STRESS CONCENTRATION FACTOR OF NOTCHED HYBRID RECYCLED CARBON COMPOSITE

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ABSTRACT

Recycled carbon fiber (r-CF) holds significant promise for reducing both production waste and costs associated with its manufacturing, which is characterized by high energy intensity. However, its full potential remains untapped due to limited understanding of its mechanical behavior, particularly concerning stress concentration factors in notched recycled carbon fiber-reinforced polymer (r-CFRP). This study is dedicated to investigating the mechanical properties of r-CFRP and characterizing the tensile behavior of notched composites. Additionally, it explores new functionalities of r-CF and introduces a methodology for correlating strain fields obtained from digital image correlation (DIC) with stress concentration factors (SCF). Three types of composite materials—glass fiber-reinforced polymer (GFRP), r-CFRP, and hybrid GFRP/r-CFRP—are included in this research, encompassing both unnotched and notched composites subjected to tensile tests. DIC was chosen as the strain field measurement technique for its enhanced accuracy and speed compared to conventional methods such as strain gauges. The analysis revealed that GFRP exhibits the highest Young's Modulus (E) at 19.64 ± 0.72 MPa, followed by hybrid GFRP/r-CFRP at 15.22 ± 0.99 MPa and r-CFRP at 12.97 ± 0.48 MPa. For notched composites, this study analyzed SCF and strength retention for each material. r-CFRP exhibits the highest SCF at 1.57 and the lowest strength retention at 63.70%, signifying its high notch sensitivity. However, the incorporation of r-CFRP in hybridization with GFRP enhances the SCF to 1.46 and increase the strength retention to 81.02%, which was the highest among the three laminates. These results demonstrate that r-CFRP has the potential to mitigate stress concentration, making it an ideal material for producing notch-insensitive hybrid glass fiber composites.

KEYWORDS

Recycled Carbon Fiber; Stress Concentration Factor; Digital Image Correlation, Notched Composite

INTRODUCTION

Carbon Fiber Reinforced Polymer (CFRP) composites have gained widespread adoption in various industries, including aerospace, infrastructure, and automotive, owing to their exceptional mechanical properties and the ability to customize their properties to specific needs. These composites offer high stiffness and a lightweight alternative to conventional materials like steel. However, the production of CFRP is energy-intensive, estimated at 800 MJ/kg for CFRP with a 50% fiber volume fraction, compared to 50 MJ/kg for steel [1]. This energy intensity, coupled with the high cost of virgin carbon fiber, contributes to the overall cost of CFRP production [2].

Despite these challenges, the demand for CFRP remains high, with a global market value of 8.2 billion U.S. dollars and a production volume of 150,000 tons in 2021. However, this increased production has led to a significant accumulation of waste, as many CFRP products are disposed of in landfills or incinerated after use. In fact, an astonishing 62,000 tons of unused end-of-life (EOL) and production waste is generated annually, despite the pressing need for new fiber composites [3]. In certain developed nations, traditional CFRP disposal methods are now restricted due to environmental concerns, economic losses, and adherence to international legal standards [4]. Addressing the rising costs and waste associated with CFRP production is imperative. Recycling CFRP is a promising solution that can reduce the ecological footprint and enhance sustainability.

However, despite the potential benefits of recycled carbon fiber-reinforced polymer (r-CFRP), its full utilization in structural design is hindered by limited knowledge regarding its mechanical behavior, particularly the stress concentration factor (SCF) in notched r-CFRP. SCF is a dimensionless parameter used to quantify stress concentration in mechanical components, notably in notched regions where stress concentrations are typically high due to geometric disruptions. Stress concentration is often the site of initial damage and can lead to various detrimental effects, including stress and strain gradients. Holes or notches in composite structures can serve as potential initiation points for fractures [5]. A study conducted by Selver et al. found the open-hole tensile strength of hybrid glass/thermoplastic was only reduced by 11%, compared to 28% strength reduction of pure glass laminate [6]. Thus, it would be interesting to see the notch sensitivity of hybrid glass r-CFRP since r-CFRP was found to improve some mechanical properties such as impact and flexural energy absorption [7].

SCF can be studied through three primary research methods: experimental, analytical, and numerical. While analytical and numerical methods have yielded significant insights into SCF, experimental approaches have faced challenges, resulting in inaccurate data. For instance, some experiments using non-interferometry techniques have been sensitive to vibrations and involved complex optical setups [8]. Consequently, the application of digital image correlation (DIC), an advanced non-interferometry technique, has emerged as a preferred choice for studying experiments related to composite materials.

In this study, we aim to investigate the stress concentration factor in notched r-CFRP using digital image correlation. Additionally, we will explore the application of r-CFRP in hybridization with Glass Fiber Reinforced Polymer (GFRP) to assess its potential in mitigating stress concentration effects.

METHODOLOGY

In this experiment, three types of materials will be used, which are r-CFRP, GFRP and hybrid composite of r-CFRP/GFRP. For r-CFRP, the recycled fibre used was 240gsm non-woven IM56D, which was from prepreg waste of Airbus, recycled using pyrolysis method. For GFRP, the fibre glass used is 270gsm E-glass plain weave fabric. All the materials are cured into fibre composite laminates with EpoxAmite™ 100 Base Resin and EpoxAmite™ 103 Slow Hardener. The specimen plate will be fabricated using vacuum infusion process. The steel plate will be covered with a layer perforated release film before placing layers of fiber on top of it. After the layer of fiber, a layer of peel ply and resin infusion mesh will be placed and taped to the plate. A resin feed spiral and resin infusion silicone connector with tube connected to mixture of epoxy resin and hardener will be placed on right side of the fiber while a resin infusion silicone connector connected to catch pot and vacuum pump will be placed on the left side of the fiber. Finally, a vacuum bagging film will be taped to the plate. The full setup was as shown in Figure 1.

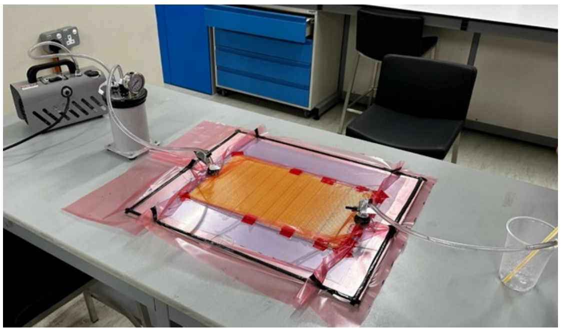

Figure 1: Vacuum infusion process setup

For each laminate, five repetitions will be made for both notched (3.2mm hole diameter) and unnotched. The dimensions and stacking sequence of the specimens were shown in Figure 2 and Table 1.

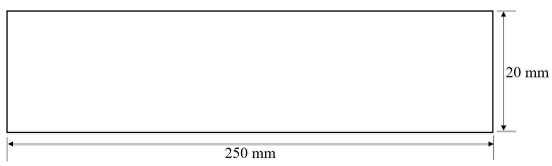

Figure 2: Sample specimen with dimension

Table 1: Dimension and stacking sequence of the specimens

Composites	Stacking sequence	Length (mm)	Width (mm)	Thickness (mm)
GFRP (G)	$[GF]_9$	250	20	1.8
r-CFRP (K)	$[r\text{-}CF]_4$	250	20	2.3
Hybrid GFRP/r-CFRP (M)	$[GF]_4/[r\text{-}CF]/[GF]_4$	250	20	2.3

The test specimens were sprayed with matte white paint as the background followed by black speckles for use with the DIC system. Stereo DIC system was set-up as shown in Figures 3. The displacement rate of the test was fixed at 2 mm/min and the DIC images were acquired at 5 Hz. The DIC data was analysed using correlation software provided by MatchID. The stress concentration factor, K and strength retention (%) was calculated by using Equation 1 and 2 respectively for further analysis.

$$K = \frac{\sigma_{max}}{\sigma_{nom}} \quad (1)$$

$$Strength\ retention = \frac{\sigma_{nom}}{\sigma_{max}} \text{ X } 100 \quad (2)$$

where σ_{max} is unnotched stress and σ_{nom} is nominal stress.

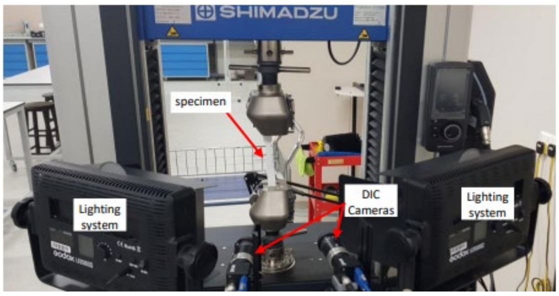

Figure 3: Stereo DIC setup with sample specimen

Results and Discussion

Figure 4 shows the stress-strain diagram of unnotched specimens subjected to tensile test for GFRP (G), r-CFRP (K) and hybrid GFRP/r-CFRP (M). From this graph, the Young's Modulus (E) of the composites was determined by the slope of the linear trend line. All the laminates exhibit a similar response with slight variations in the curves. All these specimens exhibit a brittle failure mode. The graph shows that GFRP can withstand the highest stress among the three, followed by the hybrid composite and the r-CFRP. Besides that, the graph also shows that GFRP has higher strain value than r-CFRP and hybrid composite, indicating its ability to absorb greater strain energy. From the graph, we could notice some errors from the data collected for the hybrid sample, in which there is a large difference on two of the hybrid samples. One of it fails at the stress of 269 MPa and strain of 0.016 which is lower compared to the other samples. This is because this specimen fails at the grip area during the experiment which caused the specimen to undergoes limited delamination. On the other hand, the other sample fails at similar stress range with the other samples at 313 MPa but at a higher strain at 0.023 compared to the other samples. This sample undergoes a prolong delamination which we can see from the flat region of the graph. The presence of r-CFRP within the hybrid composite lead to a complex stress redistribution which causes the inconsistencies between each result [9].

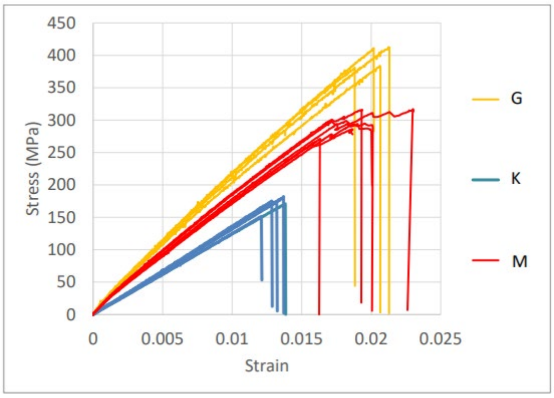

Figure 4: Stress-strain diagram of unnotched GFRP, r-CFRP and hybrid GFRP/r-CFRP

The summary of the results based on average values of tensile strength and failure strain are stated in Table 2. From the table, we can observe that the GFRP has the highest tensile strength. The hybrid composite has a 25.35% reduction of tensile strength compared to GFRP and still has higher strength than r-CFRP which induce 57.01% lower tensile strength compared to GFRP. Meanwhile for the failure strain, the hybrid composite was only 0.07% lower compared to GFRP, as opposed to the huge reduction from r-CFRP which was 0.71% lower than GFRP. The Young's modulus of the three laminates shows the same trend as the tensile strength, in which the hybrid composite and r-CFRP has 22.5% and 33.9% lower Young's modulus compared to GFRP respectively.

Table 2: Mechanical properties of the composites

Composite	Tensile strength, σ (MPa)	Failure strain (%)	Young's modulus, E (GPa)
GFRP (G)	397.23 ± 14.81	2.03 ± 0.09	19.64 ± 0.72
r-CFRP (K)	170.76 ± 10.24	1.32 ± 0.06	12.97 ± 0.48
Hybrid GFRP/r-CFRP (M)	296.55 ± 16.15	1.96 ± 0.20	15.22 ± 0.99

Hole Elongation

The hole elongation of the specimen was obtained by analyzing captured images using DIC using MatchID software. Figure 5(a) shows the graph of nominal stress versus hole elongation of notched GFRP. The graph shows a linear trend at the start, but slowly curves as the hole elongation increases. The ultimate nominal stress of notched GFRP has to the average of 272.40 MPa compared to the tensile strength of unnotched GFRP, which was mainly due to the stress concentration around the notch. Figure 5(b) shows the graph of nominal stress versus hole elongation of notched r-CFRP. The graph shows a linear trend from the start to the end. The ultimate nominal stress of notched r-CFRP has reduced to the average of 108.77, which was a lot compared to the tensile strength of unnotched r-CFRP. Figure 5(c) shows the nominal stress versus hole elongation of notched hybrid GFRP/CFRP. The graph shows linear trend at the start but curves at the end. The initial region of the graph which is the linear trend represents the behaviour of hybrids when the GFRP and r-CFRP are well bonded together and elongate uniformly. Then the graph starts to curve, which indicates that GFRP is starting to undergo deformation. The hybrid composite exhibits a non-linear stress-strain behaviour, which can be explained by matrix microcracking, interfacial debonding in glass layers along with progressive fracture of fibres at higher stresses.

Stress Concentration Factor

Table 3 shows the stress concentration factor (SCF) and strength retention of GFRP, r-CFRP and hybrid GFRP/CFRP composites. The hybrid composite has the lowest SCF which indicate that it is better at distributing the applied stress. The GFRP and r-CFRP has 17.74% and 26.61% higher SCF compared to the hybrid composite. This indicates that r-CFRP is subjected to more localized stress concentration. The hybrid composite also has the highest strength retention which represents that the ability to maintain its original strength is higher compared to other laminates in the presence of notch. According to Khan et al., hybrid composite have lower notch sensitivity due to the progressive damage modes of different materials, which delays the final failure of the specimen[10].

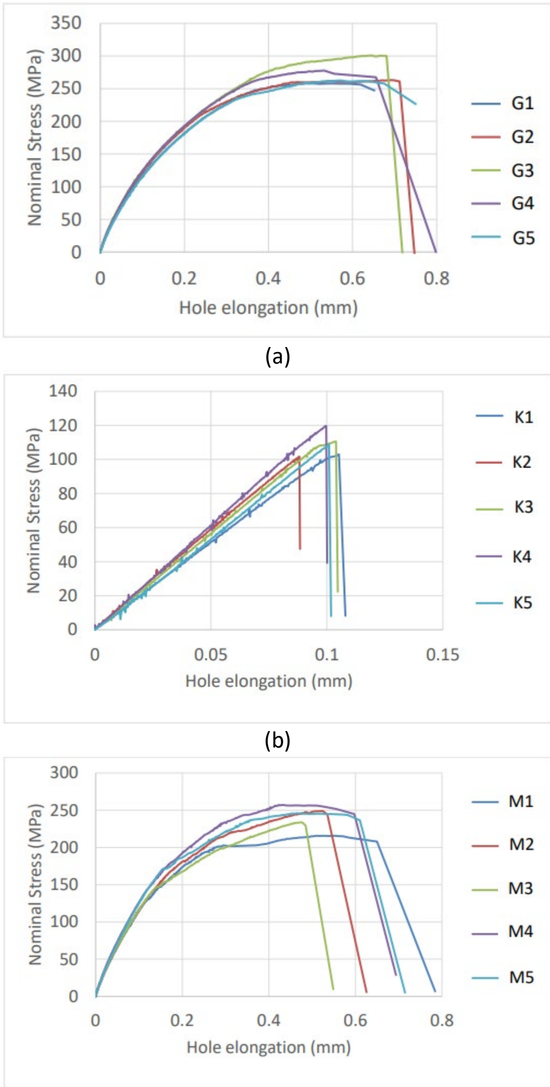

Figure 5: Nominal stress versus hole elongation for, (a) GFRP, (b) r-CFRP, (c) hybrid GFRP/r-CFRP

Table 3: Stress concentration factor and strength retention

Composites	Unnotched Tensile Strength, σ_{max}	Notched Tensile Strength, σ_{nom}	Stress Concentration Factor, K	Strength Retention (%)
GFRP (G)	397.23 ± 14.81	272.40 ± 15.68	1.46	68.57
r-CFRP (K)	170.76 ± 10.24	108.77 ± 6.40	1.57	63.70
Hybrid GFRP/r-CFRP (M)	296.55 ± 16.15	240.27 ± 14.41	1.24	81.02

CONCLUSION

In this study, the stress concentration factor of notched GFRP, r-CFRP and hybrid composite subjected to tensile test has been discussed. The sudden stress drops in the stress-strain graphs indicate that all of the materials experienced the catastrophic brittle fracture, which is common for composite material. The results shows that GFRP has the best performance, where it has the highest tensile strength, failure strain and Young Modulus, E. Besides that, the methodology of applying digital image correlation in obtaining the strain field and stress concentration factor has also been developed for notched composite.

It is shown that r-CFRP has the potential to be a multifunctional. It is proven that when r-CFRP is interleaved with GFRP, the r-CFRP was able to blunt the stress concentration around the hole of the hybrid composite, making it more insensitive to notch as compared to GFRP. This mechanical behaviour of r-CFRP reduced the notched hybrid composite's SCF to 1.24 and increased its strength retention to 81.02%. In conclusion, r-CFRP has shown its potential in its application to toughen the open-hole structure of composite as it able to relieve the stress concentration around the hole. This study has proven that carbon fibre is worth to recycle and the potential of applying r-CF in different industries especially in manufacturing is possible.

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REFERENCES

[1] Energetics Incorporated, 2016. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Carbon Fiber Reinforced Polymer Composites. Energetics Incorporated.

[2] Das, S., 2011. Life cycle assessment of carbon fiber-reinforced polymer composites. The International Journal of Life Cycle Assessment, 16, pp.268-282.

[3] Karuppannan Gopalraj, S. and Kärki, T., 2020. A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: Fibre recovery, properties and life-cycle analysis. SN Applied Sciences, 2, pp.1-21.

[4] Sukanto, H., Raharjo, W.W., Ariawan, D. and Triyono, J., 2021, February. Carbon fibers recovery from CFRP recycling process and their usage: A review. In IOP Conference Series: Materials Science and Engineering (Vol. 1034, No. 1, p. 012087). IOP Publishing.

[5] Mohamed Makki, M. and Chokri, B., 2017. Experimental, analytical, and finite element study of stress concentration factors for composite materials. Journal of Composite Materials, 51(11), pp.1583-1594.

[6] Selver, E., Dalfi, H.K. and Potluri, P., 2023. Enhancing the mechanical performance of notched glass/epoxy composite laminates via hybridisation with thermoplastic fibres. Journal of Composite Materials, 57(23), pp.3703-3721.

[7] Wu, Y., Gao, Q., Chen, B., Wan, Y., Huang, W., Tong, X., Gu, B. and Takahashi, J., 2024. Impact and flexural energy absorption mechanism of hybrid composites interleaved CF/PA6 fiber papers based on real-time cracks tracking. Applied Composite Materials, 31(1), pp.149-170.

[8] Toubal, L., Karama, M. and Lorrain, B., 2005. Stress concentration in a circular hole in composite plate. Composite structures, 68(1), pp.31-36.

[9] Swolfs, Y., McMeeking, R.M., Verpoest, I. and Gorbatikh, L., 2015. Matrix cracks around fibre breaks and their effect on stress redistribution and failure development in unidirectional composites. Composites Science and Technology, 108, pp.16-22.

[10] Abdallah, A.W., Sandwich Carbon-Kevlar Composite Laminates with Progressive Damage Mode and Enhanced Notch Sensitivity. Available at SSRN 4403069