Enhancing Structural Performance of Recycled Fiber-Reinforced Thermoplastic Composites Through Incorporating Composite Laminate Precuts

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Abstract

Composite recycling has gained significant attention due to the increasing global sustainability problems. The mechanical recycling process of fiber-reinforced composite parts involves shredding long continuous fibers within the composite into shorter discontinuous fibers. Since the performance of the resulting short fibers is not as high as that of the original long fibers, the application of mechanically recycled composites is limited. The objective of this study is to enhance the structural performance of recycled composite parts by integrating of a set of continuous fiber composite precuts during the molding process. The 2-dimentional precuts were positioned in the structurally critical regions of the recycled composite part, and the remaining area was then filled with shredded composite material. An aircraft overhead bin door pin bracket was used as the part geometry. The mechanically recycled material and the precuts were made from 60% by weight carbon fiber reinforced polyetherketoneketone (PEKK) composite. Three different combinations of precuts were designed to create the pin bracket, and their performance was assessed by mechanical testing of the pin bracket. Additionally, digital image correlation (DIC) technology was used to analyze local strain changes and investigate the failure mechanisms of the parts throughout the testing process. The test results demonstrated that the inclusion of properly designed precuts significantly improved the performance of the recycled composite part. This research contributes to the advancement of composite recycling by providing insights into methods for enhancing the structural performance of mechanically recycled composites through the strategic integration of continuous fiber precuts into recycled composite part.

Introduction

The fiber-reinforced composite materials have widely used across various industries such as aerospace, aviation, automotive, wind energy, construction, and sporting goods [1]. The advanced composite materials offer advantageous mechanical and physical properties, including high strength-to-weight ratio, stiffness, and low coefficient of thermal expansion (CTE) [2]. As a result, their demand has been steadily increasing, with projections indicating substantial growth in the global composites market [3], [4]. However, along with the increased usage of composite materials comes the challenge of addressing their sustainability throughout their lifecycle [5], [6]. The management of end-of-life (EOL) composite parts has been a significant concern, as their disposal through traditional methods like landfilling has not only ineffective in terms of sustainability but also severe damage to environment [5], [7]. To solve this issue, many countries have begun implementing policies to encourage recycling or promote alternative waste management practices for composites [6].

Composite recycling methods generally fall into three categories: mechanical, pyrolysis, and chemical recycling [8]. Mechanical recycling is one of the most commonly used methods due to its simplicity and cost-effectiveness [7]. Composite mechanical recycling includes shredding and grinding the composite material to reduce it into smaller fragments [9]. These shredded recycled composite materials are reused in new composite product or reinforcement additives. However, the mechanical recycling process may result in a reduction in the performance of the recycled composite compared to the original composite [6], [9]. The shorter fibers generated through mechanical recycling may have degraded mechanical strength and other desirable characteristics. Therefore, the applications of mechanically recycled composites are often limited [6], [9]. Therefore, it is important to find a way to enhance the performance of recycled composite parts and broaden the application range of them to enhance the sustainability and to promote the recycling of composite materials.

This study demonstrated an innovative approach to enhance the mechanical performance of recycled composite parts through the integration of two-dimensional continuous fiber composite precuts. These precuts are fabricated by cutting them from composite laminates. They are selectively placed in structurally critical areas to reinforce the parts and provide additional strength in mechanically demanding sections. Even the continuous fiber composite laminates themselves, which the precut is cut from, can be sourced from EOL composite parts. Rather than shredding all composite parts in the composite recycling process, the suitable composite parts can be used for precut fabrication. To implement this approach successfully, careful planning and consideration are required regarding precut design and how they will be cut from the parts. Not all composite parts have a two-dimensional flat geometry. Additional processes, such as composite part flattening, may be necessary before the precut fabrication. However, by utilizing EOL composite parts to create precuts, the need for additional new continuous fiber composite materials can be eliminated. This approach represents a closed sustainability loop, where materials can be continually recycled and repurposed without the introduction of new resources as shown in Figure 1.

In this study, recycled composite parts were manufactured using mechanically recycled composite material. The load-critical areas were identified, and the precuts were specifically designed to reinforce those regions. Sets of precuts with different designs were fabricated and integrated into the recycled composite parts during the molding process. The mechanical performance of the recycled composite parts with precuts was then tested to assess how different precut designs improved their structural performance, and these results were compared to the performance of recycled composite parts without precuts. With the novel recycling approach, this study aims to contribute to the enhancement of sustainability by effectively utilizing EOL composite part and recycled composite materials, thereby creating additional applications and improving overall sustainability of the composite materials.

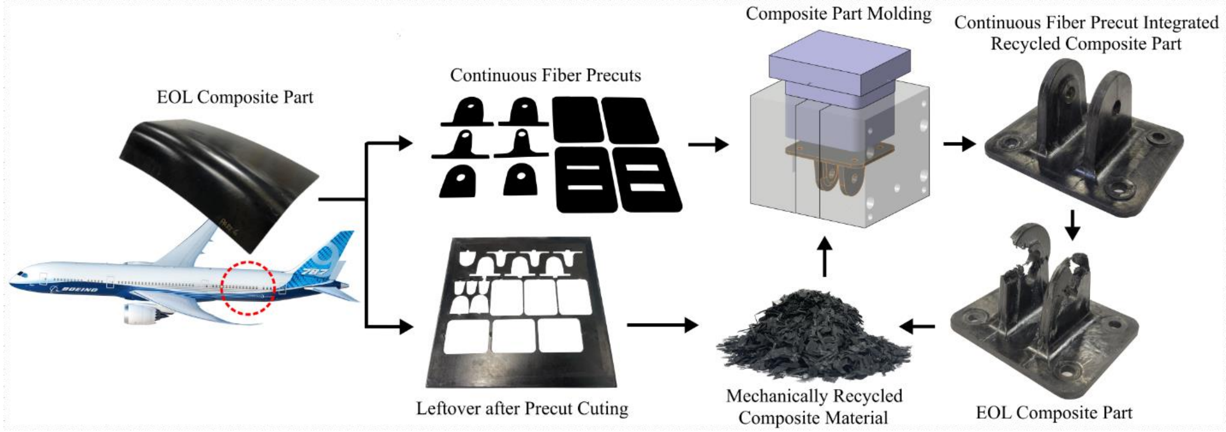

Figure 1: Closed composite material sustainability loop via continuous fiber precut integration approach.

Methodology

An aircraft overhead bin door pin bracket was selected as a part geometry for this study. The pin bracket plays an essential role in providing strength and ensuring safety while maintaining a lightweight design. Furthermore, the manageable size of the pin bracket facilitated the production of multiple samples for testing purposes. The pin bracket consisted of two ears which have holes for pin insertion. The ears had an approximate height of 30.48 mm, with varying thicknesses. The thicker section measured approximately 5.08 mm. These ears were connected to a base with dimensions of around 63.40 mm by 50.70 mm and a thickness of approximately 2.54 mm. The base has four screw holes to which screws are fastened to install the pin bracket. Figure 2 shows the pin bracket design.

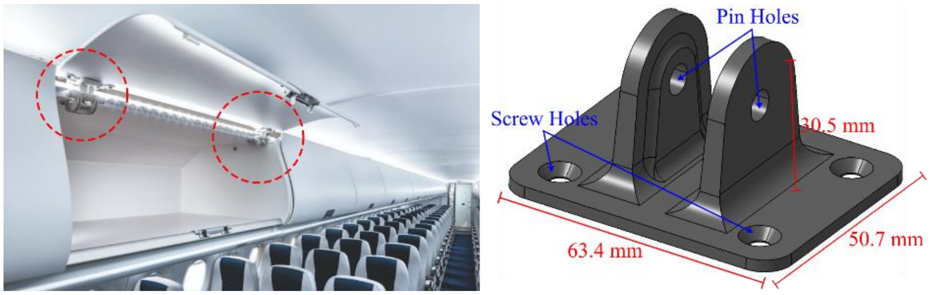

Figure 2: Aircraft overhead bin door pin bracket design.

First, the continuous fiber precuts that was integrated into the pin bracket needed to be designed. The strategic design of the precuts was crucial to optimize the load distribution and maximize the structural performance of the part. The previous testing on sheet molding compound (SMC) pin brackets showed that failures occurred in the ear and base regions. In the ear section of the pin bracket, particularly in the areas above the pin hole and in the center where the load was applied was failed. During the compression molding process of manufacturing pin brackets using SMC, the material flow resulted in the formation of welding lines at the ear above the pin hole. Welding lines occur when the molten material flows around obstacles or merges with other material flow fronts, resulting in a line that can weaken the structural integrity of the pin bracket. In the base section, the failures occurred in the areas where screws were installed. This is due to the localized stress formation around the screw holes when the screws are installed and subjected to loading.

To address this issue, it was essential to reinforce the ear section, specifically the upper portion above the pin hole, with continuous fiber. The precut had an ear-shaped with a pin hole, allowing for the simultaneous molding with the pin during the manufacturing process was designed. This design approach eliminated potential welding lines and enabled the precise placement of continuous fiber around the pin hole area. To improve the performance of the base section, a continuous fiber precut of the same size as the base was integrated into the design. The base design aimed to reinforce the base and distribute the load more evenly, reducing stress concentration and the risk of failure in the screw-fastened areas Figure 3(a) shows the precut design set 1.

In the primitive experiment, the pin bracket with the precut design 1 was mechanically tested. The test result showed that the pin bracket no longer experienced failure at the ears or the base. However, it failed at the area where the ears were connected to the base. The test result addressed the need to develop a precut design that would effectively connect the ears and base sections with continuous fiber. The new precut design was developed to have slots in the base and allowed the ear to pass through the slot. The ear precuts had a wider section on the bottom that enabled the ear to withstand the pulling load without simply slipping through the slot. This precut design concept is similar to three-dimensional puzzle, where the components interlock and provide structural integrity. Figure 3(b) shows the precut design set 2

As a final iteration of the precut design, additional layers of precuts were added each ear, while the basic design of the ear and base were same as the previous three-dimensional puzzle design. This designed aimed to enhance the load-carrying capacity by increasing the amount of continuous fiber within the pin bracket. Through these design refinements, the study aimed to achieve a more robust and effective precuts design that would contribute to the overall improvement of the recycled composite part's mechanical performance. Figure 3(c) shows the precut design set 3.

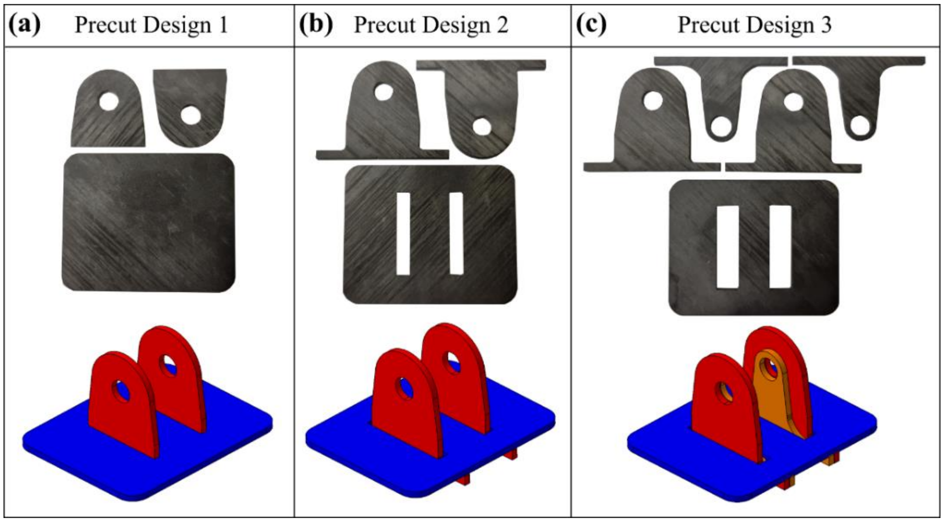

Figure 3: Precut set and assembled precut image for (a) the precut design 1, (b) the precut design 2, and (c) the precut design 3.

For both precut and mechanically recycled material, 60% by weight carbon fiber reinforced polyetherketoneketone (PEKK) composite was used. The precut was fabricated from a 20-ply thick quasi-isotropic laminate, approximately 2.54 mm thick, with a fiber orientation of [45/90/-45/0/90/0/0/45/90/-45]s. The precuts were cut from the laminate with an abrasive waterjet. After the cutting, the surface of the precut was lightly sandblasted to clean any remaining release agents or grease and to enhance bonding with the recycled material. The precut design set 1 was 16.67 g, and the precut design set 2 was 19.37 g, and the precut design set 3 was 22.17 g. To investigate the fiber length of the recycled composite material, the shredded material was thermally decomposed in a furnace to remove the polymer matrix. The remained fiber was collected and microscopic analysis was performed to measure the fiber lengths. By measuring 100 individual fibers, the average fiber length was 4.7 mm. Figure 4 shows the mechanically recycled composite material and the fiber length distribution.

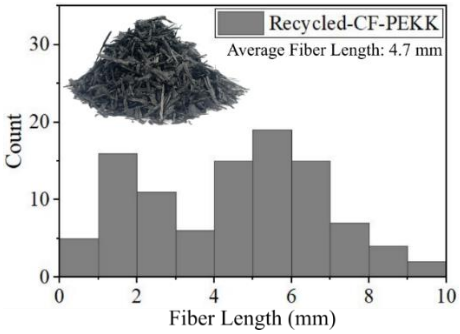

Figure 4: The mechanically recycled CF-PEKK and the fiber length distribution.

A compression molding tool made from H13 tool steel was used to fabricate the pin bracket geometry. The exploded view of the compression molding tool shown in Figure 5 provides an overview of the different sections of the tool and the inserts used to mold the pin hole and the screw holes at the base of the bracket. The tool is equipped with a thermocouple well to record temperature during manufacturing.

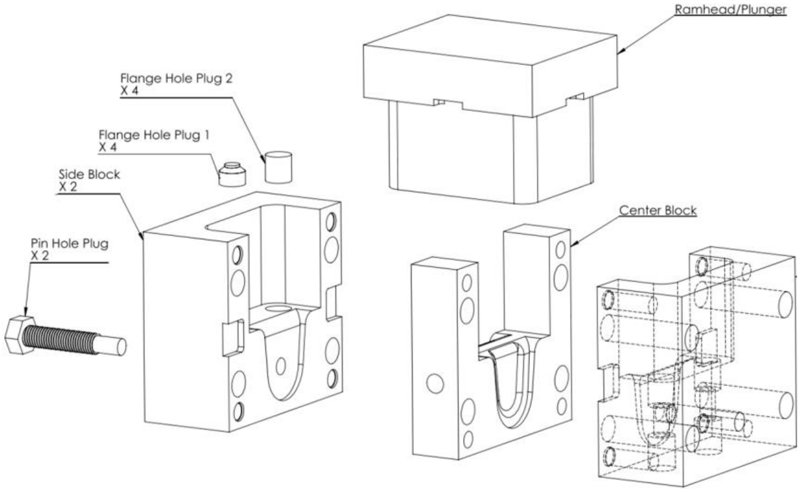

Figure 5: Compression molding tool used to fabricate the pin bracket [10].

Each precut design had a unique method for installation. For the first precut design, the ear precuts could be easily installed to the tool during the tool assembly process as shown in Figure 6(a). Then, the recycled material was poured into the tool, and the base precut was placed on the top of the recycled material as shown in Figure 6(b). The second and third precut designs had more challenges since the ear and base precut were interlocked, prohibiting separate installation. Therefore, the ear and base precuts were assembled together and integrated into the tool while the tools were assembled as shown in Figure 6(c) (precut design 2). Then, the recycled material was poured into the tool. To ensure that there was an enough material to fill the ear cavities fully, some recycled material was pushed into the ear cavities through the slots on the base precut while the recycled material was poured as shown in Figure 6(d). All pin brackets were fabricated with the same amount of composite material. The total amount of composite material including both continuous fiber precuts and the recycled material in the pin bracket was 31.4 g.

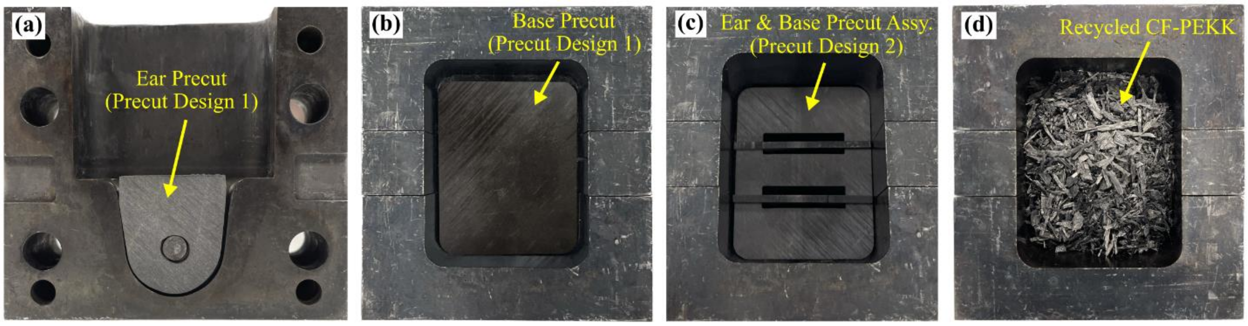

Figure 6: Manufacturing of the pin bracket including continuous fiber precuts. (a) The placement of the ear precut of the precut design 1 and (b) the placement of the base precut of the precut design 1. (c) The placement of the assembled ear and base precuts into the tool while the tools were assembled, and (d) the tool cavity filled with the recycled materials.

Following the preparation of the compression molding charge, the tool's plunger was installed, and the tool assembly was heated to the processing temperature in a forced convection oven. Upon reaching the processing temperature, the tool assembly was transferred to a hot press for the flow and consolidation of the molding charge into the tool cavity. A pressure of 124.1 Bar was applied while the tool cooled down to below the glass transition temperature of the polymer. The platens of the hot press were preheated to reduce the cooling rate and allowed the development of crystallinity in the polymer. Table 1 lists the process conditions used for the compression molding.

Table I: Process conditions for compression molding [10].

Process Parameter	**Value**
Material	CF-PEKK
Process Temperature (°C)	390
Consolidation Pressure (Bar)	124.1
Demolding Temperature (°C)	150
Platens Temperature (°C)	220

Quasistatic tests of the pin brackets were conducted with a universal test machine MTS 810 equipped with a 100 kN load cell. A displacement control procedure was carried out at a rate of 2 mm/min until the ultimate failure of the bracket was reached. A custom-made fixture was utilized to load the pin bracket in tension as shown in Figure 7(a). The pin bracket was installed on the test fixture with four 10-32 screws torqued to 40.67 Nm. Digital Image Correlation (DIC) was used to record the strain field developed at the surface of the pin bracket's ear during loading. Figure 7(b) shows the strain field in the load direction developed before and after ultimate failure of a pin bracket reinforced with continuous fibers. Three pin brackets for each precut design and four pin brackets with only recycled material for the baseline were tested.

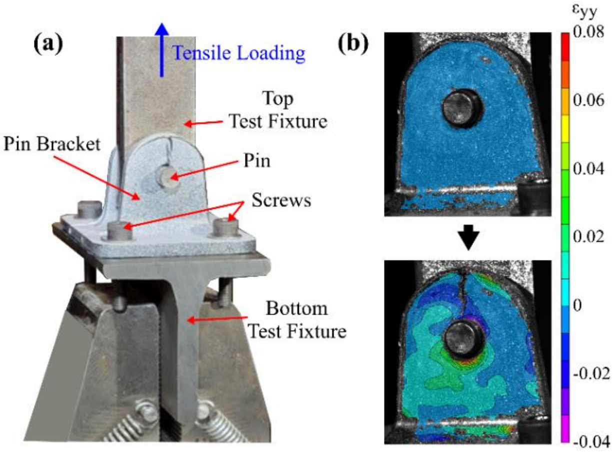

Figure 7: (a) Mechanical testing setup for the pin brackets. (b) Strain field in the load direction obtained from DIC analysis before and after failure in the pin bracket.

Results

The pin brackets with three different precut designs and the pin brackets without precuts, only with the recycled composite material, were successfully fabricated. Three pin brackets were manufactured for each precut design, and four pin brackets were fabricated without any precut, making a total of 13 pin brackets. There was no evidence of any defects such as void or crack on the surface of the pin brackets. After manufacturing the pin brackets, the pin holes on the ears and screw holes on the base were finished, as well as sanding to remove any burrs. To observe the fiber distribution within the molded pin brackets and to observe any defects, such as void, inside of the pin brackets, microscopic image of the cross-section of the pin bracket with different precut were made as shown in Figure 8. The microscopic images demonstrated that the fibers were effectively placed along the boundaries of the ear and pin hole sections. Similarly, in the base sections, the fibers adequately covered the screw holes. For the precut design 1, it was found that the ear precut were pushed inside of the ear cavity and it made a noticeable gap between the ear precut and base precut. The gap between the precuts was filled with the recycled composite materials. In the precut design 2 & 3, the ear precut held its position during the forming process. The continuous fiber was observed across of entire ear, and the wider bottom section of the ear preform positioned properly underneath of the base precut. For all the precut designs, it was found that the quasi-isotropic fiber orientation of the ear precut did not maintained during the forming process, resulting many wavy fiber orientations and buckling were observed in the precut. The base precut relatively remained same location where it was installed during the precut placement process. No defects were observed on the cross-sectional area of the pin bracket in the microscopic image.

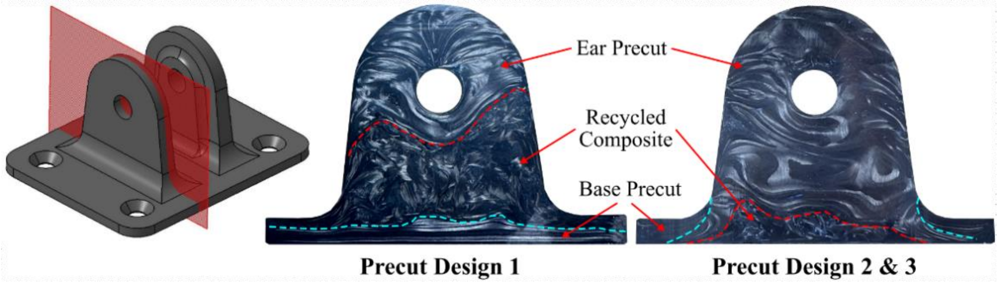

Figure 8: The microscopic image of cross-sectional area of the pin brackets fabricated with the precut design 1 and 2 & 3.

The mechanical test results compared the maximum load, onset failure load, and displacement at failure for each pin bracket with different precut designs. The maximum load represents the highest load experienced by the pin bracket during the test. While some pin brackets reached the maximum load and failed immediately, others demonstrated a gradual decrease in load due to crack propagation before experiencing complete failure. The pin brackets without any precut, that is only made with the recycled material, had an average maximum load of 10.5 kN. The pin brackets fabricated with precut design 1 had an average maximum load of 12.8 kN, which is 22% higher than the average maximum load of pin brackets fabricated only with the recycled material. The pin brackets with the precut design 2 had an average maximum load of 13.6 kN, which is 30% higher than the average maximum load of the recycled pin brackets. The pin brackets fabricated with precut design 3 had an average maximum load of 14.1 kN, which is 34% higher than the average maximum load of the recycled pin brackets without the precuts.

The onset failure load refers to the load at which the pin bracket begins to show signs of failure or damage. For the pin brackets made only with the recycled composite material, the onset failure load was 8.4 kN. The pin brackets made with the precut design 1 had the average onset failure load of 10.2 kN, indicating a 23% increase compared to the pin bracket without any precut. The pin brackets with the precut design 2 showed the average onset failure load of 11.3 kN, which is 35% higher than the recycled pin brackets. The pin brackets with the precut design 3 had the average onset failure load of 9.1 kN, which is 9% higher than the pin brackets without any precut. While the pin brackets fabricated with the precut design 1 and precut design 2 showed significant increases on onset failure load, the precut design 3 did not show a significant increase. The pin brackets fabricated with the precut design 3 showed large variation on the onset failure load. While two pin brackets out of three had an onset failure at low loads (5.5 kN and 7.5 kN), one pin bracket had highest onset failure load among all the pin brackets tested (14.3 kN).

The pin brackets fabricated with different precut designs yielded various displacement at failure values. The pin brackets without the precut had the average displacement at failure of 1.58 mm. The pin bracket made with the precut design 1 had the average displacement at failure of 1.42 mm, which was 10% lower than the recycled pin brackets value. The pin bracket fabricated with the precut design 2 and 3 showed higher average displacement at failure values, 2.11 mm (33.5% higher than recycled material) and 2.48 mm (56.7% higher), respectively. The load-displacement plot of the pin bracket mechanical testing showed that the pin bracket without the precuts had two or three major failures before the complete failure of the pin brackets. The pin brackets with the precut design 1 tended to have a single complete failure, while the pin brackets made with the precut design 2 and 3 had numerous minor load drops before the complete failure.

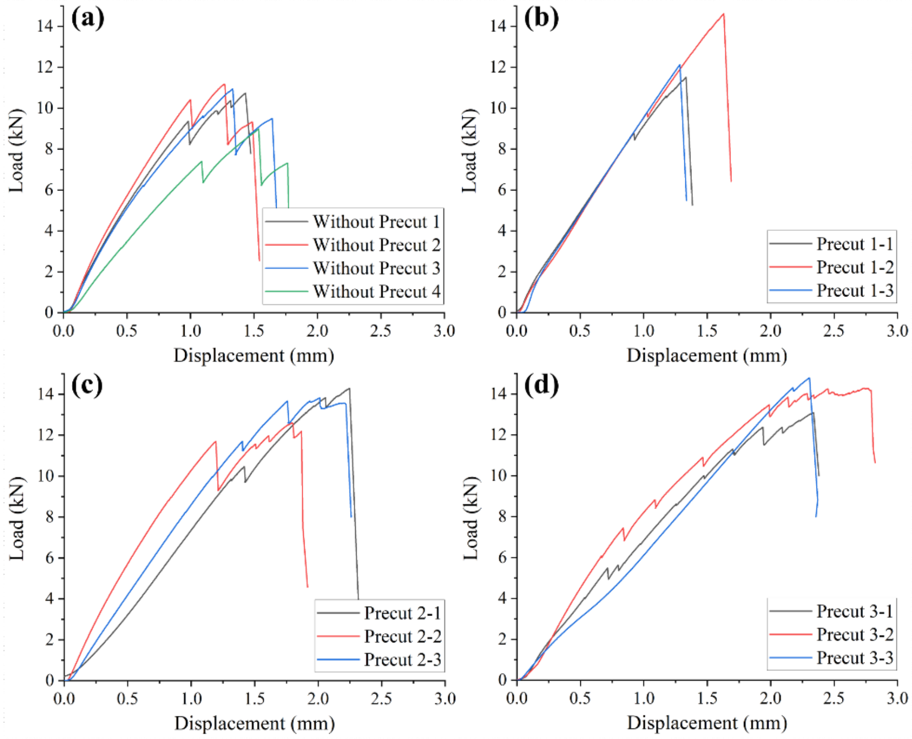

Figure 9: Load-displacement plot during the mechanical testing of the pin bracket (a) without precut, (b) with the precut design 1, (c) with the precut design 2, and (d) with the precut design 3.

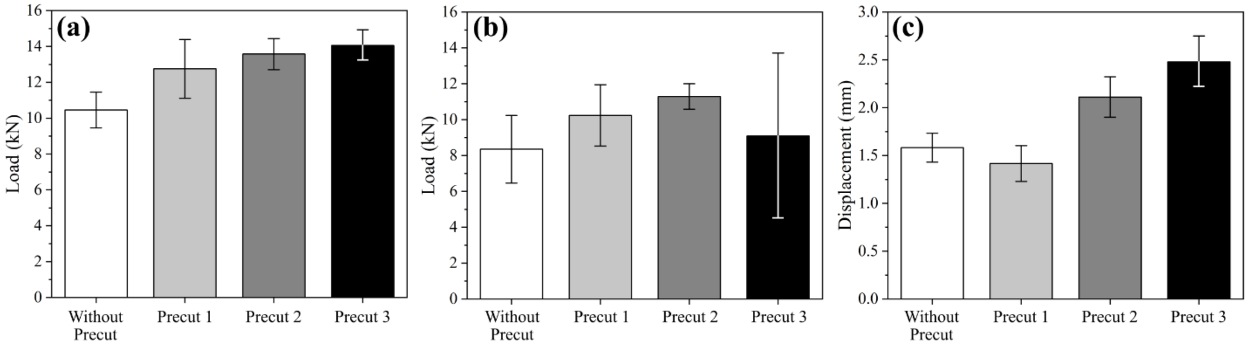

Figure 10: Average (a) maximum load, (b) onset failure load, and (c) displacement at failure of the pin brackets fabricated without precut and with the precut design 1, 2, and 3.

DIC analysis was conducted to observe local strain changes and the failure behavior of the pin brackets. The pin brackets without precuts showed significant strain changes, particularly in the upper portion of the pin hole during the test. The strain did not show a distinct pattern, but the cracks occurred in the upper region of the pin hole toward the load was applied. The failed pin bracket fabricated without precut and the DIC analysis are shown in Figure 11(a). All pin brackets made only with the recycled composite material without precuts failed in the same way.

The pin brackets fabricated with the precut design 1 initially experienced strain changes at the flange where the ear and base connected. During testing, a drastic strain change occurred at the bottom of the ear region, where the recycled composite material was filled. The strain change in this region gradually increased and led to failure. When one side failed at the bottom of the ear region, the pin tilted, and the strain on the opposite side at the bottom of the ear was relieved. Eventually, the angled pin failed the ear pin hole region of the opposite side ear. The failed pin bracket fabricated with the precut design 1 and the DIC analysis are shown in Figure 11(b). All pin brackets fabricated with the precut design 1 had the same failure behavior.

For the pin brackets with the precut design 2, the failure occurred at the flange where the ear and base were connected. The failure in the pin brackets with the precut design 2 did not happen suddenly like in the precut design 1. Instead, it occurred gradually as the ear was slowly pulled out from the base through the slots. Similar to the pin brackets with the precut design 1, when one side failed at the ear-base connection region, the pin tilted, and the ear on the opposite side failed.

The pin brackets with the precut design 3 had a similar failure behavior to those with the precut design 2. However, the strain changes in the ear region were less significant compared to the precut design 2 due to the greater amount of continuous fiber in the ear region. The strain changes at the flange occurred at a slower and more gradual pace compared to the precut design 2. Unlike the precut designs 1 and 2, the pin brackets with the precut design 3 experienced failures at the flange area for both ears.

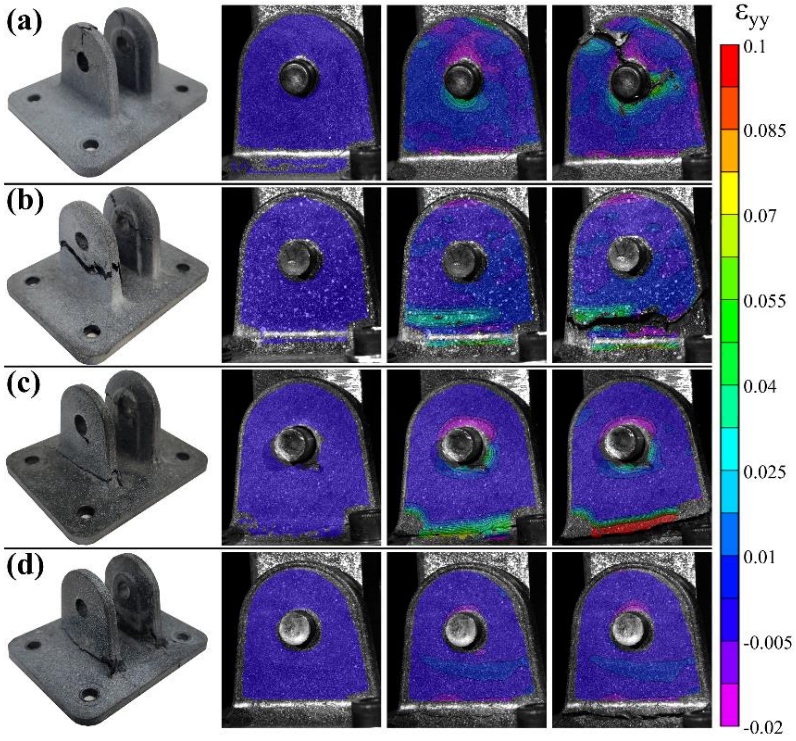

Figure 11: Images of the pin bracket after failure and local strain changes via DIC analysis for each design: (a) without precuts, (b) with the precut design 1, (c) with the precut design 2, and (d) with the precut design 3.

Discussion

The precut design 1 had a weight of 16.67 g which was approximately 53% of the total weight of the pin bracket. Integration of the precut design 1 resulted in an increase in the average maximum load, from 10.5 kN to 12.8 kN, increasing by 2.3 kN which is approximately 22% compared to the pin bracket without precuts. The precut design 2 had a weight of 19.37 g which represents that the 62% by weight of the pin bracket is continuous fiber. The average maximum load was 13.6 kN which was 3.1 kN (30%) higher than the pin bracket without precuts. The precut design 3 had a weight of 22.17 g which is 71% of the total weight of the pin bracket. The average maximum load increased by 3.6 kN (34%), reached to 14.1 kN, compared to the pin bracket without precuts. The test results showed a positive relationship between the amount of continuous fiber integrated through precuts inside of the pin brackets and the corresponding increase in maximum load. Performance enhancement-to-continuous fiber content ratio also can be calculated by dividing the increased maximum load value by weight of the continuous fiber precuts for each precut design. The performance enhancement-to-continuous fiber content ratio of the precut design 1, 2, and 3 was 0.137 kN/g, 0.161 kN/g, and 0.162 kN/g respectively. Although the results in this study showed a positive relationship between the amount of continuous fiber and both the average maximum load and the performance enhancement-to-continuous fiber content ratio, it may vary depending on the specific precut design. Therefore, depending on the application and conditions, the prioritization can be aiming to develop the precut design that yields the highest performance enhancement-to-continuous fiber content ratio, prioritizing maximum load capacity without considering of the weight of the continuous fiber, or a combination of both factors.

Through the innovative precut approach introduced in this paper, the integration of various continuous fiber precuts into mechanically recycled materials has demonstrated significant potential. This study contributes to promoting the recycling of EOL composite parts, improving the overall sustainability of composite materials, and providing valuable insights for the industry on effective ways to expand the application of recycled composite parts. However, this approach has several considerations that need to be addressed for industrial application. Firstly, not all EOL composite parts are flat. Therefore, a flattening process may be necessary. While the flattening process may be simple for parts with simple curve shapes, there are also parts where flattening poses challenges. Therefore, careful selection of composite parts suitable for precuts is required. Also, considering the varying thicknesses of the EOL parts, a strategic planning for precut design and incorporation is required. Moreover, continuous fiber precut integration approach does not always offer the optimal utilization of continuous fibers inside of the recycled composite part. Although efforts were made to design the most suitable precuts for the part, achieving the ideal fiber orientation for the structure may not always be possible. Further research is necessary to explore more effective precut designs, strategic planning for precut processing from EOL composite part, and methods to achieve optimal fiber orientation for maximize the structural performance of the part through precuts.

Conclusion

In this study, an innovative method to enhance the structural performance of mechanically recycled composite materials by integrating continuous fiber-reinforced composite precuts was demonstrated. Through the strategic design of various precut to reinforce critical load-bearing areas of the composite parts, significant improvements on structural performance were achieved. Three different precut designs were developed and their performance were evaluated by comparing them to the pin bracket without any precut. The microscopic image of the pin brackets indicated the location and shape of the continuous fiber in the pin brackets when they were fabricated with the different precut designs.

The pin brackets featuring various precut designs showed notable structural enhancements. The precut design 1, which incorporated separate precuts for the ear and base, showed a 22%

increase in maximum load compared to the pin bracket without any precuts. For the precut designs 2 and 3, the base precut featured slots for the insertion and interlocking of the ear precuts. In Precut Design 3, two ear precuts were used in each ear to increase the amount of continuous fiber within the pin bracket. As a result, the maximum load of the pin brackets increased by 30% and 34% with Precut Designs 2 and 3 respectively. Also, not only the maximum load, but the onset failure load and displacement at failure also increased. The precuts inside of the pin brackets also affected the failure behavior of the pin brackets. Without any precuts, the pin bracket failed at the top of the pin hole in the direction of the applied load due to the localized stress in that specific region. The integrated ear precuts reinforced the top of the pin hole and transferred the load to the ear and base. Overall, the precuts integrated in the pin brackets enhanced the load-bearing capacity of the pin bracket.

The integration of continuous fiber precuts to enhance the structural performance of the recycled composite part showed a promising approach to overcome the limitations associated with mechanical recycling of composite materials. By strategically designing precuts, it is possible to maximize the utilization of continuous fiber within EOL composite parts and redirect their application towards continuous fiber precuts for recycled composite part, rather than shredding them all to short fibers. This study contributes to the advancement of sustainable fiber-reinforced composite materials and introduces an innovative approach to recycling composite materials to establish an environmentally friendly and economically sustainable loop.

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