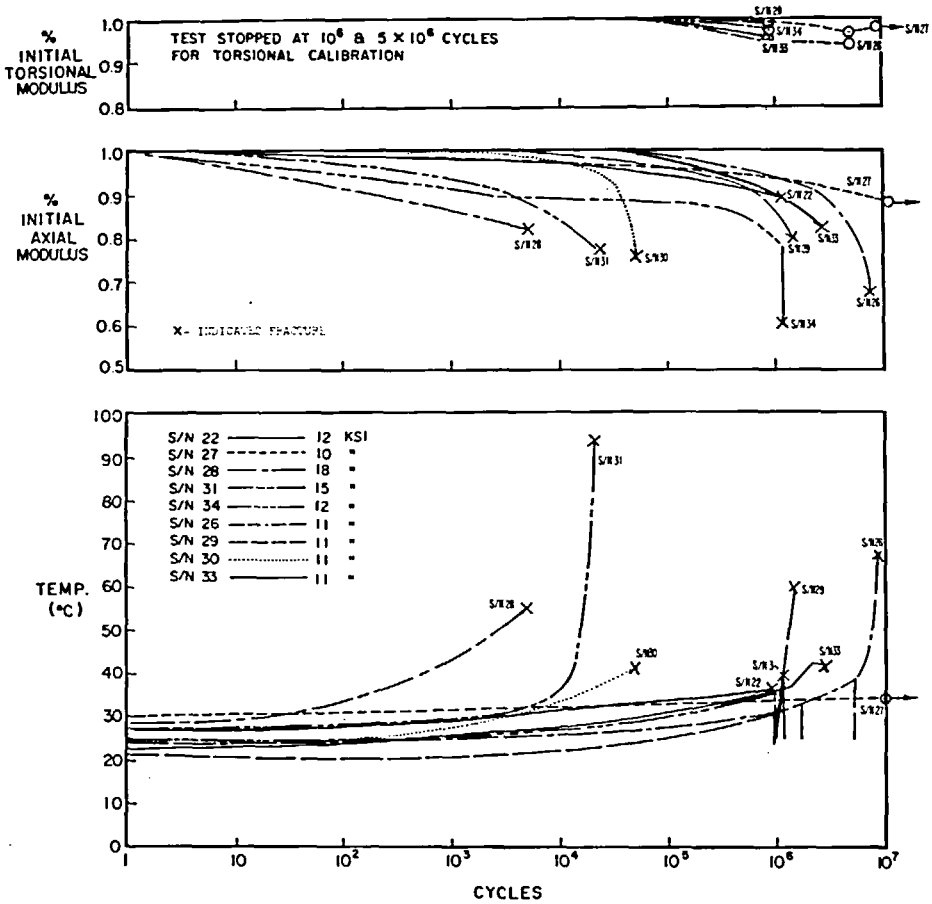

Figure 5. Modulus reduction and corresponding temperature increase indicate irreversible fatigue damage, and the onset of failure. $(\pm 45^\circ)_S$ E-glass/epoxy specimens.

tion of damage in the latter stages of fatigue. All of the specimens which were stopped at 10^7 cycles exhibited a leveling off of temperature. Had these tests been continued to fracture, it is believed that they too would exhibit a rise in temperature prior to fracture.

Although the heating and modulus decrease appear to change simultaneously throughout much of the fatigue life; by contrast, the heating and modulus decrease at final fracture do not correlate well. It is believed that early fatigue damage is more widespread throughout the volume of material with many small damage sites contributing to both specimen heating and modulus degradation. Later fatigue damage is probably the result of agglomeration of many small origin sites to form a dominant defect which propagates more rapidly. This is analagous to the early

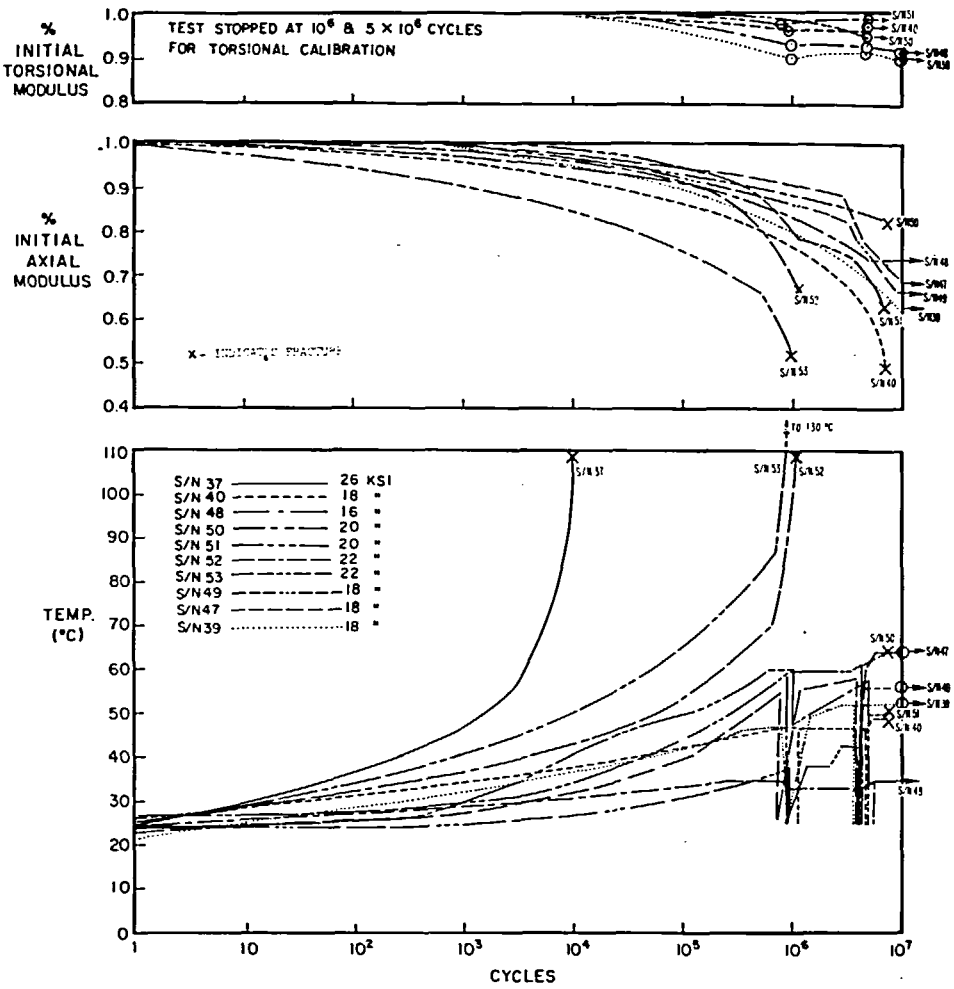

Figure 6. Modulus reduction and corresponding temperature increase indicate irreversible fatigue damage, and the onset of failure. $(\pm 45°/0°/\mp 45°/0°)_T$ graphite/glass/epoxy specimens.

states of fatigue initiation and later crack propagation in metals. The dominant defect might contribute significantly to stiffness decrease but only cause localized rather than general heating just prior to fracture. This could account for the behavior of some specimens which exhibited a slower temperature rise accompanied by a more rapid modulus decrease just before fracture. A late occurrance of the dominant defect could account for the behavior of specimens exhibiting a more rapid temperature rise but slower modulus decrease prior to fracture.

The damage detected in composites is also anisotropic in direction. The torsional

modulus did not change to the same extent as the axial modulus. This phenomenon is directly related to the choice of specimen orientation and type of tests. Orientations of $(\pm 45^\circ)_s$ and $(\pm 45^\circ/0^\circ/\mp 45^\circ/0^\circ)_T$ would tend to sustain matrix damage while being tested in the axial direction. The axial modulus is thus expected to decrease. However, because the ±45° fibers are still continuous they still carry the load when loaded in torsion even though matrix damage exists. Thus, one would expect to observe less change in torsional stiffness. By contrast, 0° specimens would be expected to exhibit little change in axial stiffness but large changes in torsional stiffness, as has been shown [9].

The feasibility of detecting local damage through local heating observations was accomplished by the use of temperature sensitive coatings and strips. An example is shown in Figure 7. It can be seen that local heating has turned regions of the white strip to black. This indicates that the temperature has exceeded 71°C (160°F) locally. The specimen subsequently fractured along the line indicated by the heating.

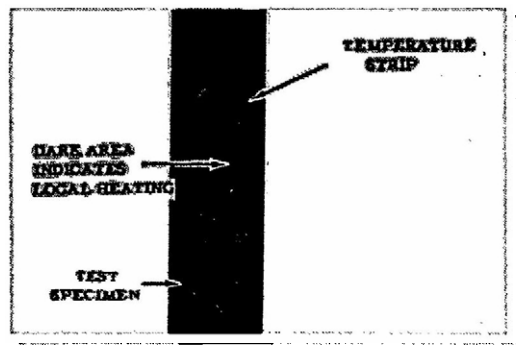

Figure 7. Early local fatigue damage indicated by heating is detected by temperature sensitive strips. (S/N 29 at 1.495 × 10^6 cycles)

Coin tap tests were conducted on all fatigue specimens. This procedure was found to be a poor indicator of early fatigue damage because significant indications were observed only at places of obvious visual damage. It is believed that the specimen configuration was too small to accurately detect any difference in pitch from one area to another because the sound was damped by the doubler and end plugs. Coin tap inspections might provide valid damage indication in large structures.

The two specimens of each laminate chosen to undergo more substantial nondestructive evaluation were fatigue tested at a stress level designed to cause fracture between 5×10^6 and 10^7 cycles as determined from prior fatigue testing. At this level it was believed that sufficient fatigue damage would be present to evaluate the effectiveness of the non-destructive inspection methods. The damage detection

methods employed were penetrant, ultrasonics, X-Ray radiography, and holography and were performed at 0, 10^6, 5×10^6, and 10^7 cycles.

Penetrant inspection failed to produce any indications of surface damage due to fatigue prior to fracture.

X-Ray radiation was evaluated using "soft" X-Rays of approximately 23*KV* with a beryllium window but did not prove to be a valuable inspection technique. No void or crack indications appeared evident. Very faint indications of the specimen seams were visible. These seam indications can be detected more positively by ultrasonic inspection.

Ultrasonic inspection proved to be valuable in detecting the presence of defects at the seams of the $(\pm 45^\circ)_S$ glass/epoxy specimens, as shown by a *C*-scan of *S/N* 30 in Figure 8. A photograph of the fractured specimen is also shown in Figure 8, and the fracture surface coincides with the locations of the indications in the ultrasonic *C*-scan. Other than defects at the seams, no other indications of fatigue damage were noted in the glass specimens prior to fracture. By contrast, the graphite-glass specimens exhibited localized regions of fatigue damage which were detected after 10^7 cycles but not present at 5×10^6 cycles (Figure 9). Because these tests were terminated at 10^7 cycles, it is not clear whether or not these indications would have precipitated fatigue failure eventually. Additional work is needed in this area.

A major problem encountered with ultrasonic inspection is the presence of noise and spurious signals during the ultrasonic inspection. This is to be expected for composites because of the large number of internal interfaces which reflect and attenuate sound.

Holographic interferometry was also evaluated as a damage detection method. The defect detected in the glass specimen *S/N*30 by the hologram constructed using a two-pulse system (Figure 10) coincides with the seam defect detected by ultrasonic *C*-scan (Figure 8). Defects were also detected in holograms taken at 10^7 cycles on graphite-glass specimens *S/N*47 and *S/N*49, as seen in Figure 11. These indications of fatigue damage were not present at 5×10^6 cycles. The indications are also in approximately the same position as the damage indications present on the ultrasonic *C*-scan plots as seen in Figure 9.

Ultrasonics, holography and thermography seemed to show the most promise as damage detection techniques. Further studies are needed to define the relative applicability of these three techniques. No quantitative relationship between these techniques and fatigue damage can be deduced at this time due to the paucity of data.

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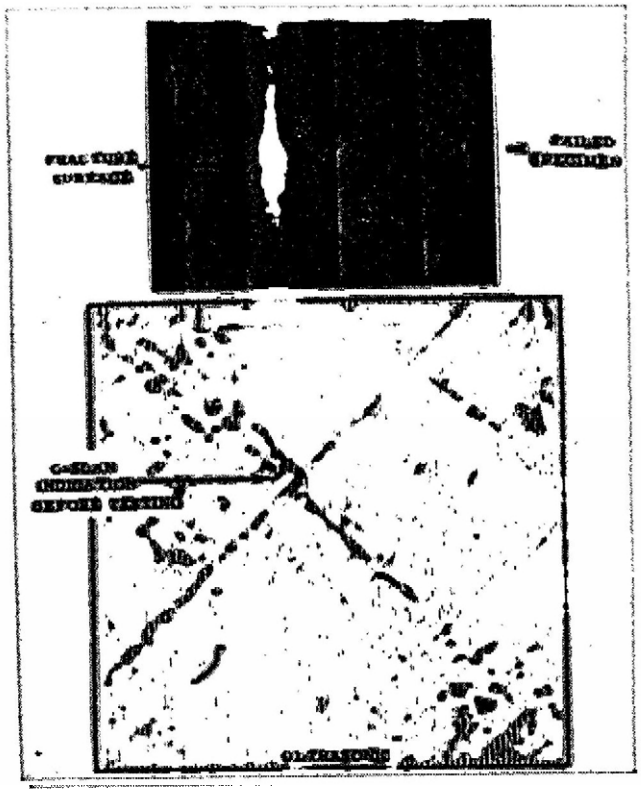

Figure 8. Ultrasonic C-scan detected the presence of seam defects which ultimately resulted in fatigue fracture.

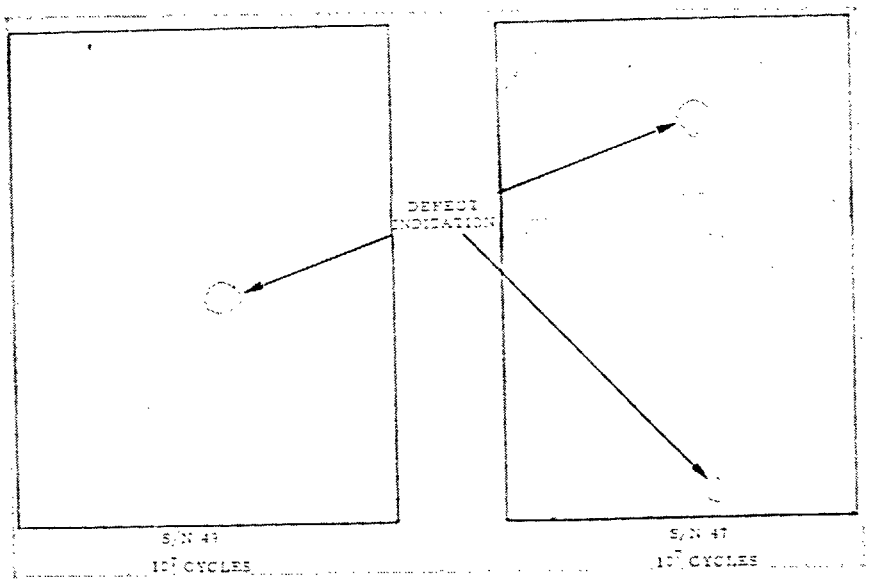

Figure 9. Fatigue damage indications were located by use of ultrasonic inspection.

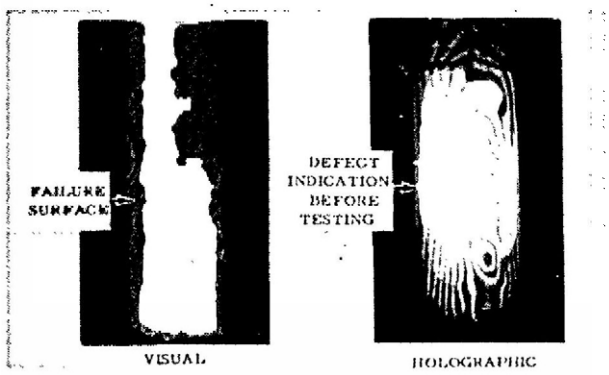

Figure 10. Holographic inspection detected a defect in the composite tube, which ultimately resulted in fatigue fracture.

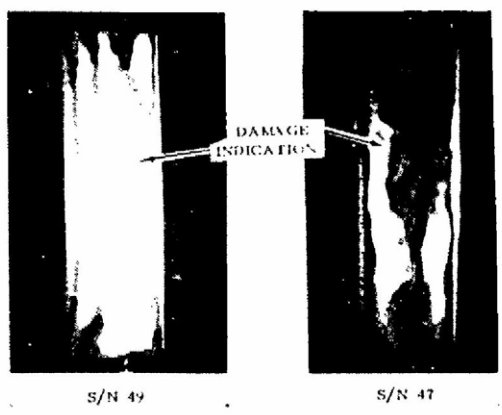

Figure 11. Fatigue damage indications detected through holographic inspection.

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