Effect of Gaps on the Damage Initiation and Failure of Thin Composite Laminates Manufactured by AFP Under Out-of-Plane Loading

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Abstract

Advanced robotics as one of the elements of the smart factory has attracted interests in the composite industry through the last decade, and Automated Fiber Placement has found its way to be one of the well-established composite fabrication techniques in both aerospace and automated industries. However, because of using the fiber tows instead of composite prepreg sheets, new types of defects may be formed during the fiber deposition by a robot arm. These defects can induce interlaminar/intralaminar damages under the service loading, which reduces the mechanical performance of the final products. Although the effect of these defects on the performance of the composite structure can be found in the literature, there is still a lack of knowledge in the mechanism of interaction between the manufacturing defects and damages. In the present study, the effect of automated manufacturing gaps on the damage initiation and propagation in Carbon/Epoxy composite beams under out-of-plane loading is investigated. Short beam shear and three-point bending tests are carried out on the samples with defects. Flexural and interlaminar shear strengths of the samples are measured and compared with the samples with no defects (baseline sample). Furthermore, a series of microscopic observations are performed, and the effect of the manufacturing defects on the delamination and matrix damages initiation and also on matrix cracks propagation is investigated.

1. Introduction

Automated Fiber Placement (AFP) is an advanced robot technology for the manufacturing of large composite structures, especially in the aircraft industry. Despite many benefits of using this technology, such as rapid manufacturing, structures manufactured by AFP techniques are prone to have induced defects during the fiber deposition process. These defects can be categorized as gap, overlap, missing tow, tow wrinkling, upfolding, twisted tow, bridging, and crowning (Figure 1). However, gap is the most probable type of defects that may occur between two adjacent fiber tows during the automated fiber deposition. This defect may bring local material and geometrical discontinuities that affect the mechanical performance of the composite structures, which cannot be neglected [1]. It can also accelerate the process of catastrophic failure under different loading conditions, initiate the internal damages and decrease the durability of the structures. These defects can even affect the flexural and in-plane stiffness of the structures, which might be an issue for the structures in which the deformation is one of the main design criteria.

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Experimental studies show that the effect of gaps on the tensile strength is negligible [2, 3]. However, a reduction of compressive strength between 5-27% can be expected for the composite plate under compressive loading [3–6]. The wide range of the effectiveness comes from the fact that different scenarios of the embedding the gaps into the structures can be defined. For instance, an experimental study on the quasi-isotropic laminates with 2.0 mm intentional gap and overlap between the tapes has been performed in Ref. [7] and it was shown that compressive strengths of the composite beams could be reduced by around 7% and 15%, respectively. However, the existence of the stress concentration due to having an open hole makes this effect negligible to consider [8]. An experimental in-plane fatigue test has also been performed on a unidirectional laminate with a single intentional gap with the dimensions of 0.125×0.25 square inch in Ref. [9]. Results reveal that the effect of gaps becomes more severe with increasing the maximum applied stress. However, this effect is negligible for the low level of fatigue stress.

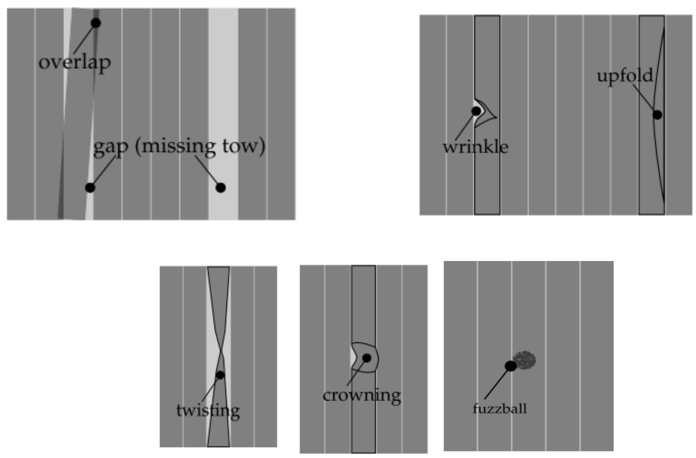


Figure 1. Different types of AFP manufacturing defect (reproduced from ref. [10])

It is also important to note that, although the induced gaps are the result of machine malfunction for regular composite laminates, it is impossible to avoid these defects in the new concept of composite manufacturing with fiber steering. Designing the structure with the curvilinear fiber path changes the in-plane stress distribution and causes a considerable increase in the buckling capacity of the composite structures [11–17]. However, the existence of the induced gaps is still a significant issue for these types of structures.

Although the effect of fiber tow gaps on the ultimate strengths of the composite plates under in-plane loading can be found in literature, there is still a lack of knowledge on the effect of induced gaps for the structures under out-of-plane loading. Furthermore, the interaction of this defect with the interlaminar and intralaminar damages needs to be studied.

The main objective of the present paper is to study the effect of fiber two gaps induced in the thin quasi-isotropic Carbon/Epoxy plates on the ultimate strength and also on the damage propagation under transverse loading. For this purpose, standard flexural and short-beam shear tests are carried out to observe the effect of the manufacturing defects on the flexural behavior and interlaminar shear strength of the composite beams. Furthermore, microscopic observation was performed on the damaged sample to investigate the interaction of the defects with delamination initiation and matrix cracks propagation.

2. EXPERIMENTAL PROCEDURE

In this study, the hand-layup (HL) technique was chosen for fabricating the composite plate with no defects. These samples, which are made by using prepreg sheets, are considered as baseline samples. A ZX130L Kawasaki 6-axis articulated robot arm was used to fabricate the samples with the periodical gaps between fiber tows (AFP-G). The process of embedding the gaps between each fiber course was proceeded by adjusting the AFP software to consider the fiber tow's width, 2.0 mm larger than the real width, which is 6.35 mm (Figure 2). These gaps cause 8% of the free spaces (Gap percentage) in the whole laminate during the fiber deposition.

Two composite plates with the dimensions of 19×17 inches were fabricated with both HL and AFP techniques and have been vacuumed and cured in an autoclave for six hours under the constant pressure of 90 psi and curing temperature of 180° C. An Aluminum hard tool (Caul plate) was also used to reduce the out-of-plane fiber waviness caused by free spaces between the fiber tows. The plates are then cut into the desired samples for both flexural and short beam shear tests. Table 1 shows the properties of the composite beams prepared for this study.

Table 1. Geometrical properties of the experimental samples

Type of the test	Sample Dimensions	Stacking Sequence	Material	Curing Type
Three-point bending	100 ×13 mm^2	$[0_2/45_2/90_2/\text{-}45_2]_s$	Cycom 977-2 HTS 40	Autoclave
		$[90_2/\text{-}45_2/0_2/45_2]_s$		
Short beam shear	15 ×5 mm^2	$[0_2/45_2/90_2/\text{-}45_2]_s$		

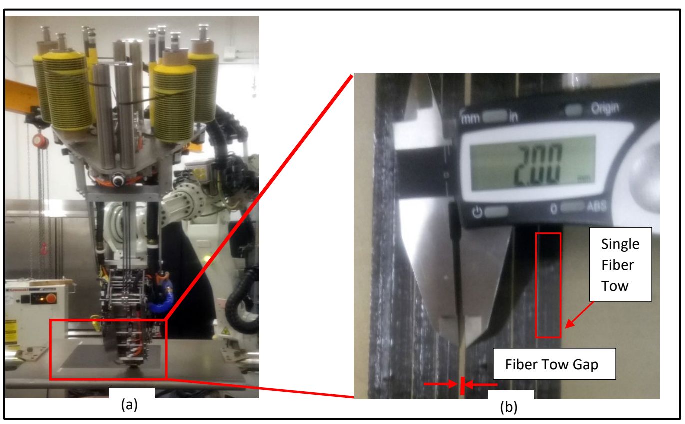
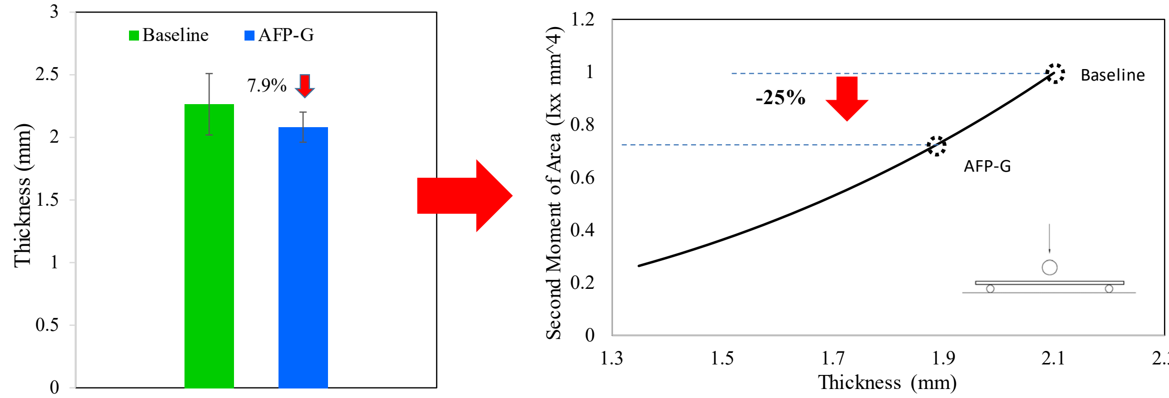


Figure 2. Automated Fiber Placement process (a) Fiber deposition by a robot arm (b) Fiber tow gap between the fiber courses

The effect of free spaces between the fiber tows on the quality of the cured plates was investigated by measuring the thickness and also by the microscopic observation of the cross-section of the intact samples. Figure 3.a. shows that embedding the 8% of the gap during fiber deposition may decrease the final thickness of the plates by 8%. This change has a significant effect on the flexural behavior of the samples. For example, it can reduce the second moment of area (I_{xx}) of the composite beam by 25% (Figure 3.b.). Figure 4 shows the cross-section view of the AFP-G samples at gap area. It can be seen that the thickness of the -45° plies has been reduced at the gap area, which has been filled with resin.



(a) (b)

Figure 3. Effect of fiber tow gaps on (a) thickness reduction (b) second moment of area

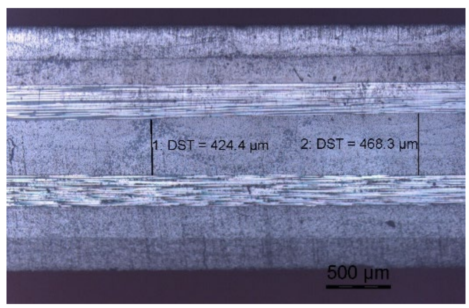


Figure 4. Local thickness reduction at the gap area

The other effect of the existence of the pre-set gaps on the quality of the composite samples can be found in Figure 5. The preset gap affects the uniformity of the Fiber Volume Fraction (FVF) in the gap area. For instance, FVF drops by 50% at the -45°lamina and reaches 27% at the center of the gap area. It is also worth to note that the width of the resin-rich area (pre-set gap area) is reduced due to fibers movement during the curing process. However, the domain of the FVF reduction seems to remain around 2.0 mm, which is equal to the width of the intentional gap.

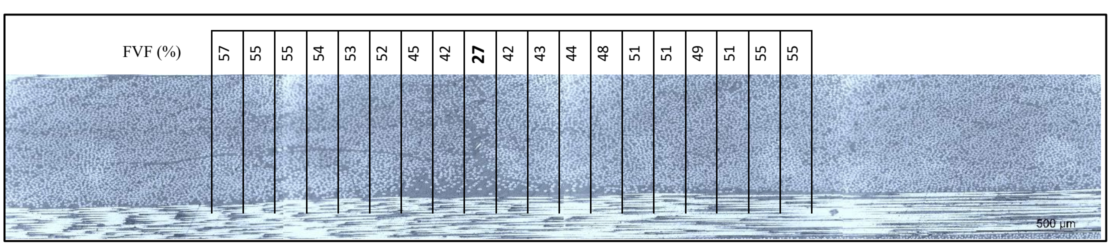
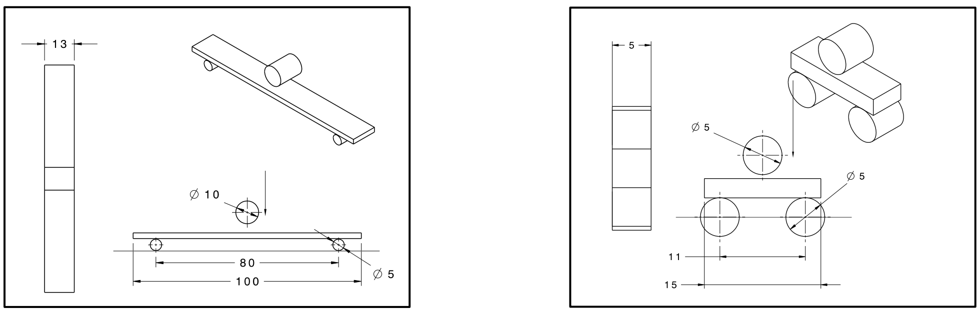


Figure 5. Distribution of the Fiber Volume Fractions at the gap zone at 45° lamina

The effect of the distributed gaps on the out-of-plane behavior and interlaminar behavior of the composite beams was investigated by performing a series of three-point bending and short-beam shear (SBS) tests. Figure 6 shows the dimensions and applied boundary conditions for flexural and SBS tests setup, which are based on ASTM D7264 and ASTM D2344 standards, respectively. It can be seen that the specimens for the flexural tests have the dimensions of 100×13 mm with a span length of 80 mm (Figure 6.a.). Besides, two 5.0 mm diameter rollers simulate the simply-supported boundary conditions, and the out-of-plane load is applied by a 10 mm diameter roller. The same boundary condition but with a crosshead roller with diameter of 5.0 mm is used for SBS tests (Figure 6.b.). A universal testing machine with a maximum load capacity of 5 kN was used for measuring the flexural strength and Interlaminar Shear Strength (ILSS) of the composite beams. The machine can record 50 data per second with the displacement and load precision of 0.01 mm and 0.1 N, respectively. In order to achieve consistency in the results, four samples per each category were subjected to loading with the loading rate of 1.0 mm/min.



(a) (b)

Figure 6. Dimensions and boundary condition of the specimens for the (a) three-point flexural test and (b) Short-beam shear test (All dimensions are in mm)

3. RESULTS AND DISCUSSION

It is recommended by ASTM standard to find the flexural stiffness and strength and also ILSS of the beams by the following formulae:

Flexural strength $$\sigma_m = \frac{3P_m L}{2bh^2} \quad [1]$$

Flexural Stiffness $$E_F^{Secant} = \frac{L^3 m}{4bh^3} \quad [2]$$

Interlaminar Shear Strength $$F^{sbs} = 0.75\frac{P_m}{bh} \quad [3]$$

In the above, P_m is the maximum applied load, L is the span length, b, and h are the width and thickness of the specimens, respectively, and m is the slope of the secant of the force-displacement curve. Note that a reference value of 2.1 mm (baseline thickness) has been used for the thickness of all specimens.

Table 2 shows a summary of the results for both flexural and short beam shear tests. It shows that the effect of fiber tow gaps on the flexural stiffness and strength, and interlaminar shear strength is significant. While the flexural stiffness of the baseline beam is around 75 GPa, there is 35% reduction for the samples with periodic gaps. Almost the same reduction can be expected for the flexural strength. In this case, flexural stiffnesses are about 1200 MPa and 840 MPa for the baseline and AFP-G samples, respectively. It is important to note that part of this reduction comes from the assumption of using the reference thickness for both baseline and AFP-G samples. For example, applying the actual thickness for AFP-G samples in the formula (2), the flexural stiffness of the samples would be around 65 MPa. It means only 12% reduction in flexural stiffness is the result of the thickness reduction and material properties reduction due to the existence of resin-rich area. The reason for using the reference thickness instead of the actual one is that widespread gaps can take place at a partial zone of a structure in the actual practice. It is more practical to consider the effect of the manufacturing gap as local material degradation rather than local thickness reduction. The same explanation can be said for the reduction of the flexural strength.

Furthermore, there is no difference in the failure mode of the quasi-isotropic beams under flexural loading. For both series of the beams, ultimate failure is the fiber breakage under compression loading at zero layers and the delamination between the zero and 45° laminae (Figure 7).

Table 2. A comparison of the flexural behavior and ILSS of the composite beams with gaps and baseline samples

	Baseline	AFP-G	Difference (%)
Flexural Stiffness (GPa)	74.08 Std. Dev. = 1.7	47.98 Std. Dev. = 1.88	35
Flexural Strength (MPa)	1232 Std. Dev. = 20	836.6 Std. Dev. = 26	32
Interlaminar Shear Strength (MPa)	94.86 Std. Dev. = 2.7	81.6 Std. Dev. = 4.8	13

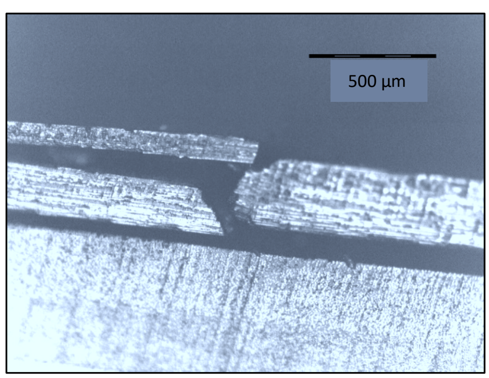


Figure 7. Failure mode of the composite beams under flexural loading

Fiber tow gaps also reduce the interlaminar shear strength of the composite laminates. It was shown in Table 2 that this defect can decrease the ILSS by around 13%. Note that because of the small dimensions of the short beams, there is a possibility of not having gap area in the tested samples, which means that all of the studied samples are not necessarily the representative of the samples with the gap. In order to overcome this issue, more than 15 samples were tested experimentally, and then by using microscopic observation, the average value has been calculated from the samples with the gap. Looking at the zone of delamination initiation for the AFP-G samples, it was realized that the resin pockets can be the sources of delamination initiation for the beams under short beam shear tests. Figure 8 shows two different short beams that have been failed under transverse loading. It is clear that the delamination, which is the primary mechanism of the failure, initiates from the resin-rich areas which have been created due to the intentional gaps.

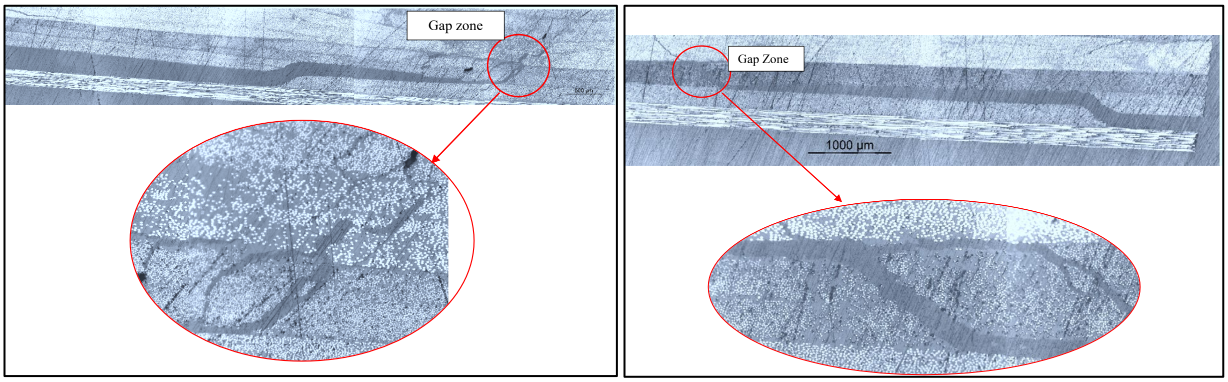
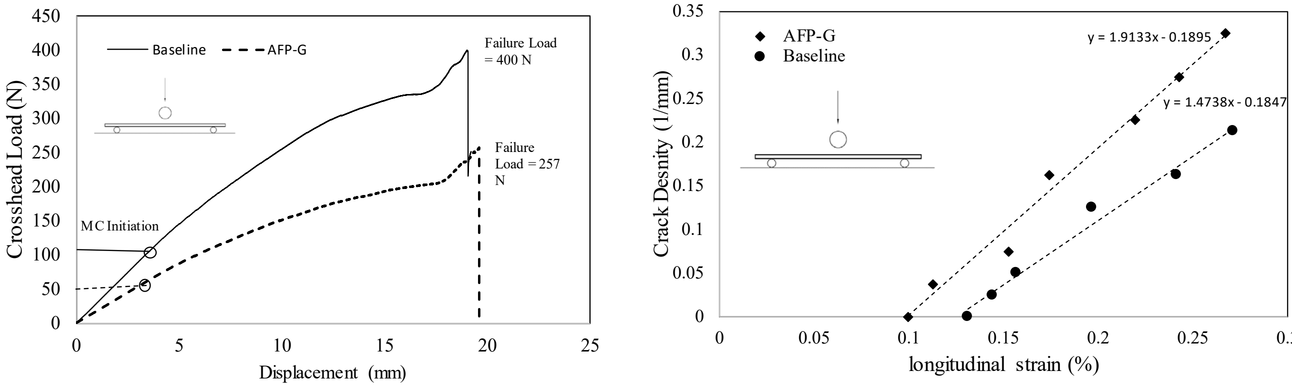


Figure 8. Delamination initiation from the resin-rich area induced by fiber tow gaps

The effect of the intentional gaps on the Matrix Crack (MC) propagation in the beams under transverse loading was investigated by three-point bending tests on the composite beams with the stacking sequence of $[90_2/\text{-}45_2/0_2/45_2]_s$.

For this purpose, the crack density of the bottom layers (90˚ plies) at different crosshead loads was measured. Figure 9.a. shows the load versus displacement curve for both baseline and AFP-G samples. It shows that the intentional gaps have significant effect on the loading capacity of the composite beams with low flexural rigidity. Manufacturing gaps can reduce the loading capacity of the beams with the stacking sequence of $[90_2/\text{-}45_2/0_2/45_2]_s$ by about 50%. Although matrix cracking is not a catastrophic failure, it reduces the stiffness of the materials and also might induce the delamination. MC also reduces the level of the stress due to free surface area and causes stress perturbation at MC zone [18, 19]. In this study, the crack density of the 90˚ plies at the bottom was measured experimentally at different loads. These layers are under tension load perpendicular to the fiber directions. Thus, matrix cracks propagate from the spot with the highest level of the stress, which in this case it places at the middle of the beam. Figure 9.b shows the graph of the crack density versus the longitudinal strain of the bottom surface at the center of the beams. Note that, the longitudinal strain (ϵ_{xx}) was calculated based on the Euler-Bernoulli beam theory. It is evident that the MC initiates at lower strain for AFP-G sample. However, there is no major difference between the MC propagation for both samples. That probably shows that gap defects do not have any significant effect of the matrix crack propagation. Furthermore, no evidence on the interaction of MC and gap defects was also found by microscopic observation. However, more experimental studies are required to confirm this statement.



(a) (b)

Figure 9. Comparison of Crosshead load versus (a) transverse displacement (b) crack density of 90˚ plies for AFP-G and baseline samples with the stacking sequence of $[90_2/\text{-}45_2/0_2/45_2]_s$ under flexural loading

4. Conclusion

In this paper, the effect of fiber tow gaps on the interlaminar and intralaminar damage initiation and propagation and also on the failure of the thin composite beams under transverse loading was investigated experimentally. For this purpose, both three-point bending and short beam shear tests were selected to measure the flexural stiffness and strength and also the interlaminar shear strength of the beams in the presence of the gaps. A quasi-static composite plate with periodic gaps between the fiber tows was fabricated by Automated Fiber Placement technique. This plate is the representative of the samples with the manufacturing gap and the results were compared with that of the samples with no defects (baseline samples).

Results show that the flexural stiffness of the beams are reduced by around 35% due to thickness reduction and material degradation caused by fiber tow gaps. The same percentage of reduction can also be expected for the flexural stiffness of the quasi-isotropic beams. Interlaminar shear strength is also decreased by about 13%. Microscopic observation shows that the delamination was initiated at the gap areas for the short beam samples with defects. It emphasizes that the resin-rich areas caused by gaps are prone to be the sources of the delamination initiation.

The effect of the fiber tow gaps on the matrix cracks propagation under bending load was studied by performing three-point bending test on the beams with the stacking sequence of $[90_2/\text{-}45_2/0_2/45_2]_s$ in which the matrix cracks propagate at 90˚ layers under tensile loads. No significant difference between the results was found for both the samples with the gaps and the baseline. It probably shows that the effect of the gaps on the matrix crack initiation and propagation can be neglected. However, more studies are required to confirm this statement.

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