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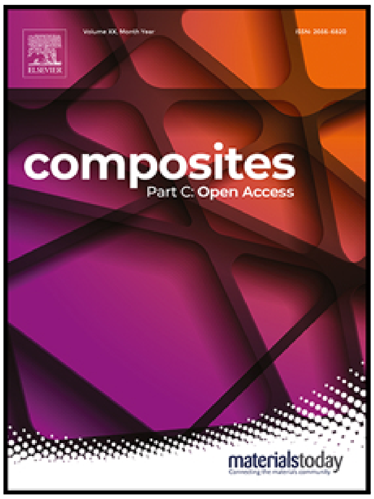

Experimental study on a new generation of recycled composite laminates

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Highlights

- Assembling uncured patches of scrap prepreg is a sustainable way of producing laminates with still relevant mechanical properties and recover useful material;
- The way the patched laminate is assembled affects stiffness rather than strength of the new laminate;
- Patch size and aspect ratio have negligible effect within the investigated range while a partial overlap between patches brings higher mechanical properties;
- Fracture mode, under investigated bending stress, is dominated by fiber breakage rather than delamination.

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Experimental study on a new generation of recycled composite laminates

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Abstract

Composite manufacturing processes generate a significant amount of waste due to the raw material being supplied in sheet form and cut-outs. The unused scraps of prepreg are typically discarded, leading to the disposal of up to 35% of the purchased material, accompanied by economic losses and negative environmental impacts. The authors propose collecting these scraps, cutting them into smaller, regular patches, and assembling them into a new, patched prepreg sheet. This study presents an experimental investigation into the mechanical properties of such patched material, assembled using two different architectures and three patch geometries. Five different configurations are designed, manufactured, and tested, with results compared to samples made from the original unpatched material through four-point bending tests. When patches are assembled in a regular geometry, the new material possesses around 50% and 90% of the original strength and stiffness respectively, demonstrating potential for use in load-bearing applications. The methods of assembling the patches following a regular pattern also resulted in significantly better properties than a random deposition, which despite its lower cost to implement does not retain relevant mechanical characteristics. Of the two arranged investigated architectures, the one being more complex to manufacture shows 9% and 5% higher stiffness and strength, respectively, than the simpler one. Fracture analysis shows that failure mainly takes place in between of a patch, rather than the superposition areas.

Keywords: composite material, scrapped prepreg, recycled material, mechanical testing, fracture

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1. Introduction

In the last decades industry has widely increased the use of composite materials, in fields such as aerospace, automotive, wind energy, sports and many more [1]–[4]. For example, the use of carbon fiber-reinforced plastics (CFRPs) has increased from 6% to more than 50% in today's aircraft from the 90s [5], while it is estimated that more than a third of the million wind turbines installed around the world use composite blades [6]: this trend does not seem to have peaked yet, as the market of composite materials is expected to double in the next eight years[2]. Such extensive use of composites produces significant waste in different forms throughout the entire production cycle [7], ranging from uncured prepreg scraps to end-of-life products. Various waste management strategies exist, with prevention being the most favoured and disposal being the least preferred. Reuse and recycling fall in between, providing sustainable solutions for waste management[3]. This paper explores the recovery of uncured thermosetting carbon-fiber composites, an area still open for innovation. Typically, ply cutter scraps, varying between 25% and 50% of the purchased material, are disposed of, despite being potentially useful [8], [9]. These scraps often end up in landfills or incinerators, leading to significant economic losses for manufacturers and contributing to environmental pollution on multiple levels [10]. Consequently, developing a strategy to preserve valuable material, lessen environmental impact, and reclaim some of its original value is crucial. Spini et al. [11] provide an extensive review of recycling methods for thermoset composite materials. These methods include, only to mention a few, mechanical recycling [12], [13], thermal recycling processes such as pyrolysis [14]–[16], and chemical recycling techniques including solvolysis and other treatments [17]–[19].

Researchers here propose a technique to process directly uncured prepreg waste, simplifying the recycling process, without going through thermal or chemical treatments that would result in a source of pollution. A new recycled composite material with still considerable mechanical properties will be designed, suitable for a number of load-bearing applications.

The largest amount of studies dealing with recovery of unused prepreg follows the approach of Discontinuous Fiber Composites (DFCs), obtained by chopping cut-outs or end-of-rolls in regular smaller patches of material, to be then assembled and used in different ways [20]–[23]. Among those of interest for this present work, Nilakantan et al. [8] describe different intermediate products that can be obtained from unused uncured rolls and scraps such as Loose Chip Form (LCF) and Reused Scrap Roll Form (RSRF). LCF are small rectangular chips that can be obtained from scraps through an automated process: by randomly laying them down on a tool plate, and consolidating at certain temperature and pressure, a recycled roll, the RSRF, is

[2] www.precedenceresearch.com/composites-market
[3] https://environment.ec.europa.eu/topics/waste-and-recycling/waste-frameworkdirective.en

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produced and employed as traditional prepregs. A similar approach has also been followed by Jin et al. [24], who exploited rectangular patches of different aspect ratios randomly oriented to create recycled panels with quasi-isotropic mechanical properties. Their results show that regular internal structures result in better control of both thickness and flatness of the panel and lower amount of internal voids, therefore leading to better mechanical properties. Similarly, We et al. [9] developed a method with random patches deposition, taking into consideration several parameters such as size of the patches, orientation of the fibers, temperature, pressure and time of the compression moulding, and advancement of the resin cure grade. However, such random deposition approaches might generate partial undesired overlaps between patches that can lead to a reduction in mechanical properties: Bao et al. [25] propose to place the randomly-deposited patches inside a water dispersion device, where ultrasonic vibrations allow them to be arranged homogeneously before curing. The main issue with such approaches is that a random deposition leads to composites with much lower properties than the original material, making them unsuitable for many load-bearing applications and hindering their use.

Based on the existing literature, the approach proposed in this paper consists in producing a new composite laminate starting from small regular patches tidily arranged, investigating not only the effect of the shape/size of the patches, but also different architectures, to exploit the best possible outcome from the new recycled material, and widen its potential fields of application.

A similar approach has been deeply investigated in the past by Kravchenko et al. [26]–[28], using regular patches cut up from UD tapes. Their work clearly shows that a random distribution, despite its economic and technical simplicity, leads to much poorer laminates compared to those where the patches are arranged in an ordinated manner. They experimentally and numerically investigated the tensile properties and fracture modes of coupons made from UD material; this paper, instead, focuses on the flexural behaviour of woven patches. Nakagawa et al. [29] also studied the flexural properties of discontinuous fiber composites obtained by chopping the material into rectangular elements randomly oriented, considering the effect of patch sizes and panel thickness. Both Flexural Modulus and Strength increase with patch length, and thus with fiber length. The thickness effect, however, depends on size. A controlled deposition of prepreg scraps was also proposed by Bandaru et al. [30], using laser assisted tape placement. Different sample configurations with different gaps and overlaps were manufactured and tested under various conditions, providing useful information for manufacturing purpose.

In the present study, samples with two different architectures and different patch sizes and shapes have been manufactured and tested under 4-point bending (4PB) conditions to compare properties and highlight features of interest. The aim is to investigate the behaviour of the new material and identify strategies to maximize mechanical properties to develop a material suitable for the lamination of load-bearing

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components. In this paper, architectures, samples and testing methods are presented in Section 2; mechanical results are exposed in Section 3; micrographs and ANOVA have been used for the discussion presented in Section 4; Section 5 draws the conclusions alongside with economic and feasibility considerations.

2. Materials and Methods

The material used in this work is the prepeg HexPly M49/42%/200T2X2/ CHS-3K[4], purchased at FiberTech (Marnate, Italy), twill 2x2, high strength carbon fabric with a nominal fiber density of 1.78 g/cm3, nominal areal weight of 200 g/m2, and cured thickness of 0.24 mm. The material has been used within its shelf life, and flexural strength and modulus have been measured with 4PB tests to be equal to 1036 MPa and 63.7 GPa, respectively. Samples have been manufactured by assembling patches cut out using an automatic cutting plotter and laid down as presented below The cutting process was carried out using the Lectra Vector VT-TT-FX-72 automatic cutting machine available at the Politecnico's lab. A prepreg sheet, with backing paper on one side only, was laid down for processing; the machine cut the sheet into regular patches, which were then collected in a box and stored in the fridge. Stacking was performed manually, as well as the removal of the remaining backing.

2.1. Laminate architectures and equivalent lamina

The patches have been manually laid down according to two different architectures, as shown in Figure 1:

1. The so-called "No-Overlap" (NO-OV) architecture is made as follows:
    - a first layer of patches is deposited with each unit side by side with no gaps between them until the whole surface is covered;
    - a second layer is laid on top of the first, shifted of half the size of the patch in both plane directions, making sure to avoid gaps between patches;
    - layers are then again stacked one on top of the other, switching the first patch of half the size in both directions, until the desired thickness has been reached.
2. The so-called "Overlap" architecture (OV), has been built as follows:
    - a first row of patches is laid down such that each subsequent patch overlaps the previous one by half of its length;
    - other rows are assembled with the same technique and subsequently laid

[4] http://info.lindberg-lund.no/produktblad/Norge/4-6%20TD/HEX-M49CT-TD.pdf

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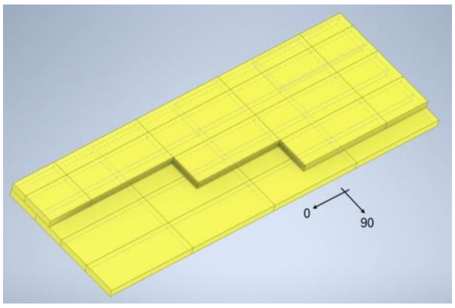
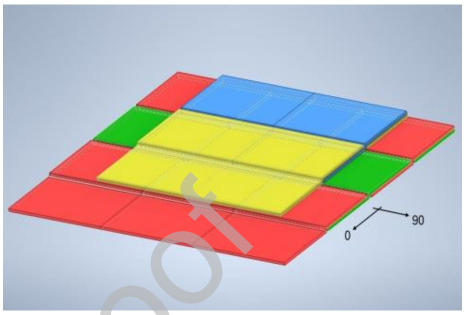
down one next to the other making sure to leave no gaps between them;

- a second layer, made in the same way as the first one, is laid on top of the first one, shifted by half a patches in both directions until the whole surface is covered again;
- the same operations are repeated until the necessary thickness is reached.



(a) NO-OV architecture.



(b) OV architecture.

Figure 1: Architectural layouts.

A closer look at the two architectures is provided by the two micrographs in Figure 2 and Figure 3.

Figure 2: Side-view of the NO-OV architecture.

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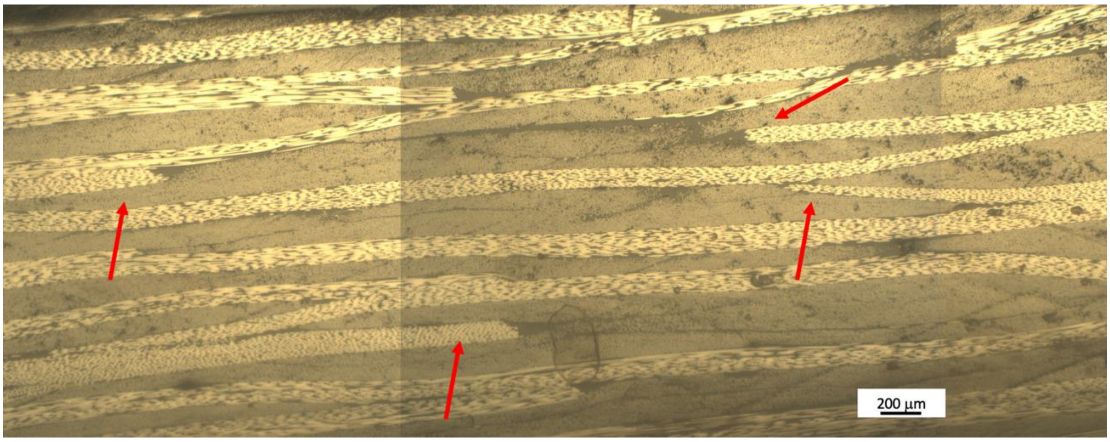

Figure 3: Side-view of the OV architecture.

In Figure 2 the red circles highlight resin pockets formed in those area where two patches meet, that is here called "butt-joint". The two patches are connected via the resin, introducing plane discontinuities. In Figure 3, instead, the arrows point the ends of patches which, in the OV architecture, do not face other patches.

Eventually, an additional architecture has been manufactured, made of patches randomly distributed in a Sheet Moulding Compound (SMC)-like type of process.

The final goal of the work is to develop an equivalent lamina made out of scraps to be used for lamination like traditional composite sheets. The equivalent lamina's thickness will depend on the architecture configuration: for this study it equals 2 and 4 times the thickness of the base laminate for the NO-OV and OV architectures, respectively. The amount of overlap directly affects the thickness of the equivalent lamina, and in order to keep it as low as possible, 50% overlap between patches has been chosen. From a practical point of view, a reduced thickness is preferable to facilitate both storage and layup. The overlapping length has been designed to ensure that the overlapping area would not be the weakest zone during tensile loads, according to the following Equation 1:

$$\begin{cases} \frac{N}{t_h} = UTS \\ \frac{3}{2} \cdot \frac{N}{l} \leq SS \end{cases} \rightarrow l \geq \frac{3}{2} \cdot \frac{UTS}{SS} \cdot t_h \qquad (1)$$

where t_h is the thickness of the original material, UTS is the Ultimate Tensile Strength of the same, SS is the Shear Strength of the resin, N the tensile load per unit width and l the minimum superposition length. Equation 1 is derived from a system of two equations: the first one is related to the tensile load experienced by the layers when the sample is loaded in bending, while the second to the shear stress experienced in the superposition area between patches, still when loaded in bending condition. The two

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equations combined provide the minimum superposition length that ensures that the failure would take place in the patch due to fiber breakage rather than delamination in the superposition area. The material here adopted would require l longer than 5 mm.

The two different architectures have been designed to investigate optimal patch arrangement strategies, aiming to enhance the overall performance of the final component. Among the various proposed designs, the “NO-OV” and “OV” configurations described above have been selected for testing. The "NO-OV" architecture represents the most straightforward approach: patches are arranged side by side in the two dimensions of the plane. This configuration can be easily automated using a simple pick-and-place actuator mounted on a robot. The backing tape can be removed after each layer is completed. It is crucial to manufacture patches as uniformly as possible to avoid unwanted overlapping and irregular displacements, which could result in large resin pockets and reduced properties. In contrast, the "OV" architecture has been designed to create a bulkier and more entangled structure, which is expected to offer superior properties, particularly in terms of strength. The partial overlap between patches, ensures a more robust process that can better accommodate misalignments and reduce variability. However, this architecture requires more time for assembly because the backing tape must be removed after each patch is laid down to allow the next one to adhere. From practical perspective, manufacturing samples with the "OV" architecture is feasible but takes longer to produce the same sample compared to the "NO-OV" configuration. Another important consideration relates to the minimum allowable thickness mentioned earlier: both architectures can be used to produce an equivalent lamina, which can be rolled and stored like any regular prepreg sheet. However, the "NO-OV" architecture will result in a thinner lamina, which directly impacts the allowable curvature the laminae can accommodate without detaching.

2.2. Panel prototypes: patch shapes and sizes

Regular patch shapes have been chosen: rectangles and squares. Patches with different dimensions have also been manufactured, to evaluate the effect of size ratio and patch surface. Selected shapes with relative dimensions are shown below:

a) rectangular patches, 60 mm long and 20 mm wide;

b) squared patches, 34 mm side length;

c) squared patches, 50 mm side length.

Patches a) and b) share the same surface area but differ on the shape ratio, while patches b) and c) share the shape ratio with different surface areas: patches c) are slightly more than double the surface of patches b), thus having longer fibers. The patches have been used to manufacture five panels, as shown in Figure 4:

1. panel *p1*: NO-OV architecture made of patches a);

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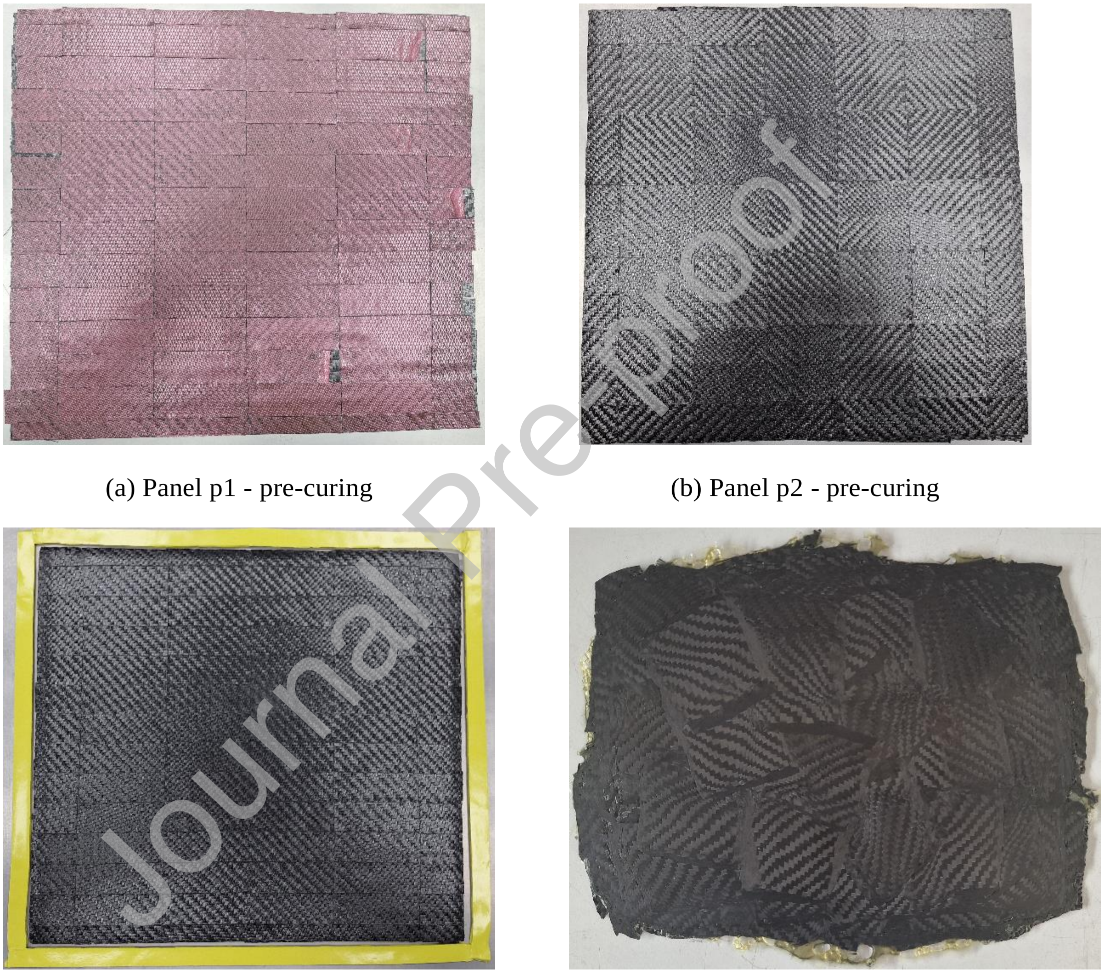
2. panel *p2*: NO-OV architecture made of patches b);
3. panel *p3*: NO-OV architecture made of patches c);
4. panel *p4*: OV architecture made of patches c);
5. panel *p5*: patches c) randomly arranged.

Additionally, a last panel, p6, has been made of long continuous fibers for comparison purposes.



(a) Panel p1 - pre-curing (b) Panel p2 - pre-curing

(c) Panel p4 - pre-curing (d) Panel p5 - post-curing

Figure 4: Details of manufactured panels.

The smaller the patches, the higher the amount of recovered value, but, at the same time, the higher the manufacturing cost. The larger the patches, the closer the properties of the recycled material are to that of the original, but at the same time, less material can be recovered. The chosen sizes of the patches have been evaluated as a suitable trade-off between such aspects, aiming to define an economically sustainable process.

2.3. *Samples and testing*

In order to investigate the properties of the panels, it has been chosen to run 4PB tests, following the procedure B of the international standard ATSM D7264, [31], aiming at determining Flexural Strength and Modulus of the newly produced architectures. According to the ASTM, specimens have been manufactured with standard 13 mm width and 4 mm thick; support span-to-thickness ratio is 32, which led to a support span of 128 mm and specimens' length of 155 mm.

Samples orientation, possibly relevant for panels p1 and p4, has been defined as follows: for panel p1, direction "0" aligns with the longer side of the patch, "90" corresponds to the shorter one; for panel p4, instead, direction "0" coincides with the overlapping, "90" is its perpendicular. There is no need to define directions for the other panels as p2 and p3 are built with squared patches, and p5 is expected to be quasi-isotropic in the plane.

Tests have been run at Politecnico di Milano with an MTS Alliance RT100 testing machine, equipped with an MTS load cell model MTS 4501058 with 100 kN of maximum load, and a deflectometer MTS 632.06H-30 opt 003&005 under displacement control conditions at 5 mm/min: researchers' past experience proved that raising the test speed from the recommended 1 mm/min to the 5 mm/min would not affect the results, and therefore this latter has been used.

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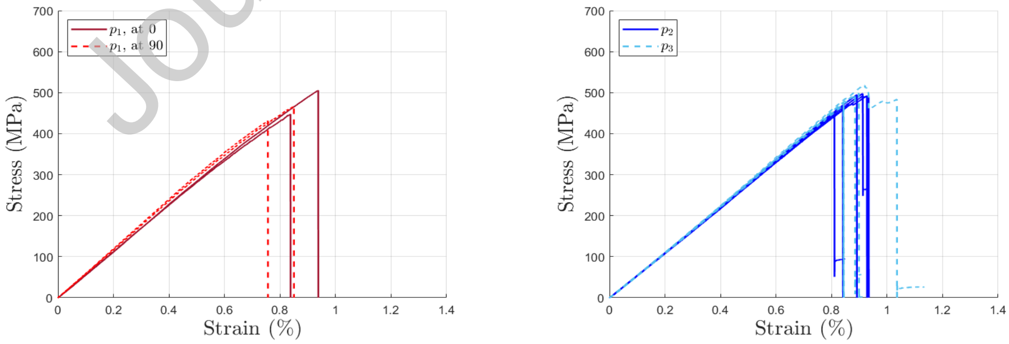
3. Experimental results and failure analysis

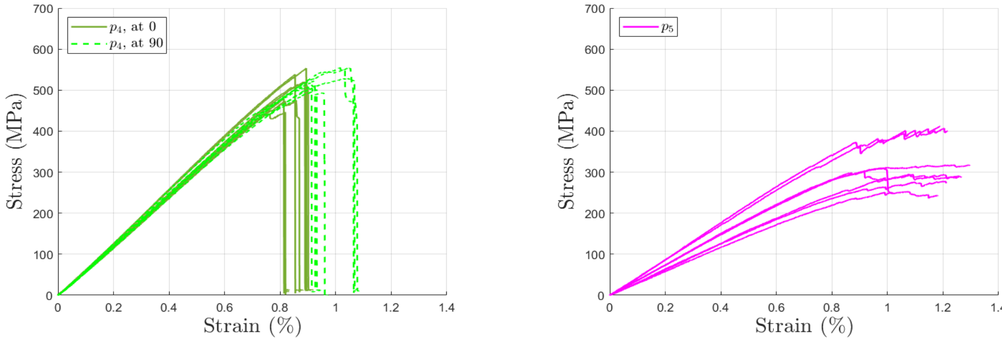
3.1. *Mechanical testing*

Stress-strain curves from 4PB tests are presented in Figure 5.



(a) Panel *p1*

(b) Panels *p2* and *p3*



(c) Panel *p4*   (d) Panel *p5*

Figure 5: 4PB stress-strain curves.

From Figure 5 the effect of the orientation within each configuration can be highlighted, while a broader statistical analysis is presented in the next section. Figure 5a shows the effect of the orientation for the NO-OV architecture with rectangular patches. The effect appears to be negligible in terms of stiffness, while a deeper investigation is required to better determine the effect on maximum stress, which, at this stage, appears unclear. Figure 5b aims to show the effect of patch surface on the mechanical properties of the NO-OV laminates with squared patches. It is clear that, in the investigated range, the responses of the samples are identical in terms of both stiffness and strength. Figure 5c shows the results from the OV architecture: higher stiffness is registered compared to the NO-OV counterparts. No differences seem to arise from the two directions, despite a different number and type of discontinuities between the two. Eventually, Figure 5d shows the curves from the panel produced with random patches deposition: a significant worsening of the performances is clearly detected. Not only much lower stiffness and strength are registered, but also a much larger dispersion between samples is clearly highlighted. As presumed, an uncontrolled distribution of fiber volumes and resin voids makes the mechanical behaviour of the product variable and unpredictable, greatly influencing its maximum resistance.

Flexural Strength and Modulus from different panels are shown and can be compared in Figure 6 and Table 1.

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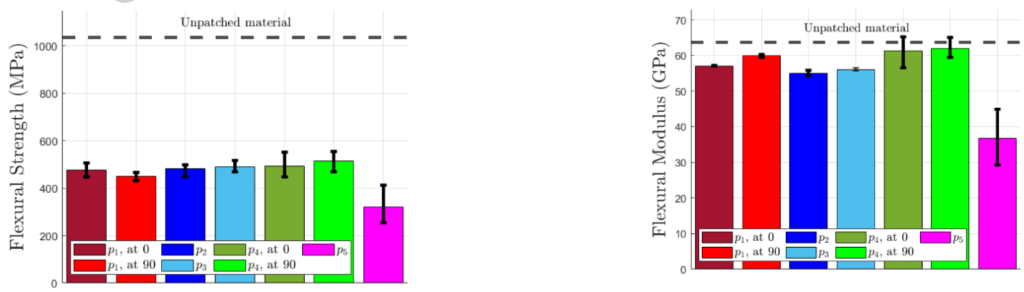

(a) Flexural Strength   (b) Flexural Modulus

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Figure 6: 4PB average results.

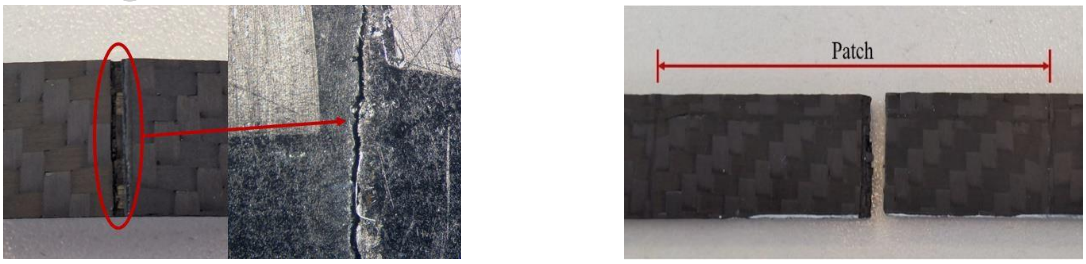
Table 1: Average Flexural Modulus and Strength.

	Modulus (GPa)		Strength (MPa)	
	μ	COV %	μ	COV %
p1	58.5	2.8	463	6.9
p2	55.0	1.1	492	4.2
p3	56.0	0.6	491	4.0
p4	61.6	3.7	504	8.2
p5	36.8	15.3	322	17.9

Before dwelling into a discussion of the results (Section 4), it is worth highlighting the low values of the variances along the whole experimental campaign for both the organised architectures. Despite a hand-lay-up, which proved to be quite challenging, even tedious perhaps, the patches have been laid down with precision in both the configurations, proving the feasibility of the approach here pursued. Projecting the idea at an industrial level, where the patches will be arranged automatically, possibly with a pick-and-place robot, the COVs are expected to shrink even further.

3.2. *Fracture analysis*

In this section, a detailed analysis of failure modes is presented. As expected, the weakest zones, where damages and fractures initiate, are the discontinuities at butt-joints between patches. To better analyse how the samples fail, visual inspections and micrographs are performed on tested coupons, keeping the organised (”NO-OV” and ”OV”) and random architectures separated, as very different behaviours are expected to be identified. Samples with organised architectures all fail on the tense side: 83% showing a crack initiation along the discontinuity between two patches of the bottom layer, clearly indicating where the crack started propagating from, and 17% showing fracture crossing around the middle of such patch in the bottom layer, as shown in Figure 7.



(a) Fracture along a butt-joint (b) Fracture in the middle of a patch

Figure 7: Different types of crack initiations.

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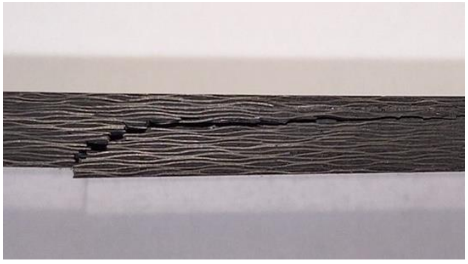
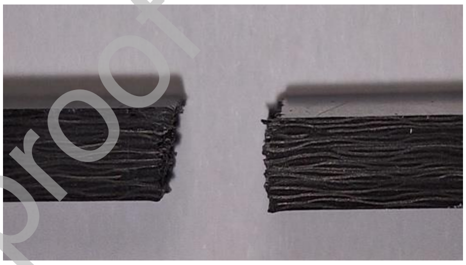
In this second scenario it is believed that the crack initiated at the second- bottom layer, in correspondence of a butt-joint between two patches, and propagated downwards breaking the fibers of the underlying patch and upwards towards the rest of the sample. This is confirmed from the fact that the fracture on the outer skin of the sample is located in correspondence of the discontinuity in the inner layer. After the crack initiates, two different propagation behaviours have been observed:

a) partial propagation (PP): the crack propagates upwards, breaking fibers layer after layer, until a large delamination occurs (Figure 8a);

b) full propagation (FP): the fracture propagates through the whole thickness splitting the sample in two in a straight line (Figure 8b).



(a) Partial propagation (PP)



(b) Full propagation (FP)

Figure 8: Different types of crack propagation.

Those samples showing a PP, 23% of the total, see the crack propagating straight for few plies breaking alternatively butt-joints and patches before following an interlaminar path causing a long delamination. This path has been confirmed when tested samples have been investigated with the microscope. Figure 9 shows the detail of a failed NO-OV samples.

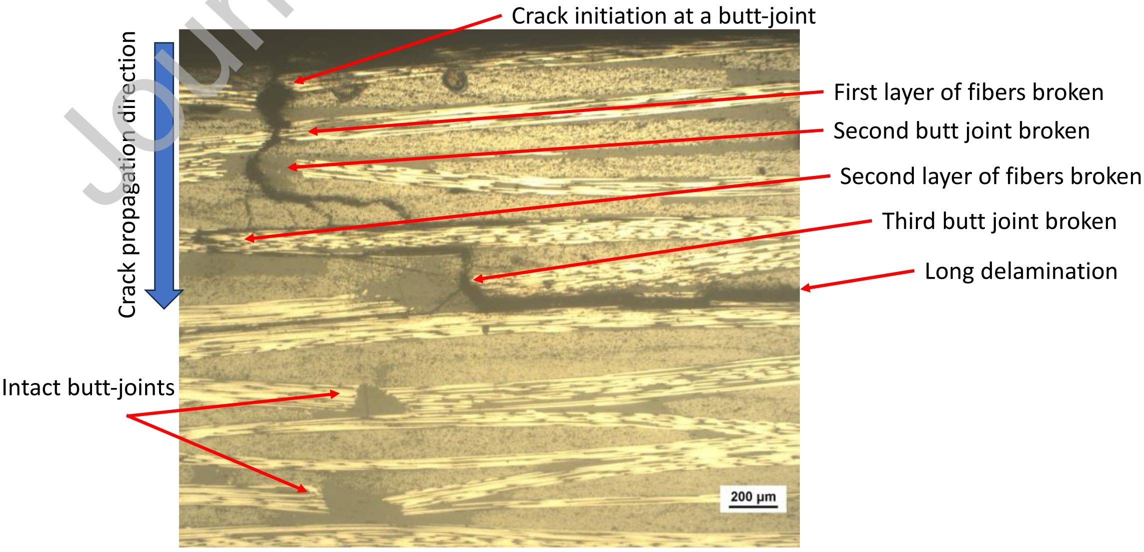


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Figure 9: Crack path in a NO-OV sample.

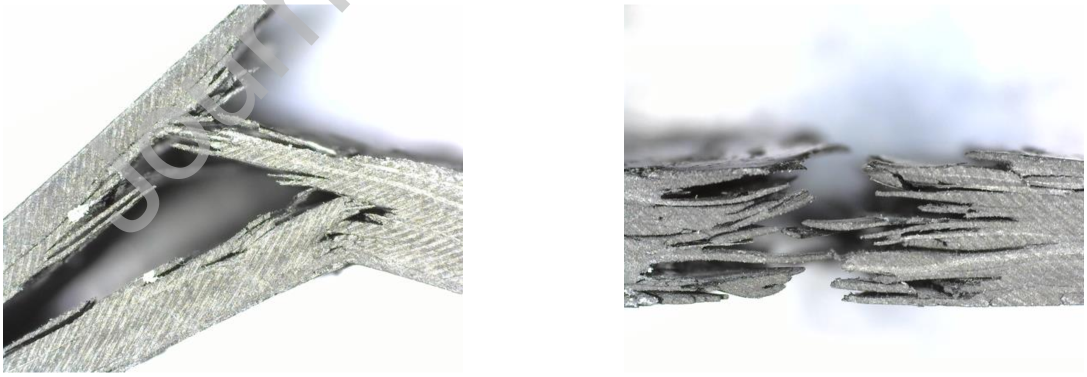
Figure 9 shows that the crack initiates on the outer side of the sample (the one in tension during bending), breaks five layers before reaching a new discontinuity, from which the delamination is triggered. The other 77% of samples, those with FP, are split in two, and the crack propagates vertically breaking all the plies with no sign of delaminations, still starting at an outer butt-joint.

Table 2 summarises the different failure modes along with their frequency of occurrence.

Table 2: Propagation modes and frequencies of occurrence for panels p1 to p4.

	p1-0	**p1-90**	**p2**	**p3**	**p4-0**	**p4-90**	**NO-OV**	**OV**
PP	0%	0%	67%	100%	0%	23%	45%	12%
TP	100%	100%	33%	0%	100%	77%	55%	88%

In the case of the random panel *p5*, more complex failure modes were observed due to the non-homogeneous distribution of the constituents, along with the presence of voids, that also contributed to the higher variability in mechanical properties mentioned above. However, much like their ordinate counterparts, also random panels failed from the side in tension, with several internal delaminations likely arising from the high density of random internal weak points. In terms of fracture propagation, the specimens exhibited both partial and complete propagation, characterized by more jagged edges and violent, irregular fracture patterns as depicted in Figure 10.



(a) Failure with delaminations (b) Detail of fiber breakage

Figure 10: Failure modes from random panel p6.

4. Discussion

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The first important aspect to be highlighted is the comparison of the results with long-fiber, continuous samples (*p6*). In general tests show that patched samples exhibit, on average, slightly lower stiffness and approximately half the strength when compared with long-fiber samples, as presented in Table 3.

Table 3: Percentage drops in strength and stiffness with respect to the virgin material.

	p1	p2	p3	p4	p5
Strength	-55%	-52%	-53%	-51%	-69%
Stiffness	-8%	-14%	-12%	-3%	-42%

This general observation alone proves that patched samples retain enough good properties and that have the potential for use in load-bearing applications. The decrease is likely due to bending-twisting coupling caused by misalignment or overlap of the patches during the manufacturing process, as suggested by [5], and the number of resin pockets as also shown in Figure 2 and Figure 3. Regarding the two directions in the OV configuration, data in **Error! Reference source not found.** reveal that the overlap direction exhibits lower strength, likely due to the bending of fibers in direction 0, which occurs at the overlaps between patches, thereby compromising material integrity in those areas. Conversely, panel *p1* demonstrates enhanced strength at 0, where the fibers are longer compared to the ones in the other direction.

Before introducing a statistical analysis, it is worth mentioning that results from *p5* will be excluded, as those samples show much lower values for both strength and stiffness, and the configuration can be easily labelled as the worst and not worth discussing.

Regarding panels *p1* to *p4*, due to the small number of samples, the statistical analysis follows the Kruskal-Wallis [32] approach, which is more general than the standard ANOVA approach. However, the results have been also checked with those provided by the latter and deliver the same conclusion. Table 4 shows the Kruskal-Wallis (KW) ANOVA results for the samples tested here.

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Table 4: Kruskal-Wallis ANOVA results.

Stiffness		Strength	
χ^2	Prob>χ^2	χ^2	Prob>χ^2
23.2068044	$3.66 \cdot 10^{-5}$	5.6186996	0.132

Kruskal-Wallis (KW) tests were conducted by clustering the samples into four groups, each corresponding to one panel. A standard p-value threshold of 0.05 was used to determine statistical significance. The results revealed two distinct outcomes:

p-values of 0.132 and $3.66 \cdot 10^{-5}$ (denoted as "Prob > χ^2" in Table 4) were obtained for strength and stiffness, respectively. These results indicate that strength is almost unaffected by the different patch architectures, as the p-value for strength exceeds the significance threshold. Conversely, the p-value for stiffness falls well below the threshold, suggesting a strong influence of patch architecture on stiffness.

The literature offers limited studies on the strength of Discontinuous Fiber Composites (DFC) [29], [33]; however, those studies predominantly focus on samples made with significantly smaller patches and broader surface area ratios, which fall outside the range investigated in this study. The patch sizes considered here were chosen as a balanced compromise between maximizing recycled prepreg usage and minimizing the effort required to construct equivalent lamina. On the other hand, the observed stiffness differences prompted a Mann-Whitney U-test to further investigate whether sample pairs from different groups belong to the same population. The outcomes of this test are presented in Table 5.

Table 5: Mann-Whitney results.

	Mann-Whitney-U value	
Panel pairs	Stiffness	Strength
p1 – p2	0.0105	0.3938
p1 – p3	0.0143	0.1416
p1 – p4	0.0233	0.1082
p2 – p3	0.0176	0.3613
p2 – p4	0.0004	0.1048
p3 – p4	0.0013	0.1864

Being the all the MW-U values for stiffness way below the threshold 0.05, they clearly confirm that the architecture plays a significant role; on the contrary, the same values for strength are all above the threshold, confirming the non-effect of the architecture. Very few experimental campaigns have been found in literature, comparing the properties of patched laminates with those of the original material; among those few, Kravchenko et al. [27] axially tested UD patches, showing very similar stiffness reduction compared to the original long-fiber samples to that found here, but a much greater strength reduction, due to the significantly shorter superposition length of their patches. From the results it appears clearly that the adopted superposition length of the patches has proved successful, as the samples fail at discontinuities rather than for the lack of bonding between patches. This is also proved by the fiber breakage observed in failed samples, and also by the fact that the strengths measured for panels *p1* to *p3* are very similar, showing that an increase in superposition surface does not bring any additional benefit. Furthermore, even when the crack originates along a discontinuity, it propagates breaking fibers on the close

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layers before reaching a new discontinuity, as shown in **Error! Reference source not found.**Figure 9. From a practical point of view, the OVs show significant better properties than the NO-OVs but the minimum allowable thickness for the equivalent lamina is doubled, making it more difficult to use, especially around small radii of curvature.

Regarding fracture behaviour, rectangular-patch specimens (*p1*) at 90 present more crack initiations in correspondence of a butt-joint at the outer layer with respect to specimens at 0, probably due to a higher number of discontinuities in length. The opposite situation occurs for the OV architecture (*p4*) as it exhibits a greater number of discontinuities along direction at 0 due to overlapping. On the contrary, in both cases the propagation mode does not appear to be affected by the orientation, as all the samples fail with a TP. Going on with architectural layouts, a critical distinction between the two cases emerges in how the crack develops: the NO-OV experienced either PP or TP while the OV exhibited a TP behaviour only. This phenomenon is likely due to the reinforcing effect of the overlapping regions, which significantly enhance the resistance to delamination.

5. Conclusions

This study explores the feasibility of using uncured scraps of composite prepreg material to manufacture a new composite sheet with adequate mechanical properties for load-bearing applications. The scraps were processed into uniformly shaped geometries and strategically arranged to create an equivalent lamina suitable for conventional lay-up methods. Compared to the original, un-patched material, the newly formed composite exhibits approximately 90% of the original stiffness and 50% of the strength. Various patch shapes and sizes were considered, resulting in the development of two distinct architectures: one featuring simple juxtaposition of patches and the other incorporating overlaps between them. Multiple panels were fabricated, and four-point bending tests were conducted on standard samples. Results revealed that the architecture built up with overlaps demonstrated slightly superior mechanical performance, being, however, significantly more complex and time consuming to be built and with a thicker minimum allowable thickness. Failure mode analysis revealed that all specimens exhibited failure at the butt-joints on the tension side, with crack propagation alternating between fiber breakage and delaminations.

In conclusion, the technique presented in this paper processes and effectively recovers uncured prepreg waste, resulting in a new recycled composite material with load-bearing mechanical properties. A crucial aspect of the proposed methodology is its industrial feasibility and sustainability. The researchers envision that the proposed recycling method might be of interest for medium to large-sized enterprises, which can integrate the production of ready-to-use equivalent lamina into their existing manufacturing lines by adding an automated pick-and-place tool after the cutting phase. Large composite manufacturers, already equipped with automatic cutters for

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nesting prepreg materials, can use the same tool to cut unused material into regular patches, which can then be picked up and placed on a separate tray to produce equivalent lamina, to be rolled and stored like any other prepreg roll. In the present work authors performed the pick-and-place operation manually, and the very low dispersion of the experimental curves demonstrates the robustness of the process, which is expected to be even more reliable when executed by a robot, with far superior accuracy compared to a human operator.

The economic sustainability of reusing composite scrap primarily depends on the quantity of scrap generated. Assuming a raw material cost of €30/m^2 and an average waste rate of 30%, manufacturers lose €9 per square meter of purchased prepreg. A robotic arm with a payload of a few grams and an operational radius of 1.5 meters is estimated to cost €40,000. The break-even point would then be approximately 4,500 m^2 of purchased prepreg, equivalent to roughly 1.7 tons of material. Although this estimation is rough and does not take into account many factors, it offers a general perspective that, within a few years, even a medium-sized company could easily recover the investment by implementing the proposed solution.

In addition to the amount of recycled scrap, another relevant aspect from the economic point of view is the quality of the recycled material. The developed process enables the production of a new material with significant mechanical properties, making it suitable not only for secondary components but also for more demanding applications. The values obtained in the tests, with stiffness around 60 GPa and strength of about 500 MPa, are in line with those of many structural materials. Therefore, composite manufacturers could leverage these materials still for high-value applications.

Further studies are needed to evaluate the effectiveness of the proposed technique for manufacturing more complex artifacts and to assess the benefits and drawbacks of using the equivalent lamina in practical applications. Additionally, exploring new architectures or patch geometries could further optimize the final properties of the material.

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Data Availability statement

Data will be shared and made available upon request.

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Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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