COMPARISON OF MODE II AND III MONOTONIC AND FATIGUE DELAMINATION ONSET BEHAVIOR FOR CARBON/TOUGHENED EPOXY COMPOSITES

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Abstract: Monotonic and fatigue tests were performed to compare the Mode II and III interlaminar fracture toughness and fatigue delamination onset for Tenax-HTA/R6376 carbon/toughened epoxy composites. The Mode II interlaminar fracture toughness and fatigue delamination onset were characterized using the end-notched flexure (ENF) test while the Mode III interlaminar fracture toughness and fatigue delamination onset were characterized by using the edge crack torsion (ECT) test. Monotonic tests show that the Mode III fracture toughness is higher than the Mode II fracture toughness. Both Mode II and III cyclic loading greatly increases the tendency for a delamination to grow relative to a single monotonically increasing load. Under fatigue loading, the Mode III specimen also has a longer life than the Mode II specimen.

INTRODUCTION

Resistance to composite delamination is typically characterized using test methods designed to measure interlaminar fracture toughness due to opening (Mode I), sliding shear (Mode II) and scissoring shear (Mode III) fracture Modes. The Mode I toughness, G_{Ic}, is generally characterized using the double cantilever beam (DCB) test (see Figure 1) and the Mode II toughness, G_{IIc}, is often characterized using the end notched flexure (ENF) test (see Figure 2). The DCB Mode I interlaminar fracture toughness test has been standardized and resulted in the publication of ASTM Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites (D5528-94a). Standardization development for ENF Mode II interlaminar fracture toughness is underway. The DCB and ENF specimens consist of a unidirectional laminate with a mid-plane embedded insert at one end subjected to tensile and three-point bending loading, respectively. The resistance to these two fracture Modes has been compared in the literature [1-2]. However, there has been no comparison of the Mode II and III interlaminar shear fracture toughness and fatigue behavior of laminated composites in the literature due to the lack of a viable Mode III interlaminar fracture toughness test. However, recent analytical and experimental evaluations on the edge crack torsion (ECT) specimen reaffirm that the ECT test is a promising Mode III interlaminar fracture toughness test method for laminated composites [3-6]. The ECT test consists of a $[90/(\pm45)_n/(\mp45)_n/90]_s$ symmetric laminate with a delamination introduced by a non-adhesive film at the mid-plane along one edge and loaded in a special fixture to create torsion along the length of the laminate (Figure 3). Both experimental evidence and three dimensional finite element analysis of the ECT test specimen indicated that a Mode III delamination initiates from the insert in the ECT specimen [6].

The objective of this paper is to carry out an experimental investigation to compare the Mode II and III interlaminar fracture toughness and fatigue delamination onset for Tenax-HTA/R6376 carbon/toughened epoxy composites. The Mode II fatigue behavior was characterized using the ENF test [1-2]. The Mode III interlaminar fracture toughness and fatigue delamination onset was characterized by using the ECT test [7].

MODE II FRACTURE AND FATIGUE TESTS

The ENF specimens were cut from a unidirectional laminated panel made from Tenax-HTA/R6376 carbon/toughened epoxy tape plies. The average specimen width b and thickness h were 25.5 and 4.1 mm (see Figure 2). A 13 μm non-adhesive Polytetrafluoroethylene (PTFE) film was placed at the laminate mid-plane during manufacture. The length between the two supports (2ℓ) is 100 mm. The ENF apparatus is shown in Figure 2 (b) where a spring-loaded displacement gauge is mounted under the specimen as shown.

The specimens were loaded and unloaded in the elastic range first to obtain the specimen compliance for initial delamination lengths of a=0, 14, 19, 24, 29, 34, and 39 mm. This was achieved by keeping the supports fixed and sliding the specimen in the rig to simulate different initial delamination lengths. Sliding the specimen produced different distances between the right roller support and the tip of the insert (a in Figure 2a). Specimens were loaded in displacement control with a constant stroke rate of 0.5 mm/min.

Load (P) and displacements (δ) were recorded and compliance ($C=\delta/P$) was calculated. After the compliance measurements, a least squares linear regression of the following form was performed, yielding

$$C = C_0 + m' a^3 \tag{1}$$

where C_0 and m' are constants. The specimen was then positioned in the test fixture so that $a/\ell=0.5$, and loaded until the delamination started to grow from the insert. The Mode II fracture toughness was evaluated based on the compliance calibration method [1] as

$$G_{IIc} = \frac{3m' a^2 P_c^2}{2b} \tag{2}$$

where P_c is the critical load corresponding to delamination onset from the insert and G_{IIc} is the Mode II interlaminar fracture toughness.

A total of four specimens were tested. The test results are presented in Table 1. Note that δ_c is the displacement correspond to the critical load, P_c. The average Mode II fracture toughness G_{IIc} from the four ENF specimens is 1.12 $kJ{\cdot}m^{-2}$ with a coefficient of variation of 3%.

Table 1. Monotonic ENF Test Results

Specimen	Thickness (mm)	m' (N^{-1} m^{-2})	δ_c (mm)	P_c (kN)	G_{IIc} (kJ·m^{-2})
1	4.05	0.0169	2.34	1.38	1.08
2	4.11	0.0165	2.26	1.41	1.11
3	4.08	0.0184	2.16	1.36	1.15
4	4.09	0.0175	2.24	1.39	1.12

Fatigue ENF tests were performed to establish the relationship between the peak cyclic value of strain energy release rate, G_{IImax}, and the number of fatigue cycles until the onset of delamination growth. Because the onset of delamination growth in fatigue was too subtle to observe visually, a criterion based on a small reduction of stiffness (increase of compliance) was used. Two definitions to determine the number of cycles until the onset of delamination growth were used in this investigation. These are the number of cycles until the compliance has increased by 1% and 5%, respectively, which are approximately equivalent to a 1% and a 5% decrease in the peak cyclic load. These two levels were chosen to be consistent with the Mode I DCB fatigue test method currently balloted within ASTM committee D30 as a candidate standard test method for Mode I fatigue delamination growth onset of unidirectional fiber reinforced polymer matrix composites.

The fatigue ENF tests were run under displacement control in a servohydraulic loading machine. The test frequency was 5 cycles per second (Hz). The displacement ratio, ($R=\delta_{min}/\delta_{max}$), was 0.1 (R=0.1). The positive displacement ratio was chosen to maintain constant contact of the loading point and the specimen. The ratio R=0.1 was chosen to be consistent with the Mode I DCB fatigue test method mentioned above. Five values of G_{IImax} were used, corresponding to G_{IImax}=40, 30, 20, 15 and 10% of G_{IIc} (448, 336, 224, 168 and 112 J/m^2). Two specimens were tested at each G_{IImax} value. A 1%, and even a 5%, peak cyclic load reduction is not easy to discern in the experiment. Frequent stops to determine compliance from monotonic loading is necessary to get the number of cycles close to the targeted increase in compliance. Figure 4 shows the compliance change (%) as a function of the number of cycles for an ENF specimen at G_{IImax}= 224 J/m^2. The fluctuation of the compliance change seen in Figure 4 is an indication of the accuracy in compliance measurement. Hence, the 5% compliance increase as the onset of fatigue delamination may be more reasonable. Also, there is clear evidence of fatigue delamination growth by observing separated ENF specimens after reaching 5% compliance increase (Figure 5).

MODE III TESTS

The ECT laminate specimen is an 83 mm × 38 mm, shown as L'×B in Figure 3, rectangular plate. The average specimen thickness (2h) was 3.8 mm. The ECT specimens were cut from a $[90/(\pm45)_n/(\mp45)_n/90]_s$ symmetric laminated panel with 13 μm PTFE films embedded at the mid-plane along one edge. Due to the unstable delamination growth of the ECT specimen [6], 15 specimens with five delamination lengths of 8, 11, 15, 19 and 23 mm were used for compliance calibration. In the ECT test, the transverse load is introduced at one point by compression of the loading pin while the fixture provides reaction supports at three other points (Figure 3). The specimen is subjected to end torsion induced by a pair of counteracting moments at a distance L=76 mm. Each moment is generated by a pair of forces with a moment arm W=32 mm.

Monotonic tests were performed to establish the expression relating compliance, C, to delamination length $\tilde{a}$. Each specimen was loaded in the elastic range with a constant stroke rate of 1.5 mm/min first to determine the compliance. The load, P, applied monotonically to the loading pin and the load-point displacement, δ, were monitored during the test. The inverse of the compliance ($1/C=P/\delta$) versus the normalized delamination length ($\tilde{a}/B$) for all the specimens were established. A linear least squares fit yielded

$$\frac{1}{C} = A\left[1 - m\left(\frac{\tilde{a}}{B}\right)\right] \tag{3}$$

with the values of constants m=0.95 and A=176 kN/m.

The Mode III fracture toughness, G_{IIIc}, was evaluated based on the compliance calibration method [6] as

$$G_{IIIc} = \frac{mP_c^2C}{2LB\left[1 - m\frac{\tilde{a}}{B}\right]} \tag{4}$$

where P_c is the critical load at delamination onset denoted by a drop in P-δ plot. The critical load P_c, the inverse of the compliance (1/C), and the fracture toughness of individual specimens are presented in Table 2 along with the specimen thickness and initial delamination length. Four specimens were tested to failure monotonically to obtain a Mode III fracture toughness G_{IIIc} of 1.54 kJ/m^2 with a coefficient of variation of 16%.

Table 2. Monotonic ECT Test Results

Specimen	2h (mm)	$\tilde{a}$ (mm)	1/C ($kN \cdot m^{-1}$)	P_c (kN)	G_{IIIc} ($kJ \cdot m^{-2}$)
1	3.82	7.6	161	1.17	1.72
2	3.79	15.2	117	0.76	1.28
3	3.79	19.1	102	0.67	1.36
4	3.81	22.9	87.6	0.64	1.79

Fatigue ECT tests were performed to establish the relationship between the peak cyclic value of strain energy release rate, G_{IIImax}, and the number of fatigue cycles until the onset of delamination growth. The onset of delamination growth was defined by the reduction of stiffness (increase of compliance). Similar to the ENF fatigue tests, 5% compliance increase were used to define the onset of fatigue delamination growth. Fatigue delamination onset was observed by dye penetrant enhanced X-radiographs of the ECT specimens after fatigue tests. The fatigue tests were run under displacement control in a servohydraulic loading machine. The test frequency was 5 Hz. The displacement ratio, ($R=\delta_{min}/\delta_{max}$), was 0.1 (R=0.1). Four values of G_{IIImax} were used, corresponding to G_{IIImax}=40, 30, 20 and 15% of G_{IIIc} (614, 461, 307 and 230 J/m^2, respectively). Frequent stops were made during the fatigue test to record the load-displacement curve from static test to obtain the compliance after certain numbers of cycles.

RESULTS AND DISCUSSION

The maximum applied G for Mode II and III against the numbers of cycles to reach 5% compliance increases are shown in Figure 6. The toughness data for both Mode II and III are shown on the N=1 line. As noted earlier, runouts in the tests are shown by symbols with arrows pointing to the right. The Mode III toughness is greater than the Mode II toughness. Both Mode II and III cyclic loading greatly increases the tendency for a delamination to grow relative to a monotonically increasing load. When comparing the fatigue Mode II (circular symbols) and III (diamond symbols) responses, the number of cycles to delamination onset is higher for Mode III than that for Mode II at similar applied G levels. Hence, at the same applied maximum G, the Mode III specimen has a much longer life than the Mode II specimen.

SUMMARY

Both monotonic and fatigue tests were performed to compare the Mode II and III interlaminar fracture toughness and fatigue delamination onset for Tenax-HTA/R6376 carbon/toughened epoxy composites. The Mode II interlaminar fracture toughness and fatigue delamination onset was characterized using the End-Notched Flexure (ENF) test. The Mode III interlaminar fracture toughness and fatigue delamination onset was characterized by using the Edge Crack Torsion (ECT) test. Both Mode II and III interlaminar fracture toughness were obtained from compliance calibration method. Monotonic tests show that the Mode III interlaminar fracture toughness is higher than the Mode II interlaminar fracture toughness. Fatigue delamination onset growth was observed for both Mode II and III fatigue tested specimens after the 5% compliance increase was reached. Both Mode II and III cyclic loading greatly increases the tendency for a delamination to grow relative to a monotonically increasing load. When comparing the fatigue Mode II and III responses, the number of cycles to delamination onset is higher for Mode III than that for Mode II at similar applied G levels. Hence, at the same applied maximum G, the Mode III specimen has a much longer life than the Mode II specimen.

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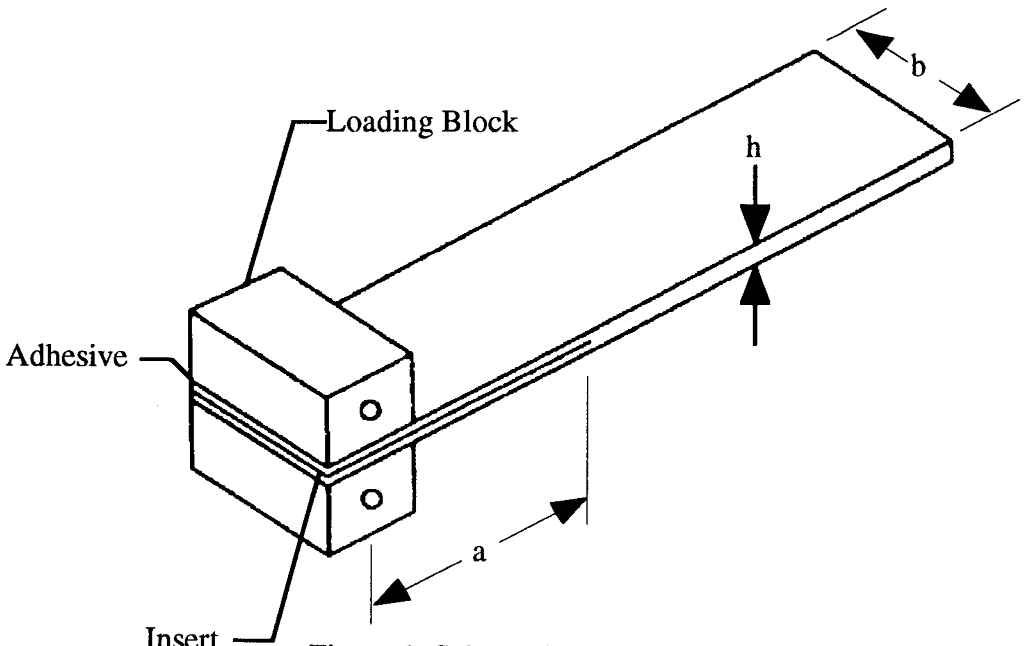
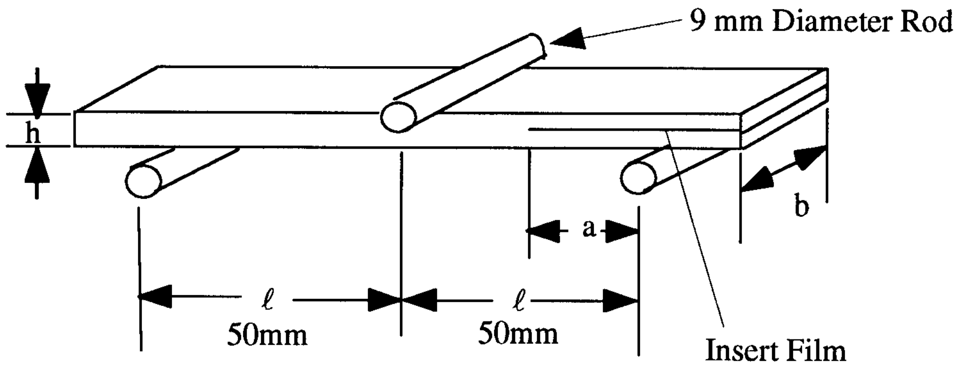
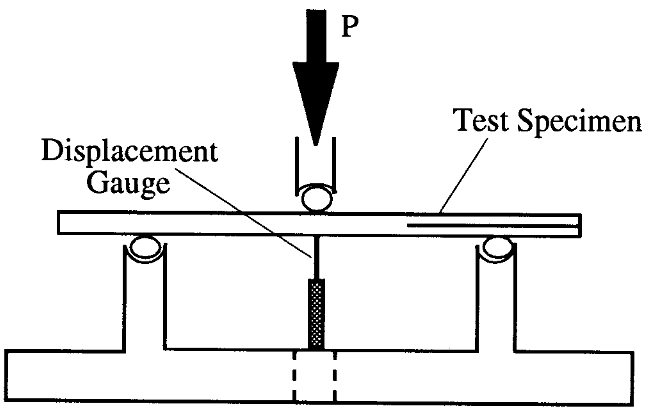


Figure 1. Schematic of the DCB Specimen.

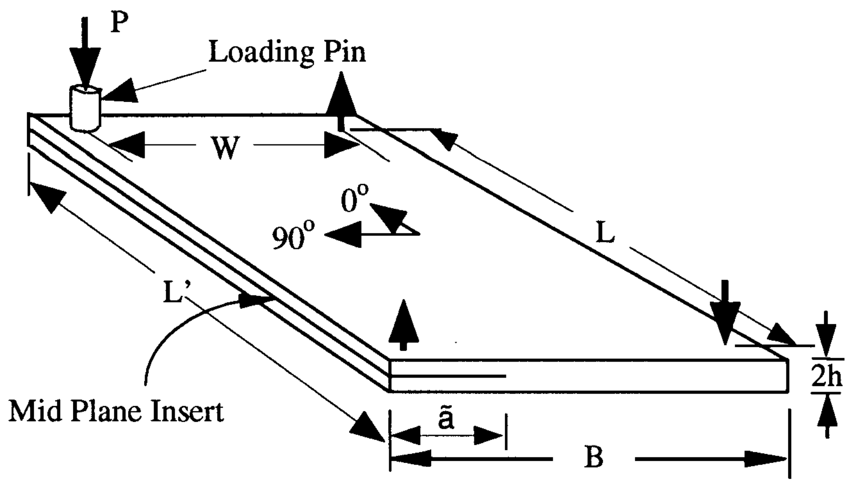


(a) ENF Test Configuration

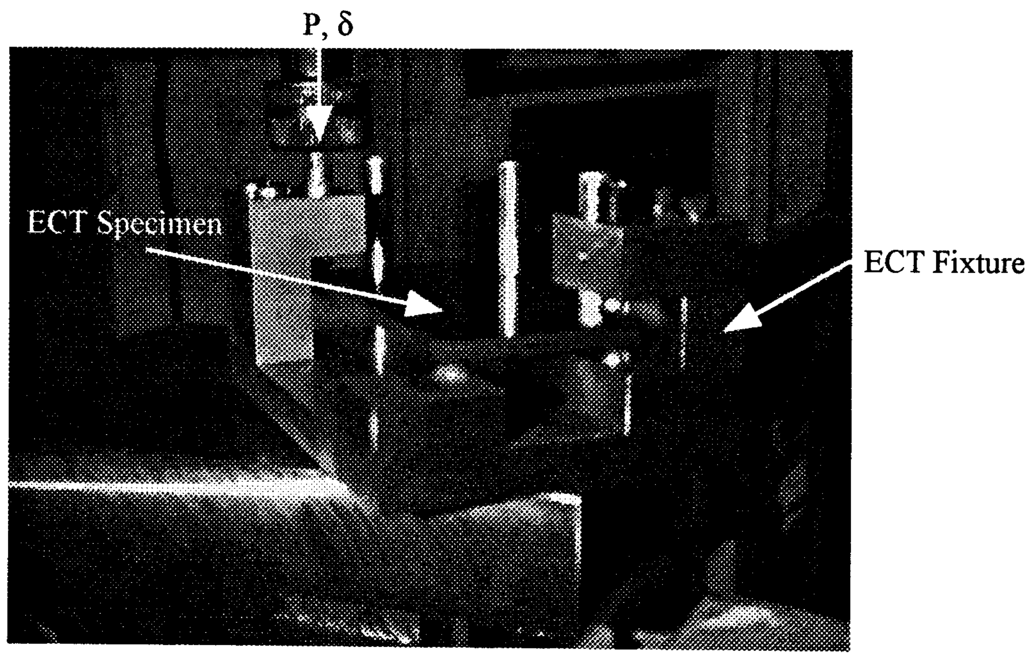


(b) ENF Test Apparatus

Figure 2. ENF Test Specimen and ENF Test Apparatus.



(a) ECT Test Configuration



(b) ECT Test Setup

Figure 3. ECT Specimen and ECT Test Setup.

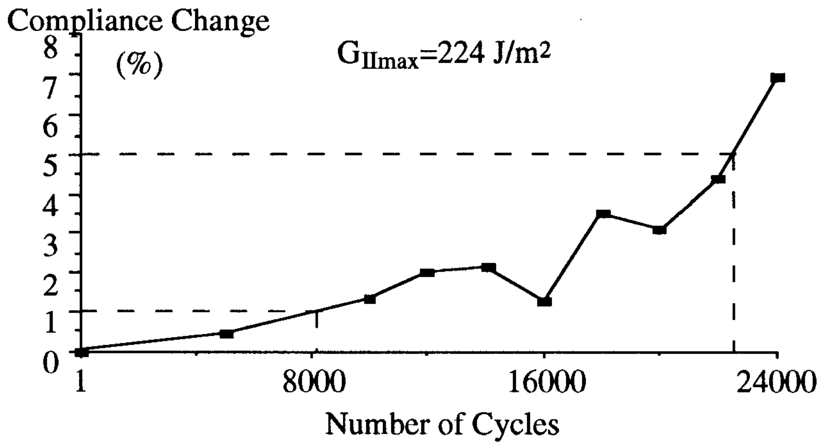


Figure 4. Compliance Change as a Function of the Number of Cycles for an ENF Fatigue Specimen.

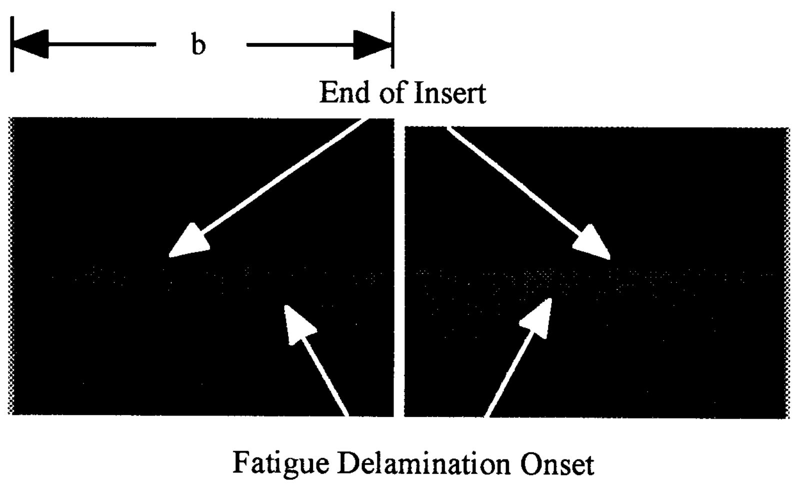


Figure 5. Separated ENF Specimen after 5% Compliance Increase.

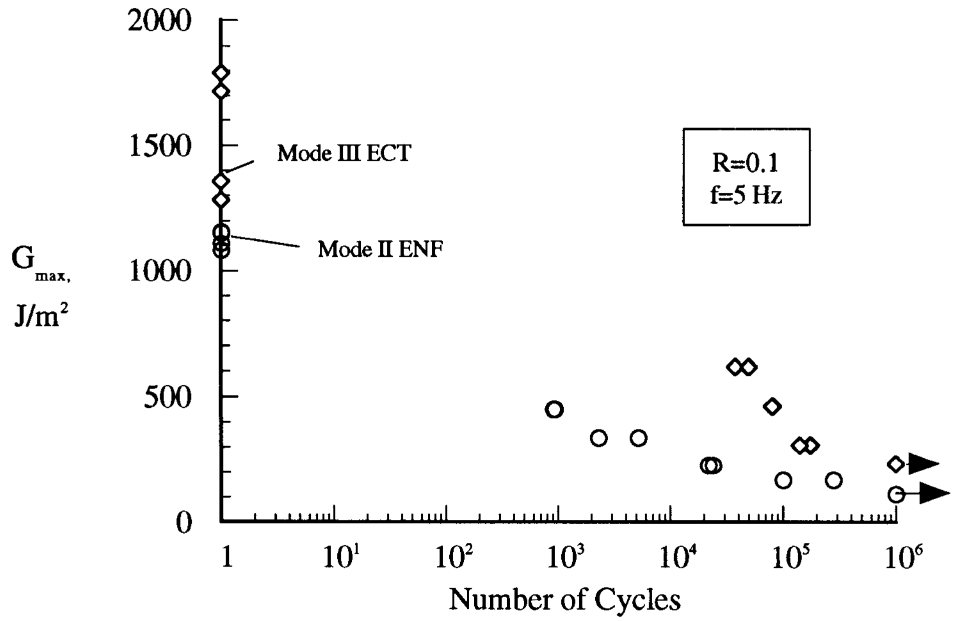


Figure 6. Comparison of Mode II and Mode III Fatigue Delamination Onset Response to Reach 5% Compliance Increase for Tenax-HTA/R6376.