Interlaminar Shear Strength of the Carbon/Epoxy Composites Containing Gaps Induced by Automated Fiber Placement Process

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ABSTRACT

This paper presents an experimental study on the effect of Induced gaps by Automated Fiber Placement (AFP) on the Interlaminar Shear Strength (ILSS) of the Carbon/Epoxy composite plates. Both AFP process and hand layup technique have been used for manufacturing the test specimens with Out-of-Autoclave Prepreg. Standard Short Beam Shear (SBS) test has been conducted to measure the ultimate shear strength of beams in the presence of the gaps and the results are compared with the baseline specimen which has been manufactured by hand layup technique. Due to the widespread distribution of the gaps, shear strength has been measured at two different zones: (1) No Intentional Gaps and (2) Intentional Gaps zones. Results show that the tow-drop gaps can decrease the Interlaminar shear strength of the structure by around 55% in the vicinity of the gaps.

KEYWORDS: Automated Fabrication, Interlaminar shear strength, Manufacturing defect, Composite materials

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 suffer from induced distributed defects due to gaps or overlapping between adjacent composite material tapes. These manufacturing defects may bring local discontinuity and affect the mechanical performance of the structure at both macro and micro levels. In other words, having a widespread source of the AFP manufacturing defects can decrease the macro-mechanical performance of the structures such as tensile and compressive strengths. On the other hand, these defects can also be a source of damage initiation which can cause a catastrophic failure and needs to be addressed at the micro level study of the composite structures.

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 (Hyer and Lee, 1991; Z. Gürdal, B. F. Tatting, K. C. Wu, J. H. Starnes, 2005; Lopes, Gürdal and Camanho, 2008; Setoodeh *et al.*, 2009; Fayazbakhsh *et al.*, 2013; Marouene *et al.*, 2016; Rouhi *et al.*, 2018). However, the existence of the induced gaps is still a major issue for these types of structures.

A macro-mechanical study of the effect of different types of manufacturing defects including the gap, overlap, half gap/overlap, and twisted tow has been conducted in Ref. (Croft *et al.*, 2011). Results show that the defects may change the tensile strength of the structure up to 13%. A similar study but with the quasi-isotropic laminates with 2 *mm* intentional gap and overlap between the tapes has been performed in Ref. (Woigk *et al.*, 2018) and it was shown that the tensile and 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 (Falcó *et al.*, 2014). An experimental in-plane fatigue test has also been performed on a unidirectional laminate with a single intentional gap with a dimension of 0.125×0.25 in. square in Ref. (Elsherbini and Hoa, 2016). 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.

Induced gaps can also affect the interlaminar behavior of the composite plates. These defects can create a resin-rich-area between two adjacent tapes and bring sources of discontinuities at the vicinity of the gap areas. However, to the knowledge of the authors, no research studies provided the experimental results on the effect of induced gaps on the interlaminar shear strength of the composite structures manufactured by the AFP process. The main objective of the present paper is to study this effect for the quasi-isotropic Carbon/Epoxy plates manufactured by the AFP process. For this purpose, a standard short beam shear test has been conducted, and Interlaminar Shear Strength (ILSS) of the short beam samples including gaps has been compared with the ones manufactured by hand layup process. Results show that the induced gaps can significantly reduce the ILSS of the composite plates.

2 FABRICATION PROCESS AND EXPERIMENTAL WORK

Three series of composite plates with a dimension of 330×330 mm^2 have been manufactured by both AFP and Hand Layup (HL) process. The plates are quasi-isotropic and of sixteen layers with the stacking sequence of $[0_2/45_2/90_2/\text{-}45_2]_s$. The first plate has been made from Prepreg Carbon sheet using hand layup (HL sample), and it is considered as baseline sample and two other plates were fabricated by AFP process. This process has been performed using the Automated Dynamics machine which uses a ZX130L Kawasaki 6-axis articulated arm robot, and it can place four fiber-tows per course. The width of each tow is 6.35 *mm* (1/4 *in.*).

In order to place gaps between fiber tows, the fiber placement software needs to be adjusted for a predefined tow width which is more than the real fiber tows. In this study, the program has been designed to put on an average a 2.0 *mm* gap between the courses for all layers of AFP-G (Figure 1) and 1 *mm* gap for all layers of AFP-R samples. However, the automated placement process does not necessarily follow this pattern for all course placements. In order to control the gap area, the average and maximum widths of the gaps were measured during the fabrication process. Table 1 shows the predefined tow width and also the average and maximum observed sizes of gap width for AFP-R and AFP-G plates. It can be seen that the maximum observed gap width is 3.1 *mm* and 1.4 *mm* for AFP-G and AFP-R, respectively. However, the average tow width of the gap patterns can be considered to be the same as the predefined tow width for both AFP-R and AFP-G.

CYCOM 5320-1 T650-35 3K 8HS composite material with a nominal fiber volume of 56.7% was used for both hand layup and AFP processes. This material is an Out-of-Autoclave material which is cured in ambient pressure. The composite plates have been vacuumed and placed in an oven for a total of four hours for curing. It includes two hours curing at a temperature of 120°C and then two hours post-curing at 180°C. Note that, no caul plate has been used during the vacuuming and curing process of composite plates.

Table 1 Average and maximum observed dimensions of the gaps for the plates manufactured by the AFP process

Type	Predefined tow width*	Avg. observed gap width (mm)	Max. observed gap width (mm)
AFP-R	0.26 inch	1.0	1.4
AFP-G	0.29 inch	2.0	3.1

* Real tow width is 0.25 in.

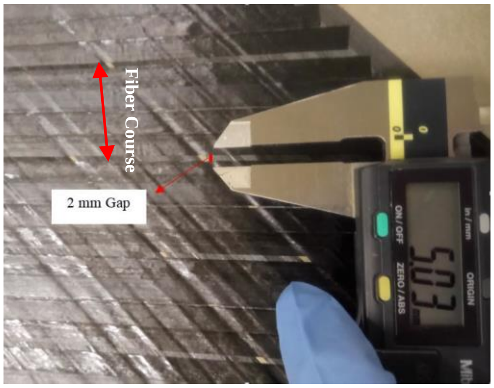

Figure 1: Fiber tows placement including gaps

It is interesting to note that the average thickness and also the weight of the samples in the different groups are not the same due to the existence of the intentional gaps between the fiber tows. Table 2 shows the average thickness and also the weight of three series of the specimens with the standard deviation of around 0.1 *mm and 7.0 mg*, respectively. AFP-G samples have a thickness of 2.11 *mm* which is about 93% of the thickness of HL samples. However, no significant thickness change is observed in AFP-R samples. Due to the existence of the gaps in the plates manufactured by AFP, the average amount of the weights of the samples are lower than the ones manufactured by hand layup process.

Table 2 Average thickness and weight of the specimens manufactured by AFP and Hand Layup techniques

Type	HL	AFP-R	AFP-G
Avg. Thickness *(mm)*	2.27	2.24	2.11
Avg. Weight (*mg*)	311	288	276

Figure 2 shows the dimensions and applied boundary conditions for the short beam shear (SBS) test setup which is based on ASTM D2344 standard. It can be seen that the specimens have the dimensions of 15×5 *mm* with a span length of 11 *mm*. Two 2.5 *mm* diameter rollers simulate the simply-supported boundary conditions, and the out-of-plane load is applied by a 5.0 *mm* diameter roller. 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*.

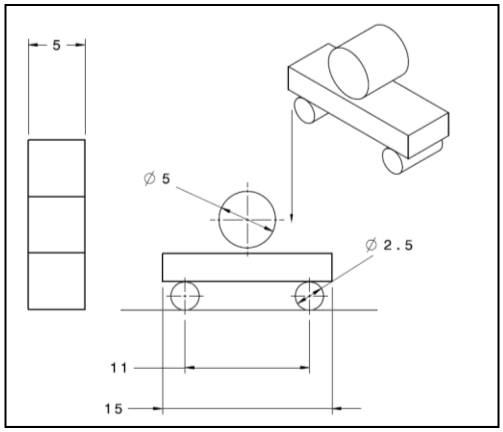

Figure 2: Dimensions of the samples and applied boundary condition for the SBS test
(All dimensions are in *mm*)

A universal testing machine with the load precision of 0.1 *N* has been used for measuring the ultimate load capacity of the composite short beams as shown in Figure 3. Based on the ASTM D2344 standard, tests continue until either of the following occurs:

- A load drop of 30 %,
- Two-piece specimen failure
- The head travel exceeds the specimen nominal thickness.

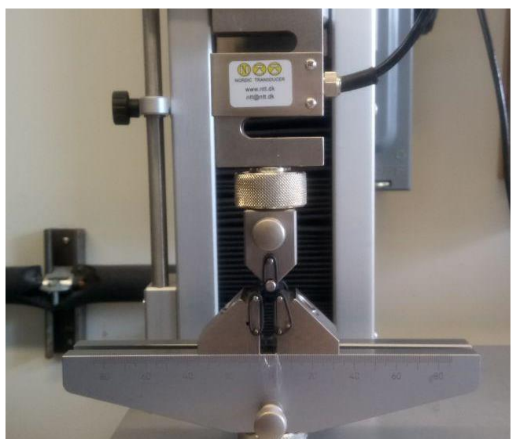

Figure 3: Short Beam Shear (SBS) test setup for short flat beams

3 RESULTS AND DISCUSSION

It is recommended by ASTM standard to find the interlaminar shear strength of the beam by the following formula:

$$F^{sbs} = 0.75\frac{P_m}{bh} \tag{1}$$

In which, P_m is the maximum load, and b and h are the width and the thickness of the sample, respectively. Note that the average thickness of the baseline samples has been chosen as a reference value for the thickness of all specimens (t_{ref} = 2.27 *mm*). Figure 4 shows the measured ILSS of three series of samples. It can be seen that the existence of the gaps in the laminates can significantly affect their interlaminar shear strengths. The average ILSS of the AFP-G laminate is around 34 MPa which is 23% and 45% less than that of AFP-R and HL laminates respectively. Furthermore, comparing the results of AFP-R and HL samples, it can be understood that having an average value of 1.0 *mm* gap can also decrease the ILSS by around 30%.

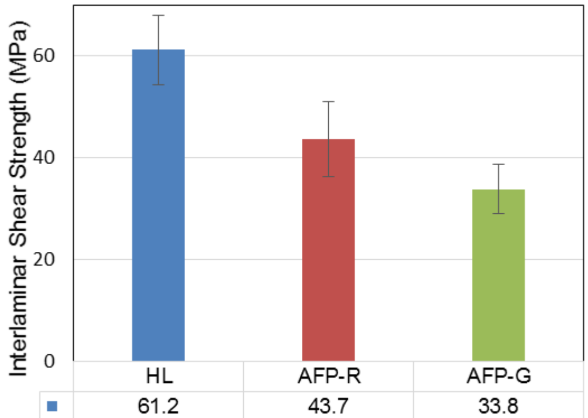

Figure 4: Comparison of the ILSS of the $[0_2/45_2/90_2/-45_2]_s$ short beam samples

It is also important to note that in order to find an average value of the shear strength, short beam samples have been cut from different locations of the plates. It means that there might be some short beams with no intentional gaps inside it in AFP-G group. Although it is difficult to inspect the existence of the gaps before performing the test, microscopic observation has been used to inspect the existence of the gap in the samples after the test. Hence, AFP-G specimens can be divided into two series of samples: Samples (1) with Intentional Gaps (I.G.) and (2) with No Intentional Gaps (N.I.G.).

Microscopic observations revealed that there is just one sample in the I.G. zone (AFP-G-4) in which there is a 2 *mm* gap in the third layer from the top of the short beam (45° lamina). Figure 5 shows the ILSS of four samples in AFP-G group. It is interesting that the ILSS of the sample in the I.G. zone is 24% less than the average ILSS of the samples in N.I.G. zone. In other words, although based on the results illustrated in Figure 4 an average shear strength reduction of 45% can be considered for the plates including intentional gaps, the largest amount of reduction occurs at the I.G. zone with a 55% reduction.

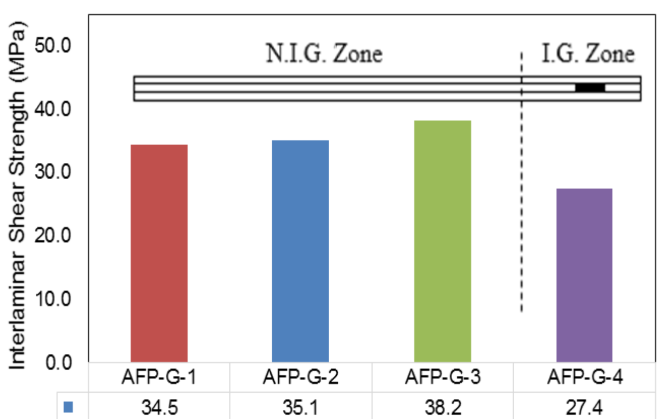

Figure 5: Comparison of the ILSS of the AFP-G samples in I.G. and N.I.G. zones

4 CONCLUSION AND FUTUR WORK

In the present study, the effect of induced gaps by AFP process on the interlaminar shear strength of the composite plates was investigated. For this purpose, an experimental short beam shear test has been performed and the results were compared with the baseline sample manufactured using hand layup process. In order to get a better understanding of the effect of gaps on ILSS, shear loading capacity of the laminate at two different zones of Intentional Gaps (I.G.) and No Intentional Gaps (N.I.G.) has been measured. Results indicate that 1.0 *mm* and 2.0 *mm* periodical patterns of gaps in the composite plates can reduce the average ILSS of the laminates by 24% and 45%, respectively. However, the maximum reduction in ILSS of 55% occurred in the short beams that included 2 *mm* gaps (I.G.).

Further numerical studies are required to simulate the interlaminar damage mechanism of the composite short beams in the presence of the gaps. Effects of multiple gap areas and also the location of the gaps on the ILSS of short beams need to be and will be addressed in future research study of the present authors.

5 ACKNOWLEDGEMENTS

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