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Morphology of ply drops in thermoplastic composite materials manufactured using laser-assisted tape placement

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Abstract

Mechanical properties of composite laminates can be tuned by either tailoring ply orientations or by using ply drops to change thickness profiles. The latter cause resin-rich pockets to form in thermoset composites that are autoclave cured after lay-down. This paper focuses on the morphology of ply drop regions with carbon fibre thermoplastic composites manufactured using in-situ consolidation with laser-assisted tape placement. Our work shows that when laying a 0 deg ply (parallel to the ply drop) over a ply drop then the ply readily conforms to the shape of the ply drop, eliminating voids. However, when a 90 deg ply covers a ply drop, the processing direction affects behaviour. When the ply ascends a ply drop, a void is created. On the other hand, when the ply descends a ply drop, the substrate changes its shape due to combined laser heat and roller pressure, leading to significantly smaller voids.

Keywords: Automated fiber placement; Tape placement; Defects; thermoplastic resin

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1. Introduction

Due to their high specific stiffness and strength composites have found increasing use in recent years. Composite structures with enhanced efficiency can be achieved by spatially varying their mechanical properties [1, 2]. Two methods exist to spatially vary mechanical properties: varying the fibre angle by steering the fibres, or varying the thickness by dropping plies. The latter is the focus of the current work.

Many studies have focused on optimising composites with varying thickness. The most commonly-used approach uses evolutionary algorithms, typically genetic algorithms, to optimise the number of layers per 'patch' (i.e., a sub-domain of the structure), while simultaneously optimising the ply

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drop order and stacking sequence, limited to a discrete set of angles (e.g., 0°, ±45°, and 90°). This area of research is referred to as laminate blending [3, 4, 5, 6, 7] and assumes that potential ply drop locations (i.e. patch boundaries) are pre-specified by the user. Other works do not necessarily limit possible fibre angle orientations to a pre-defined set [8]. Techniques where the ply drop locations are not pre-specified use continuous optimisation methods. Shape optimisation is used to determine the areal shape, hence ply coverage and ply drop locations of the different layers [9]. The discrete material and thickness optimisation method is another technique, where the fibre angles belong to a discrete set and fictitious density variables are used to select the ply angles at any given location. This method has been applied to compliance and buckling optimisation problems [10, 11, 12].

The simplest ply drop schemes consider inner or outer blending, where the layers are dropped from the symmetry plane or from the outer layers, respectively. To determine the optimal ply drop order, guide-based designs can be used [4]: a stacking sequence for the thickest laminate, called the guide laminate, and the number of layers per patch are defined. The stacking sequence is then derived by dropping layers from the inside or outside of the guide laminate, depending on whether inner or outer blending is used. A method that offers more possible ply drop orders and takes into account industrial guidelines employs stacking sequence tables [13, 14, 15]. Both ply drop order and guide laminate are optimised.

An important consideration that is often neglected during optimisation is the (local) effect of ply drops. A ply drop is schematically shown in Figure 1. The plies that are not influenced are referred to as core plies, the plies covering the ply drop are the belt plies. Due to the stiffness of the belt plies, a resin pocket arises. The size of the resin pocket is described by the thickness of the dropped plies and the taper angle, which is defined as the angle the belt plies make with respect to the core plies.

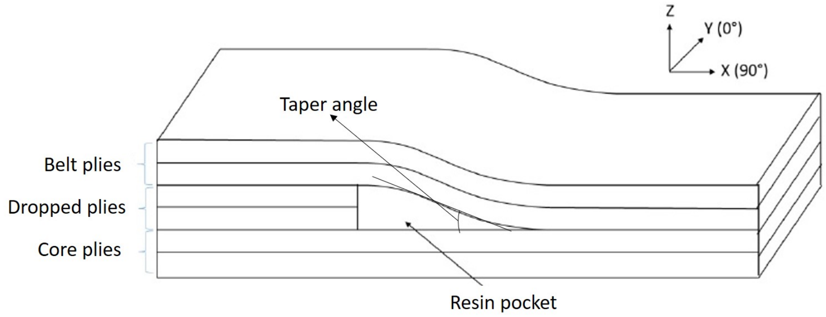


Figure 1. Schematic view of a ply drop.

Taking the effect of ply drops into account is computationally expensive. Instead, guidelines are often used during optimisation. Some guidelines for ply drops were generated by Cairns et al. [16], who showed that the influence of the ply drop depends on the percentage of the thickness that is dropped. Hence dropping multiple plies at the same location has a large effect: the delamination growth rate is increased. To limit the effect of multiple ply drops at the same location, adjacent plies were recommended not to be dropped. Finally, internal ply drops were shown to be preferable over external ply drops because external ply drops promote delamination

[16]. Later, more guidelines were developed: the staggering distance (i.e., distance between ply drops) was limited to three times the thickness of the drop off, unless a 45° ply is dropped, in which case it should be eight times the thickness of the drop off. Dropping a 45° ply leads to higher interlaminar shear stresses, hence the higher staggering distance. Finally, to reduce the relative drop in stiffness, it was recommended that 0° plies be dropped in thick sections, while 90° plies be dropped in thin sections [17].

Embedding tubes or other foreign materials in laminates creates discontinuities into the stress flow of the laminate. Indeed the neighbouring ply to an inclusion could be expected to behave similarly to that of a dropped ply. For structural health monitoring systems using embedded tubes, the size and shape of these tubes and of the resulting resin pocket have been investigated. Two examples are shown in Figure 2, clearly highlighting the location of the resin rich areas [18]. Later, it was shown that the resin pockets are not always symmetrically located around the embedded tube, which was shown both experimentally and also by finite element analysis (FEA) [19, 20]. In related work, it is noted that if the adjacent plies are made parallel to the optical fibre, the resin rich area can be minimised, or even eliminated [21]. This effect is attributed to the resin flow that occurs during infusion [22].

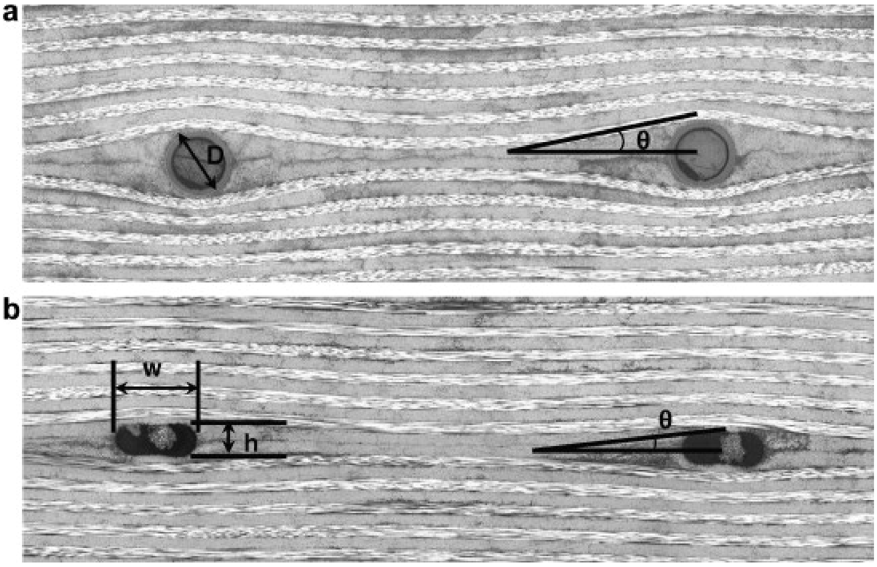
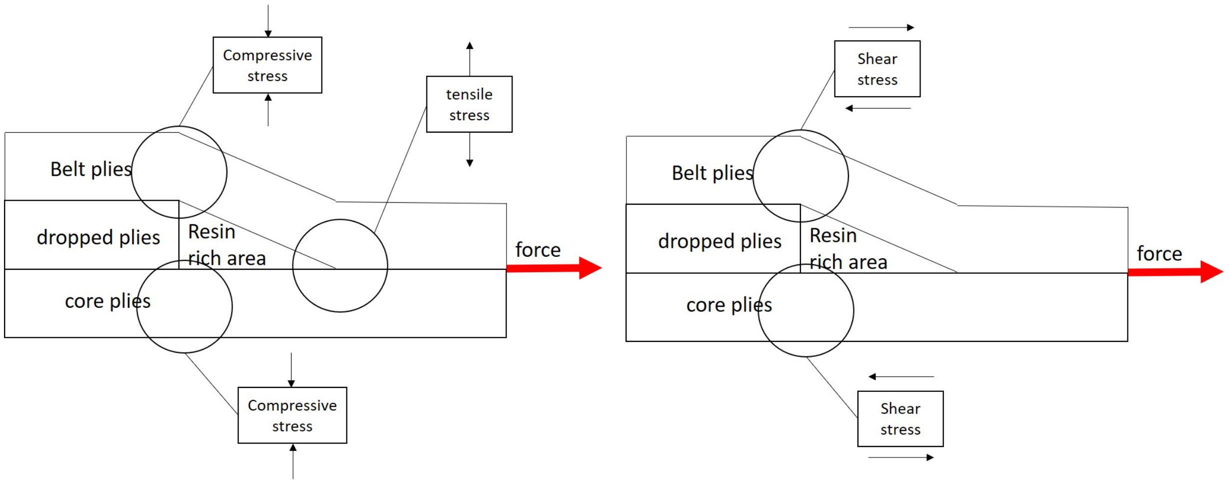


Figure 2. Shape of the resin rich area around tubes for structural health monitoring: a) circular tubes; b) elliptical tubes [18]

To model the effect of ply drops, the shape of the resin pocket is often idealised to be triangular in shape [23, 24, 25]. Usually the pocket is assumed to be resin rich, but a more conservative approach is to assume it is a void, which increases the stress intensity factor [24]. The orientation of the dropped ply has a large influence on the effect of the ply drop. When off-axis plies are dropped, significant shear stresses occur, while dropping a 0° ply (i.e., fibres perpendicular to the load) has a negligible effect on the stress distribution [26].

Two different failure mechanisms can occur at a ply drop location: when the taper angle is shallow, microbuckling occurs, while delamination happens when the taper is steep [27]. The delaminations are caused by an increase in normal stress σ_{zz} and shear stress τ_{xz}. A schematic view of these stresses is shown in Figure 3. When a tensile force is applied to the thin part of the composite (90° direction in Figure 1), and by considering the belt plies as a beam leads to a reaction (compressive stress) where the belt and dropped plies meet. At the tip of the resin rich pocket on the other hand, a tensile stress exists, trying to separate the belt and core plies. The tensile force is reacted by compression where the belt and core plies meet as well as by a shear stress which is greatest at the point of the drop off.

Recently, ply drop locations were shown experimentally to be hot spots for delamination onset. By modelling these ply drops as triangular-shaped resin pockets, good agreement between FEA and test was achieved: the stiffness matched to within 1.5%, and the maximum load to within 15%. Possible reasons for the difference is the variation in specimen dimensions [28]. Another work showed an improvement in fatigue life by having two small drops in thickness rather than one large drop. As a result, the number of cycles to failure increased by 25% [29].



(a) Normal stresses around a ply drop.

(b) Shear stresses around a ply drop.

Figure 3. Schematic view of stresses around a ply drop area (adapted from [17]).

The material type is another important factor in the ply drop morphology. All results discussed so far consider thermoset materials where the resin can flow during curing or infusion, and therefore can fill the gaps between fibres. If a thermoplastic material is used that is not heat-treated after lay-up, triangular-shaped voids may appear rather than resin-rich areas. This hypothesis is examined in the current work.

The manufacturing method exerts a large influence on pocket morphology. When using automated fibre placement (AFP), the roller plays an important role. When using a rigid roller, Gruber et al. [30] noted that the dropped ply squeezes towards its free edge, and small empty pockets arise, as shown in Figure 4. Using FEA, a conformable roller applied over non-uniform surfaces, such as ridges and gaps, showed that the force is distributed in a non-uniform way. Furthermore, a notable gap between the surface and the roller was found, implying that the behaviour shown in Figure 4 would also happen with a conformable roller [31].

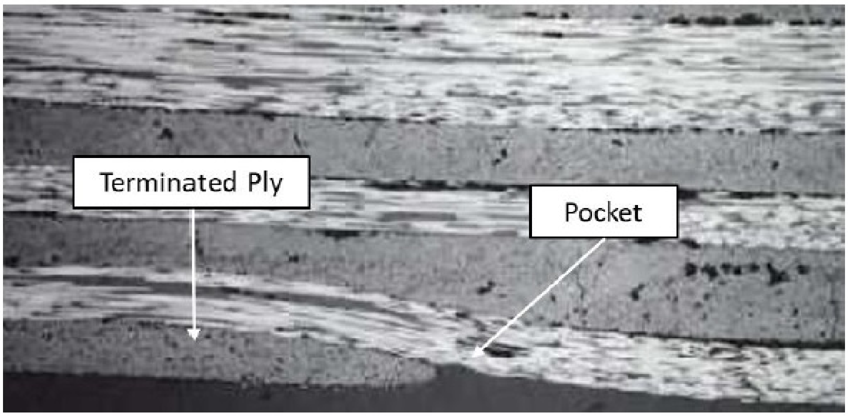


Figure 4. Micrograph of dropped ply manufactured using AFP and a rigid roller [30].

The fibre orientation of the belt plies also has an important effect on pocket morphology. For a unidirectional thermoplastic laminate containing gaps resin rich areas were shown to not arise. During infusion or curing of thermoset composite materials it is assumed that fibres migrate and in this way fill the gap that exists after placing the prepreg material. For cross-ply laminates (0/90) a resin-rich area was observed: the fibres could not migrate to fill the gap [32].

Considerably less literature is available concerning ply drops or variable thickness laminates in thermoplastic composite materials. Slange et al. [33] investigated rapid AFP followed by stamp forming, which was shown to lead to fast processing of good quality structures. Zenker et al. [34] studied the effect of small gaps (1-7 mm), where AFP and different secondary processes were used. In all cases a good final product was obtained. Other work has focused on the temperature at the location where there are small overlaps during winding. It was shown that at locations with a bump present, the temperature rose by more than $100°C$ [35].

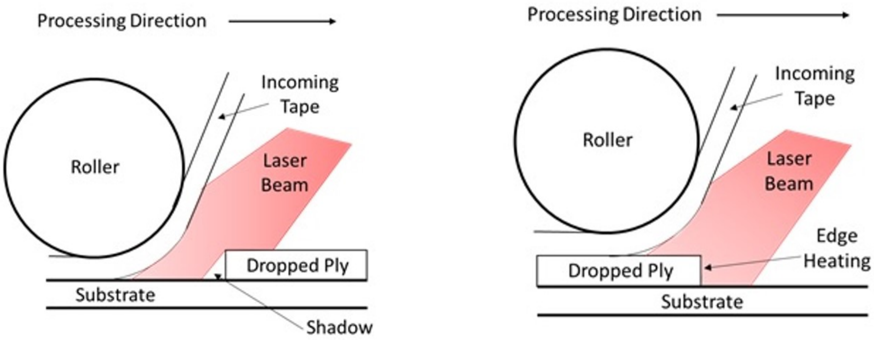
Laser angle and the resulting temperature of the tape and substrate are important parameters when considering thermoplastic composite in-situ consolidation. The heating of the tape and substrate is a complex process. Scattering of the laser beam, causing a short shadow before the nip point, resulting in the tape and substrate cooling down before they are brought into contact has to be considered [36, 37]. The most important consideration for the current work is the laser angle and focus point. Stokes-Griffin et al. [38] showed that focusing the laser equally on the incoming tape and substrate, or focusing more on the incoming tape leads to the best bond quality. Focusing the laser more on the substrate leads to a decrease in bond quality. In line with these findings, it was decided to focus the laser equally on the incoming tape and substrate in current work.

In light of these previous works, the morphology of ply drops in carbon fibre thermoplastic materials manufactured is considered using laser-assisted tape placement (LATP) with in-situ consolidation to assess the necessity of a secondary process. Since the polymer is above melt temperature for only a short time, when a roller applies consolidation pressure, it is expected voids will occur rather than resin-rich areas in thermoset composites. To investigate the possibility of obtaining good quality (i.e., void-free) ply drop areas the extreme cases for dropped and belt ply (i.e., 0° and 90°) are investigated.

2. Experimental setup

2.1. Test configuration

The orientations of the dropped and belt plies have a significant effect on the size of the resulting ply drop. The direction of roller movement when the belt ply is a 90° ply, as shown schematically in Figure 5 also affects the ply drop region. When the roller ascends a dropped ply, shown in Figure 5a, the laser does not heat up the side of the dropped ply, but only the top of the dropped ply. The shadow indicated is exaggerated in size compared to the laser beam. In reality the shadow area is not expected to have a large effect on the temperature distribution in the substrate, recognising that the side not heated does have an effect on the resulting morphology due to the increased mobility of the substrate. Furthermore, the roller pushes the material into the dropped ply. When the roller descends on the other hand, shown in Figure 5b, the laser heats up both the side and top of the dropped ply, and the roller can squeeze out the (molten) material during the pass, possibly leading to a smaller void.



(a) Ascending direction. **(b) Descending direction.**

Figure 5. Schematic view of laying down the belt ply in 90°direction.

Other possible variables include the number of plies dropped, the number of belt plies, and possible laser annealing of the laminate (i.e. heating the previously laid material with the laser and applying pressure with the roller without laying additional material). However, for our study the number of variables was limited: only one ply is dropped, and only one belt ply is subsequently added. No extra passes with the laser were performed. The orientation of the substrate was kept constant at $[0_4]$. The dropped ply and belt ply were considered to be either 0° or 90° to be able to assess the extreme cases. Also taking the roller direction into account for the cases where the belt ply is 90°, a total of six cases were studied in detail. An overview of all cases is provided in Table 1.

Even though for structural problems the sawtooth pattern that arises when dropping, for example, 45° plies could be the worst condition on the structure, these angles are not used in the current work. There are multiple reasons for not including these angles in this initial study. Firstly, rather than an extensive study, this work provides an initial study on the feasibility of making thermoplastic composite structures with ply drops using in-situ consolidation. Secondly, the number of samples would significantly increase since both the dropped and belt ply now have extra variables, and the processing direction is important in this case as well: seven additional cases would have to be checked, more than doubling the number of cases. Thirdly, taking samples for optical microscopy is more difficult with 45° angles since the location of the ply drop constantly changes, and most likely the shape of the ply drop does so as well. Hence, a 3D imaging technique such a X-ray computed tomography would be more suitable, but this was considered to be outside the scope of the current project. When 0° and 90° is used, the ply drop is a one dimensional problem since the morphology does not change along the length of the ply drop region and optical microscopy can be used. As such, only a single sample is shown for each case, but at least two samples were checked per case, all showing the same characteristics.

Table 1. Overview of the lay-ups investigated.

ine case	dropped ply	belt ply	roller direction	abbreviation
ine case 1	0°	0°	N/A	$[S/0_d/0]$
case 2	0°	90°	ascending	$[S/0_d/90_a]$
case 3	0°	90°	descending	$[S/0_d/90_b]$
case 4	90°	0°	N/A	$[S/90_d/0]$
case 5	90°	90°	ascending	$[S/90_d/90_a]$
case 6	90°	90°	descending	$[S/90_d/90_b]$
ine				

2.2. Manufacturing

The substrate for the test samples was manufactured first. For LATP of thermoplastic tapes, achieving a securely positioned first layer can be challenging. Heated tooling has been used successfully for this purpose in the past. However, for this study, the heat could influence the shape of the defect around the ply drop: the resin could stay in molten state for longer than on a non-heated tool, and fill a void that would reside if a non-heated tool was used. Instead, a square box section was used and four unidirectional layers were wound around it. This process leads to panels with the target lay-up without using a heated tool. After manufacture, the corners were cut, giving four plates. These plates were then secured on the tool and the dropped and belt plies were laid down.

The linear tape feed speed was set to $3m/min$. The LATP system used was provided by AFPT GmbH. During manufacture, the laser power was controlled using a temperature-feedback loop. The target temperature was set to 400 °C. The laser angle relative to the substrate was set before each layer such that the focus of the laser was close to the nip point (i.e., the point where the roller presses down the incoming tape on the substrate) hence the substrate and incoming tape are heated over the same length. The laser spot size was 20 mm wide in the tape direction and 40 mm along the length of the tape. The material used was provided by Toho Tenax: TPUD PEEK-IMS65 (i.e., carbon fibres in PEEK). It was slit to 6.35 mm wide tape, with a fibre volume fraction of 60%. A micrograph of the as-received material is shown in Figure 6. On each pass, a single 6.35 mm wide tape was laid down. The nominal thickness of a layer was 0.18 mm. The pneumatic pressure on the compaction cylinder was set to 2.5 bar. The roller used was a conformable silicone roller, provided by AFPT.

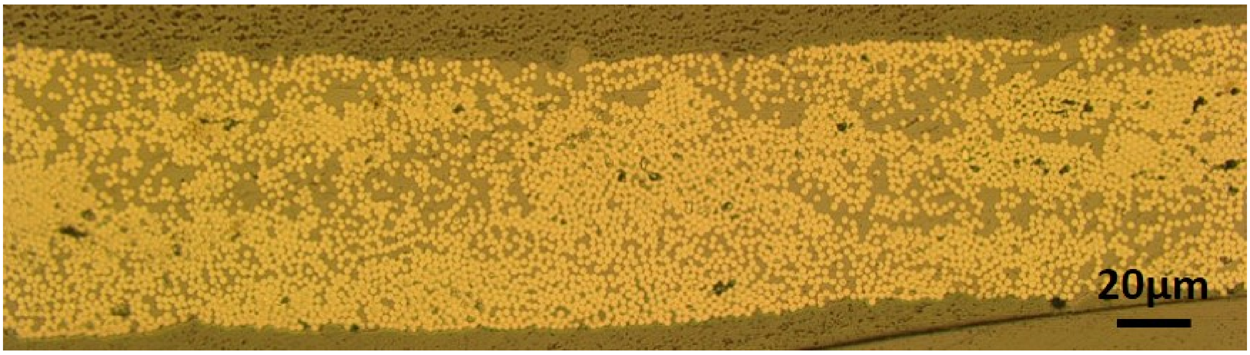


Figure 6. Micrograph of tape as received.

When adding the dropped plies, the 90° ply drops could not be laid down using the LATP machine, noting that the set-up is such that at the end of each tape laid down, an unprocessed part remains. This unprocessed part would then have to be cut off manually, introducing a lot of uncertainty about the exact location and process parameters at the location of the ply drop-off. Instead, the tapes were laid down by hand, using a soldering iron to apply heat and fix the tape to the substrate. Next, the LATP head roller was passed over the hand laid tape with the laser active to aid the consolidation process. This is done in an attempt to replicate the LATP process as closely as possible: it was noticed in earlier work that the tows were slightly wider and thinner after manufacturing [39]. The 0° plies were laid by the LATP head in the usual way; the difference in the layup strategy for the 0° and 90° dropped plies needs to be considered when examining the results. A dropped ply consists of three 6.35 mm wide tows laid one by one adjacent to each other. This process is sufficient to have the laser power (and thus nip point temperature) level off and leaves enough room on the substrate to lay down the belt ply, which covers the complete width of the panel.

2.3. Optical Microscopy

After manufacture, square (15mm side length) microscopy samples were harvested in the region of the ply drop. Care was taken during cutting to not introduce too much heat, to avoid re-melting of the resin. The samples were mounted to make the handling and polishing steps easier using Struers Durocit acrylic cold mount system as it does not require heat or pressure to be applied, guaranteeing minimum distortion of the sample. After mounting, the samples were polished using 240, 400, 600, and 1200 grit abrasive paper to obtain a smooth surface finish. Finally, the samples were studied using optical microscopy. For each case two samples were initially taken. However, some of the samples showed delamination which was expected to be due to the cutting strategy used. Hence, another set of samples was cut in a different way to check that the delaminations were due to the cutting and did not occur during manufacture.

3. Results

Before considering cross-sectional morphology around the ply drops, first the case without belt plies is discussed. Only a 0° dropped ply is considered, since this ply is expected to change shape during lay-down of the belt ply: when the resin melts, the fibres could migrate. Due to the manual manufacturing process of the 90° dropped ply and the inextensibility of the ply in the direction of the ply drop, it is expected that no change in the shape of the dropped ply will be observed. Hence, this discussion has two goals: one, establish the base state to identify any effect of belt plies; two, study the effect that the substrate has on the ply drop defect.

The external ply drop with plies perpendicular and parallel to the fibres in the ply below is shown in Figure 7. In this case the substrate is changed to be able to lay down the dropped ply in the 0° direction, however, the difference between both plies is important. On the left, where the plies are perpendicular to each other, some delamination has occurred due to cutting, however, the delamination has not influenced the lay-out severely. A clear difference is shown between the two cases: when the substrate and the dropped ply are parallel the ply 'sinks' into the substrate, while this does not happen when the substrate is perpendicular to the dropped ply. This has two important implications. One, the initial height of the ply drop is higher when the dropped ply is perpendicular to the substrate. Two, by laying the 90° ply using the method described in section 2.2, no significant change is expected: the ply would not 'sink' into the substrate in any case. Furthermore, it is observed that the edge of the dropped ply is straight.

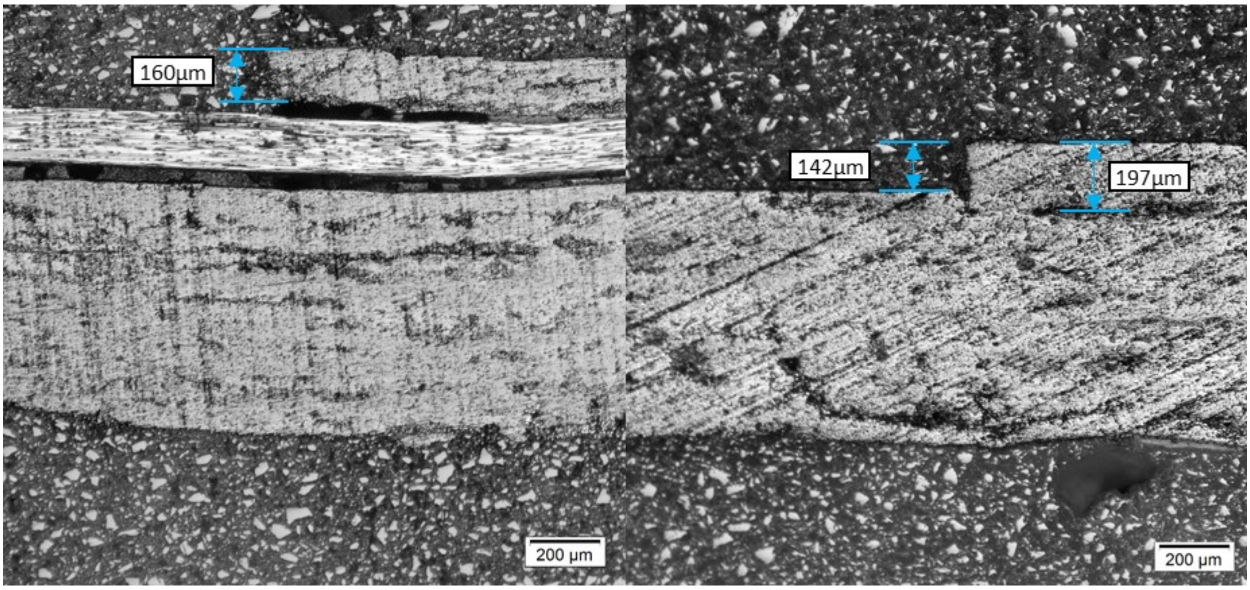
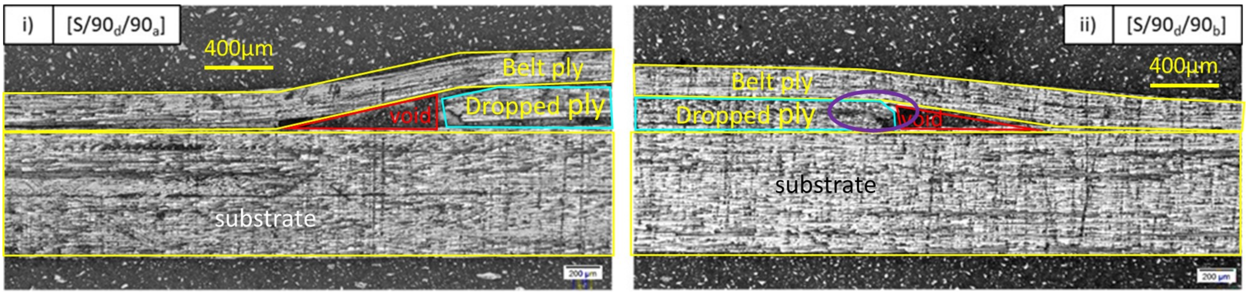


Figure 7. Micrograph of external ply drop specimens without belt plies containing a ply drop with fibres perpendicular to the ply below (left) and ply drop with fibres parallel to the ply below (right).

3.1. 90°dropped, covered with 90°, ascending

The result of dropping a 90° ply covered with a 90° ply, with the roller ascending, is shown in Figure 8 i). It is observed that the edge of the ply that is dropped is almost straight. The covering ply is slightly curved, probably due to the pressure of the roller. However, interestingly, no resin rich region exists, rather a void is evident. It appears that the thermoplastic material is not in molten state for long enough to migrate into the gap between the core plies and the covering ply. Furthermore, the void is triangular-shaped as was observed for ply drops in thermoset materials in literature. The height is roughly 0.2 mm, which is almost the same as the ply thickness, while the length is 0.8 mm.



(a) Ascending direction. **(b) Descending direction.**

Figure 8. Schematic view of laying down the belt ply in 90°direction.

3.2. 90°dropped, covered with 90°, descending

The result of dropping a 90° ply covered with a 90° ply, with the roller descending, is shown in Figure 8b. In this case the dropped ply is not completely straight, it appears that the dropped ply has been squeezed out and has become thinner towards the side. The location where this squeezing has occurred is marked by the purple circle. This squeezing is further supported by the observation that the ply is thinner: only 0.13 mm. It should be emphasized that only a single ply is dropped, hence the hypothesis that the laser heats the side of the dropped ply when the roller is descending seems to hold: the resin is in molten state when the roller applies pressure leading to the deformation of the dropped ply. Another noticeable difference is that the size of the void is slightly shorter compared to the ascending case, only 0.75 mm, however, this difference in length is negligible. A final difference is that in this case the covering ply is almost straight, implying that the tape tension is more important than the roller pressure when the roller is descending.

3.3. 0°dropped, covered with 90°, ascending

The result of dropping a 0° ply covered with a 90° ply, with the roller ascending, is shown in Figure 9. A first observation is that the edge of the dropped ply is almost straight: only at the top it is slightly deformed. This effect confirms that only the top of the ply is heated, the side of the ply outside of the heated zone remains straight when the roller is ascending. Another observation is that the belt ply is almost straight, not slightly curved as was the case when the dropped ply was 90° rather than 0°.

The behaviour of the belt ply and substrate for this configuration is different to that previously observed. The belt ply is straight in the part where it steps over the dropped ply, rather than being curved as in the previous cases. A significant thickness variation was apparent in the substrate. The substrate has been compressed in the vicinity of the dropped ply. It is likely that this compression occurred during initial laydown of the dropped ply, as both the laser spot and roller are wider than the tape width. This compression may also have been made more pronounced during laydown of the belt ply, when the LATP head repasses this region applying heat and pressure.

A large void/crack is evident in the substrate (highlighted in green) at the bottom of the dropped ply void. As the substrate contains four adjacent plies of the same orientation (0°) it is more susceptible to trans-ply matrix cracking. The crack may have been initiated by either the thermal stresses induced during processing or by the pressure applied by the roller, or a combination of both. While this is a significant defect, it can be avoided by adequate dispersion of ply orientations in a stacking sequence.

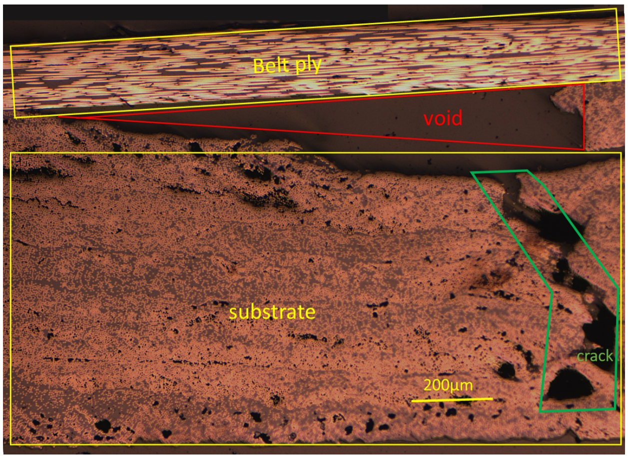


Figure 9. Micrographs of [S/0_d/90] specimens with ascending belt processing direction.

3.4. 0°dropped, covered with 90°, descending

The result of dropping a 0° ply covered with a 90° ply, with the roller descending, is shown in Figure 10. The first observation is that the dropped ply has deformed significantly in this case: it is difficult to identify the exact location where the dropped ply starts. This result confirms that when the roller is descending, and both the top and side of the dropped ply are heated, it can deform significantly. In Figure 10, the outline of the substrate and belt ply are highlighted in yellow. The extent of the substrate deformation is apparent; the thickness of the substrate varies considerably in the region bridged by the belt ply from the substrate to the dropped ply. It is also apparent that the length of the bridged region is longer than previously observed. As shown in the ascending configuration, by having the same ply orientation for the top of the substrate as the dropped ply contributes to troughs in the substrate which are difficult to fill by a belt ply of another orientation.

However, in this case (descending belt ply) the thickness of the void, as well as the taper angle is less than in the ascending case.

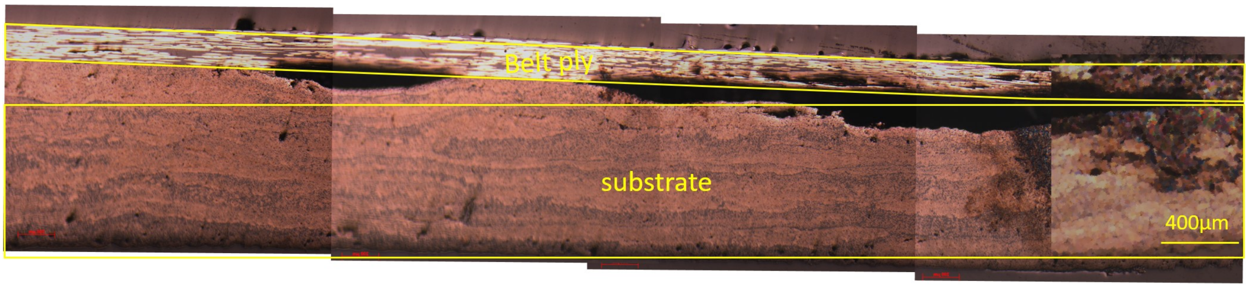


Figure 10. Micrographs of [S/0_d/90] specimens with descending belt processing direction.

3.5. 90°dropped, covered with 0°

The result of dropping a 90° ply covered with a 0° ply is shown in Figure 11. No void is observed in this figure: the covering ply adheres extremely well to the previously laid plies. This positive effect is most likely due to the belt ply being more flexible, as the fibres are running along the drop-off as opposed to across it. This fibre direction in combination with the resin in a softened/molten state, as well as a flexible roller, allows the tape to conform to the drop-off region. In addition, it appears that the 90° ply has been pushed into the substrate 0° ply, reducing the ply drop-off step.

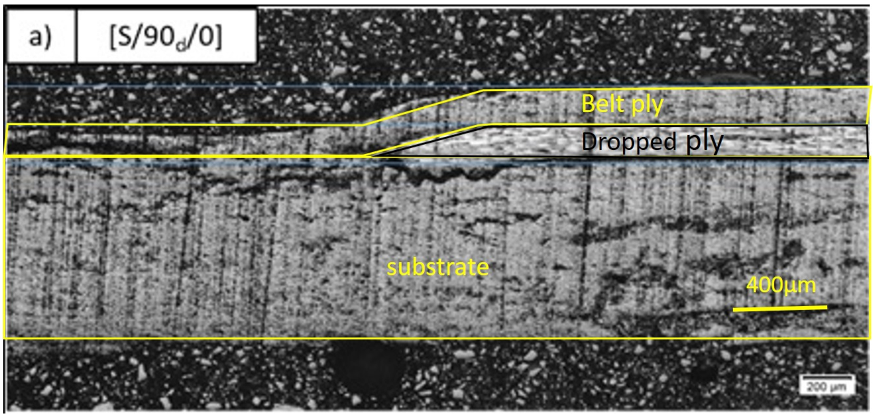


Figure 11. Micrograph of [S/90_d/0] specimen.

3.6. 0°dropped, covered with 0°

The result of dropping a 0° ply covered with a 0° ply is shown in Figure 12. No void is observed in this figure. As all of the plies have the same orientation, i.e. the fibres are running parallel to the ply-drop step, they conform well as the fibres 'wash-out' to fill any gaps during processing. The exact location of the ply drop is hard to pinpoint exactly, but from the thickness distribution the ply drop can be deduced to be located in this area: on the left the thickness equals five times the ply thickness (i.e., four plies in substrate plus the belt ply), on the right the thickness equals six times the ply thickness. The gradient of the belt ply is shallow, allowing additional plies of any orientation to be laid onto it without the risk of creating a bridging void.

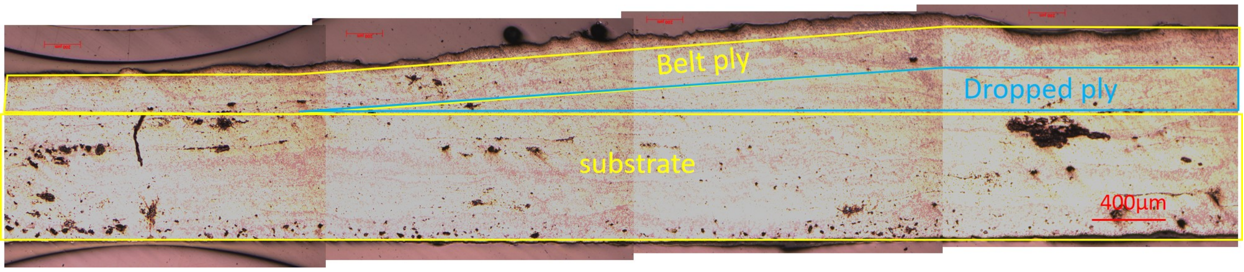


Figure 12. Micrograph of [S/0_d/0] specimen.

4. Discussion

Since most previous work with ply drops found by the authors considered thermoset material, it is worth comparing the current findings to those in the literature. First of all, it must be emphasized that the manufacturing process is inherently different. Thermoset materials are manufactured whereby fibres are laid down and infused and/or subsequently autoclaved, while thermoplastics in the current work are laid down using LATP, with in-situ consolidation. Hence, the resin is only in a molten state for a short time. It has to be emphasised that only a single material and a single set of processing parameters is checked in the current work, however, the results do give an indication of the fundamental differences between manufacturing processes.

The manufacturing methods significantly influence the triangular defects that appear during processing: for thermoset laminates, the triangular defects are filled with resin, whereas in thermoplastic laminates, voids are formed. The form of the defect directly influences mechanical properties: a resin rich pocket can be a weak spot in the laminate, but has similar thermal properties to the surrounding material. Voids were shown to increase the stress intensity factor [24], also trapped air in a void can expand on heating, potentially increasing the size of the void. The occurrence of voids was expected due to the short time the thermoplastic resin is in a molten state.

Another notable difference is the taper angle, and how to obtain it. In thermoset materials the thickness of the plies remained constant during infusion (when dry fibres were placed and infused) or curing (when prepreg was used to manufacture the laminates), while in the current work, thinning of the dropped plies is sometimes observed. This implies that the taper length is not the only measure that is important. For example, in Figure 8 the height of the void is clearly different in both cases while the same ply orientation is dropped. The influence of this difference in void shape on the onset of delamination should be investigated in more detail in future work.

In their study of variable thickness thermoplastic laminates using LATP, Slange et al. [33] showed an example of the same type of voids observed for a dropped ply in the 0° direction with the belt ply at 90° in the descending direction. Squeezing of the dropped ply before stamp forming is evident for materials from two different suppliers. The speed of placement was four times faster than in the current work, showing that the voids in this lay-up are not influenced by the placement speed or material supplier. After stamp forming the voids disappeared.

Zenker et al. [34] investigated the effect of gaps ranging from 1 to 7.35 mm in width in laminates processed by LATP along with a secondary consolidation step. Their LATP step laid tape at a speed four times faster than used in the current study, a higher compression force was also exerted during their LATP process. Due to the small distance between the ply drops, the belt ply did not always make contact with the substrate, indicating the pressure distribution differs from the work presented here. They also observed voids around the ply drop area, which were usually larger than those found in the current work due to the small gap size and different pressure distribution.

Both dropped and belt plies were found to have a large influence on the final size of the void. When using a 0° belt ply, the ply and roller are sufficiently flexible to completely comply to the substrate: with both a 0° and 90° dropped ply no voids were found. This fibre 'wash-out' was also observed in thermoset materials when a 0° ply was covered by a 0° ply, as shown in the left of Figure 13 [32]. Interestingly, for a [0/90] laminate with gaps/overlaps, resin-rich areas were found, shown in the right of Figure 13 [32]. As shown in the figure, 0° plies are dropped, and a resin rich area is created both above and below the covering 90° ply. In thermoset materials these resin-rich areas imply the fibre volume fractions decrease in these areas. Hence, for thermoset materials a 0° ply is not as conformable as when using LATP.

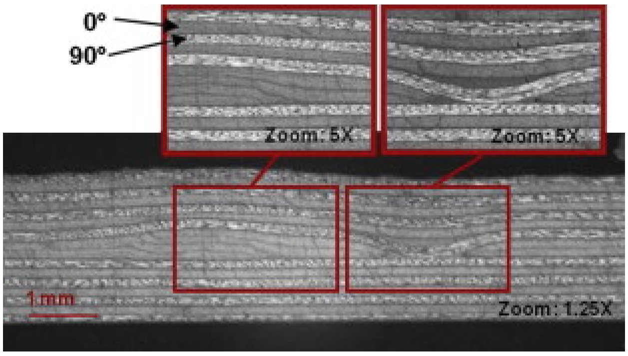


Figure 13. Micrograph of cross-ply laminate with gap and overlap [32].

When using a 90° belt ply voids do occur, and a new variable has to be taken into account: the processing direction. This was expected since neither the plies nor the roller can deform to the exact shape of the ply drop, as was also mentioned by Gruber et al. [30]. This observation is also in line with that observed for thermoset materials: the fibres have to bridge the ply-drop gap, leaving a region under the belt ply without fibres. The influence of the direction of the dropped ply is limited when the roller is ascending: the dropped ply hardly deforms and thus the height of the void is the ply thickness. The length of the resulting void differed between the 0° and 90° dropped plies with the roller ascending, but this can be attributed to the small variation in height of the substrate.

When the 90° belt ply is laid down in the descending processing direction, a clear difference between a 0° and 90° dropped ply is observed. While the 90° ply becomes slightly thinner, reducing the height of the void, the 0° ply deforms due to the laser heating the ply and the roller applying pressure, leading to a much longer, but shallower ply drop off. The reason for the shape change in the dropped ply is that the laser is heating its top and side, after which the roller applies pressure, which leads to the ply being spread out over a wider area. The laser was focused equally on the tape and substrate, resulting in the dropped ply (substrate) being in a molten/softened state when the roller pressure was applied.

Based on all these findings it can be concluded that it is possible to obtain a void-free ply drop using in-situ consolidation. In the current work this was only obtained when the belt ply was in 0° direction (i.e., parallel to the ply drop), however, it is expected that a small offset between ply drop and belt ply would still lead to a void-free ply drop region. The magnitude of this angle needs to be determined either experimentally or by developing accurate models of the ply drop region. The outcome of such research would lead to a design guideline to implement void-free ply drops using in-situ consolidation. It may be worth investigating whether the squeeze flow effect that was observed in the case of both dropped and belt ply being 0° could be induced without adding the belt ply, for example by only heating the substrate and passing the roller without laying down a new tape. This approach could lead to void-free results without a secondary process, at the expense of adding an additional robot pass.

Other variables that may be influenced include the influence of the direction of the core plies: from the non-covered ply drops it does appear that it may have a significant influence. When the core plies are in the same direction as the dropped ply, the dropped ply sinks into the core plies, reducing the ply thickness, and thus also the size of the void. However, more work needs to be done to confirm these findings.

5. Conclusion

The morphology of ply drops in thermoplastic composite materials manufactured using laser-assisted tape placement with in-situ consolidation has been investigated in the current work. Compared to thermoset materials, that are usually infused and/or autoclaved after processing, the regions that are free of fibres, are voids rather than resin-rich regions. The implications for delamination onset or fatigue behaviour are not clear: on one hand the difference in stiffness between pure resin and the composite is also large so the influence may be comparable; on the other hand, voids should be avoided in a composite material as much as possible since they often act as crack initiators.

In general, laying up a 0° ply over a ply drop proved to be the best option from those considered: the roller and ply readily conformed to the shape of the ply drop and neither void or resin-rich area were found. This result implies that the ply drop is just a feature, and does not lead to a defect. When using a 90° ply to cover the ply drop using thermoplastic materials, a new parameter comes into play with respect to thermoset materials: the processing direction. When the roller is ascending, the laser only heats the top of the dropped ply, which means that the shape of the dropped ply hardly changes. Hence the void that appears has a maximum thickness equivalent to the dropped ply thickness, and is longer in length due to the inability of the roller to comply to the exact shape of the substrate in the region of the ply drop. When the roller is descending, the laser heats both the top of the dropped ply and the side, which does lead to a change in the topology of the dropped ply: the 90° ply thins slightly towards to drop-off location, the 0° ply spreads out over a wider region. This combined effect leads to a void that is long and not as high as in the ascending case, hence showing a smaller taper angle.

Future work includes investigating the effect of the ply drop defects on the mechanical performance. The influence of having voids rather than resin-rich areas should be investigated. Also the influence of the different shape of the voids when the processing direction is ascending or descending the dropped ply on the mechanical performance requires a more detailed examination. The descending case has a smaller void area, but the smaller taper angle may induce delaminations more easily. Also the angle between ply drop and belt ply that allows good consolidation without any voids appearing should be investigated, which could lead to a new design guideline for in-situ consolidated thermoplastic composite structures. Finally, the effect of the substrate should be considered: if the substrate and the dropped plies are in the same direction, the dropped ply may sink into the substrate, reducing the effective thickness of the dropped ply and thus reducing the height of the void.

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7. Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.

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