論文

The Effect of Preload on the Fatigue Ply Cracking in Quasi-Isotropic Laminated Composites

Jeffrey L. Timmer*, S.G. Lim** and H. Thomas Hahn*

준등방성 적층 복합재료의 Fatigue Ply Cracking에 대한 Preload 효과

Jeffrey L. Timmer*, 임 승 규**, H. Thomas Hahn*

초 록

인장-인장 피로하중조건하에 준등방성 적층 복합재료에 대한 피로손상거동을 플라이 크랙 밀도를 파라미터로 하여 평가하였다. 채택된 적층 복합재료 극한인장강도의 20% - 40% 범위의 일정 하중진폭을 갖는 피로하중조건하에서 적층 복합재료의 피로손상거동을 평가하였고, 또한 극한인장강도의 50% - 80%의 Preload와 동일한 피로하중조건을 조합한 하중조건하에서 적층 복합재료의 피로손상거동을 측정하여 Preload효과를 평가하였다. 적층 복합재료의 피로손상거동에 대한 Preload 효과는 Edge Replication 기법으로부터 얻어지는 플라이 크랙 밀도로 평가하였다.

피로손상거동에 대한 Preload 효과는 Preload 하중치와 계속되는 피로하중 진폭크기와의 조합에 의존한다. 본 논문에서 채택된 Preload 하중은 계속되는 일정진폭 피로하중보다 항상 크기 때문에 저되풀이수에서의 피로손상도는 Preload를 가한 경우가 Preload를 가하지 않은 경우보다 크다. 그러나 Preload에 의한 저되풀이수에서의 초기 피로손상도는 계속되는 일정진폭 피로하중 크기가 낮을 경우 더이상 성장하지 않는다. 본 논문에서는 극한인장강도의 70% 혹은 그 이상의 Preload를 가할 경우 계속되는 일정진폭 피로하중조건하에서의 피로손상도 진전 지연효과가 있음을 확인하였다. 또한 극한인장강도의 40% 수준의 일정진폭 피로하중조건하에서, 고되풀이수에서의 피로손상도는 Preload 하중치가 높을수록 오히려 감소함을 확인하였다. 따라서 고되풀이수 피로손상거동을 적층 복합재료 설계시 고려할 경우 Preloading 기법이 유용하게 활용될 수 있다.

ABSTRACT

Two types of tension-tension fatigue tests were conducted on quasi-isotropic laminates and fatigue damage was measured in the form of ply cracks. Baseline fatigue tests were run at constant-amplitudes ranging from 20% to 40% of the ultimate tensile strength (UTS) of laminates while specimens with preloads of 50% to 80% UTS were tested in fatigue at the same amplitudes. The ply crack densities determined from edge replications in preloaded specimens were compared to those without preload. The effect of preloads on fatigue damage in composite laminates has been examined in order to better understand the modes of damage development and to assess the

* Mechanical & Aerospace Eng. Dept., University of California, Los Angeles
** (주)선경케미칼 정밀화학연구개발실

effect of proof testing.

The effect of a preload on subsequent fatigue damage growth depended on the combination of both the preload level and the subsequent fatigue stress level. Since the tension preload was always higher than the tension-tension fatigue stress level, damage in preloaded specimens was more severe in the low-cycle region than nonpreloaded specimens. However, this preload-induced damage did not grow any more if the fatigue stress level was kept low. Preloads just above levels that cause significant damage (70% UTS and above here) appeared to retard fatigue damage development. At the highest tension-tension fatigue stress level of 40% UTS, the high-cycle damage in the form of matrix cracking rather decreased with increasing preload level. Thus, preloading could be beneficial at this stress level as far as the high-cycle ply crack damage is concerned.

1. INTRODUCTION

Fatigue behavior of laminated composites has been studied by many researchers [1-7]. These researchers have studied many aspects of fatigue behavior which may be grouped into three basic ways to characterize fatigue effects on composite materials. The first is to use the method used for metals, namely the Strength-Life (S-N) curve which relates fatigue cycles to cyclic amplitude. The second method assumes that damage occurs and that the damage causes either the stiffness or the residual strength (post-fatigue static strength) of a laminate. Once the residual stiffness or strength are known, presumably, they can be related to remaining life. The third method is to investigate the actual damage occurring in a laminate. Once the types of damage that occur are determined, they can be related to loading and to remaining life. The damage can be characterized in terms of matrix cracking, longitudinal splitting, and delamination.

In this paper, a test program was developed to determine the damage development due to fatigue and proof loads or preloads. Static tests were used to obtain material properties and constant-amplitude fatigue tests were used to define a baseline. Preloads were applied to test coupons which were then fatigued. Damage accumulation in the form of matrix cracks was monitored during these tests. Finally, the trends in damage accumulation due to the varying preloads and fatigue stresses were examined.

2. EXPERIMENTAL PROCEDURE

Static tensile tests were performed to determine the mechanical properties of quasi-isotropic laminates used for testing. Additional static tests were performed to assess ply cracking development during static loading. Baseline fatigue tests were performed at a constant amplitude (CA) with a stress ratio, R of 0.1. These baseline tests were performed in 10% increments from 20% to 40% of the ultimate tensile strength (UTS). To gauge the effects of preloading, specimens were loaded from 50% to 80% UTS before being fatigued. The preloads were applied by at the rate of 0.1 hertz (R=0). All subsequent fatigue cycles had a sinusoidal loading rate of 10 hertz. The ply crack densities were periodically measured at the edge during the fatigue tests.

2.1. Specimen Preparation

The material system used was Hercules AS4/3501-6 graphite/epoxy. The laminate lay-up was quasi-isotropic [0/45/-45/90]S3 making a total of 24 plies. The laminate panels 61.0 by 61.0 cm were fabricated in an autoclave following the manufacturer's suggested cure cycle. The panels were C-scanned to check for any gross defects or delaminations and cut with an abrasive diamond saw (180 grit) into 20.3 by 2.54 cm coupons. One of the specimen edges was then sanded to 800 grit to facilitate monitoring of damage growth.

2.2. Test Procedure

For improved gripping, the specimen end section was roughed to 220-320 grit. The 6061 aluminum tab with 0.32-cm thick was used to prevent specimen damage during gripping. The aluminum tab edges that would contact the specimen gage section were rounded to a 1.5 mm radius to reduce any stress concentration. The inside face of the end tab was bead blasted and left untouched before attaching to the specimen (no adhesive was used). All tests were performed on an MTS 22 Kips servohydraulic testing machine. The grips utilized were hydraulic with 5.08-cm-wide by 7.62-cm-high jaws as shown in figure 1. All testing was conducted at ambient laboratory conditions. Static tensile tests were performed to at 0.077 cm/minute in accordance of ASTM D3039 standard.

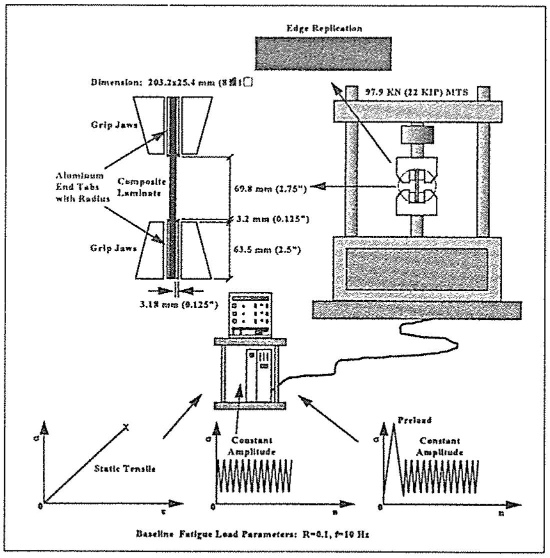


Fig. 1. Experimental Setup

2.3. Replication Procedure

The replicating tape is an acetate strip which is softened with acetone and applied with light pressure to the specimen edge while under load, where it is allowed to dry for 5 minutes. The result is an inverted replica of the edge on which damage can easily be viewed using a light microscope. The observed damage was in the form of cracks within off-axis plies of the same orientation as seen in the photograph in figure 2. The cracks in each ply were counted from the replica over a 12.7 mm length. The data was quantified in terms of a crack density which was defined as the number of cracks in a group of contiguous plies with the same orientation per unit length of the laminate. Figure 2 shows how individual plies were identified. The plies were numbered from the middle (Z=±1) toward the outer plies (Z=±12). Crack densities were averaged over each symmetric pair of (±2) plies. All replicas were taken while under tensile stress to open the cracks and allow the acetate solution to seep in. At fatigue stresses of 30% UTS and higher, the stress during replication was 30% UTS.

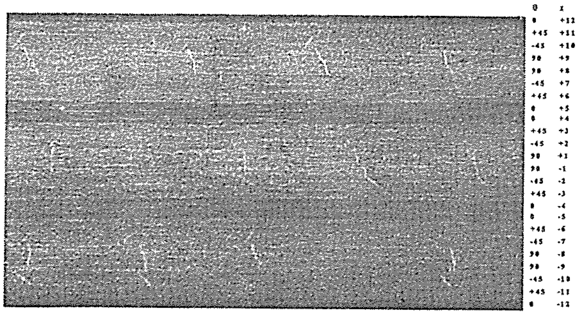


Fig. 2. Potomicrography and Ply Numbering of$[0/45\text{-}45/90]_{S3}$ Laminate

3. RESULTS AND DISCUSSION

3.1. Static Tensile Test Results

The quasi-isotropic laminates had an average ultimate tensile strength (UTS) of 747 MPa and

Table1. Static Tensile Test Results of Quasi-Isotropic Laminates

	σ_{ULT}		ε_{ULT}	$E_{11}^{(1)}$	
	[MPa]	[Ksi]	[%]	[GPa]	[Msi]
26B5	797.2	115.7	1.49	55.75	8.09
26A5	781.3	113.4	1.44	56.75	8.24
25F9	705-.5	102.4	1.33	N/A(2)	N/A
25E5	730.3	106.0	1.39	54.59	7.92
AVG	747.2	108.4	1.41	55.12	8.00
S.D.	35.63	5.2	0.05	1.26	0.18
Cov.[%]	4.77		3.67	2.29	

1. Longitudinal stiffness obtained for strain ranging from 0.2% to 1.0% by linear regression.
2. Load voltage vs strain data lost. Only the final load and strain available

an average longitudinal Young's modulus of 55.1 GPa. The average failure strain was 14,100 microstrain (see table 1). From the edge replicas of the static test specimens, the first damage identified was the ply cracking of the 90° plies. Ply cracks consist of matrix and fiber/matrix interface failure in the off-axis plies. When cracks appeared in 90° plies, they propagated immediately through the entire thickness and were arrested at the -45° interfaces. More cracks appeared in 90° plies as the applied stress increased. As shown in figure 2, most of -45° ply cracks appeared at either end of the 90° ply cracks. No cracks in +45° plies were visible during static tension.

In specimens with 16 replications under static tensile test, the first cracks appeared at 28% UTS in all three sets of 90° plies (see figure 3-(a)). The cracks in the 90° plies multiplied as the stress increased. At 44% UTS, the -45° plies began to crack. During the last replication before failure (96% UTS) the crack densities in 90° plies averaged 18.5 cracks/cm. In contrast, specimen with 8 replications shown in figure 3-(b) yielded crack densities at 96% UTS of only 13.4 cracks/cm for the outside 90° plies (Z = ±8,9) and 15.0 for the middle 90° plies (Z = ±1). In addition, first ply cracking occurred at 40% UTS for the 90° plies and 64% for the -45° plies.

There are several possible reasons for the ply cracking behavior under static tensile tests. The first is of course the specimen variability as crack densities show a large scatter. The second reason is that ply cracking may not be solely a function of the applied stress but also of load history. Loading of specimens with 16 replications was interrupted more often than that of 8 replications, effectively increasing the time under load. More frequent replications and time under load seem to increase the ply crack densities in off-axis plies

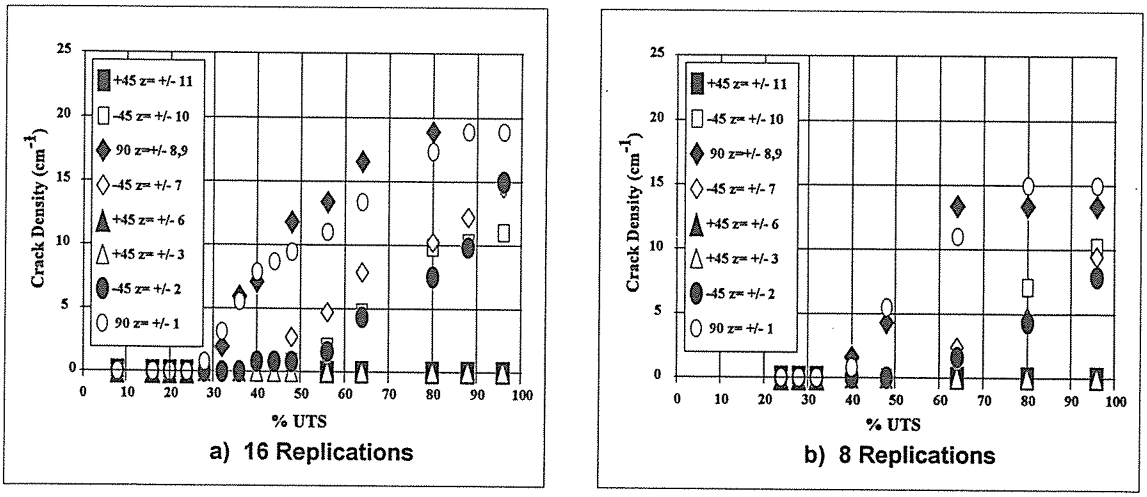
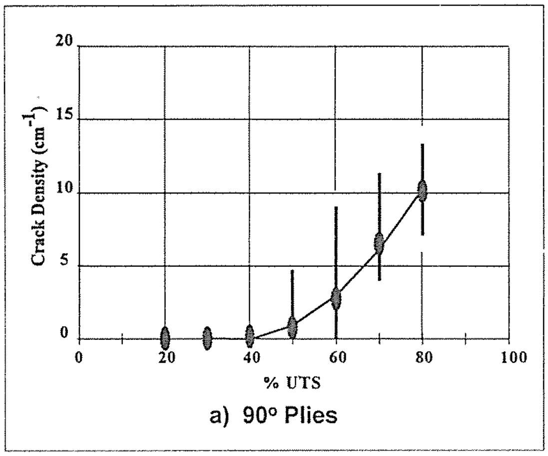


Fig. 3. Ply Cracking Due To Quasi-Static Tensile Loading



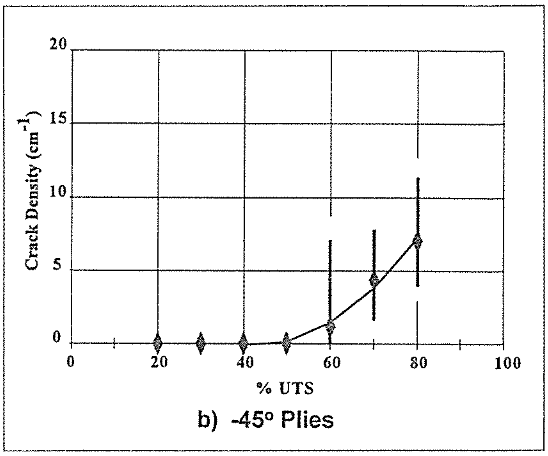
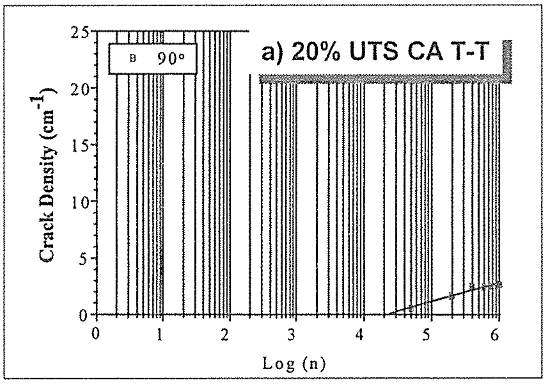


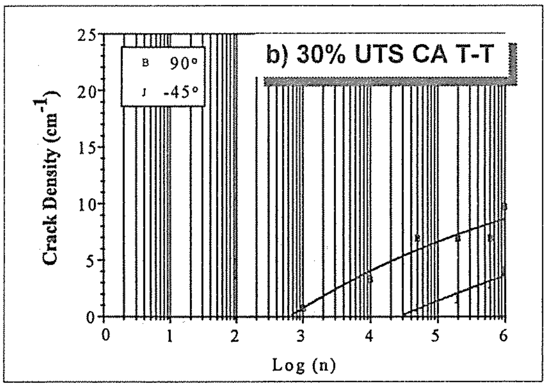
Fig. 4. First-Cycle Ply Cracking

held at the same stress level.

3.2. First-Cycle Ply Crack Densities

Figure 4 illustrates the crack densities generated after the first cycle of fatigue loading or preload The 90° plies are shown in figure 4-(a) while the -45° plies are seen in figure 4-(b), repectively. The first fatigue cycle was conducted at 0.1 Hz although the subsequent cycling after replication was conducted at 10 Hz. As shown in the static case, ply cracking appears first in the 90° plies. The first ply cracking in the 90° plies is due to ply thickness effect in the transverse cracking behavior. Also, because of Mode I ply cracking in the 90° plies, the required ply cracking energy is lower than that of the -45° plies. No cracks are found in +45° plies due to the contsraint effect of the outer 0° plies during first cycle loads.





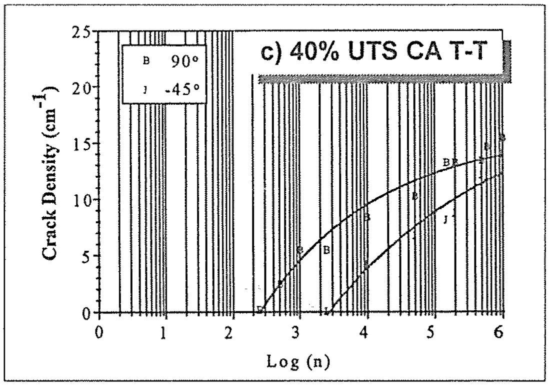


Fig. 5. Ply Crack Accumulation Due to Constant-Amplitude(CA) Fatigue Loading

Applying a preload to a specimen is very similar to quasi-static tensile loading, the only difference being the rate at which the load is applied and the time the load is held. Therefore, at the same applied stress level, the crack densities after the first fatigue cycle preload should be the same as those in static tension if there is no effect of loading rate or hold time. From the two sets of figure 3 and 4, it is seen that in static tension, cracks appear earlier and multiply more quickly than during the first fatigue cycle or preload. This observation is in agreement with the effect of the replication frequency.

3.3. Constant-Amplitude Fatigue

Ply crack density accumulation versus fatigue cycles under CA fatigue loading of 20%, 30%, and 40% UTS are shown in figure 5. At 20% UTS CA fatigue a very small number of ply cracks in 90° plies are developed at high fatigue cycles (200,000+ cycles). No cracks are initiated in -45o° plies under fatigue loading until 10^6 cycles A threshold stress level at which fatigue cracking becomes significant appears to exist between CA of 20% and 30% UTS. While 20% UTS fatigue loading produces very little crack damage at high cycles, 30% UTS fatigue loading produces significant amounts of cracking at fatigue cycles on the order of 10^6. At 30% UTS CA fatigue the -45° ply cracks begin to appear at approximately 10,000 cycles and multiply in an approximately logarithmic fashion. Both 90° and -45° ply cracking did not appear to saturate, but continued to increase until the tests were stopped at 10^6 cycles. Forty percent UTS CA fatigue produces ply cracking in quicker in both 90° and -45° plies and results in faster accumulation of ply cracks. The 90° plies begin cracking immediately and progress to just under 15 cracks/cm at close to 300,000 cycles where saturation occurs. The -45° plies start cracking later at about 2,000 cycles but increase more quickly to 13 cracks/cm at 10^6 cycles but do not saturate at that time.

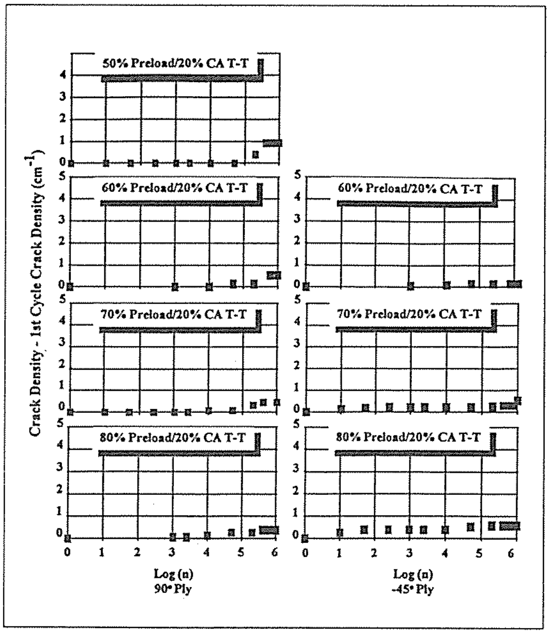


Fig. 6. Ply Crack Accumulation After Preloading Due To Preload/20% UTS CA Fatigue Loading

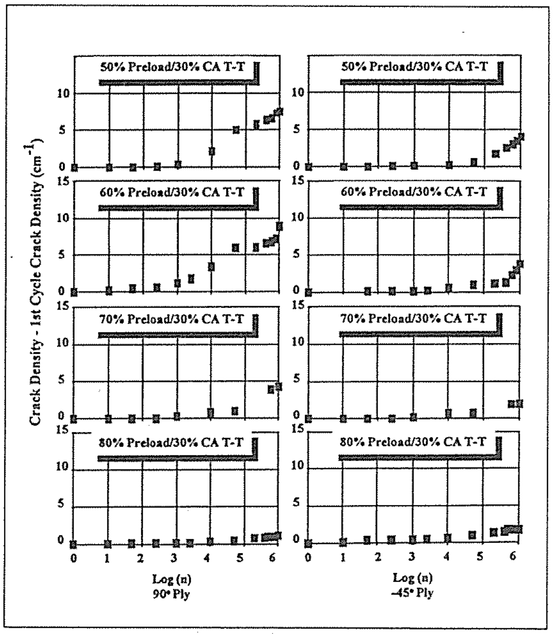


Fig. 7. Ply Crack Accumulation After Preloading Due To Preload/30% UTS CA Fatigue Loading

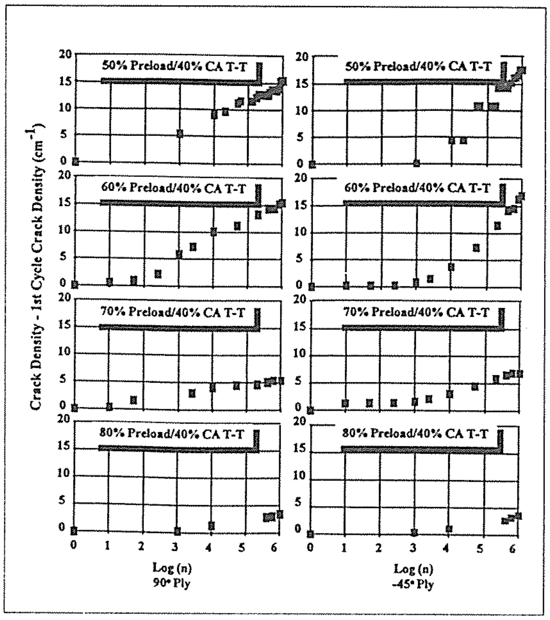


Fig. 8. Ply Crack Accumulation After Preloading Due To Preload/40% UTS CA Fatigue Loading

3.4. Constant-Amplitude Fatigue With Preloads

The effects of preload on the subsequent fatigue ply crack growth are shown in figures 6 to 8. The ply cracking due to preload/20% UTS CA fatigue as shown in figure 6 does not appear the additional ply cracking due to subsequent CA fatigue loading in both 90° and -45° plies. There is a ply cracking retardation behavior due to preload. However, as shown in figures 7 and 8, 30% and 40% UTS CA fatigues with preloads less than 60% UTS appear to induce the subsequent ply carck growth compared to higher preloaded (70% and 80% UTS) specimens. The preload effects on the ply crcking retardation of figures 6 to 8 can be summarized as follows. Higher preload causes more initial ply cracking but retard further accumulation. However, ply cracking retardation is reduced for higher load fatigue.

Figure 9 shows the first cycle crack density and the resulting crack density at 10^6 cycles of preload/CA fatigue tests. If the preload damage is more severe than the fatigue damage without preload, then there is no damage growth in subsequent fatigue. Otherwise, there will be damage growth in subsequent fatigue. The effect of preload is negligible for preload less than 60% UTS. However, higher preload may be beneficial for longterm high load level fatigue.

4. CONCLUSIONS

Recorded here is the ply cracking due to constant-amplitude fatigue loads spaced within the

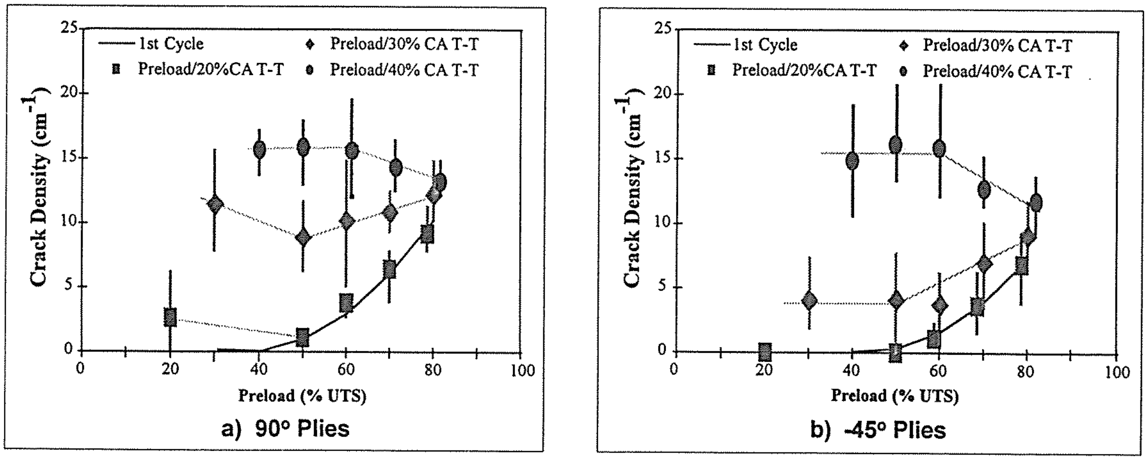


Fig. 9. First and 10^6Cycles Ply Densities Versus Preload

likely design range. At these constant-amplitude fatigue loads, the effect of preloads on damage is assessed, giving results for the simplest form of variable loading. The results can be used as a building block to use with other data to eventually predict damage due to spectrum fatigue loading. The effect of preload on subsequent fatigue damage growth depends on the combination of both the preload level and the subsequent fatigue stress level. Since the preload is higher than the fatigue stress level, the resulting damage in the low-cycle region is more severe. The preload-induced damage did not grow any more if the fatigue stress level was kept low. Preloads which are just above levels which cause significant damage (70% UTS and above here) appear to retard fatigue damage development. At the highest fatigue stress level of 40% UTS, the high-cycle damage rather decreases with increasing preload level. Thus, preloading would be beneficial at this stress level as far as the high-cycle damage is concerned.

REFERENCES

1. Awerbuch, J. and Hahn, H. T., "Fatigue and Proof-Testing of Unidirectional Graphite/Epoxy Composite," Fatigue of Filamentary Composite Materials, ASTM STP 636, 1977. pp. 248-266.

2. Hahn, H. T. and Kim, R. Y., "Proof Testing of Composite Materials," Journal of Composite Materials, Vol. 9, 1975, pp. 297-311.

3. Mar, J. M., "Fracture, Longevity, and Damage Tolerance of Graphite/Epoxy Filamentary Composite Material," Journal of Aircraft, Vol. 21, No. 1, 1984, pp. 77-83.

4. Razvan, A., Bakis, C. E., Wagneiz, L. and Reifsnider, K.L., "Influence of Cyclic Load Amplitude on Damage Accumulation and Fracture of Composite Laminates," Journal of Composites Technology and Research, Vol. 10 No. 1, Spring 1988.

5. Hwang, W. and Han, K. S., "Cumulative Damage Models and Multi-Stress Fatigue Life Prediction," Journal of Composite Materials, Vol. 20, 1986, pp. 125-151.

6. Masters, J. E. and Reifsnider, K.L., "An Investigation of Cumulative Damage Development in Quasi-Isotropic Graphite /Epoxy Laminates," Damage in Composite Materials, ASTM STP 775, 1988, pp. 40-62.

7. Stinchcomb, W. W., "Nondestructive Evaluation of Damage Accumulation Processes in Composite Laminates," Composites Science and Technology, Vol. 25, No. 2, 1986, pp. 103-118.