A COMPARATIVE STUDY ON MANUFACTURING TECHNIQUES FOR PRODUCTION OF SUSTAINABLE RECYCLATE SANDWICH COMPOSITES

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ABSTRACT

The use of natural fibres as reinforcement in composites has drawn a lot of attention for producing sustainable semi-engineered applications. Although natural fibre composite has witnessed significant progress, the suitable processes for manufacturing recycled sandwich composite remains a major challenge. This paper aims to make a comparative study of sandwich composite panels produced by two manufacturing technique namely resin transfer moulding (RTM) and vacuum assisted resin infusion (VARI). Both RTM and VARI belong to the family of liquid composite moulding (LCM) processes, but the differences in the processing methods can have a significant impact on the final product. Additionally, in an effort to determine the implications of size on the mechanical performance, sandwich composite panels were also constructed using recycled materials in the sizes of ~4 mm and ~10 mm. Density measurements, flexural and shear test performance are used to compare the composites manufactured by these two processes. The results indicate that sandwich panels produced from resin transfer moulding with recyclate size 4mm have enhanced densities and high load energy absorption, flexural strength and shear strength. The findings demonstrate unequivocally that manufacturing processes and recyclate size have a significant impact on material performance.

1 INTRODUCTION

Fibre composite materials are increasingly being used in a wide variety of applications due to their superior strength to weight ratio. Although conventional materials (like synthetic fibres and polymers made from fossil fuels) have good mechanical properties, they have high environmental impacts and are challenging to recycle [1,2]. In order to replace conventional materials, natural fibres and bio-based polymers have gained popularity over the past few decades. However, the growing interest in natural fibres as an option of sustainable reinforcements necessitates overcoming the first barrier, which is composite manufacturing [3-6]. The most common manufacturing process of natural fibre reinforced composites are injection/extrusion moulding and compression moulding where the composites are commercially used in non-structural components that are typically small-sized, high-volume, and low cycle time [7,8] (for example, decking for the construction industry and interior panels for the automotive industry). Contrarily, LCM is especially well suited for (semi-)structural components made of textile reinforcements (consisting of aligned woven, braided, or knitted continuous yarns/tows) in thermoset matrices at high fibre contents. Beside the potential to create high-performance composites, there are further reasons why LCM processes are particularly well suited to natural fibre reinforcements. Low processing temperatures do avoid the thermal degradation of natural fibres. Furthermore, minimal fibre damage during composite processing do allow preserving high reinforcement length, alignment and resulting mechanical properties. The use of liquid resins with low viscosity enables good preform impregnation and relatively low-cost tooling [9,10]. Consequently, LCM has recently attracted a lot of interest in scientific research on structurally sound products using natural fibres in past decades. RTM and VARI are widely popular processes in LCM due to the minimum requirement of labour, good surface finish, desired process control, required dimensional tolerances and lower cost when compared to other processes.

RTM includes the mould filling phase where resin is injection into the mould cavity containing the preform and curing phase by applying temperature. The main advantage of the RTM process is that the product obtained has good surface finish, good dimensional tolerances, mass production capability and advanced automated processing [11]. However, the main obstacles of resin transfer moulding are the tooling costs, the relatively limited component dimensions and the quality of composite material, which is influenced by the resin flow (racetrack, void formation) during the mould filling phase. VARI uses open rigid moulds where the layers of fibrous materials are compacted under vacuum bagging. The advantages of VARI are cost effectiveness, low void content, the ability to manufacture complex parts and ability to produce composite structures with large dimensions [12]. However, the drawbacks of the VARI process include poor surface finish, low automation, and thickness variation in the resulting component. While the cavity height and the thickness are constant in the RTM process, the thickness in the VARI process can vary due to the flexibility of the vacuum bag.

In the recent years, sandwich composites have gained attractive attention due to their improved mechanical properties compared to monolitic composites. An effective structure for resisting bending and buckling loads is produced by the separation of the skins by the core, which increases the panel's moment of inertia [13,14]. Sandwich composites can be used in a variety of industries and applications, such as wind turbine blades in the energy sector, mobility (aircraft, rail and road vehicles), as well as in civil engineering (bridge decks), shipbuilding (sailboat hulls), and many more due to their cost effectiveness, lightweight design, durability, and manufacturing efficiency [15-21]. Numerous studies have examined sandwich composites made of conventional materials (such as synthetic fibre skins, foam cores and fossil-based polymer) with a focus on enhancing weight-specific mechanical properties. However, due to growing interest in reducing the environmental impact of structures (i.e., reducing environmental harm), the focus has shifted toward researching eco-friendly composites [22]. Besides, rigorous legislation like the EU's end-of-life (EoL) regulation for vehicles [23] and polymers [24], have increased the demand for eco-friendly structures. Due to present EoL treatment methods (such as landfill, incineration) are becoming more critical for environment. Recycling and reusing the composites after their life span become key toward promoting a circular economy, reduced waste and increased efficiency for specific composite applications. Eventually, incorporating the recycled composites into the sandwich structure will lead to improved structural performance that makes the sandwich composites less expensive, with greater properties.

Several studies have been reported on sandwich composite panels using varied synthetic/natural fibres or recycled materials in past decades [25-30]. While the effectiveness of these sandwich panels still depends on components (recyclates) and manufacturing processes. However, the concern in the manufacturing of sandwich composite panel using Recyclates is limited. This paper documents the challenges in manufacturing the bio-based sandwich composite panels using recyclates. Furthermore, significance of processes and recyclate size is well established by providing evidence on materials properties which are quantified by density and flexural properties.

2 MATERIALS AND METHODS

In this work the sandwich composite panels are manufactured with same materials, in order to make the RTM and VARI processes comparable. The reinforcement ply as Amplitex 5042 flax-fibre balance-woven fabric (twill weave 4/4) from Bcomp Ltd. Fribourg, Switzerland, is used as the skin/facesheet for sandwich panels which are measured at 270 mm x 270 mm (length and width). A bio-based epoxy system from bto -epoxy GmbH is used as the matrix. It consists of resin IR 78.31 with a bio-based content of 37.58% and IR 77.11, a conventional hardener. The core recycled material used in this work is a flax/epoxy composite sheet material using the beforementioned resin and reinforcement and which are mechanically recycled using shredder and mill. The recyclate is classified into desired recyclate sizes. For this work, recycled materials with an approximation of ~4 mm (R4) and ~10 mm (R10) length were produced to study the effect of recyclate size on the material properties. Moisture absorption behaviour is a drawback of natural fibre-reinforced polymer composites and affects the dimensional stability and mechanical properties of the composites. Thus, it is mandatory to address this issue and decrease the exposure to moisture. Due to the hydrophilic nature of natural fibres, the reinforcement plies (skin/facesheet) were dried in a conventional oven (Model FDL 115, Binder GmbH, Germany) at 120 °C for 30 minutes prior to the composite fabrication.

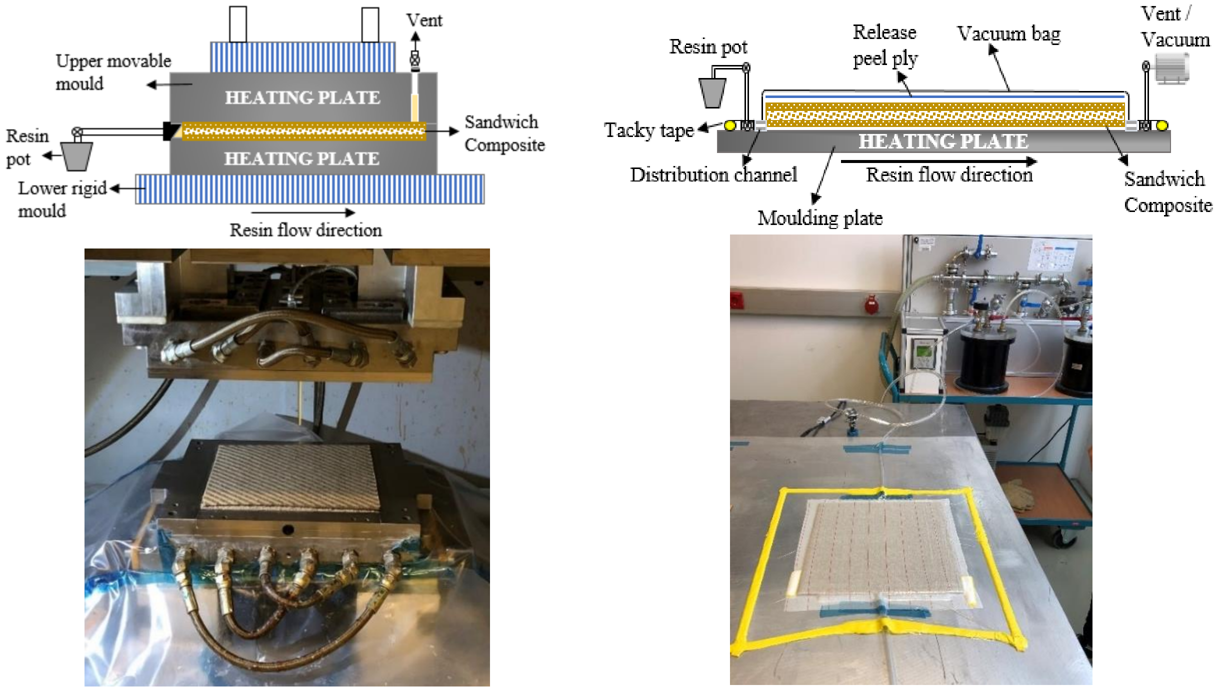
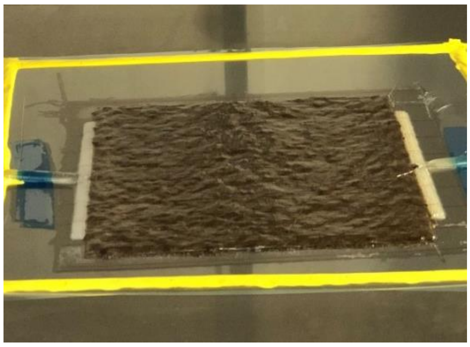


Figure 1: Schematic representation of RTM and VARI

The schematic setup of RTM and VARI are illustrated in figure 1. Since RTM is a closed mould process, a laboratory press (LZT-OK-80-SO, Langzauner GmbH, Austria) is used to form the composite panels where the upper rigid mould is closed on the lower rigid mould resulting in a 4 mm cavity. Nevertheless, VARI is an open mould process where a single sided rigid mould is used and vacuum bagging is applied to form the composite panel. The sandwich composite panels were fabricated using one flax fibre ply per skin and a core layer consisting of recyclates (i.e., R4 or R10). Various challenges arose during the process control for the production of the sandwich panels. In the RTM process, washing effects appear in the recyclate core layer due to the injection pressure, associated resin racetrack during infiltration and dry spots. Waviness and different thicknesses can be observed in the VARI process due to the random distribution of the recyclate fragments (shown in figure 2). To overcome these drawbacks of both RTM and VARI, appropriate procedures were developed. In RTM, the core recyclate materials between the skin should facilitate with uniform distribution across the mould cavity to eliminate the racetrack with associated dry spot and resin is injected at minimal constant pressure. Therefore, recyclate measuring mass of 150 g were used in RTM across the mould cavity ensuring evenly and consistent distribution. Aiming a process comparability, an exact amount of recyclates weighing 150 g were employed between the skin (flax fibre) in VARI, also. However, the wavy surface and varied thickness are eliminated by compacting the sandwich structure in a press (WPK 3500 S, Wickert GmbH, Germany) until a thickness of 4mm is reached. As a result, the sandwich construction is well-compacted and has a consistent surface which is laid on the open mould where the vacuum bagging is applied. Both RTM and VARI are carried out at mould tool temperature of 100°C. Resin and hardener mixture of a 100:25 (by weight) was mixed by hand at room temperature and degassed before injection/infusion. In RTM, resin mixture is injected at constant pressure of 3 bar, while in VARI the resin mixture is infused driven by the vacuum applied. Upon the injection/infusion completion the inlet and vent are clamped.

Following the curing cycle of 30 minutes and cooling the mould to room temperature, the composite panel are demoulded from the mould tool.

RTM Processed



VARI Processed

Figure 2: Challenges in manufacturing sandwich composite panel in RTM and VARI

The manufactured sandwich panels were assessed for their mechanical performance. In a recent paper [31] a detailed investigation of mechanical properties that includes the fibre volume fraction, density variance, tensile and flexural properties of virgin and sandwich composite panels is presented. However, in the interest of prolonging the work, for this paper in a further test series new samples were manufactured and the specimens were evaluated for density, flexural and shear properties. The flow of resin and homogeneity of panels in both RTM and VARI configurations were assessed by the density variance in accordance with DIN EN ISO 1183 [32] using the Archimedes immersion method. Distilled water was used as the liquid medium for the density measurement. Full plate thickness samples sized 25 mm x 25 mm were used. The densities are measured for at least five specimens per composite panels for in order to get statistically relevant results. Because of the uniform conditioning of all specimens utilizing the same approach and preparation guidelines, the density data are still meaningful for assessing the processes. The density of the composite was obtained using the following equation:

$$\rho = \frac{A}{A-B} * \rho_o \tag{1}$$

Where ρ is the density of composite, ρ_o is the density of distilled water (as a function of temperature), A is the weight of sample in air and B is the weight of sample in water. Further, the sandwich composites were examined for their flexural behaviour. Three-point flexural tests in accordance with DIN EN ISO 178 [33] were elaborated using a universal testing machine (Z250, Zwick Roell) with a load cell of 250 kN and a test speed of 2 mm/min. The thickness of the panels determines the specimen's dimensions in accordance with standards. However, the panels' thickness varies between 4.6 and 4.9 mm in VARI while it varies barely in RTM due to the fixed cavity of 4 mm. Thus, to ensure comparability all specimens were prepared in same size of 80x10 mm and positioned horizontally between the two supports with span length of 64 mm. The flexural strength and flexural modulus are calculated by the following equations respectively,

$$\sigma_f = \frac{3FL}{2bh^2} \tag{2}$$

$$E_f = \frac{L^3 m}{4bh^3} \tag{3}$$

Where, σ_f is the bending/flexural strength, F is the applied flexural load, h and b refer to the thickness and width of the flexural specimens, L is the support span length, E_f is the bending/flexural modulus and m is the slope of the tangent to the straight-line portion of the load deflection curve. Additionally, shear strength was measured based on three-point bending test using short beam shear specimen is suitable as a general method of evaluation for the shear properties in sandwich composites because of its simplicity [34]. Thus, the test was carried out according to the standard DIN EN ISO 14130 [35] on a Z250, Zwick Roell universal testing machine with a load cell of 250 kN and a test speed of 1 mm/min.

The samples were prepared accordingly with dimension of 50x25 mm and with span length of 20 mm. The shear strength is calculated by the given equations:

$$\tau = \frac{3F}{4bh} \quad (4)$$

Where, τ is the shear strength, F is the maximum load, h and b refer to the thickness and width of the specimens. An extensometer is used to measure the deformation induced during the flexural and short shear experiments where at least five specimens were tested from each configuration of composite panel.

3 RESULTS AND DISCUSSION

In this present work, the natural sandwich composite was examined with respect to manufacturing process and recyclates size. Figure 3 shows the distribution of densities of each configuration of sandwich panels with varied recyclates sizes and process in boxplots. From the plot, it is observed RTM sandwich panels with R4 and R10 recyclates have an average density of 1.25 and 1.22 g/cm^3 respectively; VARI sandwich panels with R4 and R10 recyclates have average densities of 1.20 and 1.19 g/cm^3, respectively. Due to the incorporation of resin between the spaces of the distributed recyclates and associated compaction behavior of sandwich composite structure, the panels produced by RTM have higher density than VARI. Additionally, the density reduction in VARI is evidence of relaxation of the sandwich's structure after the abovementioned compaction procedure while the vacuum bagging process was being prepared. However, the decreased density value can be attributed mainly to the recyclate aspects. In this context, during the sizing the recyclates will always consist of mixture of defined sizes based upon the sieve and fine fractions. The proportion of fine recyclate fragments in R4 is substantially more than that in R10 which explains the improved packing between the skin that led to enhanced in density in recyclate R4. Nevertheless, the sandwich panel are pressure-controlled between the rigid mold in RTM process whereas the sandwich panel are employed under vacuum pressure in VARI process, resulting in the thicker panels in VARI produced panels as shown in figure 4. The typical load-deformation curves under flexural loading and shear loading of the varied sandwich panels is illustrated in figure 5. It is well observed in RTM process both loading behavior that sandwich panels constructed using recyclates R4 gives the highest load absorption of 320 N (flexural load) and 2618 N (shear load). However, there is drop in the load absorption in R10 panels 309 N (flexural load) and 2452 N (shear load). This attributed to the fact that recyclates R4 and R10 had different moments of inertia. A similar manner is observed in VARI sandwich panel with recyclates R4 has effective load absorption of 302 N (flexural load) and 2372 N (shear load) while recyclate R10 has load absorption of 251 N (flexural load) and 2289 N (shear load). Further, sudden fall in the load deformation curve is represented for all samples. This force dropping is mainly correlated with failure in the sandwich core layer.

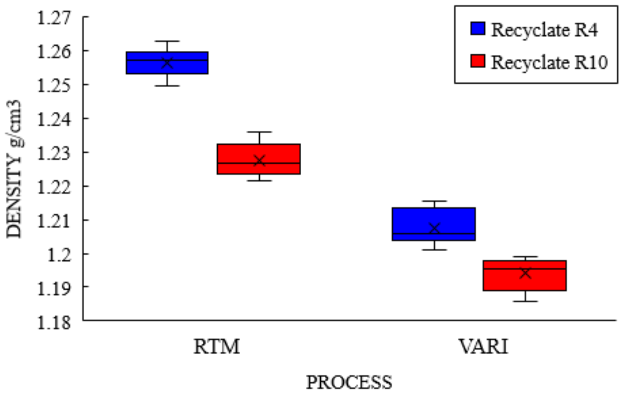


Figure 3: Distribution of densities

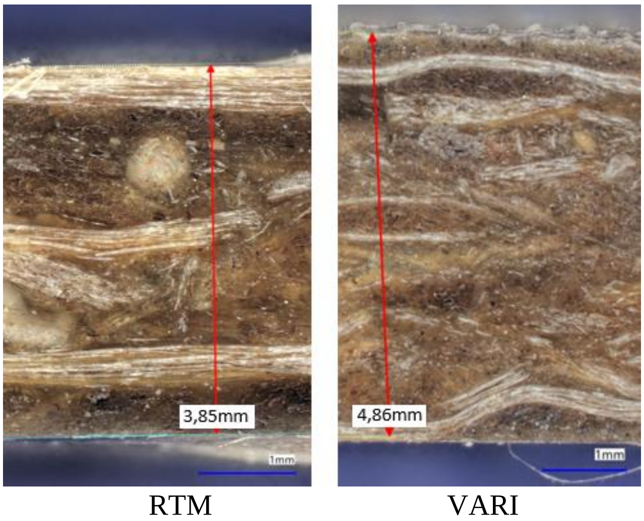


Figure 4: Sandwich composite panels thickness variation of RTM and VARI process

Table 1: Flexural and shear properties

Manufacturing technique	Recyclate size	Flexural load N	Flexural strength MPa	Flexural modulus GPa	Shear load N	Shear strength MPa
RTM	R4	320 (2.9)	190.3 (10.2)	17.4 (0.7)	2618 (81)	20.1 (2.2)
	R10	309 (5.6)	186.5 (9.1)	16.6 (0.6)	2452 (67)	18.1 (1.9)
VARI	R4	302 (1.8)	170.9 (12.7)	15.5 (0.4)	2372 (43)	18.6 (3.7)
	R10	251 (2.2)	157.1 (5.6)	12.8(0.7)	2289 (56)	16.6 (5.3)

*(standard deviation)

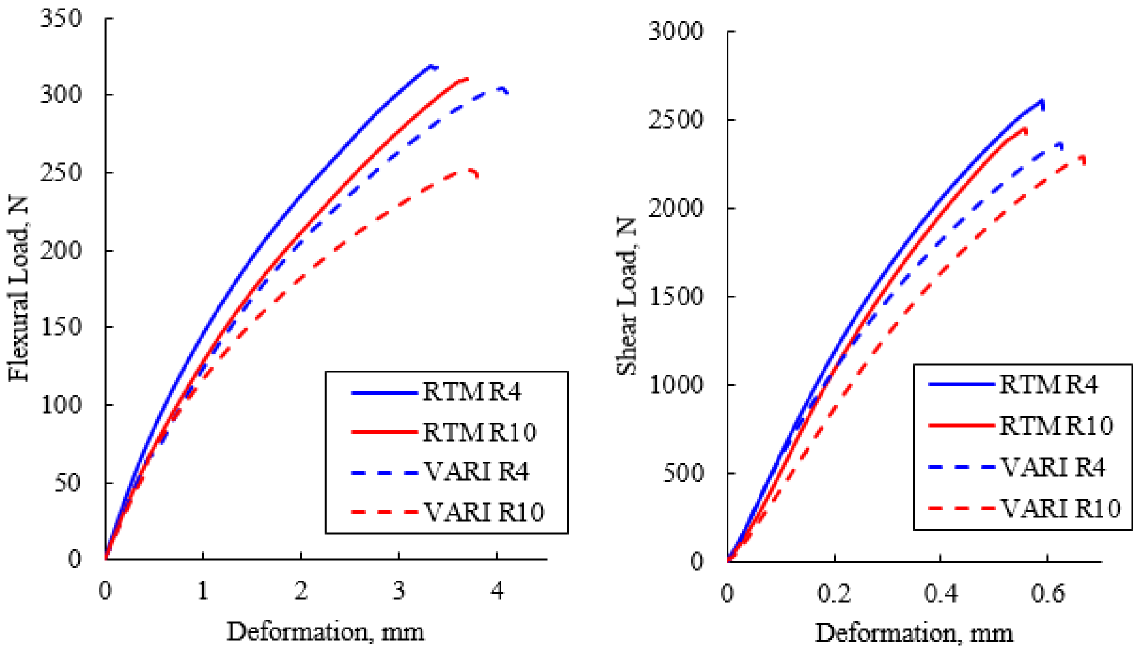


Figure 5: Load-deformation curve under flexural and shear loading

Table 1 shows the flexural strength, moduli, and shear strength of varied configuration of sandwich composite panels. Standard deviation values obtained from the test repetitions are given in parentheses. The maximum flexural strength, flexural modulus and shear strength was found as 190.3 MPa, 17.4 GPa and 20.1 MPa in the sample having recyclates R4 processed using RTM, respectively. The minimum flexural strength, modulus and shear strength was found as 157.1 MPa, 12.8 GPa and 16.6 GPa in the sample having recyclate R10 processed using VARI. According to this, panels processed by RTM have improved flexural and shear properties compared to VARI. However, it is observed that within RTM and VARI processed panels, recyclate R4 exhibits better improved properties than recyclate R10. This tendency is observed due to the crucial characteristic of recyclate's moment of inertia (as function of geometry). Additionally, on comparing the flexural properties in reference to [31], there is difference in the results provide evidence to moisture absorption in the specimens which degrades the fibre-matrix interface and affects the mechanical properties. The sandwich panel failure types include facesheet indentation, facesheet yielding, core shear failure and facesheet failure as shown in figure 6. During the flexural test and short beam shear test, the upper skin surface of the test specimen was forced to compressive under the bending load and the lower skin surface was forced to pull (tension) at the same time. This relative stress weakens the interface between the skin surface and the core. Thus, the sandwich composite specimen's ability to carry forces is lost once the skin surface material is damaged, even if it is still deforming. As a result, the fibre breaks and fracture occurred abruptly on the tension side of the specimen resulting in the formation of crack in the core that propagates along the recyclates.

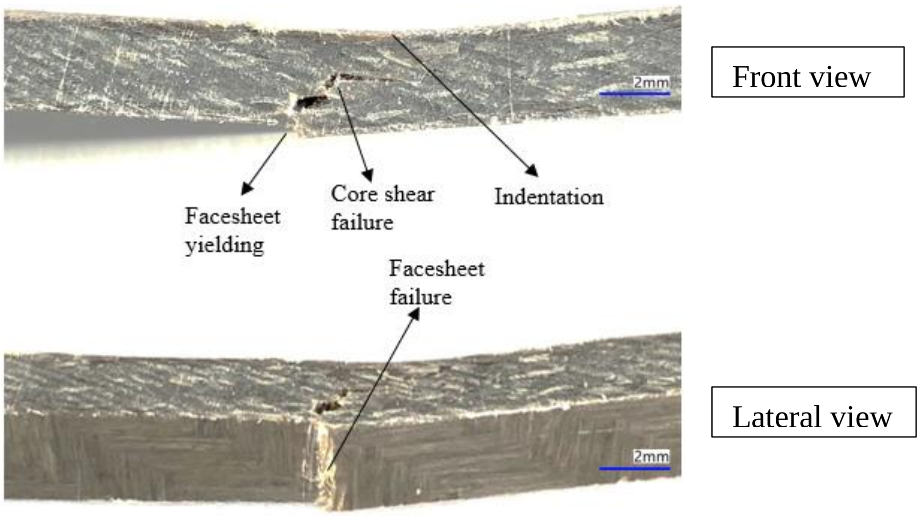


Figure 6: Failure types in flexural and shear loading. (Top) Front view and (Bottom) Lateral view of sandwich composite panels

4 SUMMARY

The objective of this paper is to quantify the optimal manufacturing method for processing ecologically sustainable recyclate sandwich composites. Resin transfer moulding and vacuum assisted resin infusion are used to integrate recyclates in the sandwich composite panel. As a result, this study provides a preliminary understanding of the constraints and prospective methods of processing environmentally friendly sandwich composites made of recycled materials. The results depict that sandwich composite panel with recyclate R4 and RTM process have enhanced density due to the improved packing of R4 recyclates fragments and better consolidation of sandwich structure. The sandwich composite showed about 15% reduction in the mechanical properties between RTM and VARI processes: whereas 8% reduction in the mechanical properties between R4 and R10 recyclates. These findings demonstrate unequivocally that manufacturing processes and recyclate size have a significant impact on material performance. Nevertheless, the RTM-processed sandwich panel using recyclate size (smaller) had the high load absorption, flexural, and shear characteristics comparing of all the sandwich panels.

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