1 General Introduction

Much of the existing literature on the experimental testing of composite materials in fatigue is focused on axial tension/tension or tension/compression testing [1-5]. Fatigue testing in structural design is performed in order to obtain S-N curve data for specific material, layup and ply orientations or to obtain statistical failure distributions for point-design structural configurations. For research purposes, fatigue testing is often performed in order to obtain experimentally derived parameters for use in phenomenological residual strength models [1,3,4].

An alternative to axial testing for fatigue is bending tests. Three-point and four-point bending have a number of advantages over axial testing in this context. Bending tests induce a more complex stress field in the coupon than do axial tests and are therefore, arguably, more representative of “real-life” loading conditions. Bending tests utilise smaller and less complex coupons than do axial tests, and require substantially lower external load levels for an internal direct stress equivalent to that of an axial test [6-11].

Difficulties associated with successful implementation and interpretation of bending fatigue tests for thin composites include coupon failure at the load introduction location(s) and excessive mid-point deflection associated with geometrically non-linear behaviour [9]. In addition, experimental data exhibits hysteresis behaviour in the load-deflection curve normally associated with fatigue damage but which has been shown to be a result of friction between the test apparatus and the coupon [8].

The purpose of the study reported in this paper is to modify the methodology for the four-point bending testing of thin laminates to improve the consistency of, and reduce the scatter in the results. The modified test method is used to study the initiation and evolution of intralaminar microcracking in cross-ply laminates. The growth of micro-crack density and the reduction in bending stiffness is examined for coupons with fatigue lives in excess of $1 \times 10^6$ cycles.

2 Experimental Testing

2.1 Test Methodology

The method used for the four-point bending tests was based on ASTM D6278 Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastic and Electrical Insulating Materials by Four-Point Bending, a standard for static flexural testing of composite materials. The dimensions of the test coupon shown in Figure 1 were chosen to satisfy the ASTM recommendation for span-to-thickness ratio while maintaining a span-to-width ratio suitable for analytical calculations using Euler-Bernoulli beam theory.

Flexural fatigue testing was done using a modified Test Resources G-238, 2200N, four-point bending fixture mounted in a servo-hydraulic load frame as shown in Figure 2. An MTS 407 controller was used to produce a sinusoidal signal and control through load monitoring. A 1.1 kN load cell was used to measure loads, the ram displacement was monitored with an LVDT and a second LVDT was used to measure the coupon mid-span deflection. All the signals were fed through the controller to an external data acquisition system. A National Instruments Labview system was used to acquire and record
data. For a loading frequency of 5 Hz the sampling rate used was 200Hz in a 40 sample buffer resulting in recording 40 data points per cycle.

At designated inspection intervals, coupons were removed from the test fixture and inspected using both scanning electron microscopy and optical microscopy using a metallurgical microscope at 200X and 400X magnification.

### 2.2 Test fixture design

The original off-the-shelf four-point flexural test fixture from Test Resources Inc. consisted of two identical mild steel supports with T-groove slots for mounting loading rollers. The loading rollers were 8mm in diameter and supported in V-grooved blocks. Although suitable for static flexural tests, this loading roller design was found to be unsuitable for fatigue testing. Friction between the roller and the coupon resulted in distortion of the load-deflection curve and caused abrasion of the coupon as shown in Figure 3, leading to fatigue failure under the loading point after as few as 10 000 cycles. The loading roller was redesigned to incorporate two steel arms, two needle bearings and a shaft as shown in Figure 4. Drift stops and alignment washers were added to the fixture to maintain the coupon position with respect to the rollers without constraining or loading it.

### 2.3 Test coupons

Test coupons were cut from 12 in. x 12 in. laminated plates manufactured at the National Research Council of Canada using Cytec Engineered Materials G40-800/5276-1 prepreg carbon-epoxy uni-directional tape. The material uses a microcrack resistant toughened epoxy resin, is widely used in aerospace structural composites and is common to a number of ongoing Canadian research efforts. The panels were 16-ply [0/90]₄s, vacuum-bagged and autoclave cured. Cured panels were inspected using ultrasonic C-scan for defects, voids and excessive thickness variations. Coupons were cut using a variable speed dry diamond saw and visually inspected for defects after cutting. The sides of the coupons were polished to facilitate microscopic detection of transverse microcracking as a result of cyclic loading. Individual coupons were prepared by sanding and polishing using 1 µm alumina, 0.25µm diamond and 0.05µm alumina.

Initial testing resulted in premature coupon failure as a result of abrasion under the loading rollers. The coupon was redesigned to add bonded tabs on the upper surface of the coupon to reduce the stress concentrations at the loading rollers and prevent abrasion of the outer plies. Several materials were tested, and the final configuration was a 5-ply Kevlar tab made from a woven prepreg material. The tabs were located on the coupon as shown in Figure 1.

### 2.4 Test procedure

The test coupons were used to perform fatigue damage accumulation experiments in four-point bending. The aim of the testing was to observe the initiation of matrix microcracking and to track microcrack growth as a function of the number of cycles and the coupon residual stiffness until coupon failure or run-out (defined in this study as 1 x 106 cycles). The coupons were cycled in load control at a load ratio of 0.1 and a frequency of 5 Hz. At predefined intervals the coupons were removed from the load fixture and inspected for damage.

Scanning electron microscopy (SEM) was used to determine the threshold for microcrack detection. A coupon was cycled until a microcrack was first detected using SEM, and the image was compared to that obtained using optical microscopy. Figure 5 shows the same microcrack observed using both methods. The results indicated that optical microscopy was adequate to detect the appearance of a microcrack and was then used throughout the testing. Coupons were cycled to failure or run-out, and the intralaminar transverse microcrack density in the most tensile 90° ply of each coupon was measured at established intervals. Microcracks density and evolution were measured by inspecting the coupon at intervals and counting the number of microcracks visible at the edge of the coupon in a 1-inch gauge section of the most tensile 90-degree ply. Microcrack density was compared to values obtained from tensile-tensile coupons subject to axial cyclic testing at a load level that produces a similar stress level in the 90° plies of the tensile test
coupons. Data for the bending stiffness evolution as a function of loading cycles was obtained from measured experimental load-deflection data.

3 Results

3.1 Testing methodology and fixturing
The modifications to the test fixture and the tabbing of the test coupons extended the coupon life from 10,000 cycles to over $4 \times 10^6$ cycles and changed the failure mode from fibre failure and buckling under the loading roller to buckling in the test section on the compression side of the coupon. Subsequent testing provided consistent and repeatable results.

3.2 Friction between the loading roller and the coupon
Previous studies have demonstrated that friction effects present during the loading and unloading of thin composite laminates in four-point bending can affect test results [8]. Figure 6 presents two curves; one is the load deflection curve for a test done using the off-the-shelf fixture and the other is the curve obtained using the fixture after it was modified to reduce the friction between the loading rollers and the coupon. The slope of the loading and unloading curves are significantly different for the coupon tested in the un-modified fixture. The apparent hysteresis behavior is entirely due to the frictional forces changing direction during the bending cycle and not to any form of fatigue damage. This is evident from the second curve obtained for the coupon tested in the modified fixture. In this case the two slopes are practically identical, reflecting the fact that the hysteresis is entirely due to friction and that the modified fixture can produce identical loading and unloading curves.

3.3 Thickness variation
It was found that the four-point bending test is very sensitive to variations in the thickness of the coupons. For composite parts made in an autoclave, a .010” tolerance on the thickness would, in most cases, be considered acceptable. In the four-point bending tests of thin laminates, however, thickness variations can contribute to significant scatter in the results. Figure 7 presents load-deflection plots for three coupons of varying thickness. Coupons 1F12 and 1F13 have a .001” difference in thickness and the slopes of their respective load-deflection curves are comparable. Coupons 1F12 and 1F4 have a .007” difference in thickness and the difference between the slopes of the two curves is significant. In the event that the slopes of the curves are used to calculate the load bending moduli for data comparison, this thickness variation must be accounted for in order to reduce the data scatter. For the purposes of this study, only coupons within a .001” thickness range were used.

3.4 Microcrack detection and damage progression
SEM was used for initial microcrack detection but it was found that optical microscopy was suitable for this purpose provided the coupons were edge-polished. Microcracks began to form in the coupons between 10 000 and 30 000 cycles. Figure 8 shows the beginning of a microcrack forming in a resin-rich zone at 30 000 cycles. Figure 9 is a photomicrograph of the same microcrack at 40 000 cycles where it has become fully developed. The microcrack then grows to produce a local delamination at 100 000 cycles as shown in Figure 10. Other forms of damage progression that were observed included microcracks splitting to produce inter-laminar fractures parallel to the loading direction as shown in Figure 11.

3.5 Microcrack growth
Microcrack density as a function of the number of loading cycles for 5 flexural and 2 tensile coupons is shown in Figure 12. Tensile tests were designed to produce the same peak stress levels in the 90-degree plies as those in the flexural coupons, and the results for microcrack growth are similar for both types of tests. The data are adjusted so that the curves begin at a 10 000 cycle threshold in order to account for a variation in the initiation of microcracking between coupons.

The data in Figure 12 fall into two regions. There is an initial phase of rapid microcrack density growth between 10 000 and 250 000 cycles, followed by a region of slower growth that begins at 250 000 cycles and flattens out to negligible growth
at or near 1 million cycles. Coupons tested to over 4 million cycles did not exhibit any change to this pattern.

In addition to looking at microcrack growth as a function of the number of cycles, the bending stiffness evolution of the coupons was recorded and the results are shown in Figure 13. There is an apparent initial, rapid decrease in bending modulus at the beginning of the test, but there is no subsequent change in stiffness for the duration of the life of the coupon. In fact, the bending stiffness does not change until the last one or two cycles before failure. The initial decrease in the slope of the load-deflection curve was shown to be due to the load introduction pads “wearing in” during the first few cycles of the testing.

4 Conclusions

In this study it is shown that modifications to both the test fixture and the test coupon can result in successful four-point bending fatigue tests. The number of cycles to failure is increased and the scatter in the results is significantly reduced. Failure at the external loading locations is eliminated and coupons fail consistently in the middle of the constant bending moment test section. The failure mode for all coupons is an instability failure under compressive stresses as a result of internal bending loads. Test results are used to demonstrate previously published results [8] where the hysteresis loop in the load deflection curve is due to friction in the experimental apparatus. In addition, it is shown that this effect can be practically eliminated by modifying the fixture and the coupon at the load introduction points. It is also shown that the previously documented initial decrease in bending stiffness at the beginning of the fatigue test may be attributed to material consolidation at the load introduction points and is not actually a decrease in material stiffness. Residual bending stiffness and microcrack density measurements are evaluated and found not to be useful parameters for the prediction of residual strength or remaining fatigue life.

5 References

Fig. 1: Test coupon geometry (dimensions in mm.)

Fig. 2: Test set-up showing coupon mounted in modified fixture and load frame.

Fig. 3: Abraded coupon after 10 000 cycles.

Fig. 4: Loading assembly.

Fig. 5: Scaled images of the same microcrack observed with (A) SEM-1500X and (B) optical-200X.
Fig. 6: Effects of friction in a flexural coupon under four-point bending with and without test fixture modification.

Fig. 7: Effect of coupon thickness variation on load-deflection curve and apparent bending stiffness.

Fig. 8: A microcrack forming at 30,000 cycles.

Fig. 9: The microcrack from Figure 8 fully formed at 40,000 cycles.

Fig. 10: The microcrack from Figures 8 and 9 evolving into a local delamination at 100,000 cycles.
Fig. 11: A microcrack splitting at $1 \times 10^6$ cycles.

Fig. 12: Microcrack density as a function of number of cycles.
Fig. 13: Load bending modulus change with number of cycles – flexural coupons.