MONITORING BENDING FATIGUE IN CARBON FIBER/EPOXY COMPOSITE STRANDS: A COMPARISON BETWEEN MECHANICAL AND RESISTANCE TECHNIQUES

Ingo Weber and Peter Schwartz*
Fiber Science Program and Field of Mechanical Engineering, Cornell University, Ithaca, NY 14853, USA

Abstract

The bending fatigue behavior of unidirectional carbon fiber/epoxy composite strands was monitored by the changes in resistivity and in bending modulus. The fibers were PAN-based carbon fibers and the matrix was a bisphenol-A based epoxy resin. A load cell connected to one jaw of the test assembly was used to monitor the resulting bending moment. Simultaneously the voltage, at constant current, along the longitudinal axis of the strand was measured, and a correlation between the increase in resistivity and the decrease in bending modulus was seen.

Keywords: fatigue, carbon fibers, nondestructive testing, polymer–matrix composites, electrical properties

1 INTRODUCTION

Compared to metals, the failure of composites is much more complicated to predict because failure in composites is generally due to accumulated damage that results in catastrophic failure. A key problem, then, is to find a way of using non–destructive methods to assess, during service, accumulated internal damage, so to remove composite assemblies from service before failure.

Non-destructive inspections currently are very expensive and so there exists an interest in finding a cheaper solution. Much research is currently being done in this area, exploring different techniques of measurement: change in resistance, acoustic analysis, magnetic, and optical methods.

All of these measurements can be used to identify a change of the composite structure. However, it seems that the use of resistivity, because of its high sensitivity,

* Present address: Department of Textile Engineering, Auburn University, Auburn, AL 36849-5237, USA

may be among the more promising techniques for composites made with conducting fibers.

Carbon fibers are intrinsically electrically conductive, having a typical resistivity of 1.5×10^{-5} Ω•m, while the epoxy matrix is an effective insulator having resistivity ~10^{20} Ω•m. Therefore, it should theoretically easy to determine the rupture of fibers in a carbon fiber–reinforced plastic (CFRP) laminate by monitoring resistivity. Unlike metals that have an isotropic electric flux, in CFRPs the conductivity depending on the direction and the orientation of the conducting fibers; so there exist large differences between conductivity in the longitudinal and the transverse fiber directions. In the transverse direction, the resistance is generally higher because of the (usually, non–conducting) matrix [1, 2], whereas in the longitudinal direction because of the continuous fiber path, there is lower resistivity. Prior to fiber fracture, the conducting path should be essential along the fiber direction, and the resistivity should be low. As damage accumulates during fatigue, and individual fibers break, in order to complete the conducting path there necessarily must be some current flow in the transverse direction, accompanied by an increase in resistivity.

Couillard and Schwartz [3] reported on a study on carbon fiber/epoxy strands subjected to repeated, reversible cycles (@ 3 Hz) of pure bending that produced a surface strain of 2.25% on the strand. They produced 0.5 mm diameter strands containing 3,000 AS-4 fibers (Hexcel, Inc.) embedded in a DGEBA–based epoxy ($V_f \approx 0.5$). Using the change in bending moment as an indicator of accumulated damage, they noted an exponential decay on the bending modulus as a function of the number of cycles. They determined that, at the decay rate observed, the bending modulus would reach zero after 7.6×10^{18} s. In reality, a fatigue limit would be reached when enough of the outer filaments broke to reduce the effective strand radius so that the resulting in the strain on the outer, unbroken filaments was below their failure strain (1.53% @ d = 0.34 mm).

This paper reports on a series of experiments designed to determine if the progression of fiber failure due to repetitive bending can be monitored by measuring the change in resistivity of the sample, and correlated to the drop in bending stiffness.

2 EXPERIMENTAL PROCEDURES

2.1 Materials

The fibers used in this work were PAN–based, AS-4 carbon fibers from Hexcel, Inc., and supplied in the form of a 3k tow. From single–fiber tensile tests performed at 21 °C, 65% relative humidity, and $\dot{\varepsilon} = 0.005\ \text{min}^{-1}$, it was determined that the ultimate fiber failure stress, $\sigma_{uf} = 3400$ MPa, the ultimate failure strain, $\varepsilon_{uf} = 0.022$, and the initial modulus, $E_f = 226$ GPa, where σ_{uf}

The matrix used was a DGEBA–based epoxy resin (D.E.R. 331, Dow Chemical Co.) mixed with a tetraethylene pentamide hardener (D.E.H. 26, Dow Chemical Co.). The epoxy was cured at 21 °C for a minimum of 72 h. Tensile tests on dogbone samples of neat matrix, done at the same conditions as those used for the fibers, yielded the ultimate matrix failure stress, $\sigma_{um} = 38$ MPa, the ultimate failure strain, $\varepsilon_{um} = 0.016$, and the initial modulus, $E_m = 2.6$ GPa.

2.2 Sample preparation

After the as–received yarn was wound over a cruciform take–up wheel, a 9 cm length was chosen and, at each end, a 2 cm length was painted with silver paint. The paint was allowed to dry for 1 hour before the sample was removed and carefully coiled in the bottom of a polyethylene cup.

The epoxy system was prepared in a weight ratio of 100:14.3 (DER 331:DEH 26), mixed thoroughly, and poured into the cup containing the silver–painted yarn. The cup was placed into a vacuum oven and held at ~40 Torr for 5 min in order to remove air bubbles formed during the mixing process. The sample was brought to atmospheric pressure and then again subjected to ~40 Torr for 5 min; causing virtually all the entrapped air bubbles to disappear.

The impregnated strand was pulled through a 0.5 mm wire sizing die (Bettner Wire Coating dies, Inc., Columbus, IN), as illustrated in Figure 1, creating a strand with an approximate fiber volume fraction of 0.52. When the Ag–painted region reached the die, the die was opened to allow the slightly thicker region to pass freely through, and closed immediately behind. Figure 2 is a photomicrograph of the end of the strand

with part of the epoxy removed, while Figure 3 is an image of the cross section of an impregnated strand illustrating excellent epoxy impregnation. Mechanical tests yielded the following strand mechanical properties: ultimate stress, σ_{um} = 1900 MPa, ultimate strain, ε_{um} = 0.025, and initial modulus, E_m = 123 GPa.

2.3 Fatigue testing

A specially constructed bending fatigue tester, described in [3] and detailed in [4], was used for these experiments. The sample was gripped in two pin vices, one pinned and one attached to a crank arm, with the Ag–coated section extending through the bottom where electrodes were soldered on. A constant, 10 mA current was passed through the sample and the voltage monitored, the resistance was determined using Ohm's Law, R = V/I, I = constant. A curvature, ± 0.09 mm^{-1} (surface strain ± 0.0225), was imposed and the applied moment was detected by a load cell (Schaevitz Engineering, Pennauken, NJ) connected to the pinned grip via a lever arm, as illustrated in Figure 4. Referring to Figure 4, the pinned grip is actually attached to the tester only at the pivot point. The grip holder is attached to a load cell a few centimeters down from the pivot point. Assuming that there are no frictional or inertial forces, the bending moment, M_b, is, at any time, balanced by the force, F, exerted on the load cell by the lever arm. Knowing the distance, L, from the pivot point to the lever arm, the bending moment may be calculated as $M_b = F \bullet L$.

The voltage signals from the load cell and the sample were monitored using a Metrabyte D.A.S.-16 G2 PC interface card installed in a Gateway 2000 486/33C computer running UnkleScope™ Level 2+ software.

Ten samples were subjected to 10^6 cycles (@ 3 Hz) of fully–reversed bending and the resulting force and voltage across the strand were sampled at regular intervals. The data were recorded, at 50 cycle increments, between 0 to 10^3 cycles, at 100 cycle increments between 10^3 and 10^5 cycles, and at 20,000 cycle increments thereafter up to 10^6 cycles. To remove the effects of noise, all data were filtered at 10 Hz.

3 RESULTS AND DISCUSSION

Figure 5 is a typical plot of the experimental data for normalized bending moment, B/B_0, and normalized resistance, R/R_0, where B_0 and R_0 are the bending moment and

resistance measured after 10 cycles. Both curves begin to diverge at approximately the same point in time indicating that the resistance is as sensitive to fatigue damage as is the measurement of mechanical degradation. In Table 1 the values for relative bending moment and resistance after 10^6 cycles are presented. A great deal of variability may be seen among the tests, which is typical of lifetime testing. The strands did not completely fail because, as the outer fibers broke, the effective strand diameter decreased to the point where the applied curvature no longer produced a strain in the surviving fibers exceeding their failure strain. Hence the fibers remained intact with no further loss in bending modulus or resistivity.

In Figure 6 are presented the normalized resistance *vs.* normalized moment trajectories for each of the ten trials. It can be observed that the trajectory for each trial is linear but the aggregate cannot be fitted by a simple linear relationship. The variability in the data among samples result both from the inherent variability of fatigue tests as well as that do to the variability in paths the current can take as fibers are broken as well as different. Because one cannot be assured that the misorientation among fibers within a strand nor the distribution of the matrix is identical, there is no reason to expect that the experimental trajectories would lie one atop another.

4 CONCLUSIONS

Resistance measurements provide a useful tool for monitoring damage in carbon fiber/epoxy composites. A decrease in relative bending modulus due to fiber breakage is accompanied by a corresponding increase in relative resistance, and the relationship is linear. Given the variability and the number of samples tested, a statistically significant regression relationship cannot be ascertained from these data. However, the results indicate that, given a sufficiently large sample size, one could reasonably expect to find such a relationship.

5 ACKNOWLEDGEMENTS

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Table 1. Normalized bending moment, B/B_0, and normalized resistance, R/R_0 after 10^6 cycles, for each specimen tested.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
B/B_0	0.52	0.75	0.71	0.82	0.54	0.46	0.59	0.42	0.64	0.57
R/R_0	1.27	1/32	1.27	1.18	1.14	1.06	1.12	1.30	1.48	1.06

LIST OF FIGURES

Figure 1. Schematic of sample preparation method.

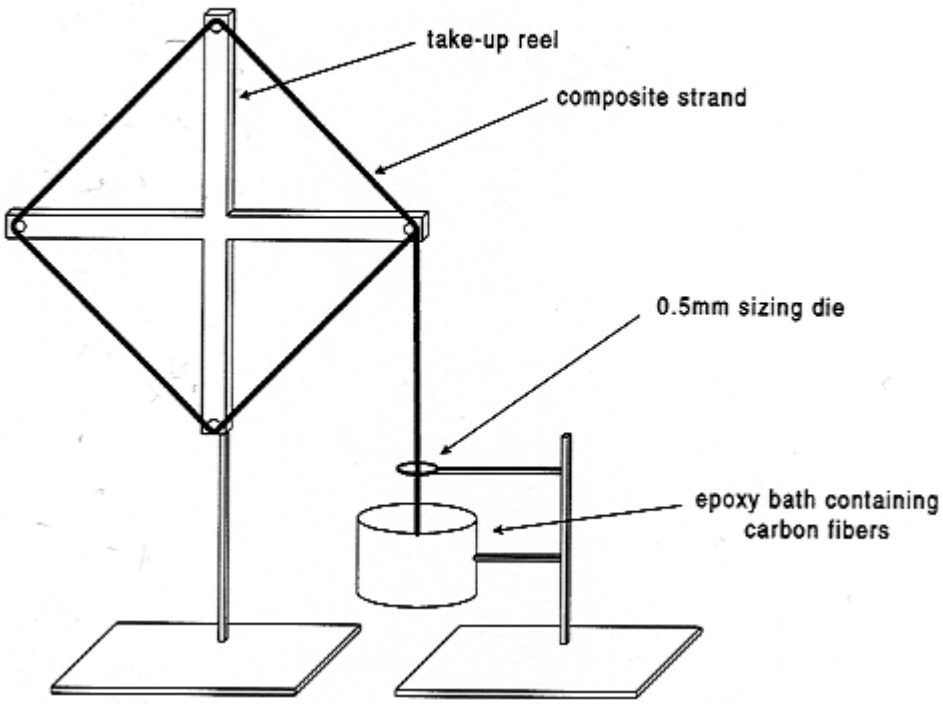
Figure 2. Silver-painted carbon fiber/epoxy strand.

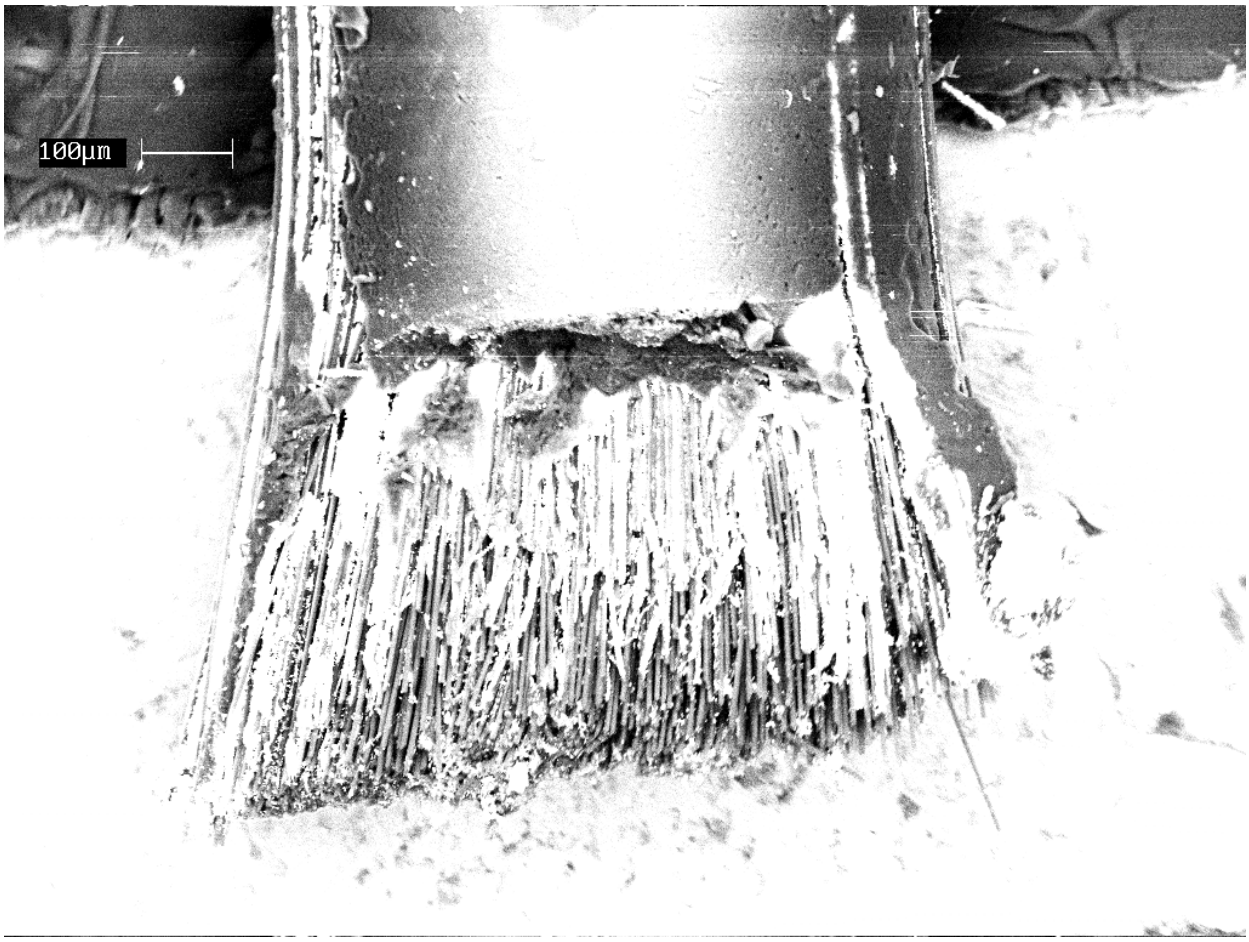
Figure 3. Cross-section of carbon fiber/epoxy strand.

Figure 4: Schematic of fatigue tester and load cell.

Figure 5: Graph of data from a typical fatigue experiment.

Figure 6: Normalized resistance (R/R_0) *vs.* normalized bending moment (B/B_0) for all fatigue experiments.


take-up reel
composite strand
0.5mm sizing die
epoxy bath containing
carbon fibers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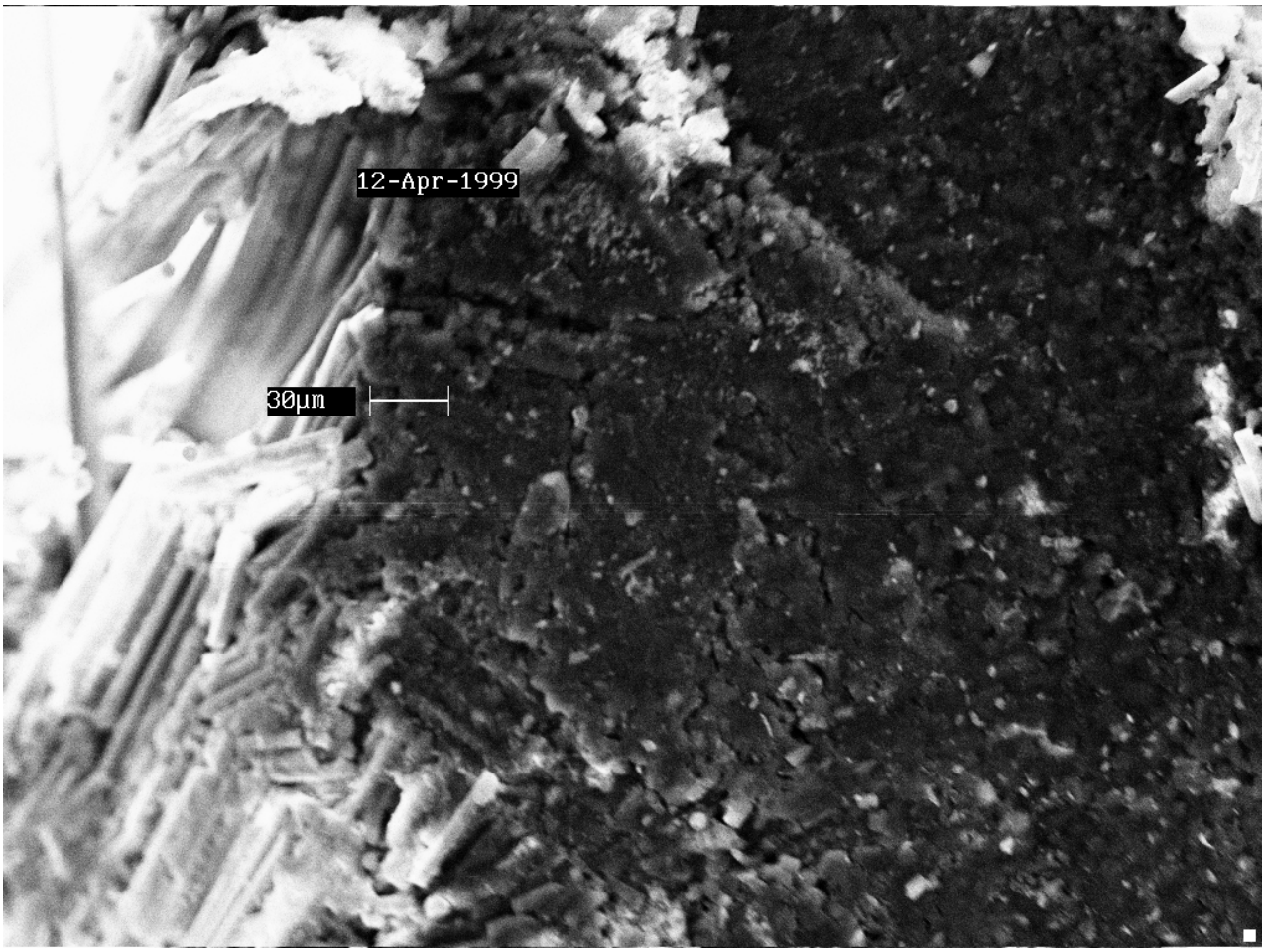
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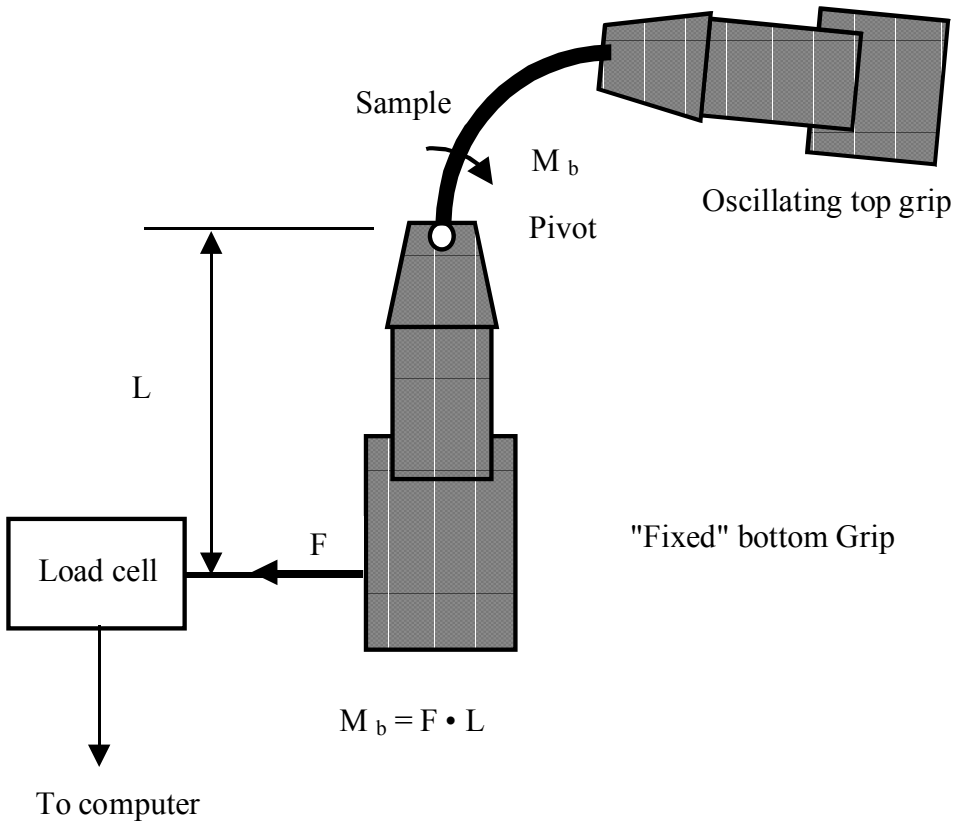
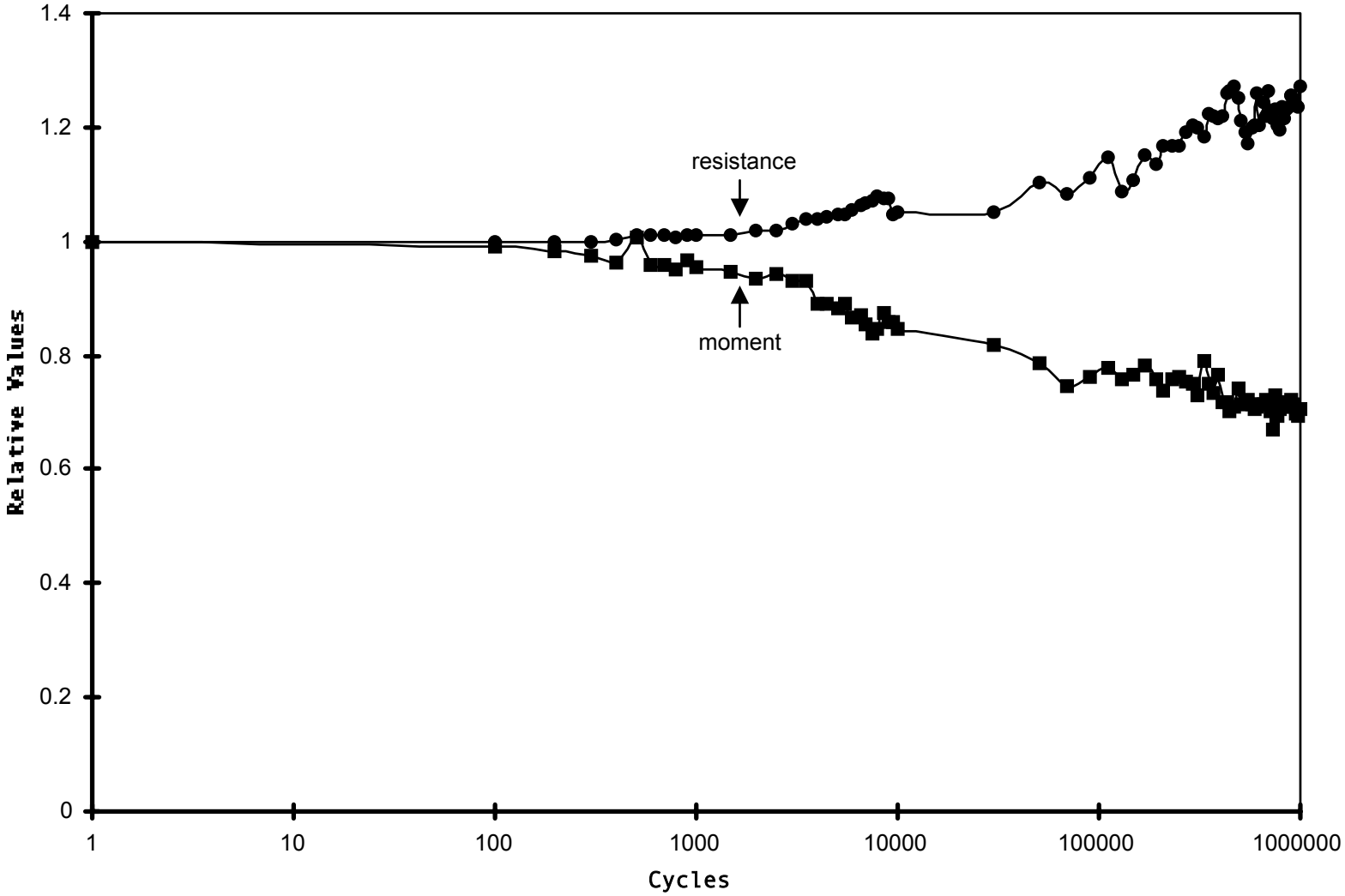
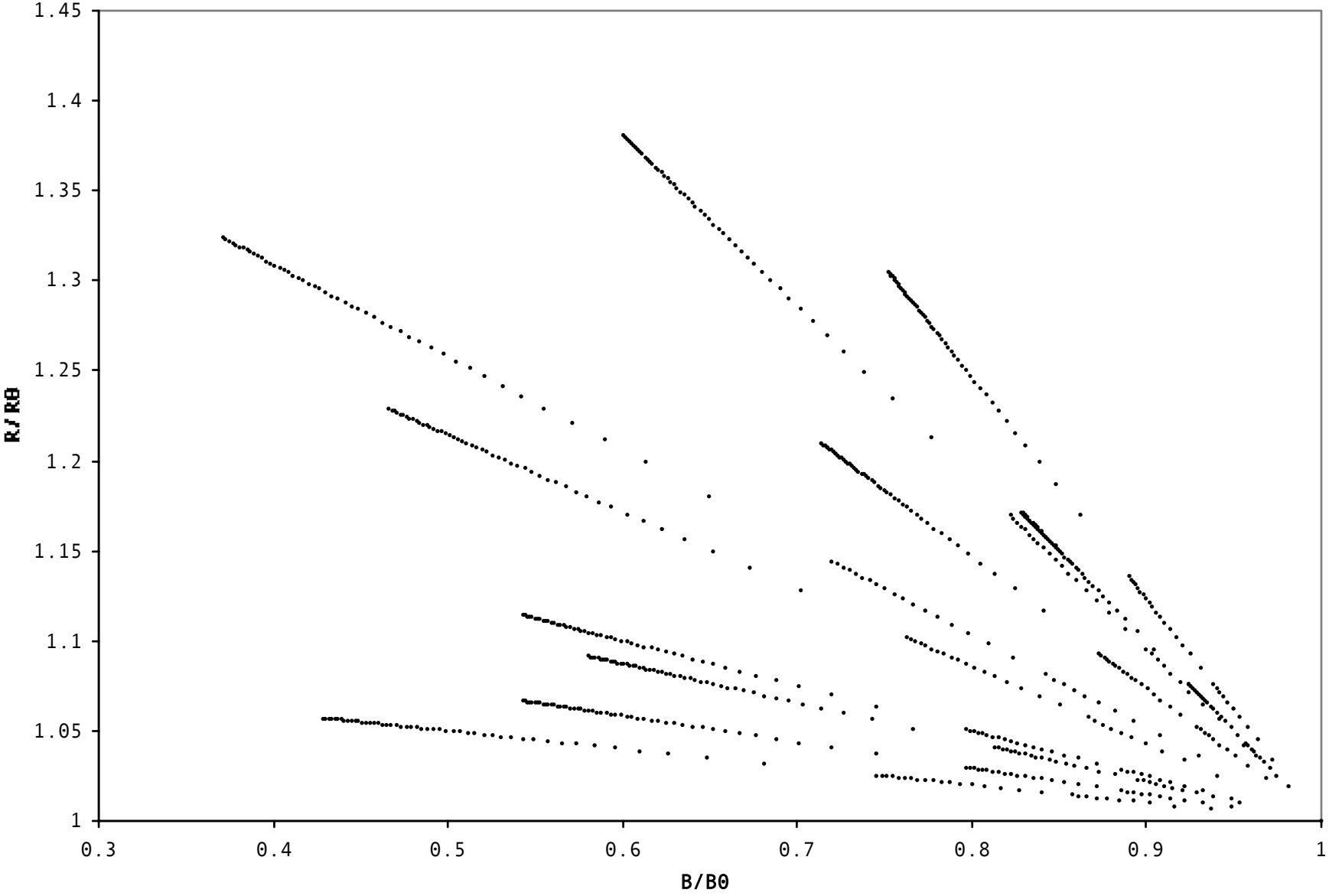
30µm


Sample
M b
Pivot
Oscillating top grip
L
F
Load cell
"Fixed" bottom Grip
M b = F • L
To computer


1.4
1.2
1
0.8
0.6
0.4
0.2
0
Relative Values
resistance
moment
1
10
100
1000
10000
100000
1000000
Cycles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1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
R/R0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
B/B0