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Each volume gathers contributions on specific topics:

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This collection contains the proceedings of the 21st European Conference on Composite Materials (ECCM21), held in Nantes, France, July 2-5, 2024. ECCM21 is the 21st in a series of conferences organized every two years by the members of the European Society of Composite Materials (ESCM). As some of the papers in this collection show, this conference reaches far beyond the borders of Europe.

The ECCM21 conference was organized by the Nantes Université and the Ecole Centrale de Nantes, with the support of the Research Institute in Civil and Mechanical Engineering (GeM).

Nantes, the birthplace of the novelist Jules Verne, is at the heart of this edition, as are the imagination and vision that accompany the development of composite materials. They are embodied in the work of numerous participants from the academic world, but also of the many industrialists who are making a major contribution to the development of composite materials. Industry is well represented, reflecting the strong presence of composites in many application areas.

With a total of 1,064 oral and poster presentations and over 1,300 participants, the 4-day event enabled fruitful exchanges on all aspects of composites. The topics that traditionally attracted the most contributions were fracture and damage, multiscale modeling, durability, aging, process modeling and simulation and additive manufacturing.

However, the issues of energy and environmental transition, and more generally the sustainability of composite solutions, logically appear in this issue as important contextual elements guiding the work being carried out. This includes bio-sourced composites, material recycling and reuse of parts, the environmental impact of solutions, etc.

We appreciated the high level of research presented at the conference and the quality of the submissions, some of which are included in this collection. We hope that all those interested in the progress of European composites research in 2024 will find in this publication sources of inspiration and answers to their questions.

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COMPRESSIVE FAILURE BEHAVIOUR OF HYBRID COMPOSITE WITH DIFFERENT LOW-STRAIN CARBON FIBRE

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Abstract
Two distinct hybrid composite configurations, glass fibre/high modulus carbon and glass fibre/standard modulus carbon fibre, were studied to characterise the failure mechanisms under compressive loading. The experiment was conducted through a 4-point flexural test with sandwich beam specimens containing unidirectional hybrid composites as a top skin. A universal testing machine equipped with a 4-point flexural test fixture facilitated the applied loads and unidirectional strain gauges attached to the specimen's centre to obtain compressive and tensile strain responses on the specimen. The compressive load-compressive strain responses and fractography from two hybrid composite configurations were characterised. It was observed that both hybrid systems exhibited a compressive failure strain improvement of the carbon fibre composites. However, the failure on each hybrid system demonstrated the distinctions between the two configurations. This investigation pointed out the key role of the low-strain fibre controlling the failure characteristics of hybrid composites.

1. Introduction

The compressive strength of carbon fibre composites stands out as one of the weaknesses of this material [1]. To improve the compressive properties of carbon fibre composites, the hybridisation concept has been studied by combining higher-strain fibres with carbon fibres [2-5]. Several studies showed improvements of compressive failure strain of carbon fibre with hybridisation [3][4][6]. The compressive behaviour of the composites has been investigated to understand the failure mechanisms of the composites and develop methods to improve behaviour. Typically, the direct compression test method is considered as the primary method to perform the test to observe the behaviour of the material but this testing method produces stress concentrations at the grips during testing and failure influenced by shear stresses [1,9].

A 4-point flexural test approach has been proposed to reduce the premature failure from stress concentrations during the test compared to the conventional direct compression test [1]. However, the 4-point flexural test introduces a through-thickness strain gradient during the test which affects the behaviour of the material. To overcome this issue, a sandwich beam specimen configuration has been proposed to reduce through-thickness strain gradients, making the experimental results more realistic. Sandwich beams are commonly comprised of honeycomb material as the core, but its low shear strength makes it susceptible to premature core crushing, and debonding [4]. The exploration of alternative materials for testing purposes becomes imperative to allow the specimen to reach the ultimate compressive failure strain rather than failing prematurely. Additionally, selecting a larger loading roller diameter is beneficial to minimise localised roller failure [1]. The objectives of this study were to characterise the failure behaviour of the high modulus carbon/S-glass fibre and standard modulus/S-glass fibre composites including the hybrid effect on each system and point out the key features of the failure of the hybrid systems.

2. Methodology

2.1. Specimen preparation

The presented sandwich beam structure, as shown in Figure 1, comprises a top skin fabricated from a hybrid composite, a core material, and a bottom skin fabricated from IM7/8552 unidirectional carbon fibre prepreg. The design is adapted from ASTM D5467 standards [6] and incorporates classic beam theory, with detailed material properties provided in Table 1. The top skin, as shown in Figure 2, consists of unidirectional S-glass and M55J for the high-modulus carbon fibre hybrid composite ($SG_1/M55_1/SG_1$). M55J/epoxy fibre composite was supplied by North Thin Ply Technology with ThinPreg 120 EPHTg-402 resin system and S-glass/epoxy was sourced by Hexcel with 913 resin system [7]. Another hybrid system is unidirectional S-glass with TC33 for the standard modulus carbon fibre ($SG_1/TC33_1/SG_1$). TC33/epoxy composite was provided by SK chemicals with K51 the resin system [8] and S-glass/epoxy was supplied by Hexcel with 913 resin system. Both top hybrid composite skins underwent a designated curing cycle compatible with both resins, while the bottom skin, IM7/8552 laminate, underwent a curing cycle as recommended by the manufacturer. The properties of the core materials were provided in Table 2 for the design process. Ashwood was chosen as the core material for the M55 hybrid composite and was cut into beams with the grain aligned in the loading direction. Poly(methyl methacrylate) or PMMA was selected over ashwood due to the incompatibility between ashwood's failure strain and the compressive failure strain of TC33 carbon fibre composite.

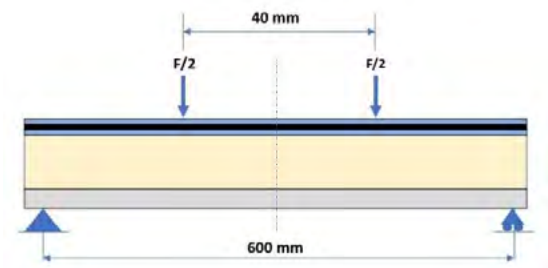

Figure 1. Sandwich beam design for the experiment

Figure 2. Schematic diagram of hybrid composite; the red region is carbon fibre layer and white region is S-glass layer (not to scale)

Table 1. Material properties of M55/epoxy, TC33/epoxy, 913 S-glass and IM7/8552 fibre composites

Prepreg type	Elastic modulus (GPa)	Cured nominal thickness (mm)
M55J/epoxy[7]	280	0.030
TC33/epoxy[8]	95.3	0.030
S-glass/epoxy[7]	45.7	0.155
IM7/8552[4]	164	0.125

Table 2. Material properties of ashwood and PMMA

Material	Core thickness (mm)	Elastic modulus (GPa)	Shear modulus (GPa)	Shear strength (MPa)
Ashwood	18	8.20[9]	1.23[9]	14.3[10]
PMMA	20	3.56[11]	1.35[11]	53 [12]

2.2. Experiment setup

Figure 3 illustrates the experimental setup in this study. An adjustable 4-point bending fixture was installed to provide support to the specimen throughout the testing, with an Instron universal testing machine equipped with a 25kn load cell. The 25 mm in diameter loading noses were clamped by the upper jaw of the testing machine and positioned 40 mm apart. two linear strain gauges were attached to both the top and bottom surfaces of the sandwich beam at the midpoint to obtain the compressive and tensile strains of the two skins during the test. A data logger was connected to collect data from the strain gauges, the applied load and displacement from the Instron testing machine.

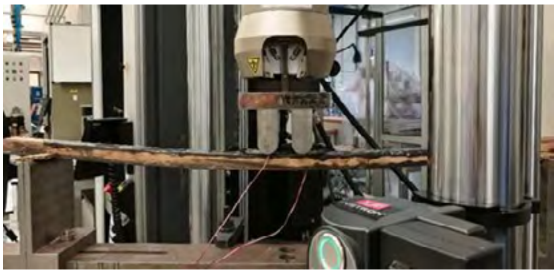

Figure 3. Experimental setup for 4-point flexural test with sandwich beam.

The compressive load-strain responses were plotted to characterise the behaviour and failure trends exhibited by the hybrid composites. Failure analysis of each specimen was conducted through visual observation, optical microscope and scanning electron microscopes (SEM). The experimental results were then compared with the monolithic M55 and TC33 carbon fibre composites from previous studies to understand the improvement in failure strain with the hybridisation concept.

3. Experimental results

3.1. $SG_1/M55_1/SG_1$

The failure modes observed in the $SG_1/M55_1/SG_1$ specimens were small carbon fragmentations dispersed along the fibre direction and across the beam's width, with delamination occurring close to the loading rollers, as shown in Figure 4. Microscopic images revealed carbon fibre fractures across the fibres rather than the typical kink band failure observed in carbon fibre composites, as evidenced in Figure 5. The compressive load-strain response displayed non-linearity with a change in slope (knee-point), followed by a non-linear response until reaching final failure by delamination at the interior carbon-glass interface, as illustrated in Figure 6. The average knee-point compressive strain on the surface was measured at 0.484%, while the average final failure compressive strain reached 0.976%.

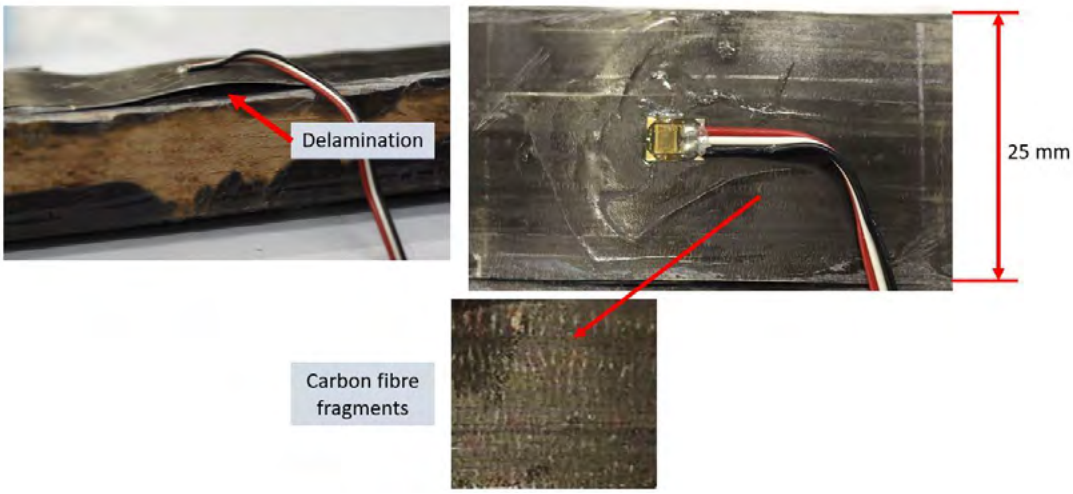

Figure 4. Failure on $SG_1/M55_1/SG_1$ hybrid composite from the top view of the specimen

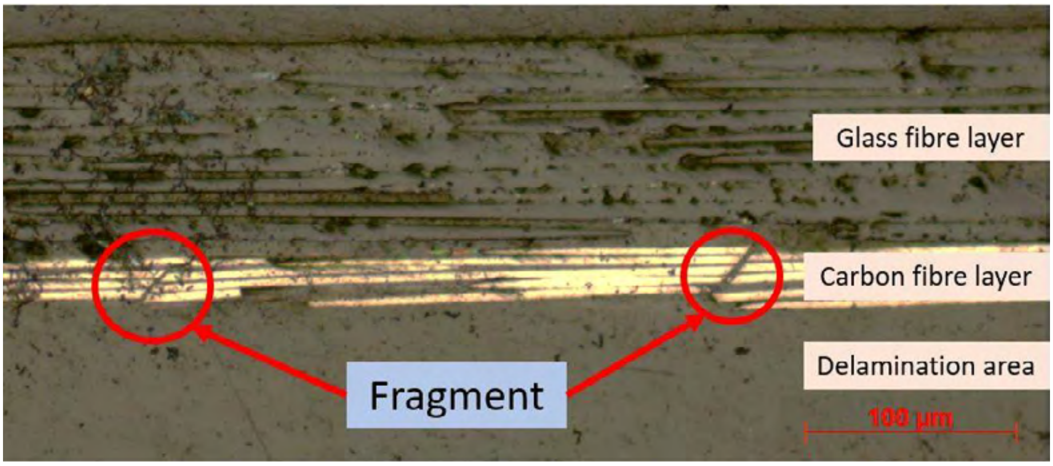

Figure 5. Carbon fragmentation in M55 layer in $SG_1/M55_1/SG_1$

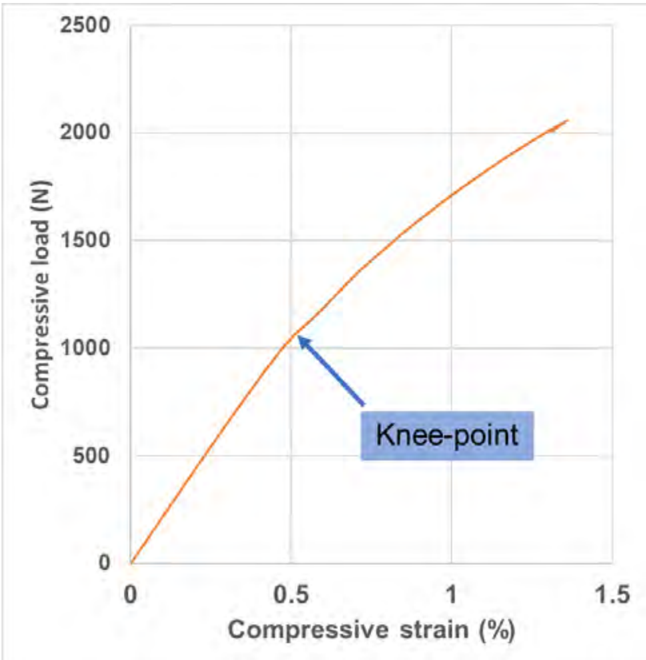

Figure 6. Compressive load-compressive strain response on $SG_1/M55_1/SG_1$

3.2. $SG_1/TC33_1/SG_1$

The $SG_1/TC33_1/SG_1$ specimens exhibited final failure characterised by localised areas of compressive failure linked by splitting distributed across the beam's width within the gauge section, accompanied by evidence of delamination at the fracture tip as shown in Figure 7. The failure was further examined through scanning electron microscopy (SEM), revealing fibre fracture and the presence of kink bands in the TC33 carbon fibre layer, as shown in Figure 8. The compressive load-strain response of $SG_1/TC33_1/SG_1$ specimens also exhibited non-linearity until reaching the final failure point with the absence of a knee-point compared to the response from $SG_1/M55_1/SG_1$, and an average final failure compressive surface strain measured at 2.609%, as illustrated in Figure 9.

Figure 7. Failure on $SG_1/TC33_1/SG_1$ hybrid composite from the top view of the sandwich beam

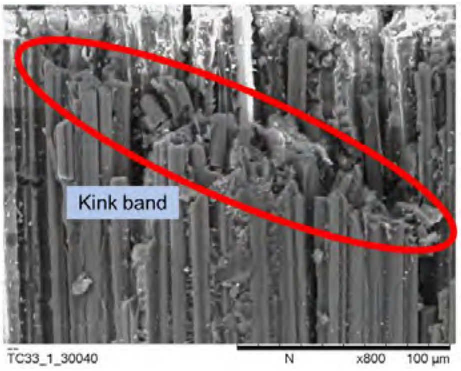

Figure 8. Failure on $SG_1/TC33_1/SG_1$ hybrid composite through scanning electron microscope (SEM)

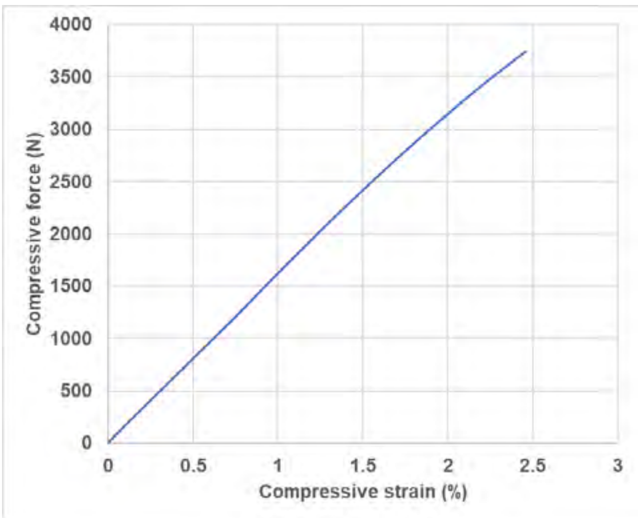

Figure 9. Compressive load-compressive strain response on $SG_1/TC33_1/SG_1$

4. Discussion

The load-compressive strain responses of the two hybrid systems were compared, focusing on distinct key features regarding failure mechanisms of the selected hybrid composites. A summary of the experimental results from each hybrid system is presented in Table 3, alongside the baseline compressive strain of the M55 and TC33 fibre composites. The load-compressive strain from the M55 hybrid composite system (Figure 6) showed a knee-point whereas the TC33 hybrid system, (Figure 9), exhibited non-linearity without a knee point in the load-strain response. The responses and failure characteristics observed in the two hybrid systems likely initiate from different mechanisms. While the M55 hybrid composite displayed small carbon fibre fragmentation distributed along the length and across the beam's width, the TC33 hybrid composite created discrete fibre fractures with matrix splitting and delamination within the gauge section of the sandwich beam. The failure micrograph of the M55 hybrid composite exhibited angled fibre fractures without evidence of a kink band, whereas the TC33 hybrid composite exhibited evidence of kink band formation within the TC33 carbon fibre layer. In summary, the distinct failure modes observed in the M55 and TC33 hybrid composites suggest that M55 carbon fibre failed as a result of fibre fracture, contrasting with the TC33 carbon fibre failure which was driven by kink band formation.

Table 3. The experimental results from the $SG_1/M55_1/SG_1$ and $SG_1/TC33_1/SG_1$ hybrid composites. The numbers in the bracket are the coefficient variation of the experimental result.

Specimen Type	Knee-point compressive strain (%)	Failure compressive strain (%)	Baseline compressive strain (%)	Failure mode
$SG_1/M55_1/SG_1$	0.484 (3)	0.976 (25)	0.311 [13]	Small carbon fragmentation
$SG_1/TC33_1/SG_1$	-	2.609 (8)	1.21[8]	Kink band

The experimental results were compared with previous studies on pure M55 carbon fibre [13] and pure TC33 carbon fibre [8] compressive failure strain. The knee-point strain from $SG_1/M55_1/SG_1$ (0.484%) was higher compared to the study by Montagnier and Hochard, who recorded 0.311% compressive strain, representing a 1.5 times improvement. Similarly, the compressive failure strain observed in $SG_1/TC33_1/SG_1$ was 2.609%, higher than the pure TC33, which was reported to fail at 1.21% [8], making a 2.1 times improvement over the baseline compressive strain of TC33 carbon fibre composite. The improvement in the M55 hybrid composite can be attributed to the constraint provided by the glass fibre layers, which means that a single fracture does not lead immediately to complete failure, which happens later, when delamination occurs. The enhancement in failure strain observed in the TC33 hybrid composite can be attributed to the higher shear stability in the glass fibre layers which maintain global stability of the hybrid composite and suppress the shear instability from the TC33 carbon fibre.

3. Conclusion

The investigation of the compressive behaviour of hybrid composites using a sandwich beam 4-point flexural test was successfully conducted. The compressive failure behaviour observed in each hybrid system signifies a notable improvement in the compressive strain compared to the baseline compressive strain of each monolithic carbon fibre composite. The improvement can be attributed to the constraint of the glass fibres, which provide additional support for the compressive fibre fracture of the M55 hybrid composite and enhance the global shear stability for the TC33 hybrid composite. This study also showed two distinct failure modes in the two hybrid systems: the S-glass/M55 hybrid composite showed dispersed fibre fragments, while the S-glass/TC33 hybrid composite showed kink band formation and splitting.

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