DAMAGE CHARACTERIZATION IN STITCHED CARBON/EPOXY LAMINATES SUBJECTED TO MONOTONIC AND CYCLIC LOADINGS

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Abstract
Damage in stitched composites appears in the form of transverse crack, delamination, stitch-induced defects and fiber breakage. In monotonic tensile case, acoustic emission testing is performed to determine the damage onset. Interrupted test is then carried out to detect the growth of damage. X-ray radiography is employed to capture the progressive damage. Quantification of crack density and delamination area is performed based on the X-ray images. In tension-tension cyclic case, fatigue test is halted at progressive cycles, and the damage progress is captured. Comparison of the damage mechanism in unstitched, moderate-stitch density and high-stitch density laminates is presented. Effect of stitch densities on the damage onset and growth is discussed. Fatigue life of stitched laminates under fatigue loading is also evaluated.

1 Introduction
Stitching for composites is performed by inserting high-strength thread into a stack of fiber preforms prior to resin infiltration and curing process. This technique alters through-thickness properties, and improves interlaminar strength of composites. It is known that although composites have been used for primary structures of civil airplanes serious problem in composite prevails: delamination. Delamination is separation between plies, and it may occur at the free-edges due to high interlaminar stresses, or due to impact loading [1]. Delamination resistance can be improved by stitching technique. However, stitching may degrade the in-plane mechanical properties. The reason may be the utilization of high linear density stitch thread (above 400 denier), which may significantly change the in-plane fiber characteristics, e.g. volume fraction, or damage characteristics. In present experiment, thin stitch thread of 200 denier is used. The objective of this paper is to experimentally study the effect of stitch density (number of stitch per unit area) on the damage characteristics of carbon/epoxy laminates subjected to monotonic and cyclic loadings. Limited studies were found on this subject [2,3]. This paper is developed from authors' published article [4] by inserting new data. Quantitative analysis on damage characteristics and mechanism is done by evaluating the X-ray images.

2 Materials and testing methods

2.1 Manufacture of stitched composites

This part briefly discusses the manufacturing method of stitched composites. Figure 1 shows the major steps in stitching the carbon preforms. The manufacturing of stitched composites was performed by Toyota Engineering Corporation, and readers should consult [5] for a more detailed technique. Carbon preforms are, firstly, arranged on the base plate at certain directions; in this case, the arrangement is symmetric-balance with ply orientation of [-45/90/45/0_2/-45/90_2/45/0]s. Carbon is T800SC made by Toray Corp. The preforms were arranged based on the specified spacing and pitch of stitching to create an arrangement of fiber bundles. The second step in producing stitched composites includes the insertion of stitch threads into the carbon preforms. Needle threads and bobbin threads are simultaneously inserted into the carbon preforms. The stitch thread is made of Vectran® yarns. To minimize fiber breakage, the stitch threads were inserted *between* fiber bundles. The stitching technique described in Figure 1 would eventually generate a modified-lock stitch pattern with specified spacing (*s* or distance between lines of needle threads) and pitch (*p* or distance between lines of bobbin threads). In present case, three materials were prepared based on the stitch density (SD), which is defined as a number of stitches per unit area: (1) unstitched or SD = 0 ($s = 0$, $p = 0$), (2) SD = 2.8 cm^{-2} ($s = 6$, $p = 6$) and (3) SD = 11.1 cm^{-2} ($s = 3$, $p = 3$). SD is calculated by following formulae: SD = $1/(s \times p)$; the unit is cm^{-2}. After the stitching process, epoxy (Denatite® by Nagase ChemteX Corp.) is used to infiltrate the stitched preforms. Resin transfer moulding (RTM) process is done at temperature (T) of 120°C for 2 hours, and subsequently at T = 180°C for 4 hours. The dimension of resulting stitched laminate is 310-mm long and 205-mm wide. The thickness of resulting plate is 4.15 mm.

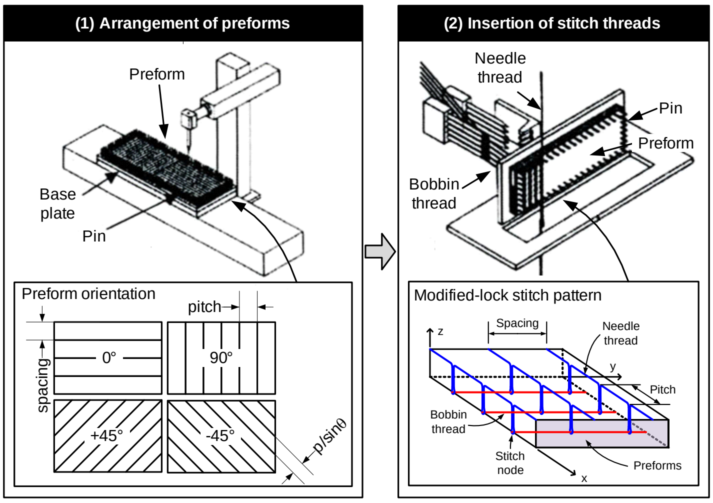

Figure 1. Stitching method adopted to produce Vectran-stitched carbon/epoxy laminates

2.2 Specimen

The stitched laminate plate with dimension of 310 x 205 mm is cut into seven or eight pieces of specimens. The dimension of specimen is 250 mm long and 25 mm wide. Figure 2 shows three types of specimen portion used in present experiment. The volume fraction of unstitched specimen is 50.6%, whilst that of stitched specimen is 49.5% (stitched 6x6) and 52.4% (stitched 3x3).

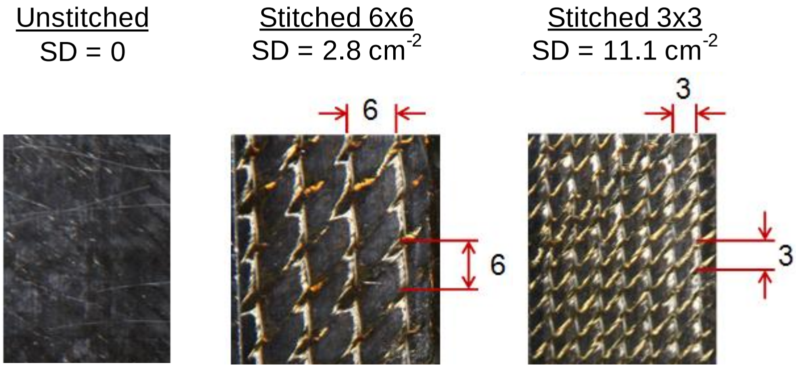

Figure 2. Three stitched carbon/epoxy laminates used in present experiment

2.3 Testing methods

Monotonic tensile test was performed using Universal Testing Machine Instron 8802 with maximum tensile capacity of 100 kN. The tensile test was done under displacement control at loading rate of 0.5 mm/min. Two strain acquisition systems were used during tensile test: strain gage and Advanced Video Extensometer (AVE). In our limited experimental programs, strain gage turns out to give strain reading with less scatter as compared to that of AVE, but the gage may break before the final failure. It is useful to use AVE as it can capture the overall strain reading up to failure, although post-processing to the raw data is sometimes needed. From monotonic test, following properties are obtained: tensile strength (σ_u), tensile modulus (E_x), failure strain (ε_f) and Poisson's ratio (ν_{xy}). Maximum load (or σ_u) can be used as a reference to define the maximum stress (σ_{max}) used in cyclic test.

Cyclic test was also done using Instron 8802. The cyclic test was performed with R = 0.1 (R = $\sigma_{min}/\sigma_{max}$; tension – tension) and the load and displacement data is obtained from the load cell. The frequency is 5 Hz, and the temperature setting around the specimen is maintained to be 20°C. σ_{max} during cyclic test is defined as 0.8, 0.7, 0.6 and 0.5 of σ_u. The specimen is tested until it fails, and the cycle-to-failure is registered to produce S-N curve. Load – displacement curve is processed to produce hysteresis plot of stress – strain, and dynamic stiffness is obtained from the hysteresis plot.

Damage characterization is done by visual inspection, optical microscopy, and X-ray radiography. Upon proper application of Zinc-Iodine onto the dry specimen after the test, X-ray radiography is useful in giving clear image of possible defects in the composites. The characterization of damage during monotonic test is done at several strain levels: ε = 0.5%, 0.6%, 0.7%, 0.8%, 1.0% and 1.2%. Strain level of 0.5% represents damage initiation level; ε between 0.6 and 1.0% represent damage progression level; ε = 1.2% represents damage before final failure (final failure would generally occur between 1.25 and 1.5%). At each strain level, the test was stopped, and specimen was taken out of the testing machine. The specimen was then inspected under X-ray. The X-ray image was observed, and quantification of damage was performed during the observation. Several types of damage were matrix cracks (transverse, bias), delamination, stitch defect and fiber breakage. The characterization of damage during cyclic test is done at several cycles (*N*): 100, 200, 500, 1000, 1500, 2000, 5000 and 10000. Similar to monotonic case, at these cycles, the test was stopped and specimen was taken out of testing machine to do X-ray. Same types of damage are quantified during damage characterization under cyclic loading.

3 Results and discussion

3.1 Monotonic test results

Monotonic tests produced stress-strain curves that were used to obtain tensile strength (σ_u), failure strain (ε_f), tensile modulus (E_x) and Poisson's ratio (ν_{xy}). σ_u and ε_f are obtained by dividing the maximum load and maximum displacement with cross-sectional area of specimen (width x thickness) and original length, respectively. Tensile modulus is obtained by evaluating the stress – strain gradient between longitudinal strain (ε_L) of 0.1% and 0.3%. Likewise, Poisson's ratio is obtained from the gradient of transverse strains (ε_T) and longitudinal strain between ε_L = 0.1 and 0.3%. Table 1 tabulates σ_u, ε_f, E_x and ν_{xy}. As mentioned, σ_u is used as reference to maximum stress (σ_{max}) during cyclic test.

Specimen	Stitch density [cm^{-2}]	σ_u [MPa]	ε_f [%]	E_x [GPa]	ν_{xy}
Unstitched	0	654	1.26	53.1	0.33
Stitched 6x6	2.8	645	1.33	51.1	0.31
Stitched 3x3	11.1	727	1.45	51.7	0.32

Table 1. Tensile properties of carbon/epoxy composites with and without stitches

3.2 Cyclic test results

Fatigue life (S-N curve) of stitched and unstitched laminates is shown in Figure 3. The abscissa indicates a ratio between σ_{max} and σ_u, whilst the ordinate is cycle-to-failure (N). S-N curve is obtained by testing 14 samples, and the σ_{max}/σ_u assigned is 0.5, 0.6, 0.7 and 0.8 for each type of materials. The test is stopped when fatigue cycle exceeds 1 million. One million cycles is deemed as fatigue limit for the specimen. It is shown in Figure 3 that under σ_{max}/σ_u of 0.8 and 0.7, stitched laminates exhibit similar or worse fatigue performance. While under σ_{max}/σ_u of 0.6 or below, stitched laminates seem to have better fatigue life because they can endure fatigue cycle for more than 1 million cycles. Specifically, under σ_{max}/σ_u of 0.5, stitched and unstitched laminates exhibit similar fatigue performance because the specimens can sustain fatigue loading of more than 1 million cycles.

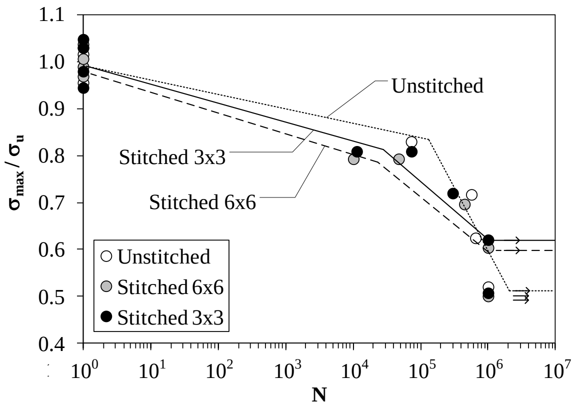

Figure 3. S-N curve of carbon/epoxy laminates

3.3 Damage mechanism under monotonic loads

Progressive damage occurred in the carbon/epoxy composites was detected using acoustic emission (AE) testing. Based on the initial rise of AE cumulative energy, which corresponds to the earliest damage occurrence registered by AE monitoring system, damage occurred earlier in stitched composites. The earliest damage type was transverse cracks, which is matrix crack occurred in 90° ply, growing inward from the edges of the specimen. The growth of internal damages in composites was then captured by soft X-ray radiography. The test was done by halting the test at strain level of 0.5, 0.6, 0.7, 0.8, 1.0 and 1.2%. Figures 4 (a) and (b) show the X-ray radiography results at ε = 0.5% and 1.2% for three specimens. Several types of damage can actually be inferred from the X-ray image. Mainly, the major types of damage is matrix microcracking (or simply ‘matrix crack’) and delamination. Matrix crack and delamination dominate the damage types during monotonic progressive loading. As depicted in Figure 4 (c), delamination occurs at the interface between between 45° and 90° plies. As shown in Figure 5 (a) matrix cracks were growing in stable manner during progressive damage process and the crack density in stitched composites is higher than that of unstitched ones. This fact suggests that stitching may induce a formation of fiber packing with higher fraction, which may be susceptible to cracking at lower strain level. Figure 5 (b) shows that delamination was slowly developed after σ = 400 MPa. It is shown that the delamination growing from the specimen edges was somewhat arrested by the presence of stitches. Delamination impediment using higher density translates into slight improvement of tensile strength. The strength of carbon/epoxy composites is also affected by the global volume fraction due to fiber compaction effect. However, to relate the local increment of fiber volume fraction (V_f) due to compaction with the global V_f remains a challenging task. At the final failure, the damage is fully developed, and it is usually characterized by on-axis fiber failure and stitch breakage.

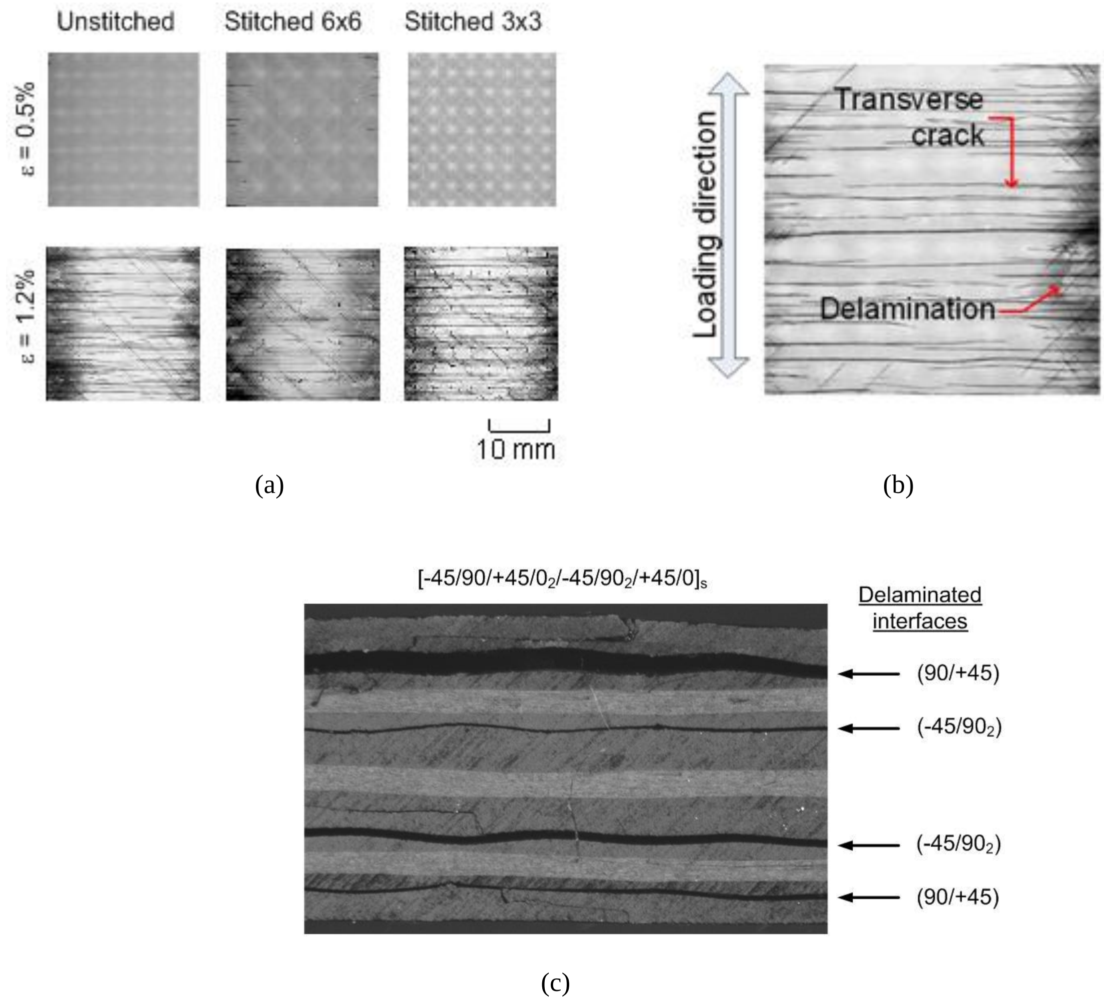

Figure 4. (a) X-ray images of damage occurs in unstitched and stitched carbon/epoxy laminates at e = 0.5% and 1.2%, (b) transverse crack and delamination, (c) delaminated interfaces

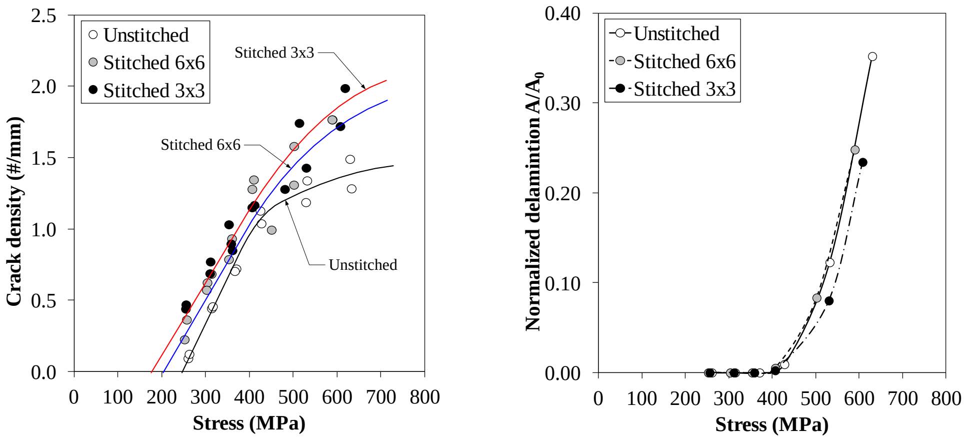

Figure 5. (a) Transverse crack growth, (b) delamination growth

3.4 Damage mechanism under cyclic loads

Damage developed in composites under cyclic loading is also observed using X-ray radiography. Similar to monotonic case, carbon/epoxy composites under cyclic test experienced matrix crack and delamination. However, damage development during increasing cycles is mainly controlled by the applied maximum stress. Figure 6 shows crack density of specimens subjected to σ_{max}/σ_u = 0.8 (represents low-cycle fatigue case) and σ_{max}/σ_u = 0.5 (represent high-cycle fatigue case). It appears that specimens under both loading cases experience saturated crack density. However, applying σ_{max} = 0.8σ_u to the composites induced saturated crack at earlier stage, i.e. N = 1k cycles. At saturation condition, number of matrix cracks does not significantly increase as the cycle is proceeded. It is noteworthy that although crack density reaches saturation level, specimen is still able to sustain the cyclic load. Therefore, matrix crack does not seem to be the controlling damage for stitched and unstitched composites.

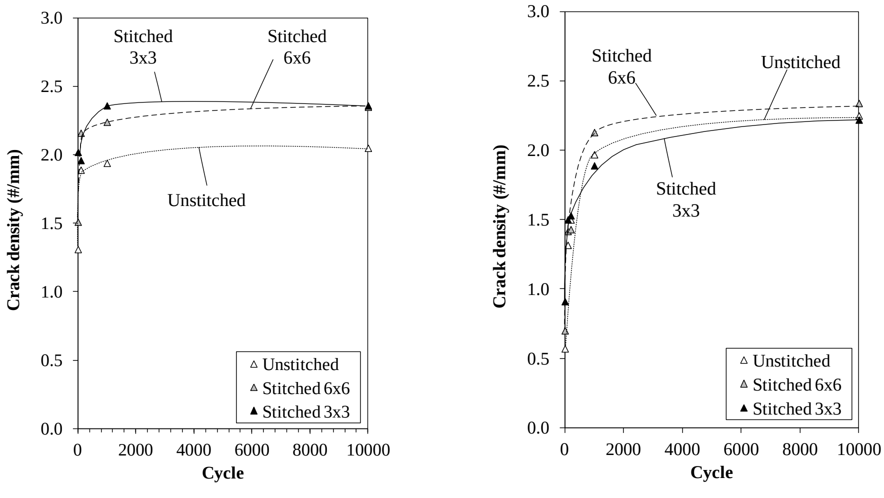

Figure 6. Development of transverse crack density under (a) σ_{max}/σ_u = 0.8, (b) σ_{max}/σ_u = 0.5

The development of delamination is mainly controlled by the σ_{max}. Specimen under high stress (σ_{max}/σ_u = 0.8) experienced rapid increase of delamination. At 10k cycles, all specimens under 0.8σ_u are fully delaminated. The delamination occurs at all interfaces between 45° and

90° plies regardless whether the laminate is stitched or not. When the interfaces are delaminated, the load is solely borne by on-axis fibers (0° plies). In stitched laminates, stitch threads cause fiber breakages in 0° plies. The fiber breakage causes a premature failure under cyclic loading. In contrast, unstitched laminate experience no damage in its 0° plies. Consequently, unstitched laminates have better fatigue performance at higher stress as compared to unstitched ones. However, the observation of delamination can be more meaningful when the applied maximum stress is somewhat below $0.7\sigma_u$. Below that level, the delamination is slowly growing and impediment of delamination can be observed. Under $\sigma_{max}/\sigma_u = 0.5$, for instance, specimen is not yet fully delaminated. It gives the opportunity for the stitch thread to suppress the delamination. In present investigation, stitched 3x3 is better than unstitched and stitched 6x6 in suppressing delamination during fatigue (see Figure 7). Figure 8 shows that stitching can reduce the delamination opening in carbon/epoxy laminates.

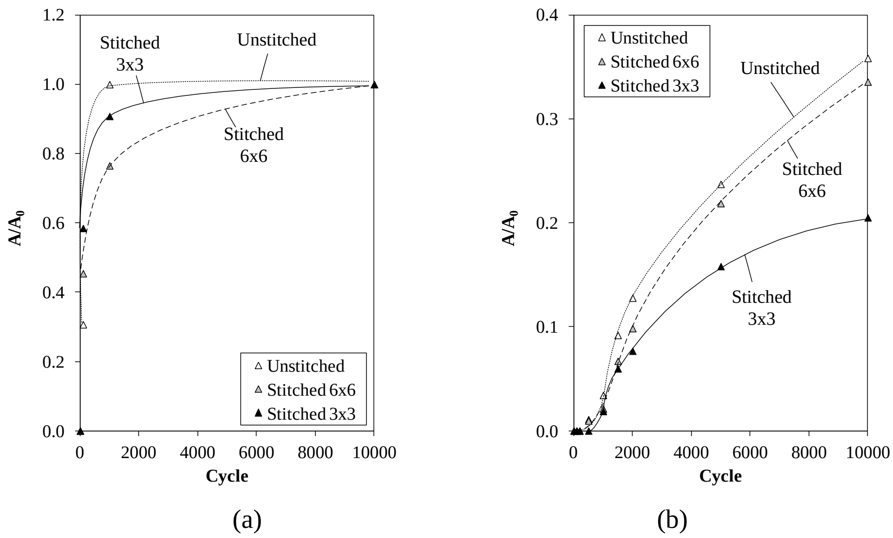

Figure 7. Development of delamination under (a) $\sigma_{max}/\sigma_u = 0.8$, (b) $\sigma_{max}/\sigma_u = 0.5$

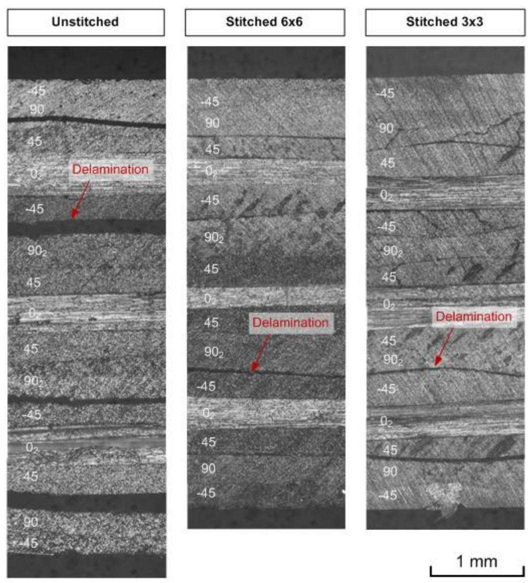

Figure 8. Delamination opening under cyclic loading for unstitched and stitched carbon/epoxy composites

4 Conclusions

Damage characterization in stitched composites subjected to monotonic and cyclic loading has been investigated experimentally. It is found that damage manifests in the form of transverse crack, delamination, stitch-induced defects and fiber breakage. Transverse crack was found to be the earliest damage mode that generally occurs around ε = 0.4%, while the delamination occurs at around ε = 0.6%. Stitching induces earlier formation of transverse crack as compared to unstitched counterpart due to fiber compaction effect. Quantification of transverse crack density and delamination area reveals that monotonic test induces stable development of damage. In tension-tension cyclic case, damage mechanism is controlled by the ratio between maximum applied stress and ultimate stress (σ_{max}/σ_u). Under $\sigma_{max}/\sigma_u = 0.8$ specimens experience saturated crack density after 1k cycles, while that under $\sigma_{max}/\sigma_u = 0.5$ would experience saturated crack after 10k cycles. Although crack reaches saturation level, specimen can still sustain cyclic loading. Advantage of stitching becomes apparent at σ_{max}/σ_u below 0.7. In that case, delamination opening can be suppressed, and fatigue life can be extended.

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