2026-CO-0078

Improvement of rCF behaviour through the introduction of NF

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Abstract

This study investigates the structural improvement of recycled carbon fibre composites through hybridisation with continuous flax fibres to address sustainability concerns and performance limitations. Recycled carbon fibres, while environmentally beneficial, suffer from short, randomized orientations and reduced mechanical properties limiting their application beyond decorative uses. This research explores whether incorporating unidirectional flax fibres can enhance rCF behaviour for structural applications. Six hybrid composite layup variants and two plain composites were manufactured using cold compression moulding with Ampro Bio Resin. Each hybrid configuration comprised eight layers, divided into four layers of recycled carbon and four layers of flax fibres oriented at 0°. Complete mechanical characterization was performed following ISO standards for tensile (ISO 527), flexural (ISO 178), and impact (ISO 179) testing. Results demonstrated significant performance improvements in hybrid composites. Among hybrids, layup 2 achieved 212.5 MPa tensile strength whilst layup 3 managed to achieve a results of 20.5 GPa in stiffness. Flexural testing revealed layup 6 achieved the highest flexural modulus of 19.6 GPa among hybrids. Impact resistance improved dramatically with layup 3 demonstrating 186% improvement in energy absorption over recycled carbon fibre. The study confirms that hybridisation creates a positive effect, producing more predictable and durable materials. The complementary behaviour between brittle and ductile materials enhances damage tolerance and structural integrity, establishing a foundation for sustainable engineering materials suitable for automotive applications without compromising reliability.

Keywords

Recycled carbon fibre, natural fibre, sustainability, compression moulding, composites, material properties, hybridisation, hybrid composites

Introduction

The demand for carbon fibre grew from 30 kt to 72 kt between 2010 and 2017 with an estimated growth of up to 12% per year until 2022 [1]. Current estimates state that 118kt of carbon fibre was used in 2021 which equate to over double the amount in 2014. In 2025 the demand was projected to extend to 185 kt of dry fibre [2]. The automotive sector is predicted to incorporate more composite materials into body in white structures, with the projected use of 15% [3]. Already, BMW utilised rCF in their I series vehicles along with the 7 series, where recycled carbon fibre was used as a support for the C-Pillar [4]. This demand correlates with waste product generated from such industries as automotive, aerospace and wind energy along with discarded test samples and end-of-life products. This leads to the notion of questioning sustainability in utilising carbon fibre since the process of manufacturing virgin carbon fibres (vCF) is energy-intensive thus increasing interest in recovery and recycling. However, this also poses some limitations in terms of usability of the recovered fibres as damage during the recycling process may lead to a decrease in mechanical properties [1]. This opens an opportunity for rCF to be utilised on a broader scale. Already the material is being used in various applications such as reinforcement in plastics as demonstrated by McNally et al. [5] when milled rCF was introduced to thermoplastics with a fibre weight fraction of 30%. This has led to increase of the Youngs modulus by 180% and the tensile strength by 27.5%. De Souza et. al. [6] investigated the use of pre-preg scrap from the aerospace sector with results showing better performance over traditional aluminium with an increase in tensile strength of 284 MPa but less than continuous carbon fibre laminate (780 MPa vs 848 MPa).

This project aims to show the feasibility of rCF in a wider range of applications through the introduction of continuous natural fibres to enhance and stabilise the unpredictability of the material. The motivation for this study was further expand of the works of Jiang et al. [7] who proposed an idea of a sandwich panel utilising rCF and flax fibres. In contrast to the aforementioned study, current work does not consider using foam to separate the central layers. Also, Tse et al. [1] put forward a notion of combining rCF and flax fibres with a PLA matrix. The study highlighted that the introduction of natural fibres into the mixture increased the compatibility rCF sheet, something which the current study will have to take into account. In comparison to the work of Wilson et al. [8] which focuses on creating a hybrid composite comprised of rCF and flax, this study focuses on utilising UD flax fibre as opposed to cross stich. Another major difference is the manufacturing methods, in which the authors utilise infusion in contrast to compression moulding.

Methodology

Material selection

Unidirectional (UD) flax fibre (280 g/m^2) was purchased from a European supplier and are of European origin. No additional treatment was required to ensure compatibility with synthetic substances. Recycled carbon fibre roll (200 g/m^2) was purchased from Gen2Carbon, UK. The material was reclaimed through pyrolysis before carding into a non-woven sheet. The morphological structure of the material consists of randomly oriented strands of carbon fibres with varying fibre length. Observed fibre length vary between 50 μm, with 130 mm lengths being observed. Figure 1 demonstrates the structure of a dry sheet. Each of the materials were cut to 300 x 300 mm sheets to be placed inside a mould. An example of dry rCF sheet is shown in Figure 2.

Ampro Bio Resin system, in combination with slow setting hardener at a ratio of 3:1 was used as the matrix for all of the composite variants.

Figure 1 Structure of dry rCF sheet

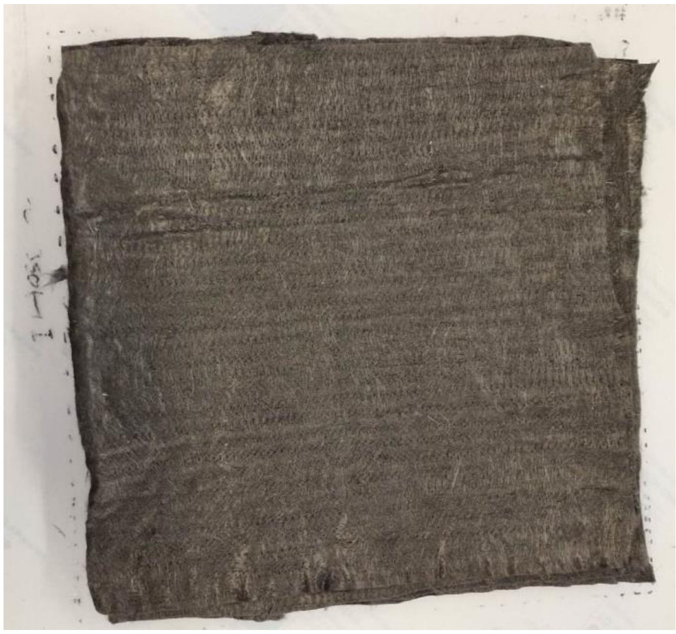

Figure 2 Sheet of dry rCF

Composite manufacture

Compression moulding was used to consolidate the fibres. Dry cut material sheets were placed inside a square mould with internal dimension of 310 x 310 mm. The order of the material placement was specified by the stacking sequence of the individual composite variants.

The resin/hardener mixture was poured manually into the enclosed mould in between the layers. Resin mixture to material ratio was 1:1 in respect to weight. Moulding pressure was ramped up to a peak value of 33.33 MPa throughout the period of 999 seconds after which the mould was manually locked and left to cold cure for 16 hours before opening. Once the material was removed from the mould, it was subjected to trimming and left to post cure for a minimum of 7 days before testing.

Two different composite types were manufactured, hybrid and plain. Hybrid composites consist of six different layup variants, with each of the variants consisting of four layers of individual precursor material, totalling eight (8) layers. All of the layers containing flax fibres were oriented in the 0° direction. The stacking sequence of each of the hybrid variants is located in Table 1. Plain variants of rCF and NF were manufactured in the same manner, with the flax fibres following a UD sequence. Physical properties of each of the composite variants were measured after trimming and are located in Table 2. A manufactured rCF plate prior to trimming is shown in Figure 3 with additional microscopic structures of rCF and NF composites in Figure 4 and Figure 5.

Table 1 Layer sequencing of hybrid variants
Orange – Flax, Grey – rCF

Layup Variant	Layer Number							
	1	2	3	4	5	6	7	8
1	🟧	⬛	🟧	⬛	⬛	🟧	⬛	🟧
2	🟧	🟧	⬛	⬛	⬛	⬛	🟧	🟧
3	🟧	⬛	⬛	🟧	🟧	⬛	⬛	🟧
4	⬛	⬛	🟧	🟧	🟧	🟧	⬛	⬛
5	⬛	🟧	🟧	⬛	⬛	🟧	🟧	⬛
6	⬛	🟧	⬛	🟧	🟧	⬛	🟧	⬛

Table 2 Physical properties of composite variants

Layup Variant	Fibre volume fraction (%)	Thickness (mm)	Density (g/cm^3)
1	0.56	2.48	1.07
2	0.59	2.41	1.14
3	0.65	2.37	1.14
4	0.57	2.43	1.17

5	0.57	2.39	1.13
6	0.59	2.30	1.14
NF	0.71	2.16	1.27
rCF	0.41	2.47	0.90

Figure 3 rCF after manufacturing

Figure 4 Magnified view of rCF after manufacture

Figure 5 Magnified view of flax fibres after manufacture

Test setup

All composite variants were subjected to tensile, flexural and impact tests based on ISO 527, ISO 178 and ISO 179. Tensile and flexural tests were performed using Tinius Olsen 50T UTM. Vector extensometer was used for tensile tests to measure the true deflection of the tested samples [9] [10] [11]. Both type of tests were performed with a crosshead speed of 2mm/min. Impact tests were performed using Zwick Roell HIT 50P pendulum impact machine with a maximum energy of 50J. For tensile and flexural tests, a total of 5 specimens were tested for each configuration whilst the number of specimens for impact test equalled 10 for each configuration.

For tensile tests, aluminium tabs were applied to hybrid and flax composite using an acrylic adhesive manufactured by 3M. All of the specimens were trimmed to 250 mm x 25 mm with the thickness levels being dictated by the individual composites. Grip position was 50mm on either side, with special markers being placed as close to the edge of the jaws for the most accurate extensometer reading. Tensile setup is found in Figure 6 with a blue light indicating measuring in progress.

Samples for flexural test samples were trimmed to 80 mm x 25 mm with the thickness being determined by the individual composites. The samples were supported at 10 mm from each of the edges with the striker set in the centre of the specimen. Figure 7 shows the setup. The tests were run until no more changes in the force were present. Some specimens were tested up to the peak force was reached, after which the test was stopped to conserve the specimen from further breakage.

Specimens used for Charpy test were trimmed to 80 mm x 10 mm with the thickness determined by the individual composite variants. None of the samples tested were notched. The samples were placed lengthways with the longer edge facing vertically, meaning the impact area equalled to 10 mm x thickness. The mass of the impact anvil is 6.90 kg with the fall height of 0.74 m and pendulum length of 0.40 m. The angle of rise (α) equalled to 147.96°. The specimens were hit with an impact velocity of 3.81 m/s. The individual impact readings were recorded by the test machine.

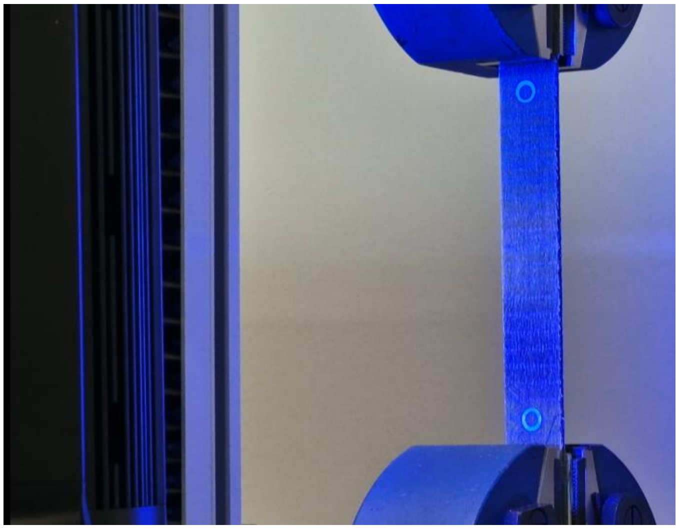

Figure 6 Tensile test setup

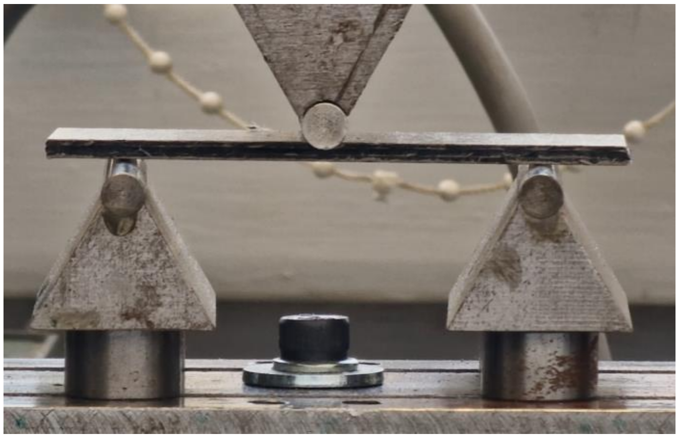

Figure 7 Flexural test setup

Figure 8 Charpy impact test setup

Results

Tensile performance

Tensile properties were measured using chord values rather than traditional linear values. This is due to the behaviour of the composites which did not exhibit a true linear performance until peak stress. Chord modulus assumes the average of two points on a graph below the elastic strain limit. This is supported by ASTM E111 standard [12].

Representative plots of hybrid, rCF and NF performance are found in Figure 9. A single plot is used to demonstrate hybrid behaviour as it is comparable across the range, albeit with varying peak stress and slope angle. The behaviour past the first failure is characteristic across all of the hybrid variants. The numerical results of tested variants are located in Table 3 with the corresponding chart in Figure 10. The results did not show a large disparity across the hybrid variants, with only minor differences. The maximum strength obtained across all of the tested variants was plain UD flax fibre with a value of 217.6 MPa and the corresponding stiffness of 21.5 GPa. In contrast, the strength and stiffness of rCF equalled to 192.8 MPa and 19.7 GPa respectively. This translates to a lower strength performance of 11.4% and lower stiffness performance of 8.4%. Interestingly, rCF showed a significantly higher chord stress performance of 45% in comparison to flax fibres indicating an internal failure of the composite at much earlier stage.

When comparing these values to the hybrid variants, some performance gains can be observed. Layup 3 showed an improvement in stiffness by 4%, the only variant to improve on this property. One outlier was layup 2 where the failure stress was the same as chord stress, signalling a very abrupt and sudden failure with minimal indicators as opposed to other hybrid variants. This would suggest that the rCF component was more dominant than NF which could be attributed to the stacking sequence which places all the of the rCF layers together, thus exhibiting strength potential but also risking a brittle failure. Most hybrid variants obtained a higher chord stress than the pure variants, excluding layup 4. Said variant achieved a 2nd lowest chord stress at 123.5 in front of NF and the overall lowest peak stress of 172.6 MPa.

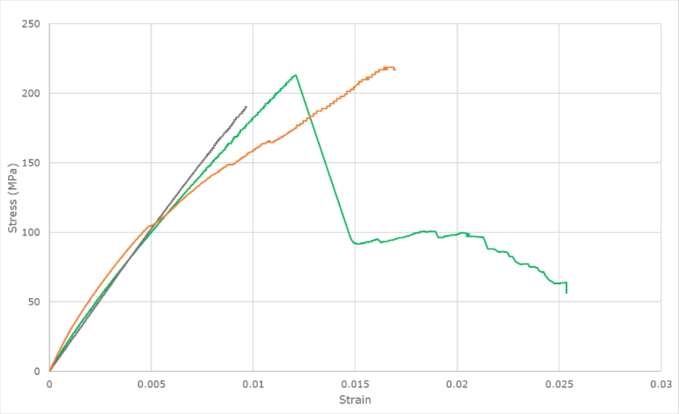

Figure 9 Representative curves from tensile tests Grey – rCF, Orange – NF, Green – Hybrid

Table 3 Results of tensile tests Values in bold indicate highest property in respect to variant category

Layup Variant	Chord Modulus (GPa)	Chord Stress (MPa)	Failure Stress (MPa)
1	17.5 ±1.1	145.0 ±12.6	198.7 ±19.5
2	18.3 ±1.2	**212.5 ±21.9**	**212.5 ±21.9**
3	**20.5 ±2.6**	152.3 ±13.8	202.7 ±23.3
4	17.3 ±0.4	123.5 ±14.1	172.6 ±13.4
5	17.9 ±0.3	143.9 ±17.5	193.9 ±15.8
6	18.7 ±0.7	152.8 ±10.8	209.4 ±11.2
NF	**21.5 ±2.5**	99.9 ±38.7	**217.6 ±24.7**
rCF	19.7 ±0.8	144.9 ±7.2	192.8 ±8.3

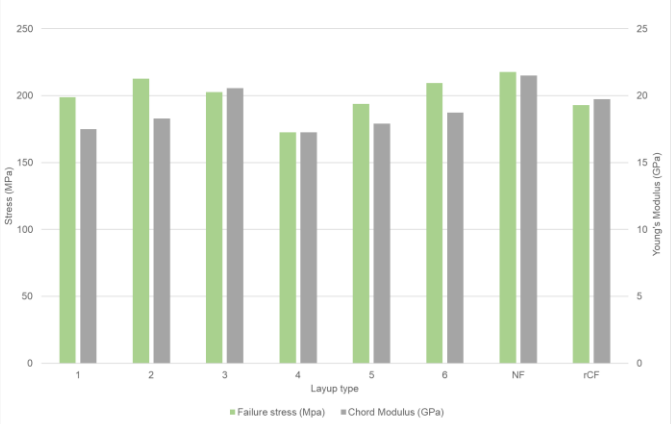

Figure 10 Visual representation of tensile results

The failure mechanisms of each of the composites are located in Figure 11. Each of the composites failed in a distinct manner. Plain rCF showed a clear split, indicative of brittle materials, in comparison to traditional carbon fibre composites. Flax fibres have shown large levels of delamination and fibre pullout throughout the length of the specimen leaving the composite without any supporting mechanisms. Fibre delamination along with fibre breakage are visible in Figure 12.

Hybrid composite displayed a behaviour which falls in between the plain variants. During testing, rCF always failed first irrespective of the stacking sequence followed by delamination of the NF layers. In this instance the presence of NF ensures an improved load transfer across the specimen due to the introduction of continuous fibres. The improvement over NF composite is achieved through a much larger elastic region which leads to an improvement in the failure stress value. Crucially, the composite did not shatter but rather maintained some structural integrity. The biggest observable failure occurred around the breakage point of rCF, after which delamination occurred around said area without any damage propagating further into the sample. Such occurrence indicates that the release energy only weakens the direct contact region preventing the rest of the composite from continuous delamination.

Figure 11 Tested tensile specimens a) rCF, b) Hybrid, c) NF

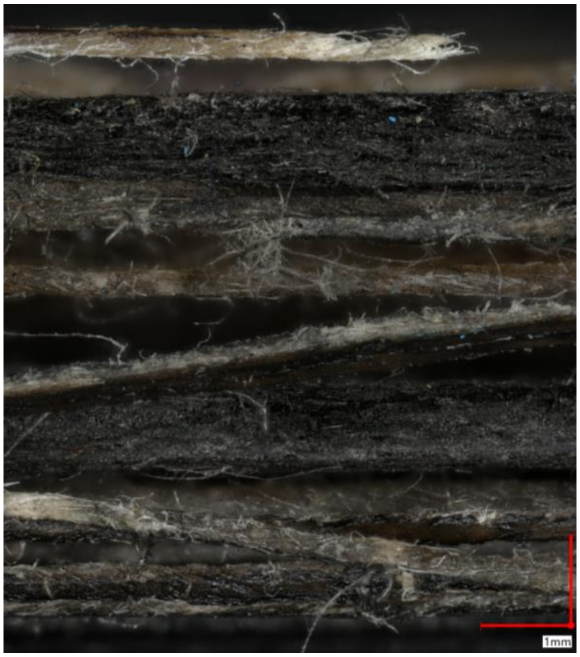

Figure 12 Magnified view of the tensile failure profile of Layup 3

Flexural performance

Flexural modulus of the samples was calculated using the peak elastic stress and corresponding strain value across all samples. The elastic stress limit was taken as the highest value before any damage occurred. The plots from Figure 13 show three very distinct characteristics. Plain rCF composite shows a very linear rise until laminate cracking at which point the stress climbs until a peak point at which the composite starts to completely shatter. This is in contrast to plain NF where a plateau is observed after peak stress is reached. This carries until the composite starts folding on itself, at this point the resistive properties of the composite are diminished. In contrast to the rCF and NF composites, the hybrid variants demonstrate a clear positive hybrid effect which combines the behaviour of plain variants. The elastic slope has a linear rise until the elastic stress limit upon which the composite breaks, however it continues to provide resistance forces until the point where the rCF is unable to support the structure, this is due to the same behaviour which was observed in tensile tests, the rCF layers always fail in the first instance. Figure 15 demonstrates the failure of rCF layers in layup 6. This observation confirms high levels of synergy between the two precursor materials in this test.

The bending performance of hybrid samples showed a larger disparity between the different variants in comparison to the other tests, although the plot in Figure 13 remains largely representative. Results of which are shown in Table 4 with the corresponding graph in Figure 14. Flexural modulus gap between top and worst performing hybrid layup is 5.9 GPa as opposed to tensile modulus where the difference totalled only 3.2 GPa. This equates to an increase of 43% from lowest to highest as opposed to only 18.5% increase in tensile results. Peak stress results follow the same trend, with a disparity of 75.1 MPa. Top performing hybrid variant in relation to stiffness was layup 6 which contained an NF core with rCF supports and outer skin and achieved a flexural modulus of 19.6 GPa, surpassing variant 3 by 2.5 GPa or 12.6% which was the next best performing out of the hybrid layups. Layup 3 had the best performance in terms of stress values, with the yield and peak stress equalling 235 MP and 249.4 respectively. Such result signals that the change in the stacking sequence plays a role in the performance of the composite.

Flax fibres observed the highest stiffness overall at 24.2 GPa but had significant reduction in strength when compared to other layups with the yield stress being observed at 100.4 MPa with the peak stress observed at 192.1 MPa. In contrast, rCF achieved a reduced stiffness value by 6 GPa which equates to 25% reduction. A significantly higher yield point and peak stress was achieved, 179.3 MPa and 224.8 MPa respectively. The failure of the two materials was similar in nature to tensile failure where the rCF variant demonstrated a brittle behaviour in comparison to NF ductile failure.
All of the hybrid variants failed in a similar manner to each other. Like the other test, none of the hybrid variants completely failed and managed to maintain their shape even after full failure. One significant observable difference between the failed samples relates to the skin sequencing, hybrid samples with rCF skins suffered breakage at lower pivot point, whereas NF skins had a tendency to stretch and partly delaminate. Comparison of fully and partially failed samples are shown in Figures 16 - 18

As mentioned, in relation to flexural behaviour the stacking sequence has a more pronounced effect on the properties of each of the composites. Layups with NF as the skins of the composite performed better on average in comparison to variants with rCF as the outer skins. Taking the average stiffness value of layups 1-3 and 4-6 yields a results around 16 GPa for each group. When considering the relation of yield point and peak stress the difference between the two groups stand at 29% and 17% higher yield and peak stress point respectively.

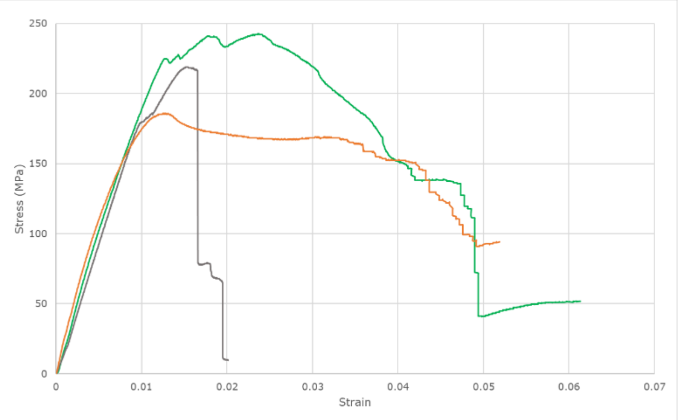

Figure 13 Representative curves from flexural tests Grey – rCF, Orange – NF, Green – Hybrid

Table 4 Results of flexural tests

Layup Variant	Flexural Modulus (GPa)	Yield Stress (MPa)	Peak Stress (MPa)
1	16.0 ±0.7	179.0 ±7.1	204.2 ±11.7
2	14.8 ±0.9	218.0 ±11.6	225.5 ±7.0
3	17.1 ±1.9	**235.0 ±54.8**	**249.4 ±47.3**
4	13.7 ±1.1	157.0 ±15.0	182.3 ±11.7
5	14.7 ±0.4	141.1 ±17.8	174.3 ±8.4
6	**19.6 ±1.6**	191.3 ±11.0	223.4 ±16.0
NF	**24.2 ±1.0**	100.4 ±2.5	192.1 ±8.9
rCF	18.2 ±2.2	179.3 ±20.3	224.8 ±25.6

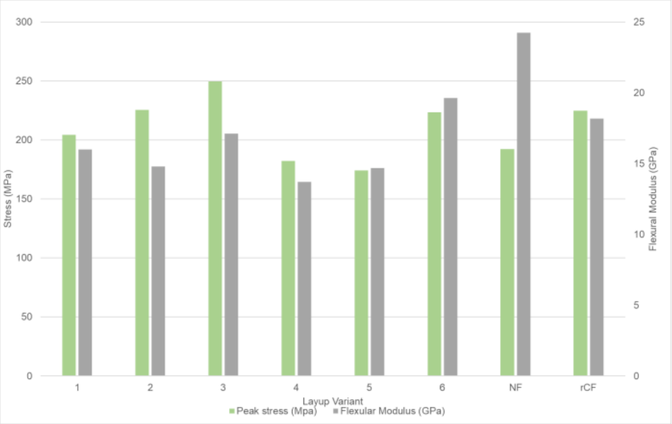

Figure 14 Visual representation of flexural results

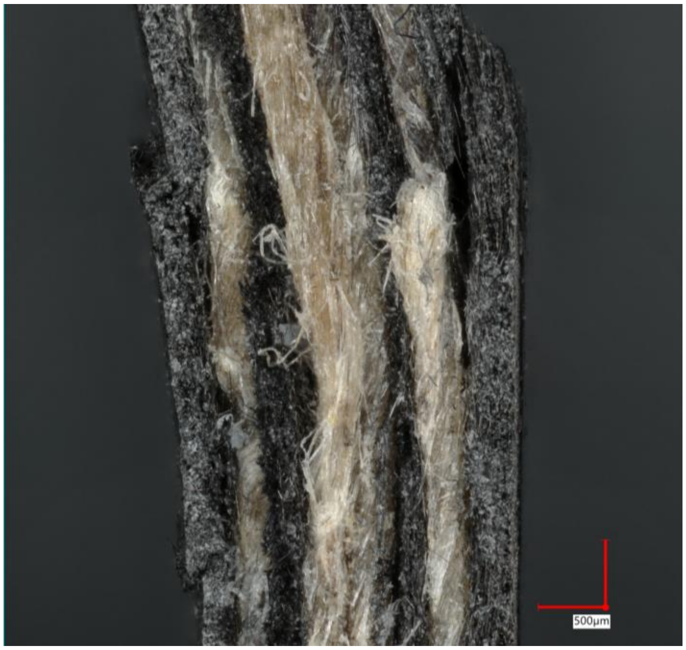

Figure 15 Magnified view of the flexural failure of layup 6

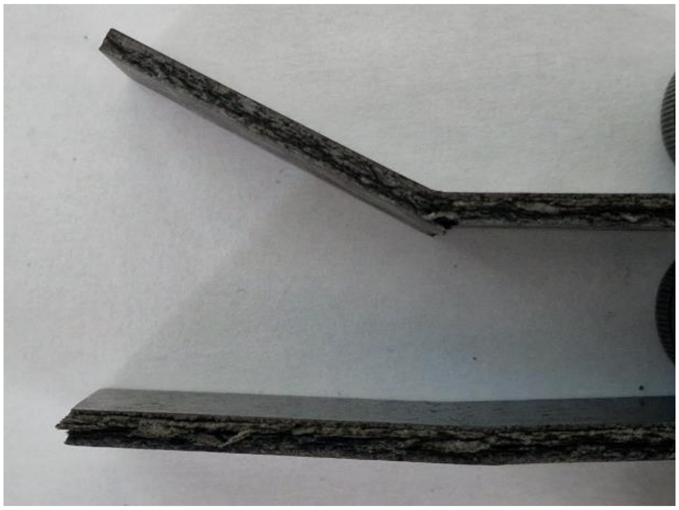

Figure 16 rCF samples after flexural test

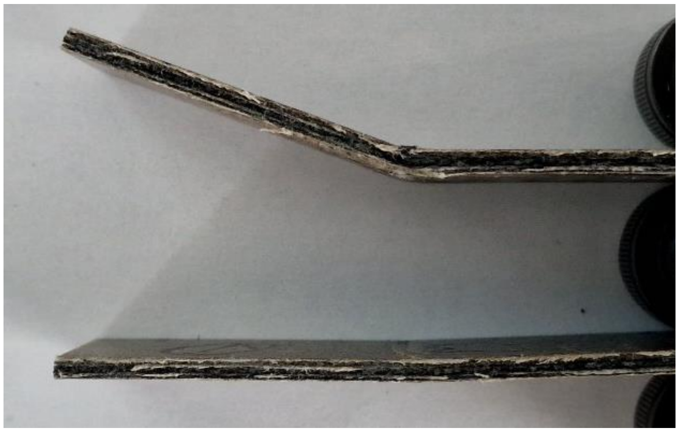

Figure 17 Hybrid samples after flexural test

Figure 18 NF samples after flexural test

Impact performance

Charpy tests of each of the composite variants showed the importance of continuous fibres during sudden force application. Due to this, NF showed an exceptional advantage over plain rCF with an increase of impact strength totalling 307%, from 23.7 kJ/m^2 to 96.6 kJ/m^2. The full spectrum of results is located in Table 5 with the visual representation shown in Figure 19.

Such a large disparity also translates to how the each of the variants failed under impact, with NF composite bending and partly delaminating due to the sudden impact, but still able to maintain its structure. In contrast, rCF composites suffered catastrophic failure upon impact and split in half in most instances. Across the hybrid range, variant 3 showed the highest energy absorption at 2J, 0.2J less than plain natural fibres, however, the increase over plain rCF equalled to 1.3J which is an improvement of 186%. For the impact strength the result is even greater at 205%, which means that the same surface area is able to absorb over 3x the impact energy. When considering the lowest performing variant, layup 6, the improvement in energy absorption stands at 129% over rCF and is only 20% less than layup 3. Interestingly, the results obtained during impact tests demonstrate that swapping four layers of short and random material for continuous and aligned fibres can increase the performance substantially.

Table 5 Results of impact test

Layup variant	**Angle of fall (°)**	**Energy Absorbed (J)**	**Impact strength (kJ/m2)**
1	141.4 ±0.8	1.8 ±0.2	70.8 ±9.9
2	141.7 ±0.6	1.7 ±0.2	61.4 ±6.6
3	**140.8 ±0.7**	**2.0 ±0.2**	**72.3 ±9.6**
4	141.9 ±1.0	1.6 ±0.3	69.0 ±10.7
5	140.9 ±1.8	1.9 ±0.6	70.3 ±18.9
6	142.0 ±1.0	1.6 ±0.3	68.4 ±14.9
NF	**140.0 ±0.7**	**2.2 ±0.2**	**96.6 ±26.1**
rCF	145.1 ±0.2	0.7 ±0.0	23.7 ±1.4

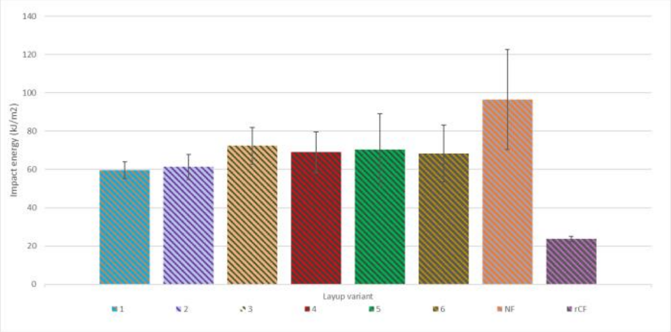

Figure 19 Visual representation of impact results

The failure of each of the variants mimics that from flexural tests, albeit with a more pronounced and localised effect. Figure 20 – 22 show the failure which occurred for each of the variants. As mentioned, the hybrid layup managed to stay intact similar to NF although with a failed rCF core. This was the case throughout all of the tested hybrid variants. Figure 23 demonstrates this phenomenon, with visible rCF fibre breakage and partial delamination around the impact area.

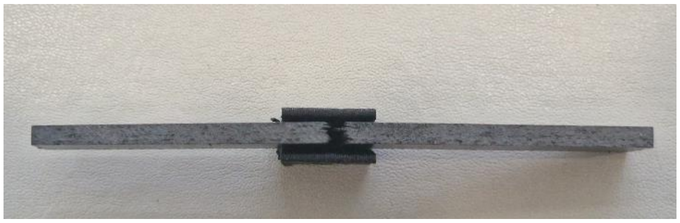

Figure 20 rCF sample after impact test

Figure 21 Hybrid Sample after impact test

Figure 22 NF sample after impact test

Figure 23 Magnified view of impact failure of layup 5

Conclusion

This study showed that it is not only possible to combine two very different fibre types but also obtain significant benefits of such mixture. The potential to use rCF in the automotive sector in combination with NF is highly feasible. This is due to the material becoming more predicable thus more enticing for wider application. Overall, hybrid variants did demonstrate a pronounced positive hybrid effect that substantially improves upon the limitations of rCF alone. In contrast to plain rCF, hybrid variants are significantly more resistance to impact damage and flexural failure with a small improvement in tensile behaviour.

The results show that NF composites have greater tensile properties of 217.6 MPa and 21.5 GPa for peak strength and stiffness respectively in comparison to plain rCF results of 192.8 MPa and 19.7 GPa. Across the hybrid variants, layup 2 showed the highest strength with a value of 212.5 MPa for peak and chord stress. Although layup 3 obtained the highest stiffness out of the hybrid variants, with a value of 20.5 GPa. Flexural tests showed that layup 3 had the highest peak stress and yield point at 249.4 MPa and 235 MPa respectively. However, the highest stiffness was achieved by layup 6 with a value of 19.6 GPa. The introduction of continuous aligned fibres resulted in a remarkable 205% increase in impact strength, from 23.7 kJ/m² for plain rCF to 72.3 kJ/m² for layup 3.

The observed failure mechanisms underscore the complementary nature of the two fibre types. While plain rCF exhibited brittle failure with clear splits, and NF showing extensive delamination and fibre pullout, the hybrid composites displayed intermediate behaviour that maintained structural integrity without catastrophic shattering. This behaviour, combined with the more predictable and constant mechanical response of hybrid variants compared to plain rCF, makes these materials particularly attractive for applications requiring damage tolerance and reliability.

Some of the tests showed that plain NF can achieve higher mechanical properties, however, it is crucial to remember that UD continuous fibres have a limited applicability as opposed to random fibre reinforcement. Combining these materials into a single composite allows for a greater improvement of attributes of both fibres. A pronounced positive hybrid effect is easily observable when looking at the property improvement of plain rCF. Overall, the layup sequencing had an effect on the performance, however, layup 3 which contains NF core supported by rCF proves to be the most universal across all of the tests, however, the layup sequencing is advised to be selected on an individual application basis.

The cold compression moulding process utilised in this study also demonstrates the industrial feasibility of producing hybrid composites containing rCF with consistent quality. The manufacture of hybrid composites also enabled higher fibre volume fraction in comparison to pure rCF, an increase from 41 % to upwards of 56 %. An increase in composite density has also been observed in hybrid composites over plain rCF by 0.24 g/cm^3. Both are attributed to higher packing density of flax fibres in combination with the manufacturing technique.

Findings of this research provide a solid foundation for the continued development and optimisation of rCF/NF hybrid composites, supporting the transition toward more sustainable engineering materials without compromising structural integrity or reliability. Additionally, exploration of alternative fibre alignments and the potential for incorporating these materials into multi-material structures also provide an interesting opportunity for future developments.

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Acronyms

rCF – Recycled Carbon Fibre
vCF – Virgin Carbon Fibre
NF – Natural Fibre
UD – Unidirectional
MPa – Megapascals
GPa – Gigapascals
J – Joules