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Crashworthiness of Micro-Fiber-reinforced Foam-Filled Carbon Fiber Composite Tubes

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Abstract

This study investigates the axial crushing behaviour of Carbon Fiber Reinforced Polymeric (CFRP) tubes, both hollow and filled with polyurethane (PU) foam infused with varying amounts and sizes of milled glass fibres. The micro-glass fibres were added to the foam during the manufacturing process to enhance its shear properties. Different weight percentage and sizes of the microfibers were studied. After full curing, composite tubes were subjected to axial crushing tests. Properties like load-bearing capacity, energy absorption, crushing efficiency, and specific energy absorption were studied. The results showed that finer 1/32-inch fibres significantly enhance load bearing and energy absorption in foam-filled tubes, with the 1-32 5% configuration demonstrating the highest performance. On the other hand, the non-filled CFRP tube exhibited the highest specific energy, indicating superior energy absorption efficiency relative to its weight.

Keywords
Micro-fibres, Axial crush, Carbon tube, Compression test, Crashworthiness, Quasi-static crush

1.Introduction
Composite materials, mainly carbon composites (CFRP), are widely used in engineering because of their advanced mechanical properties. They are associated with high performance, such as high strength, stiffness, and energy absorption capabilities. These characteristics of corban fiber composites are ideal for aerospace, marine, and many more engineering industries applications. One of the main advantages is carbon fiber composite's weight reduction, and their crashworthiness is critical (Khan et al. (2023)). Conventional engineering materials, such as metallic elements, are progressively being replaced by carbon composites due to their advanced advantages in physical, mechanical, deliquescence, and thermal properties (Sebaey and Mahdi (2017)). Including high-performance advantages, which are tensile, compressive, and low density, all outstanding fatigue properties are important structural performance adoptions. One of the main advantages the carbon composites is that they are very lightweight due to this characteristic of its impact on fuel efficiency (Junaedi et al. (2023)).

The researcher recently became inadequate and focused on improving the crashworthiness of composite structures with some modifications to the composites for reinforcement technique. Recently, many techniques for modifications with microfiber filler (milled glass), such as polyurethane (PU) foam and milled glass fibers, have enhanced the mechanical properties during axial loading (Alshahrani et al. (2022)). PU foam is generally very lightweight, and its properties can be energy-absorbing. It can also be extended and improved by adding microfiber fillers to improve the composite properties and axial loading characteristics (Hanan et al. (2023)). However, the inflation of the microfiber filler sizes and concentrations on the crashworthiness properties of foam-filled carbon composite tube structure has not been significantly studied (Sebaey et al. (2021). These investigations involved the axial crushing of composite tubes filled with PU foam imbued with milled glass fibers of varying sizes (1/16 and 1/32 inches) and weight percentages (5% and 20%) (Umarfarooq et al. (2023)).

The study's main focus is to assess the composite tube modification's crashworthiness factors, which are load-bearing capacity, energy absorption, crushing efficiency, and specific energy absorption (Mahdi et al. (2014)). The axial loading tests were conducted on the carbon composite tubes to investigate the influence of microfiber reinforcement on their mechanical properties and performance (Sebaey et al. (2023)). Furthermore, the microscope inspection was to observe any changes in PU foam cell structure affected by the addition of the altered microfiber sizes (Sebaey et al. (2021)). This research provides insights into optimizing hybrid composite materials for automotive and aerospace safety applications, offering potential advancements in lightweight crash protection systems. It also provides a comprehensive overview of improving hybrid composite materials for aerospace and automotive safety engineering applications and contributes to prospective advancements in lightweight failure protection systems.

2.Materials and Methods

The carbon composite tubes were fabricated using carbon tubes with a lay-up sequence of [±45/0]s. They were filled with PU foam containing glass microfibers at weight percentages of 0%, 5%, and 20%, with sizes of 1/16 and 1/32 inches. The experiments were subjected to axial compression testing up to 80% strain. The load-displacement data was analyzed to calculate the peak load, meaning crushing force and crushing force efficiency. Five different specimen tubes were obtained, each corresponding to the information in Table 1.

The PU foam was supplied in two parts, A and B (polyisocyanate and polyol). Both parts are liquid at room temperature. According to the product datasheet, combining equal amounts of the two parts is crucial for creating the desired foam. The electric mechanical stirrer was used to thoroughly mix part A with the microfibers for the different segments at 800 rpm for 5 minutes, then part B was added, and stirring was continued for 20 seconds. Once the foaming action commences, immediately pour the mixture into the tube and allow it to fully foam. After 20 minutes, the mixture will firmly solidify inside the CFRP tube, creating the foam with the microfiber-filled composite tube. The composite tubes were meticulously left to cure for a full 48 hours at room temperature, ensuring the highest quality result, as per the product datasheat. Figure 1 displays a graphic representation and an actual example of the campsite tube and microfiber filing arrangement.

Table 1. The Carbon Composite tubes were used for the current study.

SN.	Sample	Inner foam composition		
		Foam %	1/16 GF %	1/32 GF %
1	N/F	0%	0%	0%
2	0%	100%	0%	0%
3	1/16 5%	95%	5%	0%
4	1/16 20%	80%	20%	0%
5	1/32 5%	95%	0%	5%
6	1/32 20%	80%	0%	20%

3. Results and Discussions

3.1. Load vs. displacement

Figure 1. Shown the load vs. displacement investigations of the carbon polymer composites crushing behaver, with a high preliminary load monitored by stabilization. The specimens with different microfibers with 1/32-inch fibers at 5% concentration demonstrated good results among other samples in the load-bearing capacity and energy absorption, demonstrating enhanced stress transfer and strengthening. The NF (non-filled) carbon composite tubes performed a high specific energy due to the minimal mass density of the composite tubes. And the other hand, long microfibers

(1/16-inch) demonstrated reduced axil performance, which might be microfiber distributions in the foam. Figure 2 illustrates the failure pattern of the composite tubes under axial compression loading up to 80% of the strain.

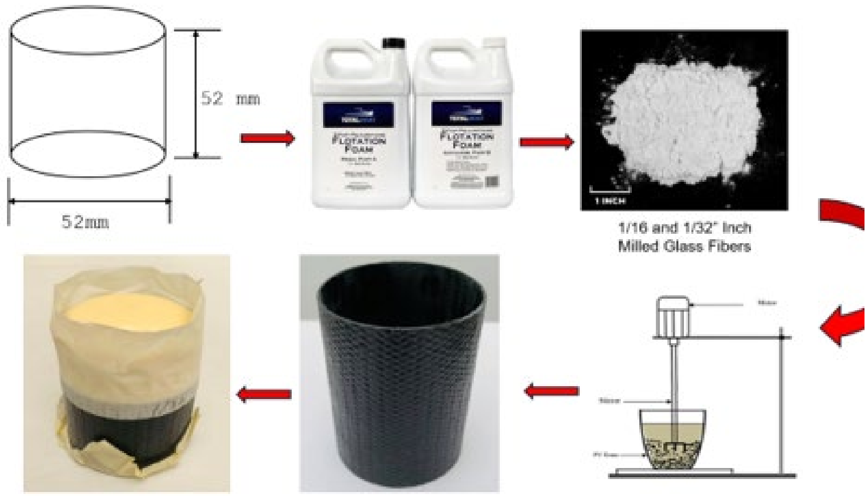


Figure 1. Composite Manufacturing Representation

3.2. Energy absorption

Figure 2. shows the energy absorption and specific energy performance of the experienced carbon composite tubes examined under axial compression load. The investigation showed that foam-filled carbon composite tubes exhibit significantly higher energy absorption than non-filled (NF) carbon composite tubes. The composite specimens reinforced with 1/32-inch fibers at a 5% concentration reached the higher energy absorption, which is (~0.49 kJ), recognized to the advanced fibers improving the stress transfer and load distribution within the foam fi matrix composites. Compared with the non-filled composite tubes, the filled composite tubes displayed the maximum specific energy (~35 J/g) due to the lower mass of the composite tubes and the absence of foam, although they had lower total energy absorption (~0.35 kJ).

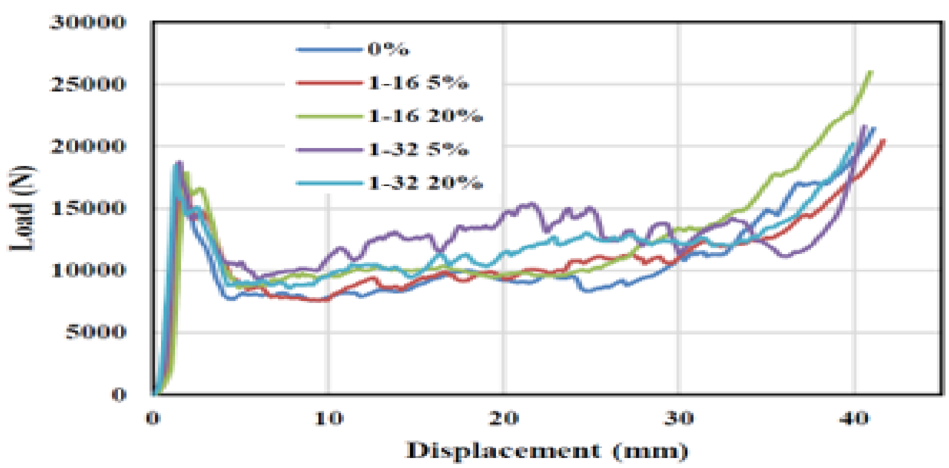


Figure 2. Load vs. Displacement plot of samples

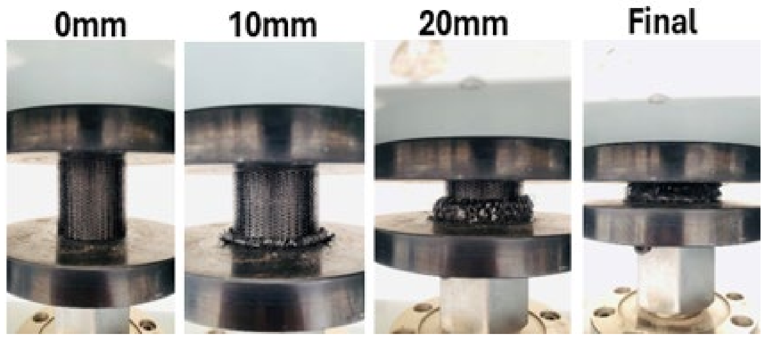


Figure 3. Axial Compression test of the specimens up to 80% of strain.

On the other hand, adding 1/16-inch microfibers decreased energy absorption and specific energy due to potential fiber agglomeration. Difficulties impeded effective load transfer, affecting ineffective load transfer. Microscopic investigations showed that finer microfiber (1/32-inch) better upheld the PU foam structure in the composite tubes, indicating more stability and high energy absorption efficiency during axial compression. These experimental investigations highlight the importance of enhancing microfiber size and content to strengthen the crashworthiness of carbon composite tubes. Choosing the systemic mixtures of the PU foam and microfibers can substantially improve energy absorption properties, making these Corban hybrid composite structures appropriate for lightweight impact fortification in automotive and aerospace applications.

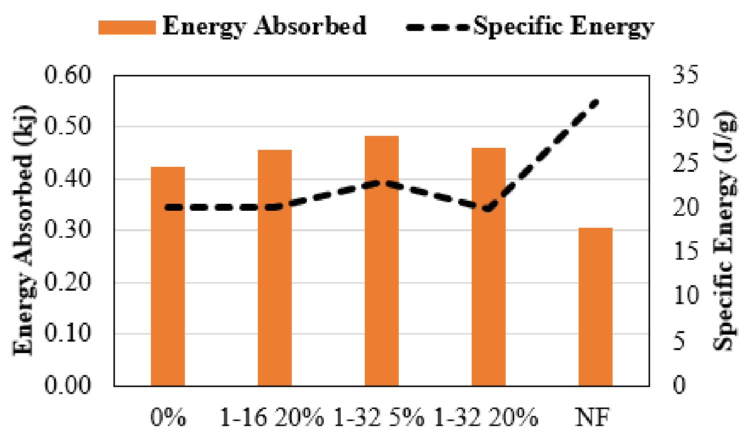
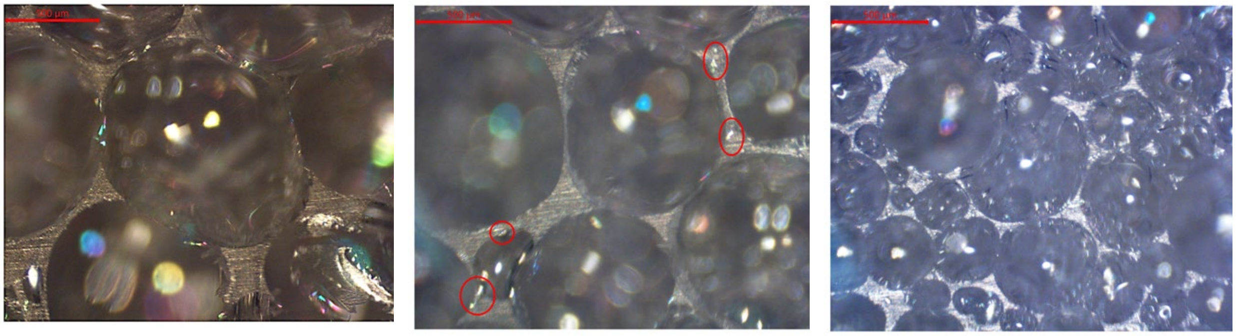


Figure 4. Energy absorption and specific energy of samples

3.3. Microscopic analysis

Figure 4. shows microscopic examinations of foam-filled carbon composites with substantial modifications in the PU foam cell structure, established by microfiber size and substance. Specimens with adequate 1/32-inch fibers at 5% concentration illustrated a more homogeneous foam cell division, representing minimum interruption to the foam structure. This equivalence caused higher load-bearing and energy absorption characteristics due to better stress transfer within the composites and matrix. In contrast, experiments with insignificant 1/16-inch fibers, specifically at 20% concentration, demonstrated random PU foam cell sizes and the presence of voids initiated by fiber accumulation. This gathering of microfibers created ineffective points within the PU foam structure, reducing its overall mechanical performance during axial load compression. The investigation outcomes proposed that smaller microfiber sizes are better for maintaining the reliability of the foam, with a good amount that can lead to variations in its microstructure. These experiments' findings emphasize the analytical role of microfiber size and spreading in optimizing the crashworthiness of PU foam-filled carbon composite tubes.



(a) 0% (b) 1-32 5% (d) 1-16 20%

Figure 5. Microscopic images comparing foam cell size across different fiber configurations (all images are using the same magnification)

Adding the milled glass microfibers into PU foam within carbon composite tubes improved the axial characteristics. The microfibers are 1/32-inch in size at 5% weight, demonstrating the most favorable axial load capacity and energy absorption performance and providing potential engineering applications in crash structures, such as automotive safety.

4. Conclusions

In this study, CFRP tubes with and without foam filler were subjected to axial crushing tests, and the results were analyzed. The effect of infusing foam filler with different sizes and weight percentages of milled glass fiber was also examined. The experimental analysis revealed changes in properties such as load bearing, energy absorption, and crushing efficiency of the composite tubes studied. The study showed that introducing milled glass fibers into PU foam within CFRP tubes significantly influences the crushing characteristics of the composite. Notably, the composite with 1/32 5% fibers achieved a peak strength of 12 kN, significantly higher than the NF tube's performance of 8.4 kN, with the composite with 0% fibers exhibiting a strength of 11.3 kN. This indicates that the 1/32 fiber size contributes to better load distribution and overall strength, emphasizing the importance of optimizing fiber dimensions for improved structure.

It was found that larger fibers (1/16 5% and 1/16 20%) exhibit lower energy absorption (~0.45 kJ) and specific energy (~20 J/g) due to fiber agglomeration, which hinders load transfer and weakens the composite. Achieving a balance between total energy absorption and specific energy is crucial, as improper fiber size and dispersion can lead to inefficient load transfer. Proper optimization of these factors is essential to enhance the mechanical performance and structural integrity of fiber-reinforced composites. The analysis of crushing force efficiency shows that the 20% sample with smaller 1/32-inch fibers at higher concentrations (1/32) achieves the highest efficiency, around 80%, in converting applied force into energy absorption. In contrast, the NF sample demonstrates the lowest efficiency. Future work could further optimize fiber parameters to improve crashworthiness in automotive and aerospace applications.

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