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The influence of consolidation force on the performance of AFP manufactured laminates

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Abstract

With the increasing use of carbon/glass fibre reinforced polymer composites for large components like wing skins, fuselages and fuel tanks in aircrafts and next generation of spacecraft, utilization of advanced automated manufacturing is critical for mass production. In-situ consolidation in automated fibre placement (AFP) technology through merging several manufacturing stages like cutting, curing and consolidation has opened up a wider range of applications as well as new markets for composite materials in several sectors including aerospace and automobile in large scale. Nevertheless, the quality and integrity of AFP manufactured composites is heavily dependent on large number of variables and parameters like lay-up speed, curing/melting temperature and consolidation force. In order to establish and understand a correlation between the key parameters in AFP and the mechanical properties, several parametric experiments were performed. This is done through manufacturing uni-directional carbon fibre reinforced polymer laminates and identifying some of their main mechanical properties at different location along the length of samples. It was found that, the strength of laminates at different locations is critically dependent on the effect of those parameters.

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THE INFLUENCE OF CONSOLIDATION FORCE ON THE PERFORMANCE OF AFP MANUFACTURED LAMINATES

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Keywords: Automated fibre placement (AFP), Mechanical characterization, Inter-laminar shear strength (ILSS)

ABSTRACT

With the increasing use of carbon/glass fibre reinforced polymer composites for large components like wing skins, fuselages and fuel tanks in aircrafts and next generation of spacecraft, utilization of advanced automated manufacturing is critical for mass production.

In-situ consolidation in automated fibre placement (AFP) technology through merging several manufacturing stages like cutting, curing and consolidation has opened up a wider range of applications as well as new markets for composite materials in several sectors including aerospace and automobile in large scale. Nevertheless, the quality and integrity of AFP manufactured composites is heavily dependent on large number of variables and parameters like lay-up speed, curing/melting temperature and consolidation force.

In order to establish and understand a correlation between the key parameters in AFP and the mechanical properties, several parametric experiments were performed. This is done through manufacturing uni-directional carbon fibre reinforced polymer laminates and identifying some of their main mechanical properties at different location along the length of samples. It was found that, the strength of laminates at different locations is critically dependent on the effect of those parameters.

1 INTRODUCTION

There has been an enormous growth on the use fibre reinforced polymer composites (FRPC) for various structural applications in different engineering sectors such as; aerospace, marine and automotive. Due to their excellent mechanical characteristics, high strength-to-weight ratio, small electromagnetic signature and lower maintenance over the traditional materials [1] , FRP structures are widely being used. Over the last decades, several manufacturing techniques such as hand lay-up, vacuum bag, filament winding, autoclave and automated tape/fibre placement (AFP/ATP) have been introduced for manufacturing composite parts[2] . Among them, the potential for making multi–stiffened laminate offered by automated fibre placement has opened up a wider range of applications as well as new markets for lightweight structures [3] .

The quality and integrity of the AFP manufactured components or structures are dependent on a large number of variables and parameters, which make this process complex. Hence, preliminary laboratory scale experiments at the coupon level using different processing parameters are required for the appropriate selection of these parameters. Typical parameters are prepreg material feed rate, curing temperature, consolidation force and robot head lay-up speed that have strong influence on the bond quality of the fabricated laminate/component. Consequently a good understanding of these variables/parameters and their influences would yield part quality enhancement and optimization of manufacturing process [4] .

Several studies have been carried out so far to show the influence of AFP processing parameters on the quality of manufactured laminates. Stokes-Griffin and Compston [5] have studied the influence of processing temperature and deposition rate (lay-up speed) on the short beam strength (SBS) of CF/PEEK laminates. In this investigation, the samples were manufactured using different processing temperatures (400ºC - 600ºC) at deposition rates of 100 mm/s and 400 mm/s. It was found that, for the deposition rate of 400 mm/s, the SBS increases with temperature. However, the authors could not find a reliable correlation between the SBS and processing temperature at 100 mm/s. Bendemra et al. [6] utilized a force control unit and pressure sensor to monitor and control the compaction force. The pressure sensor pad (Tekscan-5051) was placed on the tool at a distance of 30 mm from the starting point to measure the actual resulting force in each pass. Three parameters were considered by the researchers to take into account in their experiment for a series of eighteen passes; lay-up speed (mm/s), compaction force (N) and damping (%), which is a relation between the sensitivity of robot and compaction force. There are approximately 16 N, 48.5 N and 95 N variations at 100 N, 300 N and 500 N forces. They have clearly considered effects of dual compaction force settling and influence of conformable roller. Qureshi et al. [7] also have studied the effect of compaction force and lay-up speed on inter-laminar shear strength (ILSS). Although due to better resin diffusion, an increase of compaction force should raise the ILSS theoretically, but the authors could not find a reliable correlation between compaction force and ILSS. The effect of compaction force on thickness and dimensional variation of laminate is also an important issue that was investigated by Pitchumani et al. [8] . In order to obtain better consolidation while placing several layers for a given thickness of laminate, the consolidation force should be increased. However, that approach resulted in the thickness reduction of entire laminate. On the other hand, applying lower consolidation force leads to the formation of voids within the laminate.

In this paper, an experimental study is carried out to establish and understand the correlation between the consolidation force in AFP and the subsequent mechanical properties. The experimental program covers several parameter selection towards the specimen manufacture, followed with the conduct of experiments for mechanical characterisation. Samples are manufactured using uni-directional CFRP laminates, under four different processing conditions. The mechanical properties that are characterised are; elastic modulus and inter-laminar shear strength (ILSS) at different stages along the length of the samples.

2 MANUFACTURING TECHNIQUE AND TEST METHOD

2.1 Automated fibre placement (AFP) operation principle

Automated Fibre placement (AFP) is a hybrid process that has both advantages of filament winding [9] and automated tape lying [10] .The major advantages of this method include accuracy of the fibre placement, automatic debulking, no-need to post processing (for thermoplastic materials), significant reduction in material and labour cost [11] .

Automated Dynamics built AFP machine was used for manufacturing the laminates in this investigation. The AFP machine consists of a placement head and robotic arm which are computer controlled [12-14] , as shown in Figure 1. Since several manufacturing stages including lay-up, curing/heating and consolidation are merged together in one lay-up head, AFP offers higher productivity in comparison with the other conventional methods [15] . At the start of lay-up process, the placement head brings the prepreg tape surfaces together under heat and pressure. The pressure is applied by consolidation roller to squeeze the air out of the composite laminate and hot gas torch (HGT) or laser can be used as the heat source [16] . In this study, a hot gas troch (HGT) was utilized that can deliver high temperature nitrogen (up to 950 ºC) through a nozzle around the tape to initiate the polymerisation.

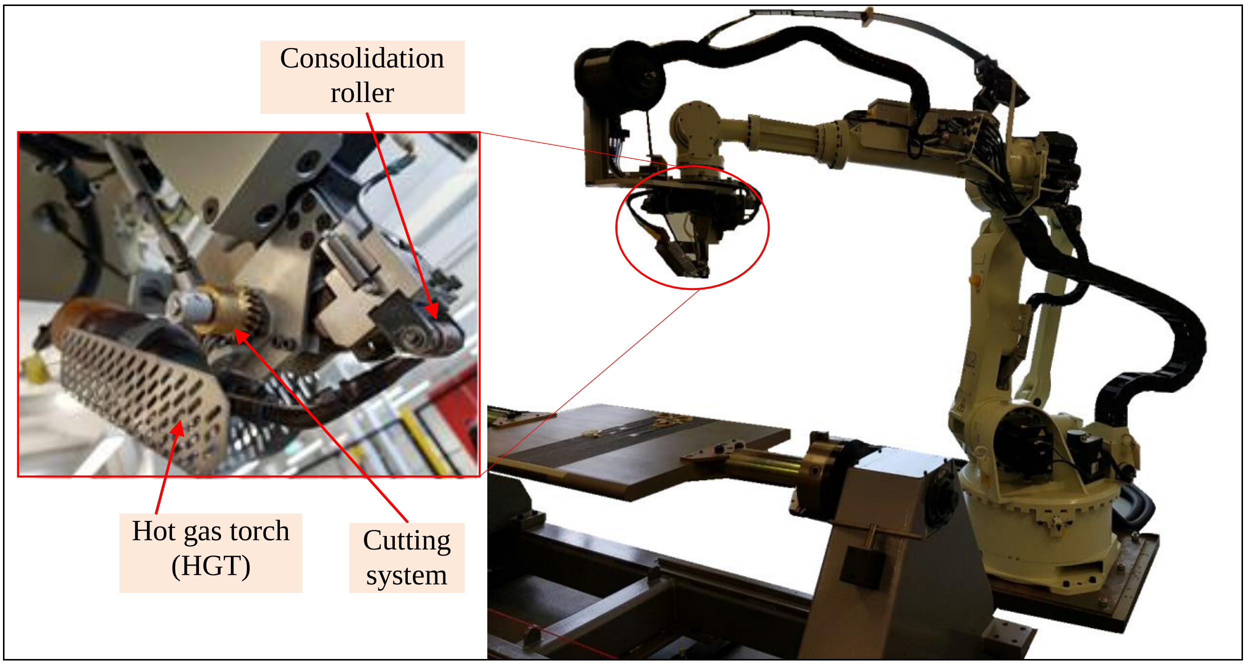


Figure 1. Automated fibre placement (AFP) machine with the thermoplastic (TP) head

2.2 Sample preparation

In this experimental investigation, four laminates were manufactured using unidirectional (UD) thermoplastic prepreg tapes, CF/PEEK (AS4/APC2; supplied by Cytec). The prepreg tapes are of 0.15 mm thick and 6.35 mm wide. The material properties of the prepreg including density, module of elasticity, shear modulus, Poisson's ratio and fibre volume fraction are 1570 kg/m^3, 138 GPa, 5 GPa, 0.28 and 0.6 respectively.

The lay-up procedures for the manufactured laminates are shown in Figure 2 (a) and (b). Each sample consists of twenty-one plies of UD prepreg tapes. The prepreg plies are processed simply by heating and cooling cycle. To study the relationship between the process parameters and the mechanical properties, four different consolidation conditions were used which are presented in Table 1. In all of these conditions, the deposition rate and temperature were kept constant at 76 mm/s and 850 ºC respectively while the consolidation force was varied between the lowest and highest load that can be applied by the AFP machine (180-450 N). The overall dimension of each sample was 200 (Length) x 6.35 (Width) x 3.15 (depth) millimetres. The samples were then cut to ten small coupons (19 mm x 6.35 mm x 3.15 mm) using a diamond saw.

Table 1. The processing conditions for manufacturing the thermoplastic laminates.

Lay-up process conditions						
Laminate Types	Processing Condition No.	Deposition Rate (mm/s)	HGT Temperature (ºC)	Actual Temperature (ºC)	Consolidation Force (N)	Number of plies
Unidirectional*	C1	76	850	~415	180	21
	C2	76			250	21
	C3	76			350	21
	C4	76			450	21

* Unidirectional: 0º

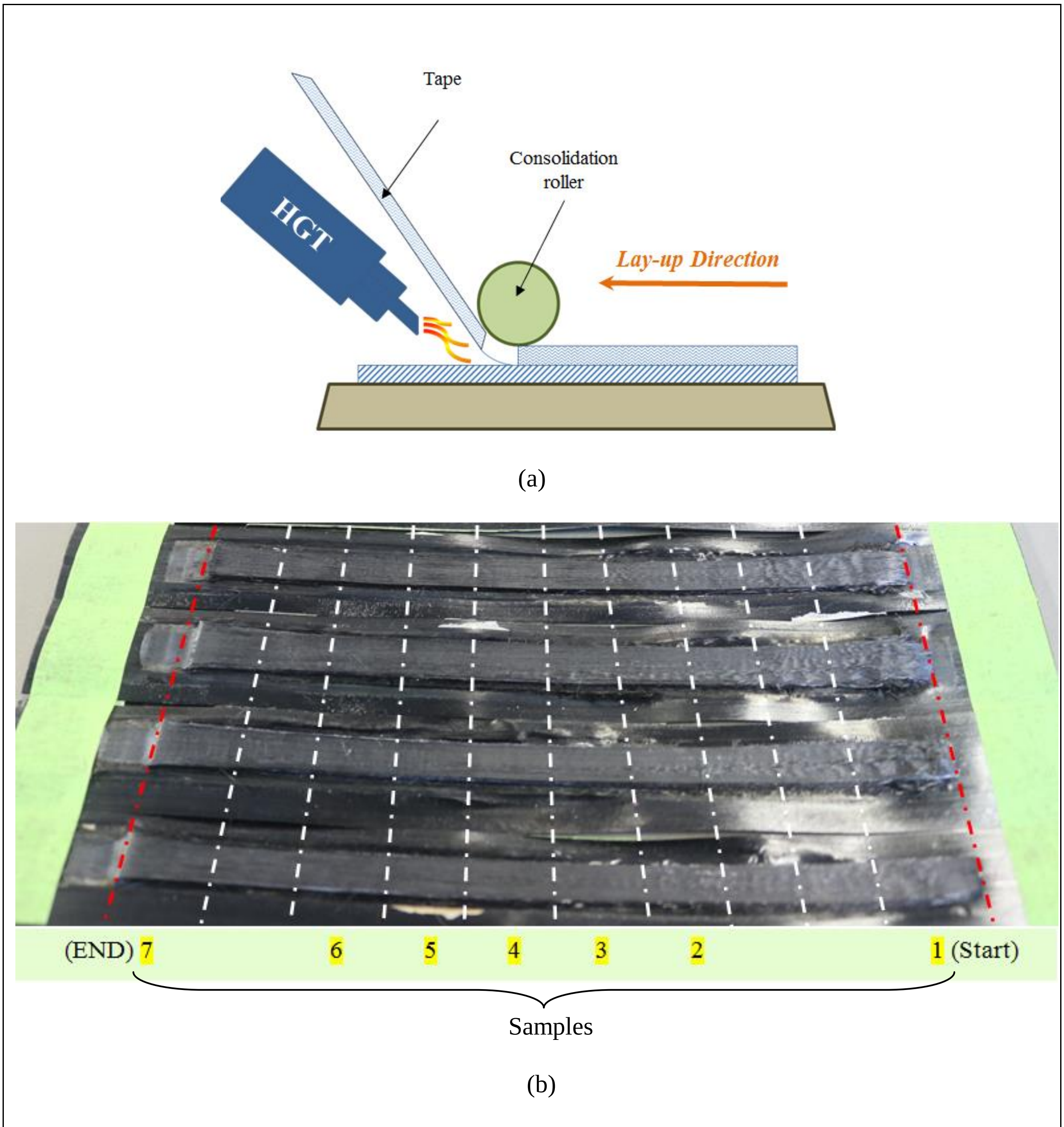


Figure 2. (a) AFP Lay-up process; (b) AFP manufactured laminates before cutting.

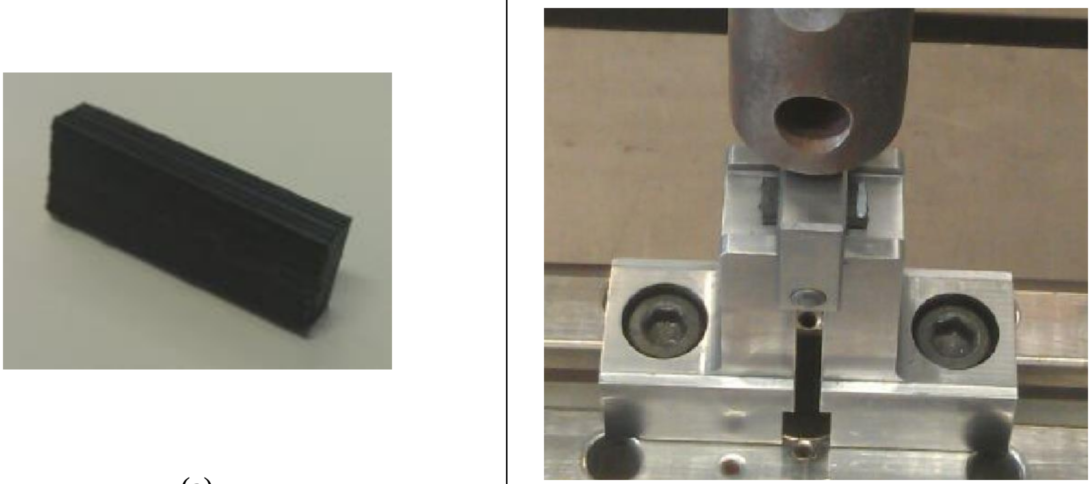
2.3 Experimental set-up

The AFP made CFRP coupon samples were loaded into a test fixture which is specially designed to perform the Short Beam Strength (SBS)/Interlaminar Laminar Shear Strength (ILSS) tests using uniaxial test machine. The experimental setup for analysing the mechanical characteristics of AFP manufactured laminates is shown in Figure 3. In order to study these characteristics at different stage of lay-up process the test coupons were chosen from different regions of each laminate, Figure 2 (b). All specimens were tested at constant loading rate of 1 mm/min in displacement control mode. The elastic modulus of five coupons from each sample were determined in accordance to ASTM-D2344.

The short beam strength /interlaminar shear strength (ILSS) of each coupon was calculated using equation (1) [17] :

$$F^{sbs} = 0.75 \times \frac{P_m}{b \times h} \quad (1)$$

where F^{sbs} is the short beam strength/inter-laminar shear strength; P_m is maximum flexure load; b is the specimen width and h is the specimen thickness.

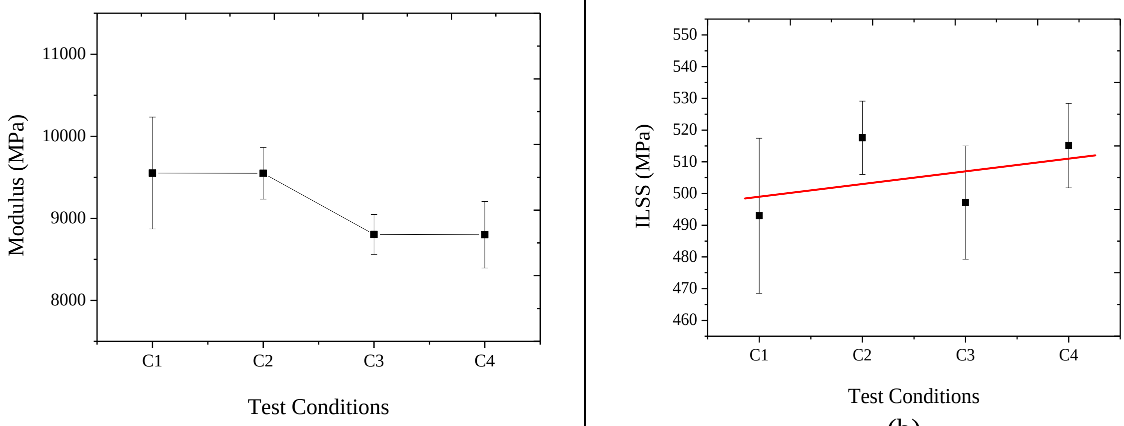


(a) (b)

Figure 3. (a) Test coupons; (b) Experimental set-up for the ILSS test using Instron 50KN.

3 RESULTS AND DISSCUSSION

The experiments were conducted on the test coupons (CF/PEEK) from the laminates made using four different processing conditions, as presented in Table 1. In order to study the influences of processing parameters on the mechanical characteristic of manufactured laminates seven coupons were selected from each laminate; five coupons from the middle region and two coupons from the both sides (start and end) of laminate, Figure 2 (b). Three-point bend tests were then carried out using Instron 3369-50KN uniaxial machine at loading rate of 1 mm/min. The summary of the obtained results, including elastic modulus and inter-laminar shear strength are illustrated in Figure 4.



(a) (b)

Figure 4. The summary of mechanical test results: (a) Elastic Modulus; (b) Interlaminar shear strength (ILSS); (c) Maximum flexural stress; (d) Maximum flexural strain (Error bars represent

standard deviation (±σ) of five individual experiments).

Since the deposition rate of material and processing temperature in AFP machine were kept constant, there is only one factor which has almost non-linear effects on the overall mechanical properties. It is observed that among all test conditions, the first and second conditions, where lower consolidation forces were applied, yield superior elastic modulus. The average elastic modulus with the standard deviation error bar (±σ) for each condition is shown in Figure 4 (a). It can be observed that, the increase of load leads to fibre reach area within the laminate and formation of voids, consequently lower elastic modulus are obtained. The average inter-laminar shear strength (ILSS) with the standard deviation error bar (±σ) for each condition is also shown in Figure 4 (b). As can be seen, with the increase of consolidation force from 180 N to 450 N, the ILSS is varied between 492.97 MPa and 515.09 MPa, with an ascending trend. This fluctuation may be attributed to the presence of random flaws like fibre or resin reach area within the laminate influenced by the increasing load. Additionally, larger number of plies (21 in this study) under increasing load will result in varied thickness at the final stage, thereby different ILSS using the relationship expressed in Eq. 1. In order to obtain same or higher strength, other two process parameters such as; lay-up speed and temperature need to be re-adjusted for the applied forces.

The comparison of the elastic modulus for all seven coupons, taken from different regions of each laminate is shown in Figure 5. It is evident that, the first coupon in all four laminates has the lowest elastic modulus. This might be due to influence of several parameters at the beginning of lay-up process such as overheating, which leads to degradation of the plies, or tow waviness. Hence, the bond quality of the laminate was negatively affected and lower elastic modulus is obtained. As can be seen, the elastic modulus of the coupons were taken from the middle region (Samples 2-6) is relatively higher and almost is at the same level. Finally, slight decrease is observed in the elastic modulus of the seventh samples which were taken from the end of the laminates (Figure 2).

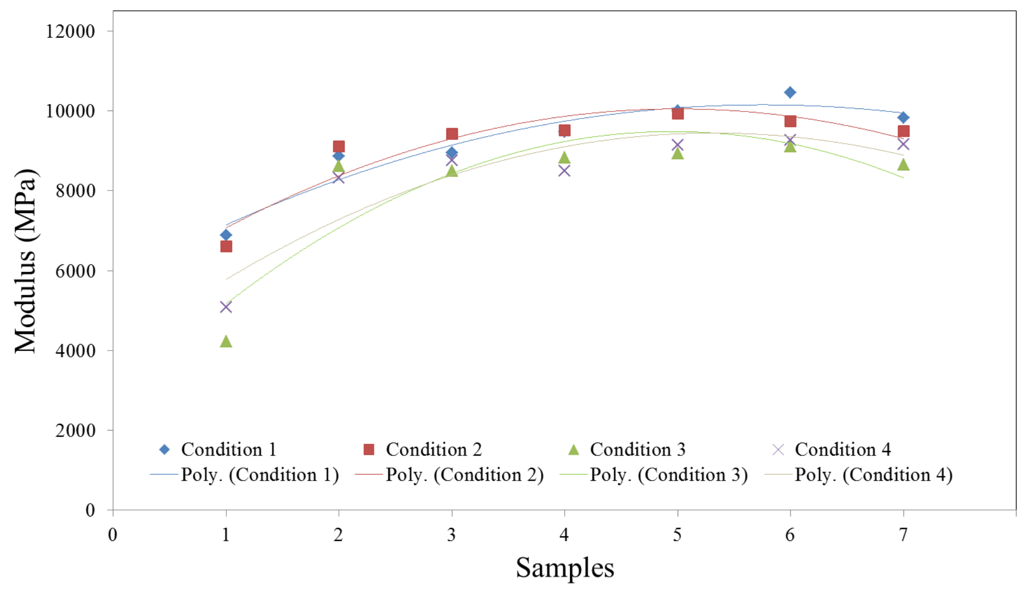


Figure 5. Comparison of the elastic modulus of test coupons.

4 CONCLUSION

In this experimental study to study the influence of process parameters on the quality of AFP manufactured laminates, CFRP laminates were fabricated using different processing conditions. The laminates were then cut to small test coupons. The mechanical characterizations of the coupons were investigated through the laboratory based mechanical tests using three-point bending test machine. From obtained results it was found that, using lower consolidation forces (while the temperature and lay-up speed are fixed) higher elastic modulus can be achieved. However, there is not a reliable correlation between the consolidation force and ILSS. In addition, the elastic modulus of fabricated laminates at different regions along the length was investigated. It was found that, the strength of laminates at different locations is critically dependent on the processing conditions. However further experiments need to be conducted on samples made using different deposition rates and temperatures which is still ongoing.

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