

# PSEUDO-DUCTILE BEHAVIOR OF GLASS/CARBON FIBER HYBRID COMPOSITE WITH CARBON/EPOXY PLATELETS

Ichenihi Amos<sup>1</sup>, Wang Qingtao<sup>2</sup>, Md. Hasan Ikbal<sup>2</sup>, Li Wei<sup>2,3\*</sup>

<sup>1</sup>College of Material Science and Engineering, Donghua University, Shanghai, China

<sup>2</sup>College of Textiles, Donghua University, Shanghai, China

<sup>3</sup> Key Laboratory of Textile Science & Technology, Ministry of Education

\* Corresponding author, E-mail address: [liwei@dhu.edu.cn](mailto:liwei@dhu.edu.cn)

**Keywords:** pseudo-ductile, prepreg, hybrid composite, carbon

## ABSTRACT

In this paper the behavior of a hybrid composite which contains two composites, one is the lower elongation carbon epoxy composite and the other is the higher elongation glass epoxy composite laminate is studied. There are several engineered advancements that have been made in different hybrids that are geared towards bringing pseudo-ductile effect which includes using a very thin layer of carbon in the glass, the use of short thin carbon platelets and also making a highly dispersed hybrid of glass with carbon fibers. Two of these engineering aspects which include thin carbon ply and carbon platelets are combined. The sample with the best pseudo-ductile property was the 2EG/1CP/1CC/1CP/2EG sample with 50% resin content carbon prepreg with a pseudo-ductile strain of  $1.204 \pm 0.038\%$ .

## 1 INTRODUCTION

High-performance composites have basically provided cheaper and lighter weight materials which are also environmentally friendly as compared to metals. This has led them to be popular as alternatives to metals and ceramics. Although they have these advantages, some have a major drawback which is a catastrophic failure. However, the catastrophic failure is a major safety issue in the end applications for some composites with brittle fibers, despite their high strength, due to lack of warning before collapsing or failure of the material.

To eliminate this catastrophic failure several designs of fiber-matrix composites have been generated to come up with the ductile property. This gradual failure property that is being introduced into composites, mainly via hybrid composite, is known as pseudo-ductility. Gergely et al in one of his studies stated that a basic strategy to achieve pseudo-ductility is to incorporate new ductile matrices and fibers, which needs extensive development and validation. Another option is to modify the structure of composite laminates made from commercially available raw materials, e.g. creating hybrids, which is faster and more straightforward [1]. Various works which were done on hybrid composites[2-8] showed there is a possibility to obtain a gradual failure over a range of strains by combining different types of fibers either by mingling them [3, 9, 10] or by constructing a ply-by-ply hybrid structure [11-14]. The so-called pseudo-ductility was first observed and shown by Hayashi et al. [11, 12] in their study on unidirectional (UD) layered glass/carbon hybrid composites. Improved strain to failure of carbon fibers in the glass/carbon hybrid composite was observed, compared to that obtained in single fiber composite specimens.

A clear definition of pseudo-ductility and yield stress is desired to compare different types of nonlinear tensile stress–strain response[15, 16]. The pseudo-ductile strain is defined here as the extra strain between the final failure point and the initial slope line at the failure stress level. If the stress–strain response includes loss of integrity such as before the final failure there are long inter laminar cracks, the pseudo-ductile strain is measured from that point. Therefore, the pseudo-ductile strain is assumed not to be there (brittle failure) if the load drop occurs as the first initial nonlinearity in the stress–strain response.

Designs that have been done on carbon/glass hybrid composites for the pseudo-ductile property are the utilization of thin continuous carbon plies[1] and the utilization of carbon platelets between glass layers (with some samples also containing continuous carbon at the center of the platelets) [16]. For this study, these two designs will be combined and studied to find out if the pseudo-ductile property can be enhanced. The thin continuous carbon was used to maintain the high strength of the carbon before fracture while the thin carbon platelets idea was decided on to act as a buffer to assist in the absorption of the energy generated during the fracture of the thin continuous carbon fiber.

## 2 MATERIALS

E-glass and carbon fiber prepregs, with specifications listed in table 1, obtained from Wei hai Guang wei Composites Co., Ltd. and Shanghai Cedar and Nissei Co., Ltd., respectively.

Table 1: Specifications of E-glass and Carbon prepregs

Type	Fiber	Tensile strength (MPa)	Tensile modulus (GPa)	Resin content (%)
EC13-600 -1	E-glass	950 <sup>a</sup>	42 <sup>a</sup>	33 <sup>a</sup>
TC-35	Carbon	1983.26 <sup>b</sup>	44.48 <sup>b</sup>	50 <sup>a</sup>
UA2438-1				41.1 <sup>a</sup>

<sup>a</sup> from company catalog, <sup>b</sup> from experimental results

The platelets were made from the carbon prepregs mentioned in table 1. The makeup of the platelets panel is shown in the Fig. 1(a). The blue lines represent the pre-cuts that were made in the carbon fiber prepreg panel before the layup of the hybrid composites. For the layup, the structure used was EG/CP/CC/CP/EG whereby: EG is the E-Glass, CP is the carbon platelets and CC is the continuous carbon prepreg. The schematic structure of the lay-up is shown in Fig.1 (b), where A is EG, B is CP and C is CC respectively. The red dashed line in Fig. 1(a) shows the cutting line when the testing coupons were made.

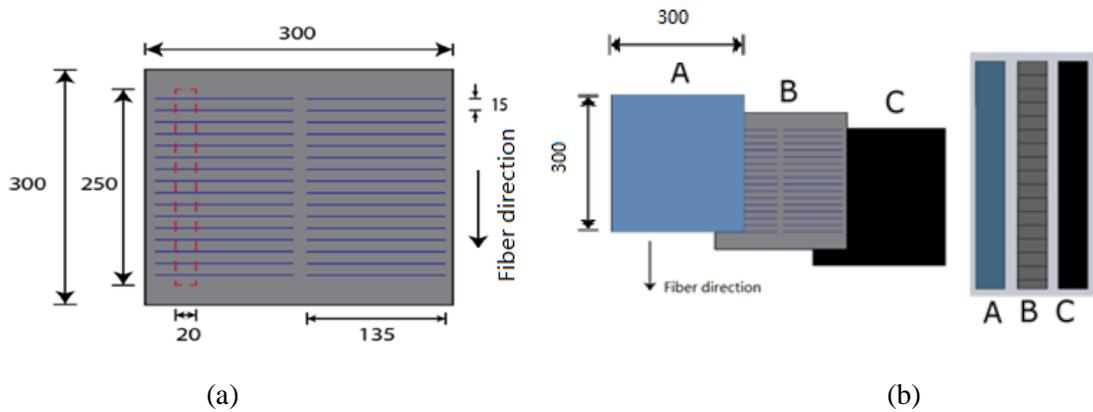


Figure 1: Schematic makeup of platelets and layup structure

The layup configurations of the 41.1% resin content (RC) with UA2438-1 and 50% RC with TC-35 carbon prepreg are given in table 2.

Table 2: Layup configuration of the tensile specimens

Sample layup with 41.1% RCCarbon prepreg		Sample layup with 50% RCCarbon prepreg	
Ply arrangement	Thickness (mm)	Ply arrangement	Thickness (mm)
4EG/2CP/2CC/2CP/4EG	1.14	1EG/1CP/1CC/1CP/1EG	0.40
4EG/2CP/4CC/2CP/4EG	1.23	1EG/1CP/2CC/1CP/1EG	0.45
4EG/4CP/2CC/4CP/4EG	1.29	1EG/2CP/1CC/2CP/1EG	0.48
2EG/1CP/1CC/1CP/2EG	0.61	2EG/1CP/1CC/1CP/2EG	0.64
2EG/1CP/2CC/1CP/2EG	0.63	2EG/1CP/2CC/1CP/2EG	0.66
2EG/2CP/1CC/2CP/2EG	0.67	2EG/2CP/1CC/2CP/2EG	0.68

### 3 SAMPLE PREPARATION

Hybrid composite panels, with 300mm x 300mm, were made by vacuum bag processing in the oven under 1 bar. The temperature was maintained at 110 °C for 150 minutes. Afterward, it was left to cool at room temperature.

### 4 TESTING

The tensile tests were done according to the ASTM D3039/D3039M. The hybrid composite panels were cut according to the size in Fig.2(dimensions are in millimeters). The loading rate used was 2mm/sec and the load/displacement data recorded.

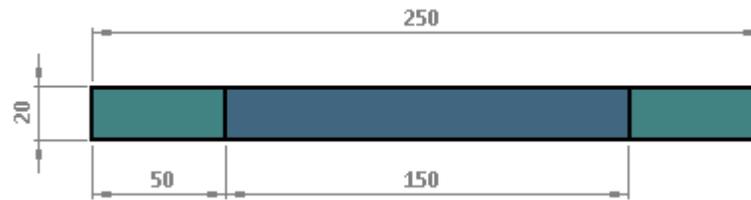


Figure 2: Dimension for the testing coupon

## 5 RESULTS AND DISCUSSION

### 5.1 Stress-strain curves

The results are shown in Table 3 and the tensile curves are shown in Fig.3 for 50% RC and Fig.4 for 41.1% RC. It was found that there are only five layups that had the presence of pseudo-ductility, while two were showing catastrophic delamination immediately after yielding before picking up to the final failure of the lower strain material. The remaining five samples didn't show any strain plateau, but a catastrophic failure after yielding. For this paper, the samples that showed some level of pseudo-ductility are discussed.

Table 3: Results of the tensile testing

Ply arrangement	ultimate tensile stress (MPa)	Modulus decrease from pure carbon (%)	Elastic modulus (GPa)	Pseudo yield strain (%)	Pseudo yield stress (MPa)	Pseudo-ductile strain (%)
41.1% resin content						
4EG/2CP/4CC/2CP/4EG	834.85 (3.14)	30.05	31.12 (17.62)	3.47	687.30	0.73 (42.46)
4EG/2CP/2CC/2CP/4EG	860.45 (3.40)	42.15	25.74 (13.85)	3.40	717.46	0.81 (6.11)
4EG/4CP/2CC/4CP/4EG	904.45 (1.67)	47.15	23.51 (4.72)	-	-	-
2EG/1CP/1CC/1CP/2EG	805.31 (2.46)	42.68	25.50 (1.00)	-	-	-
2EG/1CP/2CC/1CP/2EG	922.09 (4.49)	39.16	27.07 (7.25)	-	-	-
2EG/2CP/1CC/2CP/2EG	743.53 (3.29)	44.34	24.76 (9.23)	-	-	-
50% resin content						
1EG/1CP/1CC/1CP/1EG	621.95 (4.89)	37.12	27.98 (6.50)	1.89	585.75	0.61 (15.54)
1EG/1CP/2CC/1CP/1EG	786.93 (3.29)	40.48	26.48 (6.57)	-	-	-
1EG/2CP/1CC/2CP/1EG	581.26 (5.05)	41.89	25.86 (4.36)	-	-	-

2EG/1CP/1CC/1CP/2EG	778.80 (3.40)	47.00	23.58 (6.02)	3.72	662.42	1.20 (3.15)
2EG/1CP/2CC/1CP/2EG	645.48 (3.38)	40.89	26.30 (6.49)	-	-	-
2EG/2CP/1CC/2CP/2EG	663.78 (6.84)	49.55	22.44 (3.86)	2.47	570.04	1.55 (6.43)

**Note:** The coefficient of variance is given in the bracket.

The stress-strain curves of 12 various lay-up structures are shown in Fig. 3. Pseudo-ductile behavior was observed in 1EG/1CP/1CC/1CP/1EG, 2EG/1CP/1CC/1CP/2EG and 2EG/2CP/1CC/2CP/2EG samples for the 50% RC carbon prepreg shown in Fig. 3 (a), (d) and (f) respectively. The 4EG/2CP/2CC/2CP/4EG and 4EG/2CP/4CC/2CP/4EG samples with 41.1% RC carbon prepreg shown in Fig. 4 (d) and (e) respectively, also showed pseudo-ductility.

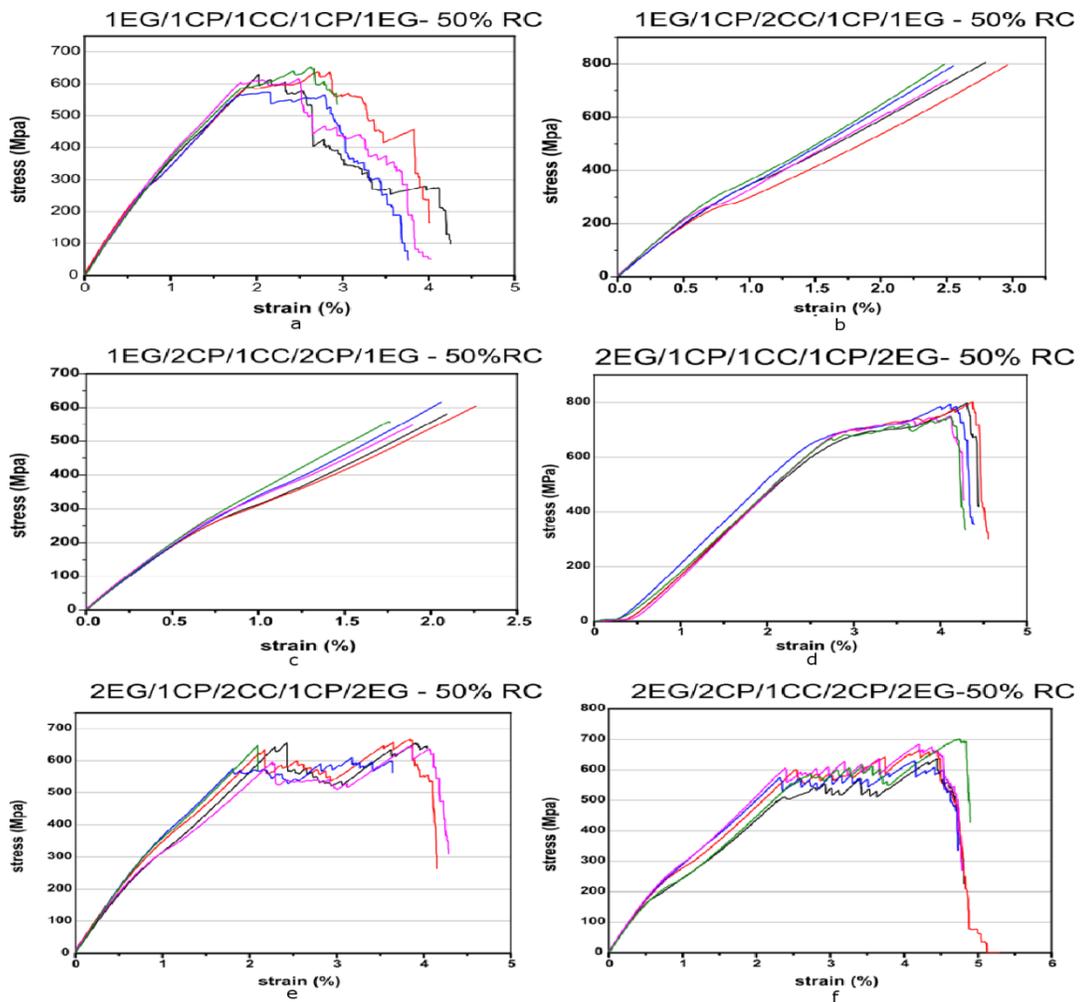


Figure 3: Tensile stress and strain curves for 50% RC carbon prepreg samples

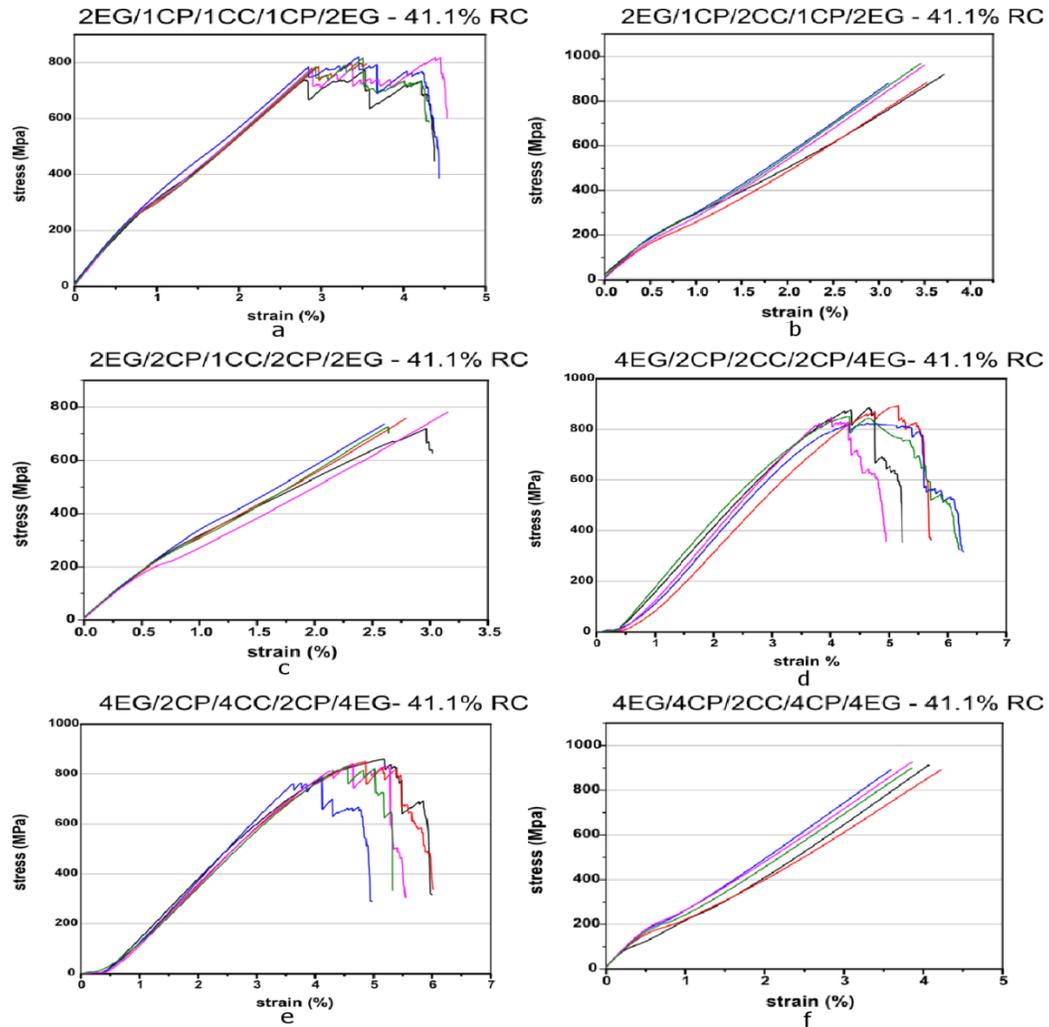


Figure 4: Tensile stress and strain curves for 41.1% RC carbon prepreg samples

For the samples 2EG/1CP/2CC/1CP/2EG of 50% RC carbon prepreg and 2EG/1CP/1CC/1CP/2EG of 41.1% RC carbon prepreg shown in Fig.3 (e) and Fig.4(a) respectively, there was a big load drop after yielding before picking up to the failure of the higher strain material. This is a traditional failure behavior of hybrid composites. The 2EG/1CP/1CC/1CP/2EG of 41.1% RC had the longest plateau before the fracture of the higher strain material but had a large load drop immediately after the initial strain due to large delaminations, shown in Fig.3 (e), which doesn't qualify it to be pseudo-ductile. Comparing the stress-strain curves of the 50% RC (Fig.3 (d)) with that of the 41.1% RC (Fig.4 (a)) carbon prepreg of the 2EG/1CP/1CC/1CP/2EG layup samples, we can also assume that the large load drop in the 41.1% RC sample is due to the lower resin content. The lower resin content means more carbon fibers thus higher energy release that comes with the fracture of the carbon fibers. Fig. 5 shows an example of a fractured sample that underwent multiple cracking and delamination. Fig.5 (A) is the image of the whole test specimen while (B) is a zoomed image of the area of rupture.

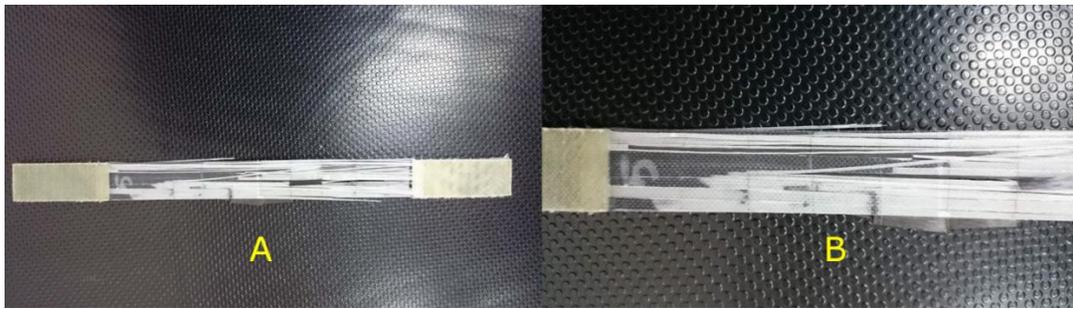


Figure 5: Failed sample of the 2EG/1CP/1CC/1CP/2EG design of 50% RC carbon prepreg.

The plateaus in the 4EG/2CP/2CC/2CP/4EG and 4EG/2CP/4CC/2CP/4EG designs (shown in graphs in Fig.4 (d) and (e) respectively) are not big because the material started yielding due to delamination. There was no picking up of the load by the higher elongation glass layers after the gradual yielding because of the high load bearing capability of the thicker carbon layers involved (with the platelets included). Thicker carbon layers between the glass layers (considering glass to carbon layer ratios) means more energy release which is more than the interfacial energy causing massive delamination at the region of crack. It is shown in the samples that failed catastrophically. In the 4EG/4CP/2CC/4CP/4EG design in Fig.4 (f), the catastrophic failure immediately at yield point is seen and highlights the assumption that there is also added stress concentrations due to the longer crack impression that is created by the thicker layers of platelets. These crack impressions are generated because while preparing the samples overlapping of platelets was not considered. The early massive delamination observed (assumed to be caused by the crack impression in the specimen) separates the glass layers entirely from the carbon layers leaving the carbon layers as the load bearers. Due to this, the failure observed is totally because of the fracture of only the carbon layers. Fig.6 shows a picture of the delamination and fracture that was observed on the 4EG/4CP/2CC/4CP/4EG sample. No fracture, and separation of the glass layers from the carbon layers is seen clearly as well as the fractured carbon layers.

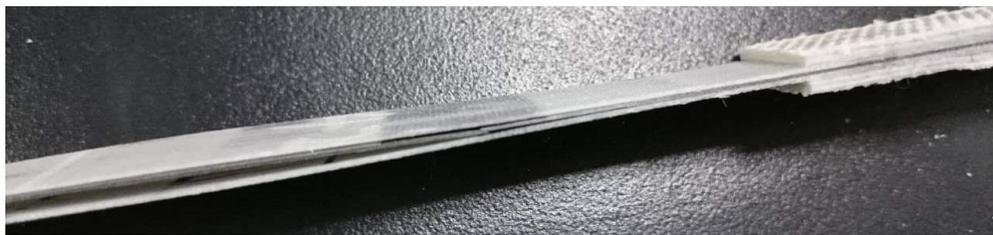


Figure 6: Catastrophic delamination and carbon layers fracture observed in the sample of 4EG/4CP/2CC/4CP/4EG design with 41.1% RC carbon prepreg

The same kind of failure that was observed in the 4EG/4CP/2CC/4CP/4EG was also observed on the 2EG/2CP/1CC/2CP/2EG and 2EG/1CP/2CC/1CP/2EG samples of the 41.1% RC carbon prepreg shown in Fig.4 (c) and (b). For the 2EG/2CP/1CC/2CP/2EG, it might be due to high stress concentration caused by the thicker platelets layers, and for the 2EG/1CP/2CC/1CP/2EG due to the thick continuous carbon layer in addition to the reason that the prepreg has a high percentage of carbon fiber. Fig.7 (A) and (B) shows the whole and the zoomed 1EG/2CP/1CC/2CP/1EG specimen image that also failed catastrophically (Graph is shown in Fig.3 (c)). This is an example of catastrophic failure caused by fracture of carbon and delamination of it from the glass layers in the 1EG/2CP/1CC/2CP/1EG and 1EG/1CP/2CC/1CP/1EG samples of the 50% RC carbon prepreg shown in Fig.3 (c) and (b). It can be seen that the high fracture energy, which caused the uncontrollable delamination, was entirely due to the fracture of the carbon layers.

There was no steady pull out of the platelets instead they fractured at the center, implying that the critical length of the carbon fiber is a major factor to be considered.

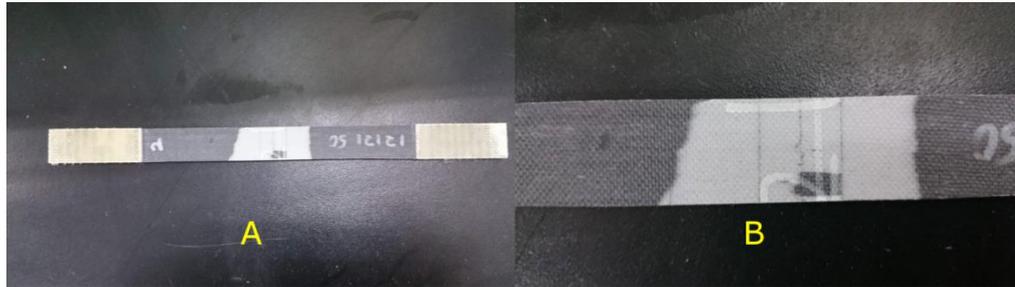


Figure 7: Failed sample of the 1EG/2CP/1CC/2CP/1EG design of 50% RC carbon prepreg. a) Whole sample b) zoomed to show the cracked region

For the 50% RC carbon prepreg, the pseudo-ductility was observed in the 1EG/1CP/1CC/1CP/1EG, 2EG/1CP/1CC/1CP/2EG and 2EG/2CP/1CC/2CP/2EG samples. Only the 2EG/1CP/1CC/1CP/2EG design exhibited the best pseudo-ductile pull out behavior, whereby a smooth curve was observed. Fig.5 shows a failed specimen of the 2EG/1CP/1CC/1CP/2EG 50% RC carbon prepreg sample which depicts multiple fracture and delamination of the sample. The Fig.8 shows a clear image of the whole delamination process to the final rupture of the sample. A steady pull out of the carbon platelets can be seen progressively at highlighted points a, b and c where there was a gradual growth in the delamination of the glass layers from the platelet layers and it was spread evenly along the length of the specimen.

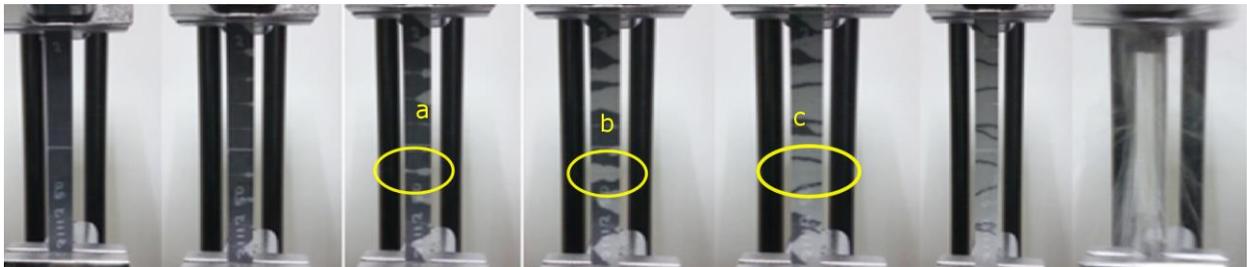


Figure 8: Delamination propagation to final rupture of the 2EG/1CP/1CC/1CP/2EG sample with 50% RC carbon prepreg

This curve nearly mimicked the metallic plastic deformation. This is seen in the graph in Fig.3 (d). The 2EG/2CP/1CC/2CP/2EG sample also exhibited pseudo-ductile behavior but also had moderate series of delamination leading to moderate load drops at the plateau before the failure of the higher strain material (Fig.3 (f)). Clearly, this larger load drops compared to that of 2EG/1CP/1CC/1CP/2EG 50% RC material is because of the thicker platelets region making a bigger crack impression, thus higher stress concentrations at that region. The 2EG/1CP/2CC/1CP/2EG showed this plateau of load drops before the final failure (Fig.3 (e)) but because its first failure was a large load drop it is not considered here to be pseudo-ductile because this failure is a traditional hybrid failure behavior. Also, the 1EG/1CP/1CC/1CP/1EG sample showed pseudo-ductility but with a shorter plateau (Fig.3a), thereason being that the layer of glass was one on both sides of the carbon layers. There was a steady pull out, therefore, a smooth yielding process but was short left faster because of the thin layer of glass which handles less stress. The other design of one layer glass sandwich failed catastrophically because of the reasons discussed above which include longer crack fault impression and thicker continuous carbon layer that releases larger fracture energies.

## 5.2 Damage analysis

The morphology of the tested samples was done using scanning electron microscope (SEM) of Hitachi TM3000 model. Fig.9 and 10 are the images of carbon fibers and glass fibers respectively obtained from a region in a pseudo-ductile failed sample. From Fig.9, it can be seen that the presence of glass fibers still stuck to the carbon fibers, which shows good interfacial properties. Also, the flaking in Fig.9 (B) shows the extent of damage due to the cracking of the epoxy. From these two observations, it shows that the interfacial properties contributed to bringing about pseudo-ductility from the excess damage it caused to both the resin and the fractured glass fibers. The damages observed here are the fracture of glass fibers evident from some of their remnants in the carbon fiber layer, and also the fracture of the resin seen clearly around the glass fiber remnants. Also, it can be seen from (B) that the carbon fibers are not covered by resin, which means it was eliminated by its fracture. It is also observed from Fig.9 (A) that there was shear between some of the carbon fibers in the same layer which proves there was steady pull out that occurred during loading.

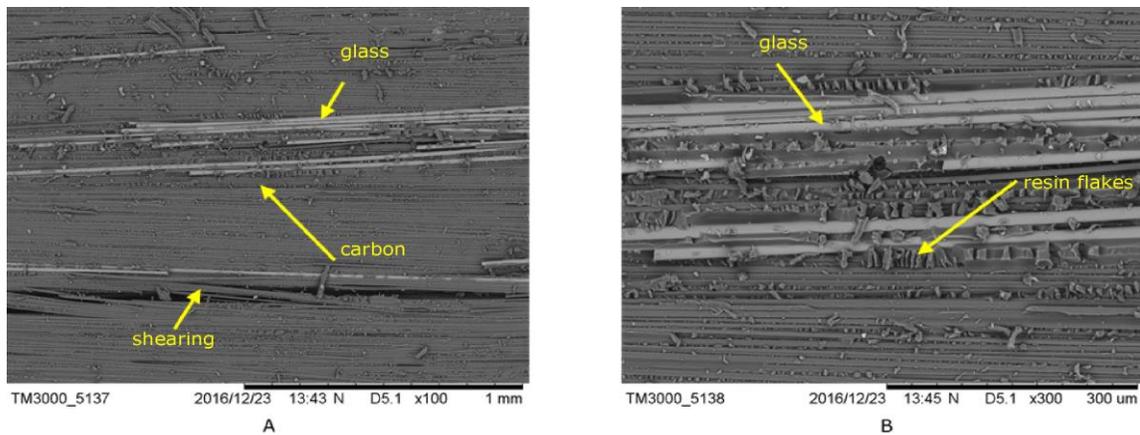


Figure 9: SEM images of carbon fibers at different magnification level (pseudo-ductile sample)

In the Fig.10 (A), it is observed that there is a fracture in the glass fibers, also in Fig.10 B, as indicated by the arrows. It shows that the glass fibers assisted in carrying the load proving the existence of the pseudo-ductile region due to improved elongation it brings about. Also, the presence of flaking is observed as seen from Fig.10 (B). This area also showed that most glass fibers are uncovered by the epoxy resin showing most was eliminated during the fracturing process.

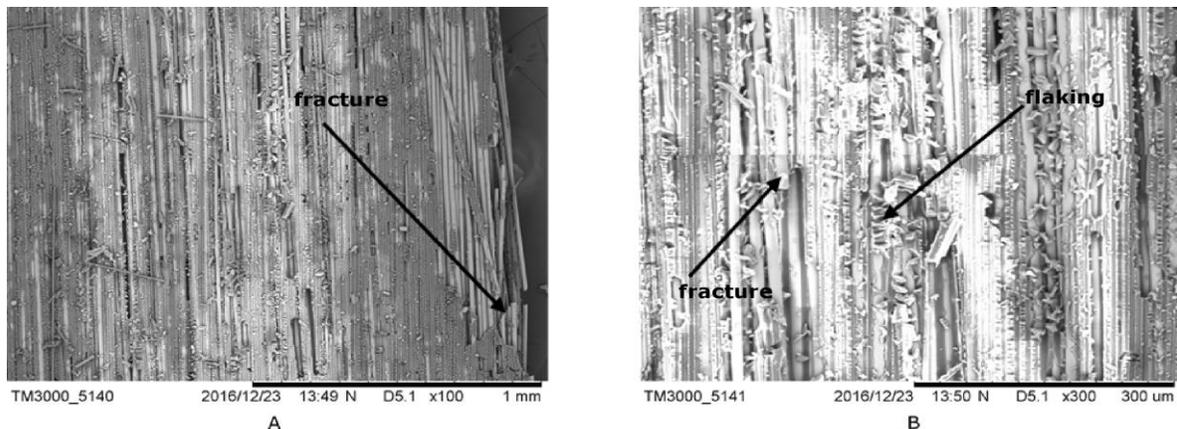


Figure 10: SEM images of glass fibers at different magnification level (pseudo-ductile sample).

It is also noted from the images that flaking is of high magnitude around the glass fibers on the carbon layer showing that this region had good cohesive properties.

It was taken at the fractured region shown previously in Fig.7 (B) of a catastrophically failed sample, to show Fig.11. The fractured carbon fibers are able to be seen in Fig.11 (A) and (C). It is also clearly seen in Fig.11 (A) compared to the previous images that this image has no or little flaking of the epoxy resin on the surface. The fracture of the resin is only seen around the region of fracture as clearly highlighted in Fig.11 (C). This means that there was no energy transferred to the interface and all the fracture energy was taken by the carbon fibers only at the region of fracture. From Fig.11B (taken farther away from the fractured area) it is seen one strand of glass fiber which when compared to the previous images of pseudo-ductile samples it has less glass fracture thus less energy transfer to the glass layers, and also less flaking of the resin. This supports the assumption that, very little or no energy transfer occurred in the interface.

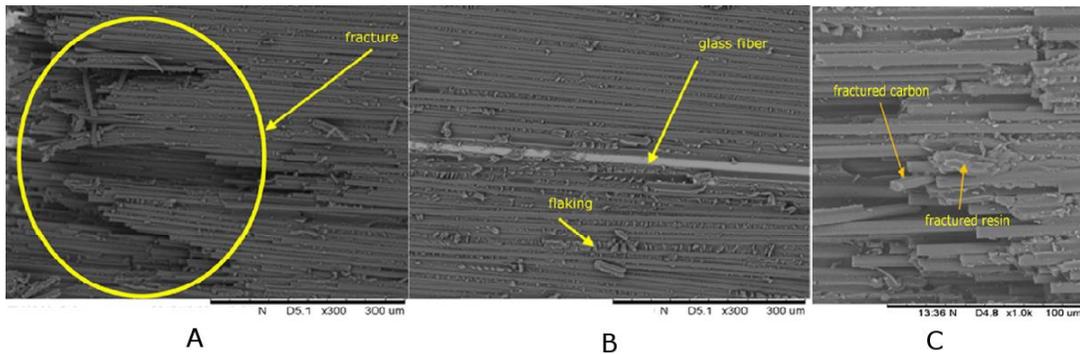


Figure 11: SEM images of carbon fibers (50% RC catastrophically failed samples).

In the glass region of the fractured area, there was a clear stripe observed across the width of the specimen. When viewed under SEM (Fig.12 (A)) it was noticed that this stripe was a region where the epoxy resin was completely stripped from the glass fibers. This explains why in the fractured carbon area there is a lot of fractured epoxy pieces. This is because the region of carbon fracture experienced a lot of energy which most was absorbed by the resin. In the outer region of the sample, the epoxy resin is still intact, while only some surface flaking was observed, which gave less contribution in the region in energy absorption. Fig.12 (B) shows the image under higher magnification and it can be observed some presence of fractured epoxy resin at the edge of the clearance stripe. Also in the glass sample, it is clear there was no fracture of glass, meaning this sample failed only due to catastrophic delamination.

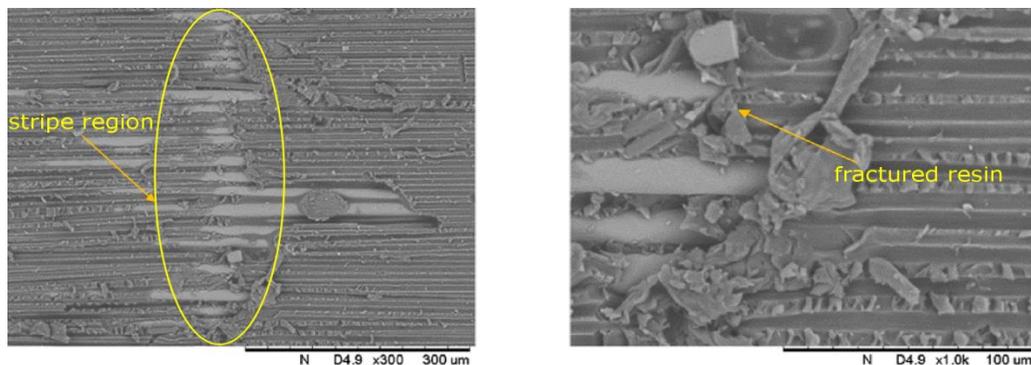


Figure 12: SEM image of the region of failure for the glass layer of 50% RC catastrophically failed sample.

## 6 CONCLUSION

With the combining the thin layer of continuous carbon and carbon platelets to make the glass/carbon hybrid composite, the pseudo-ductility was achieved. Among the 12 layups for 41.1% RC and 50% RC, there are only 5 samples, 4EG/2CP/2CC/2CP/4EG and 4EG/2CP/4CC/2CP/4EG samples with 41.1% RC and 1EG/1CP/1CC/1CP/1EG, 2EG/1CP/1CC/1CP/2EG and 2EG/2CP/1CC/2CP/2EG with 50% RC, which showed pseudo-ductile behaviors. 2 samples, 2EG/1CP/2CC/1CP/2EG with 50% RC carbon prepreg and 2EG/1CP/1CC/1CP/2EG with 41.1% RC carbon prepreg, showed conventional hybrid failure behavior. The other 5 samples, 4EG/4CP/2CC/4CP/4EG, 2EG/2CP/1CC/2CP/2EG and 2EG/1CP/2CC/1CP/2EG with 41.1% RC and 1EG/2CP/1CC/2CP/1EG and 1EG/1CP/2CC/1CP/1EG with 50% RC, did not show pseudo-ductile behavior at all. 2EG/1CP/1CC/1CP/2EG with 50% RC carbon prepreg has the best pseudo-ductile yielding, which had a long plateau of  $1.204 \pm 0.038\%$  pseudo-ductile strain and also the stress-strain curve was similar compared to what was observed by Cz $\acute{e}$  et al [16].

The resin content contributes to the pseudo-ductility behavior of the composite. The pseudo-ductility improves with the higher resin content. The sudden load drops can be observed in the samples with lower resin content.

From the SEM surface morphology study, it is clearly understood that pseudo-ductile and catastrophic failures of the samples depend entirely on the distribution of energy from the fracture of the different materials used in the hybrid. The larger the damaged region, the better the cohesive properties between the interfaces.

## ACKNOWLEDGMENT

This work was supported by the Science and Technology Commission of Shanghai Municipality (Funding No: 15XD1524700). This research was also supported by the Chinese Scholarship Council (CSC).

## REFERENCE

- [1] G. Cz $\acute{e}$ , M. R. Wisnom, Demonstration of pseudo-ductility in high-performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg, *Composites Part A: Applied Science and Manufacturing*, **52**, 2013, pp. 23-30.
- [2] K. S. Pandya, C. Veerajju, N. K. Naik, Hybrid composites made of carbon and glass woven fabrics under quasi-static loading, *Materials & Design*, **32**(7), 2011, pp. 4094-9.
- [3] H. Diao, A. Bismarck, P. Robinson, M. R. Wisnom, Pseudo-ductile behavior of unidirectional fibre reinforced polyamide-12 composite by intra-tow hybridization, In: *European conference on composite materials, Venice, Italy, 2012*.
- [4] N. Hancox, *Fibre Composite Hybrid Materials*, London, Applied Science Publishers Ltd, 1981.
- [5] J. Summerscales, D. Short, Carbon fibre and glass fibre hybrid reinforced plastics, *Composites*, **9**(3), 1978, pp. 157-66.
- [6] D. Short, J. Summerscales, Hybrids – a review Part 1. Techniques design and construction, *composites*, **10**, 1979, pp. 215-21.

- [7] D. Short, J. Summerscales, Hybrids — a review, *Composites*, **11**(1), 1980, pp. 33-8.
- [8] G. Kretsis, A review of the tensile, compressive, flexural and shear properties of hybrid fibre-reinforced plastics, *Composites*, **18**(1), 1987, pp. 13-23.
- [9] G. Marom, S. Fischer, F. R. Tuler, H. D. Wagner, Hybrid effects in composites: conditions or positive or negative effects versus rule-of-mixtures behaviour, *Material Science*, 1978, pp.
- [10] N. Svensson, R. Shishoo, M. Gilchrist, Manufacturing of Thermoplastic Composites from Commingled Yarns-A Review, *Journal of Thermoplastic Composite Materials*, **11**(1), 1998, pp. 22-56.
- [11] T. Hayashi, Development of new material properties by hybrid composition. 1st report, *Fukugo Zairyo (Composite Material)*, 1972, 1, 18-20.
- [12] T. Hayashi, K. Koyama, A. Yamazaki, M. Kihira, Development of new material properties by hybrid composition. 2nd report, *Fukugo Zairyo (Composite Material)*, 1972, 1, 21-5.
- [13] A. R. Bunsell, B. Harris, Hybrid carbon and glass fibre composites, *Composites*, **5**(4), 1974, pp. 157-64.
- [14] P. W. Manders, M. G. Bader, The strength of hybrid glass/carbon fibre composites, *J Mater Sci*, **16**(8), 1981, pp. 2233-45.
- [15] M. Jalalvand, G. Cz ą, M. R. Wisnom, Parametric study of failure mechanisms and optimal configurations of pseudo-ductile thin-ply UD hybrid composites, *Composites Part A: Applied Science and Manufacturing*, **74**, 2015, pp. 123-31.
- [16] G. Cz ą, M. Jalalvand, M. R. Wisnom, Demonstration of pseudo-ductility in unidirectional hybrid composites made of discontinuous carbon/epoxy and continuous glass/epoxy plies, *Composites Part A: Applied Science and Manufacturing*, **72**, 2015, pp. 75-84.